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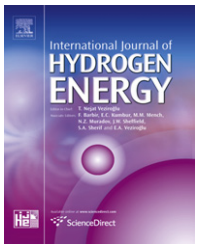

Projecting full build-out environmental impacts and roll-out strategies associated with viable hydrogen fueling infrastructure strategies

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ABSTRACT

A transition from gasoline internal combustion engine vehicles to hydrogen fuel cell electric vehicles (FCEVs) is likely to emerge as a major component of the strategy to meet future greenhouse gas reduction, air quality, fuel independence, and energy security goals. Advanced infrastructure planning can minimize the cost of hydrogen infrastructure while assuring that energy and environment benefits are achieved. This study presents a comprehensive advanced planning methodology for the deployment of hydrogen infrastructure, and applies the methodology to delineate fully built-out infrastructure strategies, assess the associated energy and environment impacts, facilitate the identification of an optimal infrastructure roll-out strategy, and identify the potential for renewable hydrogen feedstocks. The South Coast Air Basin of California, targeted by automobile manufacturers for the first regional commercial deployment of FCEVs, is the focus for the study. The following insights result from the application of the methodology:

- Compared to current gasoline stations, only 11%–14% of the number of hydrogen fueling stations can provide comparable accessibility to drivers in a targeted region.
- To meet reasonable capacity demand for hydrogen fueling, approximately 30% the number of hydrogen stations are required compared to current gasoline stations.
- Replacing gasoline vehicles with hydrogen FCEVs has the potential to (1) reduce the emission of greenhouse gases by more than 80%, reduce energy requirements by 42%, and virtually eliminate petroleum consumption from the passenger vehicle sector, and (2) significantly reduce urban concentrations of ozone and PM2.5.
- Existing sources of biomethane in the California South Coast Air Basin can provide up to 30% of the hydrogen fueling demand for a fully built-out hydrogen FCEV scenario.

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- A step-wise transition of judiciously located existing gasoline stations to dispense and accommodate the increasing demand for hydrogen addresses proactively key infrastructure deployment challenges including a viable business model, zoning, permitting, and public acceptance.

1. Introduction

Policymakers and business leaders are beginning to recognize and accept a need to transition from petroleum-based transportation fuels to alternative fuels. It is also increasingly accepted that meeting future greenhouse gas (GHG) reduction, air quality, and energy security goals will require that the future transportation mix include hydrogen in fuel cell powered electric vehicles [1]. Transitioning to hydrogen will require business and policy leaders to invest in new infrastructure that is cognizant of future energy and environment goals. An advanced planning methodology is needed to delineate a fully built-out infrastructure and impacts relative to long-term environment and energy security goals, and to facilitate the identification of an optimal infrastructure roll-out strategy. Such planning can target investments to be most effective.

While prior studies have addressed discrete elements that can contribute to a comprehensive planning methodology, key considerations for a fully integrated methodology have not been included. For example, previous studies have considered:

1. Discrete supply chain strategies for hydrogen infrastructure [2,3] but have not developed fully built-out hydrogen infrastructure strategies that integrate multiple hydrogen supply chain technologies while accounting for land use, infrastructure, geographic, and resource constraints;
2. Air pollution effects of introducing fuel cell electric vehicles (FCEVs) with discrete hydrogen production and delivery strategies [4,5], but without the spatial and temporal detail required to simulate air quality using atmospheric chemistry and transport models; and
3. The roll-out of hydrogen infrastructure but without either the spatial detail required from a planning perspective [6–8], or without weighing the multiple considerations that affect hydrogen station deployment [9].

To address the need for a comprehensive and fully integrated planning methodology, the Spatially and Temporally Resolved Energy and Environment Tool (STREET) was developed at the University of California, Irvine (UCI) to establish, then quantify and assess the full build-out and roll-out impacts of alternative transportation fuels through a comprehensive and integrated analysis that operates at a high level of spatial and temporal detail [10,11]. In particular, STREET provides the capability to:

1. Determine infrastructure needs and roll-out strategies for light-duty vehicle hydrogen fueling in a local community [10], and
2. Analyze the long-term environmental impacts (e.g., GHG emissions, air pollutant emissions, and air quality) of fully built-out hydrogen infrastructure scenarios [11].

The current study expands the utilization of STREET to establish a comprehensive vision for hydrogen infrastructure deployment from a local community to a regional focus. In particular, STREET is applied to a major urban region that is targeted for the early deployment of hydrogen infrastructure, and used to perform an assessment of (1) the impacts of fully built-out hydrogen infrastructure deployment with respect to long-term energy and environmental goals, and (2) preferred roll-out strategies for meeting infrastructure needs during the bulk of the transition from gasoline to hydrogen. The South Coast Air Basin (SoCAB) of California is selected as the urban region of interest for several reasons: The basin ranks among the most challenged in the United States with respect to air quality [12], is the most extensively studied airshed, and is the target area for hydrogen infrastructure and FCEV deployment in the US [13]. Because the SoCAB as an urban region also represents an isolated airshed, the expansion of STREET from a local community to the SoCAB region enables the study to go beyond an assessment of criteria pollutant emissions to determine air quality implications of hydrogen infrastructure deployment using an atmospheric chemistry and transport model.

The fully built-out hydrogen infrastructure deployment is assessed using hydrogen production and distribution scenarios in which it is assumed that 100% of light-duty vehicles in the SoCAB are FCEVs. The scenarios are developed with spatial and temporal detail by utilizing GIS data and the Preferred Combination Assessment (PCA) Model (a fuel supply chain impact assessment model) [14], both integral components of STREET. Other attributes of STREET are then employed to provide, for each scenario, an assessment of the future year air pollutant emissions and air quality (ozone and $PM_{2.5}$) impacts, greenhouse gas reduction, energy requirements, petroleum consumption, and water use [11].

The assumption of 100% light-duty hydrogen FCEVs represents an illustrative analysis to (1) provide insight into the effectiveness of a fully built-out hydrogen infrastructure in meeting long-term energy and environment goals, and (2) delineate both the largest investment and most stringent test case associated with FCEV technology. It is likely that the future light-duty vehicle mix will consist of a variety of

vehicles, not only FCEVs. It is also likely that future transportation strategies will include a greater amount of mass transit and encourage pedestrian-oriented development, therefore shifting a significant portion of personal mobility away from light-duty vehicles [15].

Using the fully built-out hydrogen production and distribution scenarios, STREET is then applied to establish the optimal strategies for meeting infrastructure requirements for the three target hydrogen communities in the SoCAB identified by automakers: (1) coastal and southern Orange County with a focus on Irvine and Newport Beach; (2) Torrance and the nearby beach cities; and (3) Santa Monica and West LA [16,17]. An output of STREET is the number and location of hydrogen stations in these three regions. From this result, a roll-out strategy is then developed for the transition from gasoline to hydrogen. Local, renewable feedstocks that could provide a source of hydrogen are identified as a potential strategy for meeting the 33% renewable hydrogen standard that is required in California [18].

2. Fully built-out hydrogen infrastructure

The state of California has adopted a series of aggressive policy goals to address looming energy and environment challenges. Specifically, these policy goals address anthropogenic GHG emissions that lead to global climate change, urban air quality, and reducing reliance on fossil fuels.

California Assembly Bill 32 requires a reduction of anthropogenic GHG emissions with an aim to mitigate rises in global temperatures [19]. The state of California is likely to be affected disproportionately by global climate change given its large agro-industry, its strained fresh water resources, its diverse fish and wildlife population, the high value of its coastal regions, and the fact that temperature rises will lead to higher levels of urban air pollution (in particular ozone), exacerbating an already severe urban air quality problem in many parts of California [20]. The detailed scenario design and fuel supply chain simulation and analysis capabilities of STREET provide the capability to assess GHG emissions relative to alternative transportation fuel strategies.

Due to dense population areas, high vehicle ownership and commuting rates, geographically constraining mountain ranges, and copious sunshine, southern California air quality remains the worst in the country despite aggressive efforts to reduce emissions from stationary and mobile sources [21]. Zero-emission FCEVs offer direct tailpipe emissions reductions compared to internal combustion engine vehicles. However, the net effects of light-duty vehicle emission reductions coupled with potential new sources of criteria pollutant emissions from hydrogen production and distribution is not straight-forward. Understanding the air quality implications of the perturbations in emissions requires detailed and extensive modeling efforts to account for atmospheric chemistry, transport, deposition, meteorological conditions, regional geography, and other physical phenomena that affect the balance of tropospheric chemical species [22]. STREET incorporates the University of California, Irvine-California Institute of Technology (UCI-CIT) atmospheric chemistry and transport model to model these complexities and determine the air quality impacts of replacing future gasoline automobiles with FCEVs and hydrogen infrastructure.

Two California policy initiatives reflect the state's goal to reduce reliance on fossil fuels. (1) The state's renewable portfolio standard requires that 33% of electric power generation come from renewable sources by 2020 [23]; (2) Senate Bill 1505 requires that hydrogen used for transportation must be generated from a mix of at least 33.3% renewable feedstocks (on the basis of energy content) [18]. The ability of STREET to design highly detailed fuel supply chain scenarios and assess energy efficiency provides valuable insight into the effectiveness of FCEVs and hydrogen infrastructure in reducing reliance on fossil fuels.

2.1. Scenario development

The first step in utilizing STREET is to establish an infrastructure and FCEV scenario for a future year, referred to as Scenario H. In this case the year is not specified, but rather is assumed to be a future year beyond 2050 in which FCEVs comprise virtually 100% of on-road passenger vehicles. Hydrogen production and distribution technologies in the scenario represent a vision for hydrogen infrastructure that is aggressive towards achieving California policy goals (i.e., maximizes air quality benefits, achieves GHG reductions nearing 80%, includes a high penetration of renewable hydrogen feedstocks exceeding the 33.3% renewable regulation in California, and improves energy efficiency to reduce petroleum dependence) while remaining pragmatic by integrating a mix of hydrogen feedstocks (including a significant portion of fossil fuel feedstocks), generation technologies, distribution strategies, and fueling technologies. Table 1 presents the FCEV population, fuel demand, and technology allocated to the generation, distribution, and dispensing of hydrogen in each scenario.

A gasoline vehicle scenario (Scenario G) serves as the basis for comparison. All non-passenger vehicle emissions are derived from estimates made by the South Coast Air Quality Management District (SCAQMD) to demonstrate attainment with ozone standards in the SoCAB by the year 2023 [24]. The resulting emissions inventory is applied equally to both Scenario H and Scenario G therein assuming that emissions do not exceed those estimated to achieve attainment in 2023. Gasoline passenger vehicle emissions are extrapolated based upon California Air Resources Board (CARB) projections of a future passenger vehicle fleet and associated emissions. The projection accounts for the gradual retirement of old vehicles and introduction of new vehicles compliant with the Low Emission Vehicle II (LEV II) Standards, including a higher penetration of gasoline hybrids, adopted by the California Air Resources Board through the year 2010 [25]. As a result, future gasoline vehicle criteria pollutant emissions are projected to be 70% lower than 2008 levels in scenario G.

2.2. Spatial and temporal allocation of infrastructure

2.2.1. Hydrogen fueling stations

Analyses performed in the southern California region show that sufficient accessibility to hydrogen fueling stations can be

achieved with between 11 and 14% the number of current gasoline stations when locations of the stations are optimized [26]. This result is associated in part with the high efficiency of FCEVs, emerging information technology on mobile phones or vehicle dashboard screens, and judicious planning to assure public access to fueling that is comparable to gasoline stations today.

Given previous hydrogen station optimization results provided by STREET, it is assumed in the current analysis that hydrogen stations comprising 15% the number of current gasoline stations will provide sufficient coverage for the SoCAB region. Based on a database of existing retail gasoline stations [27], the number of hydrogen fueling stations for full build-out of hydrogen infrastructure in the SoCAB region is 415 in order to achieve sufficient accessibility. However, an average throughput of about 19,000 kg of H_2/day would be required at each station to meet the hydrogen demand in Scenario H. This is approximately double that of a viable dispensing rate, based on the capacity of today's largest gasoline stations. Therefore, to satisfy the capacity demand, it is assumed that 830 hydrogen stations are required (each with an average throughput of 9500 kg of H_2/day) for Scenario H, which increases as well accessibility.

2.2.2. *Hydrogen production and distribution infrastructure*

The hydrogen infrastructure scenario described in Table 1 is designed with spatial and temporal detail based upon the STREET methodology described in the literature [11]. Fig. 1 provides an illustrative example of the spatial resolution assigned to various aspects of Scenario H. Spatially resolved hydrogen infrastructure includes hydrogen pipelines along existing pipeline corridors, truck routes for hydrogen delivery determined by shortest route algorithm, centralized and decentralized hydrogen production sites, and hydrogen fueling stations. Placement is determined by consideration of the local land use, infrastructure, and geographic details provided by geographic information systems (GIS) data.

2.3. *Assessment of long-term energy and environment impacts associated with a fully built-out hydrogen infrastructure*

Assessment of long-term energy and environment impacts incorporates the spatially and temporally resolved scenario information described above, applies the STREET Preferred Combination Assessment (PCA) model, and performs air quality simulations using the STREET UCI-CIT atmospheric

Table 1 – Fully built-out hydrogen infrastructure scenario for the South Coast Air Basin (SoCAB) of California. FCEVs comprise 100% of passenger vehicles and various hydrogen generation, distribution, and fueling technologies are used to meet hydrogen demand. Hydrogen distribution is based upon generation technologies, trucking and projected hydrogen pipeline infrastructure.

Population of FCV H_2		13,550,000		
demand (kg/day) VMT/day by FCVs[a]		7,841,000 470,456,000		
Hydrogen Generation	Number of facilities	H_2 output (kg/day)	Percent contribution	Location relative to the SoCAB
Centralized				
Steam methane reforming	15			Inside
Natural gas feed		1,921,000	24.5%	
Biomethane feed[b]		745,500	9.5%	
Coal IGCC[c]	5	846,800	10.8%	Outside
Electrolysis[d]	7	2,517,000	32.1%	Outside
Distributed				
Steam methane reforming	150	179,700	2.3%	Inside
Energy Station[e]	2020	972,300	12.4%	Inside
Electrolysis[f]	950	399,900	5.1%	Inside
Home or office fueling	39,300	258,800	3.3%	Inside
Hydrogen Distribution	Mean Distance (km/kg H_2)	H_2 throughput (kg/day)		
Remote pipelines	80	3,371,630		
Urban pipelines	24	4,077,320		
Liquid tanker	48	1,960,250		
Hydrogen Refueling	Number of fueling stations	H_2 delivered (kg/day)	Percent contribution	
140 bar gaseous fueling[g]	830 (combined)	5,488,700	70%	
350 bar gaseous fueling[g]		2,352,300	30%	

a Represents 100% of expected passenger vehicle miles travelled (VMT) in the SoCAB.
b Represents half of the current biomethane potential from landfills and wastewater treatment in the SoCAB.
c Coal integrated gasification combined cycle plant with carbon capture and storage cogenerating hydrogen and electricity.
d Electrolysis powered by mostly large-scale wind and solar facilities and some nuclear electricity.
e Cogenerates hydrogen, electrical power, and heat using high-temperature fuel cell.
f Electrolysis powered by photovoltaic electricity.
g It is assumed that efficiency increases of FCEVs coupled with the introduction of hydride storage materials in hydrogen tanks will reduce fueling pressures to 350 and 140 bar in years beyond 2050.

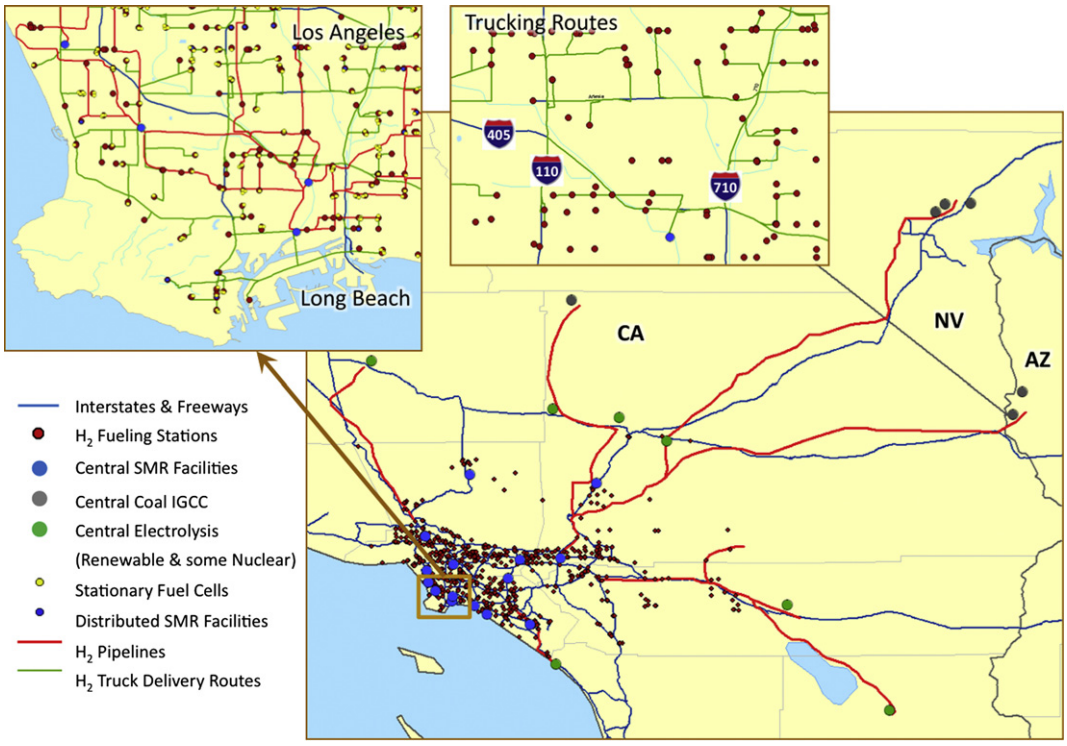

Fig. 1 – Spatial allocation of Scenario H implemented for the South Coast Air Basin of California (SoCAB). Geographic information systems (GIS) data are utilized to determine realistic sites for various components of hydrogen infrastructure at a high level of spatial and temporal resolution. Screening criteria applied in the analysis include proximity to existing fueling stations, hydrogen generation facilities, electrical power plants, roads and pipelines, density of hydrogen fueling stations, land use characteristics, and wind and solar resources. Routes for distribution of hydrogen by truck and pipeline were allocated using best route algorithms.

chemistry and transport model. Energy and environment impacts associated with the Scenario H are compared against Scenario G.

2.3.1. *Preferred combination assessment (PCA) model*

The PCA model integrates several hydrogen technologies to assess the performance of the hydrogen supply chain on a life cycle basis [14]. The hydrogen production, distribution, and dispensing mix and the average daily hydrogen demand provided in Table 1 serve as the inputs for the PCA model. The outputs from the model include GHG emissions, criteria pollutants, energy requirements, and water use associated with the hydrogen supply chain on a life cycle basis. In this case, criteria pollutant emission outputs include spatial and temporal detail.

2.3.2. *Air quality impacts*

Spatial fueling station and hydrogen generation facility analyses are combined with detailed emission factors for technologies at each component of the hydrogen supply chain. The result is a spatially and temporally resolved criteria pollutant emissions inventory that provides inputs for the STREET UCI-CIT atmospheric chemistry and transport model. The UCI-CIT model includes the Atmospheric Chemistry Mechanism (CACM) augmented by UCI advanced research in the chemical mechanisms associated with aerosol formation [28]. This chemical mechanism is designed for use in three-dimensional urban/regional atmospheric models with ozone formation and secondary organic aerosol (SOA) production. Solution of the atmospheric chemistry is coupled in a set of dynamic atmospheric transport equations with state-of-the-art solvers in an Eulerian frame of reference with 5 km × 5 km horizontal resolution. Vertical resolution is in 5 variable height cells up to 1100 m using terrain following coordinates. The model resolves atmospheric chemistry, transport, deposition, meteorological conditions, regional geography, and other physical phenomena that affect the balance of tropospheric chemical species.

Fig. 2 (a) presents 8-h average ozone and 24-h average $PM_{2.5}$ concentrations for Scenario G. Communities northeast of Riverside show concentrations of 8-h average ozone exceeding 100 ppb and communities in and around Long Beach and Riverside show concentrations of 24-h $PM_{2.5}$ reaching 50 $\mu g/m^3$. As a reference, the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Ozone Standard is 75 ppb. To attain this standard, the 3-year average of the fourth-highest daily maximum 8-h average ozone concentrations measured at each monitor within an area over each year must not exceed 75 ppb. The SoCAB region is currently, and is predicted to continue to be, out of compliance with the federal standard. For ozone levels exceeding 100 ppm, the EPA recommends that sensitive groups, such as children or seniors, limit outdoor activity. Ozone exposure has

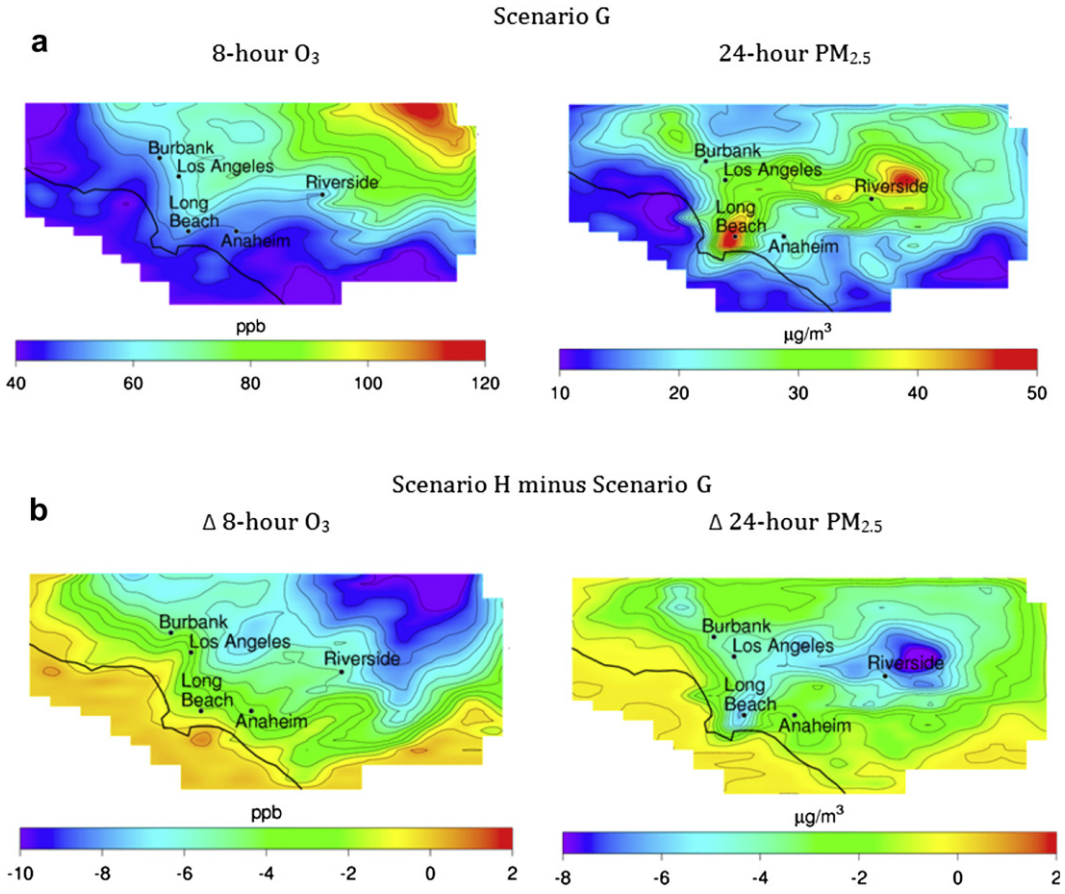

Fig. 2 – (a) Predicted ground-level peak 8-hour average ozone (O_3) and 24-hour average particulate matter ($PM_{2.5}$) distributions for a typical summer day in the South Coast Air Basin (SoCAB) of California for Scenario G. (b) Differences predicted in pollutant concentrations between Scenario H and Scenario G. Maximum reductions in 8-hour average O_3 and 24-hour average $PM_{2.5}$ due to hydrogen infrastructure implementation are 10 ppb and 8 µg/m^3, respectively for Scenario H. The most significant reductions occur in the regions of peak baseline concentrations of O_3 and $PM_{2.5}$.

been linked to asthma permanent lung damage. The EPA $PM_{2.5}$ standard is 35 µg/m^3. To attain this standard, the 3-year average of the 98th percentile of 24-h concentrations at each population-oriented monitor within an area must not exceed 35 µg/m^3. Again, SoCAB is now, and will likely continue to be, out of compliance. Elevated $PM_{2.5}$ concentrations can lead to coughing, problems breathing, and even chronic heart and lung problems [29]. These results show that while significant reductions in non-passenger vehicle emissions, and significant reductions in passenger vehicle emissions significantly reduce air pollution concentrations, clean air for large portions of southern California is not guaranteed.

Fig. 2 (b) shows the change in 8-h average ozone and 24-h $PM_{2.5}$ (difference plots) for Scenario H relative to Scenario G. 8-h average ozone reductions are observed throughout the SoCAB and reach 10 ppb (or more than 8%) in the most severe region for Scenario G northeast of Riverside. 24-h $PM_{2.5}$ reductions observed in Scenario H approach 8 µg/m^3 (or nearly 16%) near Long Beach and Riverside compared to Scenario G. It is fortuitous that in Scenario H the most significant reductions occur in communities that experience the most severe air pollution concentrations. Scenario H drops almost all SoCAB regions below the 35 µg/m^3 particulate matter limit.

2.3.3. *Impacts on greenhouse gas emissions, energy requirements, petroleum consumption, and water use*

The implementation of Scenario H leads to an 84.3% reduction in well-to-wheels (WTW) GHG emissions from passenger vehicles in the SoCAB compared to Scenario G, as illustrated in Fig. 3(a). Passenger vehicles currently account for 28.6% of California's total GHG emissions and are projected to account for 27.0% in 2020 [30] suggesting that FCEV deployment can play a significant role in meeting California's overall GHG reduction goals. The reductions in GHG emissions for Scenario H relative to Scenario G are attributed to efficiency advantages of FCEV over gasoline Internal Combustion Engine (ICE) vehicles, reduced GHG intensity of hydrogen generation strategies compared to WTW gasoline combustion, and carbon capture from coal Integrated Gasification Combined Cycle (IGCC) facilities that cogenerate hydrogen and electricity in Scenario H. It is valuable to mention that this study does not consider carbon capture from Steam Methane Reformation (SMR) facilities. Designing carbon capture into SMR facilities can further reduce GHG emissions associated with hydrogen infrastructure and FCEVs.

Additionally, implementation of Scenario H leads to a decrease in WTW energy requirements and petroleum use

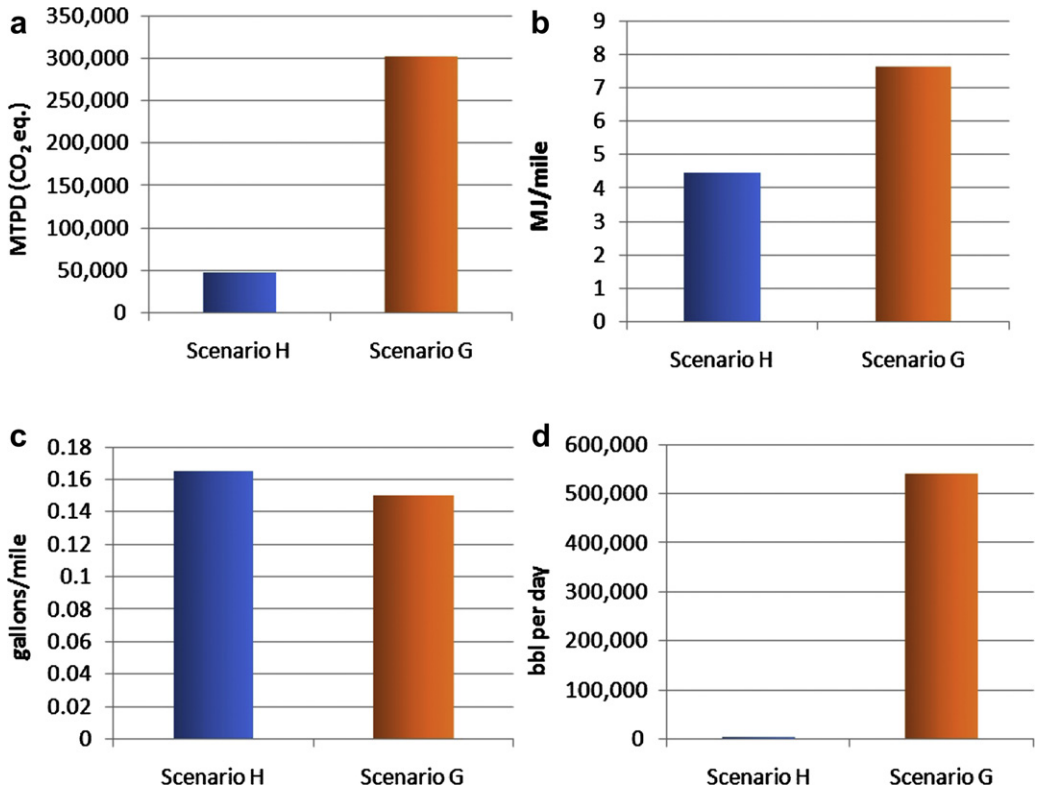

Fig. 3 – Comparison of Scenario H and Scenario G showing that (a) WTW GHG emissions from the SoCAB passenger vehicle fleet are reduced by 84% in Scenario H compared to Scenario G; (b) well-to-wheels energy requirements are reduced by 42% in Scenario H compared to Scenario G due primarily to tank-to-wheel efficiency improvements of fuel cell prime movers; (c) Water consumption increases by 10% for Scenario H compared to Scenario G; and (d) Petroleum consumption is virtually eliminated from the passenger vehicle sector for Scenario H compared to Scenario G.

from passenger vehicles in the SoCAB compared to Scenario G, as illustrated in Fig. 3b and d, respectively. WTW energy requirements from the passenger vehicle fleet are reduced by 42% in Scenario H and WTW petroleum requirements from passenger vehicles is virtually eliminated in Scenario H compared to Scenario G.

Fig. 3(c) shows that WTW water consumption from SoCAB passenger vehicles increases by 10% in Scenario H compared to Scenario G. To understand the cause of this increase, the bulk of water consumption for Scenario H is categorized by hydrogen supply chain processes in Fig. 4. Electricity production to power distribution and dispensing

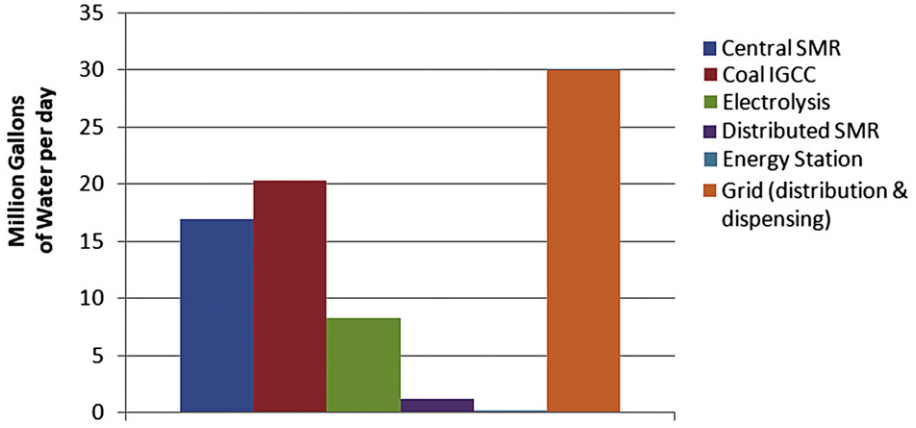

Fig. 4 – Bulk of water consumption for scenario H categorized by hydrogen supply chain processes. Electricity requirements for distribution and dispensing of hydrogen consume more water than any other sector due to the relatively high water consumption for electric power generation. Coal IGCC also contributes disproportionately to the overall water consumption given that it constitutes 10.8% of the total hydrogen generation.

Table 2 – Projected FCEV units operating in the SoCAB during early roll-out years. Projections from 2011 through 2017 are based upon automaker survey results collected and analyzed by the CaFCP. The projection for 2020 is based upon estimates by the authors.

Year	2011	2014	2017	2020
FCEV units in operation	200	1200	32,000	68,000

processes for hydrogen consumes the most water compared to other hydrogen supply chain processes. This is attributed to the relatively high water consumption associated with electric power generation processes. The use of coal IGCC for hydrogen generation also contributes disproportionately to the overall water consumption of Scenario H given that it constitutes just 10.8% of the total hydrogen generation mix.

3. Roll-out infrastructure transition from gasoline to hydrogen

An optimal strategy for a fully built-out hydrogen infrastructure can be facilitated through judicious planning during the roll-out years for FCEVs and infrastructure. To this end, STREET is applied to determine the infrastructure required during the roll-out transition from gasoline to hydrogen.

Southern California is the prime target area for FCEV deployment in the United States. The first launch of an FCEV in the United States was in 2002 at UCI, and more than 100 units were deployed in the region by the turn of the decade. Between 2011 and 2020, the number of on-road FCEVs in the region is expected to increase dramatically as the technology transitions from demonstration to commercialization. Projecting the expected number of FCEV units in the region over this period is challenging due to a combination of uncertainty in market and economic factors and the need for the industry to maintain the confidential nature of corporate strategy. This notwithstanding, the projection of FCEV units is a necessary step in the process of advanced planning for hydrogen infrastructure. Fortunately, the participation of the National Fuel Cell Research Center (NFCRC) in this history provides a database of information (based for example on market experience, interviews, OEM surveys, and confidential studies conducted by stakeholder organizations) which produces reasonable confidence in the California FCEV deployment estimates for 2011 to 2020 roll-out in Table 2.

To achieve FCEV commercialization, it will be essential to establish an early market for FCEVs and therefore to provide sufficient infrastructure for the roll-out of vehicles. Within southern California, automakers are targeting specific areas to

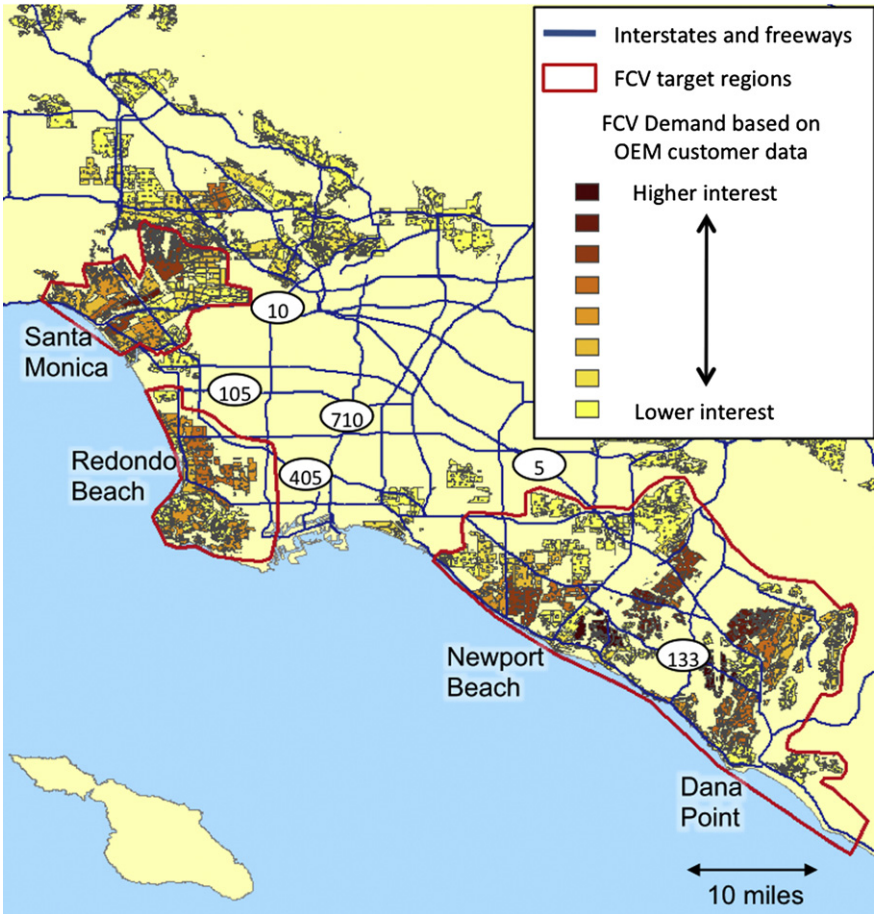

Fig. 5 – Agglomerated data provided by automakers indicating interest in FCEV deployment by zip codes. Data are consolidated, projected geographically, and overlaid with residential land use.

Table 3 – Optimization results of the number and location of hydrogen fueling stations required in FCEV cluster areas to provide sufficient coverage for all drivers comparable to the existing gasoline fueling infrastructure.

Cluster area	Number of gasoline stations	Guaranteed travel time to gas station	Number of hydrogen fueling stations	Hydrogen fueling stations as percentage of gasoline stations
Santa Monica/West LA	126	4	18	14%
Torrance and nearby beach cities	119	4	13	11%
Coastal and southern Orange County	376	5	48	13%

demonstrate FCEVs and establish an early market. These are generally referred to in the industry as "cluster areas" for FCEVs. Also, provision of hydrogen fuel that meets California's environmental standards, in particular the renewable hydrogen standard, is necessary for future years. STREET is applied to (1) define and gain insight into the cluster areas for FCEV deployment; (2) determine the hydrogen station network sufficient to serve the target areas and a strategy to build-out toward that network to catalyze the commercialization of FCEVs; and (3) identify renewable feedstocks for hydrogen production that could serve to meet the 33.3% renewable hydrogen standard mandated by the state of California.

3.1. *Target areas for roll-out of FCEVs*

For the three cluster areas of Santa Monica/West LA, Torrance and nearby beach cities, and coastal and southern Orange County, the populations are 665 thousand, 557 thousand, and 1.9 million respectfully. To facilitate the application of STREET to roll-out planning, several automakers have provided data and invaluable insights regarding zip codes within the three cluster areas where FCEV adoption interest is highest. These data are statistically consolidated and applied in the current study to determine the optimal roll-out strategy.

In addition to zip codes of high FCEV adoption interest, residential land use indicates where customers' homes are located within a given zip code. Fig. 5 shows consolidated data provided by OEMs overlaid with residential land use to further focus areas of interest for early FCEV customers. It also indicates the boundaries that are implemented on the basis of these data to select cluster areas of FCEV interest for the focus of this study.

It is important to recognize that markets will grow and evolve organically beyond these cluster areas, and that this is likely to occur before full commercial deployment numbers of FCEVs are achieved. Based on results in the three cluster areas, hydrogen fueling station requirements are projected for SoCAB (Fig. 1) as a whole in order to show how initial station deployment strategy in cluster areas could influence deployment in a fully built-out hydrogen infrastructure for the region. Noteworthy, STREET is designed so that it can be utilized consistently in the coming years to account for the evolving market and technology conditions.

3.2. *Optimizing hydrogen fueling stations in each cluster area*

Determination of the optimal number and location of hydrogen fueling stations sufficient to provide total coverage in each of the three cluster areas is achieved by applying STREET as described in previous literature [10], namely:

(1) Employ a set covering analysis over a roadway network for each cluster area that determines the number of stations required in that cluster area to achieve a guaranteed driving time comparable to that provided by gasoline stations,
(2) Apply land use constraints (using GIS tools) to limit candidate sites for hydrogen stations (in this case candidate sites are limited to existing gasoline stations only),

Table 4 – Service coverage with respect to residential land use and roads in FCEV cluster areas. Driving time to an existing gasoline station is chosen as the metric, as well as 2 min longer and 2 min shorter to provide an upper and lower bound.

Cluster area	Travel time (min)	Service Coverage with respect to residential land use		Service coverage with respect to roads	
		Existing Gas Stations	Optimized H_2 stations	Existing gas stations	Optimized H_2 stations
Santa Monica/West LA	6	99.1%	97.0%	95.6%	94.3%
	4	87.9%	85.0%	91.4%	85.5%
	2	73.0%	44.4%	76.1%	49.1%
Torrance and beach cities	6	98.4%	97.3%	96.8%	95.1%
	4	89.9%	77.4%	94.0%	83.4%
	2	62.5%	29.9%	72.1%	35.2%
Coastal and southern Orange County	7	99.3%	95.4%	96.3%	94.4%
	5	90.0%	80.1%	92.0%	82.4%
	3	67.2%	42.6%	70.9%	46.3%

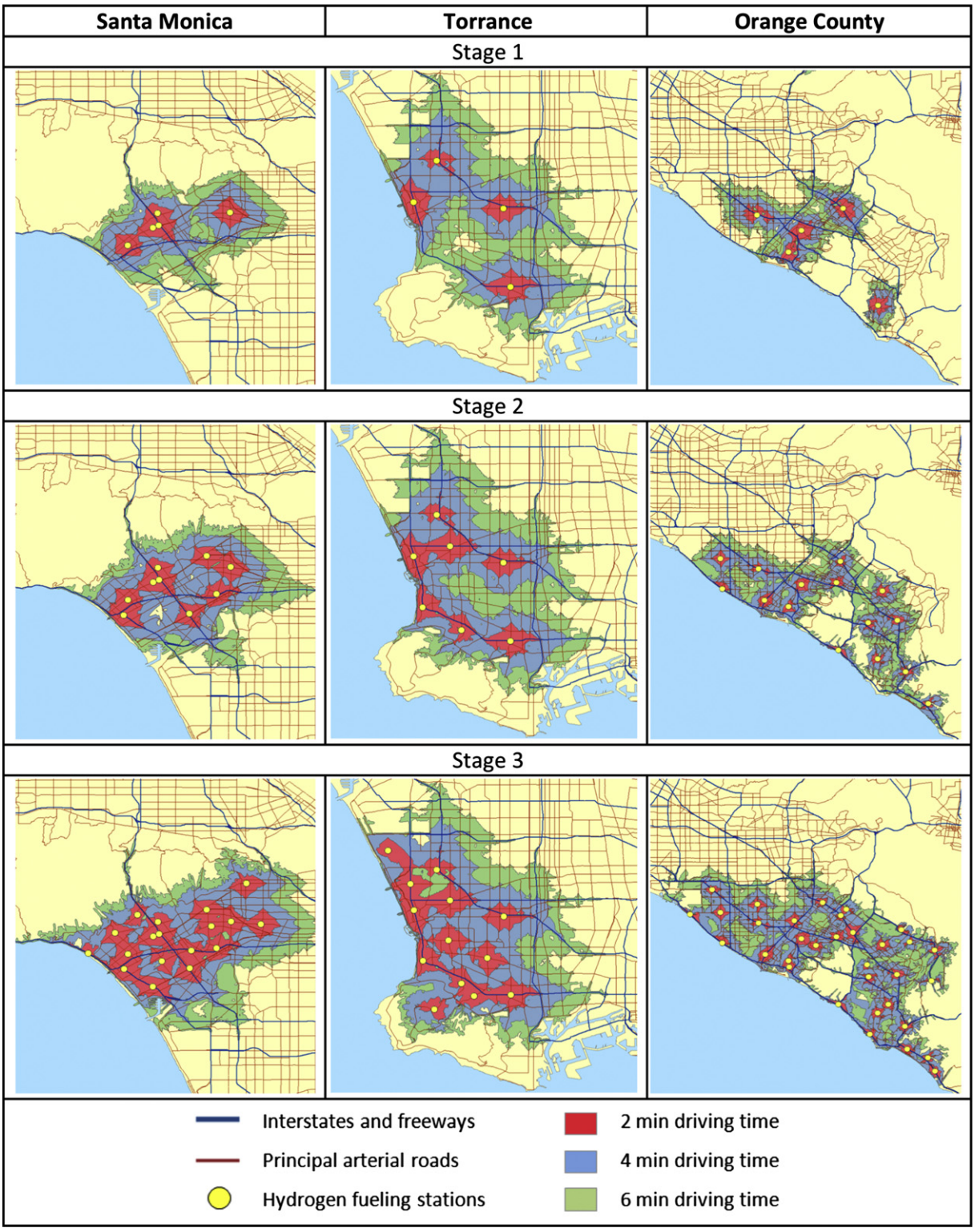

Fig. 6 – Roll-out of hydrogen station infrastructure for three SoCAB areas. Stage 1 depicts existing, planned and funded stations as of early 2011, Stage 2 represents a level of station build-out that could be sufficient for early FCEV commercialization around the year 2015, and Stage 3 shows an optimization of station placement that provides coverage similar to existing gasoline stations that will be required in some timeframe beyond 2020.

(3) Give preference to set covering solutions in which stations are in areas of heavier vehicle travel volume to provide access to a larger fraction of customers with fueling needs, and

(4) Calculate service coverage using a highly detailed GIS roadway network to confirm that proposed candidate sites offer a sufficient solution.

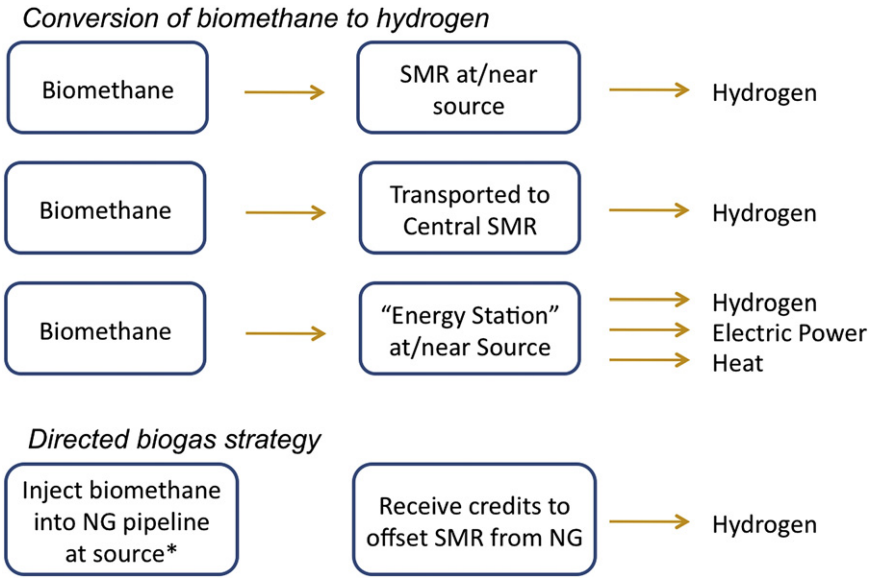

Fig. 7 – Potential supply chains for the utilization of biomethane in hydrogen production. The implementation of any supply chain will be dictated by economics and location of biomethane sources in relation to existing natural gas pipelines, electrical infrastructure, and hydrogen end user.

Application of the first three steps yields the optimum number of fueling stations and locations for each of the three cluster areas as summarized in Table 3. The number of hydrogen fueling stations provided by the set covering analysis does not change when candidate sites are limited to the locations of existing gasoline stations. This result is fortuitous because existing gasoline stations are favorable sites for hydrogen stations for many reasons. From a land use perspective, the sites are already zoned and permitted for the retail sale of vehicular fuel. Also, the layout of current stations enables delivery of hydrogen via liquid or compressed gas tanker truck. Existing gasoline stations are positioned well economically, which can help offset potentially low hydrogen-sales in the early years, and there is typically established infrastructure in the form of a convenience store and restrooms.

The optimized number and location of hydrogen fueling stations in each cluster area is confirmed by applying the fourth step in the methodology: calculating service coverage within different driving times. For this step of the methodology, a highly resolved roadway network that incorporates geographic information systems (GIS) data is employed [31]. The following driving times are chosen for comparison:

(a) The guaranteed time to a gas station;
(b) 2 min longer than the guaranteed time to a gas station; and
(c) 2 min shorter than the guaranteed time to a gas station.

These driving times are selected to illustrate an upper and lower bound for the service coverage. GIS data are utilized to determine the portion of roads and residential land in each region accessible to those sites within the service coverage for each driving time. The same analysis is performed with existing gasoline stations to determine the coverage that drivers are experiencing today for comparison. Table 4 provides a comparison between the service coverage for proposed hydrogen stations and existing gasoline stations. Results suggest that for the guaranteed driving time to a gas

Table 5 – Location and quantity of several large biomethane resources located in SoCAB. In all, over 80 landfills and over 90 wastewater treatment facilities are in southern California, though the majority are significantly smaller than those shown here.

Feedstock resource	Location	Capacity (Nm^3 of biomethane/hr)	Potential if using SMR[a] (kgpd of H_2)	Potential if using energy station[b]	
				(kgpd of H_2)	(MW of elec)
AD[c] of wastewater	Playa del Rey	9300	26,348	13,217	20.4
AD[c] of wastewater	Fountain Valley	4700	13,286	6665	10.3
Landfill gas	Sunshine Canyon SLF	46,600	82,382	41,326	63.8

a Steam methane reforming.
b An energy station utilizes a high temperature fuel cell to tri-generate electricity, heat, and hydrogen.
c Anaerobic digestion.

station, service coverage of roads and residential land is comparable between proposed hydrogen fueling stations and existing gasoline stations.

3.3. *Roll-out of hydrogen fueling stations in each cluster area*

It is important to clarify that the optimal siting of hydrogen fueling stations produced by STREET represents suitable coverage for every driver in the three cluster areas. The number of hydrogen stations sufficient to achieve initial FCEV commercialization is likely to be significantly less. This study does not provide a definitive solution for the hydrogen fueling stations required for commercialization; however, it does provide valuable insight into determining the optimal roll-out strategy for hydrogen fueling stations during the transition years. Based upon the vision established for an optimal number and location, stations can be built-out towards the goal of reaching the optimal network. Data and input from automakers can be integrated into the decision making for roll-out to target proposed station sites that are in areas of heaviest interest, while expanding the region of coverage, thus minimizing the investment risk. Fig. 6 is an example of how the roll-out can be analyzed, with stage 1 representing the existing and planned network of hydrogen stations in each of the three cluster areas, stage 2 representing an intermediate build-out, which could be sufficient for commercialization, and stage 3 representing the optimal solution, which will be sufficient to meet the expectations of every driver in the cluster area.

4. Identifying renewable hydrogen feedstocks to meet portfolio standards

California regulations require that hydrogen as an automobile fuel meet certain environmental standards, including a minimum reduction in GHG emissions, a reduction in criteria pollutant emissions, and that all hydrogen must be generated from a mix of at least 33.3% renewable feedstocks (on the basis of energy content). Previous studies have shown that the GHG and criteria pollutant regulations are easily achieved even if a significant portion of hydrogen comes from conventional fossil fuel sources [10]. The renewable hydrogen requirement, however, is dependent upon efforts by hydrogen producers to identify and develop generation capabilities from renewable resources. The STREET spatial and temporal methodology is applied to determine viable, renewable feedstocks for hydrogen that could satisfy the 33.3% renewable standard during the bulk of the transition from hydrogen to gasoline given the projected FCEV units in operation in southern California.

During the early transition from gasoline to hydrogen (2014–2020), sources for renewable hydrogen are most likely to be biomethane reformation and water electrolysis using renewable electricity. Solar insolation in the southern California region is strong, and the use of photovoltaic electricity to produce hydrogen is likely on a demonstration basis, even if it is unlikely to be an economical means of producing large amounts of renewable hydrogen. Likewise, California has several substantial wind power generation sites. However, given the desire by electric utilities to incorporate increasing quantities of renewable electricity into the grid to meet their own renewable portfolio standards and GHG reduction goals, and the relatively high cost of renewable electricity, the bulk of renewable hydrogen during this timeframe is likely to be produced from biomethane.

Biomethane reforming to produce hydrogen is accomplished at high efficiency (between 60% and 75%) [32,33], and biomethane is often available on a local or regional basis. It is often available in quantities that align with early stages of FCEV deployment when hydrogen demand is still low relative to traditional fuels. Principal examples of biomethane availability include, but are not limited to, anaerobic digester (AD) gas from wastewater treatment plants, AD gas from dairy farms, and landfill gas.

Biomethane reforming can be approached through a variety of strategies. Three strategies are likely to be viable in the years between now and 2020, which are illustrated in Fig. 7. (1) Direct steam methane reforming has been performed in industry for decades and can be performed with biomethane if appropriate levels of purity are achieved. Small-scale, or distributed steam methane reformers are commercially available to handle quantities observed from typical biomethane sources. (2) High temperature fuel cells can utilize biomethane directly to simultaneously produce electricity, heat and hydrogen. Because of their ability to tri-generate three products simultaneously, these units are referred to as energy stations [34]. (3) Directed biogas is the concept of injecting biomethane into the natural gas pipeline infrastructure to offset the natural gas used in a central or distributed SMR plant. All three strategies require extensive cleanup of the biomethane prior to subsequent processes described.

Landfills and wastewater treatment plants provide a significant source of biomethane within relatively close proximity to all three cluster areas. The biomethane resources for some of the largest landfills and wastewater treatments plants are quantified in Table 5 to illustrate the potential for hydrogen production using one of the three strategies from Fig. 7. The estimates provided in Table 5 assume that all of the biomethane resource is converted to hydrogen using just one strategy entirely. The reality will likely be a combination of all three.

If FCEV units in operation achieve 55,000 by 2020 as projected by the authors, then hydrogen demand is estimated to reach 33,000 kg/day (it is assumed that FCEVs in southern California will consume on average 0.6 kg of H_2/vehicle·day). Under these assumptions, the biomethane resources available at the chosen facilities can satisfy the renewable hydrogen standard of 33.3% (or 10,989 kg/day) by employing any one of the three strategies presented in Fig. 7.

5. Conclusions

5.1. *Fully built-out hydrogen infrastructure*

- Advanced planning can play a pivotal role in minimizing the cost of hydrogen infrastructure while assuring that energy and environment benefits are achieved.

Design and analysis of a fully built-out hydrogen infrastructure scenario using STREET demonstrates how advanced

planning can play a role in determining the extent to which deployment of alternative transportation strategies (such as hydrogen and FCEVs) provide long-term energy and environment benefits that governments and businesses seek to obtain through targeted investments. Results from the analysis suggest that deployment of FCEVs and hydrogen infrastructure lead to substantial air quality improvements, GHG reductions, improved energy efficiency, and a reduction in petroleum dependency in the case of a fully built-out, viable hydrogen infrastructure scenario.

- Replacing gasoline vehicles with hydrogen fuel cell electric vehicles has the potential to reduce the emission of greenhouse gases by more than 80%, reduce energy requirements by 42%, and virtually eliminate petroleum consumption from the passenger vehicle sector.

The state of California has proposed an 80% reduction in GHG by the year 2050 [35]. In a fully built-out hydrogen infrastructure scenario, GHG emissions reductions of 84.3% are projected from the passenger vehicle sector in the SoCAB when compared to gasoline vehicles. Remarkably, hydrogen use in FCEVs alone exceeds the goal of 80% reduction. Strategies could be adopted to reduce GHGs from hydrogen infrastructure even furtherby integrating, for example, carbon capture into SMR facilities or adopting a greater portion of renewable feedstocks for hydrogen production. Additionally, the adoption of a greater share of mass transit and pedestrian-oriented development in future years could be implemented to further reduce the portion of travel done by personal vehicle, thereby reducing GHG from the passenger vehicle sector even further. Significant reductions in energy requirements and virtual elimination of petroleum consumption from the passenger vehicle sector are other benefits that are achieved by replacing gasoline with FCEVs.

- Replacing gasoline vehicles with FCEVs has the potential to significantly improve urban air quality.

Reductions in ozone and $PM_{2.5}$ concentrations of 8% and 16%, respectively, are observed in the SoCAB in the fully built-out hydrogen infrastructure scenario compared with gasoline vehicles. Reductions of this magnitude represent significant gains towards California's attainment of Federal air quality standards, but fall short of achieving it. While reducing air pollution in the SoCAB to the level of Federal attainment is likely to require emission reductions in sectors other than light-duty vehicles, hydrogen infrastructure and FCEVs to replace gasoline ICE vehicles can significantly contribute to achieving this goal.

- Replacing gasoline vehicles with FCEVs could lead to an increase in WTW water consumption from passenger vehicles.

Due primarily to electricity requirements associated with distribution and dispensing of hydrogen and the relatively high demand for water from electric power generation, the hydrogen supply chain could lead to higher water consumption by replacing gasoline vehicles hydrogen fuel cell vehicles. The potential increase in water consumption could be mitigated by reducing the overall water requirements for electric power generation, by reducing water consumption from hydrogen generation processes such as advanced coal Integrated Gasification and Combined Cycle (IGCC) plants, and by shifting more of the hydrogen generation to strategies that require little or no water such as hydrogen generation from high-temperature fuel cells [34].

- Existing sources of biomethane in the California South Coast Air Basin can provide up to 30% of the hydrogen demand for a fully built-out scenario.

The state of California has also set a goal of adopting a greater portfolio of renewable energy sources and reducing fossil fuel consumption, in particular petroleum. The analysis suggests that this goal can be achieved in a fully built-out hydrogen infrastructure as a result of improved efficiency, hydrogen production strategies that are independent of petroleum, and the use of a combination of biomethane reforming and water electrolysis power by wind and solar electricity as a source for hydrogen. Quantification of biomethane available from landfills and wastewater treatment plants in the SoCAB shows that these sources alone can provide up to 30% of the hydrogen required for a future scenario of 100% FCEVs given current projections (i.e., no consideration of mass transit or pedestrian-oriented development, and no additional biomethane sources).

- Judicious planning can provide the same level of access with 15% of the existing gasoline station population, and provide the needed capacity with 30% of the existing gasoline station population.

Results from the analysis provide insight into how advanced planning can help minimize the need for investments in hydrogen refueling infrastructure. In this case, results from STREET suggest that a fully built-out hydrogen infrastructure scenario for the SoCAB requires 830 well-placed hydrogen fueling stations compared to the current portfolio of approximately 2700 gasoline stations. Current hydrogen fueling station costs are likely to range from $750,000 to $2 million per station depending on the technology, compression rate, and number of dispensers. Given that hydrogen stations being deployed today are "one-offs" rather than representative of a mass production strategy, it is likely that future costs will be lower even while the throughput and number of dispensers at each station increases. This suggests that a full build-out of hydrogen fueling stations in the SoCAB will require on the order of $1 billion to provide the fueling station requirements for over 10 million light-duty vehicles.

5.2. *Hydrogen infrastructure roll-out*

- Advanced planning during the roll-out of hydrogen infrastructure can help target early investments towards maximizing accessibility and throughput of hydrogen fueling stations during the transition from gasoline to hydrogen.

Early stages of FCEV and hydrogen infrastructure roll-out will likely occur in low volumes implying slow returns on investment, uncertainty on when and where investments should occur, and the need for public funds to spur the deployment of technology. Using STREET to analyze the roll-out of hydrogen infrastructure demonstrates how advanced planning can help target early investments to maximize benefit during the transition years from gasoline to hydrogen, in particular with respect to: (1) roll-out of hydrogen fueling stations and (2) meeting California regulations for hydrogen as a transportation fuel.

- Compared to current gasoline stations, only 11%–14% of the number of hydrogen fueling stations can provide comparable accessibility to drivers in a targeted region.

To develop early markets for FCEVs, three cluster areas in southern California have been identified by automakers. Applying STREET in each of the three cluster areas shows that relative to current gasoline stations, only 11%–14% of the number of hydrogen fueling stations can provide sufficient coverage. In other words, investing in only a fraction of the amount of refueling locations will provide sufficient accessibility to hydrogen stations. Service coverage is the most important factor in spurring FCEV market adoption in the near term. Capacity could easily be met by a handful of large stations, but without adequate coverage, consumer usability will be restricted resulting in poor market growth. The number of stations required to provide accessibility is the same even when candidate sites for hydrogen fueling stations are constrained to existing gasoline stations – a result that is fortuitous because gasoline station sites are zoned and permitted for retail sale of a transportation fuel, a profitable service business is already operated there, and they are designed to accommodate fuel delivery trucks. Furthermore, gasoline stations offer the possibility of replacing gasoline dispensers with hydrogen dispensers gradually, as the transition from gasoline to hydrogen occurs.

- Market research data, as well as insight and input from automakers, can be leveraged to target FCEV cluster areas during the roll-out for hydrogen fueling station deployment, with the goal of eventually building out towards the optimal network.

Enabling a commercial roll-out of FCEVs will require a number of stations that is less than the 11–14% required for full accessibility. During the roll-out years (before a full build-out is achieved) a unique set of market research data that shows where early FCEV customer interest is located combined with input from automakers informs preferred locations for early hydrogen fueling stations. Additionally, service coverage is calculated to show the degree to which stations deployed during roll-out years will improve accessibility.

5.3. *Identifying renewable hydrogen feedstocks*

- Biomethane resources in the SoCAB are sufficient to meet the region's renewable hydrogen requirement of 33.3% during the roll-out years for FCEVs and hydrogen infrastructure.

California regulations require that 33.3% of the mix of hydrogen come from renewable sources. Since hydrogen production from renewable feedstocks is not current industry practice, new investments will be required for the procurement of renewable feedstocks, and the deployment of technology solutions for production of hydrogen from those feedstocks. STREET is applied to determine regional feedstock resources for renewable hydrogen, in particular biomethane which is likely to be the most viable in the near-term, and the potential for those feedstocks to satisfy the renewable hydrogen standard based on hydrogen production strategies. During early FCEV commercialization years (up to 2020), regional sources of biomethane can provide sufficient quantities of renewable hydrogen to meet the California requirement that 33.3% of the hydrogen mix come from renewable feedstocks.

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