Changes in Air Quality from Fuel Cell Electric Vehicles and Electrolysis-Produced Hydrogen in Tandem with High Levels of Renewable Power

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ABSTRACT

The replacement of petroleum-fuel combustion engines with fuel cell electric vehicles (FCEV) operating on hydrogen represents a prominent strategy in mitigating pollutant and greenhouse gas (GHG) emissions from light duty vehicles (LDV). Furthermore, concomitant increases in renewable power generation could contribute benefits, e.g., via electrolysis-produced hydrogen as a vehicle fuel. However, it is unclear (1) how high levels of FCEV use could impact regional air quality (AQ) and (2) how co-deployment of electrolysis-based hydrogen production pathways could enhance benefits by increasing generation from renewable resources. To address these questions, this work assesses how the large-scale adoption of FCEVs powered by electrolysis-produced hydrogen and various levels of renewable resources affect atmospheric concentrations of ozone and fine particulate matter ($PM_{2.5}$) in California (CA) in the year 2055 relative to a gasoline vehicle baseline. A base year inventory of spatially and temporally resolved emissions is grown to 2055 representing a business-as-usual progression of economic sectors, including predominant gasoline consumption by LDVs. Simulations of atmospheric chemistry and transport are conducted to evaluate contributions to primary and secondary pollutant formation and fate for FCEV Cases relative to the Base Case. FCEV deployment achieves AQ benefits in important areas of the State of California with all Cases achieving reductions in ground level ozone and $PM_{2.5}$ exceeding 4 ppb and 4 $\mu g/m^3$, respectively. In addition, the importance of emissions from petroleum fuel infrastructure (PFI) activity is demonstrated in impacts on ozone and $PM_{2.5}$ burdens, with large refinery complexes representing a key source of air pollution in 2055. Emissions from the power sector are shown to have a minor impact on AQ relative to those from vehicles and PFI. Results provide insight into FCEV deployment strategies that can achieve maximum reductions in ozone and $PM_{2.5}$ and will assist decision makers in developing effective transportation sector regional AQ improvement strategies.

INTRODUCTION

The U.S. transportation sector currently represents a sector of paramount greenhouse gas (GHG) emission concern contributing approximately a third of total domestic emissions [1]. Moreover, transport sources account for an important fraction of total emissions driving regional air quality (AQ) concerns in many U.S. regions, including ambient concentrations of ozone and particulate matter (PM). Forthcoming climate change mitigation strategies will include transitions to alternative technologies and fuels in pursuit of GHG emission reductions from U.S. transportation sources [2]. Furthermore, shifts from conventional light duty vehicle (LDV) energy strategies (i.e., combustion of petroleum-based fuels) will alter pollutant emissions in tandem and impact regional AQ. Fuel cell electric vehicles (FCEVs) operating on hydrogen instead of an internal combustion engine have gained significant attention in recent years in response to environmental concerns [3]. FCEV technologies offer the benefits of high efficiencies [4-6], similar ranges and refueling times compared to combustion engines [6-8], and the promotion of domestic energy independence via displacement of petroleum fuels (hydrogen can be produced from a range of domestically available feedstocks) [9]. In addition, FCEVs are a key strategy to reduce GHG and pollutant emissions from the potential for very low lifecycle GHG and criteria pollutant emissions compared to current and future conventional LDVs [10-13].

Hydrogen is an energy carrier, not a primary energy source, and can be produced from a variety of primary energy sources, including fossil and renewable sources. Currently, low cost and widely used supply chain strategies to produce hydrogen are fossil-based options such as steam methane reformation (SMR) of natural gas, which results in the generation and release of both GHG and pollutant emissions [14]. However, hydrogen production via methods with enhanced sustainability will likely increase as GHG, AQ and additional environmental goals drive technological development and deployment [9]. Centralized and distributed electrolysis of water using power generated from renewable sources (e.g., wind and solar power) achieves near-zero carbon hydrogen production and represents a potential pathway for FCEV deployment that will significantly reduce GHG and criteria pollutants relative to current strategies [15]. Additional prospective renewable hydrogen systems include various processes (e.g., gasification, pyrolysis, fermentation, anaerobic digestion) associated with biomass or biogas feedstock and additional routes incorporating solar energy such as thermochemical splitting of water [16].

Life cycle emissions per mile for FCEVs include total emissions from vehicle and fuel production/distribution and operational vehicle efficiencies. Estimates by the U.S. Department of Energy report average life cycle emissions for a future mid-size FCEV range from 37 to 200 g CO_2eq/mile, with the high range corresponding to hydrogen produced from distributed natural gas and the low range associated with biomass gasification [17]. Replacing the current U.S. on-road vehicle fleet with FCEVs has been shown to reduce net GHG emissions across a range of hydrogen supply chain strategies [18, 19], including in California [20]. In particular, FCEVs supplied with hydrogen produced from wind-powered electrolysis have been shown to be a potential option for achieving large-scale reductions in total emitted carbon from transportation [21]. Also, the deployment of FCEVs has been demonstrated to achieve reductions in emissions of air pollutants, including oxides of nitrogen (NO_x), volatile organic compounds (VOC), PM, and carbon monoxide (CO) across a range of hydrogen supply chain strategies and HFCV efficiencies[18, 21]. Additionally, reductions in direct emissions have been shown to result in improvements in secondary air pollutants, including ground-level ozone [22, 23]. Use of a novel methodology for future hydrogen infrastructure development in the South Coast Air Basin (SoCAB) of California reported substantial reductions emissions including NO_x for the majority of scenarios [24] translating to significant AQ improvements (e.g., reductions in peak 8-h-averaged ozone and 24-h-averaged $PM_{2.5}$ concentrations) [20]. Therefore, FCEVs can be considered a GHG mitigation strategy with high potential to attain AQ co-benefits.

In addition to improved environmental performance, the integration of hydrogen production with the future electric grid could have benefits by essentially providing complementary services in the form of energy storage and can allow for greater penetrations of renewables, particularly those plagued by intermittency challenges [25]. Due to this potential, hydrogen has been proposed as an important complement to the implementation of wind energy in part as a means of coupling GHG mitigation strategies in the utilities and transportation sectors [26-28]. Similar concepts and conclusions have been reported for solar hydrogen production [29]. As many places around the world (including California) are pursuing greater procurement of renewable energy in coming decades, including significant amounts expected from intermittent wind and solar technologies, the incorporation of hydrogen energy systems to provide fueling for vehicles and stationary sources could represent an important opportunity to maximize AQ and GHG benefits and maintain grid reliability.

Although previous studies have evaluated the emissions [18, 30] or AQ [22, 23] impacts of FCEVs, few have utilized detailed 3D Eulerian AQ models that account for spatial and temporal emissions perturbations and interactions of atmospheric chemistry and transport processes to produce ground level ozone and particulate matter concentrations for an entire State. This work evaluates deploying FCEVs in tandem with renewable resources in California in 2055 to better understand how GHG mitigation strategies in the LDV and power generation sectors can improve AQ concurrently. Baseline AQ in the horizon year (2055) is established accounting for changes in various emission drivers, including demand growth in economic sectors, efficiency improvements, and utilized technologies and fuels according to a business-as-usual progression. Cases are developed for FCEV deployment and renewable resource integration accounting for spatial and temporal distribution of fundamental sources to evaluate impacts on ambient pollutant concentrations from emission perturbations, including ozone and $PM_{2.5}$.

APPROACH

To evaluate AQ impacts in 2055, emissions must be justifiably projected from current (2005) levels and spatially and temporally resolved to facilitate input into an advanced air quality model. A Base Case is developed comprising a business-as-usual continuation of current technological, energy, and economic trends with a relative lack of GHG mitigation efforts. Emissions are grown to 2055 from current levels to reflect alterations to major sources projected in the Base Case and spatially and temporally resolved to account for direct perturbations. Finally, simulations of atmospheric chemistry and transport processes are conducted to establish fully developed distributions of atmospheric concentrations of pollutants of interest.

Regional Energy System Projection

Sources, magnitudes, and spatial/temporal patterns of future anthropogenic emissions are affected by an extensive range of factors (e.g., population growth/migration, economic growth/evolution, availability and depletion of various energy resources, climatic changes, technology development /deployment, future policy implementation, human behavior) [31]. Thus, assessing regional AQ for a future year requires the projection of emissions by consistent and reasonably justifiable methods including a detailed understanding of regional emissions evolution under business-as-usual (BAU) conditions. The approach for this work for the emissions corresponding to a baseline outcome in 2055 follows the methodology described by

Loughlin et al., 2011 [31]. For this work, BAU energy system progression and associated perturbations in emissions signatures are estimated using the Market Allocation (MARKAL) model, a data-intensive energy systems economic optimization model with an EPA developed and maintained 9-region database [32]. MARKAL allows for national and regional energy system characterization. Energy system details embodied in the model framework include primary energy resource supplies, energy conversion technologies, end-use demands, and various technological options to meet specified demands in power generation, residential, commercial, industrial, and transportation sectors in future years. Model outputs include demands, technologies, fuel use and emissions of GHG and pollutants from current to 2055. Utilizing output from MARKAL, emissions from energy sources and sectors are estimated for a given region in 2055. In addition, emission deviations in the Base Case from 2005 driven by energy system changes are determined. Total emissions of CO_2 and criteria pollutants computed by MARKAL are utilized to develop growth factors to 2055. The MARKAL simulation used to generate the Base Case in this work incorporates various future policy constraints, including a representation of Federal Corporate Average Fuel Economy (CAFE) standards for LDVs, the Cross-State Air Pollution Rule (CSAPR), and the Mercury and Air Toxics Standards. Factors were generated using the 9-region MARKAL database, version 1.3, with updated electric sector and CSAPR representations (v1.5_052112_dhl and 1.3_052212_dhl, respectively). With the exception of the CAFE standard, the model was calibrated based on the 2010 Energy Information Administration's Annual Energy Outlook.

Development of Emissions Fields

Development of AQ model ready, spatially and temporally resolved emission fields is accomplished using the Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System [33]. SMOKE is an emissions processing system that develops emission fields for AQ model input using a series of matrix calculations and allows for rapid and flexible processing of emissions data. SMOKE performs the core functions of emissions processing including spatial and temporal allocation, chemical speciation, generation of biogenic emission estimates and control of area-, mobile-, and point-source emissions. Additionally, growth and control factors from MARKAL are applied to the 2005 base-year inventory via SMOKE including disaggregation of emissions into their constituent chemical species via a library of Source Classification Code (SCC) specific chemical speciation profiles. Spatial and temporal allocation into a 3-D modeling grid is accomplished through spatial surrogates and SCC-specific temporal allocation profiles. Point source emissions are allocated directly to the grid cell in which each source's coordinates are given. Non-point emission sources are characterized at the county level and emissions are allocated to grid cells via spatial surrogates. SMOKE uses temporal activity profiles to allocate emissions to hour of day. Source-specific information that is used in allocation methodologies includes factors such as land use, census data, employment information, and others.

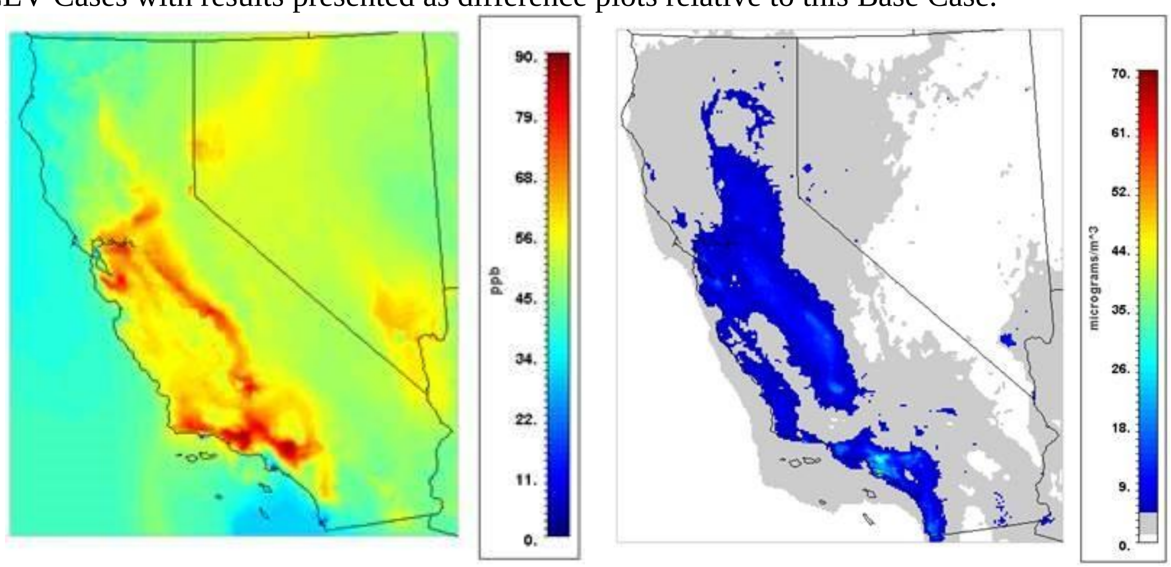
Atmospheric Modeling

Simulations of AQ are conducted using the Community Multi-scale Air Quality model (CMAQ) version 4.7, with the Carbon Bond 05 chemical mechanism [34]. CMAQ is a widely used comprehensive air quality modeling system developed by the US Environmental Protection Agency (EPA) and utilized for a range of purposes, e.g., regulatory air quality simulation applications [35, 36]. The source code and technical formulation of the model are available from the CMAQ website: www.cmaq-model.org. CMAQ is designed from the "one atmosphere" perspective and is used for studies on tropospheric ozone, particulate matter, acid deposition and visibility. The CMAQ system includes a meteorological modeling system, emissions modeling system and chemical transport modeling system. Model inputs include meteorological conditions, initial and boundary conditions, land use and land cover information, and anthropogenic and biogenic source emissions. The chemical mechanism used in CMAQ is the CB05 which includes the photochemical formation of ozone, oxidation of volatile organic compounds and formation of organic aerosol precursors. For the simulations presented in this report, the spatial resolution of control volumes is 4 km × 4 km, and a vertical height of 10,000 meters above ground, with 30 layers of variable height based on pressure distribution. Meteorological input data for CMAQ was obtained from the Advanced Research Weather Research and Forecasting Model, WRF-ARW. The National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis 1° × 1° grid data are used for WRF-ARW initial and boundary conditions.

Base Case Air Quality

The developed MARKAL Base Case follows current trends and is predominantly comprised of gasoline combustion engine technologies (a moderate to minor amount of LDV demand is assumed to be met with alternative technologies and fuels including electricity and E-85). Similar trends are observed in all major energy sectors reflecting the absence of large-scale GHG mitigation efforts.

The simulated ozone and $PM_{2.5}$ are shown in **Figure 1** for the Base Case in 2055. Various regions of the State experience high ground-level concentrations including Los Angeles, Riverside, and San Bernardino Counties in the South Coast Air Basin (SoCAB), the San Francisco Bay Area, and the Central Valley. Results serve as a basis for comparison for the FCEV Cases with results presented as difference plots relative to this Base Case.



(a) (b)

Figure 1: Predicted ground-level concentrations of (a) max 8-hr average ozone and (b) 24-hr average $PM_{2.5}$ for the Base Case

FCEV Case Development

To evaluate changes in spatial and temporal distributions of ozone and $PM_{2.5}$ from FCHV deployment a set of Cases are developed and analyzed in California for the year 2055. Assessment of Cases comprises the construction of spatially and temporally resolved emission fields appropriately accounting for all mobile and stationary source perturbations followed by simulations of atmospheric chemistry and transport. Output from atmospheric modeling is then assessed for changes in ground-level maximum 1 hour (1-hr) average ozone and 24 hour (24-h) average $PM_{2.5}$ concentrations relative to the baseline Case (i.e. gasoline internal combustion engine dominant) for the same year.

Table 1 displays the emission impacts for the various sources comprised in the assessed Cases. All Cases encompass a FCHV penetration of 90% of all LDVs in California in 2055 and direct (i.e., tailpipe) LDV emissions are correspondingly reduced fleet-wide, i.e., all Cases exhibit a 90% reduction for all direct pollutants including NO_x, PM, VOC, etc. Reductions are applied via SMOKE and occur over all road-way types throughout the State.

Reductions in gasoline consumption are assumed to translate to reductions in petroleum fueling infrastructure (PFI) emissions including those from large refineries, gasoline storage, fueling stations, etc. It should be noted that one Case is included without PFI reductions (FCEV 38 NoTurn) to demonstrate the impact of PFI emissions relative to vehicle tailpipe emissions. The largest source of PFI emissions occur from large refinery complexes that produce a range of products in addition to motor gasoline (e.g., distillate fuels, kerosene, jet fuel). Hence, the reduction in PFI emissions is assumed to correspond only to the fraction of output attributable to motor gasoline, i.e., in the CA region in 2055 gasoline comprises 42% of net refinery production. Thus, a 90% reduction in gasoline consumption is applied as a 38% reduction in total refinery emissions. Contrastingly, emissions from additional PFI sources (e.g., fueling stations) are associated predominantly with gasoline vehicles and are reduced accordingly (i.e., taxable gasoline sales comprise 80% of total with diesel thus fueling station emissions are reduced by 80% in all Cases expect for the FCEV 38 NoTurn (http://energyalmanac.ca.gov/transportation/summary.html#fuel).

Furthermore, the FCEV 75 – HDV Case is established to provide an upper bound on the potential impact that heavy duty vehicle (HDV) trucking of hydrogen may have if it was widely used (corresponding to a 10% increase in HDV emissions).

Table 1. Impacts on emissions representing evaluated Cases

Case	Power Emissions	LDV Emissions	HDV Emissions	Refinery Emissions
FCEV 21	-21%	-90%	---	-38%
FCEV 38	-38%	-90%	---	-38%
FCEV 38 - No Turn	-38%	-90%	---	---
FCEV 75	-75%	-90%	---	-38%

FCEV 75 - HDV	-75%	-90%	+10%	-38%
FCEV 85	-85%	-90%	---	-38%

Synergies are possible between advanced alternative vehicle fueling pathways and the electric grid that can assist in maximizing GHG and pollutant emission reductions. For example, electrolysis production of hydrogen can be constructed and managed to allow the grid to absorb enhanced levels of variable generation from various wind and solar technologies. Increased renewable generation could then be substituted in place of fossil generation, notably natural gas power plants in the State. Thus, for the assessed Case it is assumed that increases in generation from renewable resources, including electrolysis production of hydrogen to support vehicle fueling, results in decreases in output and subsequent emissions from existing California generators. Table 2 displays the determined reduction in output of natural gas-fired power plants occurring from displacement by renewable resources. In the Low Renewable Case it is assumed that 205 Gigawatts (GW) of renewable resources are deployed resulting in turn down of gas generators equal to 21% of the Base Case. For the High Renewable Case 425 GW are deployed corresponding to reductions of 38%, 75%, and 85% from gas generators dependent on vehicle characteristics and fueling infrastructure. The results are generated via a modeling methodology developed to examine the impacts of deploying various advanced alternative LDVs and charging/fuel infrastructure in tandem with the feasibility of meeting the 2050 GHG goal dictated in California by Executive Order S-21-09. The methodology integrates detailed models of the California electric grid operations and the State's light duty transportation sector. Comprehensive explanation of the method and results can be found at http://www.apep.uci.edu/3/ResearchSummaries/pdf/SustainableTransportation/ElectricGrid_VehicleIntegrationGHGimpacts.pdf.

Table 2. Percent reduction in MWh output of gas-fired generators from renewable resource deployment

	Low Renewable Case 205 GW	**High Renewable Case 425 GW**
FCEV 21	0.211	---
FCEV 38	---	0.375
FCEV 75	---	0.746
FCEV 85	---	0.848

The development of hydrogen fueling infrastructure includes a diverse range of potential technological and operational options, including some that represent new emissions sources, e.g., deployment of a steam methane reformation facility. A major assumption for all Cases is vehicle fueling pathways are optimized to absorb fully variable renewable generation on the electric grid resulting in pathways that do not introduce new emission sources into the State. This is assumed to be accomplished by various methods including electrolysis of water via renewable power that is then provided by pipeline to fueling stations. While this represents a highly optimistic case for hydrogen fuel provision to meet demands from a large vehicle fleet, it is a potential outcome given the horizon period (2055) considered. Further, dramatic reductions required to meet

California's 2050 GHG goals will require novel energy strategies and pathways in transportation and power generation that could reach the high deployment levels described in this work [37, 38]. Thus, this work can provide spanning information on AQ impacts.

FCEV Case Air Quality Results

For all Cases evaluated, deploying FCEVs and renewable resources at high levels directly contributes to reductions in ground-level ozone and $PM_{2.5}$. As shown in Figure 2, improvements in maximum 1-hr ozone levels exceed 4 ppb for the FCEV 21, FCEV 38, FCEV 75, and FCEV 85 Cases, including in important regions of California in terms of AQ, e.g., in the SoCAB, San Francisco Bay Area, and the Central Valley. Reductions in ground-level concentrations peak in urban regions associated with high vehicle populations and the presence of PFI. These areas currently experience high levels of ground-level ozone that often exceed Federal health-based standards and contain large urban populations [39]. Thus, improvements in these areas are desirable to the State in terms of mitigating deleterious human health outcomes from air pollution.

Impacts do not vary considerably amongst the Cases and emphasize the more significant contribution of direct vehicle and PFI emissions reductions to ozone concentration reductions compared to those from the power sector. Peak reductions observed in all of the Cases for ozone and $PM_{2.5}$ are displayed in Table 3. As can be seen, when emissions from the power sector are reduced while maintaining emissions reductions from LDVs and PFI increased ozone benefits are achieved. However, the magnitude is minor relative to the magnitude of the overall impact. For example, peak reductions increase from -4.31 ppb in the FCEV 21 Case (21% power sector emissions reduction) to -4.75 ppb in the FCEV 85 (85% power sector emissions reduction).

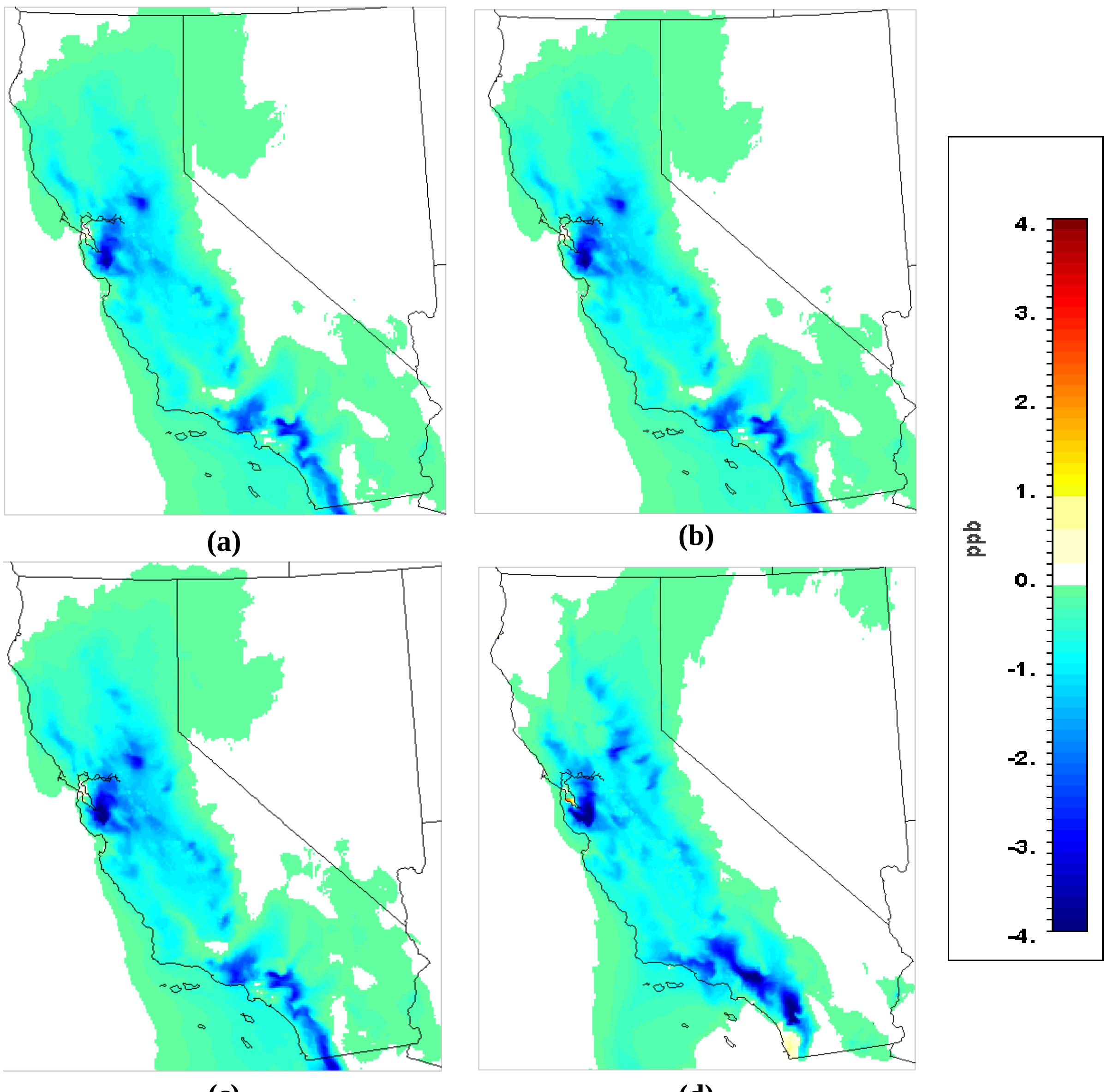


Figure 2. Differences in maximum 1-hr ozone from the Base Case for the (a) FCEV 21, (b) FCEV 38, (c) FCEV 75, and (d) FCEV 85 in California

Reductions in regional 24-hour $PM_{2.5}$ levels for all of the Cases are displayed in Figure 3. Ambient $PM_{2.5}$ concentrations in CA are reduced by over 4 $\mu g/m^3$ in some locations for all Cases. Notable regions of impact correspond to those for ozone, i.e., the SoCAB, S.F. Bay Area, and the Central Valley. Additionally, reductions show correspondence with the locations of major petroleum refinery complexes including from locations in Long Beach, Los Angeles, and Santa Maria. Also, similar to the ozone results, only minor changes occur amongst the Cases despite significant variance in power sector emissions (i.e., peak reductions of -4.17 ppb in the FCEV 21 Case relative to -4.20 ppb for the FCEV 85 Case). Thus, these particulate matter results demonstrate that the dominant contributor to $PM_{2.5}$ impacts originates from direct vehicle and PFI emissions.

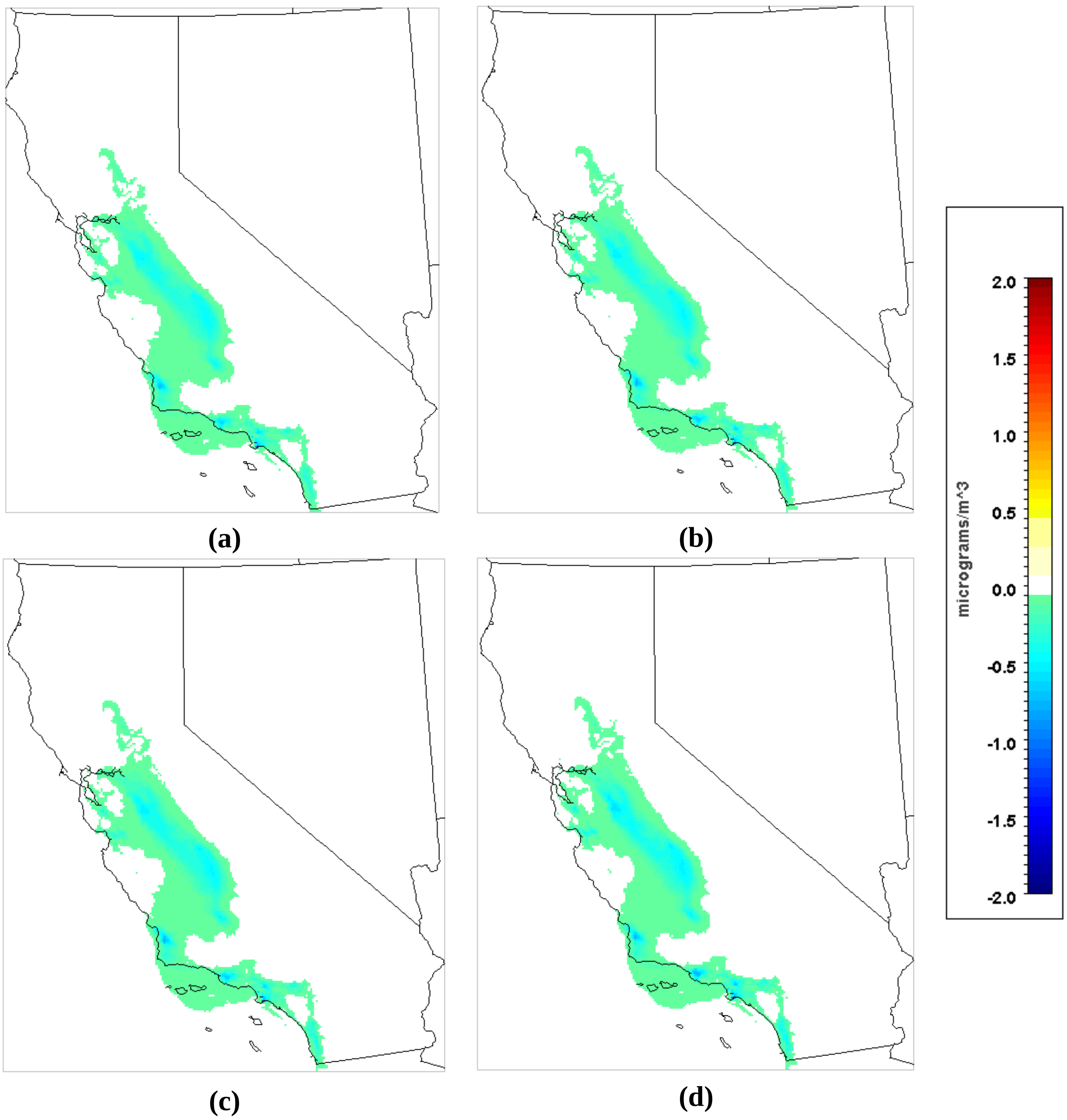
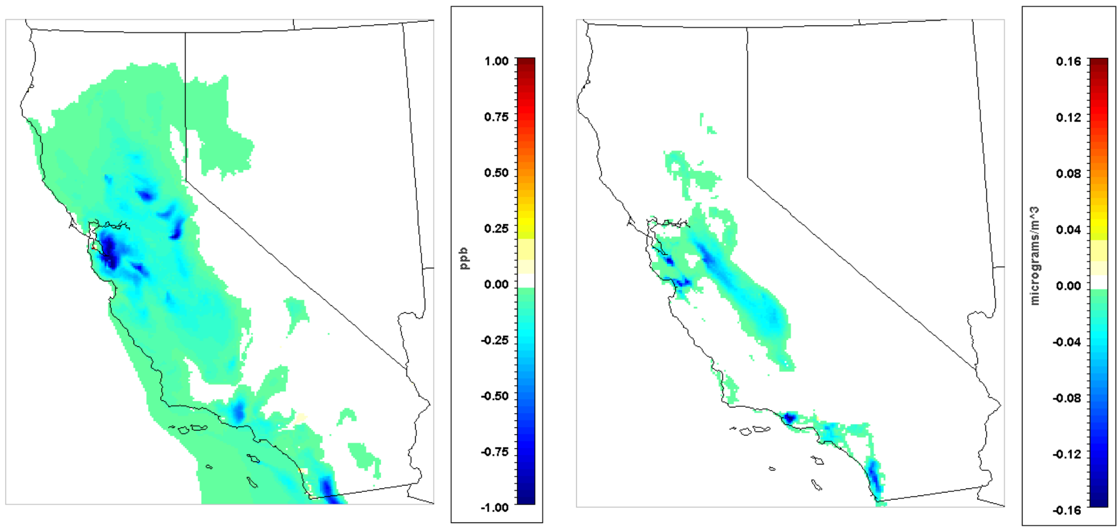


Figure 3. Differences in maximum 24-hr $PM_{2.5}$ from the Base Case for the (a) FCEV 21, (b) FCEV 38, (c) FCEV 75, and (d) FCEV 85 in California

To provide spatial information on the impacts attributable to the power sector, Figure 4 shows a difference plot for ozone and $PM_{2.5}$ between the FCEV 21 and FCEV 85 Cases. As all other emission source perturbations remain constant, differences show the effect of varying power sector emissions, i.e., -21% vs. -85%. Peak differences between the Cases reach -1.78

ppb and -0.17 μg/m^3. Relatively speaking, differences in ozone impacts are larger than $PM_{2.5}$ impacts in terms of magnitude. The spatial distribution of ozone impacts correspond to generator locations and include some in regions discussed previously (e.g., the SF Bay Area) as well as some regions that do not experience the highest background levels (e.g., northern portions of the State, San Diego).



(a) (b)

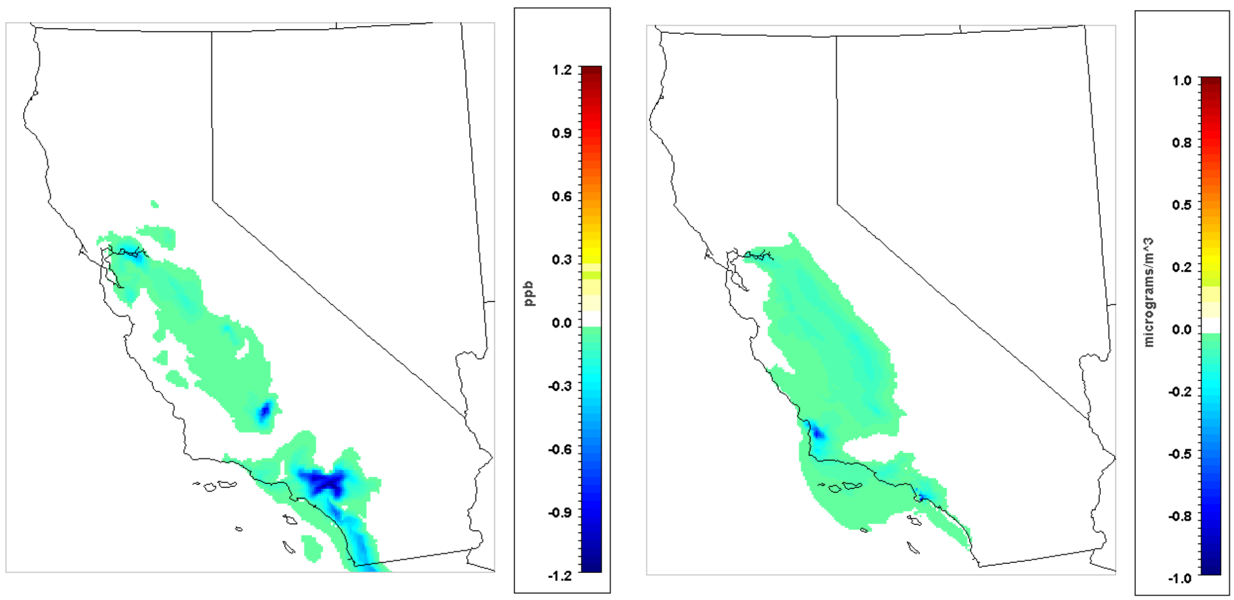
Figure 4. Impacts on (a) 1-hr ozone, and (b) 24-hr $PM_{2.5}$ for the FCEV 85 from the FCEV 21 Case

Impacts of PFI Emission Turn-down

In order to assess the impact of PFI emissions on AQ the FCEV 38 No Turn Case is compared relative to the FCEV 38 Case. As all other emission perturbations remain constant, i.e. direct vehicle and power plant reductions, the difference in ground-level concentrations is attributed solely to the difference from reducing PFI emissions associated with gasoline production and distribution. Additionally, the FCEV 38 No Turn Case is compared to the Base Case to provide information regarding the contribution of PFI emissions to overall observed impacts.

Figure 5 presents the data in terms of a difference plot between the FCEV 38 vs. the FCEV 38 No Turndown such that the results demonstrate the enhanced reduction from the PFI reductions present in the FCEV 38 Case. Ozone impacts peak at -1.28 ppb in the SF Bay Area, SoCAB and Bakersfield areas and are attributable to the presence of large refinery complexes. Additional benefits of a lesser magnitude occur in other regions of the Central Valley and San Diego. Impacts on ozone from PFI emissions are important in regards to both magnitude and spatial distribution. Reductions exceeding 1 ppb in several areas are prominent as peak impacts in the FCEV 38 Case relative to the Base Case exceeded 4 ppb. Further, the spatial distributions of reductions are important due to the high baseline concentrations experienced in those areas. The impacts of PFI emissions are significant for $PM_{2.5}$. Reductions in concentrations between the Cases peak at 4.75 μg/m^3 in an area downwind of a large refinery located in Santa Maria. Additional lesser benefits occur in the SoCAB, SF Bay Area, and Central Valley.

Table **3** lists reductions in $PM_{2.5}$ from the Base Case for the FCEV 38 No Turn Case peaking at -0.55 μg/m^3; while all other Cases containing PFI turn-down achieve reductions greater than 4 μg/m^3. Therefore, the largest peak reductions in ground-level concentrations of $PM_{2.5}$ from FCEV deployment result from the assumed reduction in PFI output and emissions. It should be noted that information regarding spatial distribution of impacts is not considered solely from comparing peak impacts. For example, the difference plot presented in Figure 4 shows that the peak impacts on $PM_{2.5}$ occur over a relatively small area with moderate reductions visible across a greater expanse. Nonetheless, results highlight the importance of considering emissions from PFI in reaching maximum AQ benefits from the deployment of advanced alternative LDV technologies.



(a) (b)

Figure 5. Impacts on (a) 1-hr ozone, and (b) 24-hr $PM_{2.5}$ for the FCEV 38 from the FCEV 38 No Turn Case

Impacts of HDV Emission Increases

If HDV were used to truck hydrogen throughout society there would be significant emissions associated with such trucking. Figure 6 displays the impacts on ozone and $PM_{2.5}$ for the FCEV 75 Case relative to the FCEV 75 HDV Case. An increase state-wide of 10% in all HDV tail-pipe emissions (a possible upper-bound for trucking emissions for hydrogen delivery) results in ground-level ozone and $PM_{2.5}$ concentration increases of approximately 1 ppb and 0.3 μg/m^3, respectively. Additionally, the largest impacts are co-located in important areas of the State in terms of AQ as previously indicated. Furthermore, when the FCEV 75 HDV Case is compared to the Base Case peak reductions of -3.88 μg/m^3 (vs. -4.19 μg/m^3 for the FCEV 75 Case) demonstrating that the increased HDV traffic to distribute fuel can erode some of the AQ benefits of FCEVs (Table 3). While the 10% increase in HDV emissions modeled here does not correspond directly to any quantified hydrogen amount or spatial distribution of trucking routes, the Case represents a spanning outcome to be interpreted as an upper bound for AQ impacts. Accordingly, results demonstrate the importance to AQ of constructing hydrogen infrastructure that seeks better distribution pathways compared to HDV truck delivery (e.g., pipeline delivery, on-site generation) rather than providing predictive information.

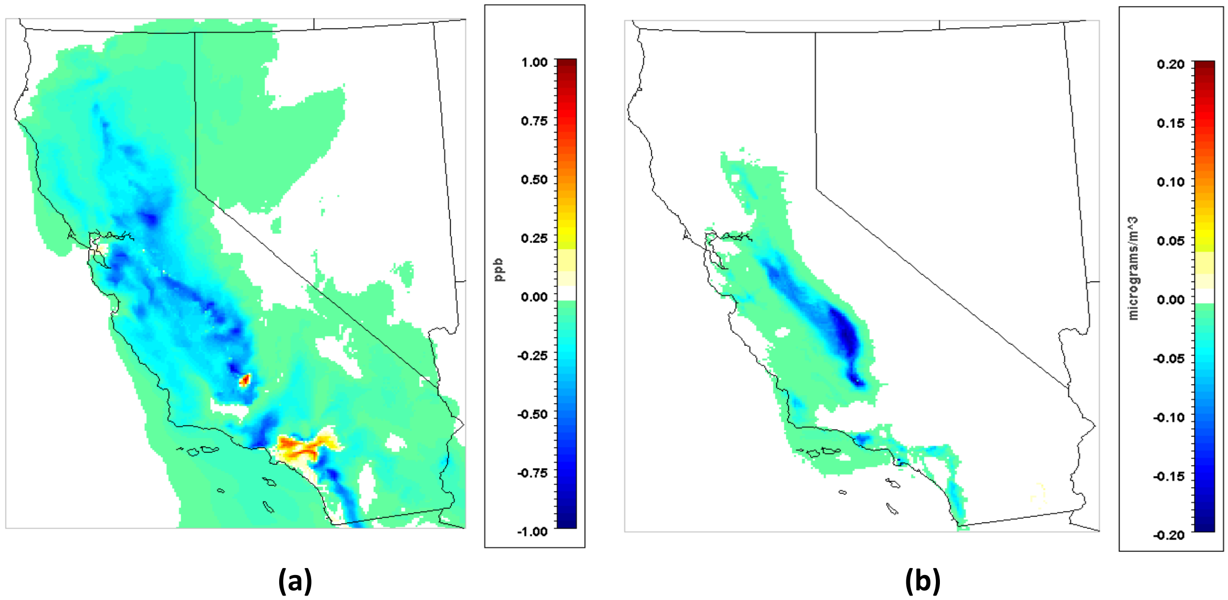


Figure 6. Impacts on (a) 1-hr ozone, and (b) 24-hr $PM_{2.5}$ for the FCEV 75 from the FCEV 75 HDV Case

CONCLUSIONS

The deployment of high levels of FCEVs (i.e., 90% LDV sector penetration) in tandem with renewable resources achieves significant benefits to AQ in California, including reductions in ground-level concentrations greater than 4 ppb ozone and 4 μg/m^3 $PM_{2.5}$. The greatest AQ impacts occur in key regions of the state where high urban populations are located and where poor AQ conditions are already occurring including the SoCAB, SF Bay Area, and the Central Valley. The impacts of not reducing PFI emissions corresponding to reduced motor gasoline production and distribution are demonstrated in lesser peak reductions, particularly for $PM_{2.5}$ (-0.55 μg/m^3 vs. 4.18 μg/m^3). Similarly, increasing HDV emissions lowers peak reductions for both ozone and $PM_{2.5}$. Despite reduced magnitudes, both the FCEV 38 No Turn (which retains PFI emissions) and FCEV 75 HDV (which introduces new HDV emissions for hydrogen trucking) Cases achieve overall AQ benefits relative to the Base Case.

Table 3. Peak reductions in ground-level concentrations of ozone and $PM_{2.5}$

Case	Δ 1-hr Ozone [ppb]	Δ 24-hr $PM_{2.5}$ [μg/m^3]
FCEV 21	-4.31	-4.17
FCEV 38	-4.37	-4.18
FCEV 38 No Turn	-4.13	-0.55
FCEV 75	-4.58	-4.19
FCEV 75 HDV	-4.05	-3.88
FCEV 85	-4.75	-4.20

The AQ benefits of all of the Cases are largely driven by vehicle and PFI emissions with moderate changes attributed to power sector impacts, e.g., the difference in peak ozone and $PM_{2.5}$ between a 21% and 85% reduction in generator emissions are -1.71 ppb and 0.17 μg/m^3. Additionally, peak impacts are generally located in less populated areas relative to those from vehicles. The composition of the California power generation sector directly impacts results as California has a lower emitting mix of electric power generators relative to other regions of the U.S. including a near complete lack of coal power generation. Thus, the benefit of reducing power sector emissions may achieve significantly higher AQ benefits in regions that deploy large coal power generation fleets.

Emission impacts from PFI supporting motor gasoline production and distribution are important factors that affect ozone and $PM_{2.5}$ in California. Peak reductions of 1.28 ppb and 4.75 μg/m^3 between Cases with and without turn down are predicted. Impacts on $PM_{2.5}$ are particularly notable as being the major driver of peak impacts for all Cases. Moreover, improvements in AQ occur in regions of the State currently experiencing poor AQ, which heightens the importance of the results, such as ozone improvements in Bakersfield and SoCAB. However, while programs and policies are in place to promote the deployment of alternative, low or zero-emitting LDV technologies that will concurrently reduce gasoline consumption, e.g., California's Zero Emission Vehicle Program, it is unknown if emission will also decrease from PFI. A potential outcome is that gasoline production at California refineries may remain constant with excess product exported. Thus, designing and deploying LDV adoption strategies seeking maximum AQ and GHG benefits should consider also reductions from sources associated with gasoline production and storage; most notably large petroleum refinery complexes.

The Cases evaluated represent a positive outcome for FCEV technology marketplace success including a penetration of 90% in the LDV sector. Assumptions regarding hydrogen fuel infrastructure are highly optimistic in that it is assumed that all of the hydrogen production is renewable and facilitated by increased renewable power penetrations in the future. Thus, results from this work should be considered as an upper bound for the AQ benefits of FCEVs in California.

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