Available online at www.sciencedirect.com
ScienceDirect
International Journal of Hydrogen Energy 32 (2007) 2731–2742
International Journal of HYDROGEN ENERGY
www.elsevier.com/locate/ijhydene

Lifecycle impacts of natural gas to hydrogen pathways on urban air quality

Guihua Wang[a,*], Joan M. Ogden[b], Michael A. Nicholas[c]

[a]*Department of Civil and Environmental Engineering and Institute of Transportations Studies, University of California, Davis, CA 95616, USA*
[b]*Department of Environmental Science and Policy and Institute of Transportations Studies, University of California, Davis, CA 95616, USA*
[c]*Institute of Transportations Studies, University of California, Davis, CA 95616, USA*

Received 21 October 2006; received in revised form 10 January 2007; accepted 10 January 2007
Available online 27 February 2007

Abstract

In this paper we examine the potential air quality impacts of hydrogen transportation fuel from a lifecycle analysis perspective, including impacts from fuel production, delivery, and vehicle use. We assume that hydrogen fuel cell vehicles are introduced in a specific region, Sacramento County, California. We consider two levels of market penetration where 9% or 20% of the light duty fleet are hydrogen fuel cell vehicles. The following three natural gas to hydrogen supply pathways are assessed in detail and compared in terms of emissions and the resulting changes in ambient air quality: (1) onsite hydrogen production; (2) centralized hydrogen production with gaseous hydrogen pipeline delivery systems; and (3) centralized hydrogen production with liquid hydrogen truck delivery systems. All the pathways examined use steam methane reforming (SMR) of natural gas to produce hydrogen. The source contributions to incremental air pollution are estimated and compared among hydrogen pathways. All of the hydrogen pathways result in extremely low contributions to ambient air concentrations of NO_x, CO, particulates, and SO_x, typically less than 0.1% of the current ambient pollution for both levels of market penetration. Among the hydrogen supply options, it is found that the central SMR with pipeline delivery systems is the lowest pollution option available provided the plant is located to avoid transport of pollutants into the city via prevailing winds. The onsite hydrogen pathway is comparable to the central hydrogen pathway with pipeline systems in terms of the resulting air pollution. The pathway with liquid hydrogen trucks has a greater impact on air quality relative to the other pathways due to emissions associated with diesel trucks and electricity consumption to liquefy hydrogen. However, all three hydrogen pathways result in negligible air pollution in the region.

Keywords: Lifecycle analysis (LCA); Transportation; Fuel cell vehicles (FCV); Hydrogen; Natural gas (NG); Hydrogen pathways; SMR; Air pollution; Source contributions

1. Introduction

There is growing interest in hydrogen as a transportation fuel. One of the key motivations for hydrogen is its potential to reduce emissions of air pollutants. Although hydrogen fuel cell vehicles (HFCVs) emit no tailpipe emissions, hydrogen must be produced from other sources and delivered to users. These steps can generate air pollutant emissions. Thus, the entire lifecycle from well to wheels (WTW) must be considered in an assessment of hydrogen's air quality impacts. Clearly, emissions for hydrogen (and associated environmental impacts) will depend on how hydrogen is made. Further, air quality is related to emissions in complex ways that depend on the mix of emissions sources, meteorology, and geography.

In this study we estimate regional air quality impacts for three different hydrogen production and delivery pathways, based on steam methane reforming (SMR) of natural gas, which is currently the most common way of making hydrogen. From a lifecycle analysis (LCA) perspective, this research compares these pathways, presents the methodology to link hydrogen pathways to ambient air quality in urban Sacramento, California, and estimates the increases in ambient pollution corresponding to some key hydrogen supply chain steps.

* Corresponding author. Fax: +1 530 752 6572.
E-mail address: wghwang@ucdavis.edu (G. Wang).

0360-3199/$ - see front matter © 2007 International Association for Hydrogen Energy. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijhydene.2007.01.006

2. Methodology

2.1. Estimating hydrogen demand

We consider two scenarios, where 9% and 20% of light duty vehicles in Sacramento are HFCVs. We keep the number of gasoline vehicles constant in both scenarios, and add hydrogen vehicles and supply systems to the Sacramento area. Thus, the total vehicle population is the sum of the year 2000 light duty gasoline fleet plus the added hydrogen vehicles. This allows us to estimate the incremental impact of hydrogen energy systems on ambient pollution levels in the Sacramento area, without the complexities of simultaneously reducing the number of gasoline vehicles (see Section 3.1). Table 1 shows demographic data for Sacramento [1]. From these and hydrogen vehicle assumptions we estimate regional hydrogen demand for vehicle use for each scenario (see Table 2).

2.2. Supply options considered

For each market penetration, the following three natural gas to hydrogen pathways are considered [2]:

- onsite hydrogen production (i.e., the onsite pathway, see Fig. 1);
- centralized hydrogen production with gaseous hydrogen pipeline delivery systems (i.e., the pipeline pathway, see Fig. 2); and
- centralized hydrogen production with liquid hydrogen truck delivery systems (i.e., the truck pathway, see Fig. 3).

The technologies making up the hydrogen energy supply are assumed to have efficiencies and emissions corresponding to current (year 2005) technologies (see Table 3) [3].

Table 1
Demographic data for Sacramento

Parameters	Value
City population in Sacramento (in 2000)	1.393 million
Vehicle ownership	0.8 vehicles/person
Vehicle miles traveled per year (VMT)	15,000 miles/year

Table 2
Hydrogen vehicle assumptions and hydrogen demand

Parameters	Scenario 1	Scenario 2
HFCV fleet fraction	9%	20%
Number of HFCVs	111,400	278,600
Hydrogen fuel demand	78,000 kg/day	195,000 kg/day
Number of hydrogen stations	27	66
Fuel economy of HFCV	60 miles/kg of hydrogen	
Hydrogen consumption	0.7 kg/vehicle/day	
Hydrogen station size	3000 kg/day	
Liquid truck capacity	3000 kg of liquid hydrogen	

2.3. Lifecycle emission inventories of hydrogen pathways

To estimate the environmental impacts of hydrogen vehicles we consider all emissions associated with the system. The full fuel cycle for a given transportation fuel, also called WTW, includes the following processes: feedstock extraction, feedstock transport; fuel production, storage, distribution, dispensing, and vehicle operation [4]. Not only direct emissions rising from a primary fuel pathway but also indirect emissions associated with sub-pathways are taken into consideration. Fig. 4 presents the concept of an integrated natural gas to hydrogen pathway with liquid hydrogen truck delivery systems, and the dashed line area delimits the parts of lifecycle system that are included in this analysis [2].

In this case study we have chosen to neglect the impact of spatially distant pathway steps (such as natural gas extraction and oil refining) on air quality in Sacramento. However, we do consider emissions from the electricity used in hydrogen pathways steps. Electricity consumed in both primary hydrogen pathway and sub-pathways is assumed to come from the average power mix for Sacramento. The electric generation mix in Sacramento is derived from US Department of Energy's eGRID2002 data for the year 2000 [5]. The power control area (PCA) of interest is defined as the Sacramento municipal utility district only. There are 17 power plants serving the region and their profiles are shown in Table 4. The electric generation mix (i.e., percentage of each kWh of electricity generated in 2000) by fuel type is summarized in Table 5. Electricity from clean renewables (i.e., solar, wind, and hydro) in Sacramento accounts for more than 42% of electric generation mix, which makes it not as severely polluting as in other regions to consume a large amount of electricity to compress or liquefy hydrogen.

Heavy-duty diesel-fueled trucks delivering liquid hydrogen are considered as a mobile source of emissions. Liquid hydrogen trucks are assumed to travel along a fixed route from the central plant and arrive at a refueling station, and then come back along the same truck route. For simplicity, the truck routes, which are determined using a GIS-based optimization algorithm, are treated as a line source of vehicle exhaust. The number of truck trips is estimated based on the assumed station size and the truck capacity (see Table 2).

To assess energy consumption and emissions of each pathway step, emissions factors and hydrogen infrastructure engineering/economic design models are used. A full fuel cycle energy use and emissions model, GREET1.7, which is developed and maintained at Argonne National Laboratory, is the source of emission factors [3,4]. We assume energy supply and vehicle characteristics that correspond to the current technologies (year 2005) represented in GREET1.7.

2.4. Spatial layout of emission sources associated with hydrogen supply pathways

The spatial locations of emission sources associated with various hydrogen pathway supply steps have a strong influence on the regional air pollution concentrations. In this study,

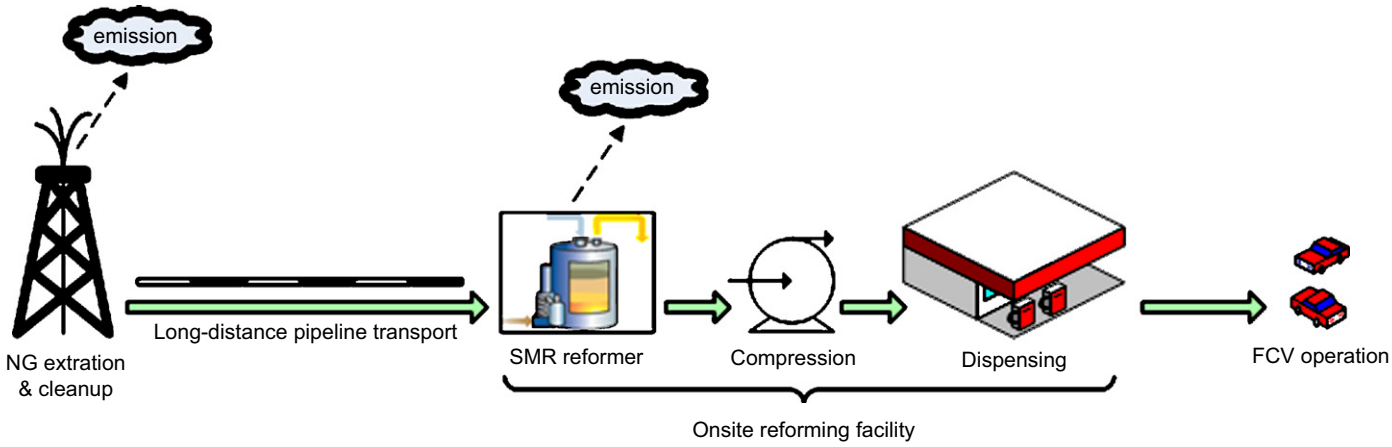

Fig. 1. NG to hydrogen pathway with onsite production.

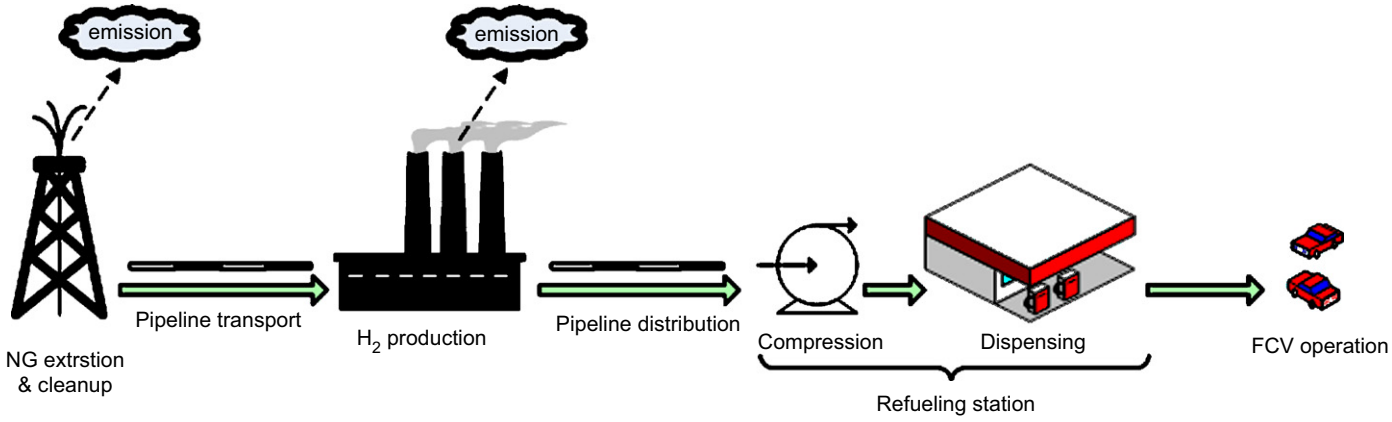

Fig. 2. NG to hydrogen pathway with pipeline delivery systems.

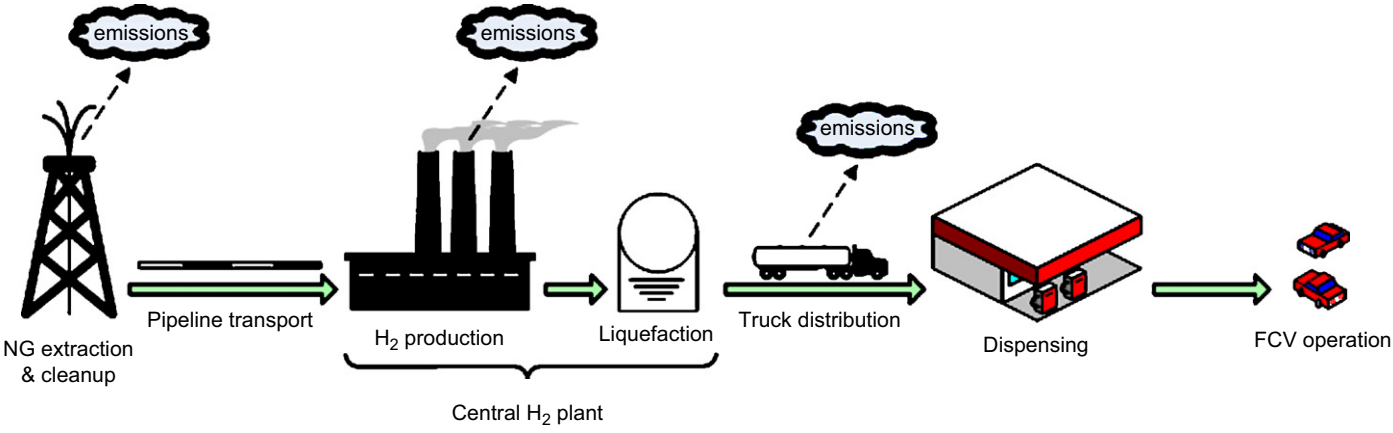

Fig. 3. NG to hydrogen pathway with liquid hydrogen truck delivery systems.

we assume particular spatial locations for each step of the hydrogen supply pathway: natural gas extraction, hydrogen production, hydrogen delivery, and refueling stations. Each is described below. (We assume that hydrogen vehicles do not emit any air pollutants during operation, so the locations of hydrogen cars are not important for the analysis.)

Natural gas extraction and transport: Natural gas fields are located far from Sacramento, and therefore the impacts of natural gas extraction and pipeline transport on air quality in urban Sacramento are neglected.

Centralized hydrogen production: A central hydrogen production plant is assumed to be close to currently existing natural gas-fired power plants in south Sacramento.

Refueling stations: We choose sites for hydrogen stations from among existing gasoline station locations in Sacramento. Hydrogen station sites are selected to minimize

the average travel time from home to the closest station for all customers, given a certain number of stations. Customer locations are approximated using traffic analysis zones (TAZs). The method employs GIS data and optimization techniques and is described in detail by Nicholas [6]. The locations of stations in our study are shown in Figs. 5 and 6. Fig. 5 corresponds to the scenario of a 9% market penetration and 27 refueling stations. Fig. 6 corresponds to the scenario of a 20% market penetration and 66 refueling stations.

Table 3
Hydrogen supply technology efficiencies, on a lower heating value (LHV) basis

	Onsite pathway (%)	Pipeline pathway (%)	Truck pathway (%)
Conversion efficiency	69.0	71.5	71.5
Compression efficiency	94.0	92.5	N.A.
Liquefaction efficiency	N.A.	N.A.	70.5

Onsite hydrogen production at stations: Emissions associated with hydrogen production from small steam reformers at refueling stations occur at the station sites.

Hydrogen delivery: Liquid hydrogen trucks are assumed to travel on real-world highways and the actual route that each truck (from the central hydrogen plant to the station) travels is determined using GIS data on a minimum travel time basis.

Electricity for hydrogen compression and liquefaction: As noted above, we use actual locations of utility plants in the Sacramento area to estimate incremental emissions associated with hydrogen compression and liquefaction at the hydrogen plant, and with compression at refueling stations.

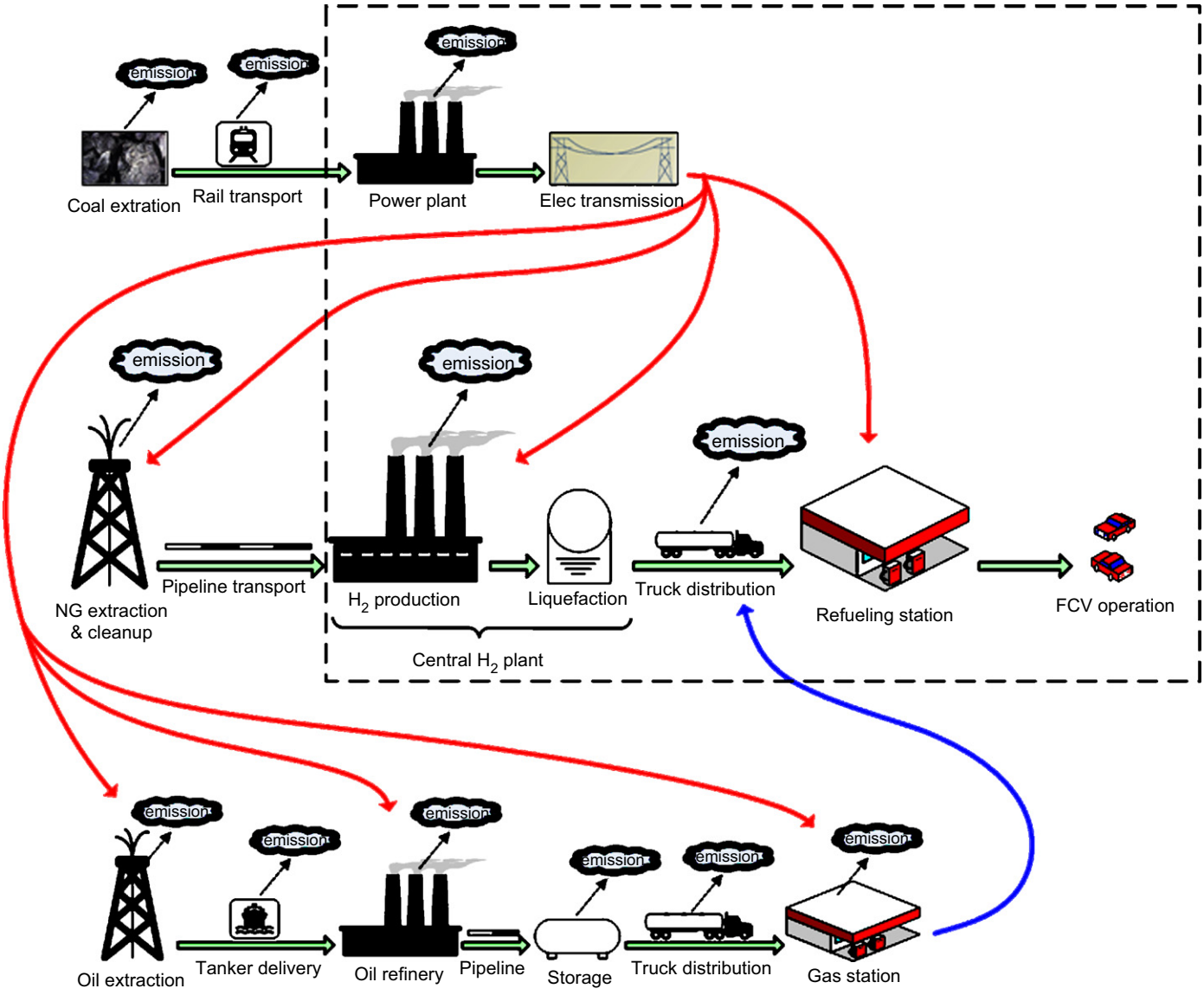

Fig. 4. Integrated NG-to-H_2 pathway (liquid hydrogen example).

Table 4
Sacramento PCA power plant profiles in 2000

Plant name	County name	Primary fuel	Generator capacity (MW)	Annual net generation (MWh)
Camino	El Dorado	Hydro	154	429,969
Camp Far West	Placer	Hydro	7	31,560
Carson Ice CG	Sacramento	NG	126	556,594
Hedge PV	Sacramento	Solar	0.2	362
Jaybird	El Dorado	Hydro	154	612,984
Jones Fork	El Dorado	Hydro	12	22,297
Kiefer LF	Sacramento	Biomass	9	74,731
Loon Lake	El Dorado	Hydro	82	98,011
Mcclellan	Sacramento	NG, Oil	74	15,743 (NG), 7 (Oil)
PVUSA	Yolo	Solar	1	253
Robbs Peak	El Dorado	Hydro	30	49,464
SCA	Sacramento	NG	150	649,213
Solano Wind	Solano	Wind	7	6774
Solar	Sacramento	Solar	2	1887
SPA	Sacramento	NG	174	1,404,149
Union Valley	El Dorado	Hydro	47	139,504
White Rock	El Dorado	Hydro	230	592,124
PCA total			1257	4,685,626

Table 5
Sacramento PCA resource mix in 2000

Power-plant type	Generation mix (%)
Oil	0.0001
Biomass	1.59
NG	56.04
Coal	0.00
Nuclear	0.00
Solar	0.05
Wind	0.14
Hydro	42.17
Total	100.00

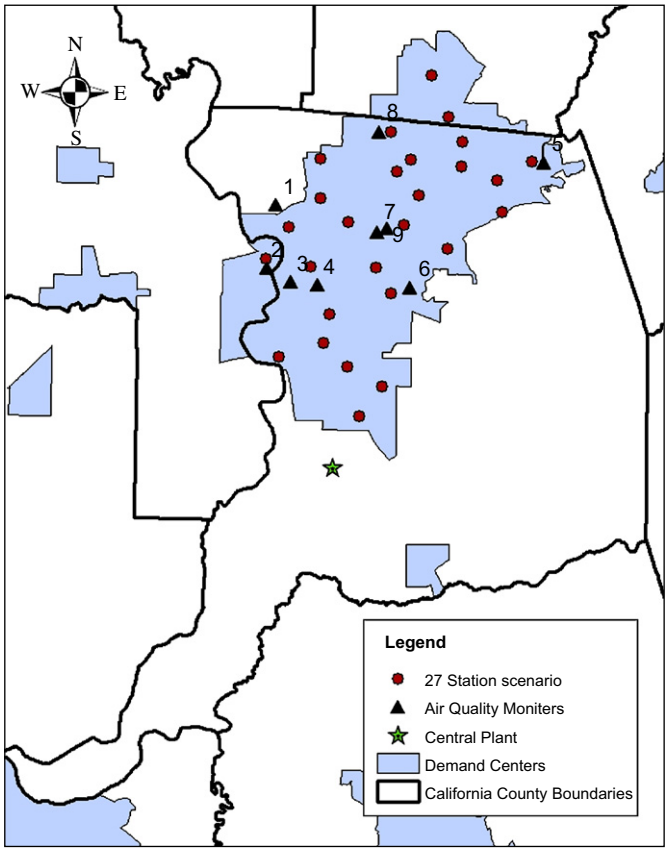

Fig. 5. Spatial layout of refueling stations, central plant, and receptors (9% scenario).

2.5. Atmospheric transport and urban air quality

We employ a complicated model for atmospheric transport of pollutants to estimate increases in pollutant concentrations in the Sacramento area for each hydrogen supply case. We employ the spatial layouts in Figs. 5 and 6 for the 9% and 20% market penetration cases.

We estimate concentrations at nine "receptor sites" in Sacramento corresponding to actual locations of air pollution monitors. This allows us to compare the incremental changes in ambient concentrations due to hydrogen against actual measured ambient concentrations. Only increases in air pollution due to primary criteria pollutants and ozone precursors are estimated; i.e. the focus is on the following directly emitted pollutants: CO, VOC, NO_x, PM_{10}, and SO_x (NO_x refers to both NO and NO_2 here, and SO_x refers roughly to SO_2.). We assume that each emission source along the hydrogen pathways emits pollutants at a constant rate. We further assume that pollutants disperse on an urban or regional scale, and the distance from an emission source to any air quality monitor of concern is less than 100 km, which assures that the above pollutants can be considered as conserved pollutants [7]. Studies by other researchers show that incremental annual concentrations are of much more interest than hourly or daily fluctuations since they are more feasible and simpler to use to estimate yearly external costs associated with human exposure to ambient pollution [7–9].

Only physical transport of the above pollutants is taken into account, without considering chemical transformation or decaying of pollutants in the atmosphere. The Industrial Source Complex short term model, ISCST3, developed by US EPA, is a steady-state Gaussian atmospheric dispersion model which can assess pollutant concentrations from a wide variety of sources associated with industrial complexes [10]. We use this model to estimate air quality at the receptor locations.

Below is the basic equation of predicting the time-average concentrations downwind of an elevated point source, accounting for superposition due to reflection from the ground [7,11,12].

$$C(x,y,z;H_E) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \left\{ \exp\left[-\frac{(z-H_E)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H_E)^2}{2\sigma_z^2}\right] \right\},$$

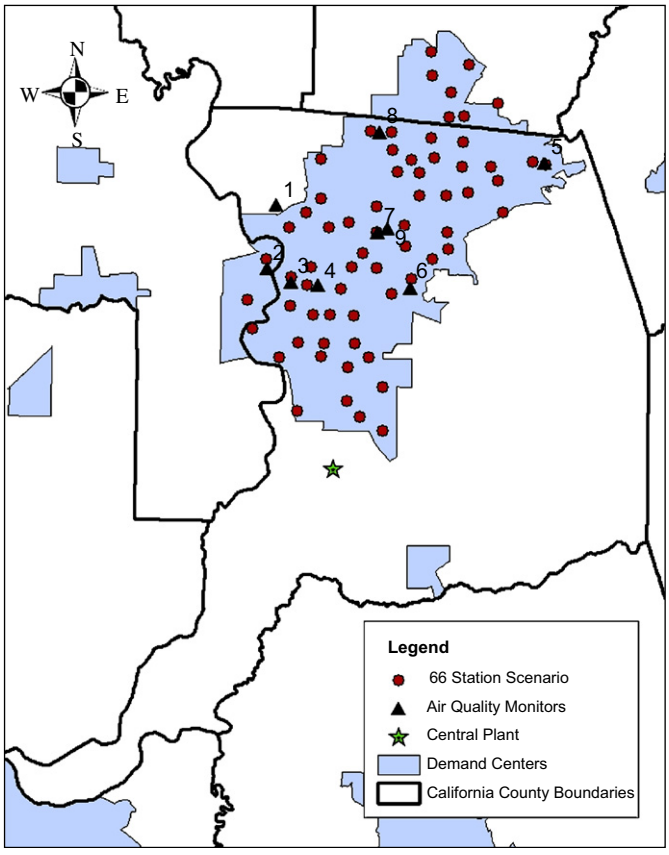

Fig. 6. Spatial layout of refueling stations, central plant, and receptors (20% scenario).

where H_E, effective stack height. H_E = physical stack height (h) + plume rise (ΔH); $C(x, y, z; H_E)$, concentration of the pollutant at a receptor location (x, y, z); Q, steady-state mass emission rate of the pollutant; u, mean wind speed at the effective stack height. $u = x/t$, where t is the travel time of the pollutant from the release point to the location (x, y, z); σ_y, transverse dispersion parameter. It is the standard deviation of the transverse concentration distribution at the downwind distance x; σ_z, vertical dispersion parameter. It is the standard deviation of the vertical concentration distribution at the downwind distance x.

The Typical Meteorological Year 2 (TMY2), developed at National Renewable Energy Laboratory (NREL), is a complete annual cycle of hourly meteorological data extracted from the 30-year period of 1961–1990 to represent a typical long-term meteorological condition in a specific region [13]. To run ISCST3, such hourly meteorological data as hour of day, wind direction, wind speed, ambient temperature, atmospheric stability class, rural mixing height, and urban mixing height are needed. The TMY2 data set for Sacramento County is adopted in this research to predict changes in ambient air pollution under a historically representative meteorological condition rather than a worst-case condition [12,14].

The Air Quality System (AQS) maintained by US EPA contains ambient air pollution data and profiles of thousands of air quality monitoring stations throughout the country; states, local, and tribal agencies submit their data directly to AQS and EPA itself also collects data [15]. There are nine appropriate air monitoring stations officially maintained within or close to urban Sacramento based on the AQS system. These stations serve as receptors of pollutants in the research, and their profiles are shown in Table 6 [15]. Figs. 4 and 5 present their spatial layout in Sacramento. The individual incremental concentrations at these receptors and their average values represent the ambient pollution level attributable to each of hydrogen pathways. A receptor is not necessarily a typical representative of urban air quality when it happens to be located very close to a truck route or a refueling station.

Table 6
Air quality monitors in Sacramento (receptors of pollutants)

Monitor	Name and address
1	Sacramento-3801 Airport Road
2	West Sacramento-15th Street
3	Sacramento-T Street
4	Sacramento-Health Dept Stockton Blvd
5	Folsom-Natoma Street
6	Sacramento-Branch Center Road
7	Sacramento-El Camino
8	North Highlands-Blackfoot Way
9	Sacramento-Del Paso Manor

Table 7 shows NAAQS primary standards, set by EPA in 1990 to protect public health [16,17], and the actual pollution level in Sacramento in 2000, which is calculated based on the AQS data set above. It is important to keep these ambient "baseline" concentrations in mind, as we discuss the incremental concentrations due to additional large numbers of hydrogen vehicles.

3. Results and discussion

3.1. Incremental pollution attributable to hydrogen pathways

We use the ISCST3 program to estimate the additional pollution at a receptor for each of our three hypothetical hydrogen pathways. Figs. 7–16 present the magnitudes of incremental annual average concentrations of conserved pollutants due to existence of hydrogen pathways. There are three pathways (i.e., the onsite pathway, the pipeline pathway, and the truck pathway), five pollutants (i.e., CO, VOC, NO_x, PM_{10}, and SO_x), and nine pollution receptors (denoted by R1–R9). It is easy to see that environmental impacts vary with receptor site, which reflect the location variations and geographic factors, even when they are attributable to the same hydrogen pathway.

The first thing to note is that all three hydrogen supply pathways result in very small incremental amounts of pollution compared to ambient pollution levels, on the order of 0.1% increase at 20% market penetration, and often much less. This is in contrast to recent results for natural gas based distributed generation of electricity in California, which resulted in more air pollution than central power plants [12].

Table 7
NAAQS and actual pollution level in Sacramento in 2000

Pollutant	NAAQS (EPA,1990)		Sac. 2000 annual ave. conc. ($\mu g/m^3$)
	Primary standards	Averaging times	
Carbon monoxide (CO)	9 ppm (10 mg/m^3)	8 h	639.69
	35 ppm (40 mg/m^3)	1 h	
Volatile organic compounds (VOCs)	No standards	N.A.	74.80 (NMOC)
Nitrogen dioxide (NO_2)	0.053 ppm (100 $\mu g/m^3$)	Annual (arith. mean)	56.64
Particulate matter (PM_{10})	50 $\mu g/m^3$	Annual (arith. mean)[a]	22.45
	150 $\mu g/m^3$	24 h	
Sulfur oxides (SO_x)	0.03 ppm (80 $\mu g/m^3$)	Annual (arith. mean)	7.92
	0.14 ppm (365 $\mu g/m^3$)	24 h	

[a]EPA revoked the annual PM_{10} standard in 2006 (effective December 17, 2006).

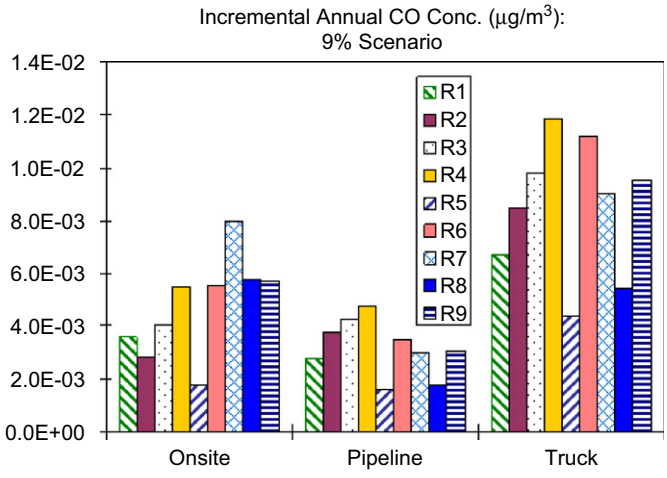

Fig. 7. Incremental annual average concentration of CO (9% scenario).

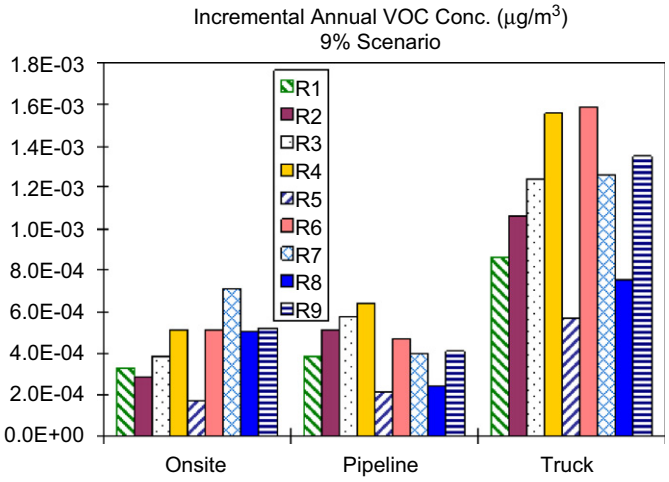

Fig. 9. Incremental annual average concentration of VOC (9% scenario).

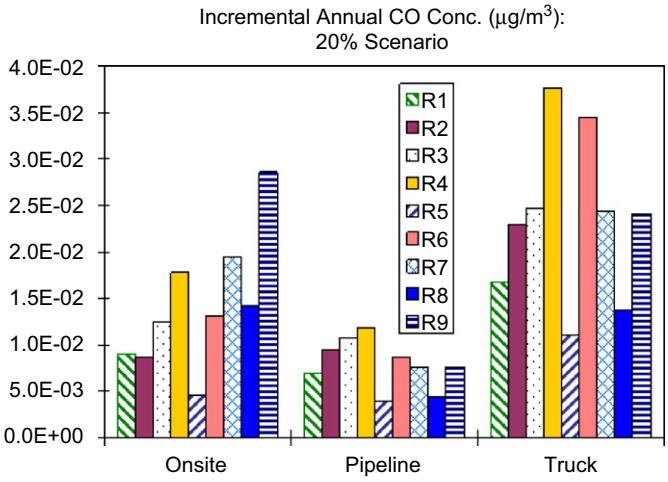

Fig. 8. Incremental annual average concentration of CO (20% scenario).

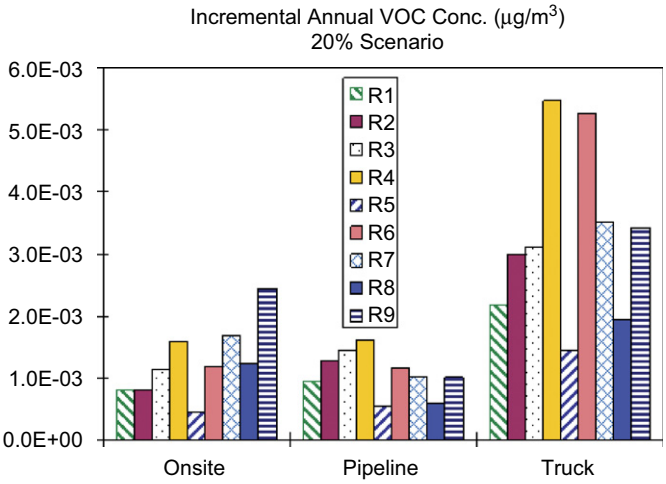

Fig. 10. Incremental annual average concentration of VOC (20% scenario).

For the truck pathway, emissions tend to be higher than for the other two supply pathways. As shown in Figs. 17–21 most of the emissions for the liquid truck pathway are due to diesel truck emissions resulting from the delivery of the liquid hydrogen and from the electricity used to liquefy the product hydrogen.

For the onsite scenario, there are no hydrogen delivery emissions since all the hydrogen fuel is produced and dispensed

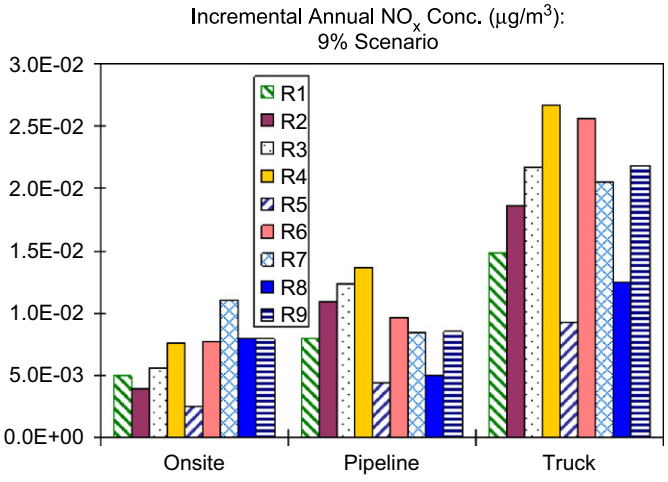

Fig. 11. Incremental annual average concentration of NO_x (9% scenario).

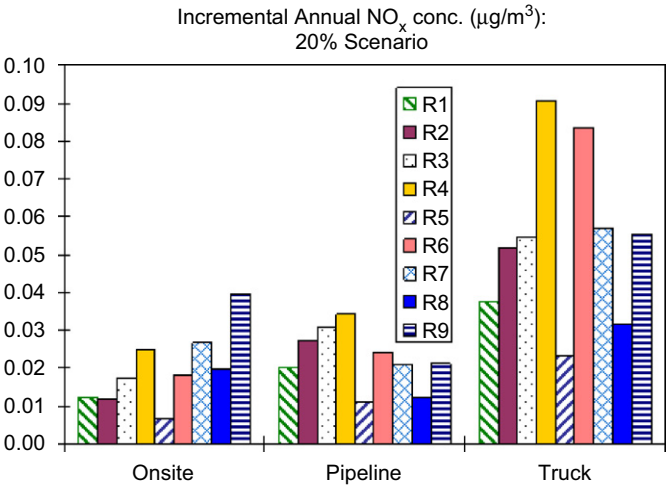

Fig. 12. Incremental annual average concentration of NO_x (20% scenario).

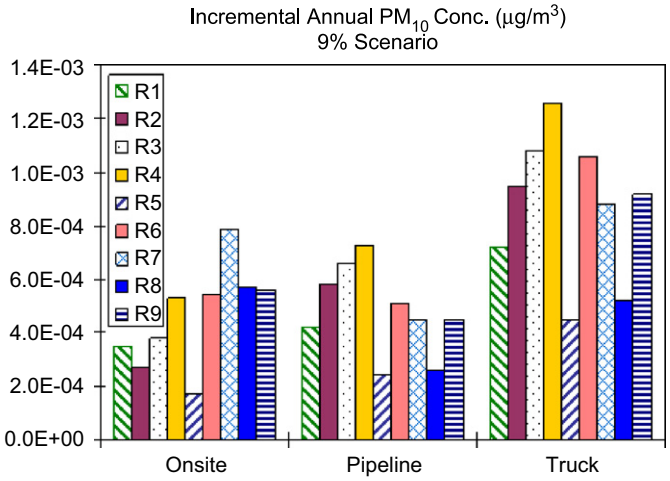

Fig. 13. Incremental annual average concentration of PM_{10} (9% scenario).

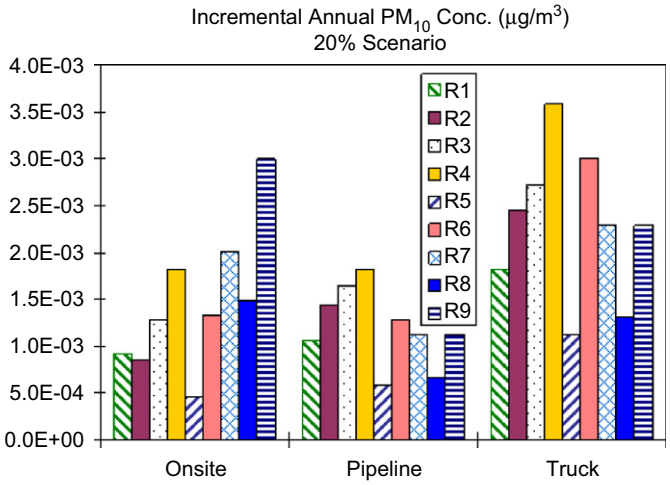

Fig. 14. Incremental annual average concentration of PM_{10} (20% scenario).

onsite at the refueling stations. Also, the emissions are distributed throughout the metropolitan area so the wind direction has little impact on the average air pollution at receptors.

It can be seen in the following charts that the change in air quality due to the onsite scenario is comparable to that caused by the central hydrogen pathway with pipeline systems, and both are very clean. The truck pathway also results in relatively low pollution levels, but higher than concentrations resulting from the other two pathways.

Meteorological conditions, especially wind directions, have a large impact on the effect of emissions from the central plant. The prevailing wind is from southwest to northeast, and wind is seldom from east to west in Sacramento. The site of the central plant can be strategically located so as to minimize the effect on urban air quality. In our example, the site is somewhat advantageous in that it is only occasionally upwind of the urban area. The site for the central plant could be further improved by placing it east of the metropolitan area since this location is almost always downwind of the urban region. Furthermore, it

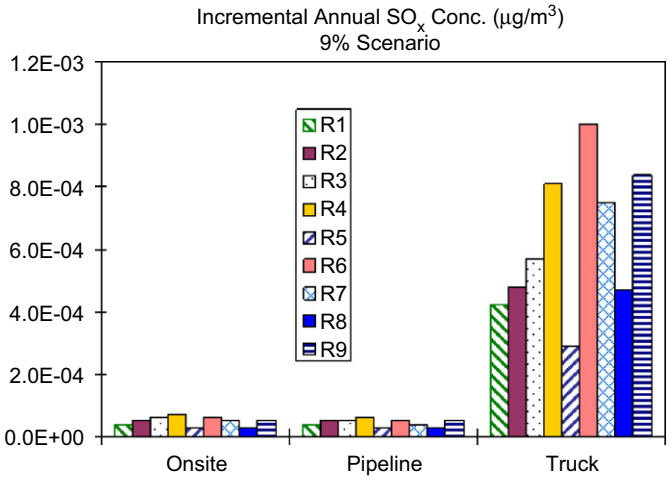

Fig. 15. Incremental annual average concentration of SO_x (9% scenario).

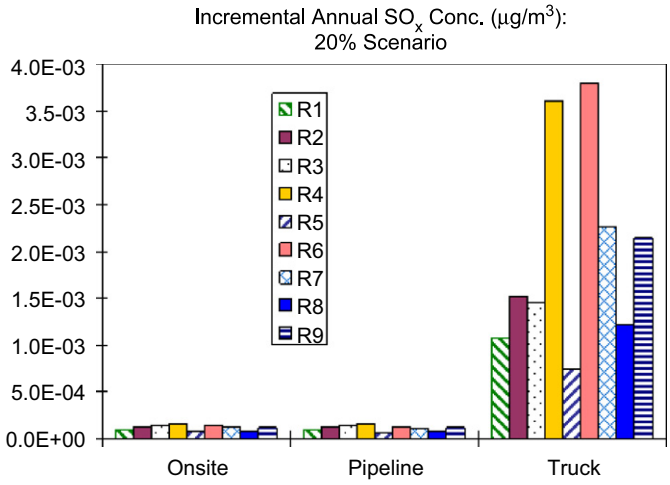

Fig. 16. Incremental annual average concentration of SO_x (20% scenario).

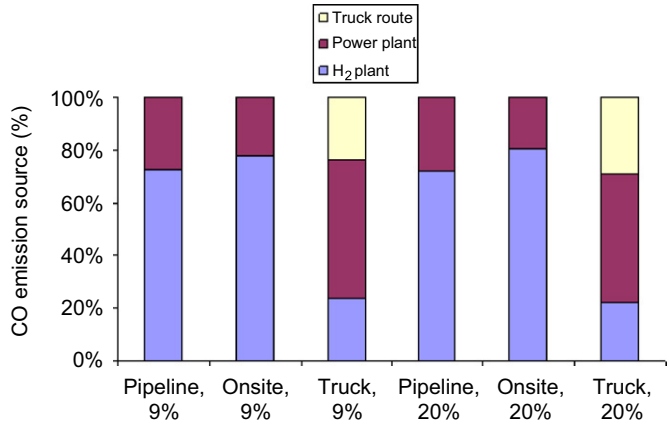

Fig. 17. Source pollution shares averaged over all receptors (CO).

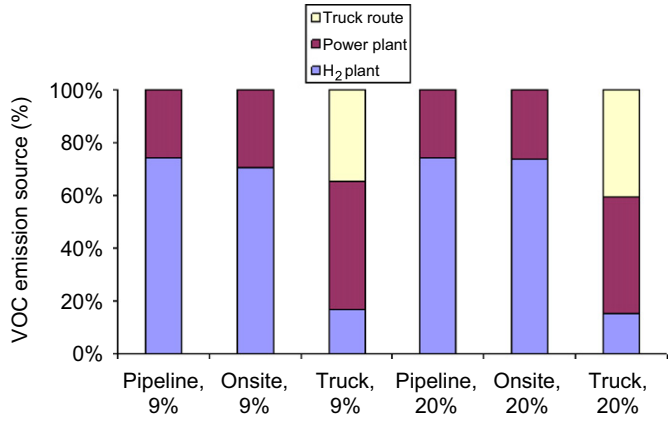

Fig. 18. Source pollution shares averaged over all receptors (VOC).

would be meaningful to carry out a sensitivity analysis regarding the central hydrogen plant siting, even though it is beyond the scope of this research. Again, geographic conditions have a significant effect on the impact of hydrogen production on urban air quality.

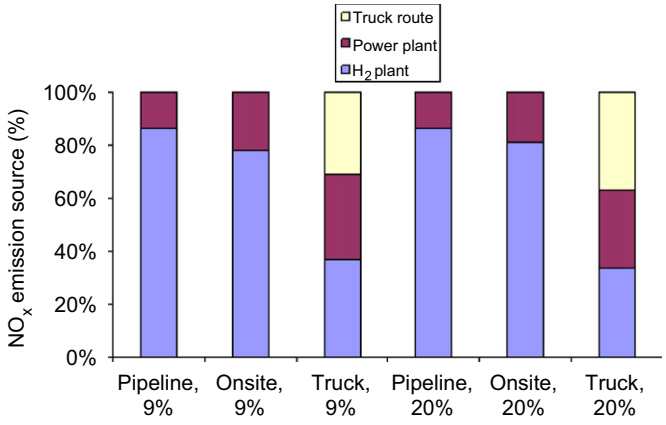

Fig. 19. Source pollution shares averaged over all receptors (NO_x).

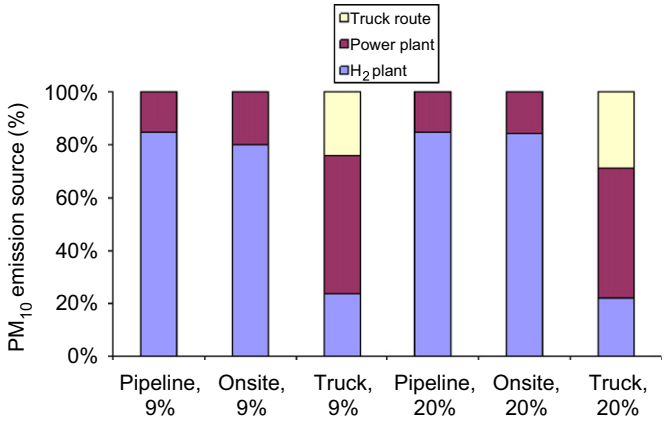

Fig. 20. Source pollution shares averaged over all receptors (PM_{10}).

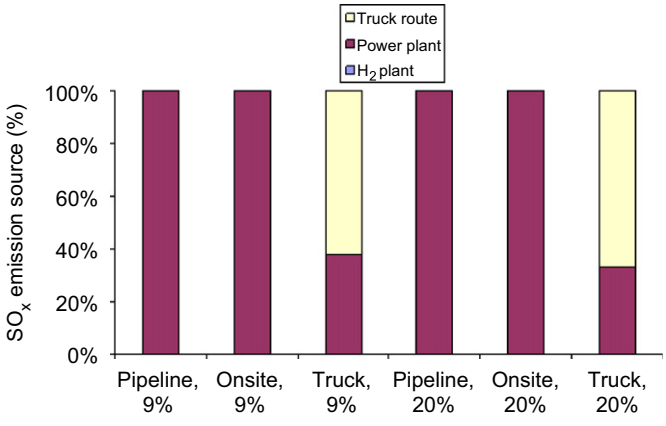

Fig. 21. Source pollution shares averaged over all receptors (SO_x).

3.2. Comparison to the current ambient pollution level

Table 8 compares the estimated incremental pollution from adding large numbers of hydrogen vehicles to the actual mean concentration of pollutants in Sacramento, averaging over all the nine receptors. For the 9% scenario, the onsite pathway leads to incremental pollution fractions ranging from 0.0006%

Table 8
Comparison of estimated incremental ambient pollution due to hydrogen pathways compared to ambient concentrations

Pollutant	Market penetration (%)	Onsite		Pipeline		Truck	
		Mean conc. ($\mu g/m^3$)	Pollution fraction (%)	Mean conc. ($\mu g/m^3$)	Pollution fraction (%)	Mean conc. ($\mu g/m^3$)	Pollution fraction (%)
CO	9	0.00473	0.0007	0.00316	0.0005	0.00848	0.0013
	20	0.01423	0.0022	0.00791	0.0012	0.02331	0.0036
VOC	9	0.00043	0.0006	0.00043	0.0006	0.00114	0.0015
	20	0.00126	0.0017	0.00107	0.0014	0.00326	0.0044
NO_x	9	0.00654	0.0116	0.00896	0.0158	0.01909	0.0337
	20	0.01967	0.0347	0.02241	0.0396	0.05394	0.0952
PM_{10}	9	0.00046	0.0021	0.00048	0.0021	0.00087	0.0039
	20	0.00146	0.0065	0.00119	0.0053	0.00229	0.0102
SO_x	9	0.00005	0.0006	0.00004	0.0006	0.00063	0.0079
	20	0.00012	0.0015	0.00011	0.0014	0.00198	0.0250

(SO_x, or CO approximation) to 0.0116% (NO_x) of current ambient concentrations. The pipeline pathway leads to pollution fractions ranging from 0.0005% (CO) to 0.0158% (NO_x), and the truck pathway leads to pollution fractions ranging from 0.0013% (CO) to 0.0337% (NO_x). For the 20% scenario, the onsite pathway leads to pollution fractions ranging from 0.0015% (SO_x, or CO approximation) to 0.0347% (NO_x), the pipeline pathway leads to pollution fractions ranging from 0.0012% (CO) to 0.0396% (NO_x), and the truck pathway leads to pollution fractions ranging from 0.0036% (CO) to 0.0952% (NO_x).

Relatively speaking, hydrogen pathways contribute the least fractions to ambient CO and the most fractions to ambient NO_x. It makes sense because most CO is released from urban mobile sources whereas NO_x is more likely from stationary sources resulting from combustion to produce high temperature steam which is used in the central hydrogen plant or in a power plant.

In summary, for all scenarios, the incremental pollution due to adding hydrogen cars at 9% or 20% market penetration is negligible. Truck pathways contribute more than onsite or central/pipeline pathways, but all have extremely low air pollution.

3.3. Further comparison among hydrogen pathways

Table 8 also shows a comparison of pathways in terms of resulting regionwide mean pollution. The truck pathway results in more pollution especially for SO_x, with concentrations more than an order of magnitude higher than those from the other pathways. Liquid hydrogen trucks fueled with sulfur-containing diesel make the biggest contribution to ambient SO_x concentrations. This is due to several factors: the trucks run on US conventional diesel with an estimated sulfur mixing ratio of 200 ppm by mass [3], steam reforming of natural gas is very clean in terms of sulfur-containing emissions, and electricity generation is relatively clean and renewables account for a very large share of production in Sacramento (see Table 5). The onsite pathway and the pipeline pathway result in very similar pollution levels, especially in terms of VOC, PM_{10}, and SO_x. However, the onsite pathway leads to more CO and less NO_x pollution than the pipeline pathway.

The incremental pollution due to each of hydrogen pathways, with the exception of the pipeline pathway, is not directly proportional to the regional hydrogen demand, denoted indirectly by HFCV market penetrations in the research (see Table 8). When the added hydrogen vehicle population increases by 2.5 times (from 10% up to 25% of the year 2000 light duty fleet), the pollution ratio increases by slightly more than 2.5 times, with the exception of SO_x pollution in the onsite pathway, which is slightly lower than 2.5 times. For the pipeline pathway, it is 2.5 times greater because it is assumed that the NG to hydrogen conversion efficiency remains the same as hydrogen demand goes up, holding the electric generation mix constant.

3.4. Source contributions to incremental ambient pollution

Based on the locations of emissions, the sources of ambient pollution are categorized into the following groups (ignoring the other emission sources that are spatially far away from urban Sacramento).

Hydrogen plant: This group includes the central hydrogen plant or onsite hydrogen production stations. Only emissions directly released from these locations are taken into consideration, and electricity consumed in a hydrogen plant is traced back to power plants that are referred to as another source contributor to ambient pollution.

Power plant: This group includes all the 17 power plants that contribute to the electric generation mix in Sacramento; in fact, only five power plants contribute to the urban air quality since the other 12 power plants, accounting for 42.36% of power mix, are on a clean energy basis (i.e., solar, wind, and hydro). For simplicity, only emissions directly released in power plants are taken into consideration, i.e. ignoring emissions upstream of power plants.

Truck route: This group only applies to the hydrogen pathway with liquid hydrogen truck delivery systems. The direct emissions are mainly diesel truck tailpipe emissions.

The source contributions to ambient pollution averaged over nine urban receptors of interest are presented in Figs. 17–21.

For the pipeline pathway, the hydrogen plant accounts for the largest share of pollution, and its contributions (among all the air quality monitors) are typically larger than 70%, and sometimes even larger than 80%. The exception is SO_x pollution, which is almost 100% from power plants.

For the onsite pathway, the hydrogen production stations account for the largest share, typically more than 70%. And again, SO_x pollution is the exception as power plants account for almost all of the SO_x pollution. Some receptors are affected by onsite stations much more severely, especially receptors that are close to and downwind from one or more stations. On average, hydrogen stations contribute around 90% of incremental pollution at receptors.

For the truck pathway, there are mainly three pollution components: truck routes, the hydrogen plant, and power plants. For all the five pollutants, truck routes and power plants are very important. The hydrogen plant contributes the smallest share, around 10–30%, and essentially 0% in terms of SO_x. Truck routes contribute 20–40% of pollution at a receptor, and particularly lead up to 70% in terms of SO_x pollution. Power plants contribute around 30% of pollution at a receptor for NO_x and SO_x, and they contribute around 50% pollution for the other three pollutants.

4. Conclusions

We have examined the potential regional air quality impacts of hydrogen transportation fuel from a LCA perspective, including impacts from fuel production, delivery, and vehicle use. The analysis focuses on in a specific region, Sacramento County, California. We consider two levels of market penetration where 9% or 20% of the light duty fleet are HFCVs. Three natural gas-based hydrogen supply pathways are considered: onsite production via small scale steam methane reformer, and large central SMR with liquid truck delivery or pipeline delivery.

The source contributions to incremental air pollution are estimated using a physical transport model for primary air pollutants NO_x, CO, particulates, and SO_x. (We use a Gaussian plume dispersion model for the atmospheric transport of pollutants. However, it does not include chemical production of secondary pollutants such as O_3 formed by VOCs and NO_x in the presence of sunlight. Therefore, this research is not a complete environmental impact assessment of potential hydrogen pathways.)

The pollution levels associated with each of the hydrogen scenarios are dependent upon the location of emitters and receptors, regional meteorological conditions, and geographic factors. The spatial layout of pathway steps therefore plays an important role in determining ambient pollution levels at air quality monitoring stations. We find that all of the hydrogen pathways considered are associated with extremely low pollution levels relative to current ambient air concentrations of NO_x, CO, particulates, and SO_x. The results are typically less than 0.1% of the current ambient pollution.

Among the hydrogen supply options, it is found that the central SMR with pipeline delivery systems is the lowest pollution option available provided the plant is located to avoid transport of pollutants into the city via prevailing winds. The onsite hydrogen pathway is comparable to the central hydrogen pathway with pipeline systems in terms of the resulting air pollution. The pathway with liquid hydrogen trucks has a greater impact on air quality relative to the other pathways due to emissions associated with diesel trucks and electricity consumption to liquefy hydrogen. The truck pathway causes more pollution than the onsite pathway and the pipeline pathway. The truck pathway causes around 15 times more SO_x, and around 3 times more of the other pollutants, compared to the other two pathways. For the pipeline pathway and the onsite pathway, hydrogen production accounts for the largest share of pollution. For the electricity-intensive liquid hydrogen truck pathway, emissions from diesel truck delivery and electric generation at power plants are much more important than hydrogen plant emissions in terms of resulting pollution. Again, compared to ambient concentrations, all of the three hydrogen pathways result in negligible air pollution in the region.

This study shows that emissions from near-term hydrogen production and delivery systems would make negligible contribution to ambient air pollution. In future work, we plan to compare the emissions from hydrogen systems to those from other advanced vehicle fuels, including advanced gasoline vehicles.

Acknowledgments

The authors would like to thank the Hydrogen Pathways program in the Institute of Transportation Studies (ITS) at the University of California, Davis for its support.

The authors appreciate the information provided by Dr. Christopher Yang (ITS, UC Davis) and Garvin A. Heath (University of California Energy Institute). For useful conversations, the authors also wish to acknowledge Dr. Mark Delucchi (ITS, UC Davis), Dr. Marc Melaina (ITS, UC Davis), Jonathan Hughes (ITS, UC Davis), Nils Johnson (ITS, UC Davis), and Nicholas Lutsey (ITS, UC Davis).

References

[1] US Census Bureau. Population, area and population density of US urbanized areas from 2000 US Census ⟨http://www.census.gov/geo/www/ua/ua2k.txt⟩; 2006 [accessed 1.25.2006].

[2] Wang G, Delucchi M. A lifecycle emissions model (LEM): lifecycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, and materials, APPENDIX X: pathways diagrams. University of California at Davis, Institute of Transportation Studies, Publication no. UCD-ITS-RR-03-17X; June 2005.

[3] GREET1.7. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. Argonne National Laboratory ⟨http://www.transportation.anl.gov/software/GREET/index.html⟩; 2006 [accessed 5.25.2006].

[4] Wang M. GREET 1.5—Transportation fuel-cycle model, 1, methodology, development, use and results, Center for Transportation Research, Argonne National Laboratory, prepared for the United States Department of Energy Office of Transportation Technologies. Report no. ANL/ESD-40; December 1999.

[5] eGRID. Emissions & Generation Resource Integrated Database. US EPA ⟨http://www.epa.gov/cleanenergy/egrid/index.htm⟩; 2006 [accessed 2.20.2006].

[6] Nicholas M. Hydrogen station siting and refueling analysis using Geographic Information Systems: a case study of Sacramento County. Masters Thesis. University of California, Davis; 2004.
[7] ExternE. Externalities of Energy, Methodology 1998 Update. European Commission ⟨http://www.externe.info/reportex/vol7.pdf⟩; 2005 [accessed 6.10.2005].
[8] Delucchi M, McCubbin D. The contribution of motor vehicle and other sources to ambient air pollution. Report #16 in the series: the annualized social cost of motor-vehicle use in the United States, based on 1990–1991 data. University of California at Davis, Institute of Transportation Studies, Publication no. UCD-ITS-RR-96-3 (16) rev. 1; October 2004.
[9] McCubbin D, Delucchi M. The social cost of the health effects of motor-vehicle air pollution. University of California at Davis, Institute of Transportation Studies, Publication no. UCD-ITS-RR-96-03(11); August 1996.
[10] ISCST3. Industrial Source Complex model (Short Term 3). US EPA ⟨http://www.epa.gov/scram001/dispersion_alt.htm⟩; 2006 [accessed 5.25.2006].
[11] Seinfeld J, Pandis S. Atmospheric chemistry and physics: from air pollution to climate change. New York: Wiley; 1998.
[12] Heath GA, Granvold PW, Hoats AS, Nazaroff WW. Quantifying the air pollution exposure consequences of distributed electricity generation. University of California Energy Institute; May 2005.
[13] TMY2. National Renewable Energy Laboratory (NREL) ⟨http://rredc.nrel.gov/solar/pubs/tmy2/⟩; 2006 [accessed 5.25.2006].
[14] Heath GA. University of California Energy Institute. Private communications; November 2005.
[15] AQS. Air Quality System. US EPA ⟨http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm⟩; 2006 [accessed 3.2.2006].
[16] NAAQS. National Ambient Air Quality Standards. US EPA ⟨http://www.epa.gov/air/criteria.html⟩; 2006 [accessed 5.31.2006].
[17] CARB. Ambient Air Quality Standards. California Air Resources Board ⟨http://www.arb.ca.gov/aqs/aaqs2.pdf⟩; 2006 [accessed 5.31.2006].