FINAL DRAFT

January 29, 2010

AN ANALYSIS OF NEAR-TERM HYDROGEN VEHICLE ROLLOUT SCENARIOS FOR SOUTHERN CALIFORNIA

Michael Nicholas and Joan Ogden
Institute of Transportation Studies
University of California, Davis

EXECUTIVE SUMMARY

There is rapid, ongoing progress in development of both fuel cell vehicle technology, and hydrogen refueling systems. Although hydrogen and fuel cell vehicles are not yet ready for full commercial deployment, they are ready to take the next step toward commercialization. This is widely seen as a "networked demonstration" in a localized region or "lighthouse city," involving hundreds to thousands of vehicles and an early network of tens of refueling stations. Because of California's ZEV regulation, Southern California has been proposed as an ideal site for this early introduction of hydrogen vehicles and is a major focus of interest worldwide (Gronich 2007, Melendez 2007, NRC 2008, Greene et al. 2008). [1]

Developing a successful early hydrogen refueling network in Southern California, even at the relatively small scale envisioned for 2009-2017, requires a coordinated strategy, where vehicles and stations are introduced together. A major question is how many stations to build, what type of stations, and where to locate them. Key concerns include fuel accessibility, customer convenience, quality of refueling experience, network reliability, cost, and technology choice.

In this paper, a strategy of "clustering" is explored. Clustering refers to the focused introduction of hydrogen vehicles in defined geographic areas such as smaller cities (e.g. Santa Monica, Irvine) within a larger region (e.g. LA Basin). By focusing initial customers in a few small areas, station infrastructure can be similarly focused, reducing the number of stations necessary to achieve a given level of convenience as measured by the travel time from home to the nearest station and "diversion time" explained later. We evaluate the potential for clustering to improve customer convenience, reduce refueling network costs, and enhance system reliability.

[1] Automakers have announced plans to bring several hundred fuel cell vehicles to California in the next three years, and are regulated to produce thousands of zero emission vehicles starting in 2012. However, the energy companies, who have been leaders in hydrogen station demonstrations, do not have the same near-term requirement to build the next round of hydrogen stations.

We analyze a variety of "clustered" scenarios for introducing hydrogen vehicles and refueling infrastructure in Southern California over the next decade, to satisfy the requirements of the California ZEV regulation. For each scenario we estimate:

- Station placement within the Los Angeles Basin
- Convenience of the refueling network (travel time from home to the nearest station and "diversion time")
- Economics – capital and operating costs of stations; cost of hydrogen for different station scenarios.

We also discuss transitional strategies for the choice of hydrogen supply pathways, as the network expands. A transitional cash flow analysis is carried out to illustrate the investments that might be needed over time to bring hydrogen fuel to cost competitiveness with gasoline.

Key Findings

Through a series of interviews with expert stakeholders, we developed scenarios for FCV volumes, hydrogen demand, station placement, and numbers of stations in LA, in 3 time periods

- 2009-2011: 636 FCVs (using an average of 445 kg H2/d) and 8-16 stations
- 2012-2014: 3442 FCVs (using an average of 2410 kg H2/d) and 16-30 stations
- 2015-2017: 25,000 FCVs (using an average of 17,500 kg H2/d) and 36-42 stations.

We assume vehicles and stations are placed in 4 to 12 "clusters" identified by stakeholders as early market sites (Figure ES-1). Some connector stations are added to facilitate travel throughout the LA Basin.

We used spatial analysis methods to develop two measures of consumer convenience, the ***average travel time*** from home to station, and the ***"diversion time"*** (average time to a station while traveling anywhere in the LA Basin). Our results suggest that clustering is a very effective way to provide good access to fuel, even with a small number of stations.

When vehicles and stations are co-located in clusters, scenarios with as few as 8 to 24 initial stations, located in 4 to 12clusters, can give average travel times of only about 2.5 - 4 minutes from home to station, and "diversion times" of about 4.5 - 5.5 minutes for travel throughout the region. (Without clustering, if vehicles had been located in homes throughout the LA Basin, the average travel time to the nearest station would have been much longer, 11-15 minutes.) Adding more stations within a cluster can significantly reduce the average travel time from home to station. Adding connector stations between clusters can significantly reduce the diversion time.

The cost of building an early hydrogen refueling network was estimated over an early transition period (see Figure ES-2 below). We conducted a literature review and interviews with stakeholders to estimate station costs[2], and technology status. From this we proposed various

[2] We assume that it costs $2 million for site preparation, upfront permitting, engineering, utility installation, for a green-field refueling station site before any fuel equipment goes in. This would be the same for gasoline or hydrogen. $2 million is the "baseline cost" of a H2 station and H2 refueling equipment costs are added to this.

station combinations over time including both portable (mobile refueler) and fixed (onsite steam reformer, onsite electrolyzer or liquid hydrogen) stations. We use conservative cost estimates to reflect near term costs, but allow for technology improvement and cost reduction by 2017. Station cost and performance numbers were developed in consult with energy industry experts, and through literature review.

We start with a significant number of mobile refuelers and a few fixed stations, and move toward larger, fixed stations over time. For each phase we estimate the cost of building new stations and operating the network. The results are summarized in Figures ES-2 and ES-3.

As the station network expands to meet a growing hydrogen demand, the average travel time and diversion times decrease. The levelized cost of hydrogen (e.g. the annualized cost of capital and operation expenses divided by the annual hydrogen production) falls from \$77/kg in 2009-2011 to \$37/kg in 2012-2014 and \$13/kg in 2015-2017(Figure ES-2). By 2015 the cost of hydrogen from the early infrastructure is approximately competitive with gasoline at \$6.5/gallon accounting for the higher fuel economy of the FCV. This transition pathway could be considered an introduction to a business case after 2017, when many more 1000 kg/d stations would be needed, if FCVs are successful in the market. These new 1000 kg/d stations could provide hydrogen at \$5-7/kg (competitive on a cents per mile fuel cost basis with gasoline at \$2.5-3.5/gallon).

We estimated the annual cash flow, assuming that hydrogen could be sold for \$10/kg throughout the transition period (2009-2025). Initially, the cash flow is negative (due to initial capital expenditures to build the stations at the beginning of each phase), but eventually, as the station size grows and more fixed stations are employed, the cost of hydrogen declines. By 2024, the initial investment of approximately \$200 million (\$170 million for station capital) is recouped, if hydrogen can be sold at \$10/kg.

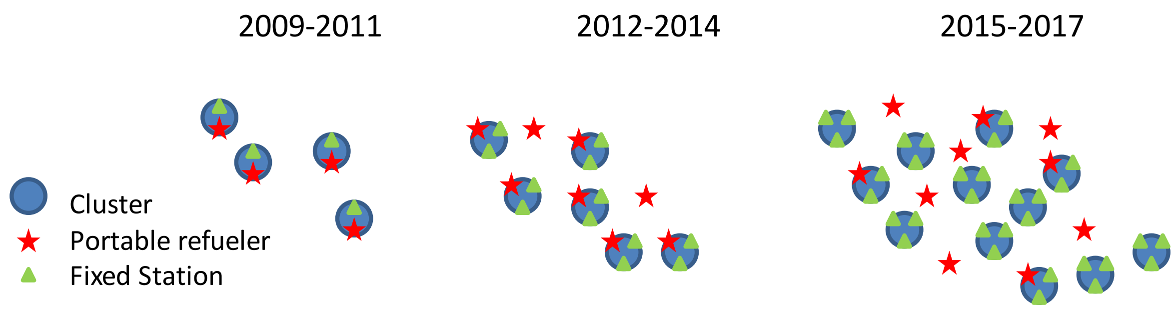
We explore the sensitivity of the cost results to station capital cost assumptions, energy prices, and rollout scenario.

There are several options for near-term renewable hydrogen production (via onsite reformation of bio-methane) that could meet California's requirement for 33% renewable sources for hydrogen production at a modest cost premium of \$0.1-0.4 per kg of hydrogen.

H2 station costs in (2009-2011) are based on interviews with energy company experts reflecting their costs today. For 2012-2014, we assume equipment costs are twice the H2A "current technology" values. (Rationale: H2A is based on producing 500 stations per year. If we reduce this by a factor of ~50-100 to reflect 2012-2014 production of stations (5-10 stations per year), the equipment cost should be about 2 times the H2A estimate (Weinert 2006). For 2015-2017, we analyze two cost cases:

1) **Low Cost**: assume that the H2A current equipment costs are appropriate (we are building 100 stations/yr in LA and elsewhere, if FCVs are "taking off")
2) **High Cost**: Costs are the same as in 2012-2014

Figure ES-1 The shaded regions above are the "clusters" which are potential sites for early hydrogen vehicle and station placement. We used GIS analysis to evaluate scenarios where vehicles are introduced in 4 to 12 of these clusters between 2009-2017 to meet the requirements of the ZEV regulation.



	636 FCVs	3442 FCVs	25,000 FCVs
# Stations	8	20	42
# clusters	4 (2 sta/cluster)	6 (3 sta/cluster)	12 (3 sta/cluster)
# connect.sta	0	2	6
Station Mix	4 Portable refuelers 4 SMRs (100 kg/d)	8 Portable Refuelers 12 SMRS (250 kg/d)	10 Portable refuelers 12 SMRs (250 kg/d) 20 SMRs (1000 kg/d)
New Equip. Added	4 Portable refuelers 4 SMRs (100 kg/d)	4 Portable Refuelers 12 SMRS (250 kg/d)	2 Portable refuelers 20 SMRs (1000 kg/d)
Capital Cost	$20Million	$52 Million	$98 Million
O&M Cost	3-5$Million/y	11-14 $Million/y	30-40 $Million/y
H2 cost $/kg	77	37	13
Ave travel time	3.9 minutes	2.9 minutes	2.6 minutes
Diversion time	5.6 minutes	4.5 minutes	3.6 minutes

Figure ES-2 Transition Pathway for Building an Early Hydrogen Infrastructure in Southern California between 2009-2017.

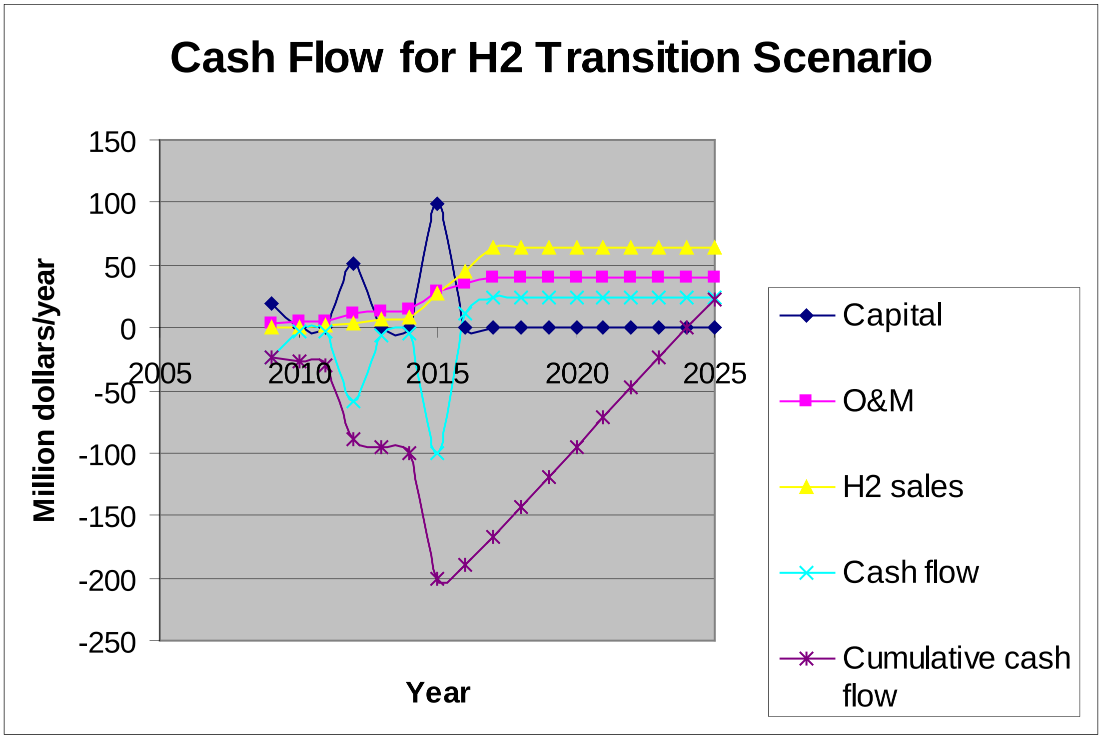


Figure ES-3 Cash Flow analysis for Transition Pathway in Figure ES-2, assuming hydrogen is sold at $10/kg throughout the transition period (2009-2025).

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AN ANALYSIS OF NEAR-TERM HYDROGEN VEHICLE ROLLOUT SCENARIOS FOR SOUTHERN CALIFORNIA

Michael Nicholas and Joan Ogden
Institute of Transportation Studies
University of California, Davis

INTRODUCTION

Hydrogen fuel cell vehicles offer the promise of near-zero well to wheels emissions of greenhouse gases and air pollutants, good performance, and a diverse primary resource base. The long-term potential of hydrogen vehicles to address societal problems has been described in many recent studies (NRC 2004, NRC 2008, IEA 2008). There is rapid, ongoing progress in development of both fuel cell vehicle technology, and hydrogen refueling systems. Prototype fuel cell vehicles are reaching goals for range and performance, and could be ready for commercialization within 5-10 years (NRC H2 Transition report 2008; NRC FreedomCar Assessment 2008). Hydrogen refueling stations based on a variety of near and long term concepts have been demonstrated. Studies by the USDOE (H2A 2007), the National Academies (NRC 2008), and industry (Shell/GM study 2007) suggest that hydrogen fuel could be provided at costs competitive with gasoline using 2015 station technology and larger sized stations (>500 kg/day).

Although hydrogen and fuel cell vehicles are not yet ready for widespread deployment, they are ready to take the next step toward commercialization. This is widely seen as a "networked demonstration" in a localized region or "lighthouse city," involving hundreds to thousands of vehicles and an early network of tens of refueling stations. Because of California's ZEV regulation, Southern California has been proposed as an ideal site for this early introduction of hydrogen vehicles and is a major focus of interest worldwide (Gronich 2007, Melendez 2007, NRC 2008, Greene et al. 2008). [3]

Developing a successful early hydrogen refueling network in Southern California, even at the relatively small scale envisioned for 2009-2017, requires a coordinated strategy, where vehicles and stations are introduced together. A major question is how many stations to build, what type of stations, and where to locate them.[4] Key concerns include fuel accessibility, customer convenience, quality of refueling experience, network reliability, cost, and technology choice.

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[3] Automakers have announced plans to bring several hundred fuel cell vehicles to California in the next three years, and are mandated to produce thousands of zero emission vehicles starting in 2012 (Table 1). However, the energy companies, who have been leaders in hydrogen station demonstrations, do not have the same near-term mandate to build the next round of hydrogen stations.

[4] Strategic placement of stations is crucial. A positive experience by customers is largely dependent on the convenience of hydrogen refueling compared to gasoline vehicles. Installing a large number of stations for a small number of vehicles would solve the problem of convenience, but would be prohibitively expensive.

In this paper, a strategy of "clustering" is explored. Clustering refers to the focused introduction of hydrogen vehicles in defined geographic areas such as smaller cities (e.g. Santa Monica, Irvine) within a larger region (e.g. LA Basin). By focusing initial customers in a few small areas, station infrastructure can be similarly focused, reducing the number of stations necessary to achieve a given level of convenience. We evaluate the potential for clustering to improve customer convenience, reduce refueling network costs, and enhance system reliability.

We analyze a variety of "clustered" scenarios for introducing hydrogen vehicles and refueling infrastructure in Southern California over the next decade, to satisfy the requirements of the California ZEV regulation. Through a series of interviews with expert stakeholders, we developed scenarios for FCV volumes, hydrogen demand, station placement, and numbers of stations in LA, in 3 time periods:

- 2009-2011: 636 FCVs (using an average of 445 kg H2/d) and 8-16 stations
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We assume vehicles and stations are placed in 4 to 12 "clusters" identified by stakeholders as early market sites (Figure 2). Some connector stations are added to facilitate travel throughout the LA Basin.

For each scenario we estimate:

- Station placement within the LA Basin
- Convenience of the refueling network (travel time from home to the nearest station and "diversion time")
- Economics – capital and operating costs of stations; cost of hydrogen for different station scenarios.

We also discuss transitional strategies for the choice of hydrogen supply pathways, as the network expands. A transitional cash flow analysis is carried out to illustrate the investments that might be needed over time to bring hydrogen fuel to cost competitiveness with gasoline.

A key idea advanced in this paper is that by concentrating both early users and stations in a relatively small number of clusters within a larger geographic area (the LA Basin), it is possible provide good convenience and reliability with a small number of stations, and at relatively low cost. As more vehicles are introduced the network expands from this initial basis, larger stations are built and the cost of hydrogen becomes competitive on a cents per mile basis with gasoline.

ROLLOUT SCENARIOS FOR H2 AND FCVS IN SOUTHERN CALIFORNIA

To develop realistic scenarios that account for major stakeholders' differing viewpoints and goals, we conducted a series of interviews with automakers (Toyota, Daimler, Honda, GM), energy companies (Shell and Chevron), fuel cell industry groups (CAFCP) and California state regulators (CARB). Each stakeholder was asked its perspective on how an early hydrogen transition might unfold in the Los Angeles area over the time period 2009-2017 with respect to:

- Potential numbers and placements of hydrogen fuel cell vehicles over time
- Potential hydrogen demand for these vehicles
- Station placements (number of stations, size and location) within the LA area to support FC vehicles
- Types of hydrogen stations ("fixed" vs. mobile; technology choice)
- Costs for hydrogen stations (current and future)

Numbers of hydrogen vehicles and hydrogen demand

It was generally agreed by all the stakeholders that the California Fuel Cell Partnership's 2008 survey of industry stakeholders (CAFCP 2008) was the best current estimate for potential numbers of hydrogen vehicles in Southern California between 2009-2017, and associated hydrogen demand. Our scenarios assume:

- 2009-2011. A total of 636 fuel cell vehicles will be placed in Southern California. This is based on announced plans by the automakers, and on information from the California Fuel Cell Partnership (CAFCP).

- 2012-2014. 3442 fuel cell vehicles will be placed in Southern California in response to the California ZEV requirement for 7500 pure ZEVs in the entire state. The only two technologies that satisfy the pure ZEV category are battery electric vehicles and hydrogen fuel cell vehicles. Based on discussions with automakers, we assume that 3442 of these will be FCVs, and that they will be placed in Southern California.

- In 2015-2017, 25,000 fuel cell vehicles are introduced in California. This is in keeping with the ZEV mandate requirement of 25,000 pure ZEVs in 2015-2017.

The total hydrogen demand is estimated based on an average hydrogen consumption per vehicle of 0.7 kg/day (or about 250 kg H2/year). (This is the hydrogen consumption expected of a car with fuel economy of 60 miles per kg, driven 15,000 miles per year.) We further assume that each refueling station operates at a maximum capacity factor of 70%. Our scenarios have total hydrogen station capacity of at least 1 kg/d for each H2 FCV in the fleet. (In the earlier years, stations are underutilized. The installed station capacity is somewhat higher than 1 kg/d, reflecting a lower capacity factor.)

Spatial Location of Early Adopters: Clustered Vehicle Placements

A recent market survey by the CAFCP identified 12 clusters in the Los Angeles Basin that are likely locations for early fuel cell vehicle adopters (see Figure 2). We assume that that all early FCV users (in 2009-2014) are located in these "demand clusters". This contrasts with earlier studies (Nicholas 2004; Nicholas and Ogden 2006; Melendez 2006) which generally assumed that customers and stations are located throughout the region.

Station numbers, station size and station locations

Although there was broad agreement on the numbers of fuel cell vehicles and hydrogen demand in Southern California in the 2009-2014 timeframe, different stakeholders had widely varying views about the ideal choices for station locations, numbers of stations, station size, and technology. Several underlying factors emerged that influenced stakeholders' preferences on the number of stations, location, size and type of stations.

Fuel accessibility: Both automakers and energy companies were concerned with providing good fuel accessibility for early adopters of hydrogen fuel cell vehicles. All stakeholders thought that it was important to locate stations near early adopters, so that drivers would have a short travel time from home to a nearby station. It was also seen as important to have a geographically dispersed station network, so that customers could readily travel around the LA Basin, and possibly beyond to attractive destinations like Las Vegas and San Diego. Clearly, there is a trade-off between having a large number of stations throughout the region (which would reduce average travel time) and cost (which would be lower for a smaller number of stations).

Refueling reliability: Station reliability was another shared concern. Instead of locating a single, isolated station within a group of users, the stakeholders favored clusters of stations, so that if a single station was out of operation, it would be easy to refuel at the next nearest station. The minimum number of stations per cluster was 2, although some stakeholders preferred 3 or more stations per cluster. The possibility of using shared mobile refuelers as region-wide "back-up" capacity was discussed. To assure reliability, our scenarios assume at least 2 stations per cluster.

Refueling Experience: For the automakers, another key factor was a "good" refueling experience for customers. Refueling should be easy, quick, and familiar. The refueling experience should reinforce the fuel cell vehicle's advantages (advanced technology; green values). Rather than locating hydrogen stations behind chain link fences in industrial settings, there was an emphasis on a familiar setting (a hydrogen bay in an existing gasoline station) or even a new "high-tech" setting. "Bricks and mortar" or "fixed" stations were seen as more conducive to customer ease and acceptance than mobile refuelers. To accommodate this concern, our scenarios require at least one "fixed" station per cluster.

Cost: For the energy companies, both station capital cost and operating costs (e.g. locating near low cost hydrogen supplies) were important. Mobile refuelers were seen as an attractive near-term option in terms of lower capital cost and flexibility, but there was also a trend toward building stations that advanced technical knowledge. There was recognition of scale economies and lower hydrogen costs possible with larger stations, but concern about utilization of these larger stations in the early years. There is a trade-off between the consumer friendliness of a familiar bricks and mortar fixed station, and the added cost compared to a mobile refueler.

Technology status: Technology readiness influenced energy companies' thinking on choice of refueling station technologies. Overall, it was agreed that 50-100 kg/day station technologies (mobile refuelers, LH2 truck delivery or onsite steam methane reformers) were available now. Larger units 400 kg/d were also seen as available now, but 1500 kg/day stations were still a few years from readiness. It was not clear whether 700 bar, 350 bar or some intermediate dispensing pressure would be preferred.

Low Carbon Hydrogen: California regulators seek to encourage low carbon and renewable hydrogen supply pathways. The existing renewable hydrogen requirement in California was seen by other stakeholders as a possible hindrance to getting started now with natural gas based hydrogen supply.

Build-out Strategy: Some stakeholders preferred starting with a single cluster, and building out to other clusters over time. Others suggested starting with all 12 demand clusters to gain initial geographic coverage and building up from there. Connector stations between clusters were seen as important to enabling more convenience region-wide travel.

The options for an early network of stations were distilled into a series of choices.

- Station number and size (fewer, larger stations vs. more, smaller stations)
- Wider geographic coverage vs. clustering in fewer key locations within the LA Basin (number of clusters chosen; number of stations per cluster; number of connector stations)
- Station technology choice
    - Mobile refueler vs. fixed stations
    - Fixed station station type: Compressed gas truck delivery, LH2 truck delivery, onsite steam methane reformer, onsite electrolyzer
    - Locate hydrogen dispenser in existing gasoline station vs. stand alone H2 station
    - Dispensing pressure of 350 bar vs. 700 bar vs. some intermediate pressure
    - Renewable energy input fraction: biomethane; green electricity from grid or solar PV.

We developed scenarios to span a broad range of choices (see Table 1).

Table 1 Station Scenarios

	2009-2011 636 HFCVs; Ave. H2 Demand 445 kg/d; Total Sta. capacity > 636 kg/d				2012-2014 3442 HFCVs; Ave. H2 Demand 2410 kg/d Tot. Sta. cap. > 3442 kg/d				2015-2017: 25,000 FCVs
Scenario	1	2 (2a)	3	4 (4a)	5 (5a)	6 (6a)	7 (7a)	8 (8a)	9 (9a)
# stations	16	12 (16)	16	8 (16)	16 (20)	18 (20)	24 (30)	24 (30)	36 (42)
Station location and layout	8 clusters 2 stations per cluster	6 clusters, 2 sta per cluster + (4 optimally located connector stations)	4 clusters, 4 sta. per cluster	4 clusters, 2 stations per cluster(+ 8 connector stations)	4 clusters, 4 stations per cluster + (4 opt. located connector stations)	6 clusters, 3 sta per cluster+ (2 opt. located connector stations)	8 clusters, 3 sta/cluster (+ 6 opt. located connector stations)	12 clusters, 2 sta/cluster (+ 6 opt. located connector stations)	12 clusters, 3 sta/cluster (+ 6 opt. located connector stations)
Ave. station capacity	40	53 (40)	40	80 (40)	215 (172)	191 (172)	143 (115)	143 (115)	694 (595)
Ave. output kg/d	28	37(27)	28	56 (27)	176 (140)	156 (140)	117 (94)	117 (94)	486 (417)

ANALYSIS OF STATION SCENARIOS

STATION PLACEMENT SPATIAL ANALYSIS

BACKGROUND

What comprises a sufficient hydrogen network has evolved over time. A short review of previous approaches helps explain in part the approach taken here. One of the earliest ideas was to create a "hydrogen highway" with hydrogen stations every 20 miles along highways in California. However, this plan had the potential to create many underutilized stations throughout the state as many would be in rural areas.

A second iteration of this idea was the California Hydrogen Highway Network Blueprint Plan (Cal EPA, 2005a, Cal EPA, 2005b). This plan focused less on the highways and more on the main metropolitan areas in the state: Sacramento, San Francisco, Los Angeles, and San Diego. Stations were placed according to population density within the regions. The assumption was that all customers had an equal likelihood of purchasing a fuel cell vehicle so that areas with higher populations would have higher adoption. The weakness in this approach is that different cities or areas within a metropolitan region may adopt the technology at a different rate. In this case, the location of stations sited by population density would not serve the customers who actually had the vehicles.

Another approach derived analytically how best to sequentially roll out stations throughout the state of Florida to provide the greatest statewide coverage and enable travel throughout the state(Kuby et al., 2009). This analysis used traffic flow capture as a way to determine the best sites for stations. The model was used to connect communities statewide and can be adapted for large and small scale networks. This approach was not explicitly used primarily because through discussions with stakeholders, the home was the most important focal point in marketing and refueling. Basing part of the analysis on the home to station time provided an easily understandable metric to evaluate different scenarios. The diversion time metric, while not flow capture, does take traffic flow into account, and a station sited based on diversion time (explained below) could be thought of as a variant of flow capture.

The analysis in this paper also benefits from the fact that there is a better idea of where the vehicles will be. Automobile manufacturers are targeting specific cites and areas for the first time. This enables fuel providers to coordinate the rollout of stations with the rollout of vehicles. In this way the chicken and egg question of what comes first the vehicles or the stations is answered: The vehicle locations are chosen first.

METHODOLOGY

The analysis is confined to evaluating vehicles placed in 4-12 clusters in the LA region (Figure 2) and addresses how best to serve refueling in two contexts: local and regional. The travel time from home to the nearest station in the direction one is already travelling is very important to establishing a convenient refueling network and local stations will be chosen to minimize this travel time. Another very important factor is the regional availability of refueling outside of one's home cluster. To address this, traffic patterns are analyzed to find out where else customers travel outside of one's home area, and with what frequency. Regional "connector" stations are strategically placed to serve these trips. Although refueling on these sorts of trips is less frequent, they are still very important to the perception of fuel availability and provide more flexibility in planning trips around the region.

Types of Stations

Stations can be broken down into *at least* four designations: local stations, local freeway stations, connector stations, and destination stations. However, the designations *need not be exclusive of one another* and one station can serve multiple functions. The following analysis will focus on local stations and connector stations but an understanding of each proposed definition helps frame the analysis. An idealized network with origins, destinations and stations is shown in Figure 1. The physical form of the actual networks in the Los Angeles basin are likely to be grid based, but the flow of traffic to and from freeway entrances will likely be functionally similar to the network shown in Figure 1. Not reflected in the Figure 1 is the situation where the customer has two freeway entrances to choose from based on his or her destination.

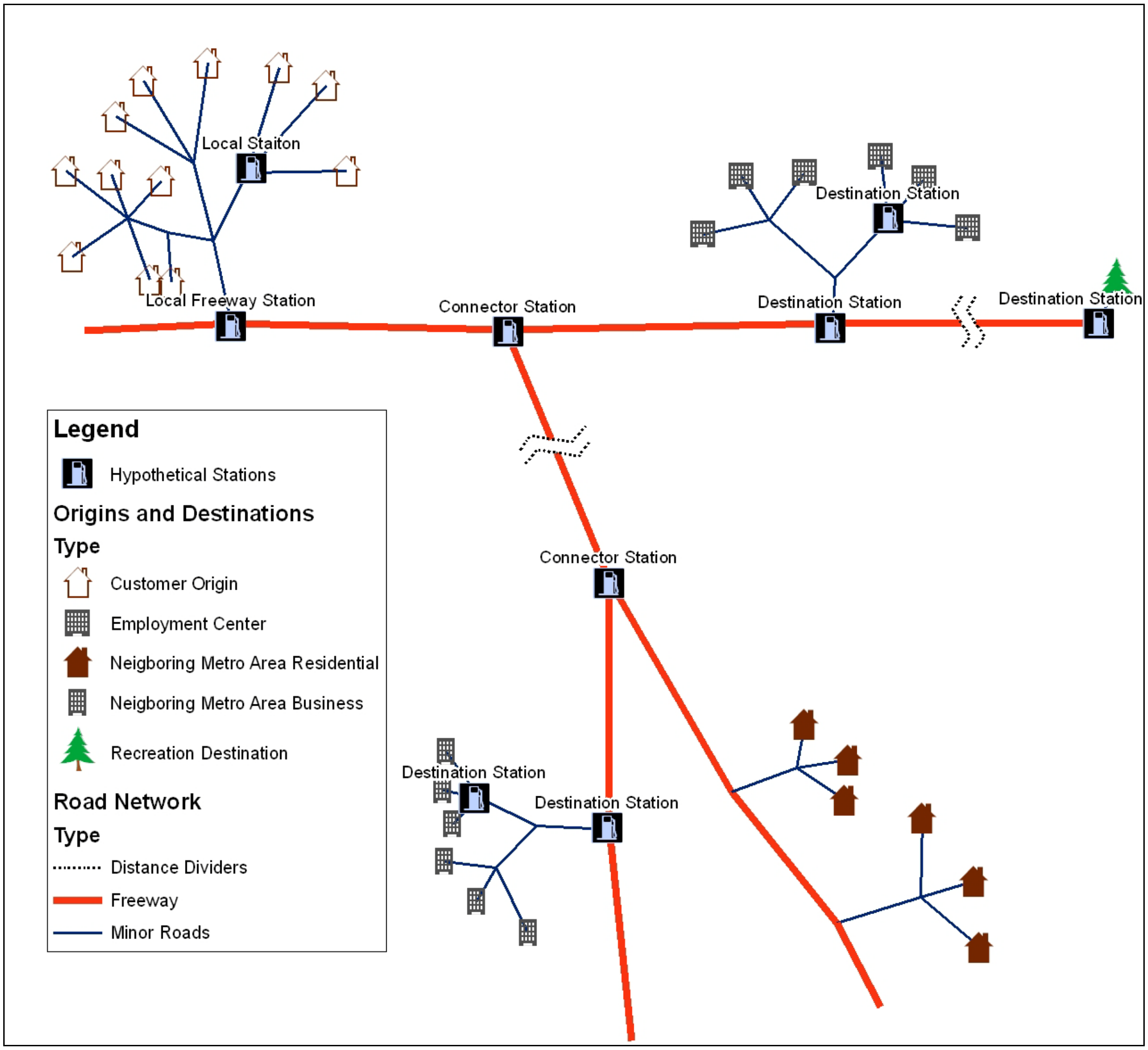

Figure 1 Example network showing origins, destinations, and stations to serve the origins and destinations. The customer cluster is the group of customer origins. Common destinations for these customers include employment centers, nearby metropolitan areas, and recreation destinations. The focus of this analysis will be on local and connector stations although destination stations remain important.

Local stations are stations close to a customer's residence. In Figure 1, these residences are denoted by the term "Customer Origin" in the legend. These customer origins and nearby destinations such as a town center can be thought of collectively as a cluster. Local stations near the customer cluster are on average the most heavily used stations for a particular customer(Kitamura and Sperling, 1987). Very similar in concept and function is the local freeway station. This station is located at the nearest freeway entrance to a customer's home. Studies (Nicholas, 2010 Forthcoming)indicate that many customers refuel between home and the freeway entrance suggesting that a local freeway station may suffice for a local station. An added benefit is that a local freeway station can serve as a connector station for others. A connector station is one located in an area that customers must transit on their way to a destination. A destination station is, as the name implies, located at a customer's destination. Common destinations include work or shopping, but also places for recreation.

A local station will suffice for most travel, but there are some important destinations where lack of refueling may be troublesome. For example, nearby metropolitan areas such as Santa Barbara and San Diego may be important destinations for customer to be able to access (Nicholas, 2009). Another type of destination that is often overlooked, but is nevertheless important to consumers is the infrequent recreation destination. For Los Angeles, this would include Las Vegas and Palm Springs. Although these destinations may be infrequently visited, they may nevertheless be very important to the consumer when considering whether or not to buy a vehicle with a limited refueling network(Nicholas, 2009). Although perhaps not feasible in the first stages of a hydrogen station rollout, enabling these destinations with stations apparently has a large psychological impact in the minds of consumers and should be an important goal.

This analysis focuses on two station types for the near term: local stations and connector stations. Local stations, not excluding local freeway stations where appropriate, will likely handle most of the demand for fuel as many customers refuel near home. Studies suggest(Kitamura and Sperling, 1987) that *destination* stations are preferable when a local station is not used. However the large number of possible destinations makes optimizing for this parameter difficult. Instead, connector stations in which customers refuel on the way to their destination can possibly serve customers going to a greater number of destinations (see Figure 1). As this study is looking at early rollout stations, connector stations will be emphasized, and destination stations will be the focus of future analyses. An exploratory analysis of destination stations is shown in Appendix A.

Clusters

This report takes clusters where vehicles may be deployed as given, and investigates scenarios involving four to twelve of those clusters. The 12 cluster locations are the taken from a California Fuel Cell Partnership (CAFCP) survey of all automobile manufacturers who manufacture fuel cell vehicles. This survey defines, in a general sense, where manufacturers see a market opportunity for fuel cell vehicles. Because plans vary from manufacturer to manufacturer, the locations of vehicle placements were only defined by the name of the locations. The size and shape of the clusters shown in Figure 2 are an interpretation of the named market areas and are influenced by city boundaries and population density as defined by the 2000 census(United States Census Bureau, 2000).

Figure 2 The shaded regions define the possible clusters where vehicles will be placed.

A few characteristics of the clusters should be noted as these differences help interpret the results. Although there are twelve named clusters, some of the clusters are adjacent to each other. The clusters surrounding Santa Monica perhaps could be considered one large cluster for analysis. This is in fact what happens in most cases when they are analyzed together. However, smaller clusters such as West LA have the same minimum station requirements as larger ones like Torrance. For instance, two stations in the Torrance area would result in a higher average travel time than two stations in West LA. However, for consistency, the minimum number of stations per cluster is equal for the scenarios. An alternative scenario with varying numbers of stations per cluster is shown in Appendix A. The I-405 corridor is also noticeably different in shape than the other clusters. This is due to the fact that its function was defined differently than other clusters. Automakers would like to site some vehicles near stations in this corridor to enable travel, but the market locations have not been defined yet.

Depending on the scenario, 4 to 12 clusters are chosen for vehicle deployment. This analysis attempts to identify if there is an intrinsic benefit to choosing more clusters over fewer clusters in the initial stages and to characterize the convenience vs. number and type of station.

Reliability and Redundancy

The issues of redundancy and reliability have become salient topics in discussions about the success of the hydrogen network up to the present. Previously, the spacing of stations was dictated by the idea that they should be as far away as possible from each other in order to maximize the coverage of the network. However, due to the newness of the technologies employed, stations went out of service occasionally. This led to customers being stranded with no backup station nearby.

As the vehicles are more widely deployed into the general population, the issue of stranding could become a problem and a source of major dissatisfaction with the technology. For this reason, reliability needs to be incorporated into the next phase of station rollouts. Reliability can either come from having more reliable stations, or by spacing stations closer together so that should one station be out of operation, another would be available close by. Backup capacity could also be supplied by mobile refuelers that could be quickly deployed in case of station failure.

Since one of the goals for the next group of stations is to evaluate new technology, reliability is an unknown. In this case, having more than one station to support demand in an area is desirable. Redundancy also provides another benefit – more stations for the customer to choose from. Greater choice, particularly for stations near the home, enables greater flexibility for refueling. Siting several stations in a cluster achieves the goals of redundancy, and convenience for refueling near home. We assume that a minimum of 2 stations is required per cluster.

For connector stations between clusters, reliability is just as important. Customers are far from home making logistics more difficult if problems do arise. If mobile refuelers are used for connector stations, extra "back-up" units could be on hand if there is a problem. Additionally, some types of mobile refuelers are more reliable if the hydrogen is pre-compressed and therefore has no compressor to break down.

Another very important aspect of reliability is the information available to customers on the status and location of stations. The need for extra stations is reduced if there is good information on which stations are open and how to get to them. As stations are rolled out there should be a universal and open format established to disseminate station information to a central database accessible from the internet. This central database could be accessed by either the vehicle's navigation system or by smart-phone with GPS. Establishing this format early will help vehicle manufacturers integrate systems into upcoming vehicle designs. This database could have information such as station location, operating hours, format of payment, current pressure etc.

Data Used

There are two sources of data used to evaluate the convenience of potential networks. One is the population distribution within the clusters. The other is the traffic distribution originating in the clusters and ending elsewhere. The unit of analysis for both metrics is the census tract.

Population Distribution

The population distribution is taken from the 2000 census. Vehicle distribution is assumed to follow population distribution within each cluster. For the years 2009-2011 the population distribution is scaled to match the CAFCP survey vehicle distribution. Different numbers of vehicles are distributed in the Los Angeles region according to the survey for a total of 636 vehicles. For the years 2012-2014, and 2015-2017 there are only regional estimates. Therefore, an equal number of vehicles was assumed for each area, and again the distribution of those vehicles was assumed to correlate with distribution of population within the clusters. The resulting distributions are shown in Figure 3.

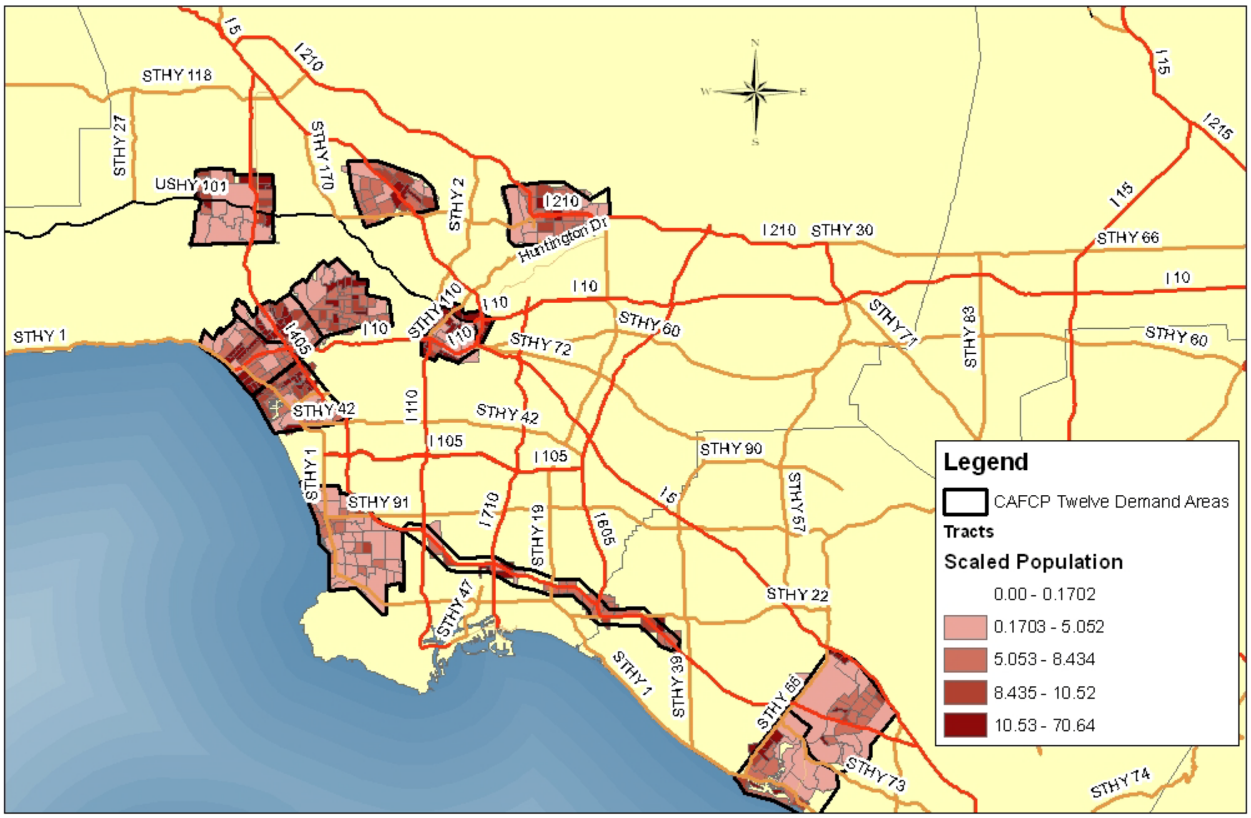

Figure 3 Scaled population distribution within the clusters so that each cluster represents the same number of people. Population is a proxy for attractiveness of vehicle placement. Having each cluster represent the same number of vehicles implies that each cluster is equally attractive.

Scaling is necessary to control for clusters of different size and population and simulates an equal number of vehicles placed in each cluster. For example, for an eight cluster scenario with 3442 total vehicles, each cluster would have a total of approximately 430 vehicles. The 430 vehicles are distributed spatially according population distribution inside the cluster. [5]

[5] This could create a situation where there may be .57 vehicles in one census tract and 2.34 vehicles in another and the sum total of all tracts in the cluster equals 430. However, this scaling has no impact on the estimated travel times within a cluster.

Vehicle Miles Traveled Distribution

A traffic distribution is used to evaluate “connector station” placements to serve demand away from clusters. These data are taken from the Southern California Association of Governments (SCAG) traffic model(Southern California Association of Governments, 2004). From this model an origin destination (OD) matrix was extracted. The morning AM period of the traffic model was chosen since the origins correspond to residences more than other periods.

Using only the trips that originate from the clusters, a traffic distribution for the clusters was created. Separating the traffic that does not originate from the clusters is important in order to only analyze the traffic relevant to hydrogen vehicles. The vehicle miles traveled (VMT) per census tract was obtained by plotting the paths from origins in the 12 clusters to any destination and calculating how many miles of the paths intersected each census tract. The path miles were multiplied by the number of vehicles taking the path, and VMT per zone was then totaled. A comparison of traffic distribution from trips originating in the clusters versus all region trips is shown in Figure 4 and Figure 5.

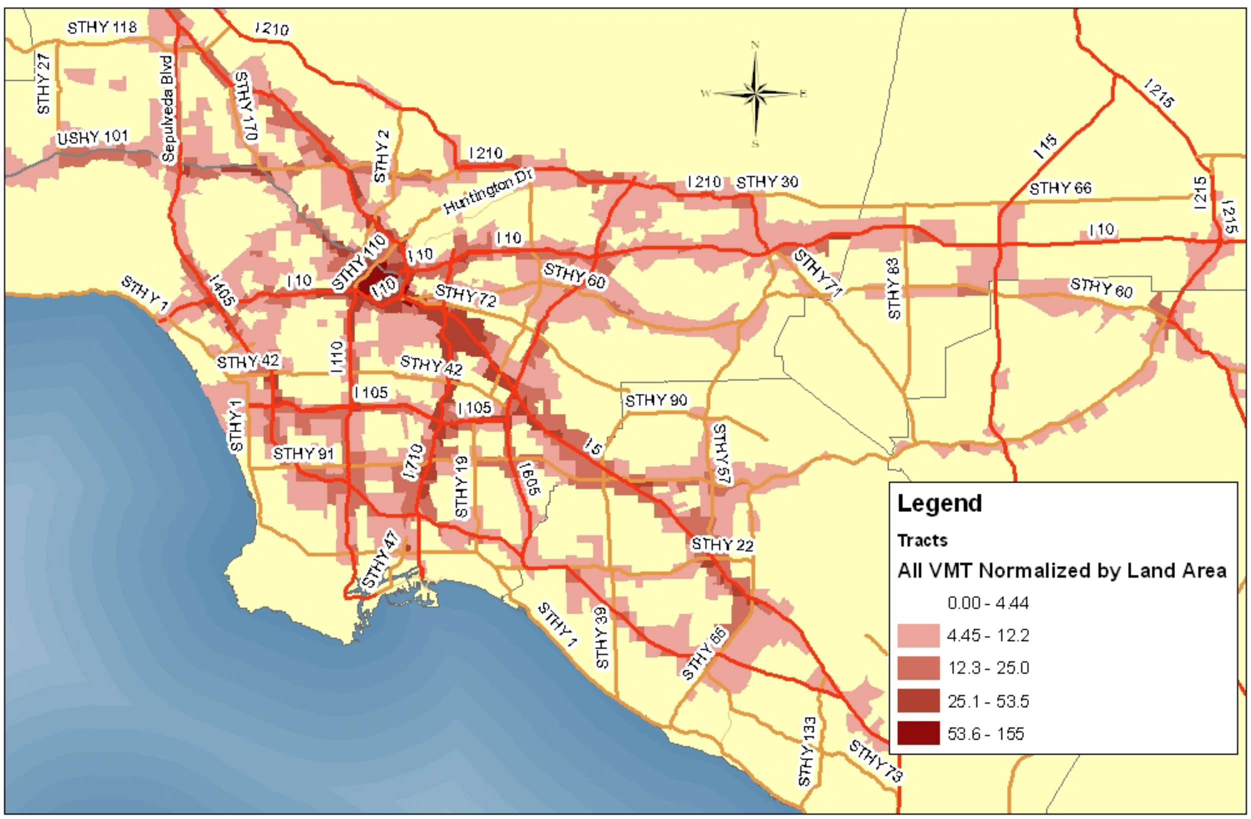

Figure 4 Relative AM VMT from all origins region-wide. Data were aggregated to census tracts and normalized by tract land area. Compare to the distribution in Figure 5.

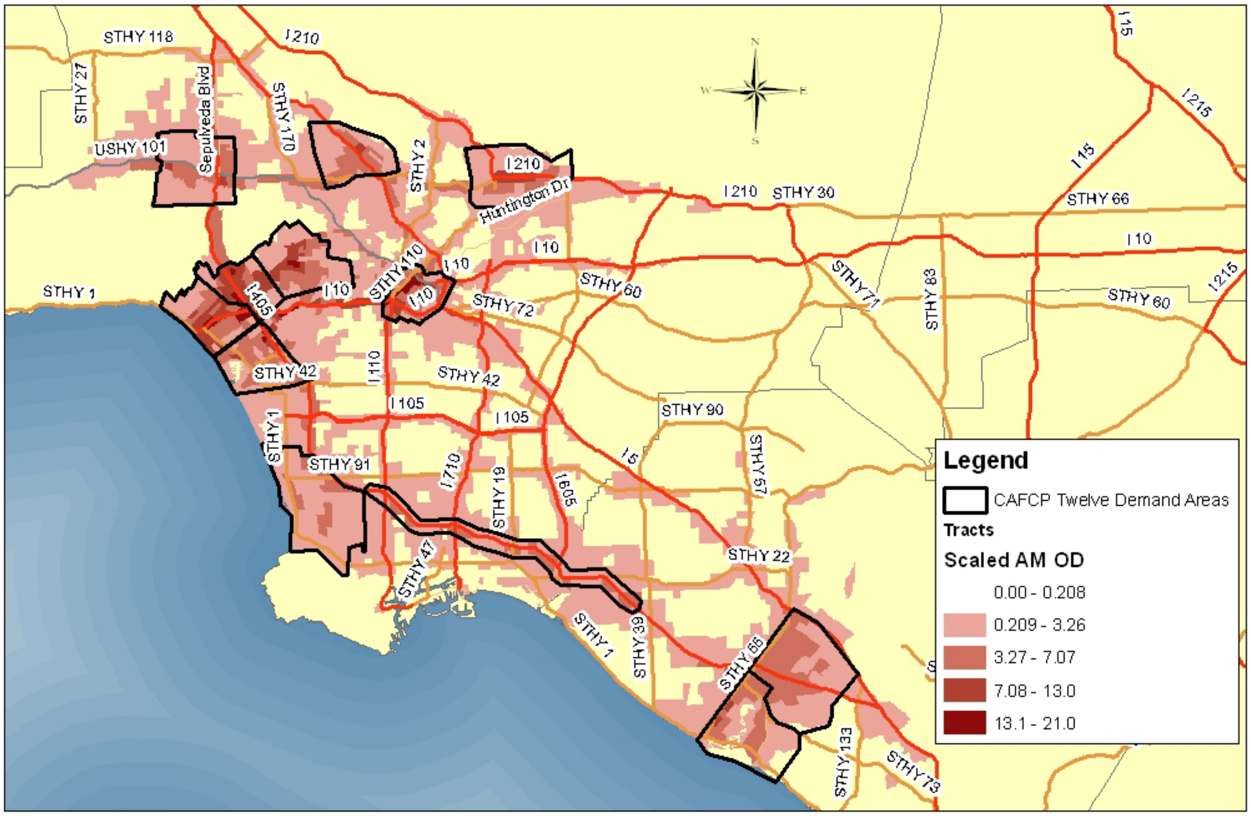

Figure 5 Relative VMT using only trips originating within the 12 clusters during the AM period. Data were aggregated to census tracts and display was normalized by tract land area.

Figure 5 shows how potential hydrogen vehicle traffic can be isolated for analysis. Because the size of the clusters varies, as does the number of trips originating from the zones, the number of trips is scaled so that an equal number of trips originate from each cluster. [6] Figure 5 represents using the traffic from all twelve clusters. Scenarios analyzing four clusters would only use the traffic from four clusters.

The rationale behind scaling is that we can weight the importance of the traffic by the number of vehicles projected to be placed in the cluster. This can be an equal distribution or can reflect the number of vehicles projected to be placed in a cluster as defined by a survey.

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[6] For example, if downtown Los Angeles actually had 200,000 trips, Irvine had 100,000 trips, and Burbank 50,000 trips originating from the respective clusters, each was scaled to have the same number of trips. If an equal distribution were desired and a number of 100,000 trips were the baseline, then the trips from downtown LA would be reduced by half, and the trips from Burbank would be doubled so that each area had only 100,000 trips originating from it.

Model Description

Refueling Within the Home Cluster

The travel time from home to the nearest station was chosen as a network evaluation metric since home appears to be a very strong indicator of refueling location preference.[7] Providing refueling around a customer's home area is likely an important feature of a convenient hydrogen refueling network. Using the p-median model (Hakimi, 1964, Hakimi, 1965) whose use in station siting is described in another paper (Nicholas et al., 2004), stations were sited to minimize the average travel time from home to the nearest station for all potential customers in the clusters.

Refueling Outside a Home Cluster

To address refueling away from home, regional connector stations outside of any of the designated clusters are needed. These stations facilitate travel to destinations farther away or provide flexibility in how refueling is incorporated into traveling around the larger region. The homes where the vehicles are located do little to inform where additional stations are needed. Instead, the distribution of VMT (Figure 5) reflects where customers in the clusters go. Using the VMT of traffic originating in the AM from the clusters as weighting factors for a p-median model, a network of stations to serve traffic outside the clusters is obtained.

The model minimizes the average travel time from a vehicle mile traveled to the nearest station for all vehicle miles traveled. This called the "***diversion time***". Weighting by VMT scales the tract values to match the chance that a vehicle originating from a cluster will be in a tract. In essence, this simulates the situation where a customer suddenly realizes he or she needs fuel, and then looks to find a station nearby. This is as opposed to a customer carefully planning fuel consumption and always refueling near home before longer trips. In reality, the situation may be a combination of these situations: a customer may realize he or she needs fuel and decides how to incorporate refueling into the present trip path. The closest station may not be chosen over a more distant station if the more distant station is on the trip path. Flow capture models can be used to analyze this situation. Nevertheless, using the p-median model with VMT as a weighting factor does take the trip path location into account and so should provide reasonably good results.

Scenarios

Different combinations of clusters and stations (Table 2) were evaluated on both home to station time and diversion time. The scenarios do not take into account the planned and existing stations. This analysis can be seen in Appendix A.

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[7] One study by Kitamura and Sperling shows that of 1521 drivers surveyed while refueling, home was the origin or destination for 74.8 percent of them.

Table 2 Cluster scenarios analyzed with the number of stations in the scenarios.

	Total Stations				
Clusters	8 Total Stations	16 Total Stations	20 Total Stations	30 Total Stations	42 Total Stations
4 Clusters	Yes	Yes	Yes		
6 Clusters		Yes	Yes		
8 Clusters		Yes		Yes	
12 Clusters				Yes	Yes

The cluster scenarios are designed to illustrate the tradeoffs of more versus fewer stations and to compare the results of using varying numbers of clusters.

The clusters chosen for the scenarios were based on the locations vehicle manufacturers see potential customers (see Figure 2). This means the stations follow the market rather than the markets being defined by station location. Importantly, the clusters analyzed are not a result of selection by the model. The cluster scenarios are shown in Table 3 and in Figure 2.

Table 3 Clusters used for scenarios.

4 Cluster Scenario	6 Cluster Scenario	8 Cluster Scenario	12 Cluster Scenario
Irvine	Irvine	Irvine	Irvine
Santa Monica	Santa Monica	Santa Monica	Santa Monica
Newport Beach	Newport Beach	Newport Beach	Newport Beach
Torrance	Torrance	Torrance	Torrance
	Downtown LA	Downtown LA	Downtown LA
	Burbank	Burbank	Burbank
		West Hollywood	West Hollywood
		Pasadena	Pasadena
			West LA
			LAX
			I 405 Corridor
			San Fernando Valley

RESULTS

On the basis of average travel time to the nearest station, each individual cluster shows a similar pattern: the first few stations provide large decreases in travel time, but with diminishing returns for each station added (Figure 6).

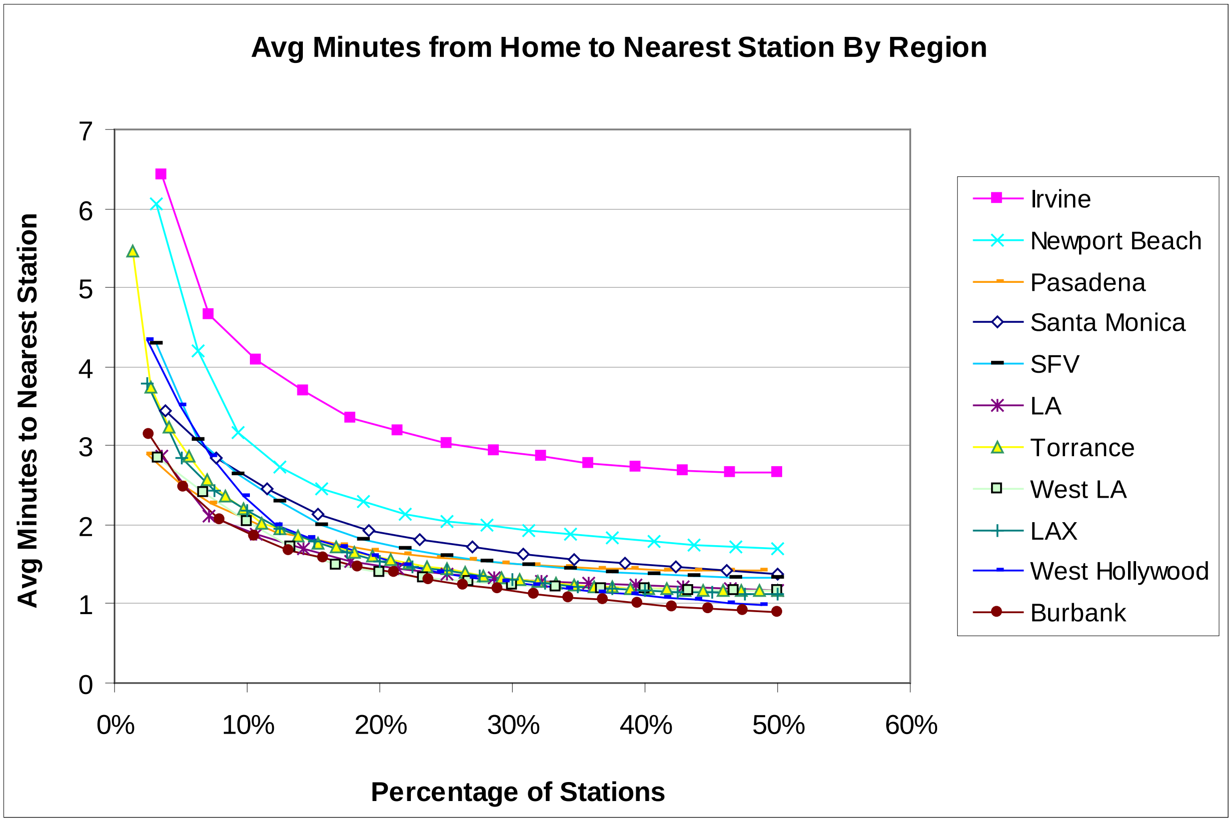


Figure 6 Due to the varying number of stations per cluster, the average minutes to the nearest station is plotted as a function of the percentage of gasoline stations that offer hydrogen. Each dot signifies a hydrogen station. One station is signified by the leftmost dot in each line. Subsequent dots signify additional stations. Irvine, as defined by the cluster boundary, shows poorer access to fuel than other clusters. If there were 50% as many hydrogen stations as gasoline stations, most clusters would average a little over a minute to the nearest station.

Figure 6 shows that each cluster is different and that if the physical size of the cluster increases, more stations are needed to achieve the same average travel time. For example, due to cluster size and road access, one station in Irvine results in a 6.5 minute travel time to the nearest station whereas one station in Downtown LA results in a 3 minute average travel time.

Scenario Results

The numbers of clusters and stations in Table 2 are applied to the clusters in Table 3 and are evaluated on travel time and diversion time as defined in the model description above. The four cluster examples in Figure 7 and Figure 8 illustrate some of the advantages and disadvantages of clustering both vehicle placements and station locations. The “area wide” in the figures refers to the situation where the vehicles would be distributed throughout the Los Angeles basin based on the density of population. Areas of high population would have more vehicles than areas with less population, but there would be no clustering.

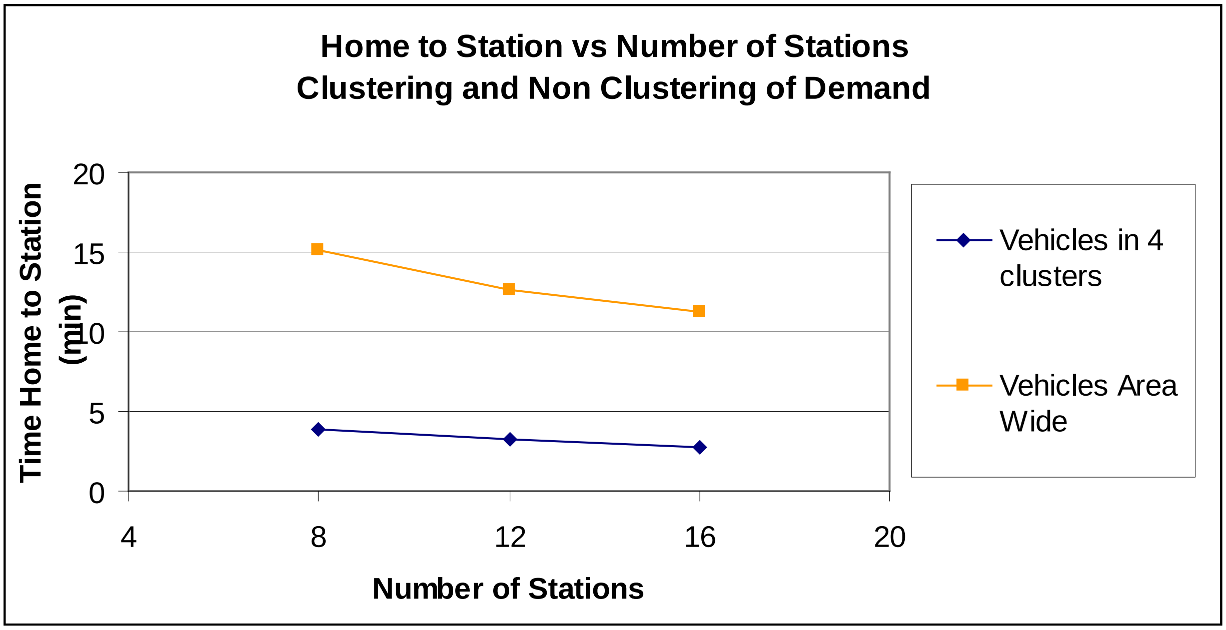


Figure 7 Clustering the placement of vehicles increases the effectiveness of a given number of stations when evaluating on the home to station travel time.

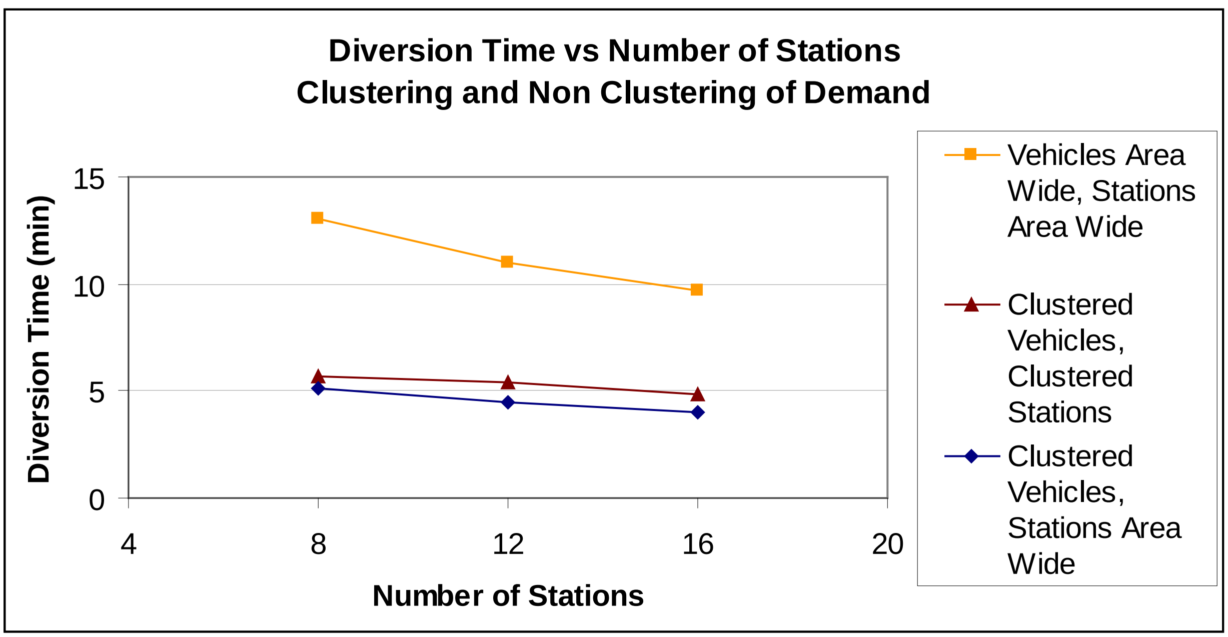


Figure 8 A similar benefit can be achieved in terms of diversion time by clustering vehicles. Focusing on only the traffic patterns of fuel cell vehicles reduces the diversion time with a given number of stations. Note that confining stations to clusters has a negative effect on diversion time.

The above figures show two general results. First, focusing demand in clusters rather than area wide enables greater convenience in terms of both travel time from home to station and diversion time. Second, placing stations only in clusters negatively impacts diversion time. (We want to be able to put connector stations outside the clusters to reduce diversion time.) Even though the difference between only siting in clusters and unrestricted siting is slight, a few well placed stations outside the clusters have a comparatively greater effect in decreasing diversion time than packing more stations into a cluster.

Hybrid Approach

Focusing solely on minimizing time from home to station can be at the expense of minimizing diversion time and vice versa. This is because people travel outside their home area and during those times, they would not be near a station. Similarly, focusing on travel patterns may tend to site stations away from home. However, focusing solely on travel patterns would not necessarily attract all stations out of the cluster since many trips are local trips. These local trips attract station development in the model. Nevertheless, to ensure local availability of stations near home, a hybrid approach is suggested. The hybrid approach suggests that there should be a minimum of two stations in a cluster (with some caveats mentioned below) sited based on home to station travel time, and an additional number of stations sited based on diversion time.

Based on conversations with stakeholders, we assume that at a minimum, there should be two stations in a cluster for redundancy. This is a minimum and for larger clusters, two stations may not provide parity with other clusters and the cluster size needs to be reduced (vehicle locations should be limited to a smaller part of the cluster), or the number of stations needs to be increased. Cluster shape can also be changed to more closely align with roads that connect to stations. In this way cluster boundaries are shaped by the time it takes to get to a station rather than by an arbitrary circle. Each cluster could be a different shape and size depending on the road access connecting customers to a station. The cluster boundaries as drawn in Figure 2 are only a suggested boundary, so changing cluster shape and size is in keeping with the intent of the cluster strategy

Once demand near home is satisfied providing some redundancy, reliability and convenience, station locations can be determined based on diversion time, increasing regional mobility for those living in the clusters. Using this paradigm of satisfying demand near home and also siting for regional mobility yields better results than confining stations to clusters. An example of the results of a hybrid approach is shown in Figure 9.

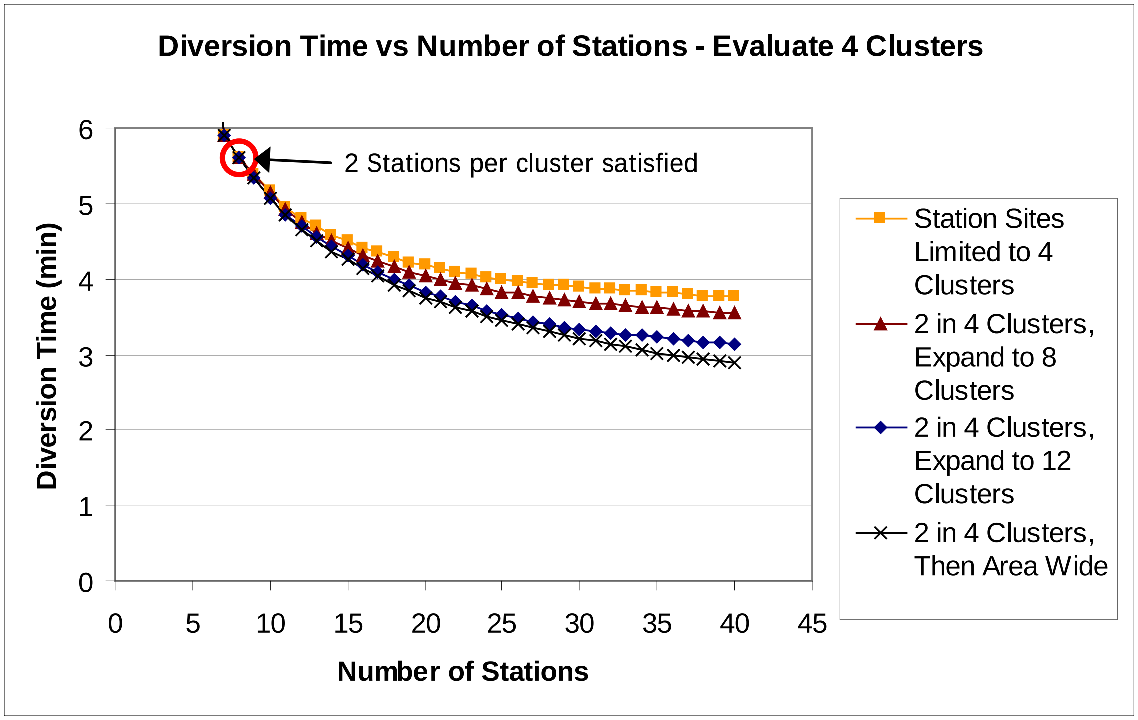


Figure 9 Diversion time is reduced if stations outside clusters are permitted. In this example, two stations per cluster are the minimum to provide some redundancy in the local network. The effect of opening up more areas for station sites has the effect of reducing diversion time.

Table 5. Average travel time from home to station and average diversion time for scenarios.

	2009-2011 636 HFCVs; Ave. H2 Demand 445 kg/d; Total Sta. capacity 636 kg/d				2012-2014 3442 HFCVs; Ave. H2 Demand 2410 kg/d Tot. Sta. cap. 3442 kg/d				2015-2017: 25,000 FCVs
Scenario	1	2 (2a)	3	4 (4a)	5 (5a)	6 (6a)	7 (7a)	8 (8a)	9 (9a)
# stations	16	12 (16)	16	8 (16)	16 (20)	18 (20)	24 (30)	24 (30)	36 (42)
Station location and layout	8 clusters 2 stations per cluster	6 clusters, 2 sta per cluster + (4 connector stations)	4 clusters, 4 sta. per cluster	4 clusters, 2 stations per cluster (+ 8 connector stations)	4 clusters, 4 stations per cluster (+ 4 connector stations)	6 clusters, 3 sta per cluster+ (2 connector stations)	8 clusters, 3 sta/cluster (+ 6 connector stations)	12 clusters, 2 sta/cluster (+ 6 connector stations)	12 clusters, 3 sta/cluster (+ 6 connector stations)
Ave time home to station in min.	3.2	3.5 (3.5)	2.8	3.9 (3.8)	2.8 (2.8)	2.9 (2.9)	2.7 (2.7)	3.2 (3.0)	2.6 (2.6)
Ave diversion time in min.	5.1	5.2 (4.4)	4.8	5.6 (4.1)	4.8 (4.1)	4.8 (4.5)	4.6 (3.9)	4.4 (3.9)	4.0 (3.6)

Figure 9 depicts four ways to address diversion time in a four cluster scenario: stations can continue to be sited in the four clusters, the stations can be sited in any of the 8 clusters, in any of the 12 clusters, or the stations can be placed anywhere in the region. Maps showing some of these placements are shown in Appendix A. The scenario expanding to eight or twelve clusters but using the traffic from only four clusters is an attempt to look at how to transition from one stage to the next. In this case, pursuing a strategy of restricting stations to the next potential clusters where vehicles will be deployed results in increases in convenience as measured by diversion time. The six, eight and twelve cluster hybrid scenarios show much the same result: restricting stations to clusters sacrifices some regional access.

Using the scenarios postulated earlier in the report (reproduced in Table 5), we can compare the hybrid approach to the approach of siting stations only in clusters. The parentheses in the average times below indicate siting connector stations outside of clusters. Home to station times and diversion times not in parentheses show the cluster only siting.

The effect that cluster selection can have on average time to station can be seen by comparing scenarios one, two and four (home to station times of 3.2, 3.5, and 3.9 minutes respectively). If all clusters were equal in size and access, the average travel time to station would be equal since there two stations per cluster in each scenario. However, as shown in Figure 6, having two stations per cluster does not garner the same result for each cluster. In the case of the scenarios above, Irvine's longer travel time to the nearest station has a greater effect on average travel time as the number of clusters is reduced. This points to an important result. Care should be taken when selecting customers so that they are close to a station. Irvine is not an inherently poor choice to deploy hydrogen vehicles, but care must be taken to site customers near the stations.

The tradeoff between placing more stations in a cluster versus adding more connector stations can also be seen in the scenarios. This is shown most clearly in scenarios 3 and 4a (home to station times 2.8 minutes and 3.8 minutes respectively and diversion time of 4.8 versus 4.1 minutes). Each scenario has 16 stations and four clusters, but the tradeoff is whether to focus on increasing local convenience (home to station) or to make regional travel easier. Eight connector stations results in a 0.7 minute drop in diversion time, whereas placing those eight stations in clusters decreases home to station time by about a minute.

Survey evidence (Nicholas and Ogden, 2008) suggests that regional accessibility is very important. Although regional accessibility is important, no research has been done on how to value diversion time versus home-station travel time. Consequently it is hard to assess whether the 0.7 minute drop in diversion time is more or less important that the 1 minute drop in home-station time. However, adding connector stations as in 4a instead of cluster stations as in scenario 3 results in more parity between the home to station time and the diversion time (3.8 minutes and 4.1 minutes respectively). This is in contrast to the disparity between home to station time and diversion time when siting only in clusters (2.8 minutes and 4.8 minutes respectively)

The effect on consumer convenience of having more versus fewer clusters can be seen in scenarios 1 and 4a. The time from home to station should be equal since their number of stations per cluster is equal. This inequality is due to the factors discussed above (Irvine has a comparatively large average home to station time). Assuming two stations per cluster is equivalent, the choice becomes whether to invest capital increasing regional availability for two clusters or to expand the number of clusters from four to eight. On the one hand more clusters increase exposure to the technology. On the other hand, increasing exposure may do no good if there is a poor consumer experience due to lack of regional availability. Within this model framework, the analysis suggests that customers may better served by expanding connector stations over expanding the number of clusters.

SPATIAL ANALYSIS CONCLUSIONS

Clustering demand reduces the number of stations that are required to satisfy a given number of customers versus not clustering customers and stations. Starting with a small number of clusters appears feasible from a convenience perspective (as measured in travel time from home to station and diversion time), but providing some stations outside of those clusters provides better regional mobility. Putting fuel in all twelve clusters increases regional mobility, but it appears that some stations outside of the named clusters are important as well (See Appendix A). Although the majority of refueling is local, smaller stations that enable travel throughout the region, and perhaps in nearby regions provide flexibility in planning how to refuel, and ease the fear of running out of fuel.

Redundancy and reliability can be addressed in several ways. First, the number of stations can be increased. Second, backup capacity in the form of mobile refuelers can supplement the network when stations go down. Third, the redundancy and reliability concerns can be ameliorated with an integrated navigation and refueling information system.

The minimum number of stations per cluster in the scenarios is two to provide redundancy in the case of a station failure. However, the number of stations necessary for convenience in each cluster needs to be evaluated for every cluster separately. Generally customers are currently about one minute away from their nearest gasoline station. Two hydrogen stations in Downtown LA results in a 2.1 minute average time, whereas 2 stations in the Torrance cluster results in a 3.7 minute average time to a station. Creating parity in the number of minutes to the nearest station among regions may be more important than creating parity in the number of stations among regions. A closer look at parity can be seen in Appendix A. As mentioned before, the size of the area that vehicles are marketed could be reduced to bring parity in terms of travel time from home to station.

Varying the number of clusters from four to twelve presents some interesting tradeoffs given a fixed number of stations. Given 16 stations, and the choice of four, six, or eight clusters, the anomalous drop in home to station time because of Irvine notwithstanding, adding connector stations reduced diversion time more than adding new clusters.

However, it is recognized that adding stations where there are not future clusters presents a problem with finding partners to help site and construct the station. Stations sited not in future clusters may also not find a sufficient load to make them cost effective. Therefore a strategy of siting connector stations in future cluster may be the most effective strategy. Interestingly, using the traffic from the four cluster scenario, some connector stations fell into future market areas such as Downtown LA, West LA and the I-405 corridor pointing to a possible bridging strategy to progress from rollouts in one cluster to the next. More analysis of this bridging strategy can be seen in Appendix A.

More detailed analysis is needed as customer locations become more exact so that individual stations are sited to match those customer locations. More information on siting stations near customers homes can be seen in Appendix C.

COST ANALYSIS OF HYDROGEN ROLLOUT SCENARIOS

One of the key questions facing early hydrogen infrastructure is cost. In this section, we analyze the economics of alternative strategies for infrastructure build-up over the next decade. Hydrogen station costs (both capital costs and operating costs) are estimated for different station types and configurations, based on the scenarios in Table 1. A transitional cash flow analysis is conducted to estimate station investments needed over the next decade, to meet ZEV regulation requirements, and ultimately to bring hydrogen to cost competitiveness with gasoline.

Hydrogen Refueling Station Technology Description and Cost Data

To develop estimates of hydrogen refueling station costs, we reviewed the literature on both on near and long term hydrogen refueling station costs, and collected information during stakeholder interviews. There are various refueling station technologies that could be deployed in the 2009-2017 timeframe. Several types of stations are considered in this analysis (with potential station sizes):

- Mobile refueler stations (50-100 kg/d)
- Portable refueler stations with compressed gas truck trailer delivery (100 kg/d)
- Liquid H_2 stations with truck delivery (100 kg/d; 250 kg/d, 400 kg/d, 1000 kg/d)
- Onsite Steam Methane Reforming (SMR) stations (100 kg/d; 250 kg/d, 400 kg/d, 1000 kg/d)
- Onsite Electrolyzer stations (100 kg/d; 250 kg/d, 400 kg/d, 1000 kg/d)

For 2009-2011, we consider 100 kg/day stations; from 2012-2014, we consider placements of 100, 250 or 400 kg/day stations. For 2015 and beyond, we also consider 1000 kg/day stations.

Mobile Refueler Stations

A mobile refueler station consists of high-pressure gaseous hydrogen storage (mounted on a truck trailer), a compressor (optional) and a dispenser. The hydrogen storage truck trailer is towed to and from hydrogen production facilities so that the hydrogen tanks can be refilled when needed. This type of hydrogen supply is being used in several sites in California. Mobile refuelers are self-contained on the truck trailer (see Figure 10a). This allows refueling sites to be added or changed rapidly as the need arises.

Portable Refueler Stations (Compressed Gas Truck Delivery)

Alternatively, "portable" refueler stations could have a compressor and dispenser mounted into a separate trailer located at the station. Compressed hydrogen is delivered by truck in a tube trailer and connected to the compressor/dispenser system (Figure 10b). These stations are "portable" in the sense that these could be moved to another site in an upgrade.

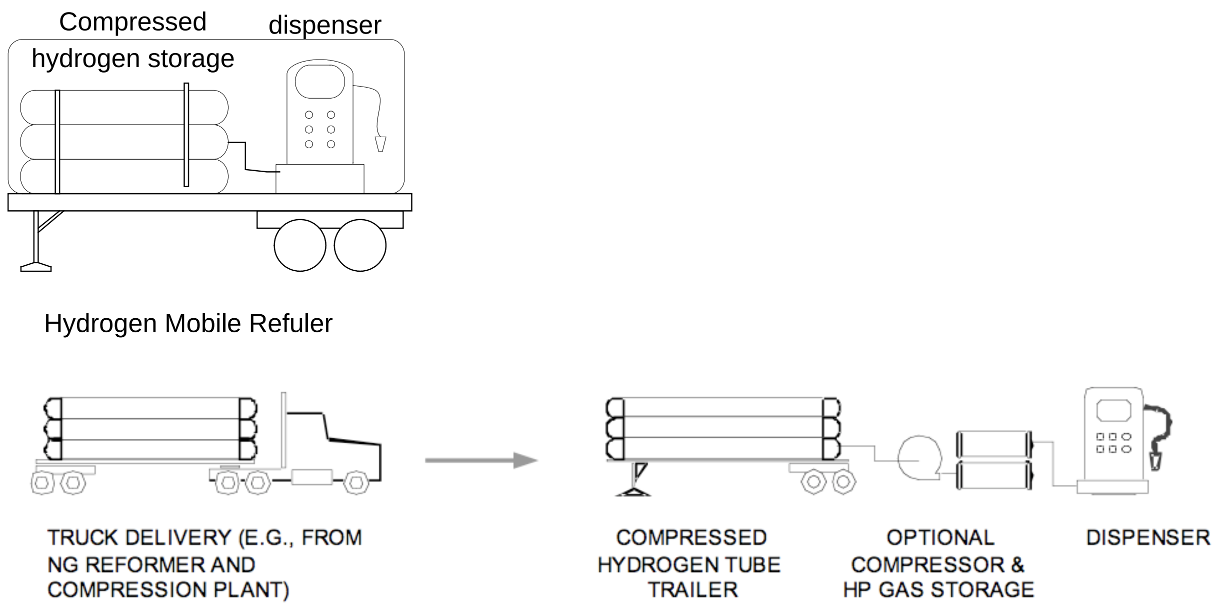


Figure 10 Mobile refueler hydrogen station (top 10a)
Portable refueler with compressed gas delivery, (bottom 10b).

Liquid H_2 Stations with Truck Delivery

Liquid H_2 (LH_2) refueling stations that take truck delivery of liquid hydrogen have the possibility of dispensing either liquid or compressed hydrogen. Most current stations have liquid delivery and storage, and dispense fuel as compressed H_2. A typical configuration of a LH_2 station that dispenses compressed H_2 is shown in Figure 11 below. Liquid H_2 is used for delivery and storage because of its relatively higher density than compressed H_2. It is converted to compressed H_2 since most current and planned fuel cell vehicles use compressed gas at either 350 or 700 bar storage pressure.

Liquid hydrogen has a relatively high density so that it is possible to transport approximately 10 times more hydrogen on a truck than when using compressed gas. This can significantly lower the delivered cost of H_2, especially when transport distances are moderate or long. In the longer term (beyond the scope of this project timeframe), pipelines will also be a competitive method for transporting hydrogen, and can significantly lower costs and energy use associated with transporting hydrogen if large volumes (associated with supplying hundreds or thousands of stations) are needed (Yang and Ogden 2007).

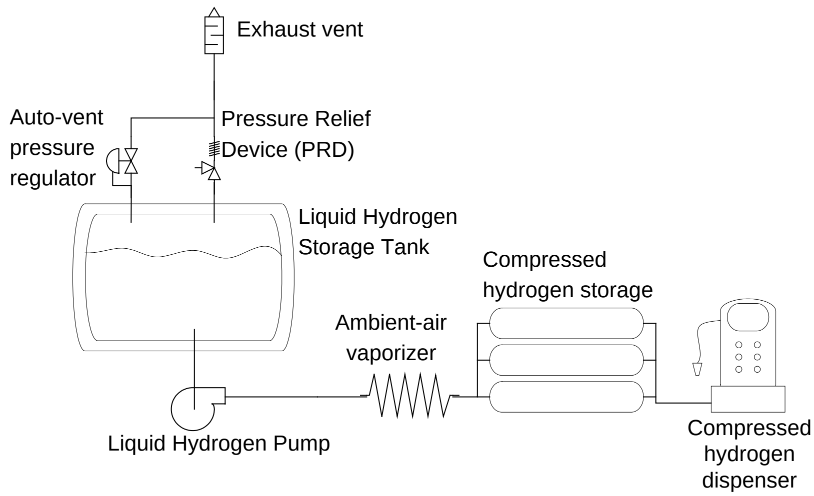


Figure 11 Liquid hydrogen station dispensing compressed gas.

The key components of the system are the LH_2 storage tank with safety equipment to prevent overpressures from boil-off, and the cryogenic hydrogen pump and vaporizer, which conserve energy by pumping a liquid to pressure before vaporizing rather than compressing a gas. Once hydrogen is vaporized, it can be compressed further before dispensing onto a compressed gas vehicle.

Onsite Steam Methane Reforming (SMR)

Several recent studies indicate that distributed (or onsite) production of hydrogen from natural gas at refueling stations is an attractive option for early hydrogen supply to vehicles. Onsite production avoids the cost and complexity of hydrogen delivery. Hydrogen is produced in a small-scale Steam Methane reformer (SMR), which is located at the station. Distributed production also requires less capital investment than central production, which would be useful during a transition to hydrogen vehicles. Also included at these stations, are H_2 compressors, storage tanks, and fuel dispensing equipment. A number of companies have developed small SMR systems ranging in size from tens to several hundred kilograms per day. It is likely that larger onsite reformers in the range of 1000 kg/d will become available over the next 5 years.

Figure 12 shows a sketch of an onsite SMR system.

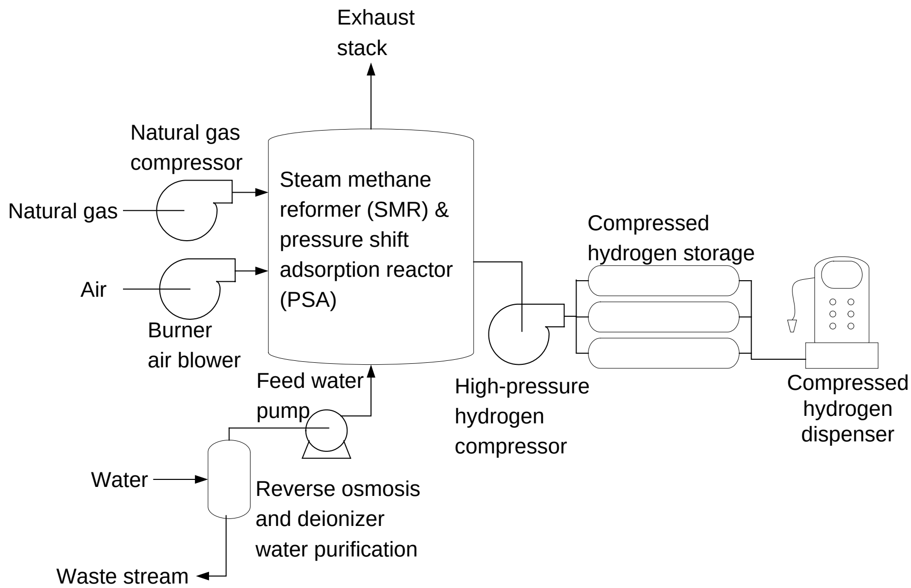


Figure 12 Hydrogen refueling station employing a small-scale steam methane reformer.

Onsite Electrolysis Station

Onsite electrolysis stations can use either grid power or a dedicated renewable electricity source (or combination of the two) to produce hydrogen via electrolysis using water as a feedstock. For this station type, we assume either grid electricity or solar photovoltaic (PV) electricity.

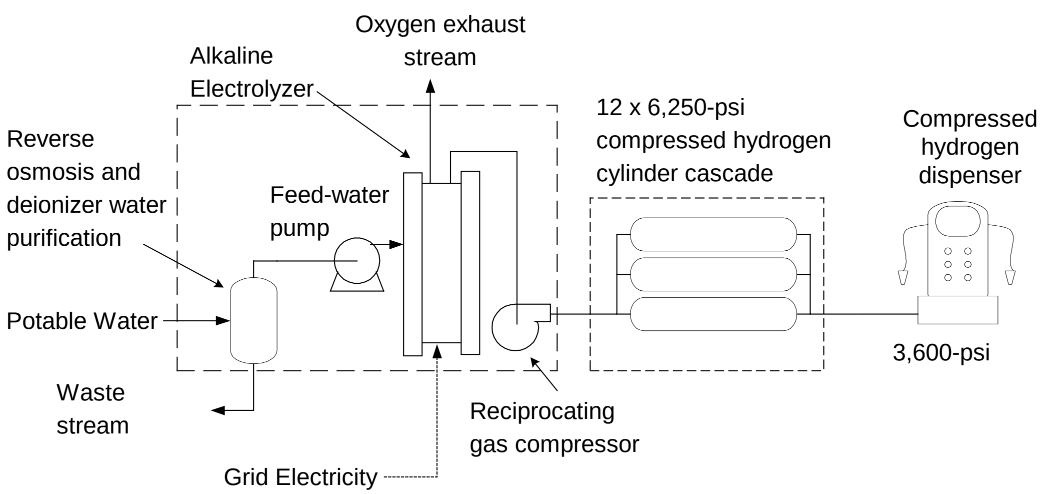


Figure 13 Hydrogen refueling station employing a small-scale electrolyzer.

Summary of Station Costs

For our scenario analysis we make the following assumptions about the capital costs of hydrogen stations over time (see Table 6). More details on station cost assumptions are in Appendix B.

We assume that mobile refuelers have a capital cost of $1 million through 2014, with the cost reduced to $0.4 million after 2015.

For fixed stations (all station types except mobile refuelers), we assume that it costs $2 million for site preparation, permitting, engineering, utility installation, and buildings, for a green-field station site before any fuel equipment goes in. This $2 million is the "baseline cost" for any type of refueling station, independent of the fuel (e.g. it would be the same for a new gasoline station). For hydrogen stations, hydrogen equipment costs are added to this baseline.

2009-2011: we assume that mobile refuelers cost $1 million, and that fixed 100 kg/d stations cost $3-4 million. These costs are higher than H2A estimates or estimates by Weinert et al. (2006, 2007), but are consistent with current station costs reported in interviews with energy industry stakeholders. One reason for the high cost is that these stations are essentially "one of a kind" or "few of a kind" projects.

2012-2014: we assume that the costs for refueling stations in the size range 100-400 kg/d are the baseline $2 million plus hydrogen equipment costs that are twice the H2A "current technology" values. [8]

2015-2017: we analyze two cases. In the "low cost" case, we use a $2 million baseline plus equipment costs based on H2A "current technology" numbers. In the "high cost" case, we use the same station costs as in 2012-2014.

It is important to note that these costs are higher than those used in some recent hydrogen transition analyses (H2A 2008, NRC 2008, DOE 2008).

Operations and Maintenance costs for hydrogen stations are given in Table 7. To find the annual variable O&M costs, prices are assumed for electricity (for compression or electrolysis at stations), natural gas (for onsite reformers), compressed hydrogen delivered to the station in mobile refuelers, and liquid hydrogen delivered to the station by truck (Table 8). Land rent is considered to be a fixed O&M cost. We use a land rent value of $5 per square foot per month, which is typical of the Los Angeles area. (This cost is about 10 times higher than the value used in H2A.)

[8] The rationale for choosing twice the H2A "current technology" equipment cost is as follows. H2A's costs are based on production of 500 stations per year. But in 2012-2014, we would expect many fewer stations to be produced. If we reduce annual station production by a factor of 50-100 (5 to 10 stations per year), the equipment capital cost should be about 2 times the H2A estimate according to studies by Weinert (2006). See Appendix B for details.

Table 6. Capital Costs for Hydrogen Refueling Stations (million $)

	2009-2011	2012-2014	2015-2017 (high)	2015-2017 (low)
Mobile Refueler 100 kg/d	**1.00**	**1.00**	**1.00**	**0.40**
Comp.Gas Truck Delivery 100 kg/d	**3.00**	**2.22**	**2.22**	**2.11**
LH2 Truck Delivery				
100 kg/d	**4.00**	**2.58**	**2.58**	**2.29**
250 kg/d		**2.67**	**2.67**	**2.33**
400 kg/d		**2.81**	**2.81**	**2.40**
1000 kg/d		**3.21**	**3.21**	**2.61**
Onsite Reformer				
100 kg/d	**3.50-4.00**	**3.18**	**3.18**	**2.59**
250 kg/d		**3.99**	**3.99**	**3.00**
400 kg/d		**4.81**	**4.81**	**3.41**
1000 kg/d		**7.76**	**7.76**	**4.88**
Onsite Electrolyzer				
100 kg/d	**-**	**3.22**	**3.22**	**2.61**
250 kg/d		**4.21**	**4.21**	**3.11**
400 kg/d		**5.25**	**5.25**	**3.63**
1000 kg/d		**9.26**	**9.26**	**5.63**

Table 7. Summary Operations and Maintenance Costs for Hydrogen Refueling Stations

	Variable O&M	Fixed O&M
Mobile Refueler	**Compressed H2 supply** $20/kg H2	100 kg/d: 13 % cap.cost /y + $130,000/y (land rental)
Portable Refueler (Compressed Gas H2 Truck Delivery)	**Compressed H2 supply + station H2 compression** $20/kg H2 + 1.25 kWh/kg H2 x electricity price $/kWh	100 kg/d: 13 % cap.cost /y + $130,000/y (land rental)
LH2 Truck Delivery	**LH2 supply+ station LH2 pump/compression** $10/kg LH2 + 0.81 kWh/kg H2 x electricity price $/kWh	100 kg/d: 11 % cap.cost /y + $130,000/y (land rental) 250-1000 kg/d: 11% cap.cost /y + $360,000/y (land rental)
Onsite Reformer	**NG feed + station H2 compression** 0.156 MBTU NG/kg H2 x NG price $/MBTU + 3.08 kWh/kg H2 x electricity price $/kWh	100 kg/d: 10 % cap.cost /y + $130,000/y (land rental) 250-1000 kg/d: 7% cap.cost /y + $360,000/y (land rental)
Onsite Electrolyzer	**Electrolyzer electricity + station H2 compression:** 55.2 kWh/kg H2 x electricity price $/kWh	Same as onsite reformer

Table 8. Assumed energy prices and economic assumptions

ENERGY PRICES	CURRENT PRICE
Natural Gas (Commercial rate)	$12/MMBTU
Electricity (Commercial rate)	$0.10/kWh
Compressed H2 (for mobile refueler)	$20/kg
LH2 (truck delivered)	$10-12/kg
Bio-Methane	$20-40/MMBTU
Ethanol	$2-4/gallon gasoline equivalent
Green Electricity premium	$0.01-0.05/kWh
Land rent (Los Angeles)	$5.0/sq.ft/month
ECONOMIC ASSUMPTIONS	
Real discount rate	12%
Equipment lifetime	15 years

Steady-state Cost Results

Before considering transitional costs, we compare the capital and operating cost for different individual station types and sizes, as technology evolves. Figure 14 shows the levelized cost of hydrogen for a range of station types and sizes for current (2009-2011) and future station technologies (2012-2014; 2015-2017) based on the costs in Tables 6 and 7.

To calculate the levelized cost, we assume that the station operates at "steady state" providing the same annual hydrogen production throughout its lifetime (constant capacity factor). We assume that the station lifetime is 15 years, and the real discount rate is 12% (the annual capital recovery factor is 15%).

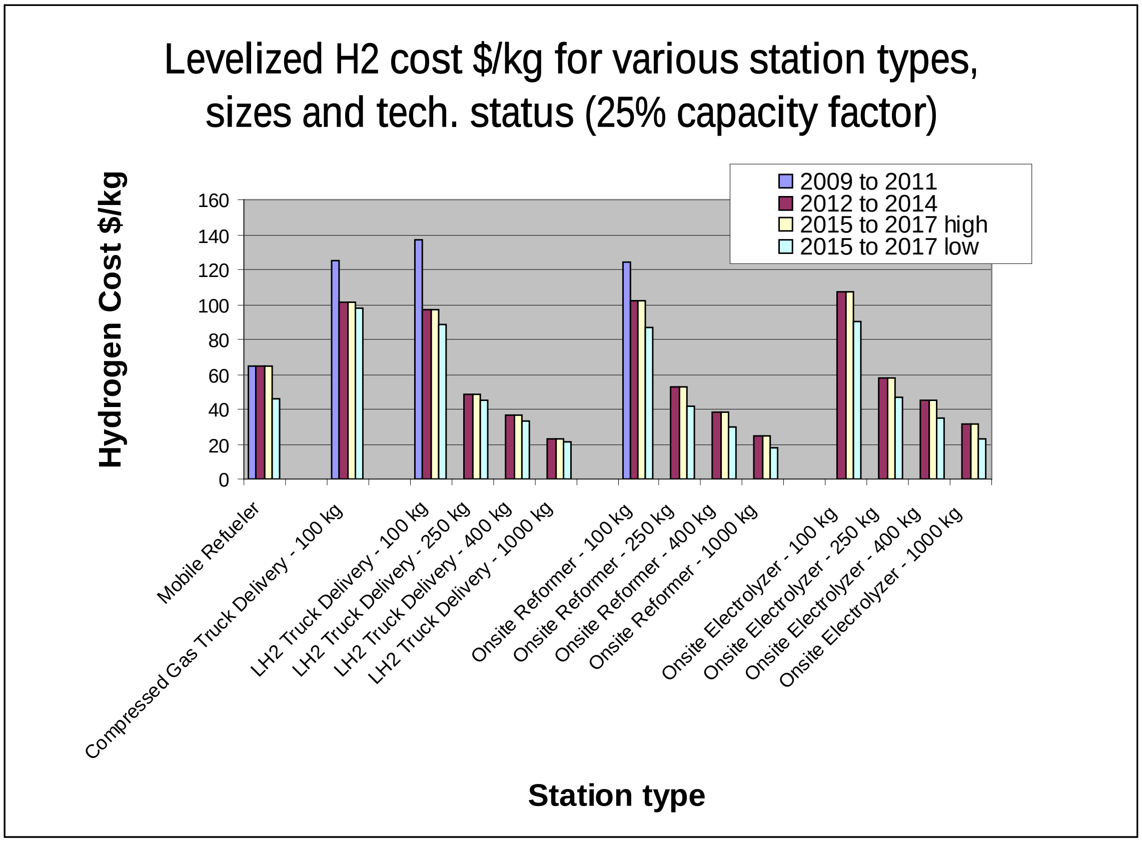
Figures 14a, b and c correspond to assumed capacity factors of 25%, 50% and 70%.

Several factors impact the levelized hydrogen cost.

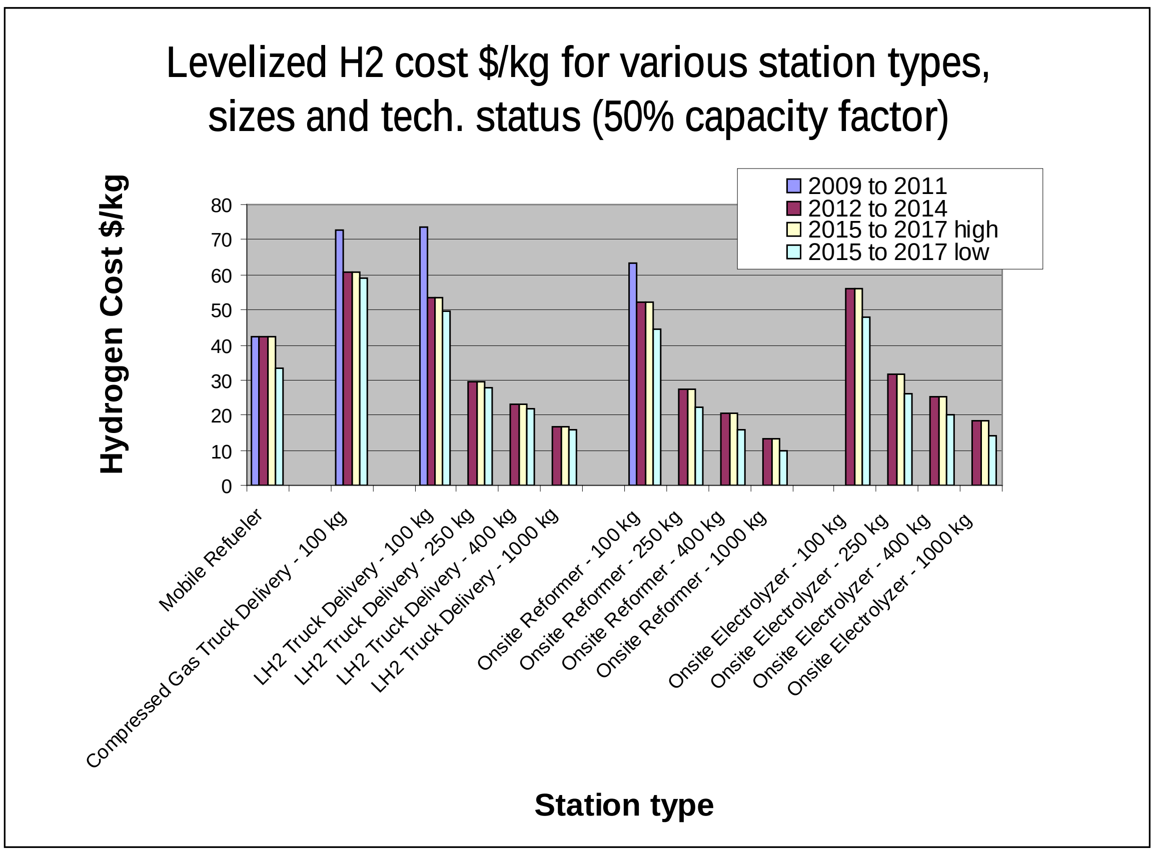
> First is technology status. For each station type and size (e.g. 100 kg/d onsite reformer), the hydrogen cost drops over time, as station technology improves. Initially, we assume only 100 kg/day stations are available.
>
> The size of the station impacts the cost. For each type of station (e.g. onsite reformer), the hydrogen cost decreases as the station size increases, because of scale economies in station capital costs.
>
> Finally, the assumed capacity factor has a significant influence on the levelized hydrogen cost. (Levelized hydrogen cost scales inversely with capacity factor.)

In the early years of developing an infrastructure, when technology is new, capacity factors are low (25-50%) and station sizes are small (100 kg/d), we would expect much higher hydrogen costs than for a large (1000 kg/d) fully utilized (70% capacity factor) station with more mature technology.

The estimated steady-state hydrogen costs shown above are significantly higher than H2A's estimates. There are several reasons for this: 1) we include a $2 million "baseline" cost for site-preparation appropriate for the entire station; 2) the cost of land rental is about 10 times that of H2A; 3) the costs of feedstocks like natural gas and electricity are relatively high in Los Angeles, 4) the assumed station equipment costs in 2015-2017 are higher than H2A's future costs.



Levelized H2 cost $/kg for various station types, sizes and tech. status (25% capacity factor)
2009 to 2011
2012 to 2014
2015 to 2017 high
2015 to 2017 low
Hydrogen Cost $/kg
160
140
120
100
80
60
40
20
0
Mobile Refueler
Compressed Gas Truck Delivery - 100 kg
LH2 Truck Delivery - 100 kg
LH2 Truck Delivery - 250 kg
LH2 Truck Delivery - 400 kg
LH2 Truck Delivery - 1000 kg
Onsite Reformer - 100 kg
Onsite Reformer - 250 kg
Onsite Reformer - 400 kg
Onsite Reformer - 1000 kg
Onsite Electrolyzer - 100 kg
Onsite Electrolyzer - 250 kg
Onsite Electrolyzer - 400 kg
Onsite Electrolyzer - 1000 kg
Station type



Levelized H2 cost $/kg for various station types, sizes and tech. status (50% capacity factor)
2009 to 2011
2012 to 2014
2015 to 2017 high
2015 to 2017 low
Hydrogen Cost $/kg
80
70
60
50
40
30
20
10
0
Mobile Refueler
Compressed Gas Truck Delivery - 100 kg
LH2 Truck Delivery - 100 kg
LH2 Truck Delivery - 250 kg
LH2 Truck Delivery - 400 kg
LH2 Truck Delivery - 1000 kg
Onsite Reformer - 100 kg
Onsite Reformer - 250 kg
Onsite Reformer - 400 kg
Onsite Reformer - 1000 kg
Onsite Electrolyzer - 100 kg
Onsite Electrolyzer - 250 kg
Onsite Electrolyzer - 400 kg
Onsite Electrolyzer - 1000 kg
Station type

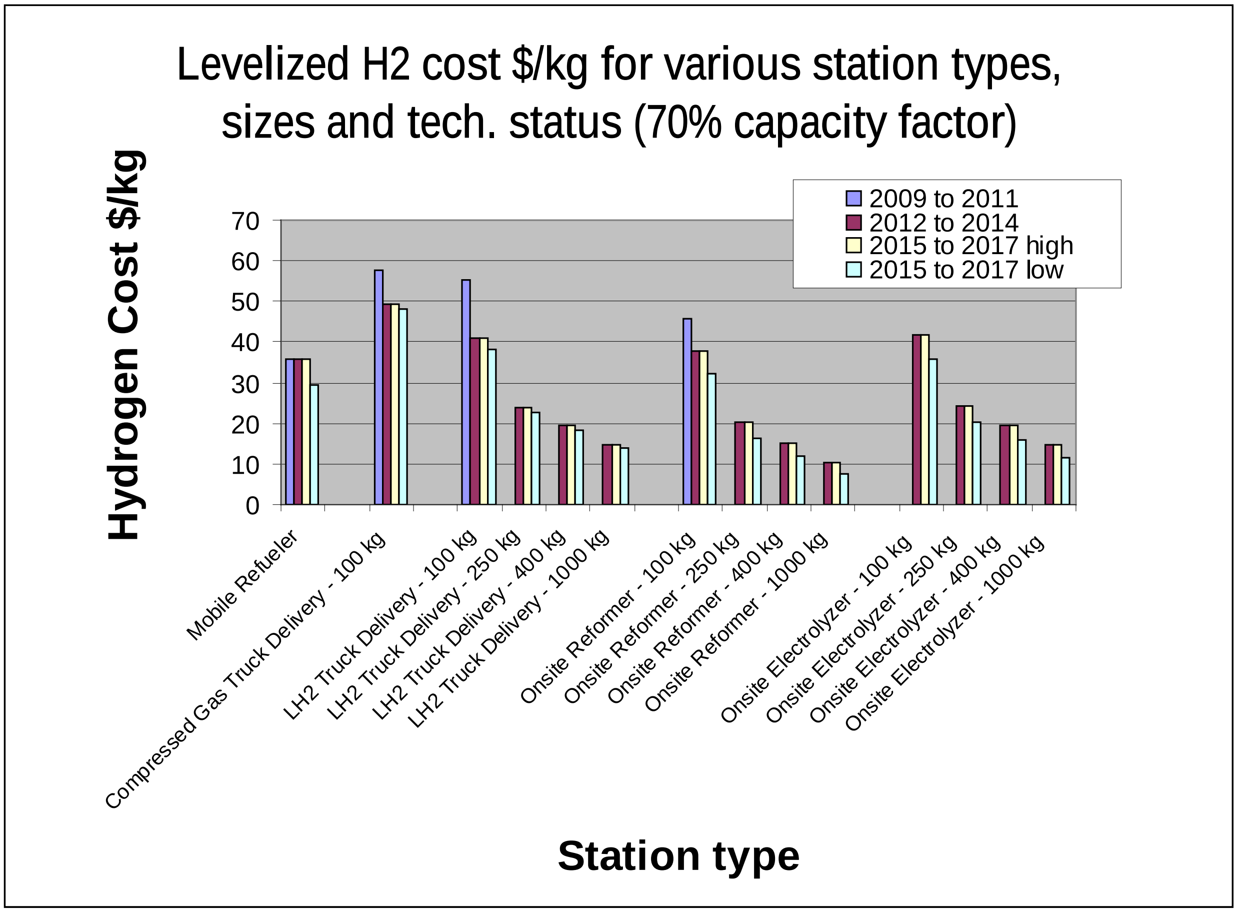


Figure 14 Levelized hydrogen cost from various station types, sizes and technology status. Station costs are from Tables 6 and 7. Three different capacity factors are shown: 25% (Figure 14 a - top); 50% (Figure 14b - middle), and 70% (Figure 14c - bottom).

Table 9. Assumed Station Mix for Various Scenarios

	2009-2011 636 HFCVs; Ave. H2 Demand 445 kg/d; Total Sta. capacity 636 kg/d				2012-2014 3442 HFCVs; Ave. H2 Demand 2410 kg/d Tot. Sta. cap. 3442 kg/d				2015-2017: 25,000 FCVs
Scenario	1	2 (2a)	3	4 (4a)	5 (5a)	6 (6a)	7 (7a)	8 (8a)	9 (9a)
# stations	16	12 (16)	16	8 (16)	16 (20)	18 (20)	24 (30)	24 (30)	36 (42)
Station location and layout	8 clusters 2 stations per cluster	6 clusters, 2 sta per cluster + (4 optimally located connector stations)	4 clusters, 4 sta. per cluster	4 clusters, 2 stations per cluster (+ 8 connector stations)	4 clusters, 4 stations per cluster + (4 opt. located connector stations)	6 clusters, 3 sta per cluster+ (2 opt. located connector stations)	8 clusters, 3 sta/cluster (+ 6 opt. located connector stations)	12 clusters, 2 sta/cluster (+ 6 opt. located connector stations)	12 clusters, 3 sta/cluster (+ 6 opt. located connector stations)
Station Mix	8 portable (50-100 kg/d) 8 fixed (SMR 100 kg/d)	6 (10) portable (50-100 kg/d) 6 fixed (SMR; 100 kg/d) (+ 4 portable refuelers)	12 portable (50-100 kg/d) 4 fixed (SMR; 100 kg/d)	4 portable (50-100 kg/d) 4 fixed (SMR; 100 kg/d) (+ 8 portable refuelers)	8 (12) portable (100 kg/d) 8 fixed (SMR 400 kg/d) (+ 4 portable refuelers)	6 (8) portable (100 kg/d) 12 fixed (SMR 250 kg/d) (+ 2 portable refuelers)	16 (22) portable (100 kg/d) 8 fixed (SMR 400 kg/d) (+ 6 portable refuelers)	12 (18) portable (100 kg/d) 12 fixed (SMR 250 kg/d) (+ 6 portable refuelers)	4 (10) portable (100 kg/d) 12 fixed (SMR 250) kg/d) 20 fixed (1000 kg/d) (+ 46portable refuelers)

Transitional Cash Flow Analysis

We now develop cost estimates for building up early hydrogen infrastructure over time, based on the scenarios in Table 5. We combine scenarios to describe a transitional station rollout from 2009-2017. We estimate the cash flow over time, and the investments required to build up an early, clustered hydrogen infrastructure.[9] We choose a mixture of station sizes and types for each scenario (Table 9). One constraint is that each cluster must have at least one "fixed" station, for customer attractiveness, although other stations within the cluster can be mobile refuelers. Connector stations are assumed to be mobile refuelers. The average station size grows over time, as more vehicles are introduced and hydrogen demand grows. In the table below, we assume that fixed stations are onsite SMRs, as these offer the lowest hydrogen costs (see Figure 14).

Pathway 1: **4 Cluster Rollout**; Start with a relatively limited geographic focus (4 clusters) and a small number of stations (8 stations) and expand to more clusters.

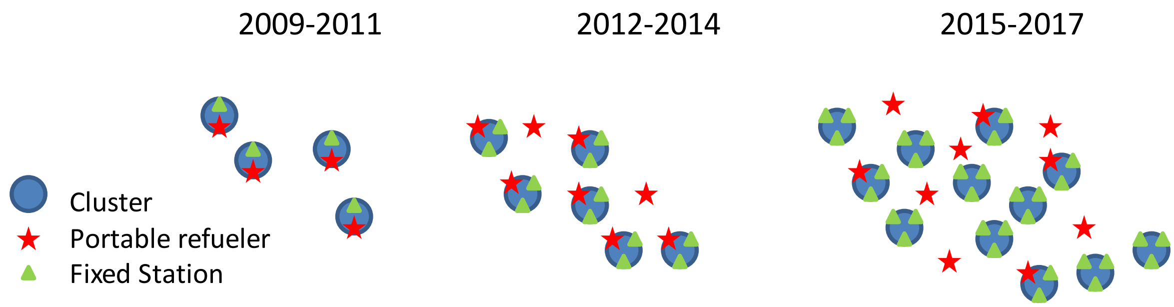
[9] An additional transition pathway is analyzed in the Appendix. The number of fuel cell vehicles in Southern California is expected to increase from an estimated 636 in 2011 to 3442 by 2014. This has an effect on station placements and sizes of stations. To have adequate capacity for the next phase, stations can be oversized for the 2009-2011 phase, or capacity can be added in the form of additional stations in the 2012-2014 phase. This has an implication for cost, and land availability.

2009-2011 -> 2012-2014 -> 2015-2017
Scenario 4 -> Scenario 6a -> Scenario 9a
4 clusters -> 6 clusters -> 12 clusters
8 stations 20 stations 42 stations

2009-2011: Pathway 1 starts with 8 stations, serving 636 FCVs, located in 4 clusters of 2 stations each. Four of the stations are fixed (100 kg/d SMRs), the other 4 are mobile refuelers. The average travel time from home to station is 3.9 minutes and the diversion time is 5.6 minutes. The total capital cost for this phase is $20 million, and annual operating costs are about $5 million per year. To pay back only operating costs, hydrogen would have to sell for $45/kg. To cover the full annualized cost (including capital), hydrogen would have to sell for about $77/kg.

2012-2014: In 2012, we expand the network to 20 stations, serving 3442 FCVs, located in 6 clusters of 3 stations each, plus 2 connector stations. The new stations include 4 additional 100 kg/d mobile refuelers plus 12 250 kg/d SMRs. The capital investment during this phase is $52 million, and annual operating costs are about $11-14 million/year. To pay back only operating costs (for the entire network) hydrogen would have to sell for $20/kg. To cover the full annualized cost (including capital from both 2009-2014), hydrogen would have to sell for about $37/kg. The average travel time from home to station is 2.9 minutes and the diversion time is 4.5 minutes.

2015-2017: In 2015, we expand the network to 42 stations, serving 25,000 FCVs located in 12 clusters of 3 stations each, plus 6 connector stations. The new stations include 20 1000 kg/d SMRs. The capital investment during this phase is $98 million, and annual operating costs are about $30-40 million/year. To pay back only operating costs hydrogen would have to sell for $8/kg. To cover the full annualized cost (including capital from 2009-2017), hydrogen would have to sell for about $13/kg. The average travel time from home to station is 2.6 minutes and the diversion time is 3.6 minutes.



	636 FCVs	3442 FCVs	25,000 FCVs
# Stations	8	20	42
# clusters	4 (2 sta/cluster)	6 (3 sta/cluster)	12 (3 sta/cluster)
# connect.sta	0	2	6
Station Mix	4 Portable refuelers 4 SMRs (100 kg/d)	8 Portable Refuelers 12 SMRS (250 kg/d)	10 Portable refuelers 12 SMRs (250 kg/d) 20 SMRs (1000 kg/d)
New Equip. Added	4 Portable refuelers 4 SMRs (100 kg/d)	4 Portable Refuelers 12 SMRS (250 kg/d)	2 Portable refuelers 20 SMRs (1000 kg/d)
Capital Cost	$20Million	$52 Million	$98 Million
O&M Cost	3-5$Million/y	11-14 $Million/y	30-40 $Million/y
H2 cost $/kg	77	37	13
Ave travel time	3.9 minutes	2.9 minutes	2.6 minutes
Diversion time	5.6 minutes	4.5 minutes	3.6 minutes

Figure 15 Summary of Transition Pathway 1.

Cash flows are plotted in Figure 16 for Pathway 1, assuming hydrogen is sold for $10/kg throughout the transition period (extended to 2025). The annual cash flow is negative through about 2015. The cumulative investment required is negative for the first 15 years (until 2025), but the strategy fully repays by about 2024. After that time, there is significant profit. A clustered early infrastructure costing about $170 million to build, pays for itself in about 15 years.

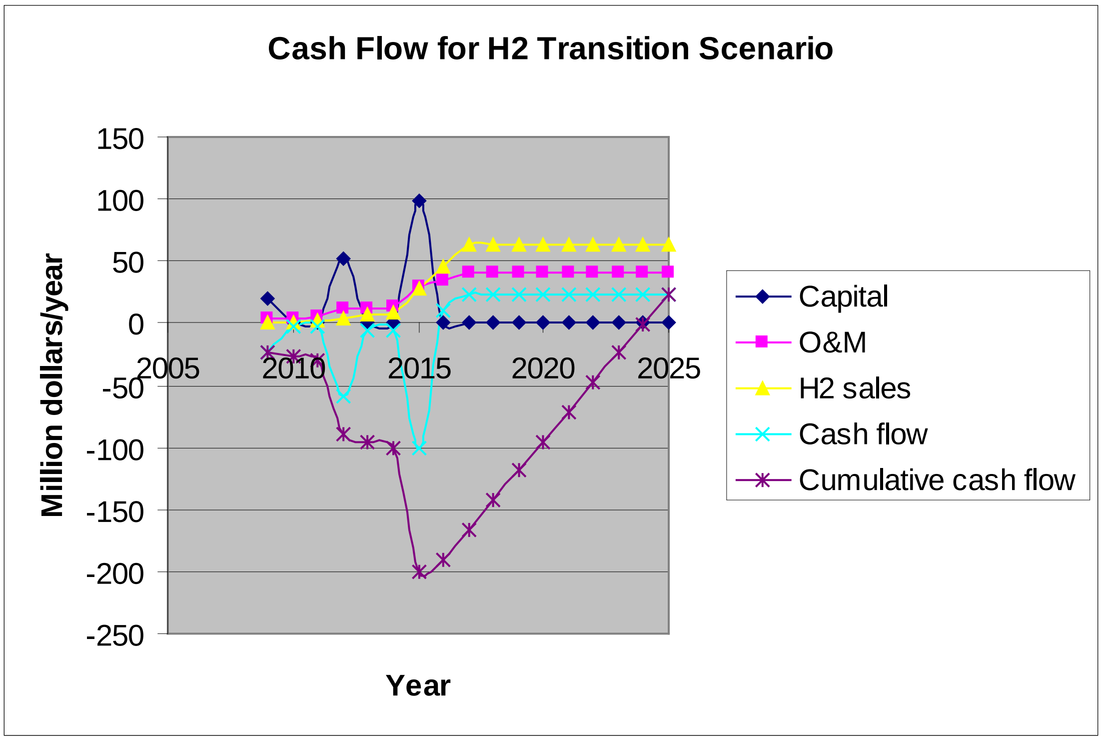


Figure 16 Cash Flow for Pathway 1 assuming that hydrogen is sold for $10/kg.

This transition pathway could be considered an introduction to a business case after 2017, when many more 1000 kg/d stations would be needed, if FCVs are successful in the market. These new 1000 kg/d stations could provide hydrogen at $5-6/kg (competitive on a cents per mile fuel cost basis with gasoline at $2.5-3/gallon), using H2A “near term” technology assumptions, and including $2 million baseline station costs and land rental at LA rates.

An alternative build-out strategy is analyzed in Appendix B, which begins with 8 clusters and 16 stations. This pathway is more costly in terms of capital costs for stations, but gives a somewhat lower average travel time. In general, there is a trade-off between cost (which is higher with more stations early on) and consumer convenience (which is greater with more stations).

Economics of Hydrogen Stations with Convenience Stores or Other Revenue Streams

In our cash flow calculations, we charge all the station capital and O&M costs against hydrogen fuel sales. In most gasoline stations today, fuel sales pay for only a fraction of station capital and O&M expenses. Convenience stores, repair shops and car washes are significant revenue streams for gasoline station owners. For a future hydrogen station with a convenience store or car wash, how much would the owner have to charge for hydrogen?

For a typical gasoline station, the baseline capital cost is $2 million plus $0.3-0.5 million for gasoline refueling equipment. For a gasoline station supporting a fleet of 1400 cars (similar in throughput to a 1000 kg/d hydrogen station), daily gasoline sales might be 2000-3000 gallons. We assume that the profit on each gallon of gasoline sold is 5 cents. So the daily revenue from gasoline sales might be $100 - $150 per day or $36,500 - $54,250 per year. Assuming the stations sells 1 kg H2 for each 2 gallons of gasoline that would have been sold (to account for the 2 X higher efficiency of FCVs versus gasoline cars), then we would need to make 10 cents profit per kg of hydrogen to break even, if hydrogen refueling equipment cost as much as a gasoline refueling equipment.

Of course, hydrogen station equipment costs more than gasoline equipment (to buy and to operate), and the hydrogen fuel sales must pay for this. If we pose a scenario where new hydrogen equipment is put in to replace gasoline fueling capacity, the cost of buying and operating the new hydrogen equipment must be paid for, plus $0.10/kg to replace the lost profit from sales of gasoline.

If convenience store sales carried some of the station costs, the required selling price of hydrogen during a transition could be several $ per kilogram less than our earlier estimates of $10-12/kg. For example, for our first transition scenario the capital costs directly related to hydrogen are reduced from $163 million (which counts the $2 million baseline cost plus hydrogen refueling equipment) to about $110 million (which counts only the hydrogen refueling equipment). The required selling price over the transition period is about $8/kg (to break even by 2025) instead of $10/kg, and the levelized cost of hydrogen from a new 1000 kg/d SMR station built in 2015-2017 is $5.2/kg (instead of $7/kg).

Each future hydrogen station will be unique, and some sites might not have room for a convenience store, especially if hydrogen storage takes up significant land area in the station. However, the required selling price for hydrogen could be lower than our earlier estimates, if the station was configured like today's gasoline stations with multiple revenue streams.

RENEWABLE HYDROGEN SCENARIOS

California requires that state-funded hydrogen stations derive 33% of the hydrogen from renewable sources. Once more than 10,000 kg per day are dispensed statewide, all new hydrogen stations must satisfy this requirement. We investigated the how the cost of hydrogen would be effected by the renewable requirement. Several near term renewable hydrogen sources were considered:

- Onsite Reformer using pipeline delivered bio-methane
- Onsite Reformer using biomass ethanol
- Onsite electrolysis (green electricity via grid)
- Onsite electrolysis (Solar PV at station)

Table 10 gives the assumed prices for renewable energy inputs for hydrogen production, based on various recent studies.

Table 10. Near Term Renewable Hydrogen Scenarios

RENEWABLE ENERGY INPUTS	PRICE	Source
"Green" electricity via grid for electrolysis	\$0.11-0.15/kWh (\$0.01-0.05/kWh premium)	NREL Survey of green electricity prices in the US
"Green" electricity (onsite PV) for electrolysis	\$0.39/kWh (intermittent, 22% capacity factor on electrolyzer)	This study
Renewable pipeline quality bio-methane delivered to station via short pipeline (5-12 miles)	\$20-40/MMBTU	CEC 2008; USDA 2003
Renewable ethanol delivered to station	\$2-4/gallon gasoline equivalent energy basis (NREL)	NREL 2008

Table 11 summarizes the results for different renewable hydrogen scenarios. Meeting the 33% renewable requirement after 2012 with 33% bio-methane blend in natural gas and 33% "green" grid electricity adds only 1-4% (\$0.1-0.4/kg) to the cost of hydrogen, for our assumptions.

With 100% biomethane used in an onsite reformer and 100% green grid electricity, hydrogen costs are \$1.2-4.2/kg higher (an increase of 12-42%).

Biomass ethanol is projected to cost \$2-4 per gallon gasoline equivalent energy, or about \$16-32/ MMBTU. The capital cost of a refueling station based on small scale reformation of ethanol should be similar to that for an onsite steam methane reformer. The reformer is similar conversion efficiency of the feedstock to hydrogen. Thus, using biomass ethanol in an onsite reformer should give similar hydrogen costs to using bio-methane (which we assume to cost \$20-40/MBTU).

Table 11. H2 cost Increment for Near-Term Renewable H2 Scenarios Compared to a Base Case Transition Scenario with w/Onsite SMRs using natural gas and conventional grid electricity.

Renewable Scenario	**H2 Cost Increment vs. Base Case Transition Scenario**
ONSITE SMR: 33% Renewable Biomethane + 33% Renewable Grid Electricity for compression	\$0.1-0.4/kg
ONSITE SMR: 100% Biomethane + 100% Renewable Grid Electricity for compression	\$1.2-4.2/kg
ONSITE SMR: 33% Bioethanol + 33% Renewable Grid Electricity for compression	\$0.1-0.4/kg
ONSITE SMR: 100% Bioethanol + 100% Renewable Grid Electricity for compression	\$1.2-4.2/kg
ONSITE ELECTROLYSIS: grid electricity, no renewables	\$4.2/kg
ONSITE ELECTROLYSIS: 33% Renewable Grid Electricity for electrolysis and compression	\$4.5-5.5/kg
ONSITE ELECTROLYSIS: 100% Solar PV Electricity for Electrolysis and Compression	\$20/kg

Even without an added cost for renewable electricity, hydrogen from onsite electrolysis is about \$4.2/kg costlier than hydrogen from onsite reforming. Electrolysis with 33% green grid electricity is about \$5/kg more costly than hydrogen from our transition base case using onsite SMRs. Hydrogen from 100% solar photovoltaic powered electrolysis is about \$20/kg more expensive.

In the near term, onsite reforming of either bio-methane or bio-ethanol appear to be the most attractive renewable routes in terms of hydrogen cost. Initially, because of the small number of hydrogen cars on the road, the total amount of bio-methane needed is small. Beyond 2017, availability of low cost bio-methane might become an issue, due to competition for this resource for power generation, to satisfy California's renewable portfolio standard. The well to wheels greenhouse gas emissions of biomass-derived ethanol vary with the supply pathway, and might not represent much of an improvement over gasoline. Corn ethanol has higher GHG emissions than ethanol from sugar cane or future ethanol derived from cellulose.

CONCLUSIONS

Clustering is an efficient way to design an early hydrogen refueling network, with seemingly good accessibility for users located within the clusters. Systems with as few as 8-16 stations can yield average travel times of less than 4 minutes, and average diversion times of less than 6 minutes. If a few connector stations are added between clusters, the diversion time is further reduced.

Beginning with a smaller number of stations (8 vs.16) yields significant savings in capital costs and gives a lower delivered hydrogen cost, at the expense of slightly higher average travel times and diversion times (see Appendix B). Hydrogen costs are lower because of better station utilization and scale economies.

Transition paths that begin with 4 clusters and evolve toward 6 and then 12 clusters will "break even" in about 2024, assuming hydrogen is sold at $10/kg during this time period.
We estimated the annual cash flow, assuming that hydrogen could be sold for $10/kg throughout the transition period (2009-2025). Initially, the cash flow is negative (due to initial capital expenditures to build the stations at the beginning of each phase), but eventually, as the station size grows and more fixed stations are employed, the cost of hydrogen declines. By 2024, the capital investment of approximately $170 million is recouped, if hydrogen can be sold at $10/kg. (Depending on how hydrogen fuel sales are valued vs. station revenue from a convenience store, car wash, etc., the required hydrogen price to breakeven by 2024 might be several $/kg lower.)

As the station network expands to meet a growing hydrogen demand, the average travel time and diversion times decrease. The cost of hydrogen (e.g. the annualized cost of capital and operation expenses divided by the annual hydrogen production) falls from $77/kg in 2009-2011 to $37/kg in 2012-2014 and $13/kg in 2015-2017. By 2015 the cost of hydrogen from the early infrastructure is approximately competitive with gasoline at $6.5/gallon accounting for the higher fuel economy of the FCV. Once the hydrogen demand is sufficient to support fully utilized 1000 kg/day stations (probably starting after 2017), hydrogen could be produced at $5-7/kg, (competitive on a cents per mile fuel cost basis with gasoline at $2.5-3.5/gallon.

Renewable hydrogen could be produced in the near term via onsite reforming of bio-methane or biomass-derived ethanol. Using these supply pathways, the cost premium to satisfy California's requirement for 33% renewable hydrogen would be modest (less than $1/kg). Electrolysis using green power from the grid would be $5/kg more costly than hydrogen from natural gas; solar PV electrolysis would be perhaps $20/kg more costly.

Even with relatively conservative cost assumptions, an emerging hydrogen infrastructure could pay for itself within about 15 years if hydrogen is sold at a price competitive with gasoline at $5/gallon. The early infrastructure could be considered an introduction to a business case after 2017, when many more 1000 kg/d stations would be needed, if FCVs are successful in the market, and hydrogen could compete with gasoline at $2.5-3.5/gallon.

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APPENDIX A

MAPS AND SCENARIOS

In the section above “Station Placement Spatial Analysis”, the characteristics of the cluster strategy are explored in terms of travel time to the nearest station from home and diversion time. In this appendix, more information is given on these scenarios - and variations of these scenarios in the form of maps and tables.

The first variation of the cluster strategy is a look at the effect of using destinations instead of traffic volumes to evaluate station placements. The difference can be shown by way of example. Suppose a customer starts a trip in Santa Monica and drives to downtown LA. If the traffic is used to evaluate the station placements, station placements are attracted to the path of the vehicle that travels between those two places. If the destinations are used to attract station placement, station development will be attracted to the endpoint of the trip, in this case downtown Los Angeles. A benefit to this type of siting is that customers tend to refuel at the start of end of a trip. Having the destinations be the attractors for station placement could better enable this type of refueling. However, favoring station placement along trip paths produces a network with the potential to serve more people who need fuel. Perhaps stations along trip paths are more important in an early network, and destination stations become important once a network of connector stations is put along trip paths.

The second variation on the cluster strategy presented in the main body of the text is the incorporation of planned and existing (P&E) stations into the network scenarios. The scenarios in the main text are presented to show the characteristics of siting stations in clusters without the confusing effect that P&E stations might have on the calculations. However, knowing how new stations fit into the network of P&E stations is useful information.

Cluster Strategy Maps

To help visualize the scenarios in the main text, three maps are provided in this section. Endless map variations can be produced, but for the sake of brevity, the maps shown here are the most illustrative cases. For example, an examination of a single cluster is not shown due to the fact that the exact locations of customers are not known. Instead, the suggestions in Appendix C provide some considerations for this type of siting.

Some caution should be employed when interpreting these maps. The exact locations of stations are only illustrative since the data used is not an exact representation of reality. More study is needed for the appropriateness of each site. Nevertheless, these maps can provide a basis for discussion. Additionally, as the station placements are computer generated, the “best” site may be elsewhere. For example, as discussed in the main text, some stations that enable important destinations such as San Diego, Santa Barbara, Las Vegas or Palm Springs may be more essential in the minds of consumers than the stations chosen by the model. Other station sites not chosen by this model may be important to customers; information that can be garnered through surveys.

The basic tradeoffs displayed in this section show the effect of restricting station sites to clusters versus being able site stations anywhere in the Los Angeles basin. Additionally, the effect on station locations of increasing the number of clusters is shown.

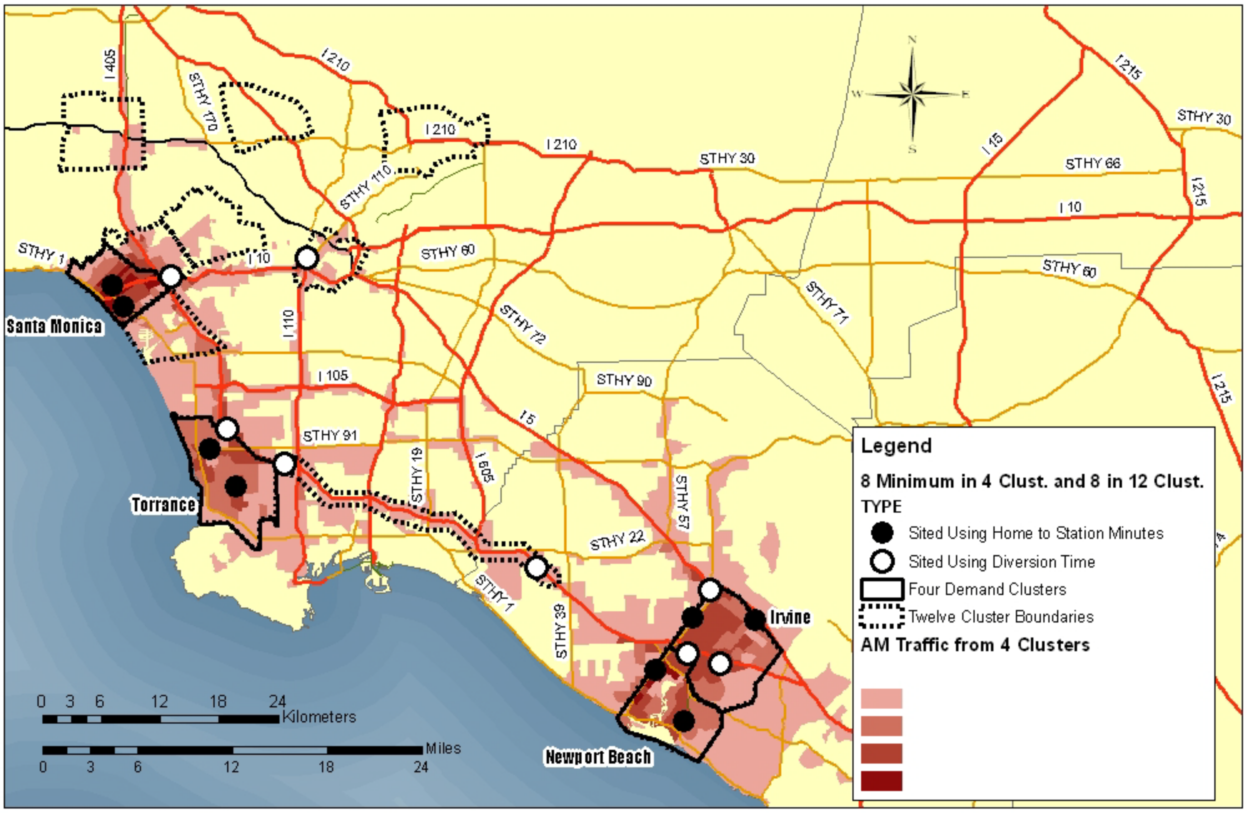


Figure A1 The distribution of traffic originating in the clusters surrounded by the solid border is displayed in the red color. Two stations per cluster are fixed based on siting stations using the home to station travel time for a total of 8 stations in the four clusters. The additional eight stations shown in white are sited using the traffic distribution shown and are restricted to any of the twelve future clusters whose outlines are denoted by the dotted line.

Figure A1 shows how stations would be sited using a traffic distribution from four clusters, but restricted to the twelve possible cluters. Eight stations are sited previously by using the home to station travel time and the model decides the placement of the next eight takes the first eight in to account and sites the rest based on how much a station placement decreases diversion time. Interestingly, four stations are sited in clusters such as Irvine that already have two stations reinforcing the notion that much travel is local.

If the additional eight stations are not restricted to the 12 named clusters, there is a slightly different arrangement of stations chosen by the model (Figure A2).

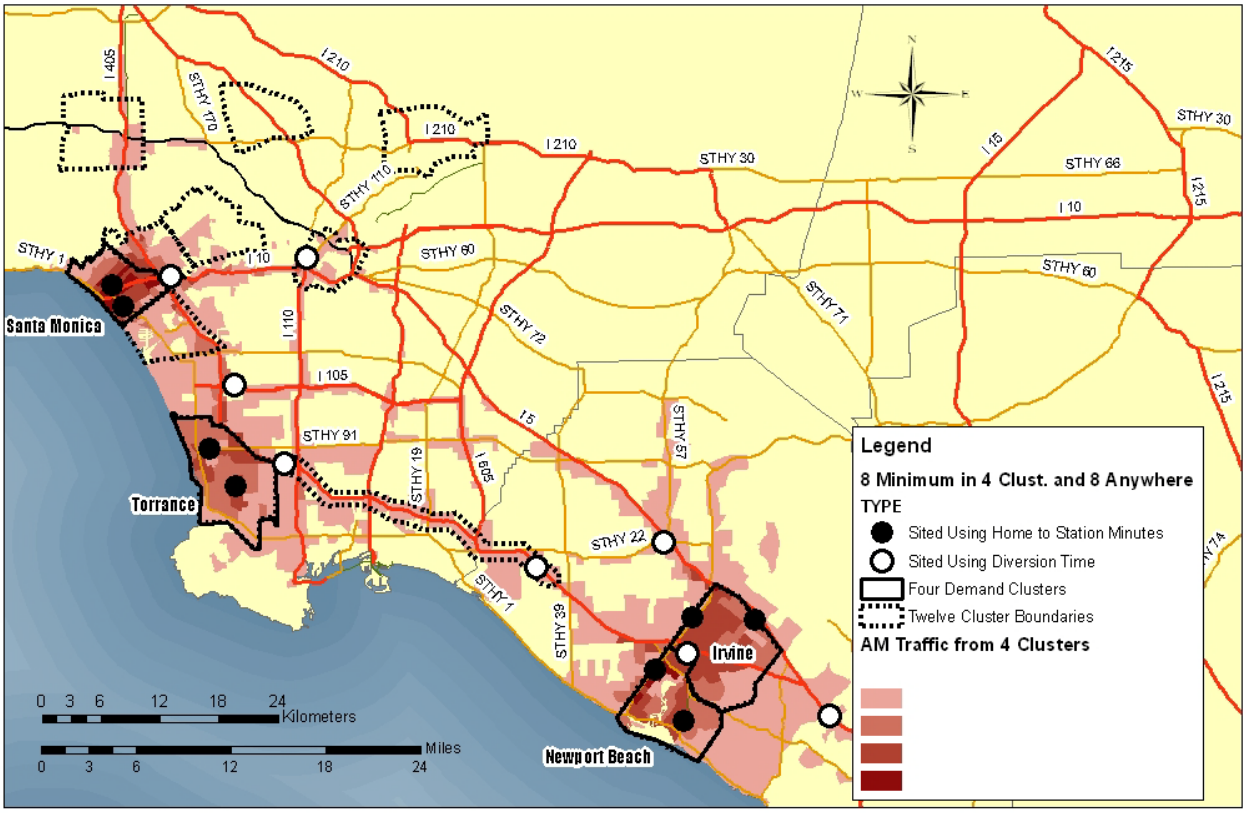


Figure A2 The distribution of traffic originating in the clusters surrounded by the solid border is displayed in the red color. Two stations per cluster are fixed based on siting stations using the home to station travel time for a total of 8 stations in the four clusters. The additional eight stations shown in white are sited using the traffic distribution shown and are not restricted to any clusters. The outlines of the twelve cluster are for reference only.

Comparing Figure A1 to A2 we see that the stations previously sited in Irvine now move out along the I-5 corridor north and south. The station previously in Torrance moves north to the intersection of I-405 and I-105. The other placements remain unchanged.

When the distribution of traffic from 12 clusters is used instead of 4, the station choices change slightly as shown in Figure A3.

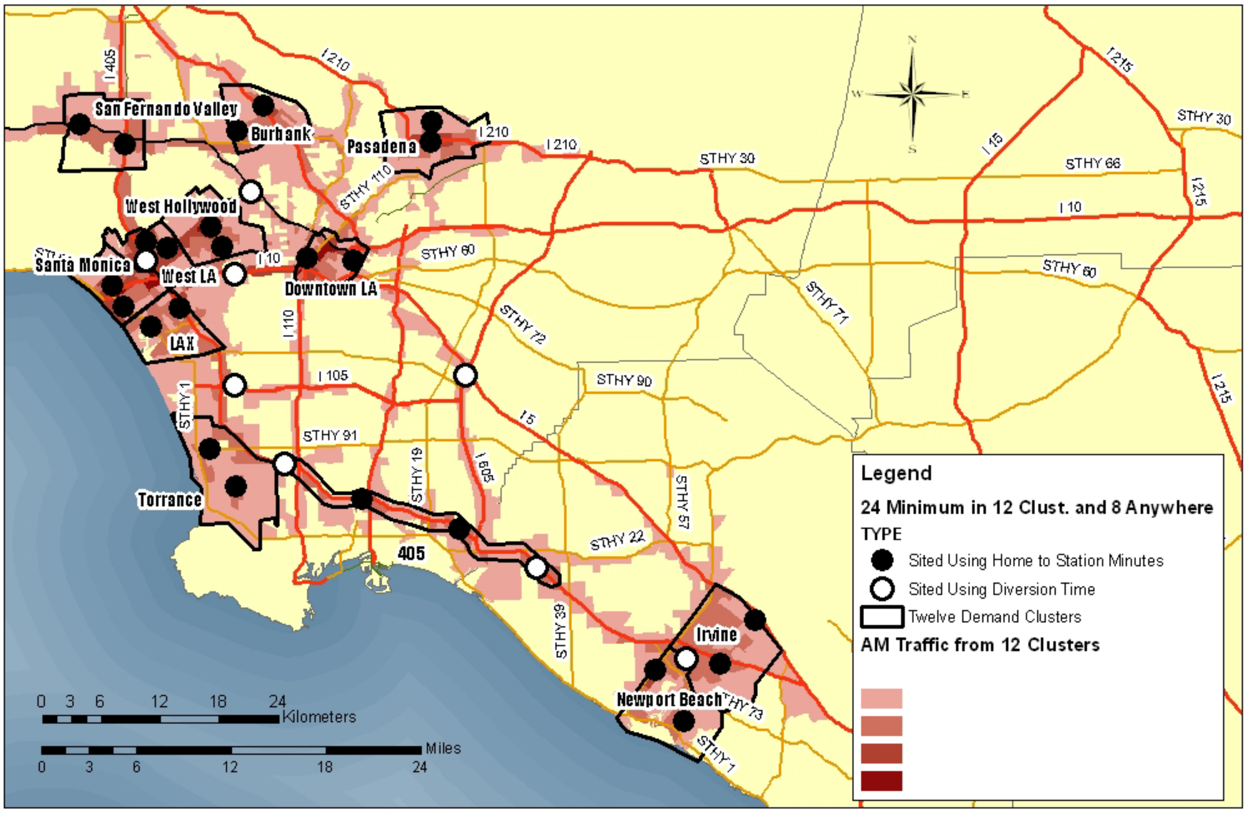


Figure A3 The distribution of traffic originating in the clusters surrounded by the solid border is displayed in the red color. Two stations per cluster are fixed based on siting stations using the home to station travel time for a total of 24 stations in the twelve clusters. The additional eight stations shown in white are sited using the traffic distribution shown and are not restricted to any clusters.

The "center of mass" of the traffic distribution shifts northwards, and some stations shown in Figure A2 disappear. However, the I-405 corridor remains important. A station now appears at the intersection of I-5 and I-605 near Santa Fe Springs. A few new stations appear on I-10 and US 101 north of Downtown LA.

Using Destinations Instead of Traffic Density to Site Stations

Since many people prefer to refuel at the end of a journey and alternate station siting attractor was experimented with. These maps can be compared to the maps above for similarities and differences. The home to station time was not used as an attractor in these scenarios to site the initial eight stations.

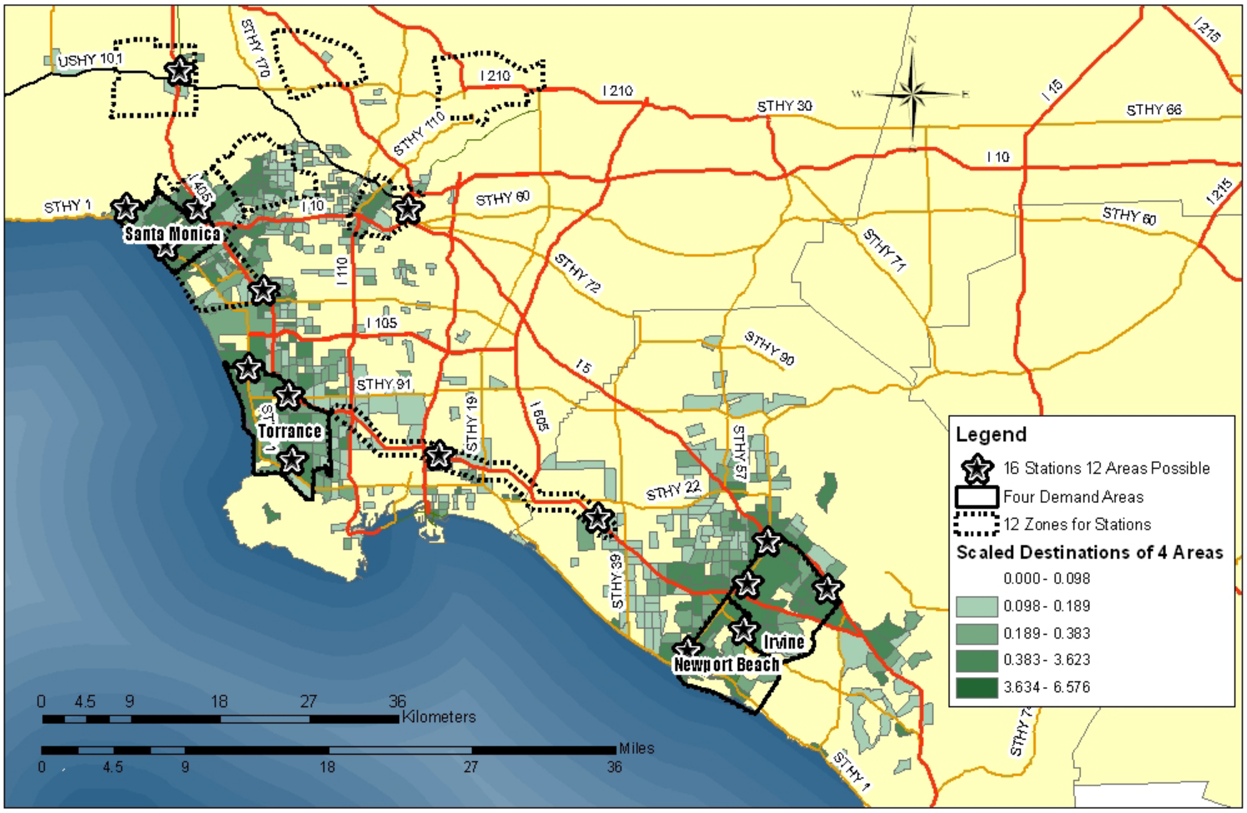


Figure A4 The distribution of destinations for trips originating in the 4 clusters surrounded by the solid border is displayed in the green color. None of the sixteen station locations is decided a priori. The locations of the stations is restricted to the twelve future clusters whose outlines are denoted by the solid and dotted line.

Comparing Figure A1 and Figure A4, the distribution of stations is similar. The I-405 corridor is important as well as downtown LA. Figure A5 shows the distribution of stations when the locations are not restricted to the twelve future clusters.

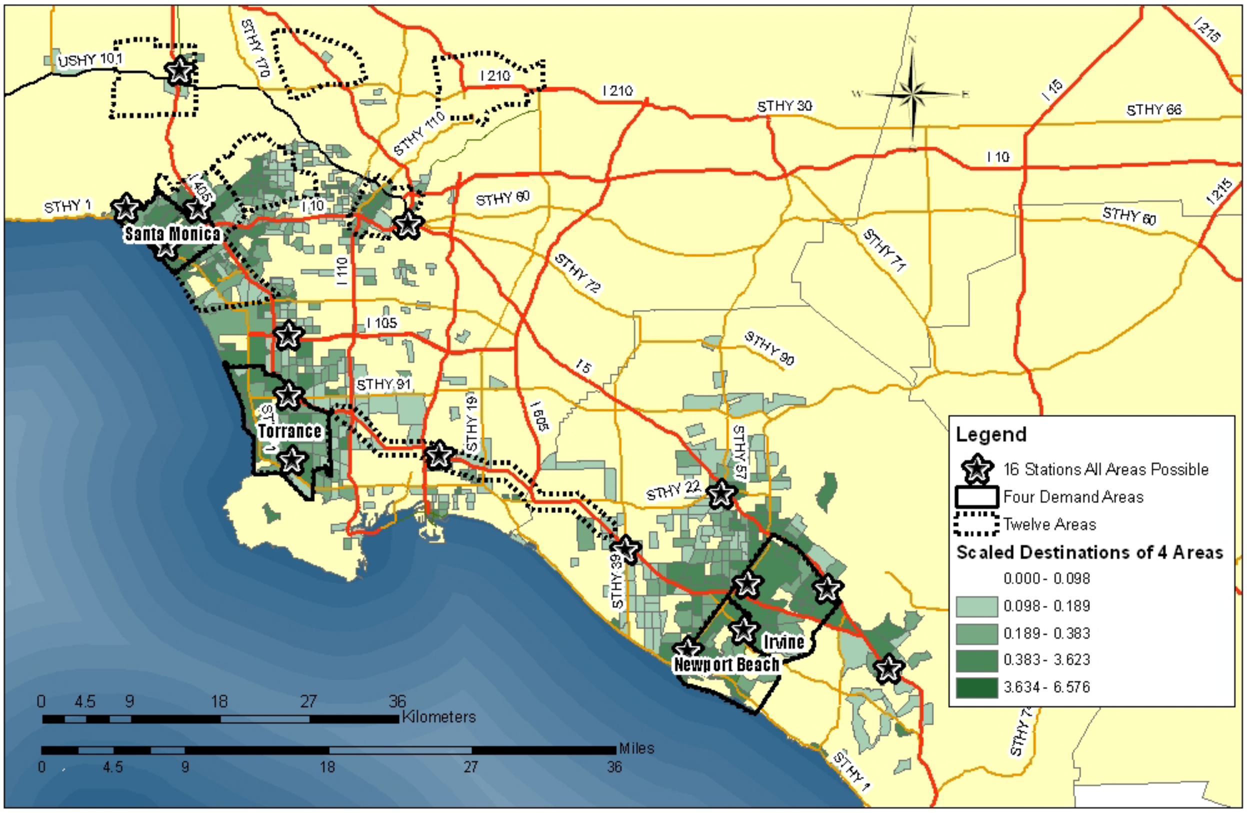


Figure A5 The distribution of destinations for trips originating in the 4 clusters surrounded by the solid border is displayed in the green color. None of the sixteen station locations is decided a priori. The locations of the stations are not restricted to fall into a cluster. The twelve future clusters whose outlines are denoted by the dotted line are shown for reference only.

If we compare Figure A5 to Figure A4, we see a shift of the locations of a few stations similar to the shift of stations seen from Figure A1 to Figure A2. A few stations are sited north and south of Irvine along the I-5 corridor, and a station appears at the intersection of I-405 and I-105.

Accounting for Planned and Existing Stations

The station scenarios in the main text, and in the maps above do not account for planned and existing (P&E) stations. These stations are potentially useful to future fuel cell vehicle drivers, but how useful? To begin to answer this question, the individual cluster travel times from home to station shown in Figure 6 were compared to what the average travel time would be if stations were added to the network of existing stations.

First, the travel time from home to station for each area was calculated using solely the 11 P&E stations. The average travel times can be seen in Figure A6.

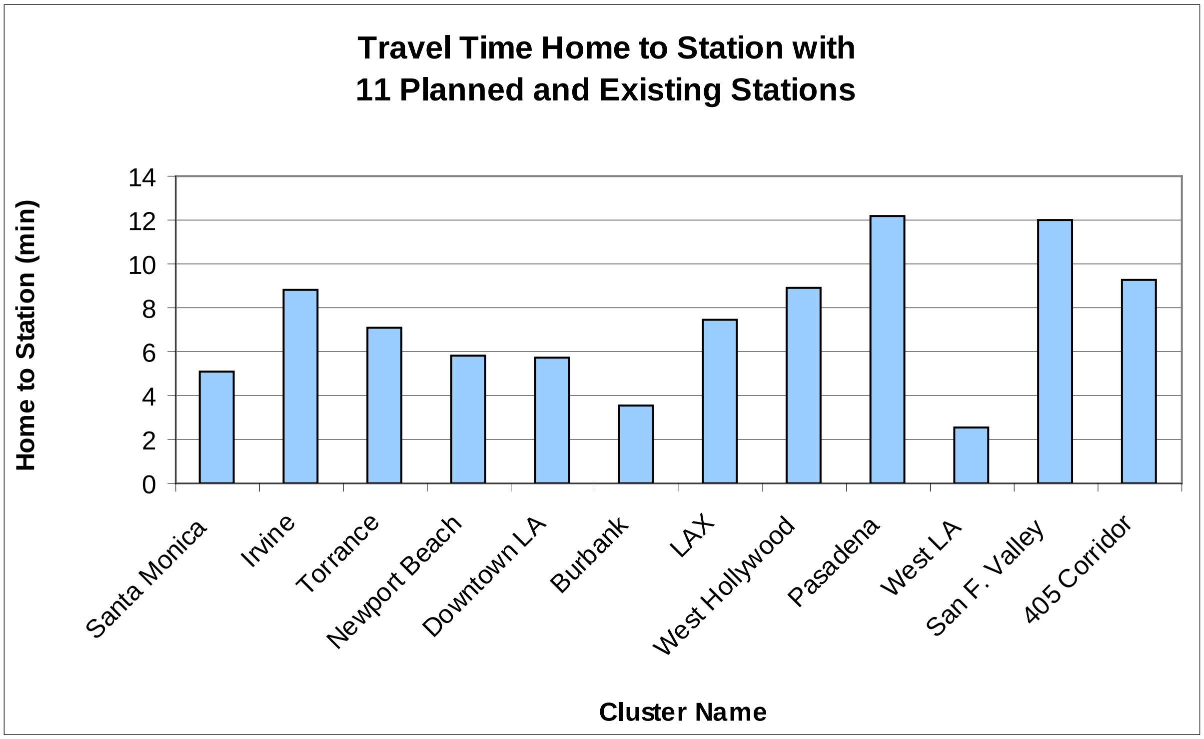


Figure A6 Travel time from home to station using only the 11 planned and existing stations. Some areas such as West LA are well served whereas others such as Pasadena have no stations nearby.

The variation in travel times shows that some areas need stations more than others. To investigate this, the travel times in Figure A6 were compared to the average travel time from home to station of two stations which can be seen in Figure 6 in the main text. Stations were then added to the network in order to bring the travel time for each cluster to parity with the two station per cluster level as shown in Figure 6. In all cases, a certain number of stations did not bring exact parity and the average travel time was either higher or lower than the two station level. For example, two stations in Santa Monica represents an average travel time of 2.86 minutes to the nearest station. Adding one additional station in the context of the P&E network equals 3.02 minutes. Adding two stations to the network results in a 2.65 minute average travel time meaning that one is “not enough” and two is “too many”. Consequently, a maximum and minimum for each area was developed.

# of Stations	Santa Monica	Irvine	Torr-ance	Newp. Beach	Down-town LA	Burbank	LAX	W Holly-wood	Pasa-dena	West LA	San F. Valley	405 Corridor
"+11"	5.07	8.8	7.13	5.8	5.77	3.51	7.5	8.91	12.2	2.53	12.03	9.27
1	3.015	5.628	4.758	3.466	2.681	2.786	3.663	4.28	2.893	2.051	4.299	5.17
2	2.65	4.631	3.575	2.909	2.11	2.252	2.837	3.266	2.518	1.772	3.083	3.924
3	2.374	3.87	3.107	2.504	1.885	1.849	2.431	2.646	2.27	1.518	2.63	2.969
4	2.161	3.609	2.753	2.305	1.697	1.68	2.184	2.235	2.081	1.409	2.291	2.444
5	1.963	3.368	2.538	2.17	1.543	1.574	1.943	1.98	1.908	1.321	1.988	2.219
6	1.83	3.129	2.334	2.051	1.447	1.474	1.791	1.826	1.805	1.278	1.821	2.096
7	1.714	2.988	2.198	1.987	1.385	1.394	1.643	1.687	1.721	1.248	1.706	2.001

Table A1 The minimum and maximum number of stations is denoted by the two green shaded cells in all but Downtown LA, LAX, and Pasadena. If the P&E stations make no difference in the average travel time to the nearest station versus a network without them, they are shaded in yellow. For example, the calculations for Downtown LA show no benefit in terms of home to station time so it is shaded in yellow. The cells that are outlined show how many stations would be needed in the context of the P&E station to equal a 3 minute travel time to the nearest station. The +11 signifies the travel time to the nearest station with the 11 planned and existing stations.

From Table A1, the benefit of the P&E stations can be investigated. Some areas such as Downtown LA showed no benefit in terms of average travel time to the nearest station if the P&E stations are taken into account. This is somewhat surprising since CSU LA is quite close to Downtown LA. Other areas have a minimum and maximum number to achieve parity with the two stations per cluster level.

Also shown in Table A1 are the numbers of stations needed in each cluster to achieve an approximate three minute travel time (an arbitrary level) to the nearest station. This is in recognition of the fact that some clusters are bigger than others, and may need more stations. If the number of stations in addition to the P&E stations are totaled, 25 additional stations would be needed to achieve travel time parity between the clusters. Alternatively, clusters such as Irvine could be reduced in size to reduce the number of stations to reach a 3 minute target.

P&E stations also affect station placement. Two examples of the “minimum” scenarios discussed above are shown in Figure A7 and Figure A8. The minimum number of stations for four clusters is three (as shown in Table A1), eight additional stations are sited using diversion time as an attractor (Figure A7).

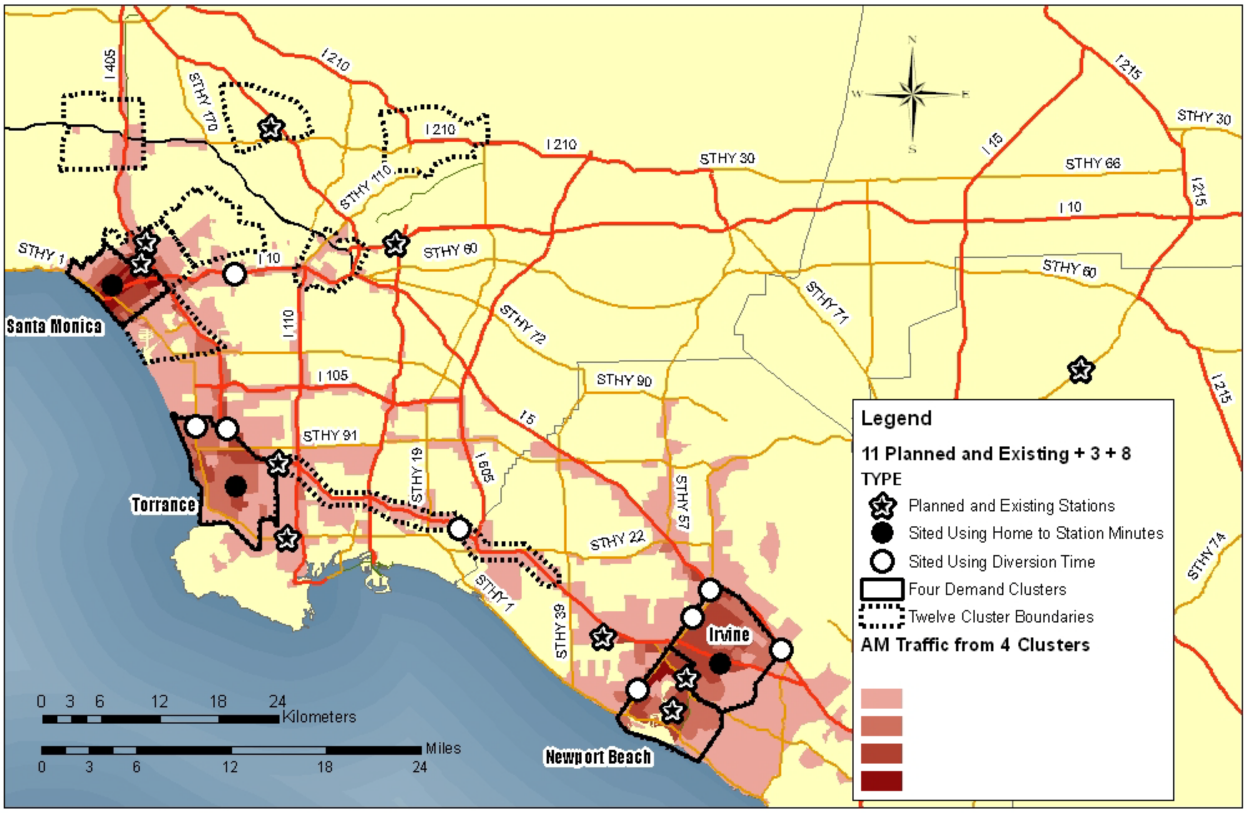


Figure A7 Traffic distribution from four clusters is used to site stations in addition to the P&E stations and the 3 "minimum" stations sited. Note, not many stations are sited outside the four areas possibly indicating the "minimum" is not enough.

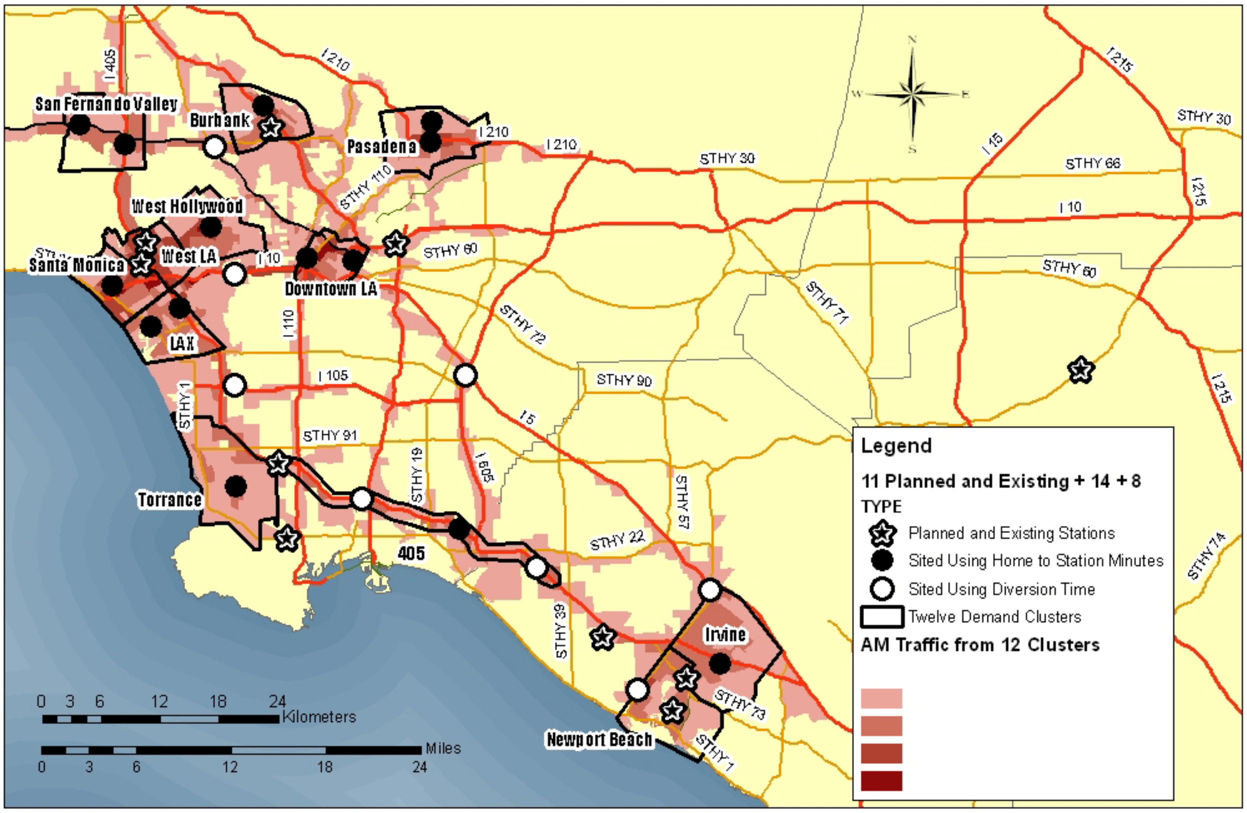


Figure A8 Traffic distribution from twelve clusters is used to site stations in addition to the P&E stations and the 14 "minimum" stations sited.

In Figure A7, many stations are sited within clusters perhaps indicating that the minimum is not sufficient to satisfy demand. In Figure A8 some stations appear outside of the clusters, notably one near the intersection of I-405 and I-105 and one near Santa Fe Springs.

Scenario Conclusions

Some common station sites occur across all scenarios. The I-405/I-105 junction near LAX consistently appears. The I-405 corridor between Newport Beach and Torrance appears to be a critical link as well. Mission Viejo, and Anaheim also show up multiple times.

When using diversion time as an attractor for station development, stations appeared inside the clusters as well as outside which was a somewhat surprising result. However, since much traffic is local, population and traffic will naturally track together creating a situation where stations that are sited using traffic and stations sited using home to station travel time are sometimes the same.

Also important to reiterate, these station locations were estimated using a computer with no consumer survey research. As such these are only suggested locations. Preliminary surveys indicate that stations which extend the territory a driver can access are extremely important. These indicators are not revealed in this analysis.

APPENDIX B.

HYDROGEN REFUELING STATION COST AND PERFORMANCE ASSUMPTIONS

In section we give cost and performance assumptions for hydrogen refueling stations, used in our analysis

To develop estimates of hydrogen refueling station costs, we reviewed the literature on both on near and long term hydrogen refueling station costs, and collected information during stakeholder interviews.   There are various refueling station technologies that could be employed in the 2009-2017 timeframe.   Several types of stations are considered in this analysis (with potential station sizes):

- Mobile refueler stations (50-100 kg/d)
- Portable refueler stations with compressed gas truck trailer delivery (100 kg/d)
- Liquid H_2 stations with truck delivery (100 kg/d; 250 kg/d, 400 kg/d, 1000 kg/d)
- Onsite Steam Methane Reforming (SMR) stations (100 kg/d; 250 kg/d, 400 kg/d, 1000 kg/d)
- Onsite Electrolyzer stations (100 kg/d; 250 kg/d, 400 kg/d, 1000 kg/d)

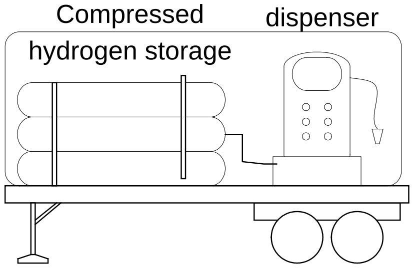
For 2009-2011, we consider 100 kg/day stations; from 2012-2014, we consider placements of 100, 250 or 400 kg/day stations. For 2015 and beyond, we also consider 1000 kg/day stations.

Mobile refueler stations

A mobile refueler station consists of high-pressure gaseous hydrogen storage (mounted on a truck trailer), a compressor (optional) and a dispenser. The hydrogen storage truck trailer is towed to and from hydrogen production facilities so that the hydrogen tanks can be refilled when needed. This type of hydrogen supply is being used in several sites in California. Some mobile refuelers do not have any permanent fixed equipment and everything is self-contained on the truck trailer (see Figure B1a). This allows refueling sites to be added or changed rapidly as the need arises.

Portable Refueler Stations (Compressed Gas Truck Delivery)

Alternatively, portable refueler stations could have a compressor and dispenser mounted into a separate trailer located at the station. Compressed hydrogen is delivered by truck in a tube trailer and connected to the compressor/dispenser system (Figure B1b). These stations are “portable” in the sense that these could be moved to another site in an upgrade.



Hydrogen Mobile Refuler

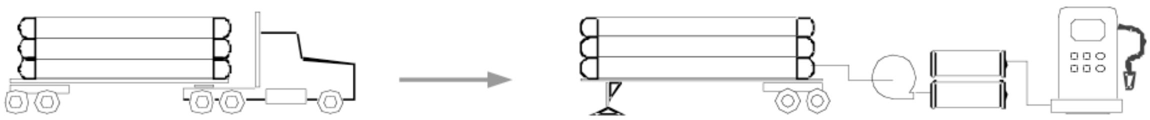


Figure B1 Mobile refueler hydrogen station (top B1a)
Portable refueler with compressed gas delivery, (bottom B1b).

Equipment costs for mobile refueler stations have been estimated for 10 kg/day units by Weinert and Lipman (2006), and from conversations with energy company experts. These are summarized in Table B1 below.

Table B1 Capital Cost and Operating Cost for Mobile Refuelers

Station Type	**Station Capacity kg/d**	**TOTAL CAPITAL COST ($)**	**Fixed O&M $/yr**	**Variable O&M Purchased compressed H2**
Mobile refueler 75 kg H2 storage (Weinert 2006)	10	250,000	17,000	Not estimated
Mobile Refueler 70-100 kg/d (This study)	70-100	$1 million	Land rental + 13% capital	$20/kg

To estimate costs for a 100 kg/day portable refueler station, we adapted information from the H2A delivery model for a station with tube trailer delivery (see Tables B2 and B3). We assume that a tube trailer is truck-delivered to the station site, and attached to a fixed dispenser. Two types of stations are shown. In the first, compressed gas is delivered at 2700 psi, and a compressor at the station brings it to the required pressure for dispensing to compressed gas vehicles. In the second, we show costs for a higher pressure tube trailer (7000 psia), which requires no separate station compressor. Note that we have not included the capital cost of the tube trailer as part of the station capital cost total. (If the station contracted with a hydrogen supplier to deliver tube trailers, the capital cost of the tube trailer would not be charged to the station; it would be included in the cost of delivered hydrogen instead, as an operating cost.)

Operating costs for compressed gas stations include rent for land, electricity for compression (for the 2700 psia case), the cost for purchasing compressed hydrogen at a central plant to fill the truck, plus truck operating costs and fixed O&M costs equal to 13% of the capital cost (see Table B3). In Table B2, we assume that the cost of compressed hydrogen at the station (including H2 production and compression at a central plant and truck delivery) is $20/kg. The footprint of a portable refueler station is assumed to be ~2206 sq. ft. [H2A 2007].

Table B2 Compressed Tube Trailer H_2 station equipment capital costs [H2A current technology

Source	H_2 compressor	H2 Storage	Dispensers	Controls, safety	Other (engineering, permitting, etc.	TOTAL CAPITAL COST ($)	Truck Trailer (incl. H_2 storage tubes)
H2A - 100 kg/d 2700 psia tube trailer delivery; compression at station to 7000 psi	$26,382 Max rate 100 kg/day	$31,084 38 kg @ $899/kg	1 @ $26,880 each	$22,320	$24,000	$131,666	$165,000 9 gas tubes; 280.3 kg of deliverable H2 @ 2700 psi)
H2A - 100 kg/d 7000 psia tube truck delivery, no compressor needed.	-		1 @ $26,880 each	$22,320	$24,000	$73,199	$350,000 (1 gas tube holding 420 kg of deliverable H2 @ 7000 psi)

Table B3 Summary of Capital and Operating Costs for Compressed Gas Stations.

			OPERATION AND MAINTENANCE COSTS ($/yr) (@70% capacity factor)				
Station Type	**Station Capacity kg/d**	**TOTAL CAPITAL COST ($)**	**Land (2206 sq. ft; $5/sq.ft/ mo.)**	**Purchased compressed gas H2 (25,550 kg/y @$20/kg)**	**Electricity (1.25 kWh/kg; $0.10/kWh)**	**Fixed O&M**	**TOTAL O&M $/yr**
2700 psia tube trailer delivery; compression at station to 7000 psi	100	$292,583	$132,200	$511,100	6360	$38,036[a]	$687,000
7000 psia tube truck delivery, no compressor needed.	100	$403,848	$132,000	$511,100	-	$52,500[a]	$696,000

a. 13% of capital cost,[H2A current technology].

In conversations with stakeholders, current prices for mobile refueler systems capable of dispensing 70-100 kg H2 were quoted as $1 million each. These costs are significantly higher than those in literature studies.

Liquid H_2 stations with truck delivery

Liquid H_2 (LH_2) refueling stations that take truck delivery of liquid hydrogen have the possibility of dispensing either liquid or compressed hydrogen. Most current stations have liquid delivery and storage, and dispense fuel as compressed H_2. A typical configuration of a LH_2 station that dispenses compressed H_2 is shown in Figure B2 below. Liquid H_2 is used for delivery and storage because of its relatively higher density than compressed H_2. It is converted to compressed H_2 since most current and planned fuel cell vehicles use compressed gas at either 350 or 700 bar storage pressure.

Liquid hydrogen has a relatively high density so that it is possible to transport approximately 10 times more hydrogen on a truck than when using compressed gas. This can significantly lower the delivered cost of H_2, especially when transport distances are moderate or long. In the longer term (beyond the scope of this project timeframe), pipelines will also be a competitive method for transporting hydrogen, and can significantly lower costs and energy use associated with transporting hydrogen if large volumes (associated with supplying hundreds or thousands of stations) are needed (Yang and Ogden 2007).

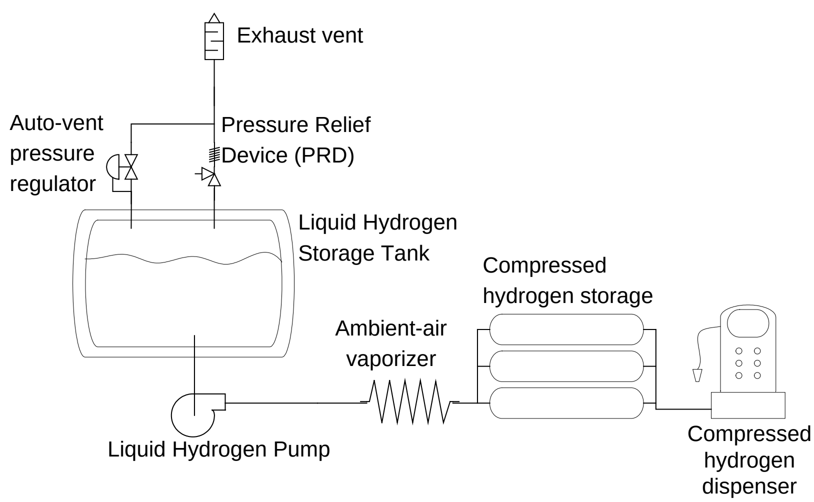


Figure B2 Liquid hydrogen station dispensing compressed gas.

The key components of the system are the LH_2 storage tank with safety equipment to prevent overpressures from boil-off, and the cryogenic hydrogen pump and vaporizer, which conserve energy by pumping a liquid to pressure before vaporizing rather than compressing a gas. Once hydrogen is vaporized, it can be compressed further before dispensing onto a compressed gas vehicle. Figure B3 shows a site plan for a 100 kg/day liquid hydrogen system located within a gasoline station (H2A 2007).

Tables B4 and B5 give a capital cost breakdown for LH_2 refueling station equipment from several recent studies. Table B6 shows operating costs from these studies. In Table B4 we have adapted these studies to estimate station costs for 100, 250 and 400 kg/day stations using current technology, and 1000 kg/day stations using current and future (2015) technologies.

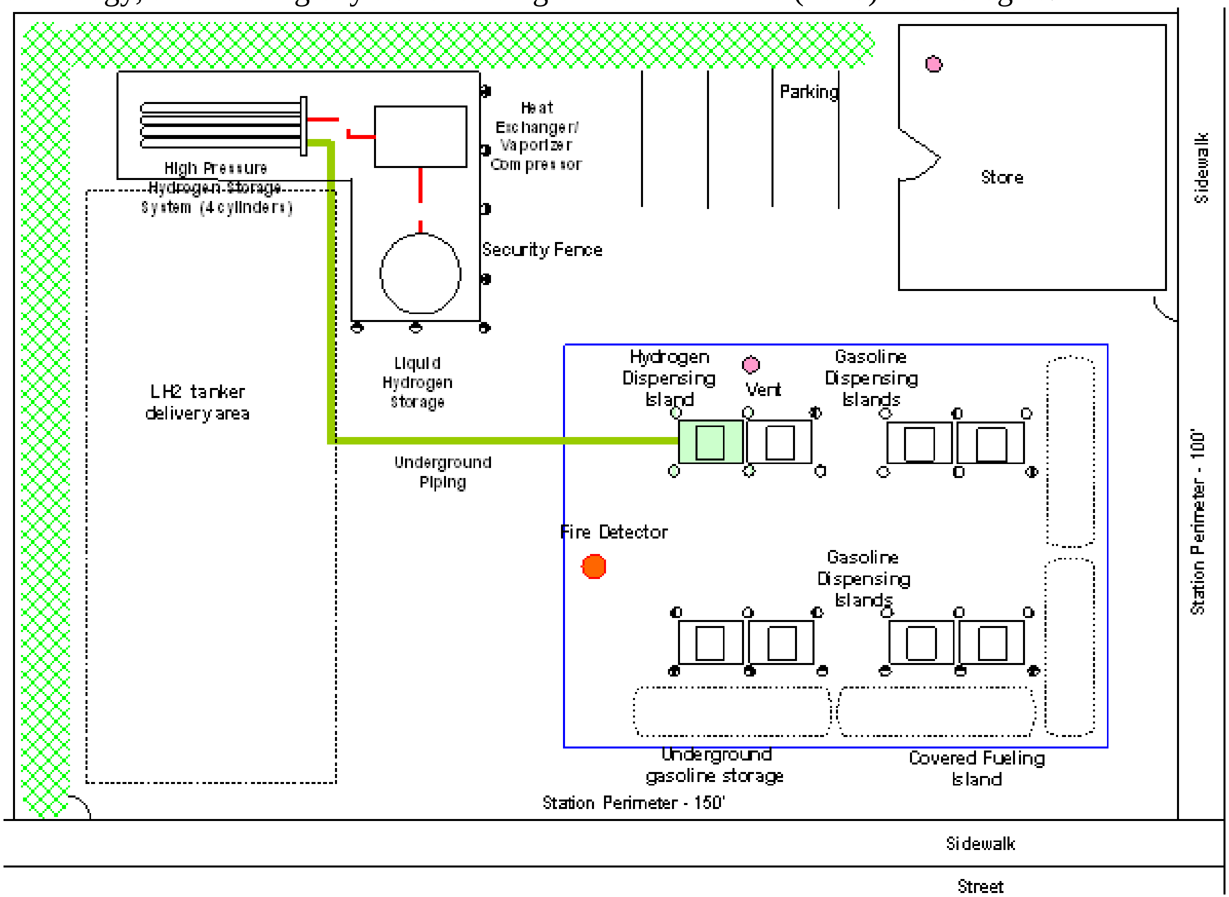


Figure B3 Site Plan for Liquid Hydrogen System at Gasoline Station (H2A 2007).

Table B4 Summary of LH_2 Station Equipment Capital Costs (H2A Delivery Components Spreadsheet v.1.1)

Station Type	Station Capacity kg/d	H_2 storage	LH_2 pump	H_2 compressor and gas storage	H_2 dispensing	Other (site prep. Engineering and design, permitting, etc.)	TOTAL STATION CAPITAL ($)
LH2 truck delivery (H2A current tech)	100	1576 kg $110,315	2 pumps (7 kg/h each) + evaporator $90,428 + 7920	38 kg H2 $31,084	1 dispenser @$26,880	$65,103	$353,960
LH2 truck delivery (H2A current tech)	250	181925	101904		1 dispenser @$26,880	76228	409257
LH2 truck delivery (H2A current tech)	400	222451	105461		2 dispenser @$26,880 each	87442	491434
LH2 truck delivery (H2A current tech)	1500	4536 kg $226,798	2 pumps + evap. $131,540	358 kg H2 $292,844	3 dispensers $80,640	$169,682	$923,824
LH2 truck delivery (Weinert - current tech)	1000	$463,681 3400 kg LH2 storage	$218,507 1000 kg/d pump capacity	$1,102,487 667 kg compressed gas storage	$127,130 3 dispensers	-	$1,911,805
LH2 truck delivery (2015 tech - Yang and Ogden)	1000	$84,355 (2000 kg LH2 storage)	$30,065 (1 LH2 pump 42 kg/h)	$59,200 100 kg compressed gas storage	$88,800 (2 dispensers)	-	$262,420

Table B5 LH2 station "other" capital costs (H2A 2007)

Other Capital Costs: 100 kg/d LH2 station	
Site Preparation (% of Initial Capital Investment)	6.5%
Engineering & Design (% of Initial Capital Investment)	3.0%
Project Contingency (% of Initial Capital Investment)	10.0%
One-time Licensing Fees (% of Initial Capital Investment)	0.0%
Up-Front Permitting Costs (% of Initial Capital Investment)	3.0%
TOTAL OTHER CAPITAL COSTS ($(2005))	22.5%

Table B6 Liquid H_2 Station Operating Costs from Various Studies

Source	Yang and Ogden	NAS	Weinert	H2A
Land	$[15000 + S_{station}]$ ft^2 \$0.50/ft^2/month	--	1200 ft^2 \$0.50/ft^2/month	15000 ft^2 \$0.50/ft^2/month
Fixed	7.5% of capital cost	8% of capital cost	8% of capital cost	11% of capital cost
Electricity	0.81 kWh/kg	0.8 kWh/kg	0.8 kWh/kg	0.33 kWh/kg

Onsite Steam Methane Reforming (SMR)

Several recent studies indicate that distributed (or onsite) production of hydrogen from natural gas at refueling stations is an attractive option for early hydrogen supply to vehicles. Onsite production avoids the cost and complexity of hydrogen delivery. Hydrogen is produced in a small-scale Steam Methane reformer (SMR), which is located at the station. Distributed production also requires less capital investment than central production, which would be useful during a transition to hydrogen vehicles. Also included at these stations, are H_2 compressors, storage tanks, and fuel dispensing equipment. A number of companies have developed small SMR systems ranging in size from tens to several hundred kilograms per day. It is likely that larger onsite reformers in the range of 1000 kg/d will become available over the next 5 years.

Figures B4-6 show a sketch of an onsite SMR system, and site plans for integrating small and large SMRs into gasoline stations.

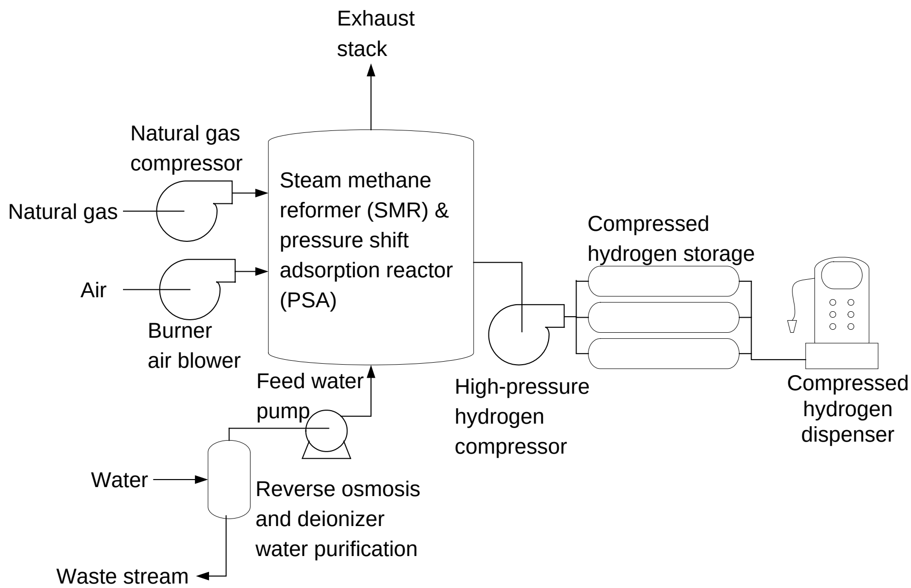


Figure B4 Hydrogen refueling station employing a small-scale steam methane reformer.

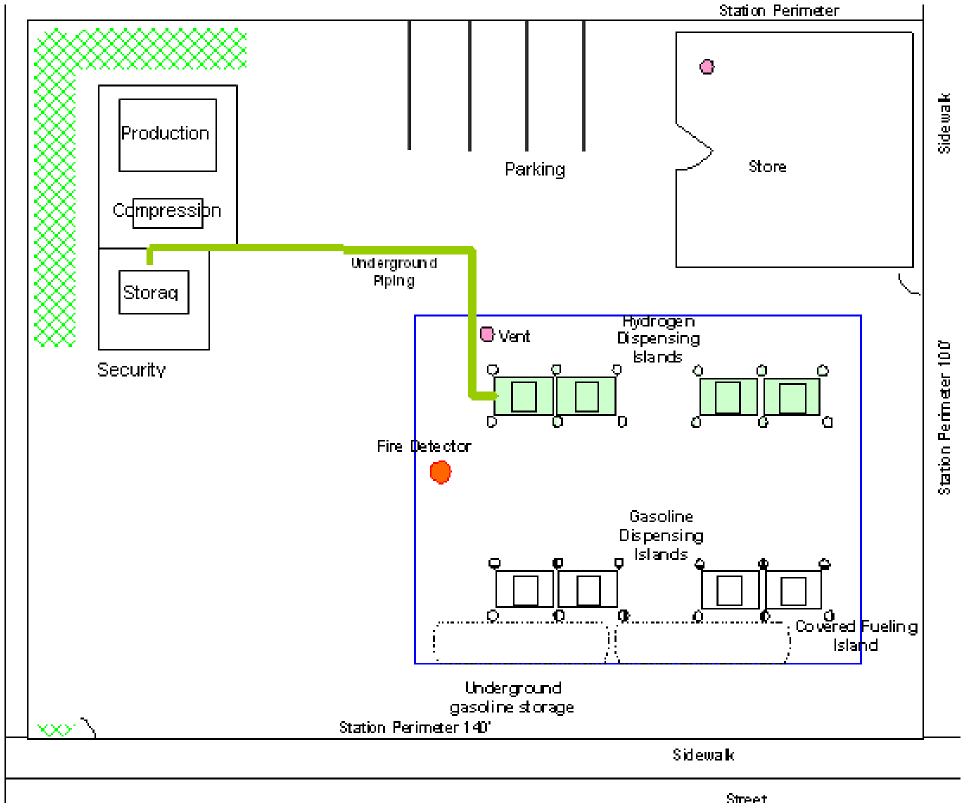


Figure B5 H2A Site Plan diagram for 100 kg/day reformer station

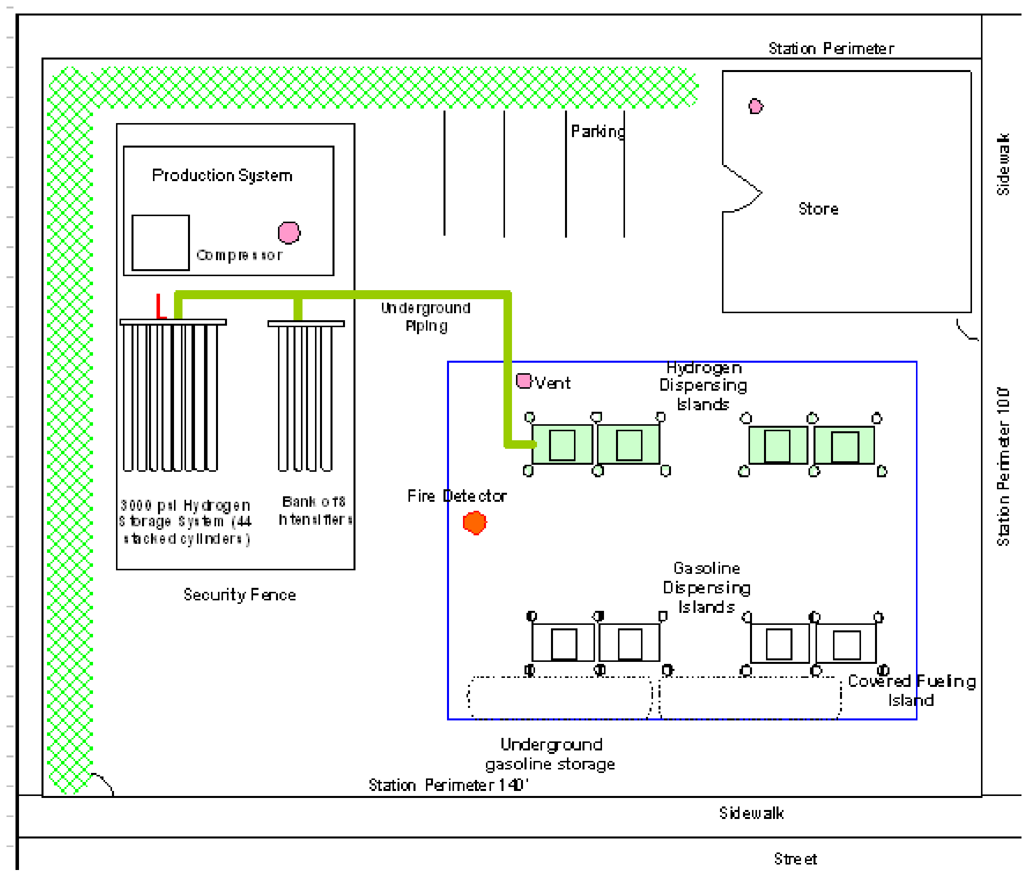


Figure B6 H2A Site Plan diagram for 1500 kg/day reformer station

Tables B7 and B8 give performance and cost data for onsite SMR systems from several recent studies. In Table B8 we have adapted these estimates for 100 and 1000 kg/day stations. Large stations could also require natural gas lines to be upgraded, resulting in additional costs, not included in these tables.

Table B7 Energy Inputs for Small Scale Onsite Natural Gas Steam Reforming

Literature Source	NG use (MMBTU/kg H_2)	Electricity use[1] (kWh/kg H_2)	System Efficiency
H2A 2009	0.156	3.1	68.4%
NAS Current	0.19	2.2	58%
NAS Future	0.16	1.7	69%

1. Electricity use for distributed SMR includes compression and station operation needs.

Table B8 Capital Costs for Onsite SMR Stations ($)

Station Type	Station Capacity kg/d	H_2 production	H_2 storage	H_2 compressor	H_2 dispensing	Other station equipment	Other (engineering. Site prep.. upfront permits)	TOTAL CAPITAL ($)
Onsite SMR (Weinert - current tech)	100	$382,000	$197,000	$52,000	$42,000		$375,000	$1,048,000
Onsite SMR (Weinert - current tech)	1000	$1,467,000	$2,372,000	$171,000	$127,000		$998,000	$5,135,000
Onsite SMR (H2A Current Tech)	100	143735	201910	50563	26880	167476	284955	$875519 = $143735 (reformer) + 446,000 (station) + 285,000 (other)
Onsite SMR (H2A Current Tech)	1500	956810	1952458	850194	80640	197323	878361	$4915788 = 956810 (reformer) + 3.08 million (station) + 878,361 (other)
Onsite SMR (2015 tech; Yang and Ogden, adapted from H2A)	1000	$787,994	$338,268	$274,085	$64,344		$216,603	$1,681,295

Natural gas use in onsite reformers is assumed to be 1.64 GJ natural gas/GJ hydrogen produced (H2A 2007).
Fixed costs are assumed to be 7.5% of capital costs per year. (Yang and Ogden 2007)
Electricity use is 3.1 kWh/kg for reformer operation plus compression to dispensing pressure. (H2A 2007)

Onsite Electrolysis Station

This station type can use either grid power or a dedicated renewable electricity source (or combination of the two) to produce hydrogen via electrolysis using water as a feedstock. For this station type, we assume either grid electricity or solar photovoltaic (PV) electricity

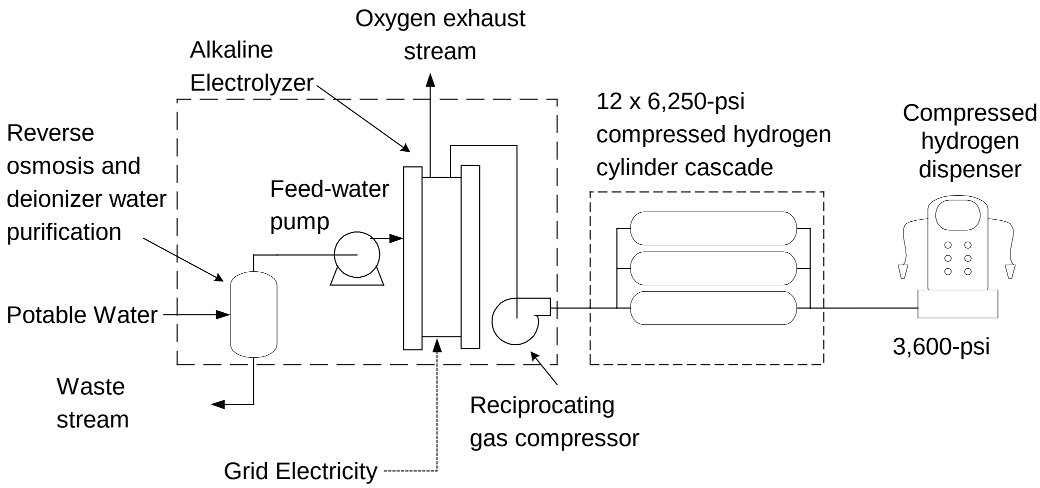


Figure B7 Hydrogen refueling station employing a small-scale electrolyzer**.**

Table B9. Capital costs for onsite electrolysis stations

Station Type	Station Capacity kg/d	H_2 production	H_2 storage	H_2 compressor	H_2 dispensing	Other station equipment	Other (engineering. Site prep.. upfront permits)	TOTAL CAPITAL ($)
Onsite electrolyzer (H2A Current Tech)	100	165330	201910	50563	26880	167267	245333	$857283 = $165330 (electrolyzer) + $446,829 (station)+ 245,333 (other)
Onsite electrolyzer (H2A Current Tech)	1500	2479950	1756787	765114	80640	190892	449234	$5722617 =$2479950 (electrolyzer) + $ 2793433 (station)+ 449234 (other)

Summary of Station Costs

Based on the literature review above, we make the following assumptions about the capital costs of hydrogen stations over time (Tables B10 and B11)

We assume that mobile refuelers have a capital cost of $1 million through 2014, with the cost reduced to $0.4 million after 2015.

For fixed stations (all station types except mobile refuelers), we assume that it costs $2 million for site preparation, permitting, engineering, utility installation, and buildings, for a green-field station site before any fuel equipment goes in. This $2 million is the “baseline cost” for any type of refueling station, independent of the fuel (e.g. it would be the same for a new gasoline station). For hydrogen stations, hydrogen equipment costs are added to this baseline.

2009-2011: we assume that mobile refuelers cost $1 million, and that fixed stations 100 kg/d stations cost $3-4 million. These costs are higher than H2A estimates or estimates by Weinert et al. (2006, 2007), but are consistent with current station costs reported in interviews with energy industry stakeholders.

2012-2014: we assume that the costs for refueling stations in the size range 100-400 kg/d are the baseline $2 million plus hydrogen equipment costs that are twice the H2A "current technology" values. [10]

2015-2017: we analyze two cases. In the "low cost" case, we use a $2 million baseline plus equipment costs based on H2A "current technology" numbers. In the "high cost" case, we use the same station costs as in 2012-2014.

It is important to note that these costs are higher than those used in some recent hydrogen transition analyses (H2A 2008, NRC 2008, DOE 2008).

The rationale for our station capital cost assumptions is as follows.

Over the next few years (2009-2011) current station costs are a good indicator for essentially one of kind projects.

In 2012, we assume that station design has become more standardized, although stations are being produced at a rate of 5-10 stations per year. H2A gives station equipment costs based on 500 stations per year. Based on a cost study by Weinert, we assume a progress ratio for station costs reflecting learning and station manufacturing scale up. Figure B8 reproduces a figure from Weinert (2006) indicating how the cost of station components scales as more units are produced. If station equipment production volume is increased from "current levels" (5-10 stations per year in 2012) by factor of 50-100 (to 500 units per year), station equipment capital costs are reduced by about 50%. Working backward, we start with the H2A costs for mass-produced equipment (500 units per year) and double these for low levels of production (5-10 units per year).

By 2015-2017 more stations will be produced each year, so we examine a range of cases from H2A "current technology" costs to twice H2A "current technology" costs (same as 2012-2014). Operations and Maintenance costs for hydrogen stations are given in Table B12. To find the annual variable O&M costs, prices are assumed for electricity (for compression or electrolysis at stations), natural gas (for onsite reformers), compressed hydrogen delivered to the station in mobile refuelers, and liquid hydrogen delivered to the station by truck (Table B13). Land rent is considered to be a fixed O&M cost. We use a land rent value of $5 per square foot per month,

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[10] The rationale for choosing twice the H2A "current technology" equipment cost is as follows. H2A's costs are based on production of 500 stations per year. But in 2012-2014, we would expect many fewer stations to be produced. If we reduce annual station production by a factor of 50-100 (5 to 10 stations per year), the equipment capital cost should be about 2 times the H2A estimate according to studies by Weinert (2006).

which is typical of the Los Angeles area. (This cost is about 10 times higher than the value used in H2A.)

Table B10. Summary Capital Costs for Hydrogen Refueling Stations

	H2A Equipment Costs (current tech)	UCD study (2009-2014) = $2 million + 2 x H2A current tech equipment costs	UCD Study 2015-2017 = $2 million + H2A current tech equipment costs
Mobile Refueler	**-**	$1 million	$1 million
(Compressed Gas H2 Truck Delivery)	**100 kg/d** **$107,000 (equip) + $24,000 (other)**	100 kg/d $214,000 (equip) + $2 million (other)	100 kg/d $107,000 (equip) + $2 million (other)
LH2 Truck Delivery	**100 kg/d** $289,000 (equip) + $65,000 (other) **1500 kg/d** $754,000 (equip) + $170,000 (other)	**100 kg/d** $580,000 (equip) + $2 million (other) **1500 kg/d** $1.5 million(equip) + $2 million (other)	**100 kg/d** $290,000 (equip) + $2 million (other) **1500 kg/d** $0.75 million(equip) + $2 million (other)
Onsite Reformer	**100 kg/d** $143,000 (reformer) + $447,000 (station) + 284,000 (other) **1500 kg/d** $957,000 (reformer)+ 3.08 million (station) + $878,000 (other)	**100 kg/d** $1.18 million (equip) + $2 million (other) **1500 kg/d** $8 million(equip) + $2 million (other)	**100 kg/d** $0.59 million (equip) + $2 million (other) **1500 kg/d** $4 million(equip) + $2 million (other)
Onsite Electrolyzer	**100 kg/d** $165330 (electrolyzer) + $446,829 (station) + 245,333 (other) **1500 kg/d** $2479950 (electrolyzer) + $ 2793433 (station) + 449234 (other)	**100 kg/d** $1.2 million (equip) + $2 million (other) **1500 kg/d** $10.6 million(equip) + $2 million (other)	**100 kg/d** $0.6 million (equip) + $2 million (other) **1500 kg/d** $5.3 million(equip) + $2 million (other)

Table B11 Simplified Cost Summary Table for Hydrogen Refueling Stations

	2009-2011	2012-2014	2015-2017 (high)	2015-2017 (low)
Mobile Refueler 100 kg/d	**1.00**	**1.00**	**1.00**	**0.40**
Comp.Gas Truck Delivery 100 kg/d	**3.00**	**2.22**	**2.22**	**2.11**
LH2 Truck Delivery				
100 kg/d	**4.00**	**2.58**	**2.58**	**2.29**
250 kg/d		**2.67**	**2.67**	**2.33**
400 kg/d		**2.81**	**2.81**	**2.40**
1000 kg/d		**3.21**	**3.21**	**2.61**
Onsite Reformer				
100 kg/d	**3.50-4.00**	**3.18**	**3.18**	**2.59**
250 kg/d		**3.99**	**3.99**	**3.00**
400 kg/d		**4.81**	**4.81**	**3.41**
1000 kg/d		**7.76**	**7.76**	**4.88**
Onsite Electrolyzer				
100 kg/d	**-**	**3.22**	**3.22**	**2.61**
250 kg/d		**4.21**	**4.21**	**3.11**
400 kg/d		**5.25**	**5.25**	**3.63**
1000 kg/d		**9.26**	**9.26**	**5.63**

Table B12 Summary Operations and Maintenance Costs for Hydrogen Refueling Stations

	Variable O&M	Fixed O&M
Mobile Refueler	**Compressed H2 supply** $20/kg H2	100 kg/d: 13 % cap.cost /y + $130,000/y (land rental)
Portable Refueler (Compressed Gas H2 Truck Delivery)	**Compressed H2 supply + station H2 compression** $20/kg H2 1.25 kWh/kg H2 x electricity price $/kWh	100 kg/d: 13 % cap.cost /y + $130,000/y (land rental)
LH2 Truck Delivery	**LH2 supply+ station LH2 pump/compression** $10/kg LH2 + 0.81 kWh/kg H2 x electricity price $/kWh	100 kg/d: 11 % cap.cost /y + $130,000/y (land rental) 250-1000 kg/d: 11% cap.cost /y + $360,000/y (land rental)
Onsite Reformer	**NG feed + station H2 compression** 0.156 MBTU NG/kg H2 x NG price $/MBTU + 3.08 kWh/kg H2 x elec price $/kWh	100 kg/d: 10 % cap.cost /y + $130,000/y (land rental) 250-1000 kg/d: 7% cap.cost /y + $360,000/y (land rental)
Onsite Electrolyzer	**Electrolyzer electricity + station H2 compression:** 55.2 kWh/kg H2 x elec price $/kWh	Same as onsite reformer

Table B13 Assumed energy prices and economic assumptions

ENERGY PRICES	**CURRENT PRICE**
Natural Gas (Commercial rate)	$12/MMBTU
Electricity (Commercial rate)	$0.10/kWh
Compressed H2 (for mobile refueler)	$20/kg
LH2 (truck delivered)	$10-12/kg
Bio-Methane	$20-40/MMBTU
Ethanol	$2-4/gallon gasoline equivalent
Green Electricity premium	$0.01-0.05/kWh
Land rent (Los Angeles)	$5.0/sq.ft/month
ECONOMIC ASSUMPTIONS	
Real discount rate	12%
Equipment lifetime	15 years

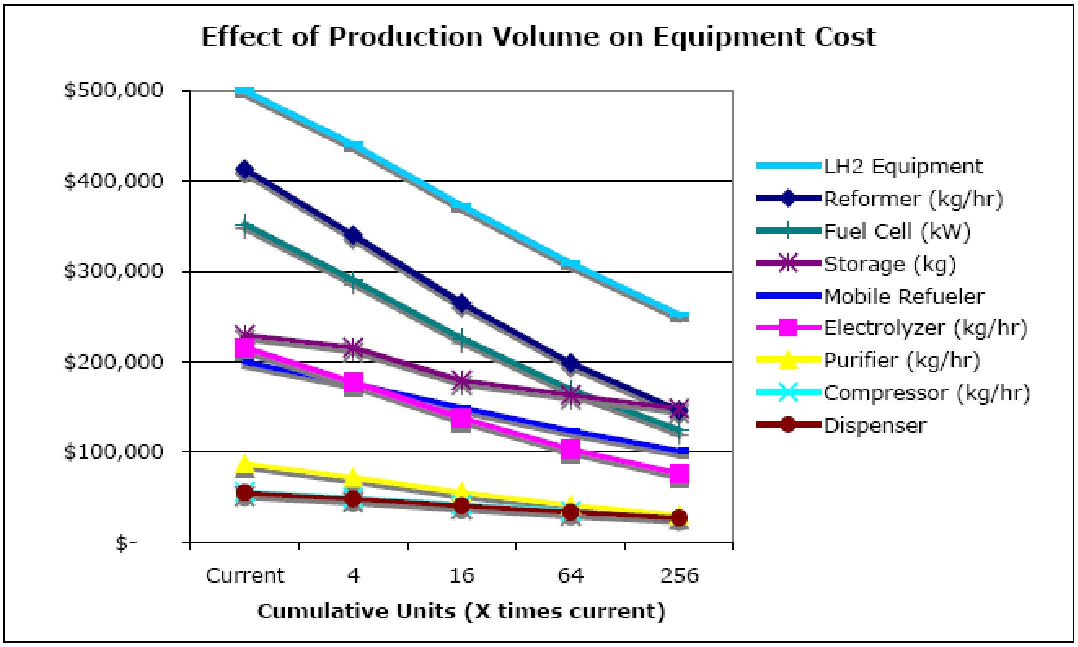


Figure B8 From Weinert (2006). Cost scales with volume of units produced

ANALYSIS OF AN ALTERNATIVE TRANSITION SCENARIO

In this section we analyze an alternative transition path that begins with a more extensive initial network. This illustrates the trade-off between cost and convenience (measured as travel time).

Pathway 2: Compared to Pathway 1 (which started with 8 stations in 4 clusters), we start with more stations and a geographically wider network of 8 clusters of 2 stations each, and build up each cluster and connector stations over time.

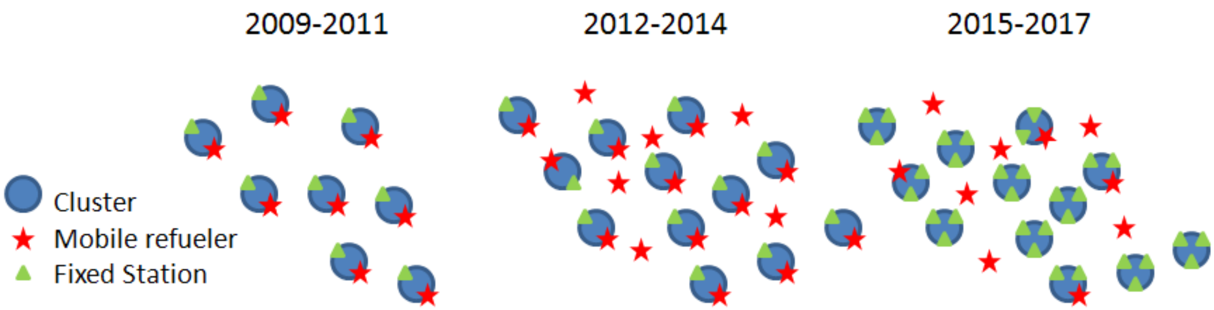
2009-2011 -> 2012-2014 -> 2015-2017
Scenario 1 -> Scenario 8a-> Scenario 9a

2009-2011: Pathway 2 starts with 16 stations, serving 636 FCVs, located in 8 clusters of 2 stations per cluster. Eight of the stations are fixed (100 kg/d SMRs), the other 8 are mobile refuelers. The average travel time from home to station is 3.2 minutes and the diversion time is 5.1 minutes. The total capital cost for this phase is $40 million, and annual operating costs are about $7-8 million per year. To pay back only operating costs hydrogen would have to sell for $78/kg. To cover the full annualized cost (including capital), hydrogen would have to sell for about $142/kg.

2012-2014: In 2012, we expand the network to 30 stations, serving 3442 FCVs, located in 12 clusters of 2 stations each, plus 6 connector stations. The new stations include an additional 10 100 kg/d mobile refuelers plus 12 250 kg/d SMRs (it is assumed that the existing 8 100 kg/d SMRs are upgraded to 250 kg/d). The capital investment during this phase is $58 million, and annual operating costs are about $15-19 million/year. To pay back only operating costs (for the entire network) hydrogen would have to sell for $27/kg. To cover the full annualized cost (including capital from 2009-2014), hydrogen would have to sell for about $50/kg. The average travel time from home to station is 3.0 minutes and the diversion time is 3.9 minutes.

2015-2017: In 2015, we expand the network to 42 stations, serving 25,000 FCVs located in 12 clusters of 3 stations each, plus 6 connector stations. The new stations include 20 1000 kg/d SMRs. The capital investment during this phase is $98 million for the 20 1000 kg/day SMRs, and annual operating costs are about $29-40 million/year. To pay back only operating costs hydrogen would have to sell for $7.6/kg. To cover the full annualized cost (including capital from 2009 to 2017), hydrogen would have to sell for about $14/kg. The average travel time from home to station is 2.6 minutes and the diversion time is 3.6 minutes.

Cash flows are plotted in Figure B10 for Pathway 2, assuming hydrogen is sold for $11/kg throughout the transition period (extended to 2025). The annual cash flow is negative up through about 2015. The cumulative investment required is negative for the first 15 years, but the strategy fully repays by about 2024. After that time, there is significant profit. A clustered early infrastructure costing about $240 million to build, pays for itself in about 15 years.



	636 FCVs	3442 FCVs	25,000 FCVs
# Stations	16	30	42
# clusters	8 (2 sta/cluster)	12 (2 sta/cluster)	12 (3 sta/cluster)
# connect.sta	0	6	6
Station Mix	8 Mobile refuelers 8 SMRs (100 kg/d)	18 Mobile Refuelers 12 SMRS (250 kg/d)	10 Mobile refuelers 12 SMRs (250 kg/d) 20 SMRs (1000 kg/d)
New Equip. Added	8 Mobile refuelers 8 SMRs (100 kg/d)	10 Mobile Refuelers 12 SMRS (250 kg/d)	20 SMRs (1000 kg/d)
Capital Cost	$40 Million	$58 Million	$98 Million
O&M Cost	6.6-8.1 $Million/y	15-19 $Million/y	29-40 $Million/y
H2 cost $/kg	142	50	14.1
Ave travel time	3.2 minutes	3.0 minutes	2.6 minutes
Diversion time	5.1 minutes	3.9 minutes	3.6 minutes

Figure B9 Summary of Transition Pathway 2.

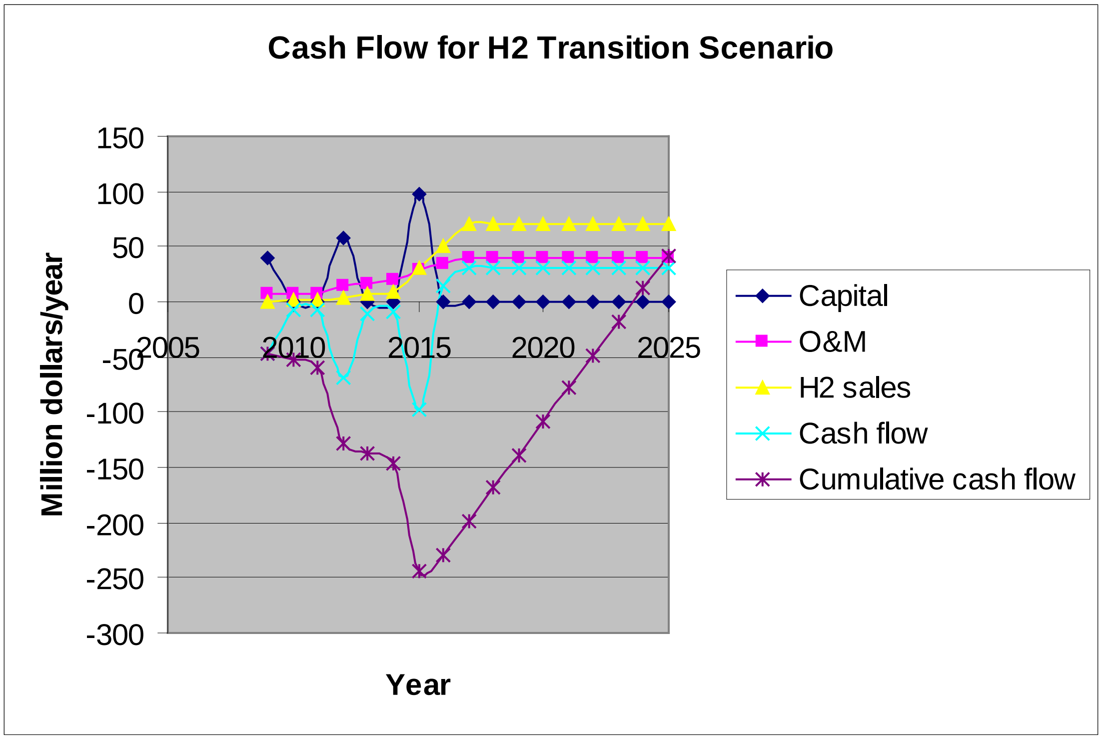


Figure B10 Cash Flow for Pathway 2 assuming that hydrogen is sold for $11/kg.

Comparing Pathways 1 and 2 suggests that it may be less costly to start with a limited number of stations and clusters and expand, rather than starting with stations located in 8 and then 12 clusters. In both cases, if hydrogen can be sold for $10-11/kg, the early clustered infrastructure pays for itself before 2025.

APPENDIX C.

ADDITIONAL STATION PLACEMENT CONSIDERATIONS

Locations of Cluster Stations

Actual sites for stations are contingent on the actual conditions of a site and are therefore beyond the scope of this report. In the local context however, general customer patterns can be used to suggest plausible strategies. For example, refueling is generally heavier near the highway as shown in Figure C1.

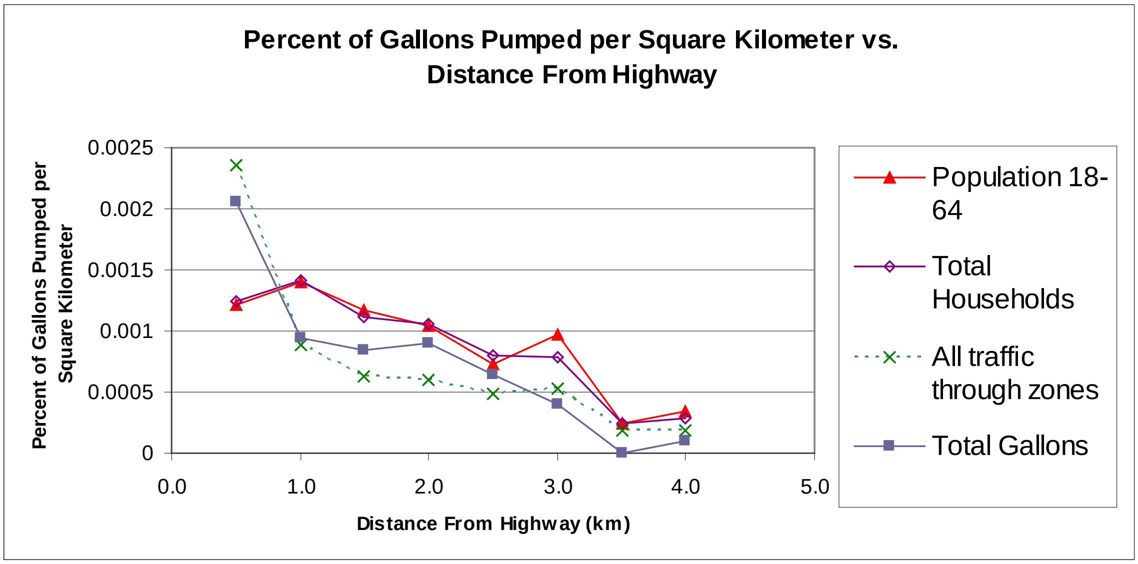


Figure C1 Intensity of gallons pumped as a function of distance from a limited access highway in greater Sacramento.

Although this is an example from Sacramento, the results are assumed to be similar for the Los Angeles region. One difference may be that high capacity roads not classified as "highways" in LA may be analogous to limited access highways in Sacramento. This graph suggests that larger stations in the system should be sited near the freeway or other high capacity roads. This tendency to refuel near the freeway may have to do with the fact that people access many services via the freeway and stations near the freeway are on the way to or from many destinations.

Using general refueling patterns we can postulate a convenient arrangement of stations with respect to the freeway (Figure C2)

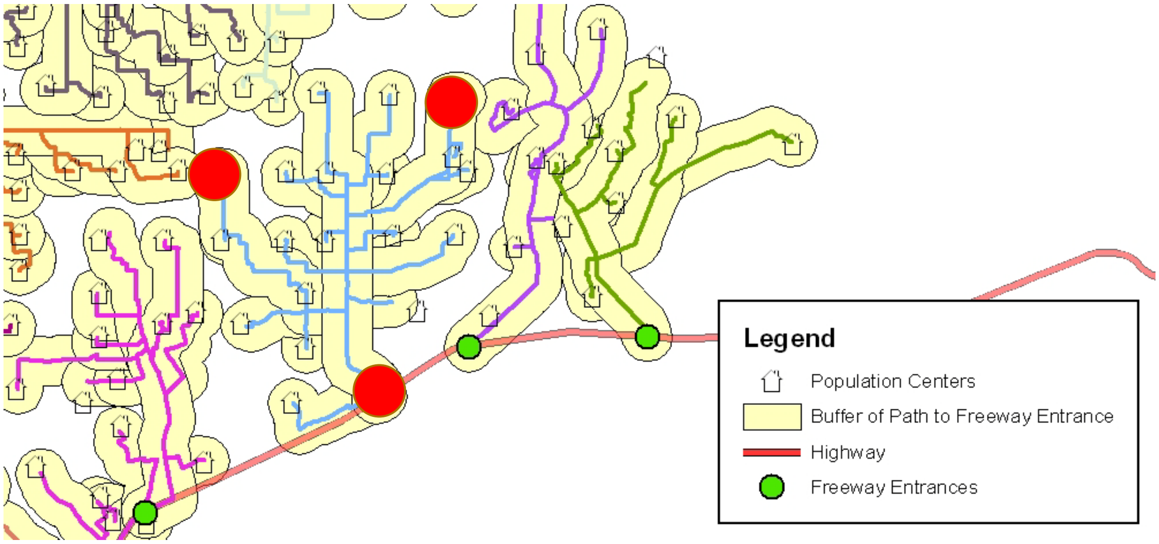


Figure C2 Possible three station arrangement (in red) where two customer centers are located near the top two stations. Both neighborhoods can conveniently access the freeway station in the event of a failure of the neighborhood station. The freeway station can also act as a regional connector station.

Due to the fact that freeway stations can act as both a local and connector station, and the general tendency of high refueling volumes near the freeway, larger stations could be sited near the freeway and act as an anchor station for the area. Also, the arrangement above suggests that the local freeway station could be sited first and serve many initial neighborhoods. Subsequent stations could be sited nearer to customers' homes.