Atmospheric Environment 275 (2022) 118996

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Assessment of the greenhouse gas, Episodic air quality and public health benefits of fuel cell electrification of a major port complex

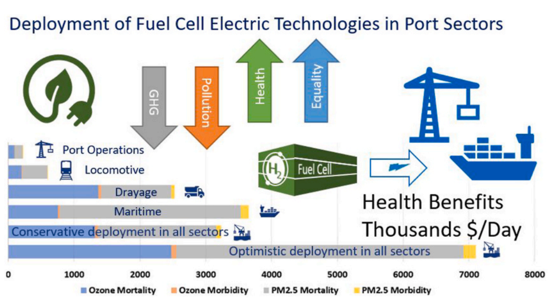
Shupeng Zhu [a], Michael Mac Kinnon [a], James Soukup [a], Andre Paradise [b], Donald Dabdub [b], Scott Samuelsen [a,*]

[a] *Advanced Power and Energy Program, University of California, Irvine, CA, 92697, USA*
[b] *Computational Environmental Sciences Laboratory, University of California, Irvine, CA, 92697, USA*

HIGHLIGHTS

- Fuel cell electrification at a port attains air quality improvements.
- Ocean going vessels and diesel trucks should be targeted first.
- Health benefits are valuable and improve environmental justice.
- GHG reductions are also sizeable if renewable hydrogen is used.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Air quality
Greenhouse gas
Public health
Fuel cell
Environmental justice

ABSTRACT

Communities located adjacent to goods movement hubs (such as major ports) experience degraded air quality (AQ) because of emissions from on-road and off-road diesel equipment, including heavy-duty diesel trucks (HDDT), cargo, and materials handling equipment (CHE), ships, and rail technologies. In response, California is pursuing transitions to efficient and cleaner freight systems by introducing zero-emission technologies as the alternative to conventional technologies. Equipment and vehicles powered by hydrogen fuel cells represent a potential zero-emissions pathway for freight technologies at ports, including HDDT, CHE, ships, and rail applications, referred to collectively as fuel cell electric technologies (FCET). This work is the first to assess the AQ and human health impacts of deploying FCET to provide goods movement services at ports. Specific focus is given to southern California due to existing AQ challenges and the presence of significant activity from the San Pedro Bay Port Complex, which includes the Ports of Los Angeles and Long Beach. Sets of future vehicle and equipment cases are developed spanning a range of FCET penetrations and assessed to quantify how FCET provides improvements in primary and secondary pollutant concentrations and the value of corresponding public health benefits. If fuel cells are used in all technologies considered, the results show significant improvements in maximum 8-h ozone (−2.69 ppb to −5.09 ppb) and maximum 24-h $PM_{2.5}$ (−0.59 μg/m^3 to −2.57 μg/m^3) can be achieved with FCET deployment, and the valuation of health benefits is estimated to range from $3.21 to $7.11 million per day depending on the level of penetration reached in each technology category. Reducing emissions from ships and HDDT is found to attain the highest health savings. Heightening the importance of these benefits, socioeconomically disadvantaged communities are found to experience larger health savings from FCET

* Corresponding author.
E-mail address: gss@apep.uci.edu (S. Samuelsen).

https://doi.org/10.1016/j.atmosenv.2022.118996
Received 25 October 2021; Received in revised form 6 February 2022; Accepted 7 February 2022
Available online 17 February 2022
1352-2310/

deployment in contrast to the population as a whole. As a co-benefit, FCET deployment is shown to result in greenhouse gas (GHG) emission reductions which will further increase with the sourcing of hydrogen from renewable sources. These findings demonstrate the importance of addressing environmental quality associated with the goods movement sector in urban areas and validate support of zero-emission projects through incentives and other policy mechanisms. Furthermore, policies designed to support zero-emission strategies within HDDT and ships powered by renewable fuels represent a promising pathway for air quality and GHG co-benefits.

1. Introduction

Communities in California located adjacent to goods movement hubs (such as major ports) experience degraded air quality (AQ) as a result of significant criteria pollutant emissions from on-road and off-road diesel equipment including heavy duty diesel trucks (HDDT), cargo and materials handling equipment (CHE), ships and harbor craft, and rail technologies such as locomotives (The Port of Los Angeles a, 2017). The San Pedro Bay Port Complex (SPBPC), which includes the Ports of Los Angeles and Long Beach and represents one of the largest and busiest container port complexes in the world (The Port of Los Angeles a, 2017), is a primary example. Located in the South Coast Air Basin (SoCAB) of California, emissions from the SPBPC impact 17 million people residing in the Los Angeles metropolitan region (See Fig. 1) including contributing to high levels of ground-level ozone and fine particulate matter ($PM_{2.5}$) (Fujita et al., 2016; Stewart et al., 2019). Despite the tremendous economic importance the SPBPC provides to both the region and the U. S., the mitigation of the associated AQ impacts is necessary given the resulting health consequences, particularly as they are often associated with environmental justice concerns (Houston et al., 2008). It is well known that air pollution health damages are not equally distributed across society, and low-income and minority communities tend to experience higher exposure burdens (Banzhaf et al., 2019; Brulle and Pellow, 2006). Therefore, finding solutions that help provide equitable access to healthy air is of paramount importance (Fowlie et al., 2020).

Current technologies operating within goods movement capacities at the SPBPC are typically diesel-powered and generate emissions of air pollutants, including nitrogen oxides (NO_x), $PM_{2.5}$, sulfur oxides (SO_x), carbon monoxide (CO), and volatile organic compounds (VOC) (Archana et al., 2016). To mitigate emissions, various regulations have been implemented at both the State and local levels, such as those targeting HDDT providing drayage services at ports and intermodal rail yards that include bans on aged engine models, diesel particle filter retrofit requirements, and incentives to replace aged trucks with newer and lower-emitting model years (Drayage Truck Regulation). However, despite improvements from regulatory efforts, polluted emissions at the SPBPC are expected to continue to be significant due to growth in demand for goods movement. For example, it is estimated that in 2035 a baseline diesel drayage truck fleet servicing the SPBPC would emit 21% of on-road NO_x emissions in the SoCAB despite meeting only 1% of

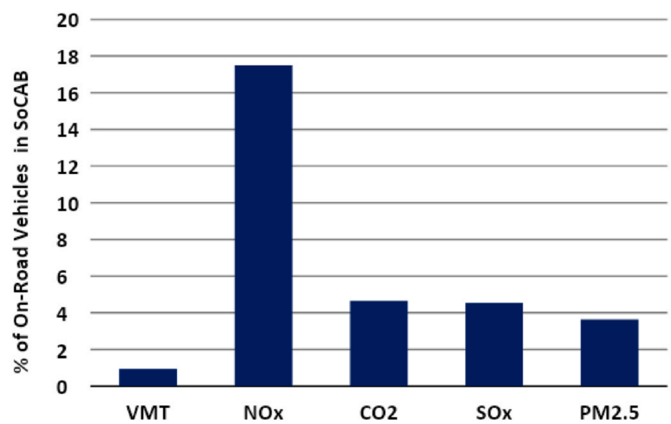


Fig. 2. Projected 2035 contribution of VMT and emissions from the drayage truck fleet in SoCAB relative to all on-road vehicles, including light-, medium-, and heavy-duty. Data from EMFAC2017 (California Air Resources, 2018a).

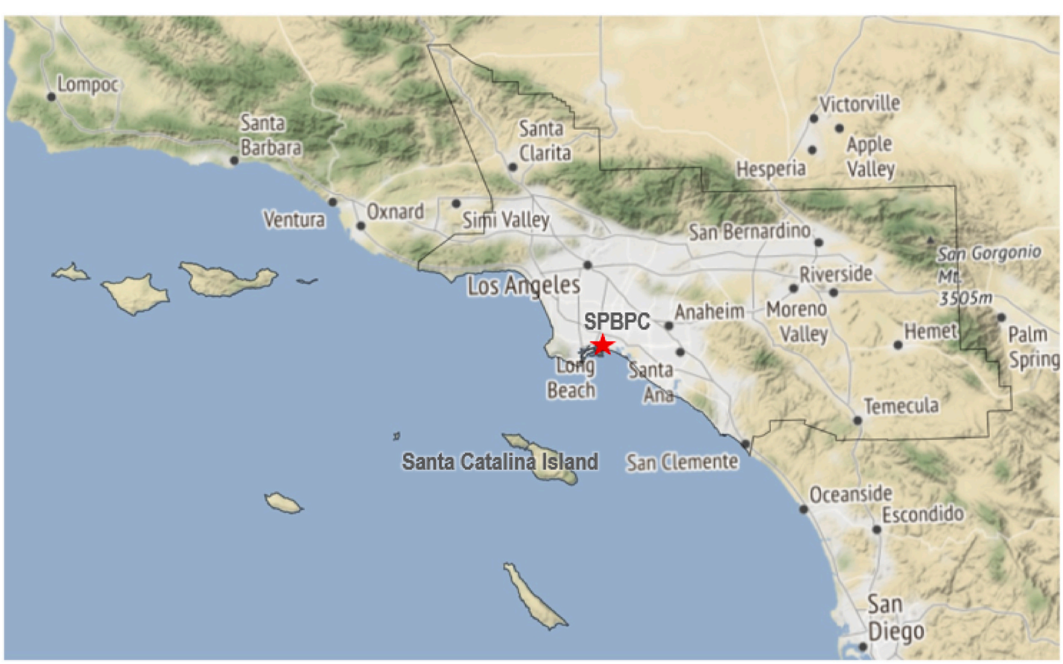


Fig. 1. Map of the SoCAB with the location of San Pedro Bay Port Complex noted in red. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

vehicle miles traveled (VMT) (Fig. 2), even if the fleet successfully meets all regulatory requirements associated with the use of newer, cleaner diesel engines.

To further reduce freight emissions, California is pursuing transitions to efficient and clean freight systems by introducing zero-emission technologies as alternatives to conventional technologies, including those operating on electricity and hydrogen (Brown, 2016). Equipment and vehicles deriving propulsive power through electric motors driven by hydrogen fuel cells represent a potential zero-emissions pathway for freight technologies at ports, including HDDT, CHE, ships, and rail applications herein referred to collectively as fuel cell electric technologies (FCET) (Hydrogen Business Council, 2018). FCET are considered a feasible alternative to conventional petroleum technologies to reduce criteria pollutant and GHG emissions as the lack of combustion results in no direct (tailpipe) emissions (Mekhilef et al., 2012).

Feasible near-term vehicle platforms for FCET are Class 4–6 urban "last-mile delivery" trucks (14,001–26,000 pound gross vehicle weight), and Class 7–8 short-haul/drayage trucks (26,001–33,000+ pound gross vehicle weight) (CaP-California Fuel Cel, 2016). The Class 7–8 heavy-duty fuel cell trucks (HDFCT) could replace the drayage HDDT used for port freight activities and reduce one of the major pollutant emission sources (Bishop et al., 2013). FCET can also replace diesel electricity generators in ships (including ocean-going vessels and other harbor craft) used for auxiliary power (van Biert et al., 2016) which are one of the largest emission sources in port activities (Kinnon et al., 2019). From prototype design to economic/environment assessment, studies have been conducted to incorporate FCET into the locomotive technologies (Siddiqui and Dincer, 2019; Miller et al., 2007). FCET in locomotive power systems is considered by the California Air Resources Board (CARB) as an emission reduction strategy (Core, 2015). The adoption of FCET is especially prudent for the ports whose railyards experience significant locomotive emissions, especially from switching and shunting applications that require operation at low speeds, which is inefficient from an emissions perspective (Starcrest Consulting Group, 2017; Guo et al., 2011). Finally, FCET has been established in use for CHE applications. Forklifts are one CHE application for FCET that is already commercialized (Mayyas et al., 2016) and identified as a candidate for emission mitigation strategies (California Air Resources, 2015). FCET powered CHE could also include other port technologies, including top loaders, side loaders, rubber-tired gantry cranes (RTG), as well as many others that are also under development (California Air Resources, 2015; California Air Resources, 2016a; E managing project for, 2018; Card, 2018).

The potential reduction in emissions from deploying FCET at the SPBPC is apparent. However, quantifying and resolving the resulting AQ and health outcomes is not as straightforward. The various equipment categories differ significantly in emission signatures, including in magnitude and in spatial resolution. For example, HDDT activity is centered at the SPBPC but includes trips throughout SoCAB while ship emissions are concentrated only at the SPBPC. Furthermore, differences in fuels and combustion technologies result in differences in the relative ratio of individual pollutants from each source. Furthermore, atmospheric chemistry and transport phenomena result in complex and nonlinear interactions with precursor emissions that must be accounted for when assessing secondary pollutant outcomes, some of which occur far from emission sources' locations. These differences directly impact the resulting AQ changes throughout the basin, which in turn directly impact the human health benefits. Therefore, additional insight is needed into how deploying FCET within different SPBPC vehicles and equipment impact AQ and health in SoCAB both collectively and individually.

A detailed accounting of direct emissions from sources at the SPBPC has been undertaken (Starcrest Consulting Group, 2020). Emissions from southern California ports have been shown to impact primary and secondary pollutant concentrations at the regional level, including ozone and secondary $PM_{2.5}$ due to transport events (Ault et al., 2009; Vutukuru and Dabdub, 2008). Furthermore, reducing the air pollution-driven health impacts from the SPBPC has been shown to provide societal value via avoided health costs (Lee et al., 2012). A diesel PM exposure assessment considered all port sources but only included on-port activity and did not account for secondary pollutant formation and fate (California Air Resources, 2006a). Therefore, a comprehensive study including all major vehicle and equipment categories and the use of a photochemical air quality model to resolve impacts on both primary and secondary air pollutant concentrations is lacking in the literature.

Future energy systems must not only address AQ concerns, but also reduce greenhouse gas (GHG) emissions contributing to climate change (California's 2017 Climate, 2017). The production, distribution, and combustion of petroleum fuels produces GHG emissions (Brown, 2016). Transitions to alternative fuels such as hydrogen can provide deep GHG reductions. However, a wide range of different production pathways is available, each with a unique carbon footprint (Reed et al., 2020). While the provision of renewable hydrogen represents an optimal outcome from an environmental standpoint, early adoption of FCET will likely require some provision of fuel from fossil pathways that produce GHG, including steam methane reformation (SMR) of natural gas. Therefore, further insight is also needed regarding the GHG implications of large-scale transitions to hydrogen at the SPBPC.

For the first time, this work provides a detailed accounting of the environmental quality benefits of utilizing FCET at a major port complex, including concerns associated with regional AQ and climate change. An assessment of the AQ and human health impacts of deploying FCET to provide goods movement services at the SPBC is conducted with a specific focus on the SoCAB. First, a set of cases representing FCET deployment in place of diesel equipment are analyzed, developing spatially and temporally resolved emissions, simulating the resulting AQ using an advanced photochemical model to account for both primary and secondary pollutant concentrations, and quantifying and valuing the human health benefits. Due to the uncertainty of projecting technology commercialization and adoption rates, cases are designed to span possible FCET deployment levels relative to baseline diesel equipment and vehicles. The AQ impacts of FCET cases are then quantified, including changes in ground-level ozone and $PM_{2.5}$ concentrations during a high pollutant formation period in summer. Finally, pollutant changes serve as input to a health impact assessment method to determine and value the corresponding health savings. Given the importance of addressing environmental justice concerns, the results are analyzed within the framework of those within socioeconomically disadvantaged communities (DACs). Additionally, reductions in total GHG emissions are assessed, accounting for a range of possible hydrogen production pathways to quantify reductions under different production cases. Results provide insight regarding policy development that can support alternative freight technology deployment in a manner that achieves maximum health and GHG co-benefits.

2. Methodology

2.1. Case development

2.1.1. Base case

In order to evaluate the impacts of deploying FCET in future years, scenarios of vehicles and equipment are developed within the categories represented by emission data for the SPBPC (Archana et al., 2016). First, a baseline scenario (Base case) is established to compare with the FCET cases. The Base case assumes the continued use of predominantly diesel vehicles and equipment at the SPBPC for HDDT, ships, CHE, and rail applications. Namely, the Base case represents a business-as-usual continuation of the technologies and fuels currently providing goods movement services and assumes little to no deployment of zero-emission strategies within the different sectors.

2.1.2. FCET cases

Next, ten alternative cases of FCET deployment are developed assuming deployment within all categories of vehicles and equipment considered. As the future deployment of FCET is impacted by uncertainties associated with future regulations, technological maturity, projected costs, etc., for each technology two spanning cases are simulated: a conservative (CON) and optimistic (OPT) FCET deployment assumption. The conservative and optimistic case assume a 25% and a 75% replacement of diesel equipment with FCET in all categories except HDDT relative to the Base case. Various policy and other drivers will influence the deployment of alternative technologies including the advancement, availability, and economics of zero emission technologies and fuels. However, significant uncertainty exists regarding many aspects of the use of these technologies at California ports. Therefore, the CON and OPT assumptions are selected to provide a realistic range for the use of zero emissions technologies in 2035. The replacement of HDDT with HDFCT is estimated based upon projections developed by Toyota North America that account for expected increases in cargo throughput at the SPBPC ranging from a conservative case (DRAYCON) with 56% and an optimistic case (DRAYOPT) with 79% of the fleet converted to HDCFT in 2035. A summary of the FCET cases are presented in Table 1.

2.1.3. Heavy duty drayage trucks

Much of the work done in transporting goods out of the SPBPC involves Class 8 HDDT, typically referred to as drayage trucks, that generally remain within the same urban region transporting goods to distribution centers, border points, intermodal terminal, etc. It is common for drayage trucks to enter fleets with high mileage after they are retired from long-haul activities, resulting in older, higher emitting vehicles being present (California Air Resources, 2006b). Several features of HDFCT and attributes of drayage activity support their use, particularly in the near-to mid-term. The vehicle must (1) have sufficient power for operation (400 horsepower, 1200–1800 foot-pounds of torque), (2) achieve the necessary range between fueling of 200+ miles, and (3) can be used on all delivery routes (Papson and Ipoliti, 2013). HDFCT has been demonstrated to achieve these benchmarks and offer the additional benefits of refueling times like conventional HDDT (relative to battery electric trucks (BET), which requires long periods of charging). Toyota's Class 8 HDFCT demonstration developed for drayage activity weighs 80, 000 lbs. and generates 670 horsepower and 1325 pound-feet (lb-ft) of torque with an estimated fueling range of 200 miles under average drayage drive cycles (Toyota unveils hydrogen f, 2017). Furthermore, the minimal hydrogen infrastructure available in that time frame could be less of a barrier for drayage cycles that could require only a home-based refueling station and a few strategically placed stations.

The on-road emission inventory projections for HDDT are estimated using the CARB Emission Factors (EMFAC2017) tool (California Air Resources, 2018a). EMFAC2017 calculates statewide emissions inventories for expected vehicle activity and emission rates from all on-road vehicle types in California. Forecasting within EMFAC2017 includes expected changes in vehicle age distributions, vehicle miles traveled, and the impact of current and future policies such as the Federal Phase 2 GHG standards. EMFAC estimates drayage truck activity growth rates based upon the 2013 Federal Highway Administration Freight Analysis Framework, which projects freight tonnage for various port regions in California and emission rates derived from current test data. EMFAC2017 is used to quantify emissions during all processes, including running exhaust, idling exhaust, start exhaust, various evaporative losses, and PM from tire and brake wear. As HDFCT has no tailpipe emissions, reductions are applied to all exhaust categories. PM from tire and brake wear is not reduced, and it is assumed emission rates are equivalent between HDDT and HDFCT.

Table 1
Summary of FCET cases.

Case Name	Technology	Description
DRAYCON	Heavy Duty Drayage Trucks	Conservative deployment (56% of HDFCT)
DRAYOPT	Heavy Duty Drayage Trucks	Optimistic deployment (79%) of HDFCT
SHIPCON	Ships	Conservative deployment (25% of FCET)
SHIPOPT	Ships	Optimistic deployment (75% of FCET)
RAILCON	Locomotive	Conservative deployment (25% of FCET)
RAILOPT	Locomotive	Optimistic deployment (75% of FCET)
OPSCON	Port Operations (CHE)	Conservative deployment (25% of FCET)
OPSOPT	Port Operations (CHE)	Optimistic deployment (75% of FCET)
ALLCON	Combined	Conservative Deployment (25% of FCET, 56% of HDFCT)
ALLOPT	Combined	Optimistic Deployment (75% of FCET, 79% of HDFCT)

2.1.4. Port Operations (cargo handling equipment)

Fuel cells could be used to power various CHE at the SPBPC. Fuel cell-powered forklifts are commercially available and have achieved success in the materials handling industry (Curtin and Gangi, 2017). Fuel cell lifts are suited for high throughput warehouses and distribution centers with similar demands as CHE at ports e.g., long shifts, satisfactory operation during all weather conditions (Mayyas et al., 2016). Fuel cell forklifts have been identified as a good candidate for SPBPC CHE emission strategies (California Air Resources, 2015). Although not currently commercial, additional zero-emission technologies for other types of CHE are also under development (California Air Resources, 2015) and could include top loaders, side loaders, rubber-tired gantry cranes, and others due to similar benefits as those achieved for forklifts (California Air Resources, 2015; California Air Resources, 2016a; E managing project for, 2018; Card, 2018).

The port operation cases consider six CHE sectors found in the CARB inventory (See Table 2). The conservative case (OPSCON) assumes a 25% deployment of FCET within all categories in Table 2 and the optimistic case (OPSOPT) assumes a 75% deployment.

2.1.5. Locomotive

The use of fuel cells to power locomotives is receiving interest due to benefits associated with efficiency and emissions (Hoffrichter, 2019). The literature supports the use of FCET in locomotive power systems, including for freight applications (Guo et al., 2011; Martinez et al., 2012a; Pocard, 2018), some with hybrid systems, including gas turbines and diesel engines (Guo et al., 2011; Martinez et al., 2012b). Even in hybrid systems, the literature demonstrates a potential for improvement of environmental impacts, including reducing GHG and criteria pollutant emissions (Hogerwaard and Dincer, 2016). In addition, some demonstration projects of FCET in locomotive power systems exist (Hess et al., 2010; Peters, 2016; Vehicle Projects de, 2009).

Two categories of locomotive emissions apply to operation at the SPBPC and include road hauling and switching. Locomotive-Road Hauling is the single largest rail contributor to daily NO_x emissions at 19.70 tons/day in 2035 (California Air Resources, 2016b). As SPBPC is among the most extensive rail yards in SoCAB, this category contributes to the degraded AQ throughout the basin. Two cases are simulated, a conservative estimate (RAILCON) of 25% reduction of all emitted species and an optimistic estimate (RAILCON) of 75% reduction of all

Table 2
2035 NO_x emissions by technology for port operations.

Technology	NO_x (tons/day)
Crane	0.40
Forklift	0.16
Material Handling Equipment	1.17
Other Cargo Handling Equipment	0.18
Tractor/Loader/Backhoe	0.47
Yard Tractor	0.48

emitted species.

2.1.6. Ships including ocean going vessels and harbor craft

Ocean-going vessels employ auxiliary engines for non-motive power for applications such as electricity generation and crew accommodations (California Air Resources, 2018b), which are usually driven by steam generated using heavy fuel oil boilers (ffice of Air Qual, 1995). FCET, particularly high-temperature fuel cells such as Solid Oxide Fuel Cells (SOFC), can provide many of these applications (Zhang et al., 2017). Indeed, the demonstration of SOFC combined heat and power systems is a potential candidate for ocean-going vessel applications as on-board or shore-assist heat and power (California Air Resources, 2018b). The literature supports fuel cell and other zero-emission technologies for providing power during various vessel operational stages, including anchorage and hoteling (van Biert et al., 2016; Pratt and Harris, 2013). Similarly, fuel cell technologies would be suitable for other vessel types, including harbor craft. For the cases considered here, emissions associated with ocean-going vessels and harbor craft auxiliary engine operation while hoteling or at-berth are included in the analysis. Therefore, those associated with vessel propulsion are not adjusted as fuel cell engines' use for propulsive power represents a more advanced outcome for fuel cell technology integration. However, it should be noted that fuel cell-powered ferries are in the demonstration phase. Therefore, the assumption of fuel cell technology only providing non-motive auxiliary power is somewhat conservative and including emissions from all ship activities including propulsion would enhance the AQ and health benefits estimated here. As with the other emission sources, auxiliary engine emissions are reduced by spanning estimates of 25% (SHIPCON) and 75% (SHIPOPT).

2.1.7. Combined

Finally, two combined cases are evaluated assuming the FCET deployments for each vehicle and equipment category. A conservative case (ALLCON) assumes 56% of the drayage fleet is HDFCT and 25% of other sectors are replaced by FCET while the optimistic case (ALLOPT) assumes 79% of the drayage fleet is HDFCT and 75% of other sectors are replaced by FCET.

2.2. Emissions and air quality modeling

2.2.1. Pollutant emissions projection and spatial resolution

For the Base case, the CARB 2012 emission inventory (CARB, 2013) serves as the baseline and is projected to 2035 using the California Air Resources, 2016b SIP– Standard Emission Tool (California Air Resources, 2016b). CEPAM provides future year estimates of pollutant emissions required for atmospheric modeling, including NO_x, PM, VOC, SO_x, and CO. The year 2035 was selected as it corresponds to the furthest year in CEPAM and provides a feasible timeframe for the deployment of alternative technologies at the levels considered in this work. The 2035 projected emissions for each vehicle and equipment category are shown in Fig. 3, demonstrating the importance of NO_x and $PM_{2.5}$ contributions from ships and HDDT. Additionally, locomotives contribute an important fraction of direct $PM_{2.5}$ emissions. Demonstrating diverging trends between pollutant and GHG emissions, CO_2 emissions are highest from HDDT and equipment used for CHE contribute notably to CO_2 emissions. Emission reductions for FCET cases are calculated based on the ratio of the assumed percentage of FCET deployment for each sector as specified in section 2.1. Then, the Sparse Matrix Operator Kernel Emissions tool (SMOKE) (Houyoux et al., 2015) is used to allocate emissions spatially and temporally throughout the modeling domain and period. In this study, the biogenic emissions are generated from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2012).

Fig. 4 provides both the total emissions by case and the spatial distribution of emission reductions throughout SoCAB. Fig. 4 (a) shows the spatial distribution of NO_x in the Base case with a clear emphasis in and around the SPBPC. Differences in NO_x between the Base and optimistic FCET cases are shown in Fig. 4(b–f). For the Heavy Duty Trucks (Drayage) case (Fig. 4 (b)), reductions occur throughout the transportation network in SoCAB, with a peak around the SPBPC. For locomotives, reductions occur along rail networks within the region, with peaks associated with two railway hubs, the Intermodal Container Transfer Facility (ICTF) in Long Beach and the BNSF Railway facility in Los Angeles (see Fig. 4 (c)). As expected, reductions occur at the SPBPC for CHE in the Port Operations case (Fig. 4 (d). Similarly, most reductions are local to the SPBPC in the Ships case, although minor reductions also occur along the coast of Santa Catalina Island from ship activity in those areas (Fig. 4 (e)). Due to limitations associated with the SMOKE modeling tool, a reduction in emissions occurs in the cases assuming ship emissions Fig. 4 (e) and Fig. 4 (f) from recreational boats operating on lakes northwest of Los Angeles. However, these impacts do not significantly impact the results as they occur in rural areas that do not contain large populations. Fig. 4 (g) shows the total emission reductions by pollutant for each case. In general, reductions are most extensive for PM, CO, and NO_x, while VOC reductions are minor, and SO_x and NH_3 are insignificant. Considering total emissions from a sector perspective, differences in technologies and fuels are evident e.g., NO_x reductions are associated with drayage trucks while PM and CO dominate the Ships case. Direct PM from auxiliary diesel engines in ships are noted due to 1) the high correlation with deleterious health outcomes in exposed populations and 2) the elevated emission from auxiliary diesel engines relative to the other sources considered.

2.2.2. Air quality modeling

Atmospheric chemistry and transport are simulated using the Community Multi-scale Air Quality model (CMAQ, v5.2) to provide a comprehensive understanding of pollutant concentrations, including ozone and $PM_{2.5}$ (ffice of Research, 2017). CMAQ was developed by US EPA and is used for various AQ assessment purposes, including regulatory compliance and atmospheric research associated with tropospheric ozone, PM, acid deposition, and visibility (Foley et al., 2010, 2014). In

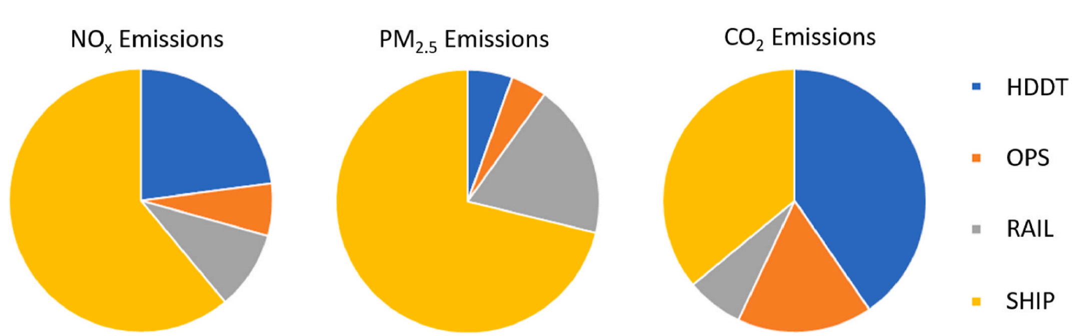


Fig. 3. Base case emissions of NO_x, $PM_{2.5}$, and CO_2 from heavy duty diesel trucks (HDDT), cargo and materials handling equipment (OPS), locomotives (RAIL), and ships (SHIP).

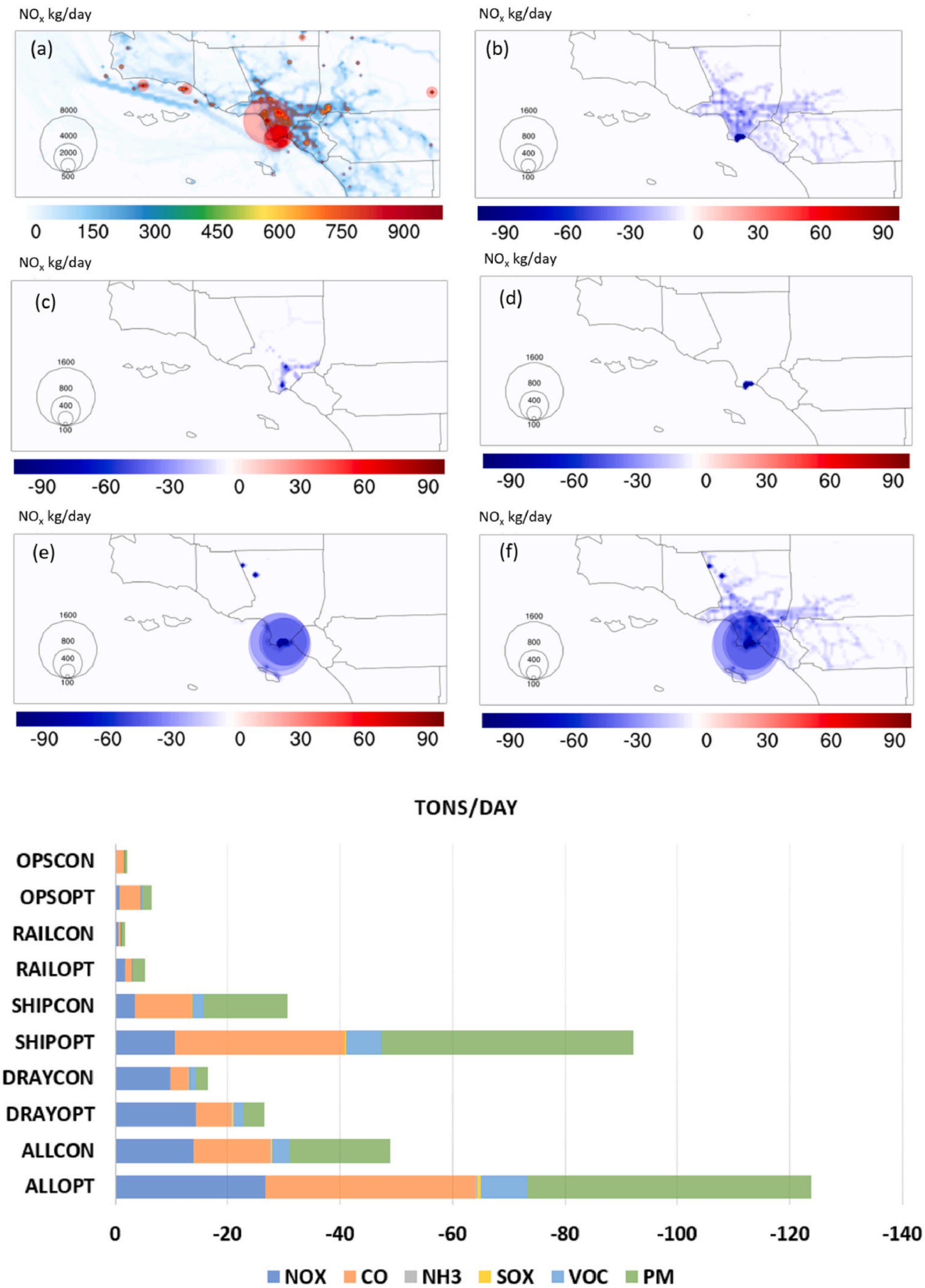


Fig. 4. (a) Spatial distribution of NO_x emission for the Base case; Spatial distribution of NO_x emission reduction (kg/day) for (b) DRAYOPT, (c) RAILOPT, (d) OPSOPT, (e) SHIPOPT; (g) Combined emission reduction for different cases (tons/day). The color bar in (a–f) represents the emission of area source and the size of circle represents the emission of point sources. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

this study, the SAPRC-07 chemical mechanism (Carter, 2010) is utilized to model gas-phase chemistry, and the AERO6 module (Pye et al., 2017) is used to calculate aerosol dynamics. The simulation domain is the same as Reference (Zhu et al., 2019), which includes all of California at a 4 km × 4 km horizontal resolution. The Advanced Research Weather Research and Forecasting Model (WRF-ARW, 3.7) is used to downscale meteorological conditions from the (Final) Operational Global Analysis data (Ncep., 2000). The boundary conditions are obtained via the Model for Ozone and Related Chemical Tracers (Mozart v4.0) (Emmons et al., 2010). Although simulations are conducted for 2035, both boundary and meteorology conditions are held constant as the base emission inventory year 2012. Thus, impacts of future changes due to transported pollution and climate change are not considered. Two weeks in July (Jul. 8th to Jul. 22nd) are selected for simulation as it encompasses conditions typically associated with high tropospheric ozone formation, including high temperatures, an abundance of sunlight, lack of natural scavengers, and the presence of inversion layers (Carreras-Sospedra et al., 2006). The first three days of the simulation period are considered model spin up and excluded from the results' analysis. The simulated period's model performance has been validated (Zhu et al., 2019) and the evaluation metrics and statistics can be found in Table S7 and Table S8 of the Supplementary data of this work.

2.3. Health impact assessment

Improvements in AQ benefit public health by reducing the pollution-related incidence of premature mortality and morbidity endpoints including non-fatal heart attacks, strokes, episodes of respiratory distress and other adverse health effects. The environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) from the U.S. EPA is used to quantify and value health savings from improvements in ozone and $PM_{2.5}$ attained through FCET deployment (Sacks et al., 2018). The methods used follow those in the South Coast Air Quality Management District's Socioeconomic Report for the 2016 Air Quality Management Plan (Shen et al., 2017). Population projections are based on Landscan data (LandScan, 2016) and extrapolated to 2035 using projections from the California Department of Finance (California, 2017). Baseline incidence rates for mortality and morbidity are obtained from the South Coast Air Quality Management District estimated from public administrative records (Industrial Economics. Rev, 2016). Mortality rates are projected to 2035 using mortality projections from the California Department of Public Health (California, 2018) and population projections from the California Department of Finance (California, 2017). Details regarding the population and incidence rates calculations are included in the SI. Concentration-response and economic valuation functions are selected based on suggested criteria from a systematic review of the epidemiological literature (Robinson, 2016; Robinson and Hammitt, 2016) and presented in Tables S1–S4 of the Supplementary data. The value of statistical life (VSL) used to value avoided incidence of premature mortality is $12.69 million based off the recommended VSL of $9 million in 2013 U.S. dollars ($) in Reference (Robinson, 2016) projected to 2035 $. Therefore, the estimated health benefits are reported in 2035 $. Though BenMAP-CE can be used to estimate long-term health impacts such as those occurring from annual average $PM_{2.5}$ changes, impacts are reported here for short-term exposure to ozone and $PM_{2.5}$ (as appropriate for the modeled episode) due to intensive resource requirements necessary for simulating annual pollutant concentrations. It should be noted that the benefits reported here are conservative, and the use of annual modeling would provide substantially higher estimated health benefits due to the larger avoided health incidence.

To characterize health benefits within the scope of environmental justice the health benefits are analyzed to better understand implications for DAC including quantifying the total benefits occurring within DACs and the quantification of health benefits per capita. To identify communities as DAC the CalEnviroScreen (alEnviroScreen 3., 2018a) tool developed by California's Office of Environmental Health Hazard Assessment is used to rank all California communities at the census tract level. Census tracts that score within the highest 25% (score $\geq$75) according to various social and environmental metrics are designated as DAC.

2.4. GHG impacts

The use of renewable hydrogen by FCET will reduce GHG emissions relative to the use of diesel and other petroleum fuels. To account for all life cycle stages, the GJG assessment includes three components: (1) well-to-tank GHG emissions associated with producing hydrogen and delivering it to the equipment at the ports, (2) displaced well-to-tank emissions associated with the production and delivery of diesel fuel for use by conventional vehicles and equipment, and (3) tank-to-wheels emissions associated with diesel combustion by conventional vehicles and equipment. As they have no tank-to-wheel emissions, well-to-tank emissions for FCET are equivalent to well-to-wheels emissions for petroleum fuel technologies.

Hydrogen production and distribution pathways are diverse, with implications for environmental performance, including GHG signatures (Reed et al., 2020). Therefore, a range of viable hydrogen production pathways is considered and included in the assessment including three renewable pathways and three nonrenewable pathways. The renewable pathways are (1) electrolysis with 100% renewable electricity, (2) reformation of renewable biogas and (3) gasification of renewable biomass. In the biogas pathway, it is assumed that four feedstocks are used in equal proportion: (1) landfill gas, (2) anaerobically digested animal waste, (3) anaerobically digested wastewater sludge, and (4) anaerobically digested municipal solid waste. The nonrenewable paths are (1) reformation of natural gas, (2) electrolysis using grid electricity and a conservative estimate of electrolysis efficiency, and (3) electrolysis using grid electricity and an optimistic assessment of electrolysis efficiency. Eight hydrogen production cases are designed using both renewable and nonrenewable pathways and are listed in Table 3. GHG emission factors for feedstocks and production are from CA-GREET 3.0 (Argonne, 2011). It is assumed that hydrogen is distributed through a pipeline network totaling 2000 miles based on a literature assessment comparing hydrogen delivery methods (Shaffer, 2018) and all hydrogen dispensing occurs at 700 bar (Stephens-Romero and Samuelsen, 2009). Well-to-tank GHG emission factors for diesel fuel and heavy fuel oil are also from CA-GREET 3.0. In addition to the carbon intensity of fuel production, additional parameters that impact fuel consumption, including engine and fuel cell efficiencies, are accounted for.

3. Results and discussion

3.1. Air quality impacts

The following section presents differences in ozone and $PM_{2.5}$ that result from emission reductions in the FCET cases. First, simulations of the Base case provide baseline concentrations for comparison with the FCET cases. For consistency with ambient AQ standards, ground-level concentrations are reported as maximum daily 8-h average ozone (MD8H) and maximum daily 24-h average $PM_{2.5}$ (MD24H). Next, differences in concentrations are quantified and spatially resolved between the Base and the FCET cases to quantify and characterize the AQ impacts.

Impacts on ozone and $PM_{2.5}$ are presented in Fig. 5 and represent the largest reduction for an individual grid cell within the modeling domain and provides the maximum benefit one location could experience. For collective FCET deployment, MD8H ozone reductions range from 2.69 ppb to 5.08 ppb, and MD24H $PM_{2.5}$ reductions from 0.6 μg/m^3 to 2.57 μg/m^3 corresponding to conservative (ALLCON) and optimistic (ALLOPT) deployments. Considering individual sectors, ships (SHIPOPT) have the largest reduction for both ozone (−2.96 ppb) and $PM_{2.5}$ (−2.45 μg/m^3) under optimistic deployment, followed by drayage trucks (−2.81 ppb and 0.29 μg/m^3). However, for conservative deployment, the drayage truck replacement (: −1.98 ppb) is more effective at reducing ozone due to the higher deployment assumed relative to other sectors, i.e., 56% vs. 25%). Despite this, ships still significantly impact $PM_{2.5}$ in the conservative deployment case (−0.56 μg/m^3 for $PM_{2.5}$. Impacts from the rail and CHE sectors are not as pronounced as those from ships and trucks. Moreover, comparing the combined case and ship cases, $PM_{2.5}$ reductions contributed by FCET use in ship auxiliary engines are the dominant driver of overall impacts. Collective emission reductions provide smaller reductions than does the

Table 3
Description of hydrogen supply pathway cases assumed for the GHG calculations.

Case Name	Case Description
RE100	100% Renewable Electrolysis
RR100	100% Renewable Reformation
RG100	100% Renewable Gasification
NGE50/50	50/50 NG SMR/Renewable Electrolysis
NGR50/50	50/50 NG SMR/Renewable Reformation
NGG50/50	50/50 NG SMR/Renewable Gasification
NGC50/50	50/50 NG SMR/Grid Electrolysis (Conservative)
NGO50/50	50/50 NG SMR/Grid Electrolysis (Optimistic)

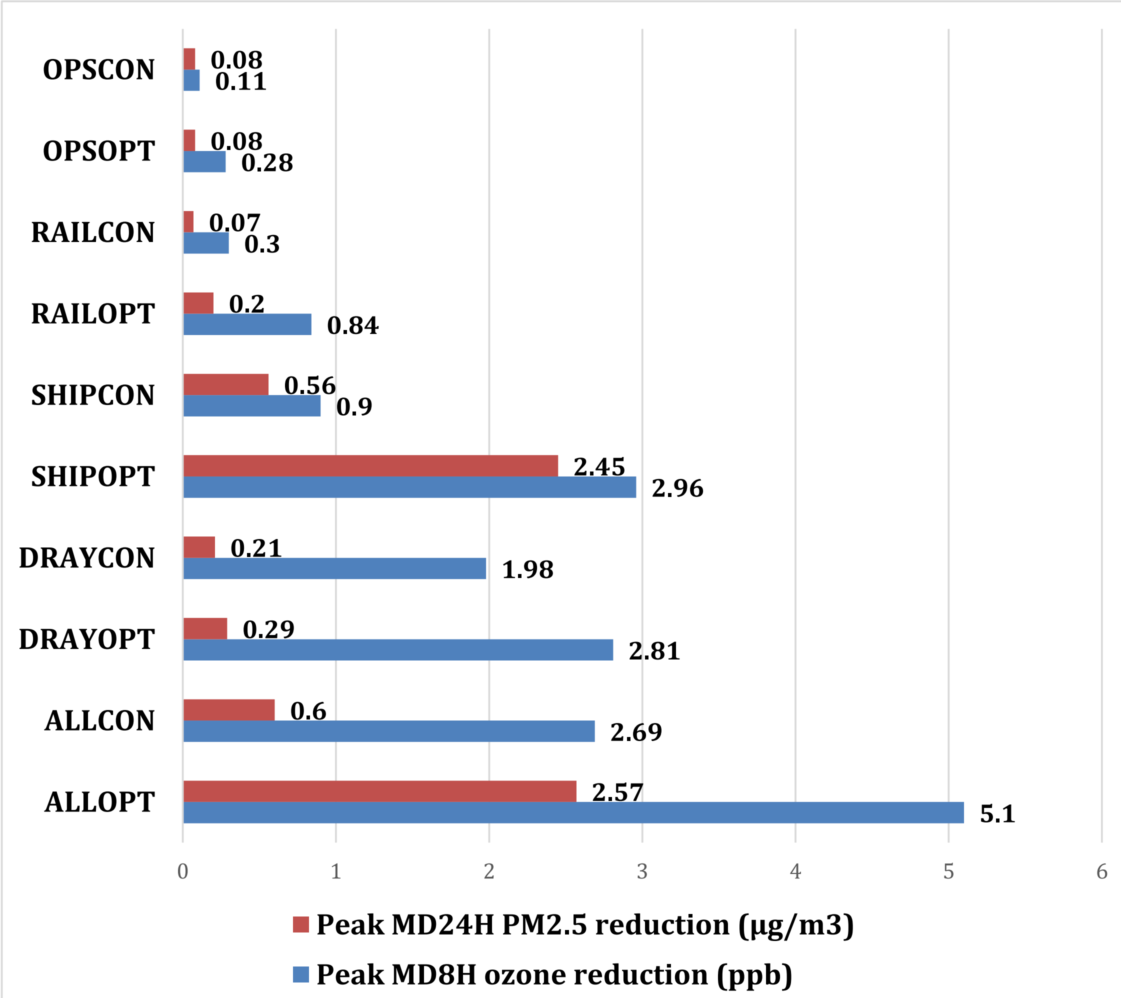


Fig. 5. Peak MD24H $PM_{2.5}$ and MD8H ozone concentration reduction for each case compared to the Base case.

sum of individual sectors, highlighting the non-linearity of atmospheric concentrations with respect to precursor emission reductions and further emphasizing the need for atmospheric modeling.

However, the locations of emission reductions also impact population-weighted exposure, which is a direct determinant of health savings. Fig. 6 illustrates the spatial distribution of ozone and $PM_{2.5}$ reductions for the optimistic FCET cases relative to the Base case. In general, most ozone reductions occur distant from the location of the SPBPC in the downwind direction. The geography and prevailing meteorological conditions of SoCAB result in stagnant conditions in eastern and northeastern regions associated with the highest ambient ozone concentrations (See Fig. 7 for baseline concentrations). Following this pattern, the largest ozone benefits occur in the same area, despite the bulk of emission reductions occurring at or near the SPBPC. The scenario involving HDFT (DRAYOPT) results in more widespread ozone and $PM_{2.5}$ reductions relative to other sectors and closely follows the pattern of ambient ozone formation (See Fig. 7 (a)) due to the regional distribution of emission reductions (See Fig. 4). Reducing emissions from locomotives (RAILOPT) achieves ozone and $PM_{2.5}$ reductions slightly northeast of the SPBPC. Conversely, an increase in ozone near the SPBPC is observed for the ship (SHIPOPT) and CHE (OPSOPT) cases and the combined (ALLOPT) case, as a result of reduced ozone titration that is a commonly observed meteorological phenomenon in SoCAB for large reductions in NO_x occurring from a single point or localized area (Lei and Wang, 2014). Also, a clear transition between ozone increases and decreases is identified, demonstrating a change of the chemical sensitivity of the ozone regime as the emissions are transported downwind (Martin et al., 2004). For $PM_{2.5}$, most reductions occur local to the SPBPC for the Ship and CHE cases.

3.2. Health impact analysis results

The following section presents the public health benefits associated with the AQ improvements described in Section 3.1. First, avoided morbidity and mortality incidence are quantified via BenMAP based on the delta concentrations of ozone and $PM_{2.5}$ and presented in Table S3. Next, health economic functions are used to value the total health savings for each FCET case and shown in Fig. 8. Additional detailed for each health endpoint can be found in Table S4. Generally, avoided incidence of premature mortality are responsible for the bulk of the health benefits and occur more from reduced $PM_{2.5}$ exposure relative to ozone for most cases except drayage trucks. For the highest collective FCET deployment (ALLOPT), the mean benefits exceed 7.10 million $/day, which is both optimistic considering the deployment levels and conservative given that estimate is for short-term exposure only. Sector-wise, the benefits from ships contribute the highest benefits followed by those from drayage trucks and locomotives. Again, highlighting the importance of ship emissions, health benefits from an optimistic FCET deployment in that sector could surpass the benefits from a conservative FCET deployment in all sectors combined.

Fig. 9(a–e) presents the spatial allocation of per capita health benefits for the optimistic FCET deployment cases. The health impacts are

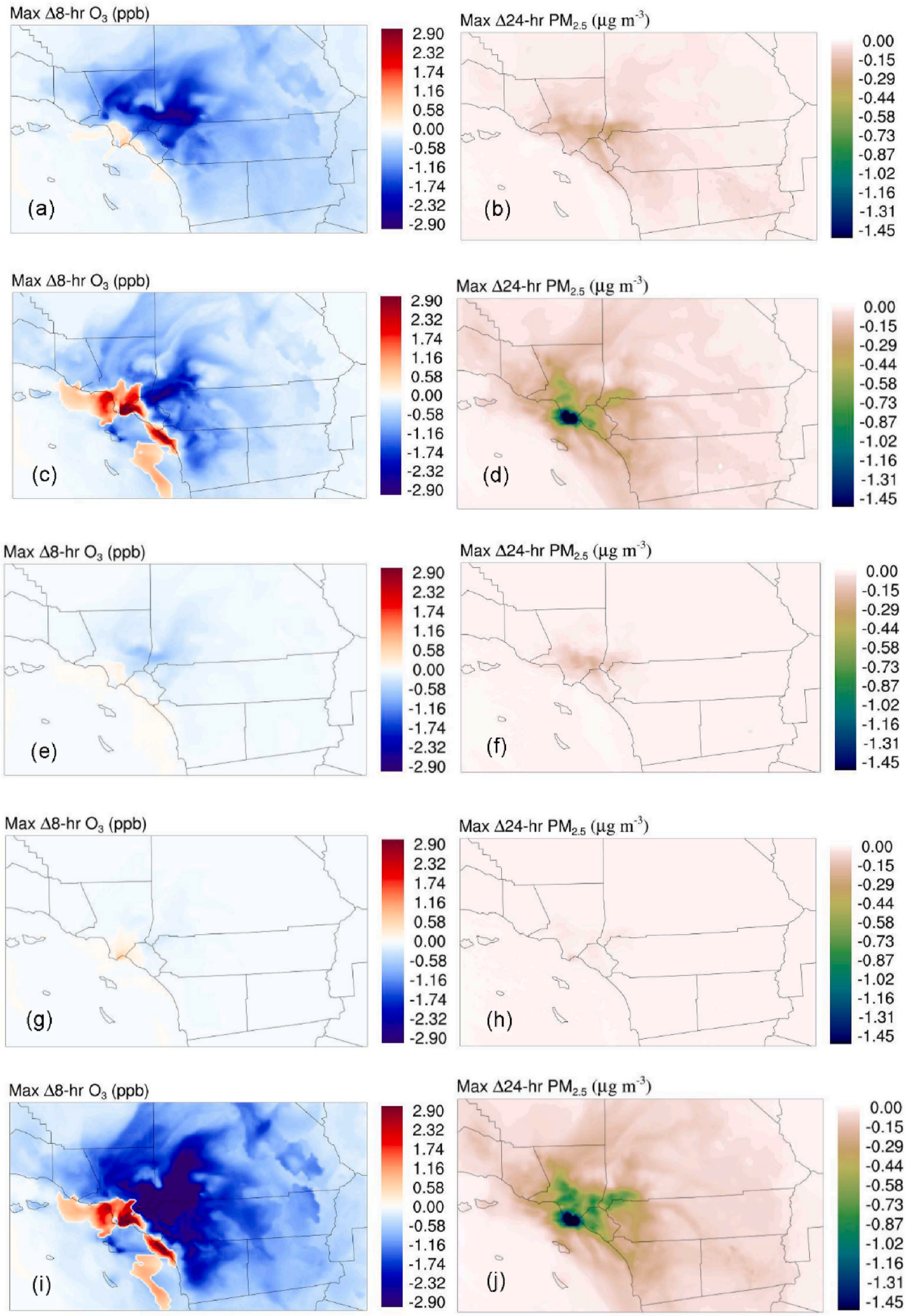


Fig. 6. The spatial distribution of air quality impacts for each case is presented in each row. The left column shows peak MD8H ozone n differences between case ((a) DRAYOPT; (c) SHIPOPT; (e) RAILOPT; (g) OPSOPT; (i) ALLOPT) and the Base case, the right column shows peak MD24H $PM_{2.5}$ differences between the Base case and the ((b) DRAYOPT; (d) SHIPOPT; (f) RAILOPT; (h) OPSOPT; (j) ALLOPT) cases.

estimated for all of California to be comprehensive as a small amount of drayage truck activity associated with the ports includes trips to other areas of California including the Central Valley. Communities located in eastern portions of the SoCAB attain the highest per capita benefits, including those in San Bernardino and Riverside Counties. For all cases that include emission reductions from ships and CHE, communities near the SPBPC benefit significantly. Comparing individual sectors, per capita, health benefits occur at a higher level in the areas previously mentioned, following trends for improvements in ozone. The ozone titration effects balance out some health benefits achieved by reducing

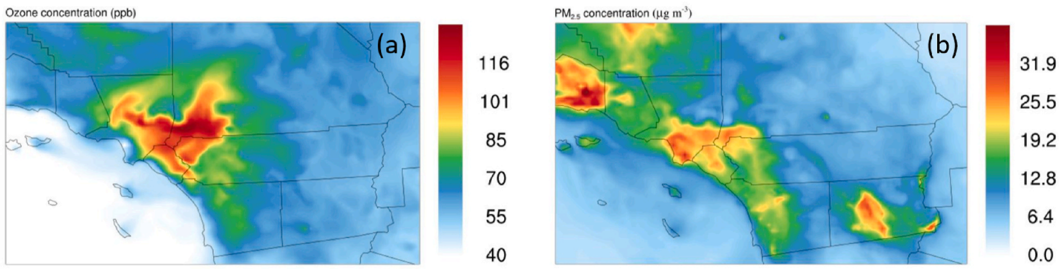


Fig. 7. Base case distribution of (a) MD8H ozone and (b) MD24H $PM_{3.5}$.

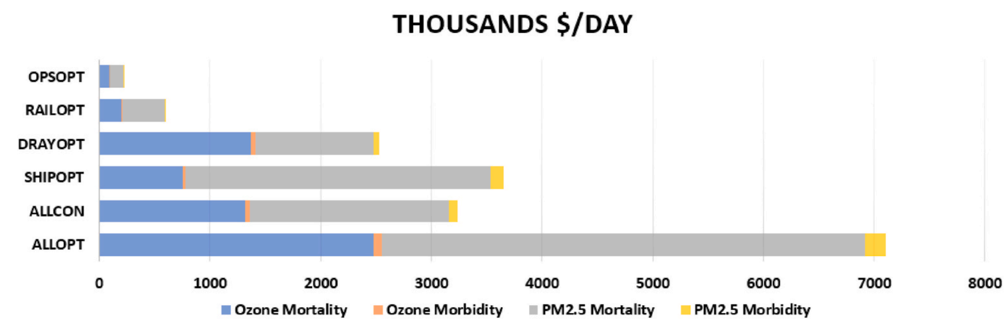


Fig. 8. Mean monetized health benefits from AQ improvements reported in 2035 $.

$PM_{2.5}$ for some coastal communities, particularly so for the OPSOPT case. Conversely, per capita health benefits are highest closer to the SPBPC for the Ships case resulting from patterns of $PM_{2.5}$ improvement. Results show differences in public health benefits associated with AQ changes in terms of both pollutant and spatial locations that deploy zero-emission strategies in goods movement technologies can achieve.

To provide insight into environmental justice implications, health benefits occurring within DAC are quantified. Census tract-level rankings for the communities within SoCAB based on various socio-economic and environmental metrics are determined using CalEnviroScreen 3.0, with the lowest scoring 25% of census tracts (25.59% of the population) designated as a DAC (alEnviroScreen 3., 2018b). The percentage of health benefits within DACs is then calculated (See Fig. S2). Fig. 9 (f) shows the percentage of total health benefits within DACs for each considered, combined with approximately 35% of public health savings within DACs. Environmental equality is improved for all cases as the benefits within DACs occur at a higher ratio than if the health benefits were evenly distributed across all census tracts, i.e., 25% of the census tracts exhibit greater than 25.59% of the total benefits. For individual sectors, reducing locomotive emissions most efficiently provides DAC benefits, while those from CHE achieve the least. However, the results show that reducing emissions from all the sources at the SPBPC provides benefits to DACs.

3.3. GHG benefits

Fig. 10 (a) provides the GHG assessment results for the combined FCET cases (ALLCON and ALLOPT). Additionally, the range of potential GHG reductions for the individual cases is shown by hydrogen pathway in Fig. 10 (b) and by the technology sector in Fig. 10 (c). Table 4 provides a comprehensive overview of the GHG results for all vehicle and equipment categories. The combined FCET cases provide the largest GHG reduction given the assumption of the simultaneous deployment of all technologies. As would be expected, the complete use of renewable hydrogen provides the largest GHG reductions, with renewable electrolysis (RE100) providing a more favorable outcome (7811.54 thousand tons CO_2 equivalent (CO_2e) per day in the optimistic case) than does renewable biogas (RG100) and renewable biomass (RR100). For the combined cases, the use of fossil hydrogen (NGC50/50 and NGO50/50) does provide a moderate reduction from current diesel technologies. However, the benefits of using renewable hydrogen are clearly demonstrated. For example, using renewable hydrogen in the conservative combined case effectively reduces GHG than the optimistic mixed case with NGR50/50, NGG50/50, NGO50/50, and NGC50/50. Considering the individual sector cases, those for auxiliary diesel engines in ships result in the largest span of possible outcomes for both conservative and optimistic assumptions, demonstrating the importance of the selected hydrogen supply pathway for that application. For the optimistic case, the use of renewable hydrogen (RE100) provides the largest GHG reduction (−2948.09 thousand tons CO_2e per day), while the same case using fossil and renewable hydrogen mixtures (NGC50/50) provide an increase of 76.10 thousand tons CO_2e per day.

4. Conclusions

The potential environmental quality benefits from implementing FCET at the SPBPC are clearly demonstrated here including both public health savings from AQ improvements and GHG reductions. FCET deployment within port activities reduce pollutant concentrations that assist the region in meeting its regulatory requirements established by National Ambient Air Quality Standards (NAAQS), especially for ground-level ozone. For example, the ozone improvements estimated here range from −2.69 ppb to −5.09 ppb MD8H, with the largest improvements occurring in SoCAB locations experiencing the highest baseline concentrations. These values are significant, considering that the margin for compliance with the current 70 ppb standard is approximately 12 ppb (the baseline level in that location is 82 ppb). FCET deployment in port activities also achieves reductions in $PM_{2.5}$ in highly populated areas that currently suffer from degraded air quality, estimated here to range from between -0.59 μg/m^3 to -2.57 μg/m^3. 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. It is expected that long-term exposure to the improvements modeled in this study would attain benefits potentially exceeding an order of magnitude higher as seen for other studies in SoCAB (Shen et al., 2017).

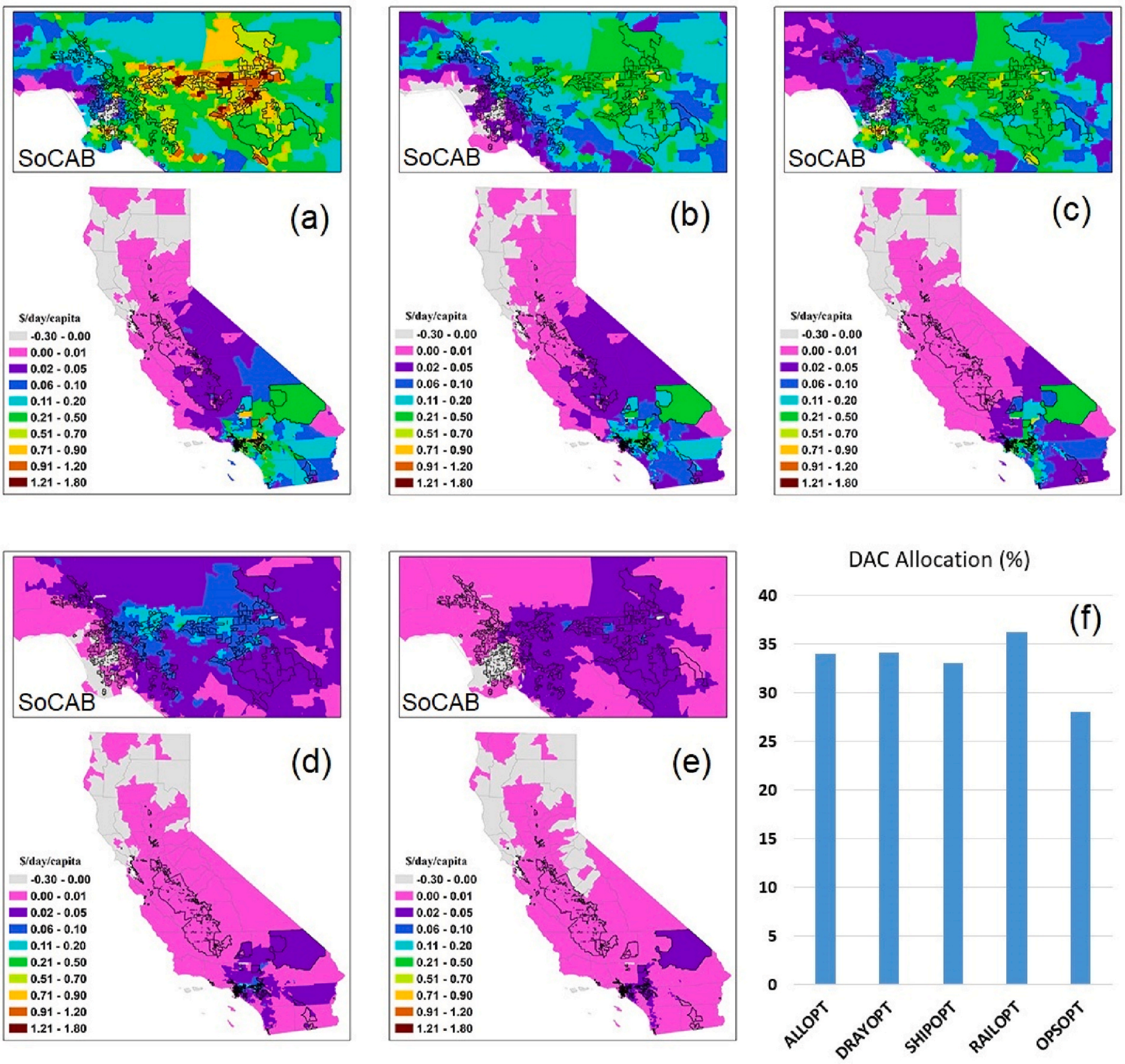


Fig. 9. Spatial allocation of per capita health benefits in 2035 $: (a) ALLOPT, (b) DRAYOPT, (c) SHIPOPT, (d) RAILOPT, and (e) OPSOPT, with DAC outline. (f) the relative percentage of health benefits occurring within DACs.

Furthermore, FCET more effectively provides public health benefits within DACs relative to the general population, a particularly desirable outcome given the current inequity in air pollution health damages in California. For example, the current regulatory framework governing air pollution mitigation has been lacking in addressing the existence of pollution hotspots occurring within DACs, which are often correlated with freight activity (Fowlie et al., 2020). Additionally, the significant presence of DACs near the SPBPC further emphasizes the importance of the benefits shown here, particularly for the use of FCET to reduce emissions from ships and trucks (alEnviroScreen 3., 2018a). While the results are specific to the SoCAB, it should be noted that major port complexes in other regions of California experience similar proximity to DACs, including Oakland, the San Francisco Bay Area, San Diego, Hueneme, Stockton, and others. The impacts assessed here can be considered within the framework that similar impacts may be attained at these and other ports throughout the world. In recognition of the environmental impacts of the SPBPC, considerable efforts have been made to transform the freight movement systems through policy efforts including various funding mechanisms (The Port of Los Angeles a, 2017). Funding support for zero-emission projects has originated from numerous Federal, State, and local agencies, private companies, and the ports themselves with examples including the Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) Shore to Store Project (Zero-and Near Zero-Emiss). The findings reported in this work demonstrate the benefits of continued support of zero-emission projects through incentives and other policy mechanisms.

Finally, utilizing hydrogen in place of conventional fuels can achieve reductions in GHG emissions that will support the State's climate mandates. GHG emissions are reduced in every case and pathway, with the sole exception of the Ships cases assuming the most conservative hydrogen production pathway that includes fossil hydrogen sources. When the hydrogen is generated from renewable sources, the reductions are significant. In the best case, with 79% deployment of HDFCT and 75% deployment of FCET in the other sectors, reducing GHG emissions by 7.81 to 1.08 million tons depending on whether the hydrogen pathway. However, given the potential increase in GHG if hydrogen is sourced from fossil fuel feedstock, policies to advance renewable pathways will benefit the adoption of hydrogen as a transportation fuel.

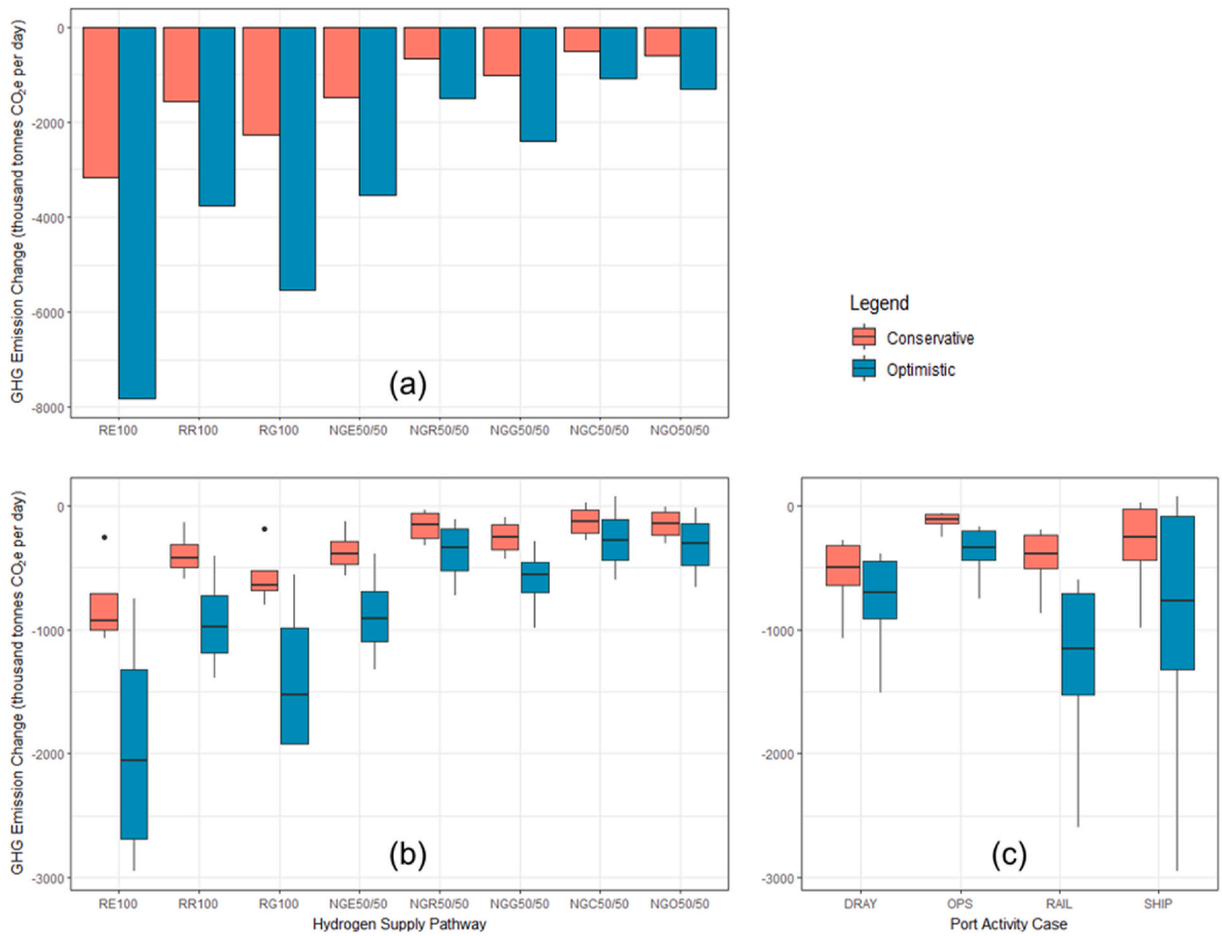


Fig. 10. GHG emissions for eight hydrogen supply pathways for (a) combined and (b) individual FCET cases by hydrogen supply chain (thousand tons CO_2e per day); (c) individual FCET cases by technology. For (b) and (c), the mean and lower/upper quartiles is presented by the box, while the whiskers mark the maximum and minimum value.

Table 4
Estimated GHG Emission Reductions for All Technology Categories (thousand tons CO_2).

	RE100	RR100	RG100	NGE50/50	NGR50/50	NGG50/50	NGC50/50	NGO50/50
ALLCON	−3171.35	−1563.07	−2272.13	−1477.00	−672.86	−1027.39	−508.03	−592.82
ALLOPT	−7811.54	−3749.48	−5540.38	−3532.10	−1501.06	−2396.51	−1084.76	−1298.90
DRAYCON	−1071.24	−591.29	−802.89	−565.60	−325.63	−431.43	−276.44	−301.74
DRAYOPT	−1511.21	−834.14	−1132.65	−797.90	−459.37	−608.62	−389.98	−425.67
OPSCON	−251.43	−134.49	−186.04	−128.23	−69.75	−95.53	−57.77	−63.93
OPSOPT	−754.29	−403.46	−558.13	−384.68	−209.26	−286.60	−173.31	−191.80
RAILCON	−865.98	−463.33	−640.85	−441.78	−240.46	−329.22	−199.19	−220.42
RAILOPT	−2597.95	−1389.99	−1922.56	−1325.35	−721.37	−987.65	−597.57	−661.25
SHIPCON	−982.70	−373.96	−642.34	−341.39	−37.02	−171.21	25.37	−6.73
SHIPOPT	−2948.09	−1121.89	−1927.03	−1024.16	−111.06	−513.64	76.10	−20.18

CRediT authorship contribution statement

Shupeng Zhu: Formal analysis, Methodology, Software, Writing – original draft. **Michael Mac Kinnon:** Formal analysis, Methodology, Software, Writing – original draft, Validation. **James Soukup:** Software. **Andre Paradise:** Software. **Donald Dabdub:** Methodology, Writing – review & editing. **Scott Samuelsen:** Conceptualization, Writing – review & editing, Project administration, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the UCI Advanced Power and Energy Program. Additionally, this work was supported by funding from Toyota North America.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2022.118996.

References

OEHHA. CalEnviroScreen 3.0 Available at: 2018.
OEHHA. CalEnviroScreen 3.0. Available at: https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30 2018.
Archana, A., Guiselle, A., Bruce, A., Rose, M., Joseph, R., 2016. Port of Los Angeles Inventory of Air Emissions - 2016. Los Angeles.
Argonne, G.R.E.E.T., 2011. GREET Model. Biomass Energy Data B.
Ault, A.P., Moore, M.J., Furutani, H., Prather, K.A., 2009. Impact of emissions from the Los Angeles Port region on San Diego air quality during regional transport events. Environ. Sci. Technol. 43, 3500–3506. https://doi.org/10.1021/es8018918.
Banzhaf, S., Ma, L., Timmins, C., 2019. Environmental justice: the economics of race, place, and pollution. J. Econ. Perspect. 33, 185–208.
Bishop, G.A., Schuchmann, B.G., Stedman, D.H., 2013. Heavy-duty truck emissions in the South coast Air Basin of California. Environ. Sci. Technol. 47, 9523–9529.
Brown Jr., Edmund G., 2016. California sustainable freight action plan. Available: http://www.casustainablefreight.org/theplan.html.
Brulle, R.J., Pellow, D.N., 2006. Environmental justice: human health and environmental inequalities. Annu. Rev. Publ. Health 27, 103–124.
California, D.O.F., 2017. Population Projections (Baseline 2016). Department of Finance, Sacramento, CA. Available at: http://www.dof.ca.gov/forecasting/demographics/projections/. state of california http://www.dof.ca.gov/forecasting/demographics/projections/. Available at.
California, C.D.P.H., 2018. Department of Public Health Informatics Portal.
California Air Resources Board, 2006a. Diesel Particulate Matter Exposure Assessment Study for the Ports of Los Angeles and Long Beach. Sacramento, CA. http://www.arb.ca.gov/regact/marine2005/portstudy0406.pdf. (Accessed August 2016).
California Air Resources Board, 2006b. Evaluation of Port Trucks and Possible Mitigation Strategies. Stationary Source Division Project Assessment Branch, Sacramento, CA. Available at: https://www.arb.ca.gov/msprog/onroad/porttruck/fullrpt.pdf.
California Air Resources Board (CARB), 2015. Technology Assessment: Mobile Cargo Handling Equipment. Sacramento, CA.
California Air Resources Board (CARB), 2016a. Heavy-Duty Vehicles and Off-Road Equipment Investments.
California Air Resources Board, 2016b. CEPAM: 2016 SIP - Standard Emissions Tool. Accessed June 2018). https://www.arb.ca.gov/app/emsinv/fcemssumcat/fcemssumcat2016.php.
California Air Resources Board, 2018a. EMFAC2017 Volume III - Technical Documentation.
California Air Resources Board (CARB), 2018b. Technology Assessment: Ocean-Going Vessels. Sacramento, CA.
California's 2017 Climate Change Scoping Plan, 2017. Sacramento, CA.
CaFCP-California fuel cell partnership. Medium- and Heavy-Duty Fuel Cell Electric Truck Action Plan for California 58, 2016.
CARB, 2013. Current CARB Emissions Inventory ver. 2012.
Card, K., 2018. Hyster receives grant for fuel cell powered container handler for port of Los Angeles. HysterCom. https://www.hyster.com/en-us/north-america/why-hyster/press-releases/2018/hyster-receives-grant-for-fuel-cell-powered-container-handler-for-port-of-los-angeles/.
Carreras-Sospedra, M., Dabdub, D., Rodriguez, M., Brouwer, J., 2006. Air quality modeling in the south coast air basin of California: what do the numbers really mean? J. Air Waste Manag. Assoc. 56, 1184–1195.
Carter, W.P.L., 2010. Development of the SAPRC-07 chemical mechanism. Atmos. Environ. 44, 5324–5335.
Core, R Del, 2015. Hydrogen for Complete Zero Emission Freight Train and Goods Movement Network. Hydrogenics.
Curtin, S., Gangi, J., 2017. Fuel Cell Technologies Market Report 2016. U.S. Department of Energy. Energy Efficiency & Renewable Energy. Available: https://www.energy.gov/sites/prod/files/2017/10/f37/fcto_2016_market_report.pdf.
Drayage Truck Regulation (n.d.).
CTE managing project for fuel cell powered top loader at LA port. Fuel Cells Bull 2018, 2018 6. https://doi.org/10.1016/S1464-2859(18)30281-5.
Emmons, S.E.F., Emmons, L.K., Walters, S., Hess, P.G., Lamarque, J.-F., Pfister, G.G., et al., 2010. Description and evaluation of the model for ozone and related chemical Tracers, version 4 (MOZART-4). Geosci. Model Dev. (GMD) 3, 43–67. https://doi.org/10.5194/gmd-3-43-2010.
US EPA Office of air quality planning and standards. Fuel Oil Combustion. Extern. Combust. Sources vol. 1, 1995, 1.3–1-1.3. U.S. Environmental Protection Agency, 29.
US EPA Office of Research and Development, 2017. CMAQ. https://doi.org/10.5281/zenodo.1167892. Version 5.2.
Foley, K.M., Roselle, S.J., Appel, K.W., Bhave, P.V., Pleim, J.E., Otte, T.L., et al., 2010. Incremental testing of the Community Multiscale Air Quality (CMAQ) modeling system version 4.7. Geosci. Model Dev. (GMD) 3, 205–226.
Foley, K.M., Napelenok, S.L., Jang, C., Phillips, S., Hubbell, B.J., Fulcher, C.M., 2014. Two reduced form air quality modeling techniques for rapidly calculating pollutant mitigation potential across many sources, locations and precursor emission types. Atmos. Environ. 98, 283–289. https://doi.org/10.1016/j.atmosenv.2014.08.046.
Fowlie, M., Walker, R., Wooley, D., 2020. Climate Policy, Environmental Justice, and Local Air Pollution. Univ California, Berkeley.
Fujita, E.M., Campbell, D.E., Stockwell, W.R., Saunders, E., Fitzgerald, R., Perea, R., 2016. Projected ozone trends and changes in the ozone-precursor relationship in the South Coast Air Basin in response to varying reductions of precursor emissions. J. Air Waste Manag. Assoc. 66, 201–214. https://doi.org/10.1080/10962247.2015.1106991.
Guenther AB, Jiang X, Heald CL, Sakulyanontvittaya T, Duhl T, Emmons LK, et al. The Model of Emissions of Gases and Aerosols from Nature Version 2.1 (MEGAN2. 1): an Extended and Updated Framework for Modeling Biogenic Emissions 2012.
Guo, L., Yedavalli, K., Zinger, D., 2011. Design and modeling of power system for a fuel cell hybrid switcher locomotive. Energy Convers. Manag. 52, 1406–1413. https://doi.org/10.1016/j.enconman.2010.10.003.
Hess, K.S., Miller, A.R., Erickson, T.L., Dippo, J.L., 2010. Demonstration of a hydrogen fuel-cell locomotive. Rail Conf 1–6.
Hoffrichter, A., 2019. Hydrogen-Rail (Hydrail) Development. https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-hoffrichter.pdf.
Hogerwaard, J., Dincer, I., 2016. Comparative efficiency and environmental impact assessments of a hydrogen assisted hybrid locomotive. Int. J. Hydrogen Energy 41, 6894–6904. https://doi.org/10.1016/j.ijhydene.2016.01.118.
Houston, D., Krudysz, M., Winer, A., 2008. Diesel truck traffic in port-adjacent low-income and minority communities: environmental justice implications of near-roadway land use conflicts. J Transp Res Board 2076, 38–46.
Houyoux, M., Vukovich, J., Brandmeyer, J.E., 2015. Sparse Matrix Operator Kernel Emissions (SMOKE) v3.7 User's Manual. Univ North Carolina Chapel Hill. Available. https://www.cmascenter.org/smoke/documentation/3.7/manual_smokev37.pdf. (Accessed 22 June 2016).
Hydrogen Business Council, California, 2018. CHBC Hydrogen and Fuel Cells in Ports and Shipping Workshop Report. Los Angeles, CA. https://www.californiahydrogen.org/wp-content/uploads/2019/03/chbc-h2fc-in-ports-and-shipping-report_final.pdf.
Industrial Economics, 2016. Review of Baseline Incidence Rate Estimates for Use in 2016 Socioeconomic Assessment . Memorandum. Massachusetts, MA. Industrial Economics, Inc. Available at: http://www.aqmd.gov/docs/default-source/clean-air-plans/socioeconomic-analysis/iecmemos_november2016/scbaselineincidence_112916.pdf
Kinnon, M.M., Zhu, S., Carreras-Sospedra, M., Soukup, J.V., Dabdub, D., Samuelsen, G.S., et al., 2019. Considering future regional air quality impacts of the transportation sector. Energy Pol. 124 https://doi.org/10.1016/j.enpol.2018.09.011.
LandScan, O.R.N.L., 2016. Oak ridge national laboratory. Available at: http://web.ornl.gov/sci/landscan/. Oak Ridge, TN: Oak Ridge National Laboratory. Available at.
Lee, G., You, S.I., Ritchie, S.G., Saphores, J.-D., Jayakrishnan, R., Ogunseitan, O., 2012. Assessing air quality and health benefits of the Clean Truck Program in the Alameda corridor, CA. Transp Res Part A Policy Pract 46, 1177–1193.
Lei, H., Wang, J.X.L., 2014. Sensitivities of NOx transformation and the effects on surface ozone and nitrate. Atmos. Chem. Phys. 14, 1385–1396. https://doi.org/10.5194/acp-14-1385-2014.
Martin, R.V., Fiore, A.M., Van Donkelaar, A., 2004. Space-based diagnosis of surface ozone sensitivity to anthropogenic emissions. Geophys. Res. Lett. 31 https://doi.org/10.1029/2004GL019416.
Martinez, A.S., Brouwer, J., Samuelsen, G.S., 2012a. Feasibility study for SOFC-GT hybrid locomotive power part II. System packaging and operating route simulation. J. Power Sources 213, 358–374. https://doi.org/10.1016/j.jpowsour.2012.04.023.
Martinez, A.S., Brouwer, J., Samuelsen, G.S., 2012b. Feasibility study for SOFC-GT hybrid locomotive power: Part I. Development of a dynamic 3.5 MW SOFC-GT FORTRAN model. J. Power Sources 213, 203–217.
Mayyas, A., Wei, M., Chan, S.H., Lipman, T., 2016. Fuel cell forklift deployment in the USA. Fuel Cells Data, Facts Fig 334–342. https://doi.org/10.1002/9783527693924.ch33.
Mekhilef, S., Saidur, R., Safari, A., 2012. Comparative study of different fuel cell technologies. Renew. Sustain. Energy Rev. 16, 981–989. https://doi.org/10.1016/j.rser.2011.09.020.
Miller, A.R., Hess, K.S., Barnes, D.L., Erickson, T.L., 2007. System design of a large fuel cell hybrid locomotive. J. Power Sources 173, 935–942. https://doi.org/10.1016/j.jpowsour.2007.08.045.
Ncep, N.C.E.P., 2000. FNL Operational Model Global Tropospheric Analyses, Continuing from July 1999. Res Data Arch Natl Cent Atmos Res Comput Inf Syst Lab. https://doi.org/10.5065/D6M043C6.
Papson, A., Ipoliti, M., 2013. Key Performance Perameters for Drayage Trucks Operating at the Ports of Los Angeles and Long Beach.
Peters, G., 2016. The Industry's Leanest, Greenest Eco-Locomotives. Railw Technol.
Pocard, N., 2018. Hydrogen powered trains: the next generation of shunters? Zero Emiss Rail Transp. https://blog.ballard.com/hydrogen-powered-trains.
Pratt, J.W., Harris, A.P., 2013. Vessel Cold Ironing Using a Barge Mounted PEM Fuel Cell: Project Scoping and Feasibility. Albuquerque, NM and Livermore, CA. Sandia National Laboratories.. Available at. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/sand2013-0501_barge_mounted_pemfc.pdf
Pye, H.O.T., Murphy, B.N., Xu, L., Ng, N.L., Carlton, A.G., Guo, H., et al., 2017. On the implications of aerosol liquid water and phase separation for organic aerosol mass. Atmos. Chem. Phys. 17, 343–369. https://doi.org/10.5194/acp-17-343-2017.
Reed, J.G., Dailey, E.E., Shaffer, B.P., Lane, B.A., Flores, R.J., Fong, A.A., et al., 2020. Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California. Sacramento.
Industrial Economics, Robinson, Lisa, 2016. Review of Mortality Risk Reduction Valuation Estimates for 2016 Socioeconomic Assessment. Memorandum. Industrial Economics, Inc., Massachusetts, MA. Available: http://www.aqmd.gov/docs/default-source/clean-air-plans/socioeconomic-analysis/iecmemos_november2016/evaluationcriteria_113016.pdf.
Robinson, L.A., Hammitt, J.K., 2016. Valuing reductions in fatal illness risks: implications of recent research. Health Econ. 25, 1039–1052.
Sacks, J.D., Lloyd, J.M., Zhu, Y., Anderton, J., Jang, C.J., Hubbell, B., et al., 2018. The Environmental Benefits Mapping and Analysis Program–Community Edition

(BenMAP–CE): a tool to estimate the health and economic benefits of reducing air pollution. Environ. Model. Software 104, 118–129.

Shaffer, B., 2018. Optimal Utilization of Forestry Biomass in Integrated Gasification Systems for Fueling Zero Emission Vehicles.

Shen, E., Oliver, A., Dabirian, S., 2017. Final socioeconomic Report . South coast air quality management District. Available at: http://www.aqmd.gov/docs/default-source/clean-air-plans/socioeconomic-analysis/final/sociofinal_030817.pdf?sfvrsn=2.

Siddiqui, O., Dincer, I., 2019. A review on fuel cell-based locomotive powering options for sustainable transportation. Arabian J. Sci. Eng. 44, 677–693. https://doi.org/10.1007/s13369-018-3607-2.

Starcrest Consulting Group, L., 2017. Port of Los Angeles Inventory of Air Emissions - 2016. Los Angeles, CA.

Starcrest Consulting Group, L., 2020. Port of Los Angeles Air Inventory - 2019. Los Angeles, CA, Available:https://kentico.portoflosangeles.org/getmedia/4696ff1a-a441-4ee8-95ad-abe1d4cddf5e/2019_air_emissions_inventory.

Stephens-Romero, S., Samuelsen, G.S., 2009. Demonstration of a novel assessment methodology for hydrogen infrastructure deployment. Int. J. Hydrogen Energy 34, 628–641. https://doi.org/10.1016/j.ijhydene.2008.10.045.

Stewart, D.R., Saunders, E., Perea, R., Fitzgerald, R., Campbell, D.E., Stockwell, W.R., 2019. Projected changes in particulate matter concentrations in the South Coast Air Basin due to basin-wide reductions in nitrogen oxides, volatile organic compounds, and ammonia emissions. J. Air Waste Manag. Assoc. 69, 192–208. https://doi.org/10.1080/10962247.2018.1531795.

The Port of Los Angeles and the Port of Long Beach. San Pedro Bay Ports Clean Air Action Plan: 2017 Update, 2017.

Toyota unveils hydrogen fuel cell drayage truck for feasibility study at Port of Los Angeles. Fuel Cell. Bull., 2017 1.

van Biert, L., Godjevac, M., Visser, K., Aravind, P.V., 2016. A review of fuel cell systems for maritime applications. J. Power Sources 327, 345–364. https://doi.org/10.1016/j.jpowsour.2016.07.007.

BNSF, 2009. Vehicle Projects demonstrate fuel cell switch locomotive. Fuel Cells Bull 2009 4. https://doi.org/10.1016/s1464-2859(09)70245-7.

Vutukuru, S., Dabdub, D., 2008. Modeling the effects of ship emissions on coastal air quality: a case study of southern California. Atmos. Environ. 42, 3751–3764. https://doi.org/10.1016/j.atmosenv.2007.12.073.

Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) Shore to Store Project. Los Angeles, CA, (n.d). https://sustainableworldports.org/wp-content/uploads/zanzeff_factsheet_final.pdf.

Zhang, L., Xing, Y., Xu, H., Wang, H., Zhong, J., Xuan, J., 2017. Comparative study of solid oxide fuel cell combined heat and power system with Multi-Stage Exhaust Chemical Energy Recycling: modeling, experiment and optimization. Energy Convers. Manag. 139, 79–88. https://doi.org/10.1016/j.enconman.2017.02.045.

Zhu, S., Horne, J.R., Mac Kinnon, M., Samuelsen, G.S., Dabdub, D., 2019. Comprehensively assessing the drivers of future air quality in California. Environ. Int. 125, 386–398.