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Authors

Stephens-Romero, Shane D
Brown, Tim M
Kang, Jee E
[et al.](#)

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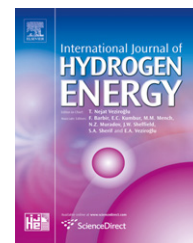
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Systematic planning to optimize investments in hydrogen infrastructure deployment

Shane D. Stephens-Romero^a, Tim M. Brown^a, Jee E. Kang^b, Wilfred W. Recker^b,
G. Scott Samuelsen^{a,*}

^a Advanced Power and Energy Program, National Fuel Cell Research Center, University of California, Irvine, Irvine, CA 92697-3550, USA

^b Institute of Transportation Studies, University of California, Irvine, CA 92697-3600, USA

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ABSTRACT

The introduction of hydrogen infrastructure and fuel cell vehicles (FCVs) to gradually replace gasoline internal combustion engine vehicles can provide environment and energy security benefits. The deployment of hydrogen fueling infrastructure to support the demonstration and commercialization of FCVs remains a critical barrier to transitioning to hydrogen as a transportation fuel. This study utilizes an engineering methodology referred to as the Spatially and Temporally Resolved Energy and Environment Tool (STREET) to demonstrate how systematic planning can optimize early investments in hydrogen infrastructure in a way that supports and encourages growth in the deployment of FCVs while ensuring that the associated environment and energy security benefits are fully realized. Specifically, a case study is performed for the City of Irvine, California – a target area for FCV deployment – to determine the optimized number and location of hydrogen fueling stations required to provide a bridge to FCV commercialization, the preferred rollout strategy for those stations, and the environmental impact associated with three near-term scenarios for hydrogen production and distribution associated with local and regional sources of hydrogen available to the City. Furthermore, because the State of California has adopted legislation imposing environmental standards for hydrogen production, results of the environmental impact assessment for hydrogen production and distribution scenarios are measured against the California standards. The results show that significantly fewer hydrogen fueling stations are required to provide comparable service to the existing gasoline infrastructure, and that key community statistics are needed to inform the preferred rollout strategy for the stations. Well-to-wheel (WTW) greenhouse gas (GHG) emissions, urban criteria pollutants, energy use, and water use associated with hydrogen and FCVs can be significantly reduced in comparison to the average parc of gasoline vehicles regardless of whether hydrogen is produced and distributed with an emphasis on conventional resources (e.g., natural gas), or on local, renewable resources. An emphasis on local renewable resources to produce hydrogen further reduces emissions, energy use, and water use associated with hydrogen and FCVs compared to an emphasis on conventional resources. All three hydrogen production and distribution scenarios considered in the study meet California's standards for well-to-wheel GHG emissions, and well-to-tank emissions of urban ROG and NO_x. Two of the three scenarios also meet California's standard that 33% of hydrogen must be produced from renewable feedstocks. Overall, systematic planning optimizes both the economic and

* Corresponding author. Tel.: +1 949 824 5468; fax: +1 949 824 7423.

E-mail address: gss@uci.edu (G.S. Samuelsen).

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environmental impact associated with the deployment of hydrogen infrastructure and FCVs.

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1. Introduction

Deployment of hydrogen fuel cell vehicles (FCVs) to replace gasoline internal combustion engine vehicles is a transportation strategy capable of achieving long-term energy security, greenhouse gas emissions reductions, and improved urban air quality [1,2]. With major automakers having announced plans to release tens of thousands of fuel cell vehicles by the year 2015 [3], the rollout of hydrogen fueling infrastructure to support FCV deployment is currently the most significant challenge facing hydrogen as a transportation fuel. To address this challenge, regional demonstration efforts have been launched in which fleets of fuel cell vehicles are deployed near a hydrogen fueling station.

A major geographic target for realizing a hydrogen fueling infrastructure is California. In 2005, The California Hydrogen Highway Initiative outlined an early vision to deploy a handful of hydrogen fueling stations in the state's major urban areas and to connect them with one or two fueling stations strategically placed along major highways [4]. This vision can be summarized as a "covering" approach with a goal to cover large areas of California with a limited hydrogen fueling station network. The inability of the State Legislature to fund the approach precluded the goal from being realized. As a result, the State of California and the industry (automobile manufacturers and energy companies) have collaborated to recommend the creation of "clusters" of hydrogen fueling stations in key California communities. The goal is to establish a typical driving and fueling experience for a fuel cell vehicle customer in that community. Communities targeted for early-stage FCV deployment are referred to as *hydrogen communities*. The concept of developing clusters of hydrogen fueling stations is the result of a survey of major automakers that was conducted by the California Fuel Cell Partnership (CAFCP) to inquire about the collective focus and scale of FCV deployment efforts. Results of the survey showed that automakers overwhelmingly favored four communities in southern California for deployment and demonstration of FCVs: Irvine, Newport Beach, Santa Monica and Torrance [5]. The identification of these areas for early-stage FCV demonstration is testament to the fact that political interests, market forces, and purchasing power are favorably aligned in these communities to encourage the adoption of hydrogen infrastructure and FCVs.

Despite the emergence of a collective vision for hydrogen communities, limited funds continue to present a challenge to early rollout efforts of hydrogen fueling infrastructure. The profitability of selling hydrogen fuel will remain low until a threshold level of vehicles is reached, but the number of on-road FCVs deployed will remain low if fueling infrastructure is not available. Achieving the desired environmental and energy security goals that are expected as a result of transitioning to FCVs requires investment by the public sector in early hydrogen infrastructure projects. Many ambitious goals

must be accomplished with the limited amount of public funds available. They include: (1) providing a basic level of hydrogen fueling service with which fuel cell vehicle customers are comfortable, (2) growing the demand for fuel cell vehicles through early rollout efforts, and (3) meeting California's stringent environmental standards for hydrogen fuel [6]. The capability to systematically plan deployment strategies for hydrogen infrastructure can help maximize the service provided with minimal infrastructure. The Spatially and Temporally Resolved Energy and Environment Tool (STREET) offers such a capability [2].

Previously, STREET has been exercised to determine air quality and greenhouse gas impacts of fully integrated and highly resolved (both spatially and temporally) hydrogen infrastructure scenarios in outlying years such as 2030 and 2060 [2]. But until now its capabilities have not been applied to optimize near-term hydrogen infrastructure deployment efforts on a community level. Of the previous studies that assess hydrogen supply chain strategies, few consider an integrated hydrogen supply infrastructure or the utilization of local resources in the hydrogen supply chain and none address these issues in the near term (i.e., over the next 5 years) [7–9]. Furthermore, while existing studies investigate the preferred number and location of hydrogen fueling stations, they generally operate at a regional level and do not achieve the spatial detail required for infrastructure planning [10–12]. Kuby et al. (2009) provide the most spatially detailed study to date for early-stage hydrogen fueling stations whereby a singular approach of maximizing the potential trips during which FCV drivers can refuel is implemented to suggest the location of early hydrogen fueling stations on a metropolitan and regional level [13]. On the other hand, STREET operates at the highest level of spatial detail and integrates multiple considerations including minimizing travel time, land use, vehicle travel density, service area zones and market data on potential FCV customers to determine (1) the optimal number and location of hydrogen fueling stations in a community to reach full-scale FCV demonstration and provide a bridge to commercialization and (2) the preferred rollout strategy for the stations.

To date, no study has exercised a planning tool to produce early-stage, integrated hydrogen infrastructure deployment scenarios for a specific community (including the location and rollout of hydrogen fueling stations), or assessed the associated environmental impacts. This study introduces additional capabilities of STREET to show how systematic planning can minimize the hydrogen infrastructure required to provide a basic level of hydrogen fueling service, guarantee environmental standards for hydrogen production, maximize environmental benefits, and utilize local resources to the fullest potential thereby optimizing what can be accomplished with limited investments in early-stage hydrogen infrastructure. The City of Irvine (City), which is targeted as a hydrogen community, serves as an example in this case study.

Systematic planning is performed with detailed spatial resolution, a combination of several optimization and assessment methodologies, and the utilization of relevant data in order to provide an integrated set of preferred scenarios for early rollout of hydrogen infrastructure in the City.

2. Analysis

Systematic planning is used to generate preferred scenarios for early rollout of hydrogen infrastructure in the City. While hydrogen infrastructure in the City serves as a case study in this paper, the methodology described herein (STREET) can be applied broadly to include other cities, larger regions, different time-frames, and a variety of alternative fuels.

In this study, aspects of hydrogen infrastructure that are addressed through systematic planning include the optimized number and location of hydrogen fueling stations required to provide a bridge to FCV commercialization; assessment of hydrogen production resources available to the region; and the quantification of the greenhouse gases (GHG), criteria pollutant emissions, energy requirements, and water demands associated with hydrogen production and delivery strategies.

2.1. Identifying hydrogen infrastructure needs

A fundamental requirement for systematic planning of hydrogen infrastructure is to project the likely number of FCV units in operation during upcoming years and the consequential need for fuel infrastructure. Table 1 summarizes such a projection for the City based on the results of a survey of 9 automakers performed by the CAFCP [5]. FCV projections up to the year 2014 are firm estimates based on direct input from automakers. Given a projection for FCVs and hydrogen fuel needs in the City, systematic planning can be applied to determine how to best deploy infrastructure.

Limited real-world data on fuel consumption by FCV drivers and continually improving vehicle efficiency lead to difficulty in estimating precisely the amount of hydrogen fuel that will be required in future years. Projections for hydrogen demand in the City by the CAFCP provide an appropriate estimate of the fuel needed to meet the needs of the projected vehicles in operation. (Projections for daily hydrogen fueling are listed by the CAFCP in terms of capacity and therefore exceed the daily dispensing requirements in anticipation of additional vehicle deployment in future years).

Table 1 – Summary of fuel cell vehicle deployment projection for the City provided by CAFCP and based on input from automakers.

	2009	2010	2011	2012	2013	2014
FCV units in operation	31	71	144		770 ^a	
Daily H ₂ fueling capacity (kg)	75	75	275	625	825	1225

a The number of FCV units in operation is projected to reach 770 sometime between 2012 and 2014.

2.2. Optimizing the number, location and rollout of hydrogen fueling stations

To determine (1) the number and location of hydrogen fueling stations in the City required to support a full-scale demonstration of FCVs and provide a bridge to commercialization, and (2) a preferred rollout strategy for those stations five criteria are applied:

1. *Travel-time analysis* is applied to establish the number of hydrogen fueling stations that can guarantee a minimum travel time to reach a station comparable to that provided by existing gasoline stations in the City.
2. *Station land use* is assessed by applying land use constraints to candidate sites for hydrogen fueling stations such as existing gasoline station sites, commercial land use, or land that is zoned and permitted to allow the operation of a fueling station.
3. *Vehicle travel density* is analyzed to give preference to hydrogen station candidate sites near regions of greater vehicle travel.
4. *Service Coverage* is calculated to confirm that the proposed candidate sites provide a desired level of coverage for drivers in the City with respect to existing roads and residential land use.
5. *Automaker (or Original Equipment Manufacturer, OEM) data* on FCV drivers are analyzed to determine where likely early adopters of fuel cell vehicles will live, and in turn, determine a preferred rollout strategy for hydrogen fueling stations in which the greatest number of customers will be reached in the early years.

2.2.1. Determining the optimum number of hydrogen fueling stations using travel-time analysis and land use

Data from the California Energy Commission [14] are combined with an investigation of public resources to determine that 34 gasoline stations, shown in Fig. 1, are currently operated in the City. A relatively simple roadway network (i.e., road speed and traffic restriction information lacks a high level of detail) in the City is designed and utilized to perform a travel-time analysis. The analysis employs System (1) in a set covering model [15]. Shortest path is calculated between intersections and gasoline stations in the City to determine the greatest travel time to an existing gasoline station in the City from anywhere within the City. Constraint (1-2) in combination with objective function (1-1) produce the general set covering analysis used to determine the number and location of hydrogen fueling stations in the City that guarantee the same minimum travel time as existing gasoline stations.

$$\text{System (1)} \\ \text{Minimize } \sum_j X_j \quad (1-1)$$

$$\sum_j Y_{ij} \cdot X_j \geq 1 \quad \forall i \quad (1-2)$$

$$Z_j \cdot X_j = 0 \quad \forall j \text{ at sites with no existing H}_2 \text{ fueling station} \quad (1-3)$$

$$X_j = 1 \quad \forall j \text{ at sites with an existing H}_2 \text{ fueling station} \quad (1-4)$$

$$X_j \in \{0, 1\} \quad \forall j$$

$$Y_j \in \{0, 1\} \quad \forall j$$

$$Z_j \in \{0, 1\} \quad \forall j$$

where

$$Y_{1ij} = \begin{cases} 1 & \text{if candidate site } j \text{ is within an acceptable travel} \\ & \text{time of intersection } i \\ 0 & \text{if candidate} \end{cases}$$

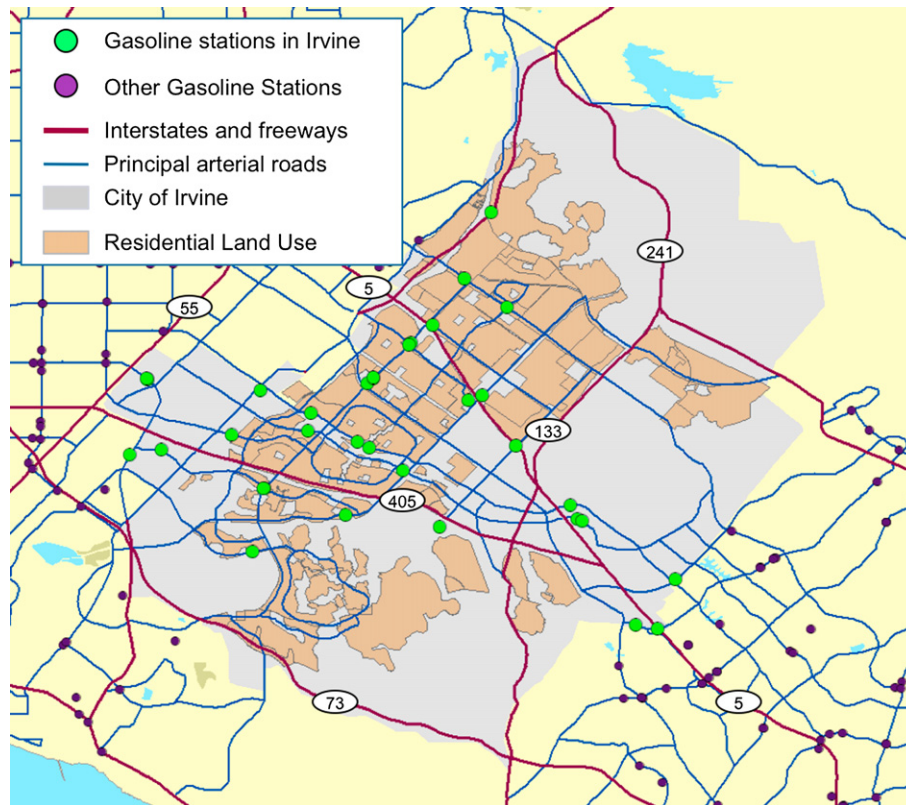


Fig. 1 – Map of the City showing existing gasoline stations, interstates, freeways, principal arterial roads, and land zoned for residential use.

$$Z_j = \begin{cases} 1 & \text{if intersection } j \text{ is not a candidate site} \\ 0 & \text{if intersection } j \text{ is a candidate site} \end{cases}$$

$$X_j = \begin{cases} 1 & \text{if solution is located at a candidate site} \\ 0 & \text{if solution is not located at a candidate site} \end{cases}$$

The roadway network used for the travel-time analysis is designed using the following assumptions:

1. Only highways and major arterial roads are designed into the roadway network; smaller roads are initially neglected.
2. Two vehicle speeds are assumed in the roadway network: 65 mph for highway, and 45 mph for major arterial roads.
3. One-way roads, freeway ramps, and U-turns are neglected in the roadway network.

Application of the travel-time analysis to this coarsely designed network of the City's roads shows that from within the city limits of the City, a driver is guaranteed access to an existing gasoline station within 3.38 min. When every intersection in the City is considered as a candidate site for a hydrogen fueling station the same guaranteed driving time of 3.38 min is achievable with just eight strategically located hydrogen fueling stations. Because a hydrogen station is currently operating on the UC Irvine campus, constraint (1-4) is employed to indicate that the site has an existing hydrogen fueling station. Not surprisingly, there are several solution sets whereby eight hydrogen fueling stations can guarantee a minimum driving time equivalent to the existing gasoline

station infrastructure. However, land use constraints are applied to the travel-time analysis, which reduces the number of possible solutions.

Land use characteristics can be applied as a constraint to candidate sites for hydrogen fueling stations using (1–3). In this study, constraint (1-3) is used to restrict candidate sites for hydrogen stations to existing gasoline station sites. The travel time analysis determines that even when imposing this restriction, a guaranteed minimum driving time of 3.38 min is still achievable with eight hydrogen fueling stations. Even when imposing the restriction, several solution sets of eight stations arranged in different configurations are produced by the travel-time analysis. 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, their layout enables delivery of hydrogen via liquid or compressed gas tanker. Existing gasoline stations are well-positioned economically, which can help offset potentially low hydrogen sales in the early years, and there is typically established infrastructure in the form of convenience store and restrooms.

Results from the travel-time problem with and without applying land use constraints are used to generate strategic candidate sites for hydrogen fueling stations and determine that a minimum of eight stations is required to provide a basic desired level of customer service (i.e., guarantee a minimum travel time to hydrogen fueling stations comparable to that of

existing gasoline stations for a driver within the city limits of the City).

While land use restriction reduces the number of candidate sites for hydrogen fueling stations, the travel-time analysis still results in a large number of solution sets. Consideration of travel density enables solutions to be further differentiated.

2.2.2. Differentiating optimum locations for hydrogen fueling stations using vehicle travel density

Consideration of vehicle travel density enables solutions for the location of hydrogen fueling stations to be further differentiated. The Orange County Transportation Analysis model (OCTAM) provides a regional travel forecasting base for transportation planning work in Orange County. It incorporates state-of-the-practice modeling components that are consistent with the Southern California Regional Transportation Model released by the Southern California Association of Governments [16]. OCTAM is used to estimate daily passenger vehicle flows in the vicinity of the City. Morning on-road traffic volume is compared to afternoon on-road traffic volume to account for disparities that might occur between travel behavior in the morning and afternoon. Upon observation, differences in on-road traffic volume between the morning and afternoon are relatively minor. As a result, average weekday on-road vehicle density, shown in Fig. 2, is utilized. Candidate sites for hydrogen fueling stations are

given preference based on proximity to regions of high on-road vehicle density. This approach relates to previous studies that have shown that locating fueling stations near regions of high on-road vehicle density provides access to a larger fraction of customers with fueling needs [17].

The candidate sites for hydrogen fueling stations are narrowed down by giving preference to sites that are located at regions of high vehicle travel density. Only gasoline station sites at sections of road lying in the upper 90 % of daily vehicle volume are chosen as candidate sites for hydrogen fueling stations. Of the 34 existing gasoline stations in the City, 14 meet this requirement.

Solution sets from the travel-time analysis are further restricted to these 14 candidate sites. Four configurations of eight hydrogen fueling stations meet all of the imposed restrictions. The addresses of the candidate sites for hydrogen stations from each of the four configurations are listed in Table 2.

2.2.3. Confirming the optimized number and location of hydrogen fueling stations using service coverage

Service coverage provided by proposed hydrogen station configurations is analyzed to confirm that the number and location of hydrogen fueling stations proposed in each of the four configurations provide a basic level of service in the City similar to that of existing gasoline stations. This step is included in the methodology because, (1) due to the modeling

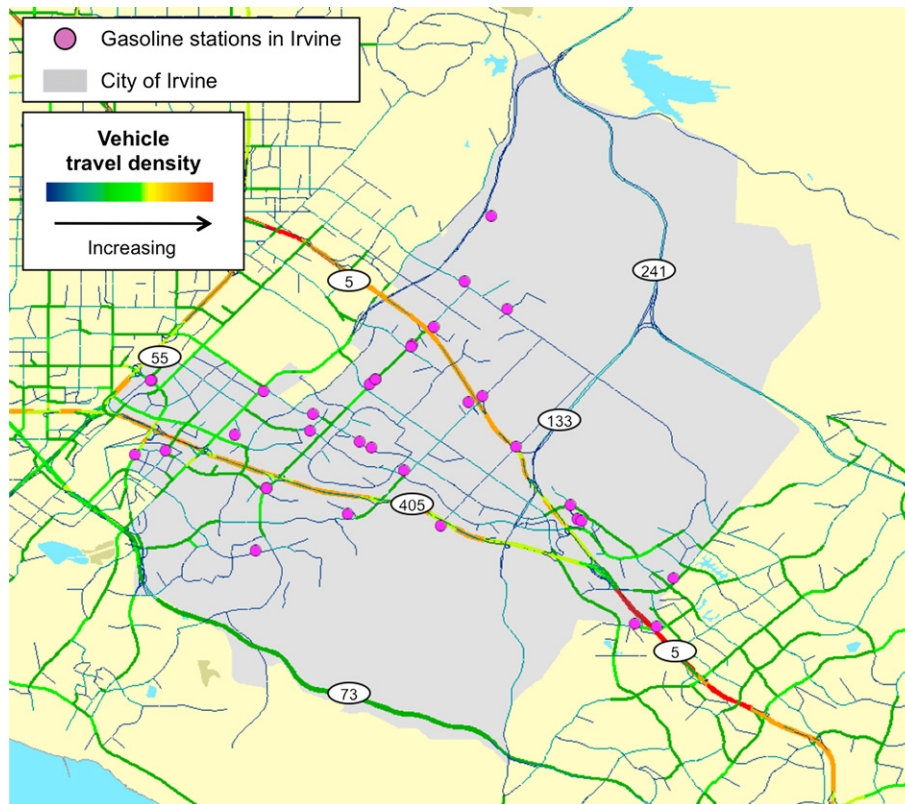


Fig. 2 – Map of the City showing volume of vehicle travel on roads in the year 2000, existing gasoline stations, and residential land use. Vehicle travel volume plotted in the figure ranges from a lower limit of 2900 to a maximum of 380,900 cars throughout a 24-hour day for a typical weekday. (Roads with daily volumes less than 2900 vehicles are not included in the plot for the sake of simplicity.)

Table 2 – List of addresses for proposed configurations for hydrogen fueling stations providing a basic level of fueling service for FCV customers in the City.

Configuration 1		Configuration 2		Configuration 3		Configuration 4	
Address	Zip	Address	Zip	Address	Zip	Address	Zip
19108 Jamboree Blvd (Existing station)	92697	19108 Jamboree Blvd (Existing station)	92697	19108 Jamboree Blvd (Existing station)	92697	19108 Jamboree Blvd (Existing station)	92697
4162 Trabuco Rd	92620	4162 Trabuco Rd	92620	4162 Trabuco Rd	92620	4162 Trabuco Rd	92620
51 Technology Dr	92618	51 Technology Dr	92618	51 Technology Dr	92618	51 Technology Dr	92618
3090 Main St	92614	3090 Main St	92614	3090 Main St	92614	3090 Main St	92614
4760 Irvine Blvd	92720	4760 Irvine Blvd	92720	4760 Irvine Blvd	92720	4760 Irvine Blvd	92720
18002 Culver Dr	92612	18002 Culver Dr	92612	15425 Culver Dr	92606	15425 Culver Dr	92606
5425 Alton Pkwy	92604	5425 Alton Pkwy	92604	5333 University Dr.	92612	5333 University Dr.	92612
14886 Sand Canyon Ave	92650	14111 Jeffrey	92620	14886 Sand Canyon Ave	92650	14111 Jeffrey	92620

complexity needed for the optimization routine the roadway network utilized in the travel-time analysis is unavoidably coarse, and (2) it provides the ability to compare service coverage over roads and residential land for several vehicular travel times.

To calculate service coverage, a highly resolved roadway network that incorporates geographic information systems (GIS) data are employed [18]. The GIS data roadway network include:

1. All roads in the City.
2. Comprehensive speed limit resolution (10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 65 mph).
3. One-way roads.
4. Freeway ramps
5. U-turns.

Service coverage provided by the four hydrogen fueling station configurations is analyzed for 2, 3, 4, and 5 minutes of driving time with respect to roads in the City and coverage of residential land. In other words, for each configuration of optimized candidate sites for hydrogen fueling stations, GIS data are utilized to determine the portion of roads and residential land in the City accessible to those sites within two, three, four or five minutes of driving time. Fig. 3 provides an example of the service coverage provided by the hydrogen fueling stations in Configuration 3. As a basis for comparison, the GIS-based roadway network is also used to analyze the service coverage provided by the 34 existing gasoline stations in the City.

Service coverage is assessed with respect to the roads in the City by determining the portion of roads within reach of a proposed hydrogen fueling station in two, three, four, and five minutes of driving time. Table 3 compares the portion of road miles in the City that are accessible by each hydrogen station configuration, as well as by existing gasoline stations. Eight hydrogen fueling stations are comparable to existing gasoline stations when considering a driving time of five minutes. However, within four minutes of driving time or less, existing gasoline stations provide service coverage to a significantly greater portion of the City's roads compared to the proposed configurations of eight hydrogen fueling stations.

Similarly, service coverage is assessed with respect to residential land by determining the portion of residential land

in the City that is accessible by the proposed configurations of hydrogen fueling stations within two, three, four, and five minutes of driving time. Table 4 shows the portion of residential land that can be reached by hydrogen stations in the four proposed configurations, as well as by existing gasoline stations for comparison. Eight hydrogen stations can serve a nearly comparable portion of the City's residential land as existing gasoline stations within five, four, and three minutes. However, within two minutes or less, existing gasoline stations provide service to a significantly greater portion of residential land use compared to the proposed configurations of eight hydrogen stations.

2.2.4. Devising a preferred rollout strategy for hydrogen fueling stations based on OEM data for early customer interest in FCVs

Through early FCV demonstration efforts, OEMs have gathered data to determine customers who are interested in buying or leasing FCVs. These customers represent a market of FCV early adopters, and are likely to be the first to receive FCVs during demonstration periods over the coming years. Several OEMs are sharing with researchers at UC Irvine data comprised of zip codes where the highest populations of FCV early adopters reside. These data are statistically consolidated and applied in the current study to determine the preferred rollout strategy for hydrogen fueling stations.

Zip codes cover large, undifferentiated areas of the City. So to determine with a higher degree of specificity where potential customers reside within those zip codes, residential land use is overlaid. Fig. 4 shows the result of overlaying FCV interest zip codes with residential land use GIS data to determine the residential areas of FCV interest ranked highest to lowest. Early markets for hydrogen fueling can be met effectively by giving preference to hydrogen fueling stations near these areas.

Devising a strategic rollout of hydrogen fueling stations incorporates (1) the optimal number and location of hydrogen fueling stations required to provide a basic minimum level of service to FCV drivers in the City and (2) giving deployment preference to residential areas of drivers that are identified by OEM market data as likely early adopters of FCVs.

To serve as an illustrative example, a preferred rollout strategy that achieves the eight desired stations for Configuration 3 is proposed in Fig. 5. Service area is calculated using

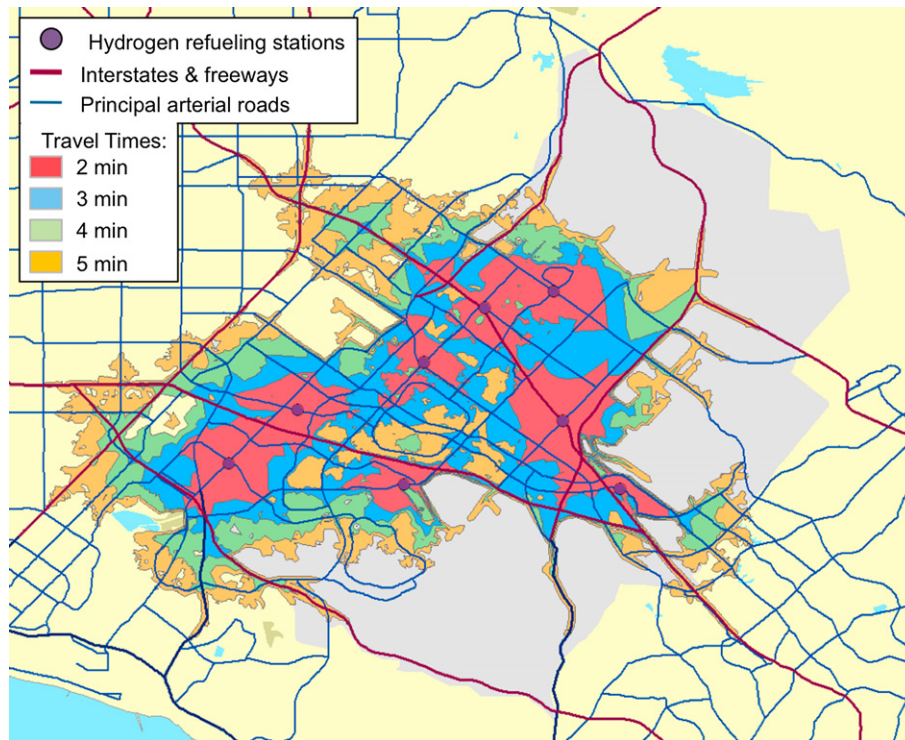


Fig. 3 – Contour plot showing service coverage provided by hydrogen fueling station configuration 3 within two, three, four, and five minutes of driving time.

the GIS roadway network after the addition of each hydrogen fueling station to provide insight into how service coverage will evolve as infrastructure is added. The service area provided by the existing hydrogen fueling station at UC Irvine

is shown in frame (1) of Fig. 5. The snapshots following frame 1 show how the addition of hydrogen fueling stations can provide an expansion of service within different driving times. Consideration of optimized station configurations, residential land use, and OEM zip code data on customer demand enables planning for a rollout of hydrogen fueling stations that meets the greatest number of users in the earliest stages.

Table 3 – Comparison of road service coverage by existing gasoline stations and proposed hydrogen station configurations within a given driving time in the City.

Configuration	Travel time (min)	Roads covered (km)	Percentage of roads covered
Gas stations (34)	5	900.51	89.1%
	4	829.41	82.0%
	3	746.03	73.8%
	2	550.59	54.5%
H ₂ stations C1 (8)	5	802.78	79.4%
	4	688.84	68.1%
	3	509.82	50.4%
	2	292.55	28.9%
H ₂ stations C2 (8)	5	765.75	75.7%
	4	657.10	65.0%
	3	470.53	46.5%
	2	281.07	27.8%
H ₂ stations C3 (8)	5	806.90	79.8%
	4	629.39	62.3%
	3	506.64	50.1%
	2	263.76	26.1%
H ₂ stations C4 (8)	5	780.24	77.2%
	4	623.39	61.7%
	3	473.63	46.9%
	2	255.40	25.3%

2.3. Assessing the environmental impacts of near-term hydrogen infrastructure deployment

The environmental impacts of hydrogen as an alternative transportation fuel depend on the production and distribution strategies that are implemented. Considering the limited availability of public investment dollars, optimum environmental benefits of hydrogen in the near-term can be achieved by characterizing potential resources for hydrogen production in the near-term and performing an environmental impact analysis of various hydrogen production and distribution scenarios. California has a particular need for advanced planning because the regulatory framework imposes constraints on hydrogen production and distribution strategies by mandating environmental impact reductions that must be achieved with hydrogen fuel. They are as follows:

1. Hydrogen must be generated from a mix of at least 33% renewable feedstocks (on the basis of energy content).
2. The use of hydrogen in transportation must achieve a 30% reduction in well-to-wheels (WTW) GHG emissions compared to the average on-road vehicle (on a g/mile basis).

Table 4 – Comparison of residential land service coverage by existing gasoline stations and proposed hydrogen station configurations within a given driving time in the City.

Configuration	Travel time (min)	Percentage of residential land covered (km ²)	Percentage of residential land covered
Gas stations (34)	5	46.35	73.5%
	4	42.45	67.3%
	3	34.06	54.0%
	2	27.03	42.8%
H ₂ stations C1 (8)	5	41.87	66.4%
	4	36.74	58.2%
	3	28.43	45.1%
	2	15.36	24.3%
H ₂ stations C2 (8)	5	40.61	64.4%
	4	36.30	57.6%
	3	36.70	58.2%
	2	15.97	25.3%
H ₂ stations C3 (8)	5	42.19	66.9%
	4	33.09	52.5%
	3	28.14	44.6%
	2	13.57	21.5%
H ₂ stations C4 (8)	5	41.57	65.9%
	4	33.78	53.5%
	3	26.53	42.1%
	2	14.25	22.6%

- The use of hydrogen in transportation must achieve a 50% reduction in well-to-tank (WTT) ROG and NO_x emissions compared to the average on-road vehicle (on a g/GJ of fuel basis).
- The use of hydrogen in transportation must lead to no increase in WTT toxic air contaminants compared to the average on-road vehicle (on a g/GJ of fuel basis). [6]

This section describes a methodology to characterize potential sources of hydrogen in the City from 2010 to 2014, assess the environmental impacts of hydrogen production and distribution scenarios during those years, and determine which, if any, scenarios meet California's environmental regulations for hydrogen production.

2.3.1. Characterizing near-term hydrogen production and distribution strategies

A variety of strategies for hydrogen production exist, but only some are commercially viable in the near-term timeframe. Furthermore, specific hydrogen production strategies may be favored in a certain region because of local resources. Local resources taken collectively with hydrogen production strategies that are commercially viable in the near-term provide a set of favorable hydrogen production strategies for a community of interest. Fig. 6 outlines strategies for hydrogen production and distribution that are both technically feasible in the near-term and utilize resources available to the City. Each production and distribution strategy is

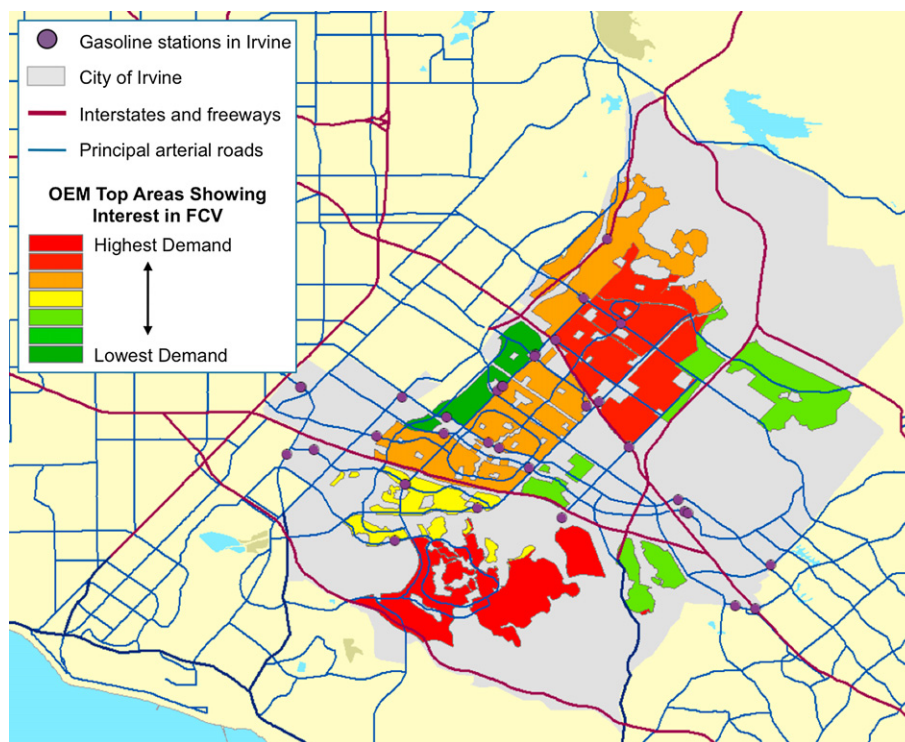


Fig. 4 – Zip codes in which the most customers are interested in leasing FCVs reside (as identified by OEMs) overlaid with residential land use data. Residential land use data provide a higher resolution of FCV demand areas by differentiating where residences are located within each zip code.

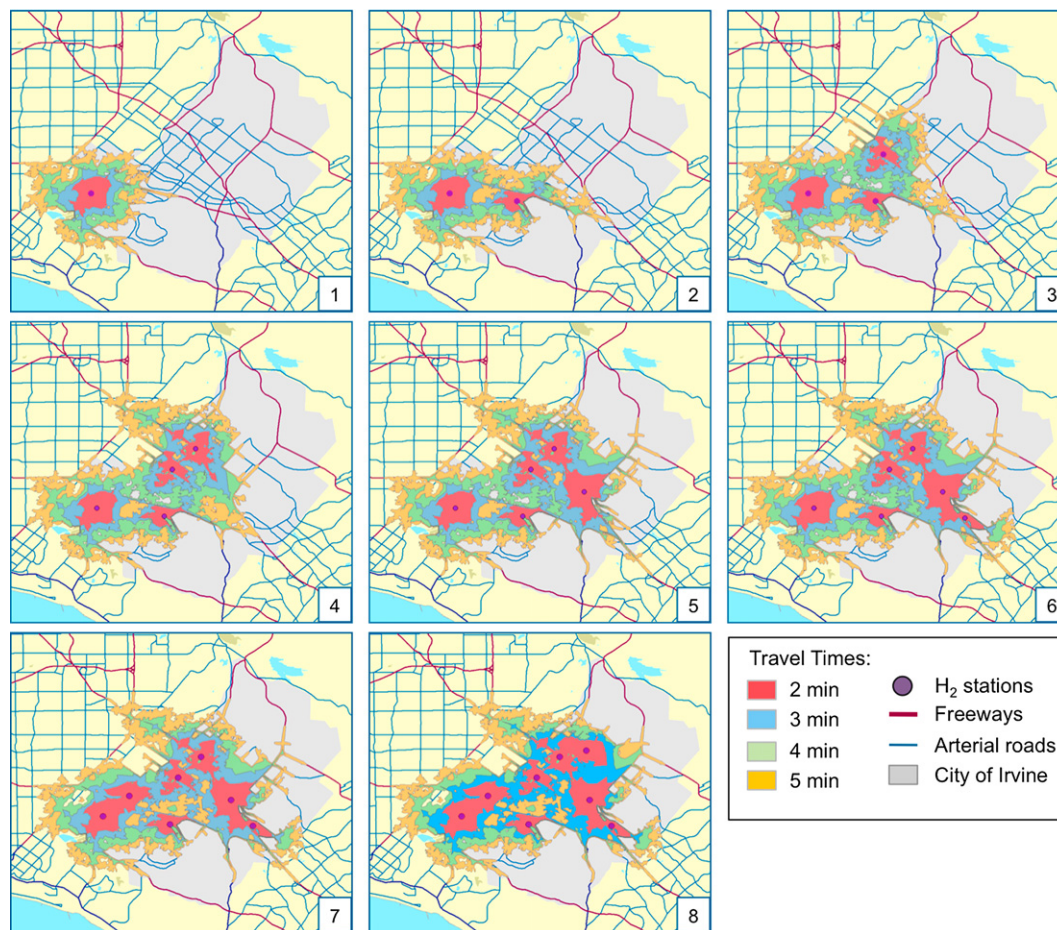


Fig. 5 – Preferred rollout strategy reaches the optimized number and locations of hydrogen fueling stations in Configuration 3. The total service area is calculated as each station is added with frame (1) representing the service area provided by the hydrogen fueling station currently operating at the UC Irvine campus. Preference is given to each station added based on residential areas within OEM top zip codes for FCV demand.

further characterized by whether the hydrogen source is renewable, and the degree to which implementation of the strategy is likely during the next five years.

Fig. 6 also categorizes hydrogen production facilities into three sizes. *Central* facilities are capable of producing tens of thousands to hundreds of thousands of kg of hydrogen daily and are located regionally. *Local* facilities are capable of producing hundreds to several thousand kg of hydrogen daily and are located in or near the hydrogen community. They can provide hydrogen to one or more nearby hydrogen fueling stations, but are not necessarily located at the site of the fueling station. *Forecourt* production facilities are capable of producing in the hundreds kg of hydrogen daily, and are located at the site of a hydrogen fueling station.

Table 5 identifies the feedstock resources for hydrogen production that are available to the City by type, location, and quantity. Fig. 7 provides the geographic location of the existing and potential hydrogen resources listed in Table 5. In the case of local biomass resources, Table 5(b) presents the total hydrogen generation potential if all of the feedstock were to be converted to hydrogen using one of two technologies: local SMR, or local high temperature fuel cell (HTFC) with hydrogen

coproduction. If HTFC is used to coproduce hydrogen there is an associated electric generation potential, which is also presented in Table 5(b). Electrolysis is not listed in Table 5 because the constraint is not dependent on the region, but rather on the electrolyzer capacity that is installed.

Hydrogen is currently produced from natural gas via steam methane reforming at multiple central scale facilities located in the southern California region. While these facilities are operated to support the hydrogen demand of nearby petroleum refineries, they have excess hydrogen production capacity that exceeds this demand. Trucks can deliver liquid or gaseous hydrogen from these facilities to hydrogen fueling stations in the City. Natural gas infrastructure is abundant in the City, so alternatively, hydrogen could be produced via forecourt steam methane reforming, that is, within the City at the site of a hydrogen fueling station. Another, perhaps more promising option for local or forecourt-scale hydrogen production from natural gas is the use of high temperature fuel cells to simultaneously produce electricity, heat and hydrogen. Because of their ability to generate three products simultaneously, these units are referred to as *energy stations* [4]. The City offers an abundance of biomass materials that are

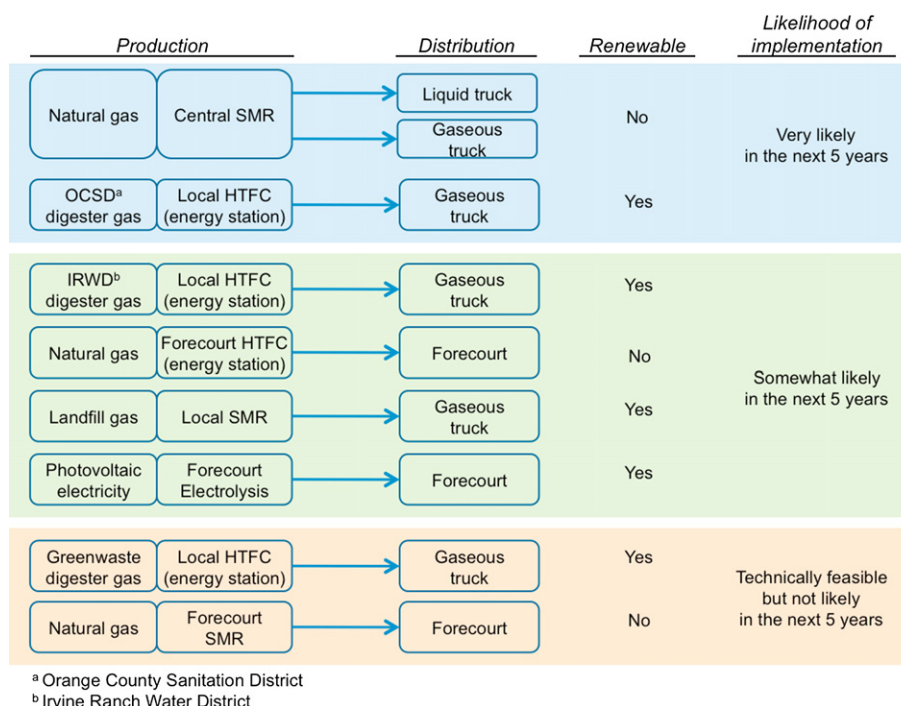


Fig. 6 – Hydrogen production and distribution strategies that are technically feasible in the near-term and that utilize resources available to the City are presented. They are also categorized by whether or not the hydrogen source is renewable, and the likelihood of implementation during the next five years.

well suited for biogas production such as wastewater that is collected and treated at the Irvine Ranch Water District, landscape clippings (green waste) that are collected and dumped at collection facilities in the City, and landfill gas available from several area landfills such as the Frank Bowerman Landfill, one of the largest in California [19]. Treated wastewater and landscape clippings can undergo anaerobic digestion to produce biogas, while landfills naturally result in pockets of methane-rich gas that can be tapped.

(Methane-rich gas from landfills must undergo rigorous cleanup before it can be utilized to produce hydrogen.) The biogas derived from these materials can serve as a feedstock to produce hydrogen via local or forecourt energy station, or via forecourt steam methane reforming. Finally, forecourt electrolysis strategies are also possible avenues for hydrogen production in the City. These include electrolysis using grid electricity, or electrolysis using photovoltaic electricity produced by the City's abundant solar insolation [20].

Table 5 – Existing and potential hydrogen sources available to the City in the near-term.

(a) Existing regional industrial hydrogen production capacity							
Operator	Location		Capacity	Units			
APCI	Wilmington		193,930	kgpd of H ₂			
APCI	Carson		224,296	kgpd of H ₂			
Praxair	Ontario		23,268	kgpd of H ₂			
(b) Hydrogen potential from local, renewable feedstocks							
Feedstock resource	Operator	Location	Capacity	Units	Potential if using local SMR (kgpd of H ₂)	Potential if using local HTFC energy station (kgpd of H ₂)	Potential if using local HTFC energy station (kW of Elec.)
AD ^a of wastewater	OCSD	Fountain Valley	4781	Nm ³ of Biogas/h	13,290	6670	10,337
AD ^a of wastewater	IRWD	Irvine	574	Nm ³ of Biogas/h	1590	796	1234
AD ^a of green waste	Tierra Verde	Irvine	16,910	MT/yr of green waste	524	263	407
Landfill Gas	Bowerman Landfill	Irvine	12,912	Nm ³ of landfill gas/h	22,799	11,436	17,734

a Anaerobic digestion.



Fig. 7 – Geographic location of existing and potential hydrogen resources available to the City on a regional and local scale.

2.3.2. Establishing near-term hydrogen production and distribution scenarios

Based on available hydrogen resources, three scenarios are designed for the evolution of hydrogen production and distribution in the City over the next five years based as described in Table 6. The mix of hydrogen production and distribution strategies varies in each scenario to represent various levels of renewable hydrogen as a portion of the total hydrogen dispensed. The hydrogen production and distribution mix in each scenario for each year between now and 2014 is represented in Fig. 8. Also represented are the number of hydrogen fueling stations proposed, and the portion of hydrogen fuel that is renewable in each year between now and 2014. These scenarios have been thoroughly vetted by industry stakeholders in the hydrogen transportation arena.

2.3.3. Assessing the environmental impact of near-term hydrogen production and distribution scenarios

The Preferred Combination Assessment (PCA) model [21] is applied to determine environmental impacts associated with near-term hydrogen infrastructure scenarios in the City. The PCA model has been previously established as a component of

STREET that assesses the environmental impacts (i.e., criteria pollutant emissions, greenhouse gas emissions, energy consumption, and water consumption) associated with various combinations of hydrogen generation, delivery and utilization strategies [2]. Proposed hydrogen infrastructure scenarios are assessed using the PCA model and results are compared against conventional (i.e., gasoline ICE) vehicles in Fig. 9. Environmental impacts for conventional vehicles are derived from the

Table 6 – Description of hydrogen production and distribution scenarios for the City from 2010 to 2014.

Scenario A	Hydrogen is generated with an emphasis on conventional means, some introduction of local hydrogen production, and relatively insignificant generation of renewable hydrogen
Scenario B	Hydrogen is generated with a heavy emphasis on using local, renewable resources as the feedstock.
Scenario C	Hydrogen is generated from a realistic and achievable mix of conventional and local resources, sufficient to meet the California goal of 33% renewable hydrogen

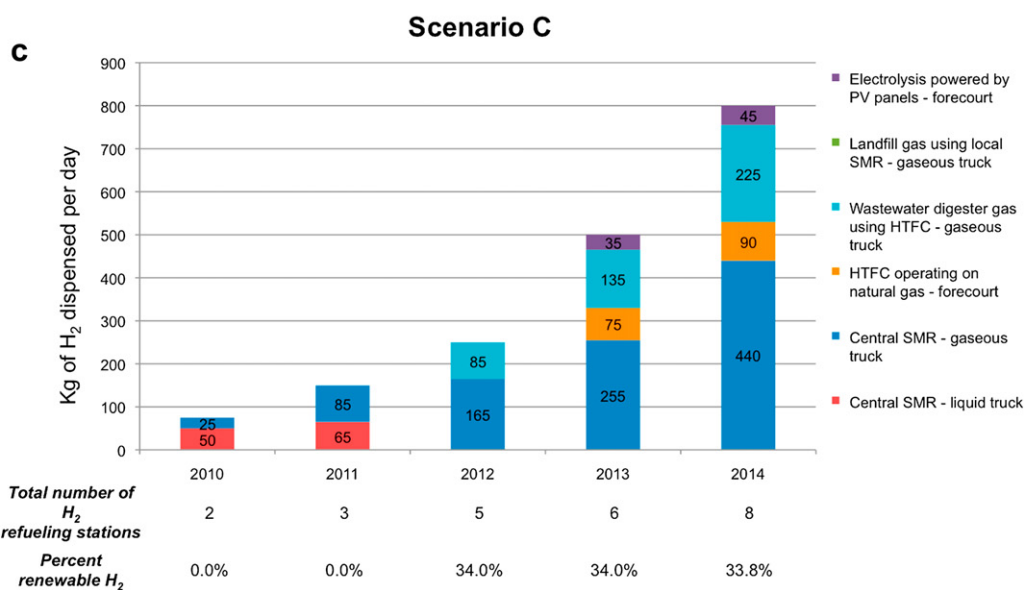
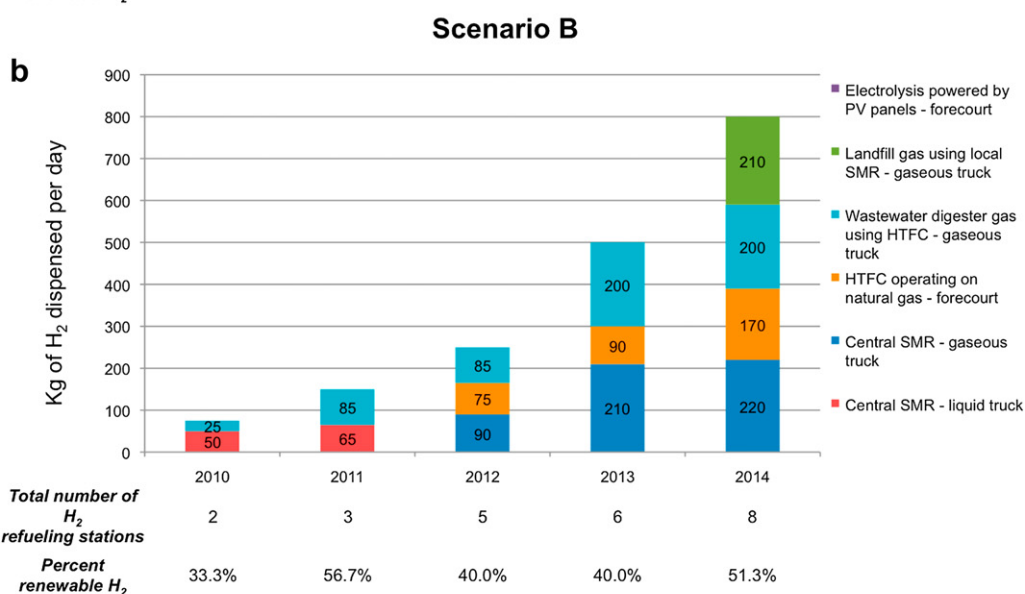
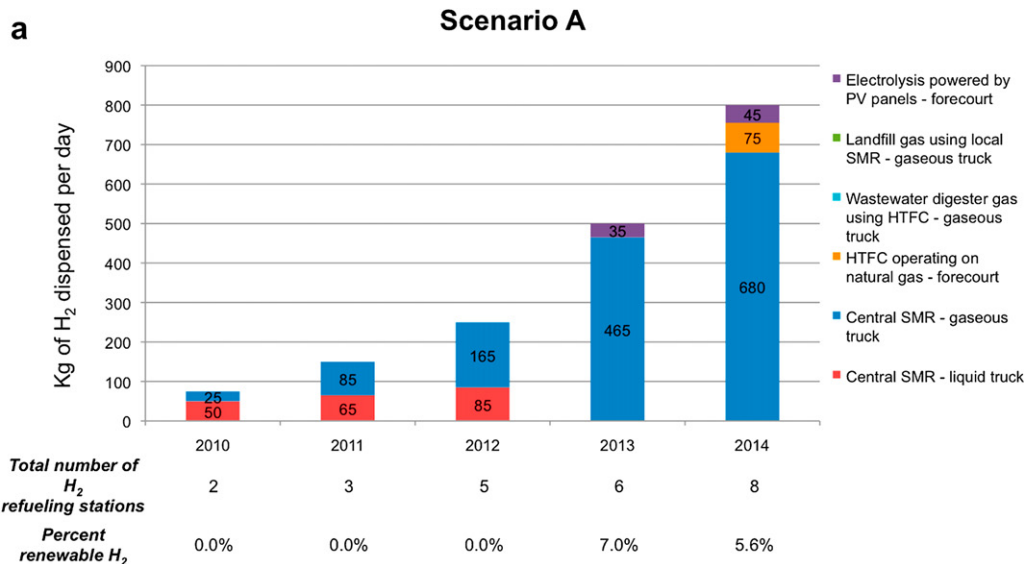


Fig. 8 – The evolution of hydrogen production and distribution strategies in the City from 2010 through 2014 for (a) Scenario A, (b) Scenario B, and (c) Scenario C are presented in terms of kg of H₂ dispensed per day. The proposed number of hydrogen fueling stations operating in the City in each given year and the portion of total hydrogen dispensed daily that is produced from renewable feedstocks are also identified.

California Air Resources Board EMFAC model [22]. Results are also compared against SB 1505 regulations for hydrogen production in California [6] in Table 7 and Figs. 10 and 11.

2.3.4. Determining if hydrogen production and distribution scenarios meet California’s environmental standards

Results from the environmental impact assessment of hydrogen production and distribution scenarios are compared to the California standards for hydrogen in transportation. The portion of hydrogen from renewable feedstocks in each hydrogen production and distribution scenario is provided in Table 7. Only scenarios B and C meet the California standard

Table 7 – Portion of hydrogen produced from renewable feedstocks in each hydrogen production and distribution scenario.

Year	H ₂ dispensed daily (kg)	Portion of renewable H ₂ generation		
		Scenario A	Scenario B	Scenario C
2010	75	0.0%	33.3%	0.0%
2011	150	0.0%	56.7%	0.0%
2012	250	0.0%	34.0%	34.0%
2013	500	7.0%	40.0%	34.0%
2014	800	5.6%	51.3%	33.8%

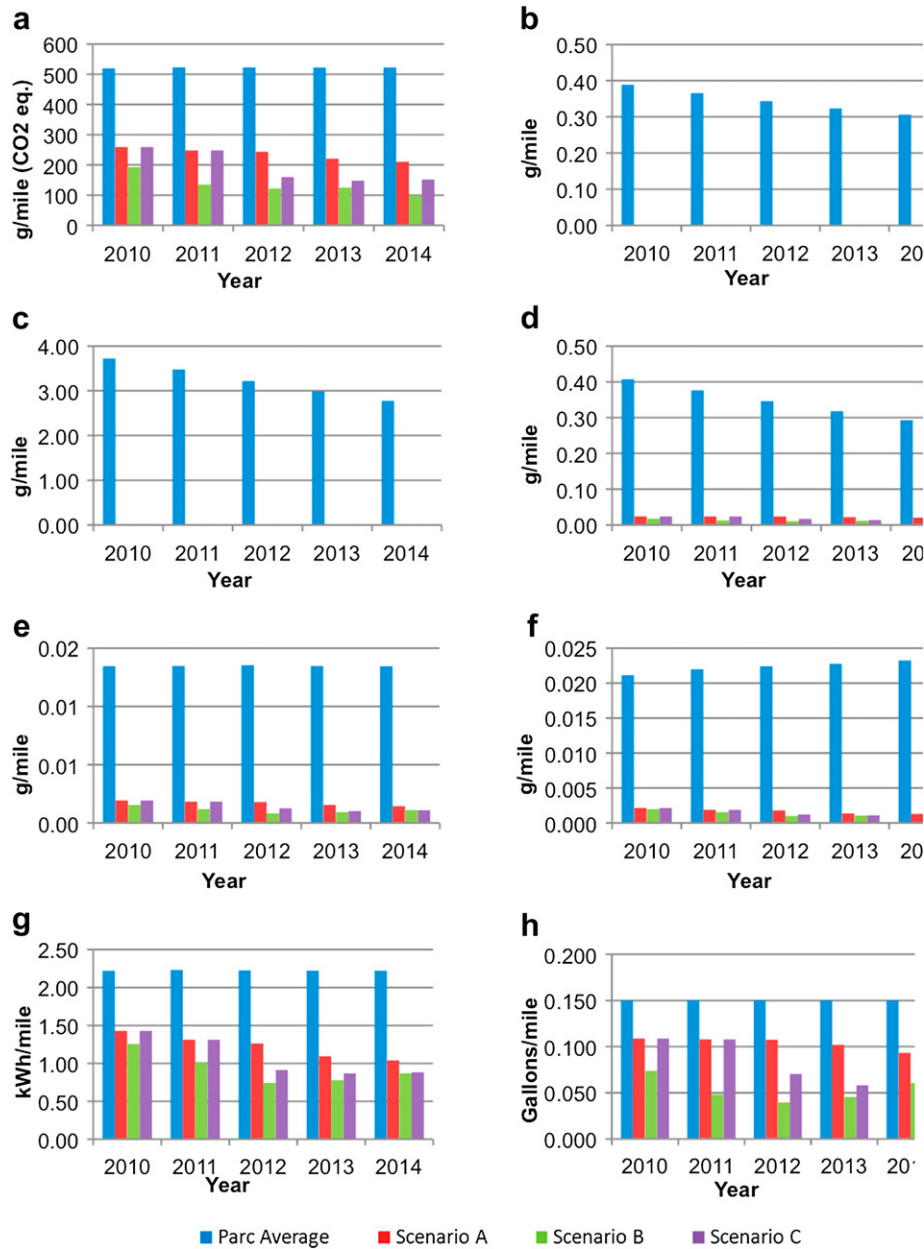


Fig. 9 – WTW (a) GHG emissions, (b) urban ROG emissions, (c) urban CO emissions, (d) urban NO_x emissions, (e) urban SO_x emissions, (f) urban PM emissions, (g) energy use, and (h) water use for hydrogen infrastructure scenarios A, B, and C compared to conventional vehicle parc average.

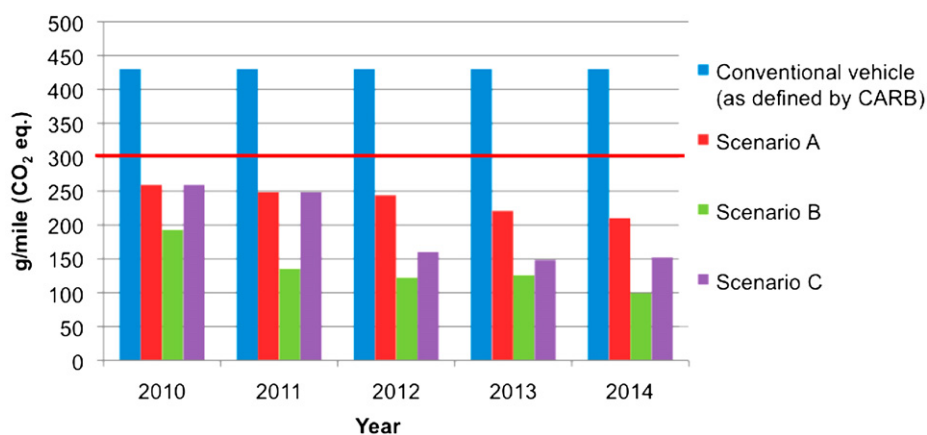


Fig. 10 – WTW GHG emissions for hydrogen scenarios compared to conventional passenger vehicles as defined by the California Air Resources Board (CARB). The red line represents the standard for hydrogen of 30% reduction compared to conventional passenger vehicles on a WTW basis.

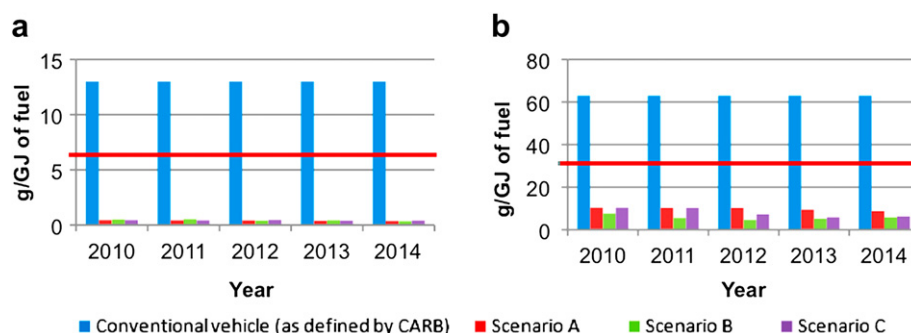


Fig. 11 – WTT (a) urban ROG and (b) urban NO_x emissions for hydrogen scenarios compared to conventional passenger vehicles as defined by CARB. The red lines represent the standard for hydrogen of 50% reduction compared to conventional passenger vehicles on a WTT basis.

of 33% hydrogen produced from renewable sources. Scenario A relies primarily on conventional feedstocks for hydrogen and therefore does not meet the renewable production standard. Scenario B meets the standard in the year 2010 and in subsequent years; and scenario C meets the standard in the year 2012 and in subsequent years.

WTW GHG emissions for each hydrogen scenario are compared to conventional vehicles on a g/mile basis to determine which scenarios achieve the California standard. The California Air Resources Board (CARB) has characterized the WTW GHG emissions for a conventional passenger vehicle at 430 g/mile [23], and the use of hydrogen must achieve a 30% reduction. Fig. 10 shows that a 30% reduction below 430 g/mile is easily achieved by all three hydrogen scenarios.

WTT urban ROG and NO_x emissions for each hydrogen scenario are compared to conventional vehicles on a g/GJ of fuel basis to determine which scenarios achieve the California standard. CARB has characterized the WTT ROG and NO_x emissions for a conventional passenger vehicle at 13 and 63 g/

GJ of fuel, respectively [23]. Hydrogen must achieve a 50% reduction compared to passenger vehicles. Fig. 11 shows that the standards for WTT ROG and NO_x are easily achieved by all three hydrogen scenarios.

3. Summary and conclusions

Considering the limited amount of funds available for hydrogen infrastructure deployment, it is critical to achieve favorable results with limited, near-term infrastructure – a goal that requires systematic planning in order to provide the information upon which business and policy leaders can optimize early investments in hydrogen infrastructure. In the present paper, STREET is utilized as the resource to provide an example of systematic planning. A case study for the City serves as an illustrative example of the effectiveness of systematic planning for the rollout of hydrogen infrastructure.

The conclusions from the study are as follows:

- Eight hydrogen fueling stations provide comparable service to the existing gasoline fueling infrastructure.

With respect to the deployment of hydrogen fueling stations, the findings utilizing STREET establish that eight strategically located hydrogen fueling stations in the City can provide a comparable basic level of service to FCV drivers as do existing gasoline stations in the City to gasoline vehicle drivers. An analysis of the service area achieved with respect to the roads and residential land use areas in the City confirms these results. Therefore, it is proposed that a configuration of eight hydrogen stations in the City, if planned strategically, will enable a full-scale FCV deployment and concomitant transition to commercialization of FCVs. Eight hydrogen fueling stations represent 23.5% of the total retail gasoline stations in the City. This result is comparable to findings in previous studies, which suggest that access to fueling is not a concern to customers of alternative fuel vehicles when 15–20% of total gasoline stations carry the alternative fuel [11,17]. This basic level of service is achievable with eight stations 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 converting gasoline dispensers to hydrogen dispensers gradually, as the transition from gasoline to hydrogen occurs. The fact that four configurations of eight hydrogen fueling stations strategically located throughout the City provide comparable service coverage over roads and residential land use zones suggests that there is some flexibility in where the stations can be located to achieve the desired result.

- Community statistics inform the rollout order for hydrogen fueling stations.

The order in which hydrogen station rollout occurs can be informed by data provided by OEMs in combination with residential land use data. In the present case, data provided by OEMs indicate zip codes in which the highest numbers of customers with an interest in FCVs reside. The location of customers interested in FCVs can be further differentiated spatially by using residential land use to determine where within those zip codes people live. The result indicates where early FCV customers are likely to be located and enables planning for a rollout of hydrogen fueling stations that meets the greatest number of users in the earliest stages.

- Systematic planning optimizes both the economic and environmental impact.

An environmental assessment of three scenarios for early-stage hydrogen production and distribution of hydrogen in the City suggests that WTW GHG emissions, urban criteria pollutants, energy use, and water use will be significantly reduced in comparison to the average parc of gasoline vehicles. This is the case regardless of whether hydrogen is produced and distributed with an emphasis on conventional

resources (e.g., natural gas), or on local, renewable resources. An emphasis on local renewable resources reduces emissions, energy use, and water use more than an emphasis on conventional resources. Furthermore, assessment of the three scenarios illustrates how California's environmental standards for hydrogen production can be met. All three of the scenarios meet California's standards for WTW GHG emissions, and WTT emissions of urban ROG and NO_x. Scenarios B and C also meet California's standard that 33% of hydrogen must be produced from renewable feedstocks. Scenario A, which emphasizes conventional resources for hydrogen production, does not meet this standard, though it does meet the others.

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