SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 3: The Hydrogen Fuel Pathway

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We turn now from biofuels and electricity to a fuel pathway that holds out promise farther in the future. Hydrogen has been widely discussed as a long-term fuel option to address environmental and energy security problems posed by current transportation fuels. Hydrogen fuel cell cars are several times more efficient than today's conventional gasoline cars, and they produce zero tailpipe emissions. They offer good performance, a range of 270-430 miles,[1] and can be refueled in a few minutes. Hydrogen can be made with zero or near-zero emissions from widely available resources, including renewables (like biomass, solar, wind, hydropower, and geothermal), fossil fuels (such as natural gas or coal with carbon capture and sequestration), and nuclear energy. In principle, it should be possible to produce and use hydrogen transportation fuel with near-zero well-to-wheels emissions of greenhouse gases and greatly reduced emissions of air pollutants while simultaneously diversifying away from our current dependence on petroleum.[2]

To reach stringent long term goals for cutting greenhouse gas emissions from transportation, it appears likely that the light duty fleet will be largely electrified by 2050 (see Chapter 8). Hydrogen fuel cells are an important enabling technology for this vision. Automakers foresee a future electrified light duty fleet with batteries powering smaller, shorter range cars and hydrogen fuel cells powering larger vehicles with longer range. To electrify all segments of the light duty market, fuel cells are a necessary complement to batteries.

Recent assessments affirm the long-term potential of hydrogen to greatly reduce oil dependence as well as transportation emissions of greenhouse gases and air pollutants—far beyond what might be achieved by energy efficiency alone. They also highlight the complex technical and logistical challenges that must be addressed before a hydrogen-based transportation system can become a reality. This chapter discusses some of the major questions regarding future use of hydrogen in the transportation sector and highlights STEPS research on these issues.

- What is the technical outlook for hydrogen vehicles and hydrogen supply?
- What are the environmental impacts of hydrogen fuel compared to alternatives?
- What would a hydrogen infrastructure look like, and how could we make a transition to hydrogen?
- What policies and business strategies are needed to support hydrogen in both the near and long terms?

CHALLENGES ON THE HYDROGEN FUEL PATHWAY

These complex technical and logistical challenges must be addressed before a hydrogen-based transportation system can become widespread:

- **Technical challenges.** While many of the technologies exist to build a hydrogen energy system, further development is needed on key emerging technologies. In particular, further development is needed for proton exchange membrane (PEM) fuel cell cost and durability, hydrogen storage on vehicles, and technologies for zero-carbon hydrogen production.
- **Logistical challenges.** Full adoption of FCVs will require a widespread hydrogen infrastructure. The issue is not producing low-cost hydrogen at large scale but distributing hydrogen to many dispersed users at low cost, especially during the early stages of a transition.
- **Transition issues / coordination of stakeholders.** A hydrogen transition means many major changes at once: adoption of new types of cars, building a new fuel infrastructure, and development of new low-carbon primary energy resources. These changes will require coordination among diverse stakeholders with differing motivations (fuel suppliers, vehicle manufacturers, and policymakers), especially in the early stages when costs for vehicles are high and infrastructure is sparse. Factors that could ease transitions, like compatibility with the existing fuel infrastructure, are more problematic for hydrogen than for electricity or liquid synthetic fuels.
- **Policy challenges.** Finally, consistent policies that reflect the external costs of energy—such as global climate change and damage to health from air pollution, plus the costs of oil supply insecurity—are lacking. This is a barrier to introducing more-efficient, cleaner technologies, including hydrogen, and to assuring that hydrogen is made from low-carbon sources. It is almost certain that technology-specific policies will be needed to support a hydrogen transition.

Technology Status and Outlook

We start with the technology status and outlook for hydrogen vehicles and hydrogen supply. Technologies that use hydrogen, notably fuel cells, are making rapid and significant progress. But while many of the technologies to build a hydrogen-based transportation system already exist, further development is needed for key emerging technologies, especially proton exchange membrane (PEM) fuel cells for automotive use, hydrogen storage on vehicles, and technologies for zero-carbon hydrogen production.

Hydrogen vehicles

Although internal combustion engines can run on hydrogen, it is the higher-efficiency, zero-emission hydrogen fuel cell that has largely captured the attention of automakers. Several automakers have embraced fuel cells as a superior zero-emission technology and have large development and commercialization programs. Honda, Toyota, Daimler, GM and Hyundai have announced plans to commercialize FCVs sometime between 2015 and 2020.[3] Hydrogen and fuel cells represent a logical progression beyond efficiency and increasing electrification of cars with hybrid and electric drive trains. As noted above, many automakers see complementary roles for hydrogen fuel cells and battery electric vehicles and are pursuing both technologies.

Fuel cells are highly efficient electrochemical "engines" that combine hydrogen and oxygen in air to produce electricity to power the vehicle. Fuel cells operate without combustion or emissions of pollutants or greenhouse gases; the only tailpipe emission is water. Today's development FCVs have fuel economies twice that of comparable gasoline cars, and 35 to 65 percent higher than gasoline hybrids.[4] FCVs use electric drive trains but have a longer range, a faster refueling time, and the potential for lower cost than battery electric cars.[5] In addition to the fuel cell stack, other key components of a hydrogen FCVs include hydrogen storage, electric motors and power controllers, and batteries for hybrid operation and cold start support (most fuel cell vehicles today are hybrids).

A key technology for automotive applications is the proton exchange membrane or PEM fuel cell. Manufacturers have reduced the weight and volume of PEM fuel cell systems so that they easily fit under the hood of a compact car. Fuel cell systems have demonstrated good driving performance and meet goals for low-temperature operation and freeze tolerance. However, several issues remain. Current automotive PEM fuel cells still fall short of the 5,000-hour lifetime needed, lasting about 2,000 hours in on-road tests,[6] although durability is steadily increasing and researchers have reported new designs that might take fuel cells to 7,000 hours and beyond. Recently, 5,000 hours durability was demonstrated in laboratory cells under non-ideal conditions that resemble on-road operation.[7]

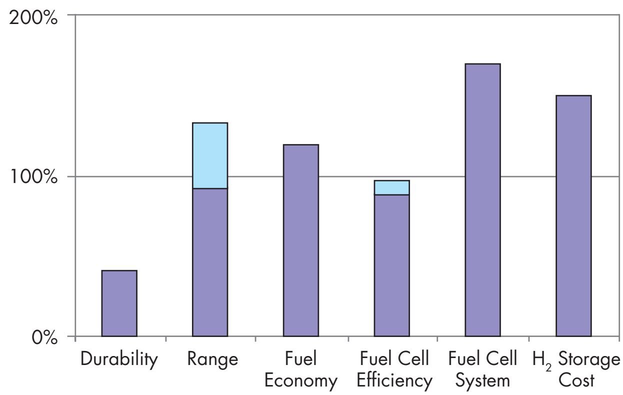
The U.S. Department of Energy (DOE) estimates that if today's automotive PEM fuel cell systems were mass-produced (at levels of 500,000 units per year), costs would drop to $51/kW (or about $4,000 for an 80-kW system), roughly twice the cost of a comparable internal combustion engine[8]. Fuel cell system costs are expected to continue declining toward the DOE goal of $30/kW because of improved materials, reductions in required platinum loading, and increased power density.

Storing enough hydrogen on a car for a reasonable traveling range (say 300 miles) is another key design issue. Storage requires high-pressure cylinders, liquid hydrogen at a super-cooled 20 K, or special materials such as metal hydrides that absorb hydrogen under pressure. Hydrogen storage systems are heavier and bulkier than those for gasoline, though less so than batteries, and compressing or liquefying hydrogen requires energy. Finding a better storage method is a major thrust of hydrogen R&D worldwide. In the absence of a breakthrough storage technology, most hydrogen vehicles today opt for the simplicity of compressed gas storage, which will be the system choice for early commercialization. Because of the low volumetric density of these systems, many FCV manufacturers have begun to design around the storage system in order to get adequate range without reducing passenger or cargo space in the vehicle. GM, Honda, Toyota, Daimler and Hyundai have all demonstrated light-duty fuel cell cars with a 270–400-mile range, using compressed hydrogen gas at 35–70 MPa (megapascals, a measure of pressure).[9] These vehicles meet the U.S. DOE goals for range.

Costs for mass-produced compressed storage tanks based upon current technology are estimated to be around $15–23/kWh (or about $2,500–3,700 for a compact FCV storing enough hydrogen for a 300-mile range).[10] Although these are substantially higher than the DOE's 2015 goals of $2–4/kWh, a recent National Academies study found acceptable overall vehicle costs with hydrogen storage tanks costing $10–15/kWh.[11]

H_2 TECHNOLOGIES: CURRENT STATUS VS 2015 DOE GOALS

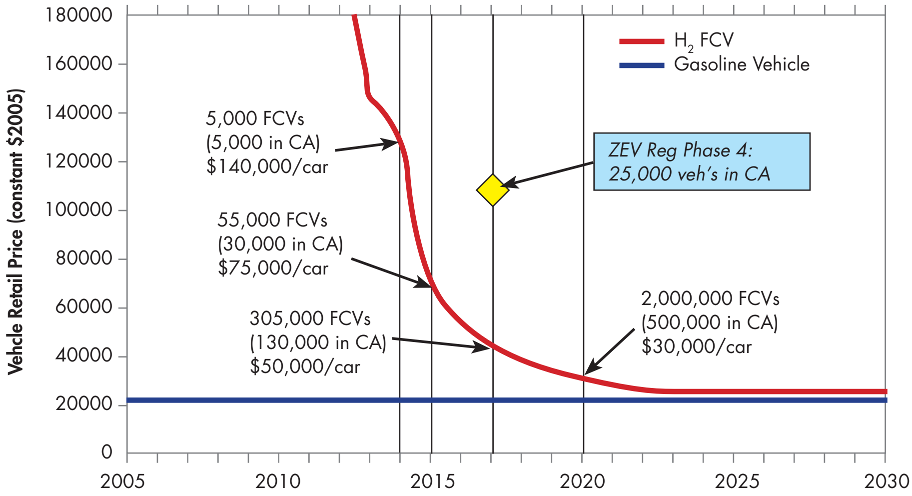
	Today	**2015 Goals**
In-use durability (hrs)	2000	5000
Vehicle Range (miles/tank)	280-400	300
Fuel Economy (mi/kg H_2)	72	60
Fuel Cell Efficiency	53-58%	60%
Fuel Cell System Cost ($/kW)	51	30
H_2 Storage Cost ($/kWh)	15-23	10-15 (NRC)
		2-4 (USDOE)



When we compare the status of current (2010) H_2 technologies in demonstration vehicles and goals set by the U.S. Department of Energy (DOE) for 2015, we can see that current technologies have farthest to go to reach durability, system-cost, and storage-cost goals. The figure at the bottom shows how close the current technology is to the 2015 goal.

While estimates of the price of mass-produced FCVs based upon projections for 2015 technology are within a few thousand dollars of conventional vehicles,[12] initial FCV models will not be produced in such high volumes and as a result will have a high price premium. At a scale of 50,000 FCVs being produced worldwide, estimated prices are around $75,000 per vehicle. Prices can drop quickly as manufacturing volume increases. Mass-produced, mature technology FCVs are estimated to have a retail price $3,600 to $6,000 higher than a comparable gasoline internal combustion engine vehicle (ICEV).[13]

ESTIMATED FCV RETAIL PRICE OVER TIME



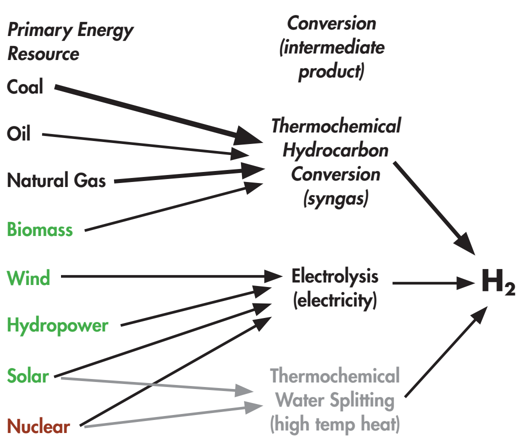
The estimated retail price for FCVs drops considerably as production scales from thousands (in 2012) to millions of vehicles per year (in 2025). The learned-out price difference between the FCV and the gasoline ICEV is about $3,600.[14]

Hydrogen production methods

Like electricity, hydrogen is an energy carrier that is produced from a primary energy resource. Almost any energy resource can be converted into hydrogen, although some pathways are superior to others in terms of cost, environmental impacts, efficiency, and technological maturity.

RESOURCES AND CONVERSION PATHWAYS FOR HYDROGEN

There are a multitude of potential primary energy resources and conversion pathways for producing hydrogen. Fossil resources are shown in black and renewable resources are shown in green. Pathways that are more technologically mature (for example, electrolysis and thermochemical conversion of hydrocarbons from coal and natural gas) are shown in bold, while the more speculative pathways (such as thermochemical water splitting) are in a lighter shade.

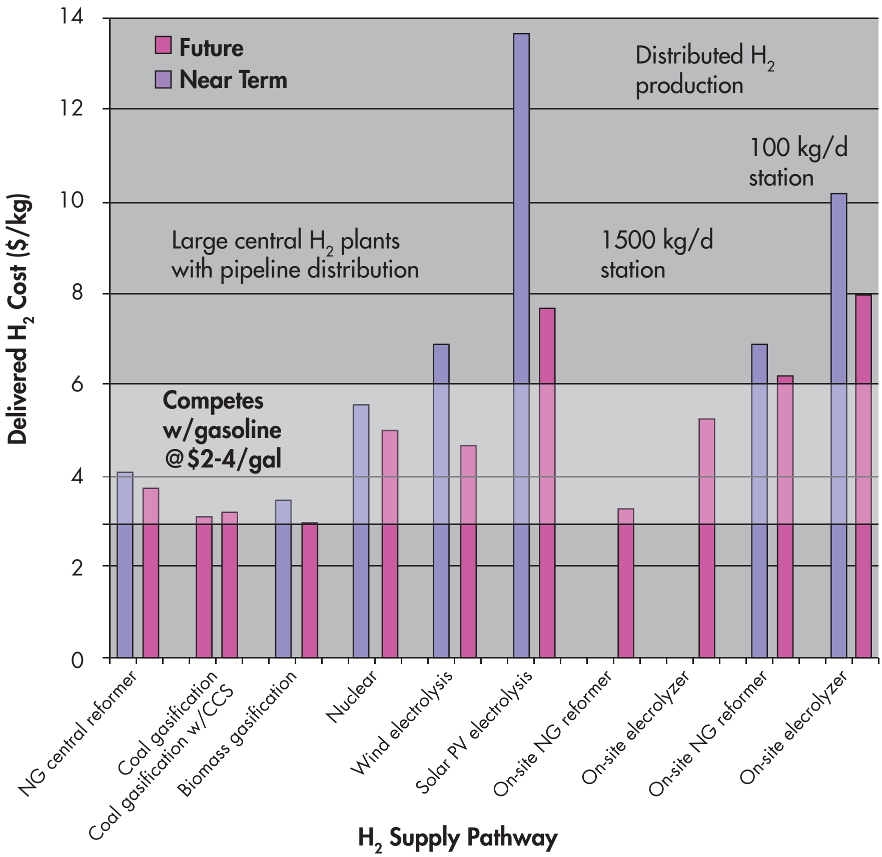


In the United States, about 9 million tonnes of hydrogen are produced each year (enough to fuel a fleet of about 35 million fuel cell cars). Steam reforming of natural gas is the most common method of hydrogen production today (mainly for industrial and refinery purposes), accounting for about 95 percent of hydrogen production in the United States.

In the near to medium term, fossil fuels (primarily natural gas) are likely to continue to be the least expensive and most energy-efficient resources from which to produce hydrogen. Conversion of these resources still emits some carbon into the atmosphere. However, future hydrogen production technologies could virtually eliminate GHG emissions. For large central plants producing hydrogen from natural gas or coal, it is technically feasible to capture the CO_2 and permanently sequester it in deep geological formations, although the widespread use of sequestration technology poses important challenges and will not happen until 2020 at the earliest.

Production of hydrogen from renewable biomass is a promising midterm option (post 2020) with very low net carbon emissions. In the longer term, vast carbon-free renewable resources such as wind and solar energy might be harnessed for hydrogen production via electrolysis of water. While this technology is still improving, high costs for electrolyzers and renewable electricity (in part because of the low capacity factors of intermittent renewable sources) suggest that renewable electrolytic hydrogen will likely cost more than hydrogen from fossil resources with carbon capture and sequestration (CCS) or biomass gasification.

DELIVERED COST OF HYDROGEN FROM VARIOUS PATHWAYS

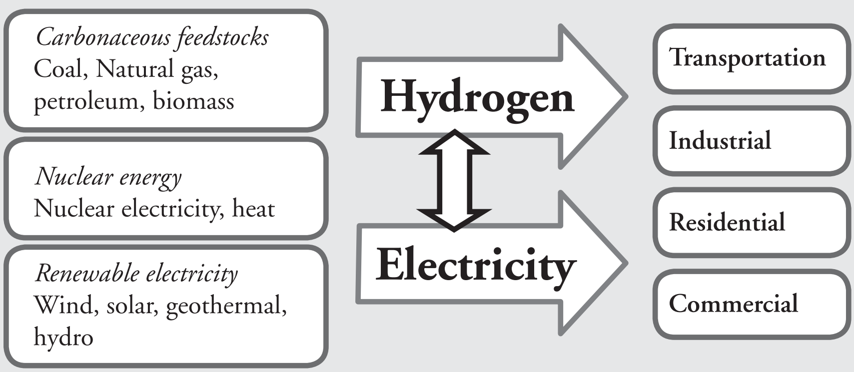


Here we compare the delivered cost of hydrogen transportation fuel produced via different pathways for "near term" (scaled up infrastructure with current technology) and "future" (full scale infrastructure with advanced technologies beyond 2015).[15] We see that costs will come down as technology advances, and that production from hydrocarbons generally costs less than electrolytic hydrogen production. All central alternatives assume hydrogen is deployed at a massive scale, which could happen beyond 2020. On-site alternatives use stations serving numbers of cars similar to today's gasoline stations (at 1,500 kg of H_2 per day). We also show estimated H_2 costs for smaller size stations (100 kg of H_2 per day) typical of near-term demonstration H_2 stations which serve a relatively small number of early FCVs. These small stations would have significantly higher hydrogen cost because of scale economies. The range for hydrogen fuel costs to compete with gasoline on a cents-per-mile basis is shown, based on an efficient gasoline hybrid competing with an FCV. If H_2 costs $3–6/kg, the fuel cost per mile for an FCV is about the same as for an efficient gasoline hybrid using gasoline at $2–4/gal, assuming that the fuel economy of a fuel cell vehicle is 1.5 times higher than that of a comparable gasoline hybrid.

In the United States, the lowest-cost low-carbon hydrogen supply pathways appear to be biomass gasification and hydrogen from coal with CCS. Each could contribute significantly to the long-term hydrogen supply. The lowest-cost option depends on the market penetration of FCVs, the local feedstock and energy prices, as well as geographic factors such as city size and density of demand. Detailed regional studies reveal possibilities for further optimizing the hydrogen supply system at the regional level. It appears that hydrogen could be delivered to consumers for about $3–4/kg, with near-zero emissions of greenhouse gases, on a well-to-wheels basis, which leads to a reduction in fuel cost per mile compared to gasoline vehicles, given the increased efficiency of FCVs.

H_2 AND ELECTRICITY AS PRIMARY ENERGY CARRIERS[16]

One compelling vision of a future decarbonized energy system involves the use of two primary energy carriers—hydrogen and electricity. H_2 and electricity are both decarbonized energy carriers that enable conversion, transport, and utilization of a wide variety of primary energy resources. In an integrated energy system, these two energy carriers could complement each other; they could be produced from the same primary energy resources and could in fact be co-produced and inter-converted. However, they have very different characteristics, which suggest specialized uses and applications for each.



Given the benefits associated with electric-drive vehicles, hydrogen and electricity are in competition as the primary energy carrier for light-duty vehicles. However, many industry experts foresee a complementary role in the future light-duty sector dominated by electric-drive vehicles in which small, shorter-range vehicles are powered by batteries and longer-range, larger passenger vehicles are powered by fuel cells. The main technical challenges facing battery-powered vehicles stem from the energy density limitations and recharge times associated with batteries. Fuel cells appear to alleviate these issues with refueling speeds and vehicle ranges that approach those of gasoline vehicles, though these benefits are traded off for greater infrastructure requirements.

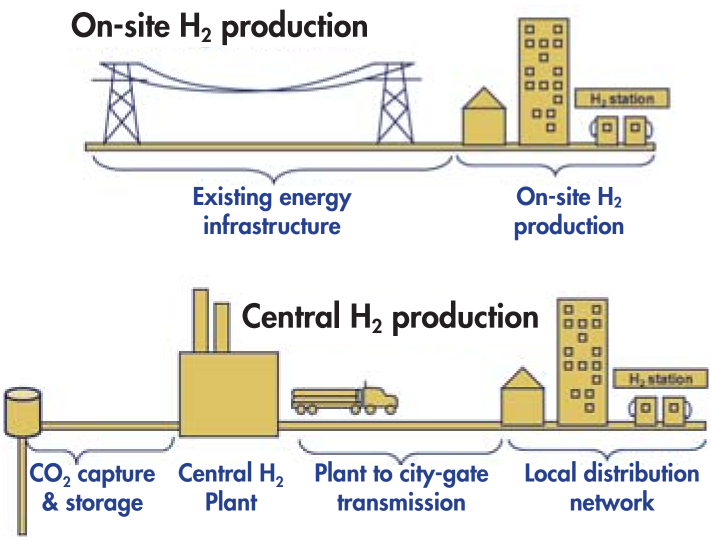
Co-production is another area where these two energy carriers may interact. They can be made from the same primary resources and can be co-produced with higher efficiency and lower cost than producing either one separately. These can occur at the large scale (for example, thermochemical conversion from fossil fuels with carbon capture and sequestration) or the small scale (for instance, separate energy stations at one refueling station).

Finally, hydrogen and electricity can be inter-converted via electrolyzers and fuel cells. While efficiency losses occur in converting one energy carrier to another, a number of circumstances may offer compelling reasons to do so. Such circumstances include electrolysis using cheap off-peak electricity, hydrogen production as a means of storing and leveling intermittent renewable electricity, and vehicle-to-grid electricity in a fuel cell vehicle.

Hydrogen delivery methods

Once hydrogen is produced, there are several ways to deliver it to vehicles. It can be produced regionally in large plants, stored as a compressed gas or cryogenic liquid (at –253° C), and distributed by truck or gas pipeline; or it can be produced on-site at refueling stations (or even homes) from natural gas, alcohols (methanol or ethanol), or electricity. No one hydrogen supply pathway is preferred in all situations.

TWO OPTIONS FOR SUPPLYING HYDROGEN

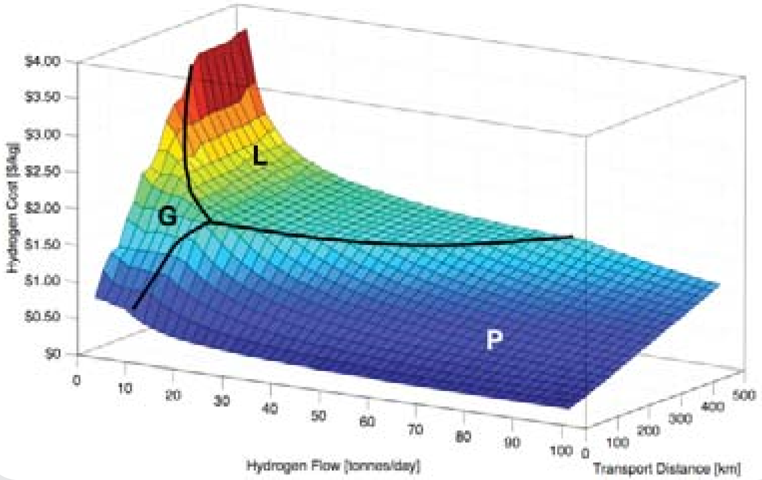


Options for producing and delivering hydrogen include on-site production and central production. Source: C. Yang and J. Ogden, "Determining the lowest-cost hydrogen delivery mode," International Journal of Hydrogen Energy *32 (2007): 268–86.*

THE LOWEST-COST WAY TO DELIVER HYDROGEN

What is the least costly way to bring hydrogen to users? It all depends on how much hydrogen is needed (the hydrogen flow) and how far it needs to travel (distance). STEPS researchers developed models to find the lowest-cost delivery mode for hydrogen, given three choices: compressed gas hydrogen trucks, liquid hydrogen trucks, and hydrogen gas pipeline.

Hydrogen flow rate is an important factor determining delivery mode choice and cost. As the hydrogen flow rate goes up, costs come down, primarily because of scale economies in pipeline delivery. Pipeline delivery is the lowest-cost delivery option at high levels of hydrogen demand, while trucks dominate at smaller quantities of hydrogen. As distance increases, liquid trucks give a lower cost than compressed gas trucks because each truck carries more hydrogen. (If the gas pressure were increased allowing more hydrogen per truckload, compressed gas truck transport could become more competitive with liquid trucks, and the border between "L" and "G" might shift in the figure below). At a given distance, pipelines beat liquid trucks when the hydrogen flows are large enough. (For reference, 10 tonnes of hydrogen per day would fuel about 10,000 cars, and 100 tonnes per day about 100,000 cars. So pipeline transport is unlikely until large numbers of vehicles are present in a concentrated region.)



We compared three different hydrogen delivery modes to find the lowest-cost method. As hydrogen flow increases, delivery by hydrogen gas pipeline (P) starts to cost the least; as transport distance increases, liquid hydrogen trucks (L) win out. Compressed gas hydrogen trucks (G) cost least when both distance and flow are limited. Source: C. Yang and J. Ogden, "Determining the lowest-cost hydrogen delivery mode," International Journal of Hydrogen Energy *32 (2007): 268–86.*

Environmental Impacts of Hydrogen Fuel

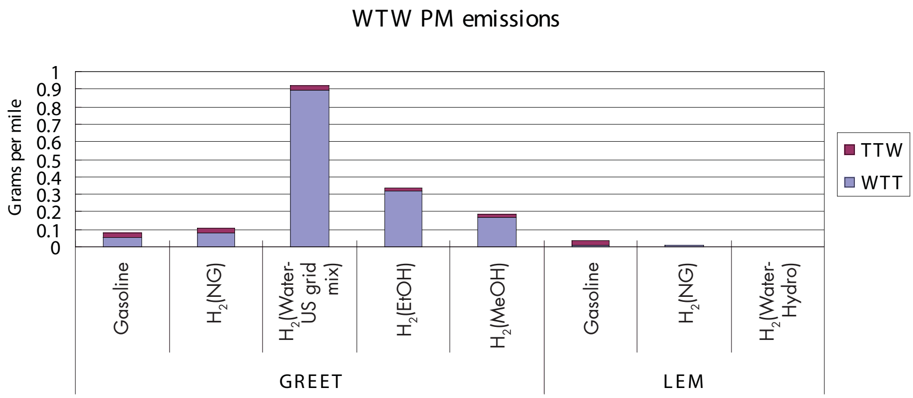
The environmental impacts of hydrogen fuel vary with the production pathway. Most life-cycle analyses of alternative fuels have focused on emissions and energy use, but recently several authors have expanded their focus to estimate primary resource, land, water, and materials use associated with hydrogen energy systems as compared to other fuels.

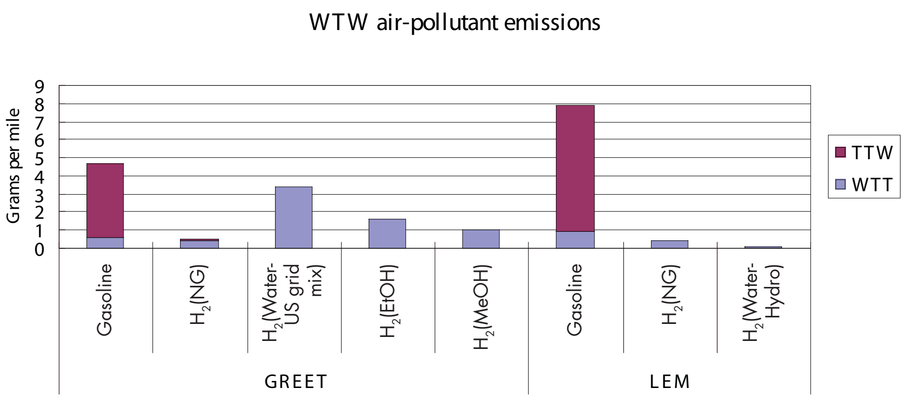
GHG emissions, air pollution, and energy use

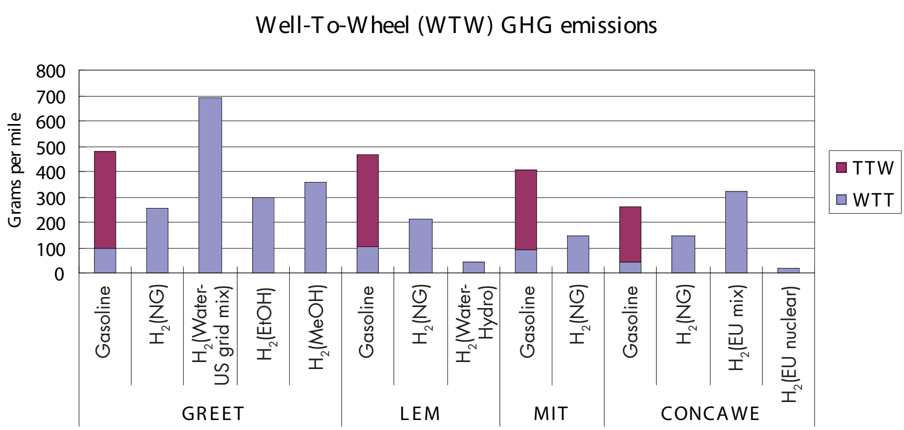
Most hydrogen production today is from fossil fuels, which releases CO_2, the major GHG linked to climate change. For the near term, FCVs using hydrogen produced from natural gas would reduce well-to-wheels GHG emissions by about half compared to current gasoline vehicles. For large central plants producing hydrogen from hydrocarbons (natural gas, coal or biomass), it is technically feasible to capture the CO_2 and permanently sequester it in deep geological formations, although sequestration technology will not be in widespread use before 2020 at the earliest. Production of hydrogen from renewable biomass is a promising midterm option with very low net carbon emissions. In the longer term, carbon-free renewables such as wind and solar energy might be harnessed for hydrogen production via electrolysis of water.

Air pollution reductions are significant with hydrogen pathways compared to gasoline, leading to better air quality[17] and lower social costs.[18] And petroleum use for hydrogen pathways is very small. The only oil use is associated with truck delivery and electricity generation for hydrogen compression or liquefaction, and this is much lower than with any gasoline pathway.

COMPARISON OF EMISSIONS FROM DIFFERENT FUEL/VEHICLE PATHWAYS







We compare the well-to-wheels (WTW) emissions of greenhouse gases, air pollutants, and particulate matter (PM) for a variety of hydrogen pathways, based on results from the Argonne National Laboratory GREET model, the UC Davis LEM model, MIT, and the European Union CONCAWE study. We break emissions down into phases: well-to-tank (WTT) and tank-to-wheels (TTW). Emissions are shown for H_2(NG) = hydrogen from on-site natural gas reforming; H_2(Water) = hydrogen from on-site water electrolysis; H_2(EtOH) = hydrogen from ethanol at refueling stations; and H_2(MeOH) = hydrogen from methanol at refueling stations.

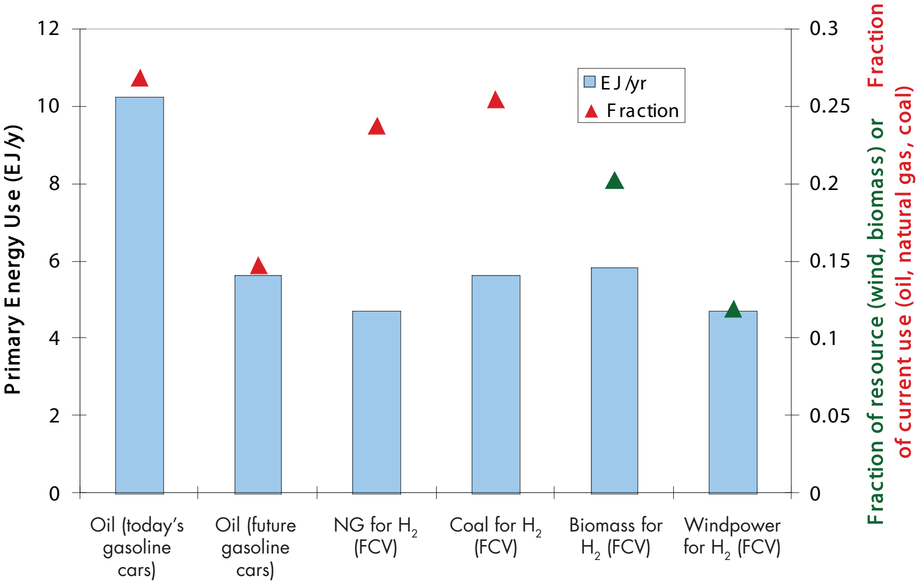
Notes: The emission results from GREET V.1.8c.0 are for year 2010 using default input parameters in the GREET model. The LEM model assumes that electricity generation is from hydropower for hydrogen production from water electrolysis. PM emissions from GREET are larger than those from LEM as LEM considers emission reductions due to emission controls while GREET does not. GREET also includes the PM emissions from brake and tire wear. According to GREET, most of the PM emissions are from the WTT phase, about 1.8 percent of total air pollution is PM from gasoline, and about 20–27 percent of total air pollution is PM from H_2 pathways.

Sources: M. Wang, "Well-to-Wheels Analysis with the GREET Model," 2005 U.S. DOE Hydrogen Program Review, May 26, 2005; M. Wang, "Well to Wheels Analysis of Vehicle/Fuel Systems with GREET at Argonne National Lab," presentation at the U.S. DOE Hydrogen Analysis Deep Dive meeting, San Antonio, TX, March 22, 2007; M. A. Delucchi, "A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials," UCD-ITS-RR-03-17-MAIN (Institute of Transportation Studies, University of California, Davis, 2003); M. A. Kromer and J. B. Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, *LEFF 2007-02 RP (Sloan Automotive Laboratory, MIT Laboratory for Energy and the Environment, May 2007); EUCAR (European Council for Automotive Research and Development), CONCAWE, and ECJRC (European Commission Joint Research Centre),* Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, *Well-to-Wheels Report, Version 2c, March 2007.*

Use of primary energy resources, land, water, and other materials

With hydrogen fuel cells the amount of primary energy required is similar to that for gasoline hybrids and considerably less than for conventional gasoline cars. There are plentiful near-zero-carbon resources for hydrogen production in the United States. For example, a mix of low-carbon resources including natural gas, coal (with carbon sequestration), biomass, and wind power could supply ample hydrogen for vehicles. With 20 percent of the biomass resource, plus 15 percent of the wind resource, plus 25 percent added use of coal (with sequestration), 300 million hydrogen vehicles (approximately the entire U.S. fleet projected in 2030) could be served with near-zero GHG emissions.

ENERGY RESOURCES REQUIRED TO FUEL 100 MILLION CARS IN THE UNITED STATES



We did a sample calculation of the amount of primary energy needed to make hydrogen for 100 million FCVs in the United States (about 50 percent of the current U.S. fleet or 33 percent of the projected U.S. fleet in 2050). The amount of primary energy required is measured in exajoules (10^{18} joules) per year by the y-axis on the left. The fraction of the available annual resource (for biomass and wind) or the current use (for coal or natural gas) is measured by the y-axis on the right.

For reference, we also plot the energy use for 100 million current gasoline vehicles and 100 million gasoline hybrids. The biomass resource is assumed to be 800 million tonnes of biomass per year, and the wind resource is assumed to be 11,000 billion kWh of electricity per year. Source: J. Ogden and C. Yang, "Build-up of a Hydrogen Infrastructure in the U.S.," Chapter 15 in The Hydrogen Economy: Opportunities and Challenges*, ed. M. Ball and M. Wietschel (Cambridge, UK: Cambridge University Press, 2009), 454–82.*

The land and water requirements for producing hydrogen also depend on the production pathway. The table below shows the land requirements to produce hydrogen for a variety of renewable pathways. For comparison, the total U.S. land area is 9.1 million km^2 and the total cropland is 1.8 million km^2. The impacts of this level of land use have not been thoroughly examined in terms of competing uses. Regarding water use, hydrogen pathways relying on renewable electrolysis or steam methane reforming are estimated to use much less water than hydrogen pathways relying on synthetic fuels from coal or biomass, and somewhat less water than gasoline production.[19] Water could become an important constraint on future energy production.

LAND AREA REQUIRED TO PRODUCE RENEWABLE H_2

Hydrogen Pathway	**Land Area (m^2) to Produce 1 GJ H_2 per Year**	**Total Land Area (km^2) to Produce H_2 for 100 Million Cars**
Electrolytic H_2		
Solar PV	1.89	5,700
Solar thermal electric	5.71	17,000
Wind	6.3-33	19,000–99,000
Hydropower	11-500	
H_2 via biomass gasification	50	150,000

Materials availability could also become an issue for widespread use of hydrogen. For example, FCVs require use of a platinum catalyst in the fuel cell. If these vehicles come into widespread use in the future, significant quantities of platinum will be needed. However, studies by STEPS researchers and other have shown that there should be sufficient platinum for FCVs (see Chapter 7 for a full discussion).

Building a Hydrogen Infrastructure

Adoption of hydrogen will require a widespread hydrogen infrastructure to fuel vehicles. Unlike the case with gasoline and electricity, there is currently no large-scale infrastructure bringing hydrogen to consumers. Because there are many options for hydrogen production and delivery, and no one supply option is preferred in all cases, creating such an infrastructure is a complex design problem. The challenge is not so much producing low-cost hydrogen at large scale as it is distributing hydrogen to many dispersed users at low cost, especially during the early stages of the transition.

Recent studies (including those at UC Davis)[20] have found that the design of a hydrogen infrastructure depends on many factors, including these:

- **Scale**. Hydrogen production, storage, and delivery systems exhibit economies of scale, and costs generally decrease as demand grows.
- **Geography / regional factors**. The location, size, and density of demand, the location and size of resources for hydrogen production, the availability of sequestration sites, and the layout of existing infrastructure can all influence hydrogen infrastructure design.
- **Feedstocks**. The price and availability of feedstocks for hydrogen production, and energy prices for competing technologies (for example, gasoline prices), must be taken into account.
- **Technology status**. Assumptions about hydrogen technology cost and performance determine the best supply option.
- **Supply and demand**. The characteristics of the hydrogen demand and how well it matches supply must be considered. Time variations in demand (refueling tends to happen during the daytime, with peaks in the morning and early evening) and in the availability of supply (for example, wind power is intermittent) can help determine the best supply and how much hydrogen storage is needed in the system.
- **Policy**. Requirements for low-carbon or renewable hydrogen influence which hydrogen pathways are used.

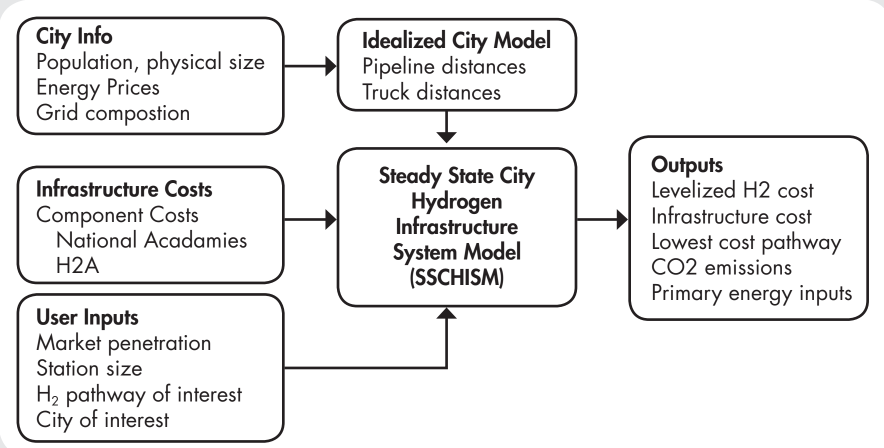
In this section, we discuss a national rollout for the United States, early infrastructure and transition issues in southern California, and regional designs for two leading low-carbon options: biomass hydrogen and coal with CCS.

A scenario for hydrogen infrastructure build-up in the United States

Building a national hydrogen refueling infrastructure in a large, diverse country such as the United States is a complex design problem involving regional considerations. We developed the SSCHISM model to study this challenge. We use SSCHISM to determine the least-cost method for supplying hydrogen to a particular city at a given market penetration.

MODELING HYDROGEN INFRASTRUCTURE: THE UC DAVIS SSCHISM MODEL

To understand the design and economics of a hydrogen infrastructure, STEPS researchers developed the Steady-State City Hydrogen Infrastructure System Model (SSCHISM).[21] SSCHISM finds the lowest-cost infrastructure design based on regionally specific information (city population and physical size, energy prices, electricity grid characteristics), plus engineering/economic models of hydrogen infrastructure component costs, and market factors. We analyzed a wide variety of hydrogen supply pathways for each of 73 major U.S. urban areas. Outputs include the levelized cost of delivered hydrogen, the infrastructure capital cost, CO_2 emissions, and primary energy requirements.



Our SSCHISM model finds the lowest-cost infrastructure design based on regionally specific information (city population and physical size, energy prices, electricity grid characteristics), plus hydrogen infrastructure component costs and market factors.

In the model, we assume that the first few thousand FCVs are successfully introduced in 2012, with tens of thousands of FCVs by 2015, 2 million in the fleet by 2020, 10 million by 2025, and about 200 million (60 percent of the fleet) by 2050. Because of the need to locate infrastructure and vehicles together, hydrogen is introduced in a succession of "lighthouse" cities, starting with the Los Angeles area. We assume that some minimum number of hydrogen stations is needed in each city to assure adequate coverage and consumer convenience and to help deal with the "chicken-or-egg" problem of assuring hydrogen fuel availability to early vehicle owners.

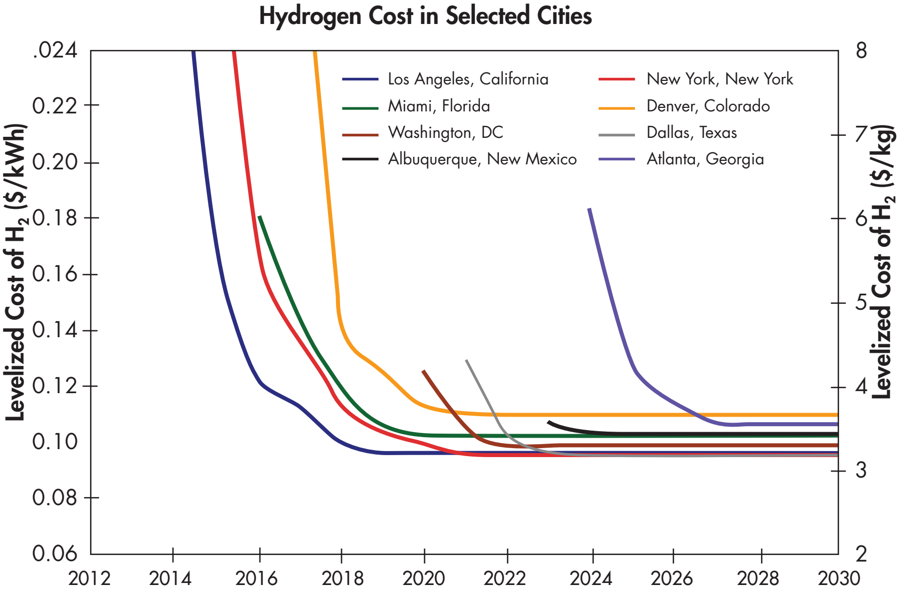
PROJECTED INTRODUCTION OF FCVS IN "LIGHTHOUSE" CITIES, 2012–2025

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Los Angeles	1	2	2	25	40	50	85	120	160	190	210	250	270	300
New York, Chicago				25	40	50	85	120	150	175	185	225	240	270
San Francisco, Washington/Baltimore					20	30	55	85	120	140	160	190	210	230
Boston, Philadelphia, Dallas						20	50	85	120	145	165	195	210	220
Detroit, Houston							25	50	80	120	140	160	190	210
Atlanta, Minneapolis, Miami								40	75	100	115	130	160	180
Cleaveland, Phoenix, Seattle									45	70	90	120	150	170
Denver, Pittsburgh, Portland, St.Louis, Cincinnati, Indianapolis, Kansas City										60	80	110	130	150
Milwaukee, Charlotte, Orlando, Columbus, Salt Lake City											55	80	110	130
Nashville, Buffalo, Raleigh												40	70	90
Nationwide													260	540

The number of light-duty FCVs sold annually in 27 "lighthouse" cities is given here in thousands of vehicles per year introduced between 2012 and 2025. The total number of hydrogen vehicles in 2025 is 10 million, and 2.5 million vehicles are sold that year. Source: S. Gronich, "Hydrogen and FCV Implementation Scenarios, 2010–2025," presented at the U.S. DOE Hydrogen Transition Analysis Workshop, Washington DC, August 9–10, 2006.

As new cities are phased in over time, hydrogen is initially costly because of the low demand in the new cities, but costs fall as demand grows. The phased introduction of hydrogen infrastructure and vehicles leads to differences in hydrogen market penetration and also contributes to differences in hydrogen cost for different cities. City size and density as well as local feedstock and energy prices also contribute to these cost differences.

PROJECTED HYDROGEN COSTS TO 2030



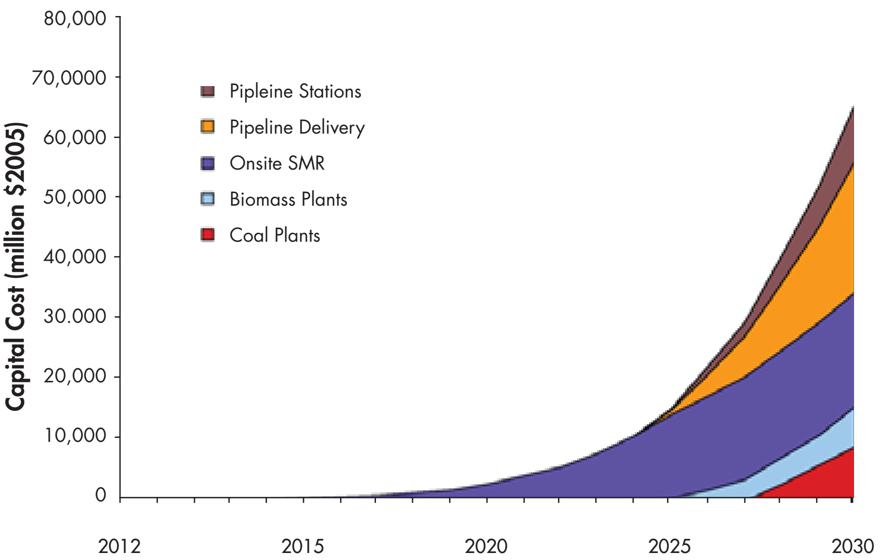
The range and progression of delivered hydrogen costs over time is shown for selected "lighthouse" cities. Cost differences are due to phased introduction of hydrogen cars as well as to city size and density and local feedstock and energy prices.

The choice of supply pathway also varies over time. At low demand, on-site steam methane reformers (SMRs) dominate because the large investments required for central production and hydrogen delivery are not yet justified. As hydrogen demand in a particular city grows, it makes sense to build central production plants and delivery systems when the economies of scale associated with large production plants overcome the additional cost associated with pipeline or truck delivery. This sequence is played out in each of the 73 urban areas in the model. However, the point at which this switch from distributed to central production occurs and the least-cost central pathway differ depending upon the size of the city, level of demand, demand density, and local energy and feedstock prices. On-site SMRs dominate until about 2025, and after that central biomass and coal plants with CCS come in along with pipeline distribution systems. The switch to central plants tends to occur at a lower market penetration for larger cities because the actual hydrogen demand is larger for these cities, while on-site SMRs tend to persist longer in smaller cities.

HYDROGEN SUPPLY PATHWAYS CONSIDERED IN OUR MODEL

Resource	H_2 Production Technology	H_2 Delivery Method
CENTRAL PRODUCTION		
Natural gas	Steam methane reforming (SMR)	Liquid H_2 truck Compressed gas truck H_2 gas pipeline
Coal	Coal gasification with carbon capture and sequestration	
Biomass (agricultural, forest and urban wastes)	Biomass gasification	
ON-SITE PRODUCTION (at refueling station)		
Natural gas	Steam methane reforming (SMR)	n/a
Electricity (from various electric generation resources)	Water electrolysis	

HYDROGEN INFRASTRUCTURE CAPITAL COSTS TO 2030



We assume that the choice of supply pathway for hydrogen fuel will vary over time as demand grows and production scales up. On-site SMRs dominate until about 2025, and after that central biomass and coal plants (with CCS) come in along with pipeline distribution systems. Source: J. Ogden and C. Yang, "Build-up of a Hydrogen Infrastructure in the U.S.," Chapter 15 in M. Ball and M. Wietschel, The Hydrogen Economy: Opportunities and Challenges *(Cambridge, UK: Cambridge University Press, 2009).*

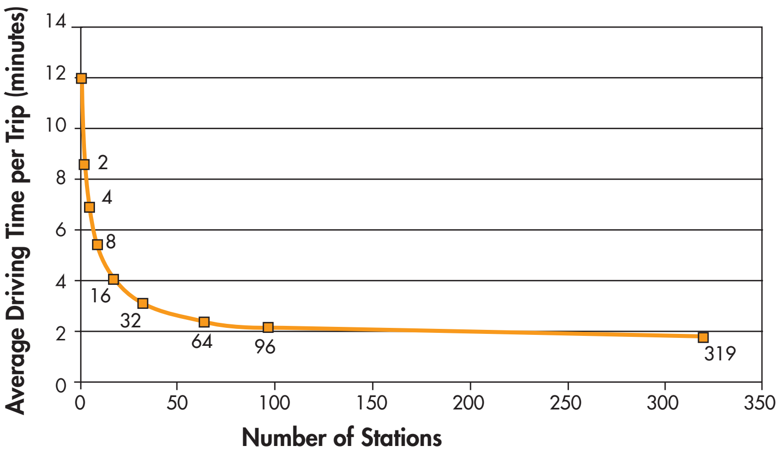
Strategies for initiating a hydrogen infrastructure

We have just sketched how infrastructure might be built in the United States assuming that fuel cell vehicles are successful in the marketplace. But the early stages of infrastructure development are still a major hurdle. How can we begin a transition to hydrogen? Consumers will not buy the first hydrogen cars unless they can refuel them conveniently and travel to key destinations, and fuel providers will not build an early network of stations unless there are cars to use them. Major questions include how many stations to build, what type of stations to build, and where to locate them. Key concerns are cost, fuel accessibility, customer convenience, the quality of the refueling experience, network reliability, and technology choice.

Automakers seek a convenient, reliable refueling network, recognizing that a positive customer experience is largely dependent on making hydrogen refueling just as convenient as refueling gasoline vehicles. Energy suppliers are concerned about the cost of building the first stages of hydrogen infrastructure when stations are small and under-utilized. Installing a large number of stations for a small number of vehicles might solve the problem of convenience but would be prohibitively expensive. Energy suppliers are also concerned about how long it would take for hydrogen to reach competitive costs with gasoline and how to endure through the early phase of uncompetitive stations to a viable business case.

A series of studies by STEPS researchers[22] analyzed how many stations would be needed for consumer convenience (defined as travel time to the station), and used spatial analysis tools to estimate where stations would be located. Based on studies of four urban areas in California, Nicholas et al. found that a strategically sited hydrogen network could provide an acceptable level of convenience if only 10 to 30 percent of gas stations offered hydrogen.[23]

TRAVEL TIME TO REACH A HYDROGEN STATION AS A FUNCTION OF NUMBER OF STATIONS IN AN URBAN AREA

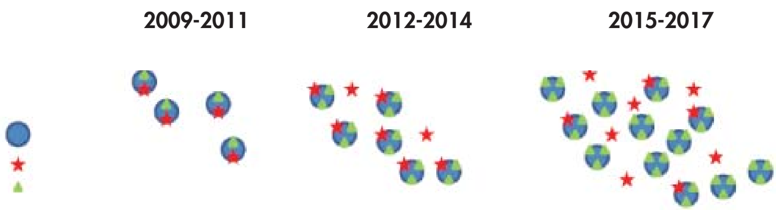


Not every existing fueling station in an urban area would need H_2 in order to provide convenience. Average driving time from home to an H_2 station goes down fast as H_2 becomes available at a relatively small fraction of existing stations. Source: M. Nicholas, S. Handy, and D. Sperling, "Usng Geographic Information Systems to Evaluate Siting and Networks of Hydrogen Stations," Transportation Research Record *1880 (2004): 126–34.*

Later we explored a "cluster strategy" for introducing hydrogen vehicles and refueling infrastructure in southern California over the decade from 2010 to 2020 to satisfy California's zero-emission vehicle regulation. Clustering refers to coordinated introduction of hydrogen vehicles and refueling infrastructure in a few focused geographic areas such as smaller cities (like Santa Monica and Irvine) within a larger region (for instance, the Los Angeles Basin). We analyzed several transition scenarios for introducing hundreds to tens of thousands of vehicles and 8 to 40 stations, considering station placement, convenience of the refueling network (for both local—home to station—and regional travel), type of hydrogen supply, and economics (capital and operating costs of stations, hydrogen cost).

A cluster strategy provides good convenience and reliability with a small number of strategically placed stations, reducing infrastructure costs. (Clustering enables the average FCV driver to reach a hydrogen station in about 4 minutes, even with a sparse network of 16 stations. In rollout plans without clustering the average travel time for a 16-station network was 16 minutes.[24]) A cash flow analysis estimates infrastructure investments of $120–170 million might be needed to build a network of 42 stations serving the first 25,000 vehicles. As more vehicles are introduced, the network expands, larger stations are built, and the cost of hydrogen becomes competitive on a cents-per-mile basis with gasoline.

STRATEGIES FOR EARLY H_2 INFRASTRUCTURE



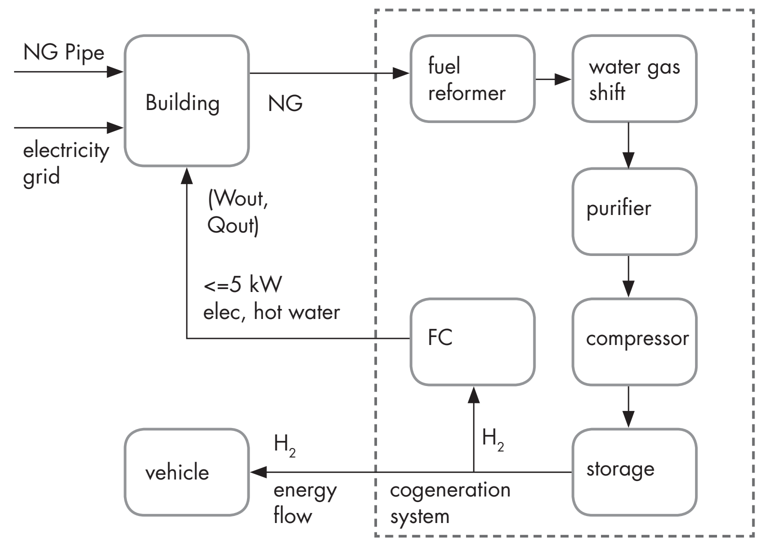
	636 FCVs	3442 FCVs	25,000 FCVs
#Stations	8	20	42
#clusters	4 (2sta/cluster)	6 (3 sta/cluster)	12 (3 sta/cluster
Connect.sta	0	2	6
Station Mix	4 Portable refuelers 4 SMRs (100 kg/d	8 Portable Refuelers 12 SMRs (250 kg/d)	10 Portable Refuelers 12 SMRs (250 kg/d) 20 SMRs (1000 kg/d)
New Equip. Added	4 Portable refuelers 4 SMRs (100 kg/d	4 Portable Refuelers 12 SMRs (250 kg/d)	2 Portable Refuelers 20 SMRs (250 kg/d)
Capital Cost	$20 million	$52 million	$98 million
O&M Cost	3-5 $million/y	11-14 $million/y	30-40 $million/y
H_2 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

Clustering is a good strategy for early H_2 infrastructure. Here is one plan for H_2 station build-out in southern California. Source: M. A. Nicholas and J. M. Ogden, "An Analysis of Near-Term Hydrogen Vehicle Rollout Scenarios for Southern California," UCD-ITS-RR-10-03 (Institute of Transportation Studies, University of California, Davis, 2010).

HOME REFUELING STRATEGIES FOR HYDROGEN VEHICLES

In contrast to the early infrastructure build-out strategies discussed above—which rely on a network of public stations, whose high cost and low utilization are discouraging to private investment—we have also explored the use of home and neighborhood refueling strategies as paths toward commercializing FCVs. In particular, we have assessed "tri-generation" systems, which are energy systems designed to meet the three energy needs of a typical household—electricity, heat, and transportation fuel. Current tri-generation technologies produce hydrogen by reforming natural gas. The economics of hydrogen refueling can be improved by co-producing electricity and heat. Home and neighborhood refueling both potentially offer convenience along with early availability of hydrogen fuel with less investment than a dedicated hydrogen station network.[25]

We developed an interdisciplinary framework and an engineering-economic model to evaluate the economic and environmental performance of tri-generation systems for home and neighborhood refueling. Based on near-term projections for system cost and performance, our model shows that residential tri-generation systems can become economically competitive, especially in regions with low natural gas prices and high electricity prices. In future work, we will examine neighborhood refueling concepts and tri-generation systems based on electrolyzers.



A typical tri-generation system simultaneously provides home electricity and heat along with hydrogen for a vehicle.

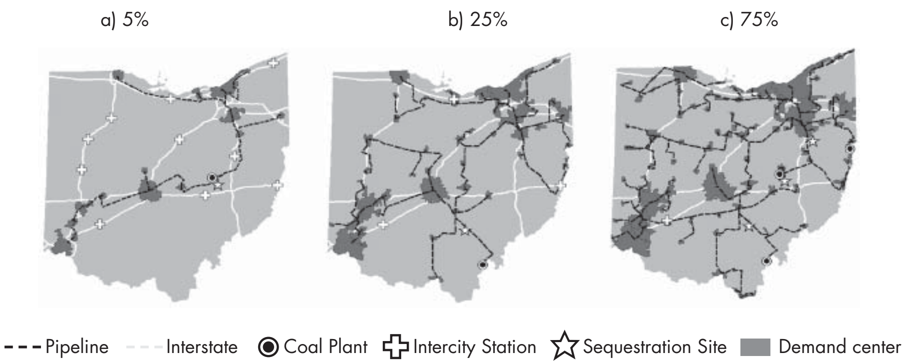
Regional hydrogen supply case studies

There are many options for hydrogen supply, and the lowest-cost design could vary by region. In this regard, hydrogen is more like electricity (which relies on regional primary energy sources) than like gasoline. To better understand the diversity of possible solutions for hydrogen supply in the United States, STEPS researchers have pioneered the use of engineering-economic models coupled with spatial information (GIS data) and optimization techniques. These models provide insight into the design, cost, and extent of regional hydrogen infrastructure. Unlike the SSCHISM model, which examines infrastructure for individual cities, these models let us evaluate whether economies of scale (and lower costs) can be achieved more quickly when infrastructure is designed for large regions encompassing multiple cities.

Coal with carbon capture and sequestration has been identified as one of the lowest-cost low-carbon, long-term hydrogen supply pathways.[26] To examine the regional deployment of centralized coal-based hydrogen infrastructure in the United States, we used regional spatial data to estimate the location and magnitude of demand and to identify potential locations for H_2 production facilities, CO_2 storage sites, and distribution networks for both H_2 and CO_2. We also used a network optimization tool to identify the lowest-cost infrastructure design for meeting demand at several market penetration levels. We evaluated both steady-state and dynamic deployment scenarios.[27]

In the steady-state scenarios, infrastructure is optimized independently for demand at different FCV market penetration levels ranging from 5 percent to 75 percent. Each design is independent of the others and represents a snapshot in time. A steady-state analysis for the state of Ohio, for example, indicates that a regional perspective lowers the levelized cost of hydrogen relative to models that examine individual cities.[28]

HYDROGEN INFRASTRUCTURE DESIGNS FOR OHIO BASED ON COAL WITH CCS



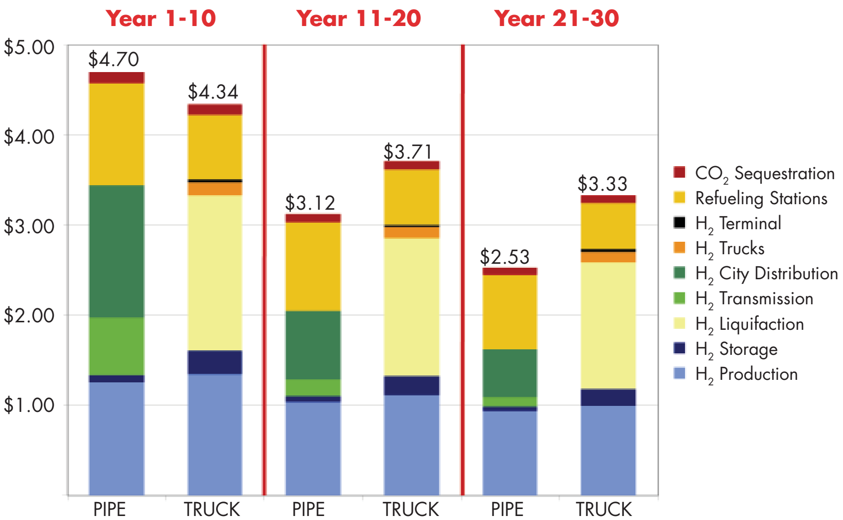
Our steady-state analysis for the state of Ohio came up with these optimal infrastructure designs at 5 percent, 25 percent, and 75 percent market penetration by FCVs. Source: N. Johnson, C. Yang, and J. Ogden, "A GIS-based Assessment of Coal-Based Hydrogen Infrastructure Deployment in the State of Ohio," International Journal of Hydrogen Energy *33 (2008): 5287–303.*

Modeling infrastructure deployment at the regional level allows for demand to be aggregated and economies of scale in production and distribution to be achieved at lower market penetration levels. At this level, pipeline delivery costs less than truck delivery, with the levelized cost of hydrogen delivered via pipeline ranging from $3.20/kg at 5-percent market penetration to $2.20/kg at 75-percent market penetration. However, the steady-state analysis assumes that the infrastructure is fully utilized and consequently does not account for the underutilization of capital that would occur during a transition. For this reason, steady-state models tend to underestimate the cost of hydrogen.

To address this issue, we conducted dynamic modeling of infrastructure deployment in which infrastructure is built over time to meet a growing demand and the timing of investments is tracked. This model accounts for underutilization of capital as large infrastructure investments are made to meet anticipated demand levels. For hydrogen infrastructure with pipeline distribution in Ohio, the levelized cost of hydrogen ranges from $4.30/kg at 5-percent market penetration to $2.70/kg at 75-percent market penetration. These costs represent a 20-percent to 35-percent increase in the cost of hydrogen compared with the results of the steady-state model.

We conducted similar dynamic modeling for California in which hydrogen infrastructure deployment with pipeline and liquid H_2 truck distribution was compared over a 30-year planning period.[29] This study found that truck distribution is competitive with pipelines in the first ten years (1-percent to 14-percent market penetration) since truck transport is less capital-intensive than pipelines and thus is impacted less by underutilization of capital. However, once the infrastructure becomes well utilized in later time periods, pipelines achieve better economies of scale since this mode is dominated by annual operating costs (for example, electricity for H_2 liquefaction and diesel for trucks). CCS represents a very small portion of the total infrastructure costs (less than 3 percent).

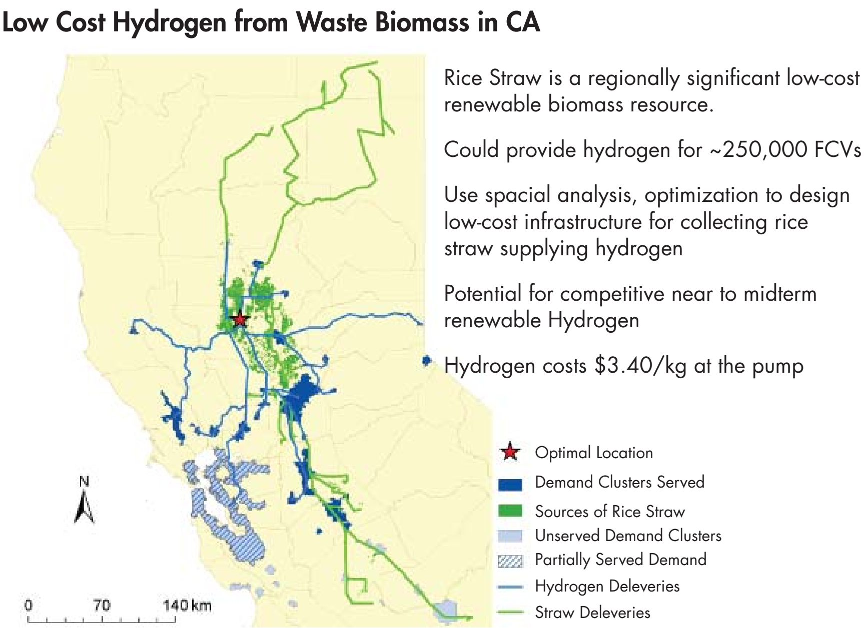
COSTS FOR HYDROGEN DELIVERY IN CALIFORNIA BASED ON COAL WITH CCS



Our dynamic modeling for California came up with these levelized costs for hydrogen delivered via pipeline and truck over a 30-year planning period.

Biomass hydrogen is another promising low-carbon pathway. STEPS researchers examined the possibility of using agricultural wastes to make biomass hydrogen in California, a region with an emphasis on renewable hydrogen.[30] He found that under certain circumstances it would be possible to reduce the costs of biomass hydrogen through optimal location of production plants and design of delivery systems. His best designs yielded delivered hydrogen costs of \$3.5–4/kg, competitive with on-site natural gas reforming. The choice of delivery mode (pipeline vs. truck) depended on the market fraction and the type of waste (dense versus more dispersed).

A HYDROGEN INFRASTRUCTURE DESIGN FOR CALIFORNIA BASED ON BIOMASS



Parker et al. examined the possibility of using rice straw to make biomass hydrogen in California and found that under certain circumstances it would be possible to reduce the costs of biomass hydrogen through optimal location of production plants and design of delivery systems. Source: N. Parker, Y. Fan, and J. Ogden, "From Waste to Hydrogen: An Optimal Design of Energy Production and Distribution Network," Transportation Research E: Logistics *46 (2010): 534–45.*

In summary, these regional case studies offer insight into what hydrogen infrastructure might look like in a specific region and illustrate the geographically specific nature of hydrogen supply design in the United States. As with the U.S. electricity system, it is likely that hydrogen will be produced from a variety of feedstocks. Regional case studies allow decision makers to assess the magnitude of required infrastructure and quantify the investments required to make it happen. These case studies can also be used to explore how and why these investments might differ between geographic regions.

Policies and Business Strategies Needed to Support Hydrogen

The results presented in this chapter (and in Chapter 9), as well as those of several recent studies,[31] indicate that the costs to buy down FCVs to market-clearing levels (through technological learning and mass production) and build the associated infrastructure might be tens of billions of dollars, spent over the course of one to two decades. The majority of the cost will be associated with early FCVs, and a lesser amount with early infrastructure. It is almost certain that government policy will be needed to bring these technologies to cost-competitive levels.

How might policy and business strategy support the future of hydrogen in the energy system? Since the start of the 21st century, the vision of hydrogen-fueled transportation has received attention from policymakers and industry worldwide, with investments of billions of dollars in public and private funds.[32] Eighteen countries have national programs to develop hydrogen energy; in North America, more than 30 U.S. states and several Canadian provinces have announced regional "roadmaps" or "hydrogen highways."[33] Automakers and energy companies like Shell and Total are working with governments to introduce the first fleets of hydrogen vehicles and refueling mini-networks in Europe (notably Germany and Norway), Japan, Korea, and the United States (notably California, Hawaii and New York[34]).

However, while there is a growing imperative for alternative fuels driven by concerns about oil supply, rising fuel costs, and climate change, and the search by politicians for a quick technical fix, the context for considering future alternative fuels is dynamic and uncertain. In the early 2000s, hydrogen and fuel cells were widely seen as the endgame. Over the past few years, though, it has become apparent that hydrogen infrastructure will take more time to develop and implement than was previously assumed. Meanwhile, technical progress continues in a variety of other alternative-fuel and efficient-vehicle technologies that are nearer term and/or more compatible with the existing energy system, especially liquid biofuels and plug-in hybrid electric vehicles. Still hydrogen fuel cell vehicles are moving forward rapidly, and several automakers plan to commercialize hydrogen fuel cell vehicles around 2015, just a few years after battery cars, which are making their initial appearance now. Hydrogen and fuel cells are part of a technical progression, building on efficiency and increasing electrification of cars that encompasses hybrid electric drive trains, plug-in hybrids, and improved batteries.

Hydrogen should be seen as one aspect of a broad move toward lower-carbon energy. To realize hydrogen's full benefits will require making hydrogen from domestic and widely available zero-carbon or decarbonized primary energy supplies. Hydrogen can benefit from ongoing efforts to develop biomass and coal gasification with carbon sequestration for electric power, as well as renewable energy sources such as wind and solar.

Finally, public policy is needed to move toward a goal of zero-emission, low-carbon transportation with diversification away from oil-derived transportation fuels. This calls for a comprehensive strategy, based on developing and encouraging the use of clean, efficient internal combustion engine vehicles in the near term, coupled with a long-term strategy supporting the introduction and scale-up of advanced transportation technologies including hydrogen and fuel cells, advanced batteries, and biofuels.

Summary and Conclusions

- Hydrogen fuel cell vehicles are making rapid progress; it appears likely that they will meet their technical and cost goals and could be commercially ready by 2015. Hydrogen infrastructure technologies are also progressing, and the technology to produce natural-gas-based hydrogen is commercial today. In the near term (up to 2025), hydrogen fuel will likely be produced from natural gas, via distributed production at refueling stations, or, where available, excess industrial or refinery hydrogen. Beyond 2025, central production plants with pipeline delivery will become economically viable in urban areas and regionally, and low carbon hydrogen sources such as renewables and fossil with CCS will be phased in.

- The environmental impacts of hydrogen fuel vary with the production pathway. For the near term, FCVs using hydrogen made from natural gas would reduce well-to-wheels GHG emissions by about half compared to current gasoline vehicles. Future hydrogen production technologies could virtually eliminate GHG emissions. On the other hand, important constraints on use of land, water, and materials required by the hydrogen pathway are not well understood. This is a key area for future work under the STEPS program.

- Building a hydrogen infrastructure will be a decades-long process in concert with growing vehicle markets. We have modeled infrastructure deployment in individual "lighthouse" cities as well as at the regional level. Since it is likely that hydrogen will be produced from a variety of feedstocks, optimal supply strategies will differ between geographic regions.

- When FCVs are mass marketed and sold to consumers in 2015 or soon after, hydrogen must make a major leap to a commercial fuel available initially at a small network of refueling stations and must be offered at a competitive price. The first steps are providing hydrogen to test fleets and demonstrating refueling technologies in mini-networks. Several such projects are now underway in Germany, Japan, and North Anerica. Learning from these programs will include development of safety codes and standards. If strategically placed, these early sparse networks could provide good fuel accessibility for early users, while forming a seedbed for a large scale hydrogen infrastructure rollout after 2015.

- Getting through the transition to hydrogen will involve significant costs and some technological and investment risks. Concentrating hydrogen projects in key regions like southern California will focus efforts, lower investment costs to make refueling available to consumers, and hasten infrastructure cost reductions through faster market growth and economies of scale.

- Even under optimistic assumptions, it will be several decades before FCV technologies can significantly reduce emissions and oil use globally, because of the time needed for new vehicle technology to gain major fleet share. Beyond this, hydrogen can yield significant benefits, greater than those possible with efficiency alone. This underscores the importance of providing consistent support for hydrogen and fuel cell vehicle technologies as they approach commercial introduction, so they can progress more quickly to scale, yielding competitive costs and greater societal benefits.

Notes

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