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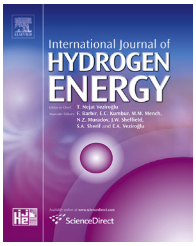

Air quality impacts of fuel cell electric hydrogen vehicles with high levels of renewable power generation

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ABSTRACT

The introduction of fuel cell electric vehicles (FCEV) operating on hydrogen is a key strategy to mitigate pollutant emissions from the light duty vehicle (LDV) transportation sector in pursuit of air quality (AQ) improvements. Further, concomitant increases in renewable power generation could assist in achieving benefits via electrolysis-provided hydrogen as a vehicle fuel. However, it is unclear (1) reductions in emissions translate to changes in primary and secondary pollutant concentrations and (2) how effects compare to those from emissions in other transport sectors including heavy duty vehicles (HDV). This work assesses how the adoption of FCEVs in counties expected to support alternative LDV technologies affect atmospheric concentrations of ozone and fine particulate matter ($PM_{2.5}$) throughout California (CA) in the year 2055 relative to a gasoline vehicle baseline. Further, impacts of reducing HDV emissions are explored to facilitate comparison among technology classes. A base year emissions inventory is grown to 2055 representing a business-as-usual progression of economic sectors, including primarily petroleum fuel consumption by LDV and HDVs. Emissions are spatially and temporally resolved and used in simulations of atmospheric chemistry and transport to evaluate distributions of primary and secondary pollutants respective to baseline. Results indicate that light-duty FCEV Cases achieve significant reductions in ozone and $PM_{2.5}$ when LDV market shares reach 50–100% in early adoption counties, including areas distant from deployment sites. Reflecting a cleaner LDV baseline fleet in 2055, emissions from HDVs impact ozone and $PM_{2.5}$ at comparable or greater levels than light duty FCEVs. Additionally, 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. Results presented provide insight into light duty FCEV deployment strategies that can achieve maximum reductions in ozone and $PM_{2.5}$ and will assist decision makers in developing effective transportation sector AQ mitigation strategies.

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Introduction

Transportation sources account for an important fraction of total emissions driving AQ concerns in many U.S. regions, including ambient concentrations of ozone and particulate matter (PM) associated with detrimental human health outcomes [1]. In California (CA), emissions from the combustion of fossil fuels by transportation sources including light duty (LDV) and heavy duty vehicles (HDV) have been shown to be major contributors to total regional pollutant burdens [2]. A shift to cleaner alternative propulsion systems is being pursued in CA to reduce the environmental impacts of the LDV transportation sector, including reducing the emissions of greenhouse gasses (GHG) and pollutant emissions and improving regional AQ [3,4]. A key strategy to attain emission reductions from LDVs includes the use of hydrogen in tandem with fuel cell electric power trains (FCEVs) as FCEVs have no direct emissions during operation [5]. In addition to LDV, FCEV technologies can be applied to reduce emissions in other transportation subsectors including HDV such as tractor-trailers, refuse trucks, transit buses, drayage trucks and others [6]. FCEV technologies also offer the benefits of high efficiencies [7], similar ranges and refueling times compared to combustion engines [8,9], and the promotion of domestic energy independence via displacement of petroleum fuels.

Impacts of transitioning to FCEVs include the full life cycle of deployed vehicle and hydrogen pathways [10]. Currently, widely-used hydrogen supply chain strategies are fossil-based including steam methane reformation which itself results in emissions [11]. However, hydrogen production methods with enhanced sustainability are desirable and can be pursued as GHG, AQ and additional environmental goals drive technological development and deployment [12]. Clean options include centralized and distributed electrolysis of water using electricity from renewable sources, representing a pathway for FCEVs to notably reduce GHG and pollutant emissions from transportation [13]. Additional renewable hydrogen systems include processes associated with biomass or biogas feedstock (e.g., gasification, pyrolysis, fermentation, anaerobic digestion) and routes using solar energy directly including thermochemical splitting of water [14,15]. Further, the integration of hydrogen production with the future electric grid could have benefits in terms of system operation by providing complementary services as a form of energy storage and could allow for enhanced integration of renewables, particularly those characterized by intermittencies including wind and solar power [16]. Therefore, hydrogen has been proposed as a complement to renewable electricity as a means of coupling GHG mitigation strategies in the utilities and transportation sectors [17–19].

The deployment of FCEVs can reduce total LDV and HDV emissions across a range of hydrogen infrastructure options from the potential for very low lifecycle GHG and criteria pollutant emissions compared to current and future conventional LDVs, including oxides of nitrogen (NO_x), volatile organic compounds (VOC), PM, and carbon monoxide (CO) [20–24]. Replacing the current on-road LDV fleet with FCEVs would reduce net GHG emissions in the U.S [25,26] and CA [27] with similar findings reported for pollutant emissions at various scales [28–30]. In particular, FCEVs supplied with hydrogen produced via renewably powered electrolysis can achieve large-scale reductions in total emissions from transportation [31]. As many places around the world (including CA) 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 criteria pollutant and GHG reductions and maintain grid reliability [32]. However, it is unknown how emission reductions from using renewable hydrogen as a vehicle fuel translates to reductions in primary and secondary pollutant distributions.

In addition to direct emissions from vehicles, the existing petroleum fuel infrastructure (PFI) encompassing the production, storage, transport, and distribution of petroleum fuels (including gasoline and distillate fuels predominantly used by LDV and HDV) emits pollutants and GHG [33,34]. Deploying FCEVs in CA could reduce the consumption of petroleum fuels – potentially offsetting emissions from PFI sources. The specific response of, for example, large in-state refinery complexes are unknown and how PFI emission perturbations impact AQ is subject to the same uncertainty as those from direct vehicles. Thus, further information is needed regarding the importance of PFI emissions to regional AQ in 2055, notably in regards to interactions with State goals for transportation strategies targeting GHG reductions and AQ improvements.

Assessing regional AQ impacts resulting from FCEV displacement of conventional LDV and HDV is multifaceted and exceeds simply quantifying emission perturbations. The complexity associated with the formation and fate of atmospheric pollutant species complicates an understanding of how FCEVs deployed in select counties will impact regional AQ generally in CA air basins. In particular, the dynamics associated with the production of ground-level ozone from pre-cursor emissions lessens the value of solely quantifying emission reductions in pursuit of AQ outcomes [35]. Similarly, atmospheric levels and compositions of PM in CA are governed by a large range of factors including sources of particulate and atmospheric processes that control particle formation that could lead to spatial and temporal variation in source-related impacts and potential mitigation strategies [36]. Therefore, detailed atmospheric models must be used to account accurately for the spatial and temporal distribution of pollutant concentrations in order to conduct a detailed assessment of how FCEVs may affect ground-level ozone and $PM_{2.5.}$

The goal of this work is to assess impacts on AQ of emission sources in the transportation, electric, and industrial sector under high renewable and advanced vehicle technology penetrations. For the first time this work uses advanced atmospheric modeling to examine how county-level FCEV adoption in the LDV and HDV sector impacts the spatial and temporal distribution of primary and secondary pollutants in CA. Although previous studies have evaluated the emissions [25,28] or AQ [37,38] impacts of FCEVs, few have utilized detailed three dimensional eulerian AQ models to account for spatial and temporal emissions perturbations and

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