The HYDROGEN TRANSITION

A NextSTEPS white paper by: Joan Ogden, Christopher Yang, Michael Nicholas, and Lew Fulton

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July 29, 2014
Final Version

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July 29, 2014

NextSTEPS White Paper: THE HYDROGEN TRANSITION

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Abstract

Hydrogen fuel cell vehicles (FCVs) experienced a surge of interest in the early 2000s due to their potential to provide significant reductions in greenhouse gas and criteria air pollution, quick acceleration, fast refill, long range and ability to use a fuel (hydrogen) derived from domestic energy resources. However, public interest waned by the late 2000s as FCVs did not materialize in the showrooms and plug-in battery vehicles began entering the commercial market. The perception was that hydrogen was too difficult, and would not appear for several decades, if at all. However, in the past few years, important factors have emerged that are re-accelerating the commercialization of hydrogen and fuel cell technologies. These include sustained automaker development of FCVs resulting in lower component and vehicle costs and better performance and durability, sophisticated new infrastructure strategies, the rise of public private partnerships for FCV rollout, increase in public support, low-cost natural gas, Zero Emission Vehicle (ZEV) and carbon policies and interest in hydrogen for storing renewable electricity.

The next two to three years will see concerted efforts to introduce hundreds of hydrogen stations capable of supporting tens of thousands of FCVs in selected regions worldwide, backed by several hundred million dollars in public investment and billions of dollars in private investment. If these regional rollouts succeed, hydrogen FCVs might be just a few years behind plug-in vehicles in the commercialization process, and might ultimately capture a larger share of the light duty vehicle market.

This paper presents an analysis of the issues surrounding a transition to large-scale use of hydrogen. We examine the current status of hydrogen vehicle and

infrastructure technologies, and ongoing early commercialization efforts. Drawing on developments in California, the US, Europe and Asia, both near term and long term transition issues are discussed. These include managing the early introduction of hydrogen vehicles and associated infrastructure, and accomplishing a longer term transition to low carbon sources for hydrogen such as renewables and hydrocarbons with carbon capture and sequestration. We discuss what kinds of policies are now in place, the roles of different stakeholders in various regions, and what future policies might be needed to catalyze introduction of hydrogen and FCVs.

Table of Contents

Contents

Abstract 1

Table of Contents 3

INTRODUCTION 4

STATUS OF HYDROGEN FUEL CELL VEHICLE AND INFRASTRUCTURE TECHNOLOGIES 10

Cost Estimates for Fuel Cell Vehicles 11

Non-Light Duty Vehicles 14

Hydrogen Fuel Production and Delivery Technologies 15

Hydrogen infrastructure: design considerations 17

DESIGNING A TRANSITION TO HYDROGEN 19

Early Transition Issues: Initiating a Hydrogen Transition 19

Consumer Adoption of FCVs 21

New Thinking on Early Hydrogen Infrastructure 23

Other strategies for early stations 31

Transition to Green Hydrogen 32

Hydrogen Transition Costs in Perspective 37

Stakeholder coordination and reducing risk 41

HYDROGEN FCV ROLLOUT ACTIVITIES WORLDWIDE 43

The Rise of Public-Private Partnerships 45

HYDROGEN POLICY 48

Policies provide an essential role for supporting and nurturing the market for fuel cell vehicles and hydrogen fueling stations. Important policies for hydrogen can include regulations, incentives, and codes and standards. 48

Public Funding for Hydrogen and Fuel Cells 48

Global overview of hydrogen-related policies 49

CONCLUSIONS AND RECOMMENDATIONS 51

REFERENCES 53

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INTRODUCTION

Hydrogen fuel cell vehicle (FCV) technologies experienced a surge of interest in the early 2000s due to their potential to provide significant reductions in greenhouse gas and criteria air pollution, quick acceleration, fast refill, long range and ability to use a fuel (hydrogen) derived from diverse domestic energy resources. However, public interest waned by the late 2000s as FCVs did not materialize in the showrooms and plug-in battery vehicles began entering the commercial market. The perception of some stakeholders was that hydrogen was too difficult, and would not appear for several decades, if at all. However, in the past few years important factors have emerged that are re-accelerating the commercialization of hydrogen and fuel cell technologies. These include sustained automaker development of FCVs resulting in lower component and vehicle costs and better performance and durability, sophisticated new infrastructure strategies, the rise of public private partnerships for FCV rollout, increase in public support, low-cost natural gas, Zero Emission Vehicle (ZEV) and carbon policies and interest in hydrogen for storing renewable electricity.

The next two to three years will see concerted efforts to introduce hundreds of hydrogen stations supporting the introduction of tens of thousands of FCVs in selected regions worldwide, backed by several hundred million dollars in public investment and billions of dollars in private investment. If these regional rollouts succeed, hydrogen FCVs might be just a few years behind plug-in vehicles in the commercialization process and might ultimately capture a larger share of the light duty vehicle market.

Perhaps the largest reason for this renaissance is several major automakers' continuing commitment to hydrogen fuel cell vehicles as a necessary complement to plug-in electric battery vehicles and a critical component of automakers' long-term strategy to provide vehicles that contribute to energy and climate policy goals. In many respects, hydrogen fuel cell cars could offer similar amenities to today's gasoline cars that are more challenging to achieve in battery-powered vehicles, including good performance, large vehicle size, refueling time of 3-5 minutes and a range of 300-400 miles. In other words, hydrogen fuel cell vehicles could enable zero vehicle emissions and significantly lower life-cycle emissions without compromising consumer expectations.

Hydrogen and fuel cell vehicle technologies are making rapid progress toward technical and cost goals. In 2013, automakers announced new alliances to commercialize FCV technology. Automakers have developed and leased demonstration hydrogen fuel cell automobiles to real-world customers for the last five years and have stated their intention to introduce these vehicles in commercial volumes of 1,000s or more in the 2014 to 2017 timeframe.

Hydrogen fueling infrastructure has also been a major challenge— the so-called 'chicken or egg' dilemma where automakers have been reluctant to market cars without infrastructure and station provider/operators have been reluctant to build stations without cars. Recently, regional public-private partnerships around the world have developed smart, comprehensive strategies for coordinating early hydrogen infrastructure development with FCV rollouts in North America, Europe and Asia.[1] Through these partnerships, key stakeholders are coming together and a few regions (notably California, Japan and Germany) have committed significant funds to support the next crucial steps forward on infrastructure build-out.

Worldwide, public funding for RD&D and policies supporting hydrogen is trending upwards (with the notable exception of the United States where federal support has fallen by about 60% from its peak in 2008). Global public support now totals about $1 billion per year, leveraging many times that amount in private funds (USDOE 2012).

The near term prospects for plentiful, low-cost hydrogen are good. The boom in low cost shale gas has improved the prospects for natural gas-derived hydrogen, especially in the United States, where it is a major force in the resurgence of Federal interest in hydrogen energy. And while natural gas derived hydrogen does produce greenhouse gas emissions, these emissions are less than half compared to a conventional vehicle due to the greater efficiency of the fuel cell (Nguyen et al. 2013). Furthermore, as discussed below, several methods of

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[1] Although light duty vehicles (LDVs) contribute over half of global transport related greenhouse gas (GHG) emissions, there is growing concern about low carbon emission options for other transport sectors, heavy-duty, marine, and aviation, where it is difficult to use batteries. While most models of low carbon futures project use of liquid biofuels for non-LDV applications, concerns about the availability of sustainable biomass has led to a reexamination of electricity and liquid hydrogen for non-LDV applications.

producing hydrogen, including from renewable sources, provide the potential for even greater benefits.

Fuel cells are succeeding in stationary power and battery replacement markets, such as forklifts, giving further confidence in the technology. Increasing numbers of fuel cell power plants are being installed for secure and reliable distributed power and central power plant applications around the world. Residential fuel cell combined heat and power systems are thriving in Japan and Europe, with tens of thousands of units installed in Japan and thousands planned in Europe (Walker 2014).

Another important driving factor is deepening concern about climate change and the growing realization that hydrogen FCVs could be a critical technology enabling a low carbon transportation future. Recent studies of low carbon futures suggest that a variety of electric drive vehicles will play a major role in the future light duty vehicle fleet (IEA 2012, NRC 2013). In the International Energy Agency's "2 degree scenarios" (corresponding to 80% GHG emissions cuts by 2050), hydrogen FCVs and plug-in electric vehicles account for over half of on-road passenger cars by 2050 with about equal shares (IEA 2012). Hydrogen also fuels some trucks, buses and trains in that scenario.

Finally, as renewable portfolio standards and carbon policies are being put in place, hydrogen is being widely discussed as a flexible energy carrier for integrating intermittent renewables like solar and wind into the energy system. For example, power grids in Europe and North America are incorporating ever more intermittent renewables (especially wind power), which are not coincident with demand, creating significant amounts of excess generation and driving a growing interest in energy storage. Hydrogen's potential advantage compared to other electricity storage technologies like batteries, compressed air and pumped hydro is its flexibility, enabling concepts like power to gas, seasonal storage as a means of better controlling the grid, and using off-peak power to make hydrogen transport fuel (Figure 2).

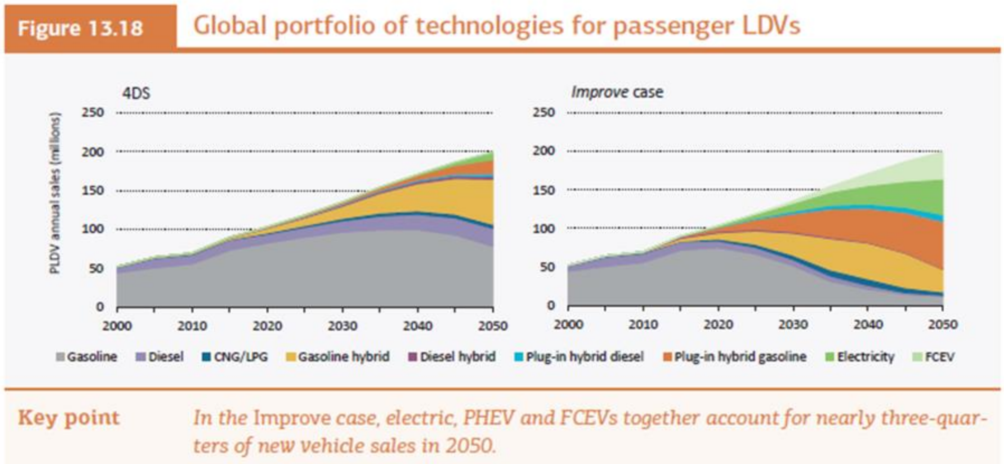

Figure 1. Source: International Energy Agency Energy Technology Perspectives 2012. This result is typical of recent studies suggesting a major role for hydrogen in low carbon transportation futures. By 2050, about two-thirds of global new light duty vehicle sales are electric drive vehicles (pure battery EVs, plug-in hybrids and hydrogen fuel cells). Another recent study for the US (NRC 2013) shows low carbon scenarios where electric drive makes up 80% of new light duty vehicle sales in 2050. (The “4DS” case (left) refers to a transport sector scenario consistent with a global average temperature rise of 4^{o}C. The “improve” case (right) is a transport scenario consistent with a rise of 2^{o}C.)[2]

[2] The *4D*S for transport represents a trajectory that unfolds with existing and upcoming policies. OECD countries continue to tighten fuel economy standards up to 2025 for both passenger LDVs and road-freight vehicles. PHEV and BEV market penetration is slow, similar to what happened with HEVs initially.
The *Improve* case focuses on technology improvements that lower GHG emissions; it implies tightening fuel economy standards through 2030 on new cars. Electric vehicles start displacing the ICE from the mid-2020s, joined by FCEVs in the 2030s. When coupled with mode shifts, it is consistent with transport sector that contributes to the 2^{o}C target.

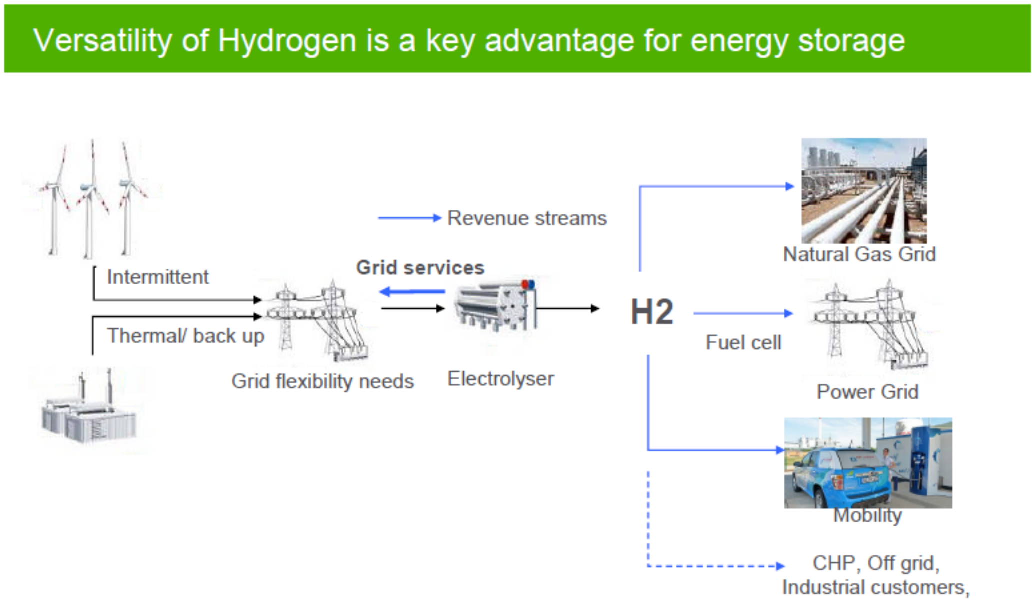

Figure 2. Options for using hydrogen to integrate intermittent renewables into the energy system. Source: P. E. Franc, "Financing Hydrogen Projects" Nov. 16, 2013, International Partnership for a Hydrogen Economy Conference, Seville, SPAIN

Within the last few years the fuel cell industry has clearly moved into a new stage of commercial development. However, hydrogen still faces technical, economic, infrastructure and societal challenges before it can be implemented as a transportation fuel on a large scale. The question now is not whether fuel cell vehicles will be technically ready; they are. The question is how to spur vehicle sales, how to coordinate the rollout of hydrogen infrastructure as vehicles arrive, how to build investor confidence in the market and how to reduce the early financial risks for fuel suppliers and automakers.

This paper examines the current status of hydrogen vehicle and infrastructure development, discusses ongoing rollout activities for hydrogen FCVs and analyzes key issues associated with a transition toward large-scale use of hydrogen in transportation. Questions include:

- What is required to initiate a transition to hydrogen and fuel cells?
- What is the latest thinking on launching hydrogen FCVs and designing a viable early infrastructure? How are plans for hydrogen and FCV rollout progressing in North America, Europe and Asia? What would be needed to overcome risk in building early infrastructure?
- How much will it cost to buy down the cost of FCVs and bring hydrogen to scale where it could compete with gasoline? How does this compare to

other energy system costs and benefits. (NRC 2013, IEA ETP 2012; Ogden, Fulton and Sperling 2014)

- How do we get to "green hydrogen?" In the long term, to realize the full climate benefits, we will need to make hydrogen from low-carbon pathways such as renewables or fossil with carbon capture and sequestration (CCS)?
- What kinds of policies are currently in place and what more policies are needed? Is there enough funding and investment capital available to launch hydrogen production, distribution and refueling systems? Are current policies moving things in the right direction? What kinds of policies might be needed to catalyze introduction of hydrogen and FCVs and reduce stakeholder risks?

Drawing on experiences from North America, Europe and Asia, both near term and long term transition issues are discussed. These include managing the early introduction of hydrogen vehicles and associated infrastructure, and accomplishing a longer term transition to low carbon sources for hydrogen such as renewables and hydrocarbons with CCS. We discuss the roles of various stakeholders and what kinds of policies might be needed to catalyze introduction of hydrogen and FCVs and reduce stakeholder risks.

STATUS OF HYDROGEN FUEL CELL VEHICLE AND INFRASTRUCTURE TECHNOLOGIES

Hydrogen and fuel cell vehicle technologies are progressing rapidly. Hydrogen fuel cell vehicles have already met the US Department of Energy's (USDOE) 2015 goals for fuel economy and range (see Table 1). And while further development is needed for key hydrogen vehicle technologies such as proton exchange membrane (PEM) fuel cells' cost and durability, cost of hydrogen storage on vehicles, and technologies for zero-carbon hydrogen production, it is anticipated that hydrogen FCVs will meet all of these goals over the next few years.

Table 1. Current Status and US DOE Goals for Hydrogen Fuel Cell Vehicles

	2013 Status	*USDOE Goals*
Fuel Cell In-Use Durability (hours)	2500 (on-road) 4000 (in lab)	5000
Vehicle range (miles/tank)	280-400	300
Fuel Economy (miles/kg H2)	72[3]	60
Fuel Cell Efficiency	53-58%	60%
Fuel Cell System Cost ($/kW) in large scale mass production[4]	55	40 (2020 goal) 30 (long term goal)
H2 Storage Cost ($/kWh)	15-23	10-15 (NRC 2009) 2-4 (USDOE)

Source: S. Satyapal, United States Department of Energy, presentation 2013.

The pace of progress is illustrated in Figure 3. The projected mass-produced cost of transportation fuel cell systems (including fuel cell stack and balance of plant but excludes H_2 storage) has dropped more than 50% since 2006.

[3] For Honda FCX clarity. Private communications 2010.
[4] The fuel cell system includes the fuel cell stack and associated balance of plant controls, but not motors. Costs are for production at 500,000 units per year (see Figure 3). At lower levels of mass production, fuel cell vehicle costs are considerably higher (see examples in Figures 4-6)

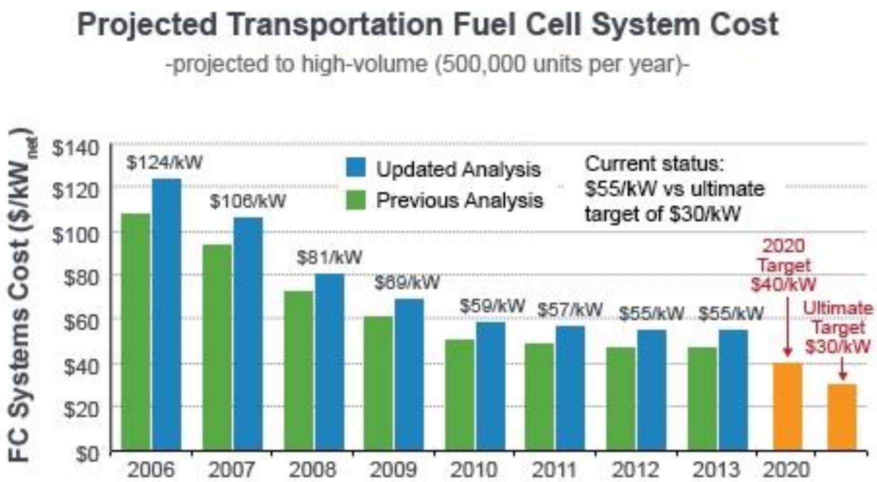

Figure 3. Estimated mass-produced cost of automotive fuel cell systems, and targets for 2020 and long term. Source: US Department of Energy, http://energy.gov/eere/fuelcells/accomplishments-and-progress, 2014.

Cost Estimates for Fuel Cell Vehicles

Various estimates have appeared for the projected cost of hydrogen fuel cell vehicles compared to other alternative fueled vehicles (Bandivadekar et al. 2008, NRC 2008. NRC 2010, Plotkin and Singh 2010, IPCC 2011, Burke et al. 2011, EPRI 2010, NRC 2013). Most of these studies projected that future mass-produced fuel cell cars will be moderately more expensive than an advanced gasoline car. For example, in a 2008 National Academies study of hydrogen transitions mass-produced, mature technology FCVs were estimated to have a retail price equivalent (RPE)[5] $3,600 to $6,000 higher than a comparable gasoline internal combustion engine vehicle (ICEV) (NRC 2008). Similar numbers were estimated by MIT, UC Davis, the National Renewable Energy Laboratory, Argonne National Laboratory, and the Electric Power Research Institute.

In 2013 a new NRC report provided updated estimates for learned out retail price equivalents for future mass-produced light duty vehicles (Figure 4). This report

5 The RPE is not the same as actual vehicle prices in the showroom. The difference between the cost and price reflects the automakers profit or loss on a given product. Automakers frequently pursue a strategy called "forward-pricing" when introducing new technologies (e.g. gasoline hybrids) in order to build product awareness, grow the volume of sales and benefit from the learning. This implies a period of losses with the expectation that eventually the product will become profitable.

pushed vehicle drivetrain and envelope efficiency for all types of vehicles, in part by downsizing and light-weighting the vehicle. Their reference gasoline car achieves a fuel economy of about 50 mpg by 2030 and 75 mpg by 2050, a more aggressive efficiency rise than past studies. The cost of gasoline vehicles is projected to increase over time due to efficiency improvement measures, and by 2045, both fuel cell and battery vehicles are projected to have lower retail prices than these advanced gasoline vehicles.[6]

While estimates of the future retail price equivalent of mass-produced FCVs may approach those of advanced gasoline vehicles, initial FCV models will not be produced in such high volumes. As a result, vehicle prices will be higher due to higher manufacturing costs (related to the size and scale of manufacturing facilities, greater manufacturing efficiency, and reduced supplier costs), and the amortization of fixed engineering, research and development costs, which are spread over a smaller number of vehicles. Incorporating factors for manufacturing scale, R&D progress and learning, we estimated a cost trajectory for EVs, PHEVs and FCVs given assumed market penetration rates (Figures 4-6). Figure 4 shows NRCs projected learned out,[7] mass produced retail price equivalent for three electric vehicle technologies, battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs) and hydrogen fuel cell vehicles between 2010 and 2030, as compared to a highly efficient gasoline internal combustion engine vehicle (NRC 2013). In Figure 5, we show a possible scenario for the adoption of BEVs, PHEVs and FCVs, roughly similar to the historical ramp-up rate for gasoline hybrids (Ogden, Fulton and Sperling 2014). In Figure 6 we estimate the RPE of each type of vehicle over time, accounting for initial low volumes of alternative fueled vehicles. Vehicle RPEs fall rapidly as more vehicles are produced, with FCV technology following the plug-in electrics by about 5 years.

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[6] The NRC did various scenarios. For their “base case”, cost parity among EVs, FCVs and ICEVs cars happens in about 2045. In the “optimistic” case, parity happens sooner, in about 2030. The NRC also analyzed light trucks where parity occurs slightly later than for cars.

[7] The learned out, mass produced RPE refers to a fully mature technology produced at large scale.

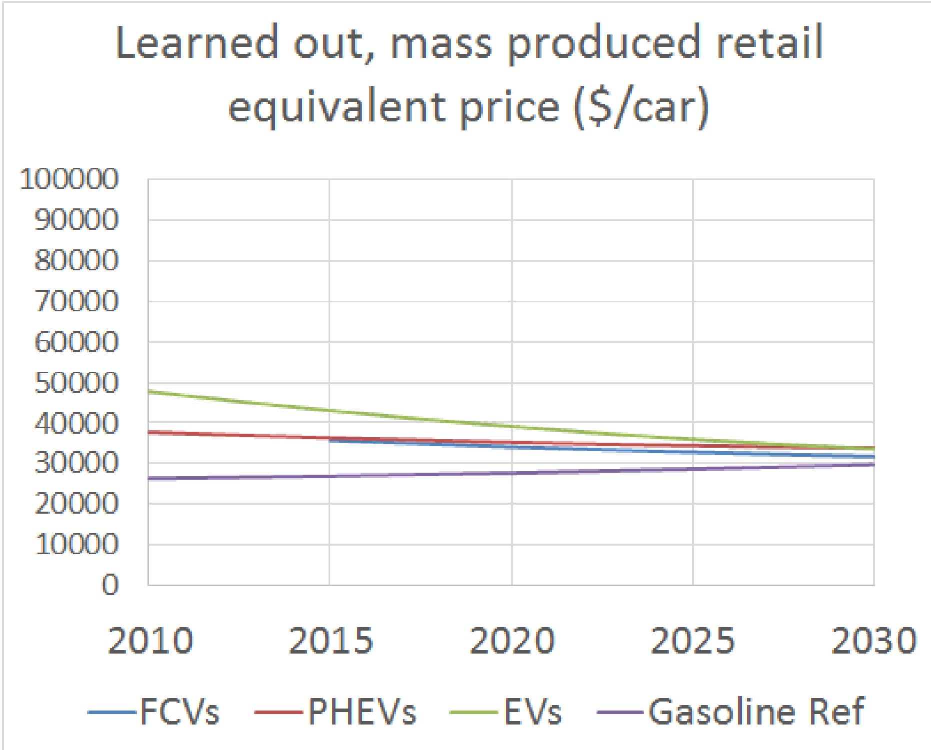


Figure 4. NRC estimates for learned out mass produced retail price equivalent for Battery EVs (EVs), plug-in hybrids (PHEVs) and hydrogen fuel cells (FCVs) compared to an efficient gasoline ICEV (NRC 2013). The battery EV is assumed to have a 100 mile range. The PHEV has a battery corresponding to a 30 mile all electric range.

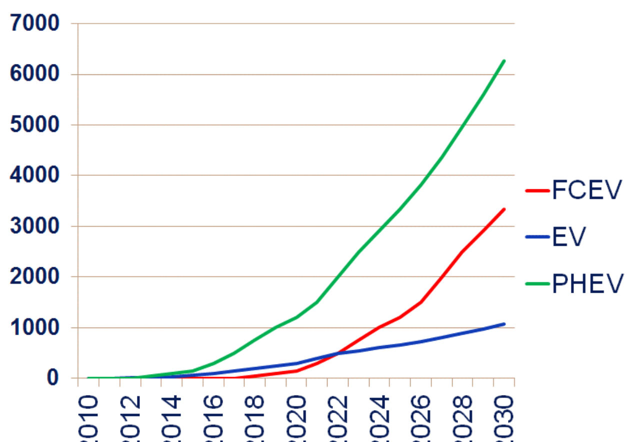


Figure 5. Scenario for introducing alternative fueled passenger cars in the US. New car sales are in 1000s per year (Ogden, Fulton and Sperling, 2014).

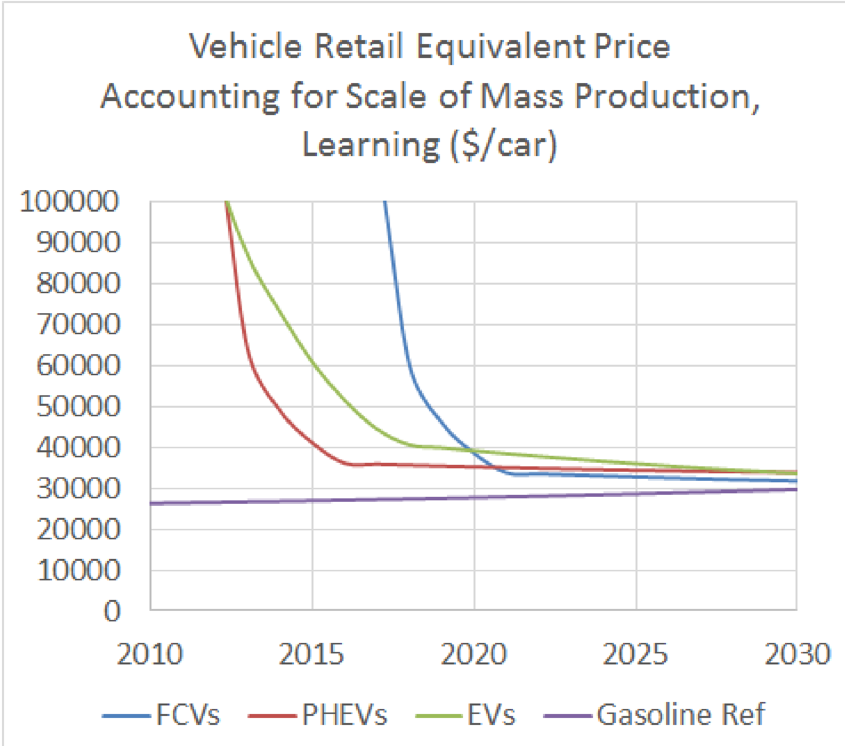


Figure 6. Vehicle retail price equivalent over time based on Figure 5, but accounting for early scale dis-economies at low levels of mass production. By the early 2020s the alternative fueled vehicles have reached mass-production volumes and learned out RPEs (Figure 4). The RPE is not the same as the showroom price of the vehicle, which can include marketing strategies such as "forward pricing" to build sales (Ogden, Fulton and Sperling, 2014).

Non-Light Duty Vehicles

Light duty vehicles are not the only transportation applications where fuel cells might be used. Hydrogen fuel cell buses have been demonstrated in Europe, North America and Asia. The technologies are similar to those for light duty vehicles: PEM fuel cells and compressed gas storage. Infrastructure issues are different and possibly easier than for light duty vehicles (see p. 30), Hydrogen is also being investigated for use in trucks, locomotives, ships and even aircraft (stored as liquid hydrogen). These applications are further away.

Hydrogen Fuel Production and Delivery Technologies

Hydrogen production systems

Like electricity, hydrogen can be produced from diverse primary energy resources (see Figure 7).

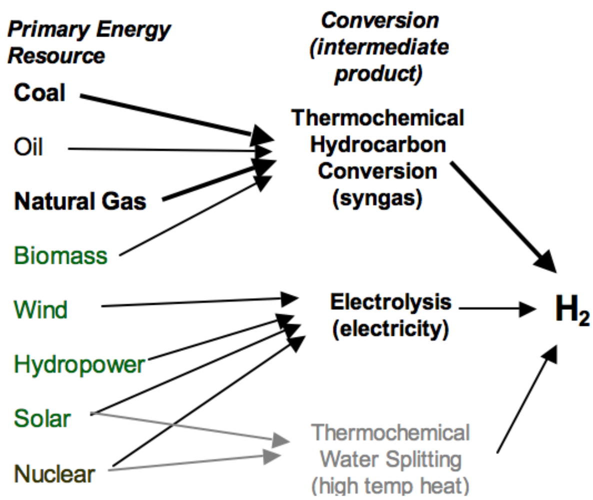


Figure 7. Production pathways for hydrogen.

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. In the United States, about 9 million metric tonnes of hydrogen are produced each year, mainly for industrial and refinery purposes. (This is enough to fuel a fleet of about 35 million fuel cell cars if it were used for that purpose.) Steam reforming of natural gas is the most common method of hydrogen production today, 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, roughly half as much as a comparable gasoline car on a well to wheels basis (Nguyen et al. 2013). The growth of low cost shale gas has been a factor boosting interest in hydrogen in the US.

Future hydrogen production technologies could virtually eliminate greenhouse gas (GHG) emissions. For large central plants producing hydrogen from natural gas or coal, it is technically feasible to capture 75-90% of the CO_2 and permanently sequester it in deep geological formations, although the widespread use of sequestration technology has several important challenges to overcome and will not happen on a wide scale 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. As mentioned earlier, there may be significant benefits to coupling hydrogen fuel production with flexible storage of off-peak intermittent renewable electricity from wind or solar intensive electricity grids.

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 and commercial facilities) from natural gas, alcohols (methanol or ethanol), or electricity. Hydrogen delivery technologies are well established in the merchant hydrogen and chemical industries today. While most industrial hydrogen is produced and used onsite, a significant fraction is delivered by pipeline or truck to more distant users. No one hydrogen supply pathway is preferred in all situations, so, like electricity, it is likely that diverse primary sources will be used to make hydrogen in different regions. Figure 8 shows the delivered cost of hydrogen for a variety of supply pathways, based on UC Davis research.

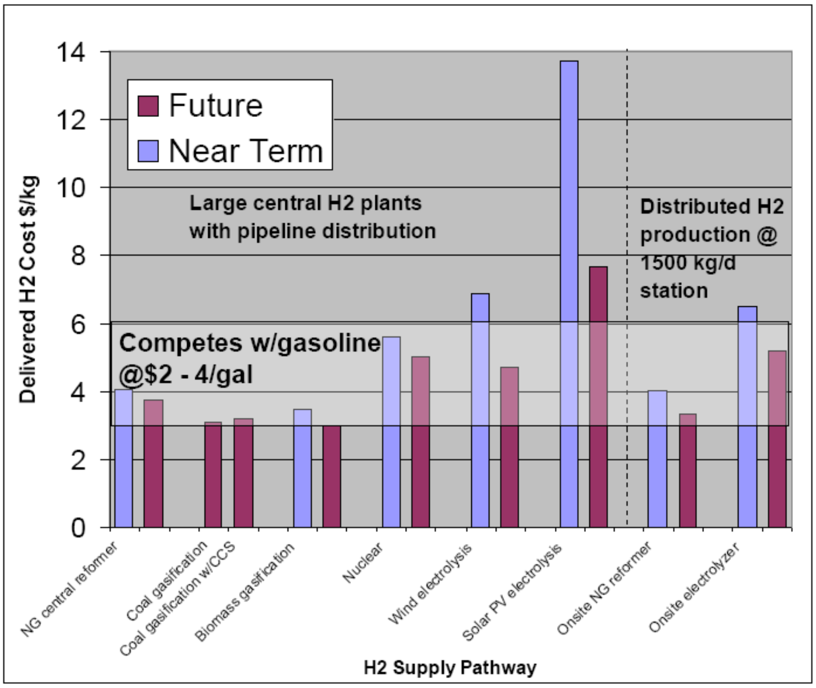


Figure 8. Delivered cost of hydrogen transportation fuel from various pathways. The grey band indicates where the fuel cost per mile for hydrogen FCVs would compete with a gasoline hybrid. (Note that fuel taxes are not included in the delivered fuel costs.) Costs assume that hydrogen supply technologies are mature and mass-produced. They are based on costs from the H2A model.

The technologies for large scale production of hydrogen from fossil sources are well established. The challenges for low carbon hydrogen supply are similar to those for low carbon electricity with respect to issues for nuclear and renewable energy and CCS.

Hydrogen infrastructure: design considerations

Adoption of hydrogen vehicles will require a widespread new hydrogen refueling infrastructure. 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 providing a convenient and low-cost network of hydrogen stations to many dispersed users, especially during the early stages of the transition.

Design of a hydrogen infrastructure depends on many factors including:

- **Scale** - Hydrogen production, storage, and delivery systems exhibit economies of scale, and costs decrease as equipment size increases and generally with increasing demand.

- **Geography / regional factors** - The location, size, and density of demand, the location, quantity 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 characteristics and status** - Assumptions about hydrogen technology cost and performance determine the best supply option. In addition, technology characteristic such as efficiency and energy requirements will determine the lifecycle energy and emissions from hydrogen infrastructure.

- **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. Incentives and subsidies for building infrastructure.

- **Integration with other energy sectors -** Choices about production also depend on interconnections of the H_2 system with other system (e.g. electricity storage, compressed CO_2 pipelines for geologic sequestration). Integrated design decisions may improve reliability, and reduce costs and emissions from the system as a whole.

Once a hydrogen infrastructure system is full scale, hydrogen can economically compete with gasoline and other fuels on cost/mile and full life-cycle basis (NRC 2008). The primary challenge lies with minimizing the cost of early infrastructure, where stations tend to be smaller and underutilized.

DESIGNING A TRANSITION TO HYDROGEN

In this section, we discuss transition issues associated with a shift towards hydrogen vehicles and fuel infrastructure. Early market transition issues focus on coordinating initial vehicle deployments and early hydrogen infrastructure, geographically and over time, and managing risk for early investors. We also consider the longer term issue of moving from fossil sources to "green" hydrogen from low carbon pathways like renewables or fossil fuels with carbon capture and sequestration (CCS).

Early Transition Issues: Initiating a Hydrogen Transition

The early stages of hydrogen infrastructure development pose special challenges. Each of the various stakeholders (consumers, automakers and station/fuel providers) have specific concerns and goals that should be satisfied if development is to proceed rapidly.

First, 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 for fuel suppliers include how many stations to build, what types of stations to build, and where to locate them. The key concerns are cost, fuel accessibility, early adopter convenience, the quality of the refueling experience, network reliability, and technology choice.

The various stakeholders can have conflicting goals for infrastructure. 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 for station providers and result in very expensive fuel for consumers. Regulators seek a way to nurture the hydrogen option, which may rely initially on fossil sources, while providing a long term path to low carbon emitting hydrogen pathways.

The infrastructure needed depends on the number of vehicles served. Not surprisingly, obtaining good projections for the future numbers and locations of fuel cell vehicles is difficult. Projections are difficult because vehicles sales and infrastructure deployment co-evolve in a dynamic and interconnected way and depend on a number of factors including consumer preferences, technology costs, technology attributes, government incentives and the competitive landscape with other vehicle types.

Automakers have announced that they will be ready to produce thousands or tens of thousands of vehicles beginning over the next few years, but have not said exactly how many cars will produced or where they will be deployed. Table 3 shows one of the few public estimates for regional FCV introduction, based on a 2010 survey by the California Fuel Cell Partnership (CAFCP 2012). These fuel cell vehicle estimates give an indication of the rate at which automakers could proceed, although the actual rate will be influenced by the availability of hydrogen, policy, consumer acceptance, vehicle prices and other factors.

Policy goals provide aspirational numbers for FCV adoption. The California Zero Emission Vehicle (ZEV) regulation suggests that 50,000 FCVs may be on California roads by 2017-8, with a goal of 1.5 million ZEVs (both FCVs and battery EVs) by 2025. A recently released memorandum of understanding among eight US states including California sets a goal of 3.3 million ZEVs by 2025.

It is interesting to compare these FCV market goals with recent data on electric vehicle sales in the United States. Figure 9 shows annual sales of electric drive vehicles in the US, including gasoline hybrids (HEVs), plug-in hybrids (PHEVs) and battery electric vehicles (BEVs) (EDTA 2014). The adoption rates are similar in the first few years of introduction for HEVs, PHEVs and BEVs. Figure 10 shows several estimates for market adoption rates for hydrogen FCVs based on NRC studies (NRC 2008). HEVs achieved cumulative US sales of 1 million in 2007 (8 years after introduction), reaching 2 million in 2010 (11 years after introduction). These are similar to stated FCV goals in the US (assuming that FCVs account for half of the 3.3 million ZEVs implemented by 2025 – 11 years after introduction).

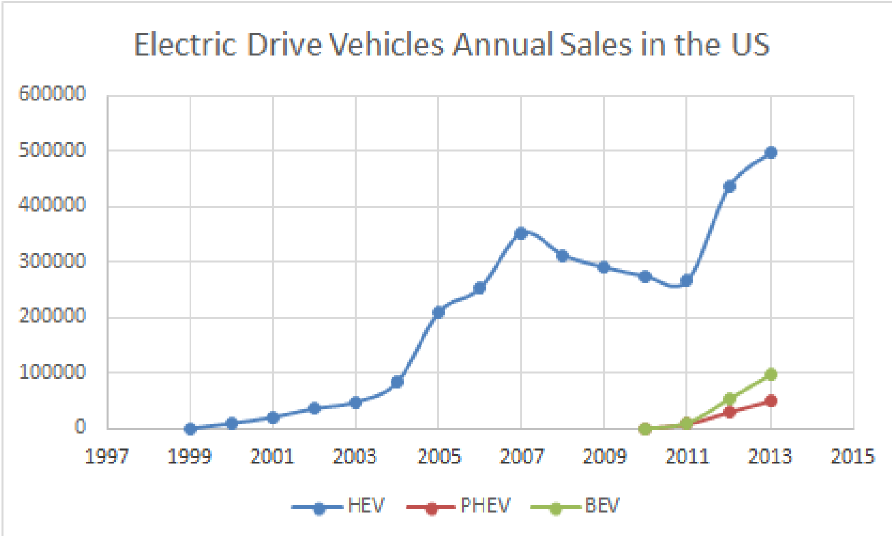


Figure 9. Comparison of electric drive vehicle sales data in the US. The adoption rate is similar in the first few years of introduction for HEVs, PHEVs and BEVs.

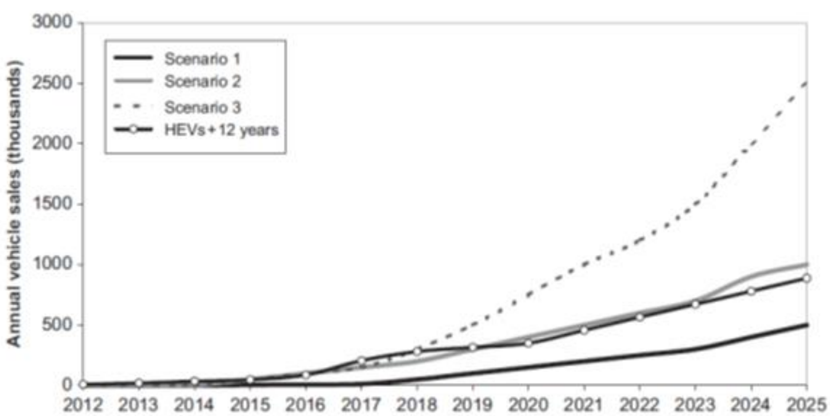


Figure 15.3. Three USDOE Scenarios for H_2 FCV market penetration (Gronich, 2006), and historical market penetration rates for gasoline hybrid vehicles displaced by 12 years.

Figure 10. Source: Greene, Leiby and Bowman 2007, as shown in NRC 2008. These scenarios were developed in 2006-2007 based on then-current policy and technology projections and were meant to be illustrative of the range of possible market ramp-up rates. The FCV introduction date (shown above as 2012) is now estimated to be the 2015-2018 range (see Table 6).

Consumer Adoption of FCVs

One of the key unknowns is how consumers will view hydrogen fuel cell vehicles and purchase these vehicles. Hydrogen has, at least initially, higher private (i.e. consumer) costs associated with fuel cell vehicles and fuel and therefore some level of government incentives is likely to be needed to overcome the high initial prices and bring vehicles and fuels down the learning curve and experience economies of scale in vehicle and fuel production.

These incentives can take the form of direct purchase subsidies on fuel cell vehicles or for fuels.

One of the key questions for consumer adoption relates to how consumers would view FCVs compared to other alternative fueled vehicles. Given the emergence of plug-in electric vehicles such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) in the last few years, consumer comparisons between these vehicles and hydrogen vehicles are inevitable. PEVs have a "head start" in consumer awareness, cost reductions and infrastructure deployment, so the comparative advantages of each vehicle type become important in considering who might purchase these vehicles (see Table 2).

Table 2. Comparison of Key Consumer Attributes of Fuel Cells and Plug-in Vehicles

	Hydrogen Fuel Cell Vehicles	**Plug-in Hybrid and Battery Electric Vehicles**
Refueling time	Shorter (3-5 minutes)	Longer (20 min to many hours), PHEV can refuel gasoline quickly
Vehicle sizes	Small to large vehicles	Small to midsize vehicles
Vehicle range	300+ miles per refill	10-200 miles of all electric range
Refueling paradigm	H_2 stations similar to gas stations	Chargers (home and public)
Fuel cost per mile	\$0.13/mile at \$8/kg H_2 \$0.08/mile at \$5/kg H_2	\$0.04/mile at \$0.12/kWh

Given the earlier introduction of electric vehicles, their lower vehicle prices relative to a newly introduced FCV, and lower per mile cost, it is helpful to ask under which circumstances a consumer might choose an FCV relative to a BEV. Given current battery costs, BEVs may be best suited for smaller commuter vehicles with fixed driving patterns that fit within the vehicles range, especially in a multi-car household. The advantages of FCVs are for drivers who would like larger vehicle sizes (large cars or light trucks/SUVs), whose driving range needs are higher, and where quick refueling would be a benefit. FCVs might also appeal to those who could not charge an electric vehicle at home and instead would use a refueling station similar to a gasoline station.

Future sales of fuel cell vehicle are dependent on a number of key factors (and the primary parties that have influence over these factors):

- ***Vehicle costs*** - includes both purchase and fuel prices and incentives (automakers, fuel providers and government)

- ***Consumer utility and convenience*** – relates to consumer preferences, vehicle characteristics, performance, range and availability of refueling locations (consumers, automakers, fuel providers)
- ***Infrastructure availability*** – expansion of hydrogen station deployment to additional regions (automakers, fuel providers and government)
- ***Other consumer perception of FCVs*** – includes many other aspects including the future viability of technology, competition with other vehicle types, environmental benefits (consumers, automakers)

New Thinking on Early Hydrogen Infrastructure

Thinking has advanced considerably over the past few years about how to build a convenient, low cost early hydrogen infrastructure that mitigates some of the 'chicken-and-egg' dilemma, by balancing the needs of stakeholders, reducing risk and encouraging confidence. There is now widespread agreement that an early hydrogen infrastructure must offer the following:

- **Coverage**: enough stations to provide convenient fuel accessibility for early vehicles
- **Capacity**: to meet hydrogen demand as the FCV fleet grows
- **Cash flow**: positive cash flow for individual station owners and for network-wide supply
- **Competitiveness**: Offering hydrogen fuel to consumers at a competitive cost with gasoline, estimated to be $10/kg initially, and $5-8/kg for the longer term.[8]

To meet these goals, rollout plans must coordinate the deployment of FCVs and hydrogen infrastructure build-out, geographically and over time. Such plans are being developed by public-private partnerships around the world (see Table 8).

California is a good illustration of how thinking on infrastructure rollout has evolved. The first proposal for the California Hydrogen Highway (2004) was an announcement by the governor that the state would build hydrogen stations every 20 miles along the interstate highways. It was soon recognized that this plan would not serve the daily refueling needs of urban populations, where most Californians live. A more analytical approach was taken by the state's Hydrogen Blueprint Plan (2006), locating hydrogen stations to serve the state's urban

[8] Hydrogen costs are typically given in $ per kilogram ($/kg). 1 kg of hydrogen has about the same energy content as 1 gallon of gasoline. Hydrogen FCVs are about 2-2.5 times as energy efficient as gasoline internal combustion engine vehicles. So the fuel cost per mile for hydrogen at $10/kg is equivalent to gasoline at $4-5/gallon.

populations, loosely based on today's gasoline infrastructure. These studies showed that consumer convenience similar to gasoline could be achieved if approximately 10-30% of gasoline stations offered hydrogen. This was an important insight: hydrogen would not be needed at every gasoline station. But even 5-10% of gasoline stations is still a large number, amounting to 200 to 400 stations in the Los Angeles area alone, costing an estimated $300-800 million just to get started (Nicholas et al. 2007, Ogden and Nicholas 2010).

The next conceptual leap was development of the "cluster strategy", the idea of co-locating the first several thousand vehicles and tens of stations in "lighthouse" communities identified as early adopter areas within a larger region (CAFCP 2012). The cluster strategy brought the required number of initial stations to a more manageable level. When Ogden and Nicholas analyzed a "cluster strategy" for co-locating the first few thousand vehicles and tens of stations in communities within the Southern California region, they found average travels times to stations of less than 4 minutes even with a very sparse initial regional network, less than 1% of gasoline stations. These targeted "clusters" only represent a fraction of the Southern California population but represent specific areas where fuel cell adoption is more likely.

Table 3 shows a possible scenario for 7-year FCV rollout and hydrogen station development in Southern California, based on a cluster strategy.[9] By year 7 the system serves 34,000 FCVs with a network of 78 stations.[10]

[9] Rollout plans in Germany, Japan, South Korea and the UK are based on variants of the cluster strategy as well.
[10] The numbers of fuel cell vehicles are based on the 2010 CAFCP survey (CAFCP 2012). More recent estimates have not appeared as of this writing.

Table 3. Scenario for rollout of 34,000 FCVs and 78 hydrogen stations in Southern California

	Year 1	*Year 2*	*Year 3*	*Year 4*	*Year 5*	*Year 6*	*Year 7*
# FCVs in fleet	197	240	347	1,161	12,106	23,213	34,320
H2 demand (kg/d)	137	168	250	800	8,500	16,000	24,000
#New Stations Installed per year by Station Size (kg/d) and Type							
Mobile Refuelers (100 kg/d)	4	0	0	0	0	0	0
Compressed Gas Truck Delivery							
Station Size							
170 kg/d	0	0	4	0	0	0	0
250 kg/d	0	0	0	10	0	0	0
500 kg/d	0	0	0	0	20	20	20
Total station capacity (kg/y)							
	400	400	1,080	3,580	11,580	21,580	31,580
Total number of stations							
	4	4	8	18	38	58	78
Average travel time home to station (minutes)							
	4	4	3.5	3	2.8	2.6	2.6

In our scenario, hydrogen is supplied via compressed gas hydrogen truck delivery, building on the current industrial gas supply system.[11] The hydrogen is largely derived initially from natural gas or industry by-products. Initially, hydrogen is supplied via mobile refuelers, a small-scale portable station incorporating storage and dispensers that can be towed to any site. After several years, we then add a network of small fixed stations (170 kg/d) to assure coverage, and as demand rises larger stations (250 kg/d and then 500 kg/d) are added to the network.[12]

In Figures 11-13, we analyze the economics of this rollout scenario from three different perspectives: the whole station network, the individual station owner and the consumer. Table 4 shows assumed costs for current and future hydrogen stations and Figure 11 shows the estimated levelized cost of hydrogen assuming the stations are operated at their rated capacities (e.g. 100 kg/d, 170 kg/d 250

[11] Another interesting option for small scale hydrogen stations is being pursued by Linde, which is developing advanced station concepts based on liquid hydrogen delivery. In July 2014, Iwatani purchased 28 such stations from Linde for deployment in Japan (Green car congress 2014). Liquid hydrogen delivery is widely practiced commercial technology, giving another avenue for building on the existing merchant hydrogen system.

[12] To put these numbers in perspective, a mid-size FCV would consume perhaps 0.7 kg of hydrogen per day on average (traveling 15,000 miles per year in a 60 mpg equivalent car). This would require a station capacity of perhaps 1 kg per day per FCV served, accounting for 70% station utilization. So a 100 kg/d station might serve a fleet about 100 FCVs, and a 500 kg/d stations about 500 FCVs.

kg/d or 500 kg/d). Hydrogen fuel costs become more competitive as the station technology develops and larger stations are built.

Table 4. Compressed gas truck delivery Hydrogen Station Cost Assumptions: 700 bar dispensing. (based on industry input).

Time frame	Capital Cost	Annual O&M cost $/yr
Phase 1 (years 1-2) **100 kg/d** **250 kg/d**	$1 million $1.5 million	$100 K (fixed O&M) + 1 kWh/kgH2 x kg H2/yr x $/kWh (compression electricity cost) + H2 price $/kg x kg H2/y (H2 cost delivered by truck)
Phase 2 (years 3-4) **170 kg/d** **250 kg/d**	$0.9 million $1.4 million	Same as above
Phase 3 (year 5+) **170 kg/d** **250 kg/d** **500 kg/d**	$0.5 million $0.9 million $1.5-2 million	Same as above

We assume that stations are built a year or two in advance of the vehicles arriving.

Figure 12 graphs the network-level station investments over time as 78 stations are built and more cars arrive. The "cash flow" is the revenue from selling hydrogen at $10/kg ("H2 sales") minus the costs of building stations ("capital") and operating costs including truck-delivered hydrogen ("O&M"). The cash flow is negative to start, but after about year 7, it becomes positive. By year 9, the cumulative cash flow become positive as well, and the network can pay for itself, even though the initial years show a negative balance. The total capital investment for all 78 stations is about $113 million. (If one entity owned the network, this would be the maximum exposure.) The minimum point in the cumulative cash flow curve is about $65 million, based on the assumption that the rollout proceeds rapidly and hydrogen sales offset costs.

In California, gasoline stations are mostly owned by independent operators rather than energy companies. In Figure 13, we look at the economics of hydrogen fueling from the point of view of a gasoline station owner who installs a 500 kg/d hydrogen supply in phase 3 (c. 2015), costing $1.5 million (Table 4). The station can dispense up to 500 kg/day per day, and we assume that demand builds up linearly over a four-year period. The station owner takes out a 10-year loan for $1.5 million at 7% to pay for the hydrogen equipment. As before the "cash flow" is the revenue from selling hydrogen at $10/kg ("H2 sales") minus the costs of paying off the equipment loan ("capital") and operating costs ("O&M").

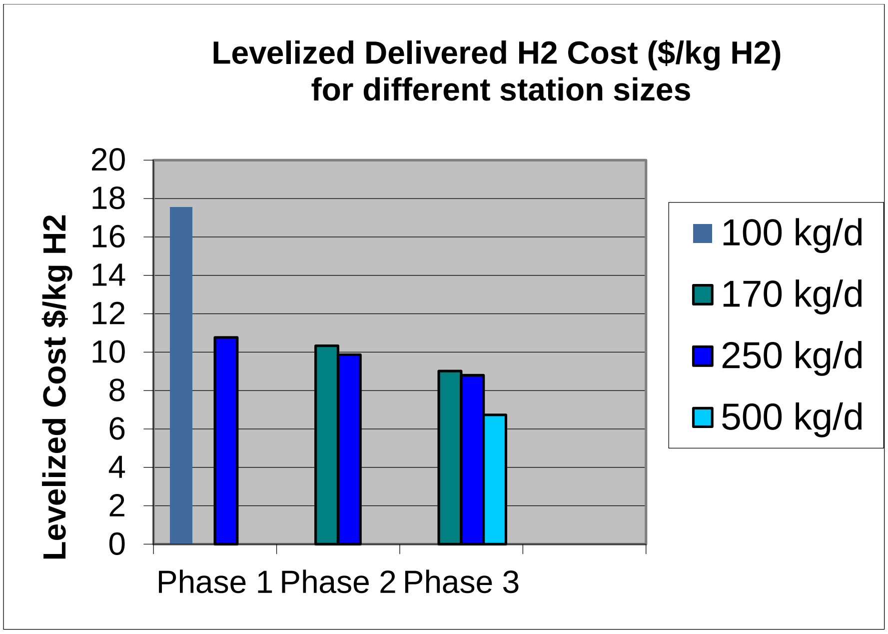


Figure 11. Levelized cost of delivered hydrogen based on costs in Table 4 for new stations built in each time frame. We assume that compressed hydrogen costs $6/kg truck-delivered to the station. The station owner's rate of return is assumed to be 12%, and the station life is 10 years. (The levelized cost is what the station would have to sell hydrogen for to make a 12% rate of return.) We further assume that each station dispenses an amount of hydrogen equal to its full capacity (full station utilization). H2 costs go down over time because of reductions in capital costs and increases in output capacity (500 kg/d stations become available).

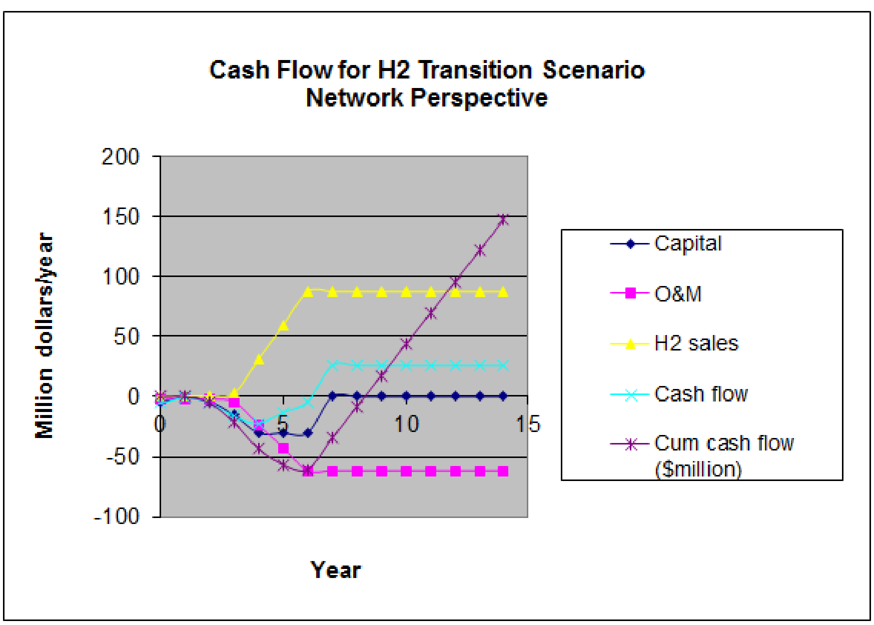


Figure 12. Cash flow from a station network perspective for the 78 station rollout described in Table 3, assuming that hydrogen is sold at $10/kg. Cash flow is the H2 sales – capital - O&M costs.

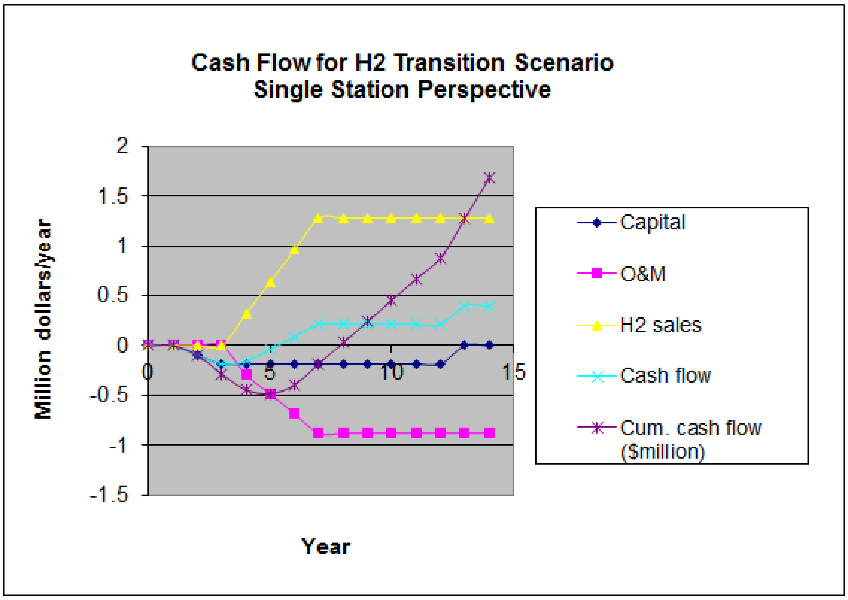


Figure 13. Cash flow from an individual station owner perspective. A 500 kg/d station is installed costing $1.5 million. Cash flow is the H2 sales – capital – O&M costs.

The annual cash flow to the station owner is negative at first but after about 4 years it becomes positive. Subsidizing the station owner by paying his loan until the cash flow goes positive would cost $400-600K per station. After about 7 years the cumulative cash flow becomes positive as well. This implies that the economics of building a large station would be attractive to the station owner, assuming the station is fully utilized within four years and that the hydrogen can be sold for $10/kg, $4/kg more than its truck-delivered price to the station.[13]

Once the FCV market takes off and demand for hydrogen grows rapidly, the large (500 kg/d) station has a business case that should attract investors, but who will build the early smaller stations? By themselves, 100 - 250 kg/d stations are not as attractive at 500 kg/d stations (see Figure 11) and involve more risk, if the cars don't appear as fast as expected. Early hydrogen station infrastructure has a first mover disadvantage which has discouraged investment.

We now estimate how much investment would be needed to build up a regional infrastructure to the "launch point" where the next station built will make money by selling hydrogen at a competitive price. In Figure 14, we extend the regional rollout scenario in Table 3 for several years, plotting the number of FCVs in the

[13] The payback time is lengthened by about 2 years if the hydrogen is sold for $9/kg and at $8/kg, the system does not payback within its 10 year lifetime.

fleet, the annual FCV sales, the total number of hydrogen stations in the network and the average size of new stations built each year. We assume that the regional FCV fleet grows rapidly from 34,000 in year 7 to 250,000 FCVs in year 11. (In year 11 the on-road FCV fleet is about 1% of all light duty vehicles in California, new FCV sales are about 6% of California's annual light duty vehicle sales) (Ogden and Yang 2009). This is similar in percentage terms to the historical early growth rate for HEVs in the US (Figure 9). We further assume that after year 4, large stations are built that employ compressed gas truck delivery (500 kg/d) or onsite steam methane reformation (1000 kg/d) (Figure 15). Hydrogen costs at the pump from these stations are estimated to be $5-8/kg (Ogden and Nicholas 2011), which would compete with gasoline vehicles on a cent per mile basis.

Station capital investments to year 12 are shown in Figure 16 versus time, along with the estimated network-average hydrogen cost at the pump. The cost of hydrogen drops rapidly from $25kg in year 1 to about $7.5/kg in year 5 and $6/kg in year 12. The average network utilization rises from 30% to about 70%, even accounting for an assumed 4 year time lag for hydrogen demand to catch up to station capacity. By the time 34,000 vehicles are on the road (year 7), we have spent about $113 million for 78 stations, and the average cost of hydrogen is $7.5/kg. By year 9, 100,000 FCVs are on the road, served by 200 stations, hydrogen costs about $7.1/kg and the cumulative station capital investment is about $300 million. Approximately $150-300 million is needed to build the first 100-200 stations, serving 50,000-100,000 vehicles. Once we reach this level of FCV and station deployment the infrastructure could be considered "launched" in the sense that there will be an economic case for building new large stations, assuming the market for FCVs is robust and growing. Moreover, the infrastructure will be widespread, convenient, and able to provide fuel at a cost competitive with gasoline, which will encourage FCV market growth.

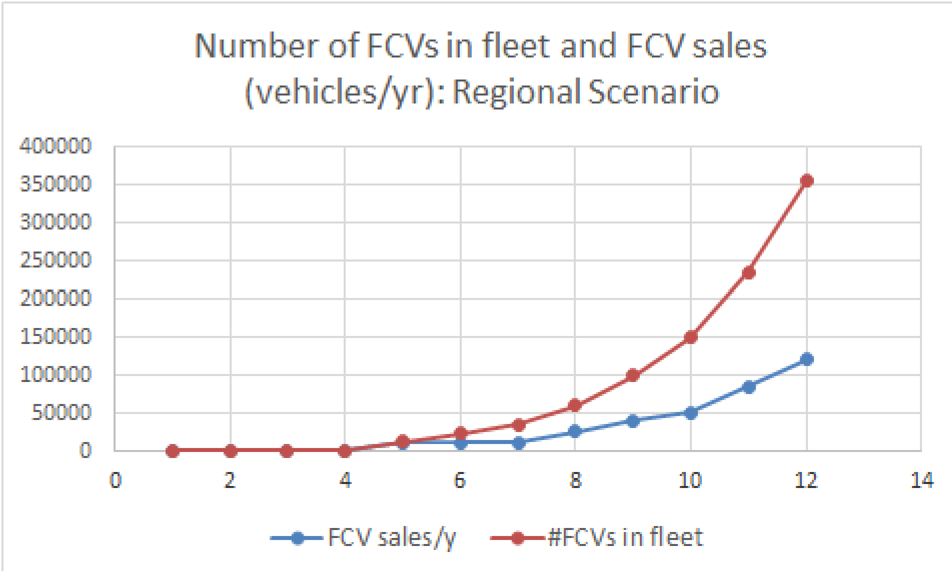


Figure 14. Scenario for regional FCV sales and on-road fleet vs. years (year 1 = start of commercialization).

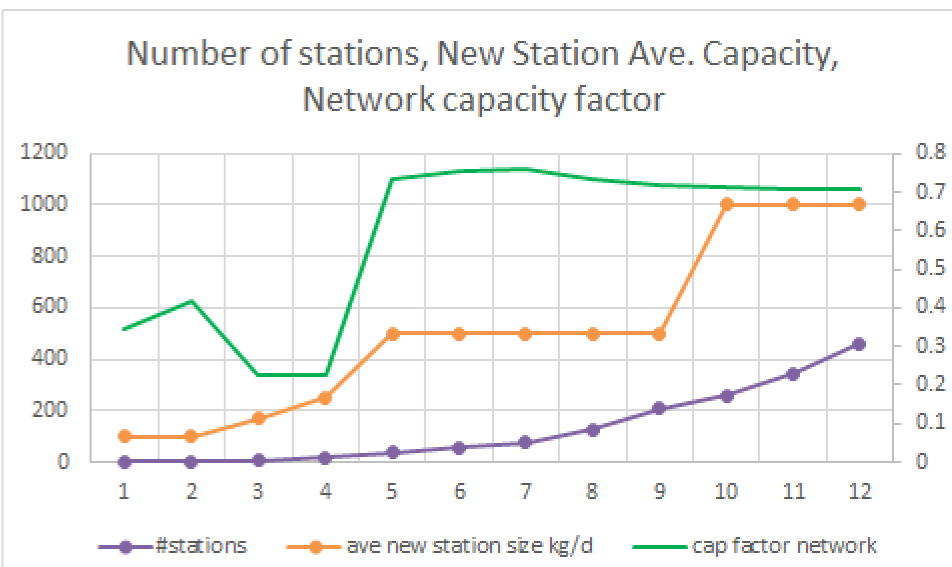


Figure 15. Scenario for total number of regional hydrogen stations, average size of new stations built and network capacity factor (= hydrogen dispensed/station network capacity). The station network serves the FCV rollout in Figure 14. The network capacity factor is low for the first few years, as stations are built ahead of vehicle deployment. Initially stations are small to provide coverage for early adopters. The network factor is plotted on the right hand y-axis; other variables on the left hand y-axis.

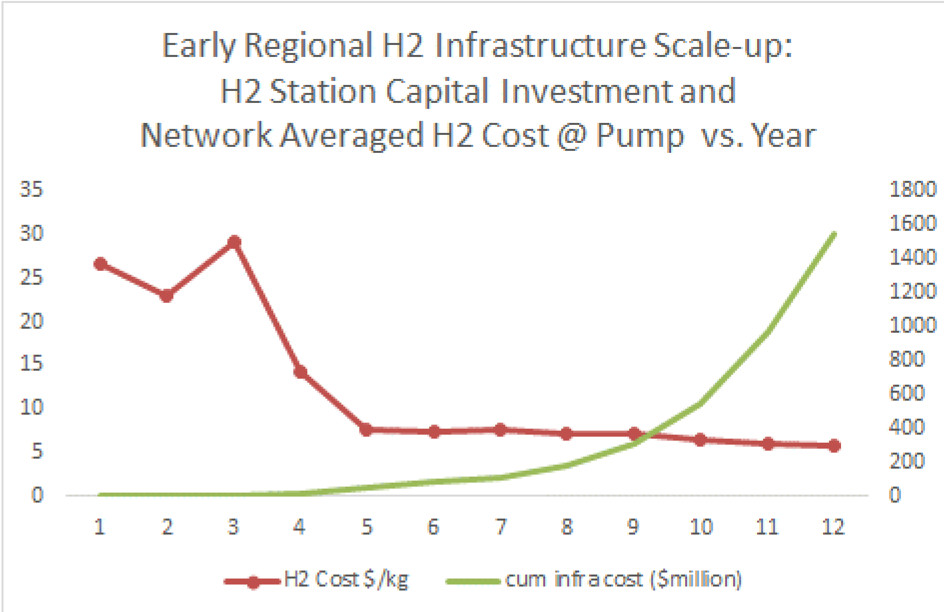


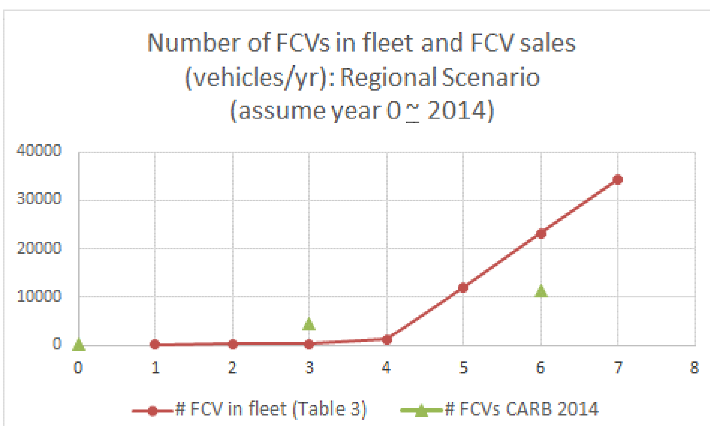
Figure 16. Estimate of the investments needed to support hydrogen infrastructure development in California (right hand y-axis) and the hydrogen cost (left hand y-axis).

Other strategies for early stations

Focusing solely on private passenger cars is not the only way to start a hydrogen fueling infrastructure. For example, early infrastructure could be designed to serve "anchor fleets" of fuel cell buses, providing a predictable early demand for hydrogen at a limited number of well-utilized large stations. To create a bridge to passenger car markets, anchor fleets could be located in cluster cities where early adopters for FCV cars might live. Another idea is building tri-generation systems where three energy carriers are produced, heat and electricity for a building plus hydrogen for vehicles. In an area with low cost natural gas and high cost electricity, the economic benefits of fuel cell cogeneration pay for the system, essentially "subsidizing" hydrogen transport fuel production and lowering the cost of refueling (Li, Ogden, Yang 2013). With tri-generation, the economics are not very sensitive to rate of passenger vehicle adoption, which reduces risk.

Sidebar: California Air Resources Board Releases First Annual Evaluation of FCV and Hydrogen Station Deployment in California

In July 2014, the California Air Resources Board released its first annual evaluation of progress on Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Development (CARB 2104). The report gathered automaker input for current and projected future FCV populations within the state, by year and location. It also listed the locations, capacities and characteristics of currently operating hydrogen stations and newly funded stations expected to be built in 2014 and 2015, and made estimates of station capacity needs in 2017-2020. The hypothetical scenario and economic analysis developed above by UC Davis researchers was based on older FCV projection data from a 2010 survey conducted by the California Fuel Cell Partnership. For the first 5 years (to 2020) our scenario has a somewhat faster ramp-up rate than the latest CARB projections. For example from Table 3 above in year 5 (roughly equivalent to 2019), there are about 12,000 FCVs in Southern California. (Also see Figure 14). The new CARB projections suggest about 11,500 FCVs in 2020 for this region of California. Similar to our scenario, the CARB report focused on building smaller stations early on to assure coverage then moving toward larger stations to meet growing capacity needs.. The details of the assumed station technologies are different in the CARB report than in our analysis, and we have not attempted an economic analysis based on the new CARB projections.



Transition to Green Hydrogen

To realize the full climate benefits of hydrogen and fuel cells, the hydrogen must be produced from low carbon pathways. However these low-carbon pathways face various challenges. For hydrogen from renewable resources (wind or solar electrolysis, biomass gasification), the issue is primarily cost rather than technical feasibility or resources (although competing uses for biomass might be an issue). Nuclear hydrogen issues are cost (for electrolytic H_2), and technical feasibility (for advanced water splitting systems powered by nuclear heat). Nuclear hydrogen also has the same waste and proliferation issues as nuclear power.

Fossil hydrogen with CO_2 capture and sequestration offers nearly zero emissions, relatively low cost, assuming suitable CO_2 disposal sites are available nearby, and hydrogen can be produced at large scale. And biomass-based hydrogen with CCS could lead to net negative carbon pathways. Despite the relatively low cost estimates for CCS based hydrogen, there is a great deal of uncertainty about the potential environmental impacts and feasibility of CO_2 sequestration.

UC Davis researchers Chris Yang and Joan Ogden analyzed different strategies for achieving a near zero carbon hydrogen transportation fuel supply system in California by 2050 (see sidebar) with an economic optimization model of infrastructure costs and emissions constraints. They found that it would be possible to develop hydrogen as a near-zero emissions transportation fuel, by relying on a combination of fossil with CCS, biomass derived hydrogen, and hydrogen from intermittent renewable electricity. If CCS is not available, then either emissions will rise (due to use of fossil resources without CCS) or costs will rise (due to reliance on intermittent renewable electrolysis) (Figures 17, 18).

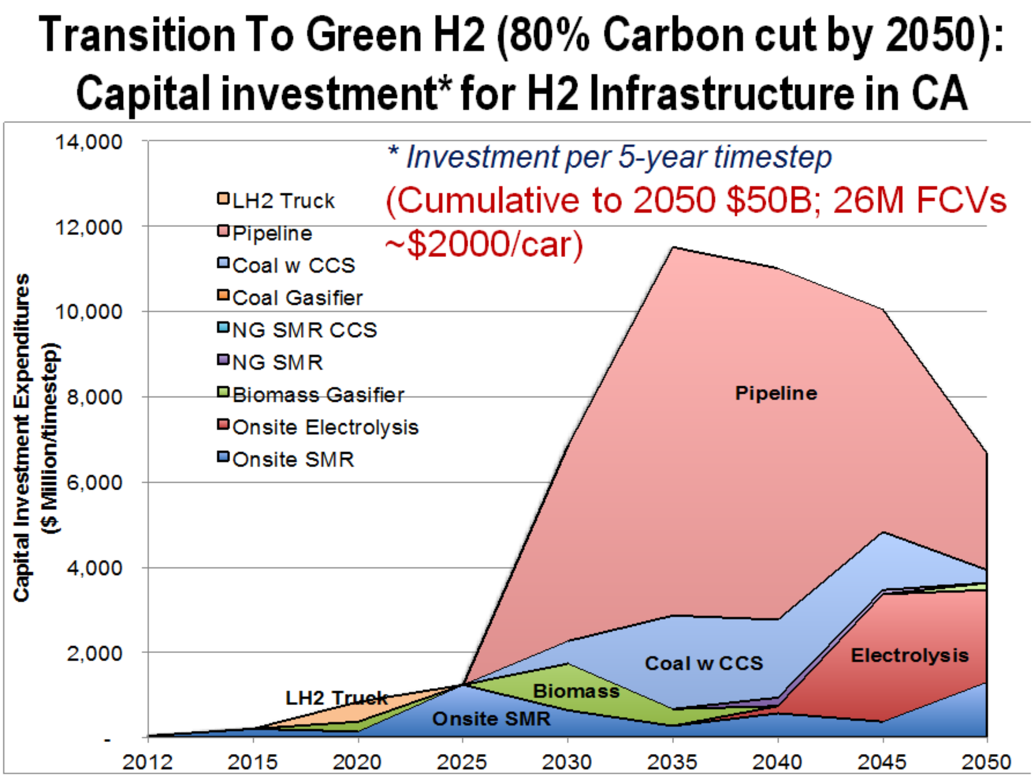


Figure 17. A possible mix for hydrogen supply over time to reduce vehicle GHG emissions by 80% compared to a gasoline reference vehicle.

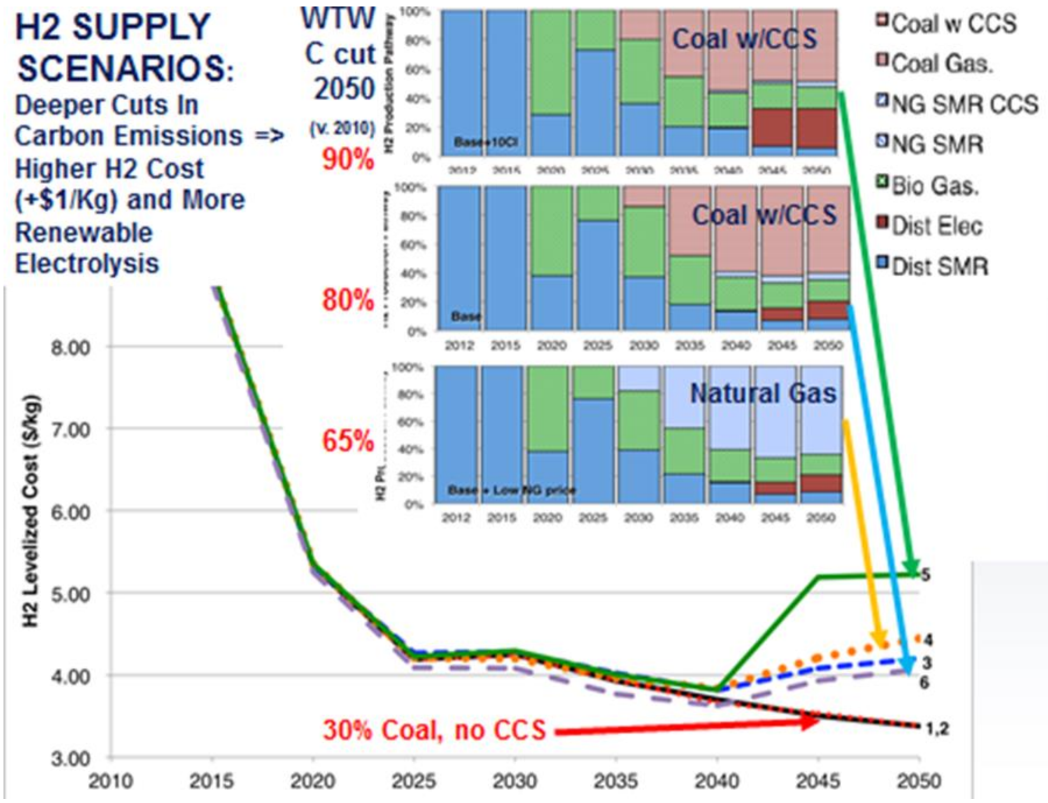


Figure 18. The hydrogen supply mix and cost of hydrogen is shown for different scenarios that reduce the hydrogen emissions by 30% to 90% by 2050 compared to a reference gasoline car. (The numbers at the right end of each curve denote 6 different scenarios in Yang and Ogden 2013.)[14]

[14] Although coal with CCS appears in some scenarios, natural gas with CCS would be an attractive option as well, especially given low NG prices.

Sidebar: Low-carbon and renewable hydrogen for California

Hydrogen is a decarbonized energy carrier that can be used with high efficiency in a fuel cell vehicle. The actual well-to-wheels carbon emissions associated with operating a fuel cell vehicle (and its benefits relative to a conventional gasoline vehicle) will depend on the emissions from hydrogen supply (production, delivery and refueling). Hydrogen can be commercially produced from any number of primary energy resources (similar to electricity). And just as the electricity grid is a mix of electricity generation sources, a number of different hydrogen methods will likely be employed to serve different roles in the H_2 supply infrastructure.

An optimization model called H2TIMES was used to model California's future hydrogen infrastructure under an assumption of H_2 demand growth. The model was used to investigate the evolution of hydrogen infrastructure in response to policy constraints and the impact on infrastructure choice and emissions. Policies such as the state's renewable hydrogen mandate (SB1505), which requires 33% of hydrogen in the state to come from qualifying renewable resources, and carbon intensity (CI) targets that are consistent with the state's low carbon fuel standard (LCFS) are modeled. The model results are also influenced by assumptions about resource costs and availability, technology costs and technical parameters, including scale economies in infrastructure investments, and spatial/geographic assumptions that influence demand density and delivery distances.

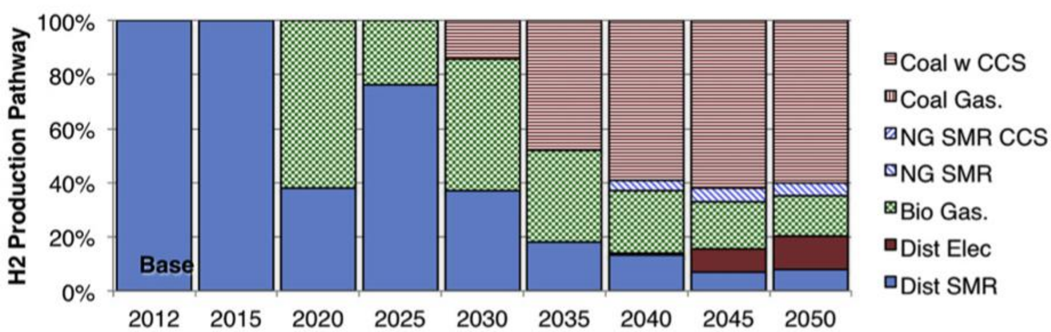


Figure 19. H2TIMES *Base case* hydrogen production choices aggregated across all regions

In the *Base case* scenario, hydrogen is made primarily from distributed SMR in the early stages (2012 and 2015) and then as hydrogen demand ramps up in the 2020 to 2030 timeframe, medium-scale biomass gasification systems are also utilized. As demand reaches a critical level to sustain large-scale infrastructure in 2030 and beyond, large scale fossil with CCS (in this case coal) is available to provide H_2 at low cost and low emissions. Also seen in 2045 to 2050 is the emergence of distributed renewable electrolysis to ensure the 33% renewable hydrogen mandate is met. In this scenario, average H_2 costs decline from over \$10/kg in 2012 to \$4.20/kg H_2 in 2050. Average H_2 carbon intensity, declines from an efficiency-adjusted value of 4350 gCO_2/kgH_2 to 1630 gCO_2/kgH_2 in 2050 (85% reduction from current gasoline on a well-to-wheels basis, taking into account higher FCV efficiency).

A number of sensitivity scenarios were also run, some remove policy constraints while others apply even more stringent policy constraints. Without any policy constraints (*Unconstrained* scenario), the cost of hydrogen is minimized ($3.37/kg) but carbon intensity increases relative to the base case (and much of hydrogen is made from coal). The requirement of CCS to coal-based hydrogen production provides great value, if CCS is available, as it achieves the biggest reduction in emissions relative for what is assumed to be relatively minor costs. H_2 CI goes from 29% below gasoline (*Unconstrained*) to 80% below gasoline with only a $0.09/kg increase in price (as the additional cost of capture, compression and injection of CO_2 is relatively low). The renewable hydrogen mandate, which in the later years comes from renewable electrolysis, increases the average cost of H_2 by around $0.75/kg, even though electrolysis only makes up ~16% of supply. This is due to the high cost of electrolyzers and limitations on low-cost renewable electricity supply (in addition to what is needed for the state renewable portfolio standard and carbon reduction targets).

If reducing CO_2 emissions is the goal, a CI mandate is preferable to a renewable H_2 mandate as it provides greater flexibility and at lower cost. If CCS is not available, making H_2 from fossil resources will not reduce emissions as much as with CCS and this limits the options for large-scale, low-cost and low carbon H_2 production.

Reference: Christopher Yang and Joan Ogden. Renewable and Low Carbon Hydrogen for California – Modeling The Long Term Evolution of Fuel Infrastructure Using a Quasi-Spatial TIMES Model. *International Journal of Hydrogen Energy*. 38 (11) p 4250-4265. 2013.

Hydrogen Transition Costs in Perspective

It appears that a regional hydrogen rollout could require $150-300 million in investments spent over perhaps 7-9 years to build the first 100-200 stations for 50,000-100,000 FCVs in that region. How does this investment compare to other money flows in the energy system? What are the costs and benefits of a hydrogen transition over the longer term?

UC Davis researchers Joan Ogden and Lew Fulton developed scenarios for electric drive vehicle sales in the US (Figures 5 and 20), and for vehicle fuel economy over time based on the mid-range estimates in the NRC 2013 Light Duty Transitions report. Future vehicle costs were estimated taking cost reductions from learning and scale economies into account (Figure 6). We also tracked fuel costs and infrastructure capital costs.

We analyze the lifetime cost of transportation for three types of electric drive vehicles (AFVs), PHEVs, BEVs and FCVs as compared to a gasoline reference vehicle, considering incremental c*ost differences* (between gasoline and AFVs) in dollars per year for both the first (i.e. purchase) costs of vehicles and fuel costs over time. Purchase prices of advanced vehicles are typically higher than gasoline vehicles while fuel costs are typically lower owing to their higher efficiency. The "break even" year is reached when the annual incremental cost of new AFVs is equal to the annual fuel savings from the on-road AFV fleet. (Fuel savings of on-road AFVs offset higher first cost of AFVs sold that year). (See Figure 21.)

Based upon the cost of vehicles declining as the volume of sales increases and the cost of fuel declining as a function of infrastructure scale, we estimate the total investments needed to purchase vehicles, and fuel infrastructure in order to reach the point where the annual incremental cost of AFVs is less than or equal to the fuel cost savings from AFVs (i.e. breakeven) for each type of vehicle, and for the electric drive strategy as a whole including both plug-in and fuel cell vehicles (Table 5, Figure 22).[15]

We estimate this total investment cost to be anywhere from a few tens to a few hundred billion dollars for vehicle cost buydown and refueling infrastructure build-up, spent over 10-15 years. Most of the investment cost is for covering the incremental cost of advanced vehicles. For hydrogen fuel cells, infrastructure costs are about a quarter of the total (Table 5). For the US as a whole, we estimate that about $1 billion investment would be needed in a series of lighthouse cities to

[15] The incremental vehicle cost (RPE) of the AFV is calculated by comparing it to a reference gasoline vehicle, which also evolves over time. Referring to Figure 6, we see that the incremental cost difference decreases over time with AFV learning and production scale-up.

bring the cost of hydrogen to $7/kg, a fuel cost roughly competitive with gasoline on a cent per mile basis. The "breakeven" point occurs a few years later, involving costs for vehicle buydown as well as continued infrastructure development that further reduces the cost of hydrogen at the pump.

Investments needed to launch new clean vehicles and fuels are much less than money flows in the current energy and vehicle system. In the US we will spend around $15 trillion on purchasing new cars and fuel through 2030. Creative policies to leverage these resources are needed.

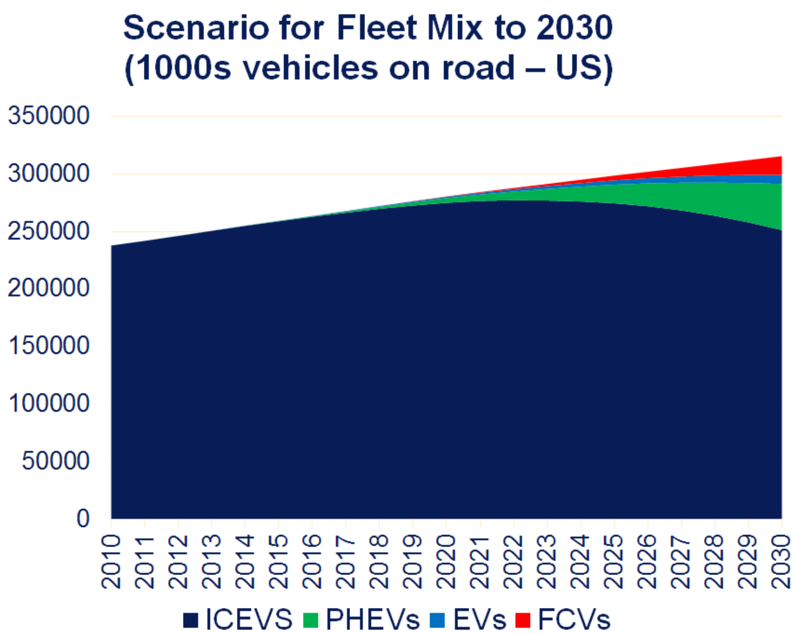


Figure 20. Numbers of electric drive light duty vehicles in US scenario (Ogden, Fulton, Sperling 2014).

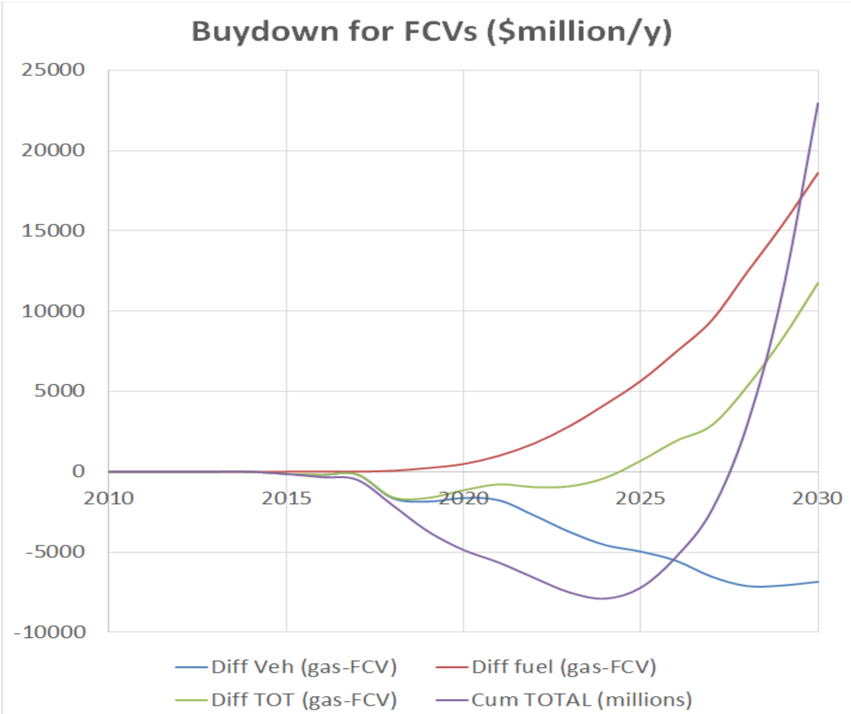


Figure 21. Buydown Costs for hydrogen fuel cell vehicles compared to gasoline reference car. Initially the incremental costs of the vehicles are higher for FCVs, but over time the fuel savings outweigh the extra vehicle costs. (Costs shown are undiscounted.)

Table 5. Investments to Support Alternative Fueled Vehicles to "Breakeven" year and to 2030 based on scenario in Figure 20. The AFV subsidy is assumed to equal the incremental RPE of the AFV compared to a reference gasoline vehicle (see Figure 6).

INVESTMENT TOTAL	**H_2 FCVs**	**PHEVs**	**Battery EVs**
To Breakeven	**Breakeven: 2025** **4 million FCVs** **~$5B for H2 supply** **~$18 B** to subsidize FCV price	**Breakeven: 2028** **28 million PHEVs** **~$28 B for chargers** **~$157 B** to subsidize vehicle price	**Breakeven: 2024** **3 million BEVs** **~$1-2 B for chargers** **~$34B** to subsidize vehicle price
To 2030	**16 million FCVs** **~$24 B** for H2 infrastructure **$56 B** if FCV subsidized to 2030	**40 million PHEVs** **$50 B for** chargers **~$231 B** if PHEV subsidized to 2030	**8 million EVs** **$8-16 B for** home and public chargers. **~$67B** if EV subsidized to 2030

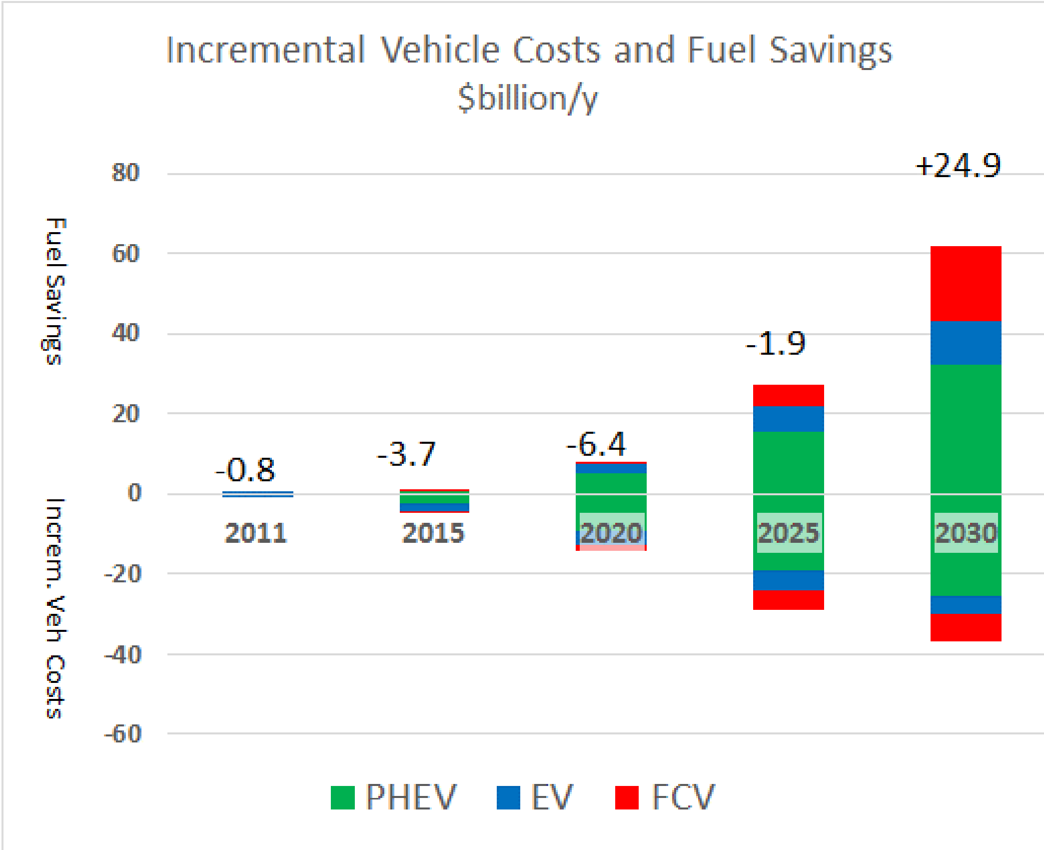


Figure 22. Alternative Fuel Vehicle Costs and Fuel Savings in "snapshot" years. Incremental vehicle costs are balanced by fuel savings by about 2027. The number at the top of each bar is the net benefit (defined as fuel savings – incremental vehicle costs) in $billions per year.

Societal Benefits of Hydrogen Transition

Beyond the changes in private economic costs (capital investments and fuel savings), one of the main reasons for considering hydrogen is the reduction of externality costs associated with current fuels. Figure 23 shows an analysis of a hydrogen-intensive light duty vehicle sector for the US, from the 2013 NRC report. The present value of direct economic costs and benefits (vehicle costs and fuel savings) and externality benefits for (GHG mitigation, petroleum reduction, and consumer benefits) are shown[16]. Over time the total NPV becomes strongly positive, outweighing cumulative investments by a huge factor. The benefits outweigh the initial cost by a factor of 10.

[16] Air pollution health effects are not shown, but would make this argument even stronger, as the benefits can be the same order of magnitude as fuel savings. (Sun, Ogden, Delucchi 2009).

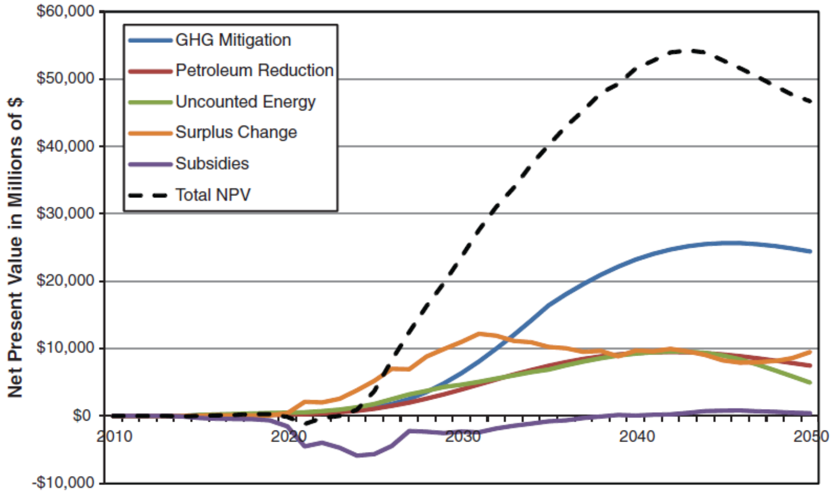


FIGURE 5.24 Present value cost and benefits of a transition to hydrogen fuel cell vehicles using midrange technology assumptions, fuel cell vehicle subsidies and additional incentives, and a low-GHG infrastructure for the production of hydrogen.

Figure 23. Costs and benefits of hydrogen fuel cell vehicles (NRC 2013). Over time the benefits greatly outweigh the costs.

Stakeholder coordination and reducing risk

A hydrogen transition means many major changes at once: adoption of new types of cars, building new manufacturing capabilities including fuel cell and hydrogen storage supply chains, building new fuel production, transport and refueling 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 policy makers), 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 biofuels (or other liquid synthetic fuels).

The need for coordination is especially acute in the early stages of a FCV rollout when the technology is still developing and stakeholders need to collaborate to have vehicles and infrastructure ready in a timely fashion.

Figure 24 illustrates early hydrogen rollout dynamics for California, indicating the actions and roles of different stakeholders. (Eckerle and Garderet 2012). This type of process is playing out in various regions of the world that are planning FCV rollouts.

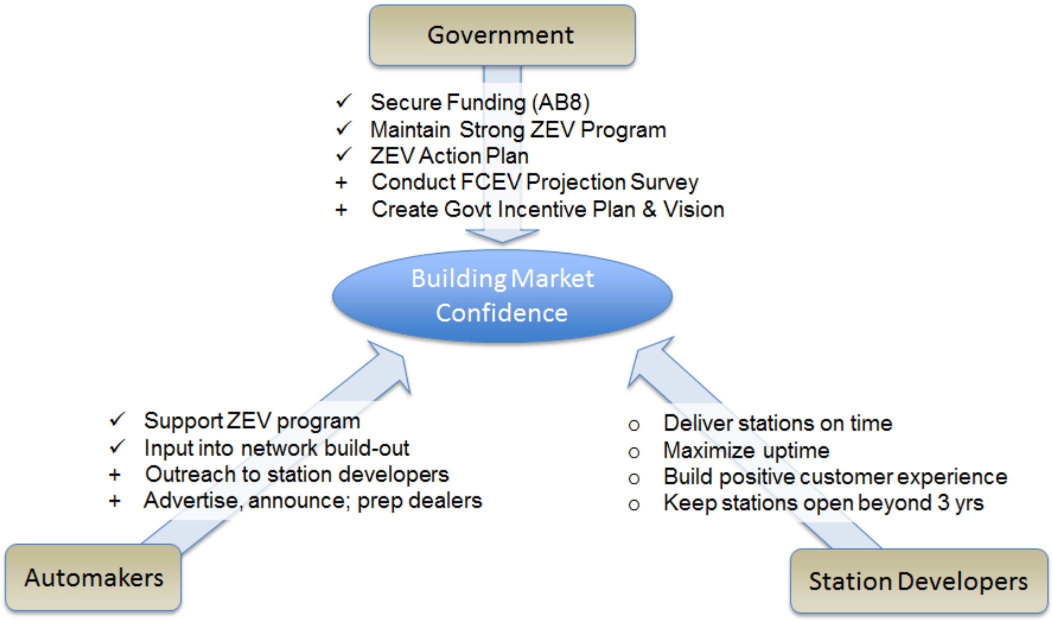


Figure 24. Hydrogen rollout dynamics require coordinated action from various stakeholders, The actions required from automkaers, station developers and government are illustrated for the case of hydrogen fuel cell vehicles in California, ZEV = zero emission vehicle regulation, ARB = California Air resources Board. Source: T. Eckerle and R. Garderet, 2012.

HYDROGEN FCV ROLLOUT ACTIVITIES WORLDWIDE

The past few years have seen an acceleration in the commercialization of fuel cell and hydrogen technologies.

Progress in Commercializing FCVs

In 2013 three strategic alliances of major automakers were announced to commercialize hydrogen fuel cell vehicles in the 2014-2019 timeframe (Tables 6, 7). Also in 2013, Ballard Power Systems signed an agreement with Volkswagen to provide engineering services to develop next generation fuel cells for VW cars.

Eight major automakers have announced dates for commercial introduction of hydrogen fuel cell vehicles (Table 7). The exact locations, numbers of vehicles and vehicle prices have not been publically released by manufacturers. Hyundai is currently leasing its Tucson fuel cell vehicles for $499 per month including fuel. Toyota has announced initial vehicle prices in the $70,000 range (Los Angeles Times 2014). It is likely that the first vehicles will be introduced in regions with the best supporting hydrogen infrastructure such as California, Germany and Japan.

Table 6. Worldwide Alliances of Automakers for Joint Development of Hydrogen Fuel Cell Vehicles

Announced	Partners	Source
Jan. 24, 2013	Toyota, BMW	http://www.autoweek.com/article/20130124/carnews/130129913
Jan. 28, 2013	Nissan, Daimler, Ford	http://www.inautonews.com/ford-nissan-and-daimler-form-partnership-to-develop-fuel-cells#.U2KbvvLn-ZQ
July 2, 2013	Honda, GM	http://www.fleetsandfuels.com/fuels/hydrogen/2013/07/gm-and-honda-team-on-fcvs/
March 7, 2013	Volkswagen, Ballard Power Systems	http://www.ballard.com/about-ballard/newsroom/news-releases/news03061302.aspx

Table 7. Launch Dates for Hydrogen Fuel Cell Vehicles

Automaker	Launch Date for H2 FCVs	Source
BMW	2019-21	http://www.bmweducation.co.uk/cleanenergy/about_mobility.asp
Daimler	2017-18	http://www.technologyreview.com/view/510416/ford-daimler-and-nissan-commit-to-fuel-cells/
Ford	2017	"
GM	Not yet announced (by 2020)	http://inhabitat.com/general-motors-hydrogen-powered-chevy-equinox-logs-100000-miles-of-real-world-driving/
Honda	2015-16	http://world.honda.com/news/2013/4131120FCEV-Concept-Los-Angeles-Auto-Show/index.html
Hyundai	2014-15	http://www.hyundainews.com/us/en-us/Media/PressRelease.aspx?mediaid=38674&title=hyundai-motor-delivers-first-15-hydrogen-powered-ix35-fuel-cell-in-europe; http://www.greencarcongress.com/2014/06/20140611-tucson.html
Nissan	2017	http://www.nissan-global.com/EN/NEWS/2013/_STORY/130128-02-e.html
Toyota	2015	http://www.toyota.com/fuelcell/

Hydrogen Infrastructure Networks

These fuel cell cars are coming and will be available for sale or lease very soon, but will the infrastructure be ready to meet the fueling needs of these vehicles? After years of discussion and one of a kind, single station demonstrations, there is growing activity toward building the initial infrastructure needed to rollout 1000s to 10,000s of FCVs in 2015. As described above, infrastructure planning has gotten more sophisticated. A cluster strategy has been adopted in California, Germany, Japan and Korea. Confidence is growing and funding has been committed.

Public private partnerships (groups of government, industry and NGO stakeholders) have led the way and practical plans for building regional station networks of stations are emerging. Activity is centered in California, Germany, the United Kingdom, Scandinavia, Japan and South Korea. At present, about 220 hydrogen stations are operating around the world (Figure 25) with plans for several hundred more over the next few years.

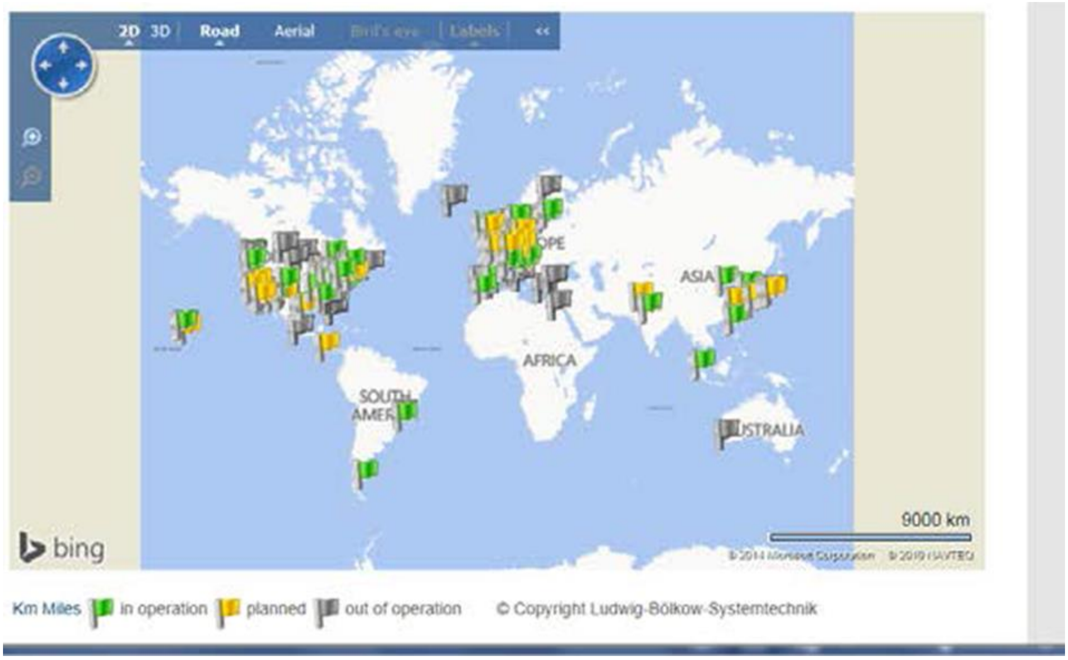


Figure 25. About 220 hydrogen refueling stations are in operation (as of April 2014). These are clustered in North America (~ 60), Europe (~70) and Asia (Japan, Republic of Korea). Source: Ludwig Bolkow Systemtechnik, http://www.netinform.net/H2/H2Stations/H2Stations.aspx?Continent=NA&StationID=-1

The Rise of Public-Private Partnerships

Coordination is key to a viable FCV rollout. A notable development has been the rise of public-private partnerships around the world to commercialize fuel cell vehicles and hydrogen. Table 8 shows scope, goals, partners and funding committed. Especially in three regions (California, Germany and Japan) a confluence of technical competence, funding and planning have come together and momentum seems to be building. The committed funding in each of these regions is on the same order as the $150-300 million investment we estimated to launch infrastructure. The partners and their roles vary depending on the location. Important questions are who will be building the stations in these various locations and how will station funding be allocated in order to ensure durable, useful station placements?

The mix of participants in regional public-private partnerships is shown in Figure 26 (broken down by the number of partners in each category.) The early developers of the hydrogen transition vary considerably by region – perhaps reflecting the regional diversity of sources for hydrogen and policy motivations. Automakers and governments are major players everywhere. However, energy companies play a larger role in Europe and Japan than in North America. In Japan, natural gas companies support residential fuel cell combined heat and power systems, and in Europe oil companies are participants in infrastructure projects, although they have pulled back from this role in the U.S.

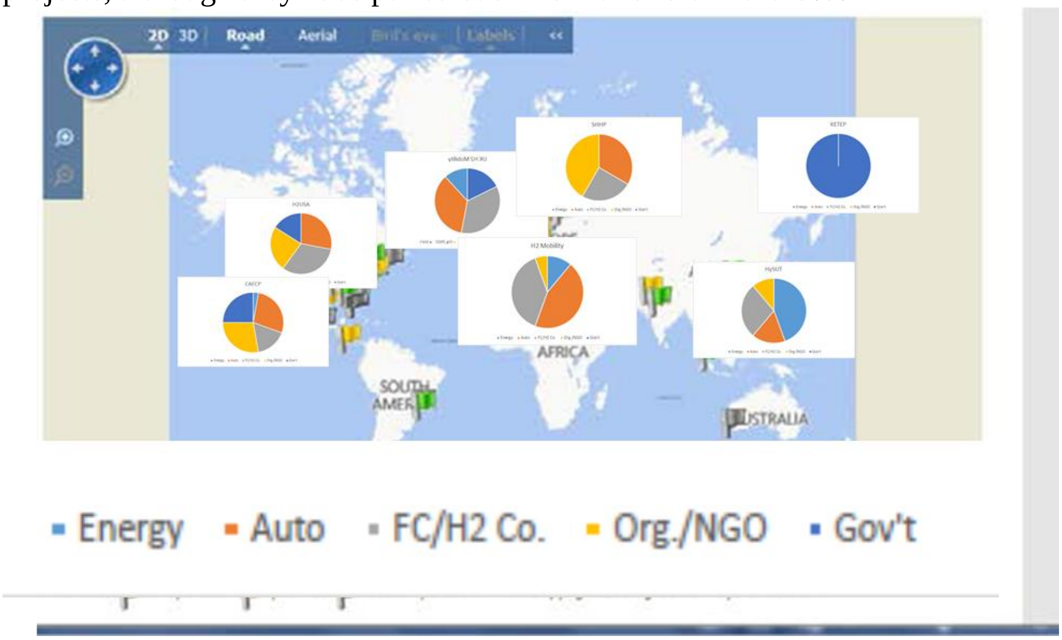


Figure 26. Participants in public-private partnerships to develop hydrogen and fuel cells vary by region of the world. The number of participants are shown for 5 categories: energy companies (oil, natural gas, electric utilities); automakers; fuel cell and hydrogen technology companies; NGOs and environmental organizations; governments.

Table 8. Public/Private Partnerships to Develop H2 FCVs

Country/ Region	**Public/Private Partnership Name**	**Goals/Timeline**	**Members**	**Gov't Funding**
Japan	HySUT	2015: 100 H2 sta in 4 urban areas 2020: 1,000 H2 sta 2030: 5,000 H2 sta. 2025: 2 million FCVs	4 Petroleum Co., 4 City Gas Co., 5 Industrial Gas & Device /Engineering Co., 3 Automotive Co., 2 Related Organizations	$53 million to start
South Korea	Roadmap under KETEP	2015: 20 stations, 1800 FCVs 2020:100 sta: 2030: 500 sta. 20% of By-product H2 could support 150,000 FCVs.	Korea Energy Technology Evaluation and Planning agency (KETEP) - manages all H2,FC R&D	Total FC R&D budget $100 million/y
EU		Supports EU-moves (Scandinavia), networks of connector stations		700 million Euro for FC and H2 R&D through Horizon 2020

Country/ Region	Public/Private Partnership Name	Goals/Timeline	Members	Gov't Funding
France	Mobilite Hydrogene			
Germany	H2 Mobility	2015: 50 H2 sta., 5,000 FCVs 2017:100 sta. 2020: 400 sta., 150,000 FCVs 2030: 1000 sta, 1.8 million FCVs	2 Petroleum Co., 7 Industrial Gas & Device /Engineering Co.,, 8 Automotive Co., 1Related Organization	$52 million public-private funds committed to build from 15 up to 50 stations. 350 million Euro public/private funds.
Scandinavia	Scandinavian H2 Highway Partnership (SHHP) Hydrogen Link (Denmark), HyNor (Norway) and Hydrogen Sweden	2014-2017: Establish network of 45 H2 stations (15 main stations, 30 satellite stations) and fleet of vehicles (500 cars, 100 buses, 500 specialty vehicles).	4 auto companies , 3 H2 infrastructure companies , 5 NGOs	MOU signed by members; EU funding for EU-Moves project.
UK	UK H2 Mobility	2015: 65 sta 2025: 300 sta 2030: 1100 sta., 1.8 million FCVs	6 auto co , 2 electric utilities, 3 engineering co., 3 H2 infrastructure co., 3 gov't dept.	$50 million for initial build-out
USA	H2USA		7 auto companies, 8 engineering/H2 infrastructure companies, 1 gov't dept., 3 national labs. 6 Related Organizations	
California	California Fuel Cell Partnership	2015: 51 stations 2017: 78 stations, 6650 FCVs. 2020: 100 stations, 18,500 FCVs Goal: 1.5 million ZEVs by 2025	37 partners, most car companies, energy/ environ agencies in US and CA, FC companies, Industrial gas companies	State of California, $20 million per year for up to 100 stations; $46 million committed for 28 stations in 2014; Post 2018 33% renewable H2 req.
8 state MOU CA, CT, MA, MD, NY, OR, RI, VT		Goal: 3.3 million ZEVs by 2025		

HYDROGEN POLICY

Policies provide an essential role for supporting and nurturing the market for fuel cell vehicles and hydrogen fueling stations. Important policies for hydrogen can include regulations, incentives, and codes and standards.

Public Funding for Hydrogen and Fuel Cells

It is clear that early and durable public policy will be needed to launch hydrogen infrastructure. Public funding for hydrogen and fuel cells in various countries is shown in Figure 27. Japan, Germany, the EU, South Korea and the US have programs of at least $100 million per year. The worldwide total exceeds $1 billion/year. Generally, budgets are trending upward with the notable exception of the United States, where the hydrogen budget has fallen over 60% from its high of about $300 million in 2008.

Public investment and strong policy spurs additional industry investment. The US Dept. of Energy estimated that its public investment in fuel cells and hydrogen led to 6 to 9 times more in private investment (USDOE Fuel Cell and Hydrogen program annual report 2013).

Our calculations suggest that regional hydrogen infrastructure investments totaling $100-200 million spent over perhaps 5-7 years in support of 100 stations could launch a cost-competitive regional hydrogen supply. It appears that this is happening in at least three places in the world California, Germany and Japan. [17]

[17] (Buying down the cost of fuel cell vehicles will require considerably more investment as shown in Table 5.)

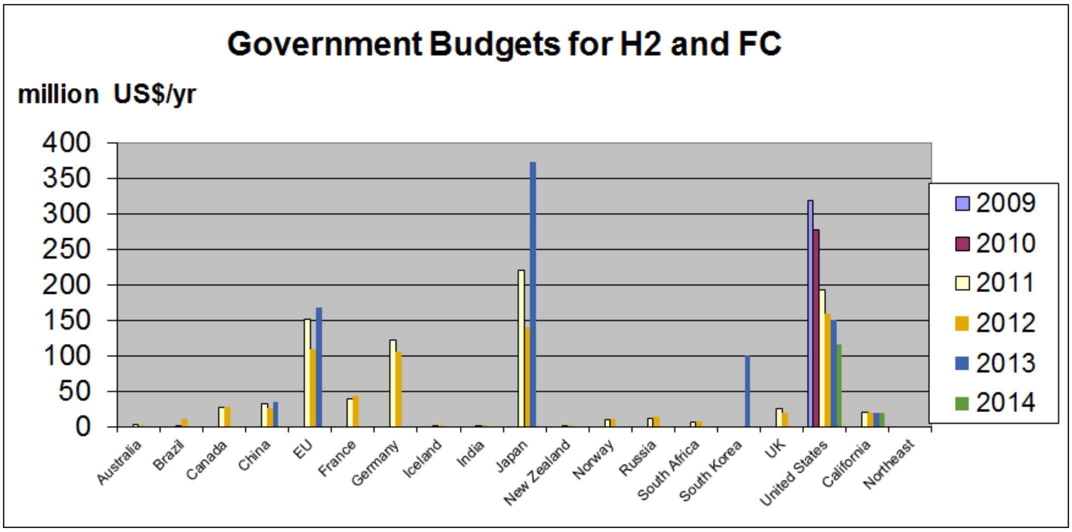


Figure 27. Public budgets for hydrogen and fuel cells by country. Source: IPHE Country Updates, November 2013.

Global overview of hydrogen-related policies

Table 9 shows the types of policies in place to support hydrogen and FCVs around the world. These policies target different stakeholders and include direct subsidies for purchasing vehicles and fuel infrastructure, tax exemptions, zero emission vehicle regulations, and low carbon and renewable fuel standards. "Perks" for hydrogen vehicle owners such as HOV lane access, free parking and free fueling exist in a few places.

What kinds of policies might be needed to catalyze a transition to hydrogen? Some analogies can be drawn to other vehicle types. Incentives and driver perks have been important in encouraging the growth of battery electric vehicles and there may be lessons from the PEV experience about what motivates consumers. Because hydrogen infrastructure is a critical part of the pathway in terms of consumer experience, convenience and utility, policies such as public private partnerships, which are aimed at coordinated infrastructure rollouts are essential.

The move toward zero emissions vehicles to improve air quality has been an important driver for hydrogen. In the long-term, policies to address carbon emissions and climate change may prove to be greatest force for adoption of hydrogen. Broad carbon policies like taxes or cap and trade systems by themselves won't be enough to cause success of advanced vehicles. It seems almost certain that policies targeted at the transport sector and zero emissions vehicles will be needed.

In the IEA's ETP 2012 report and the 2013 NRC study on light duty vehicle transitions, consumer choice of hydrogen fuel cell vs. plug-in vehicles was a key factor in the mix of light duty vehicles in 2050. Continued R&D on batteries and fuel cells, hydrogen storage and low-carbon energy production is needed.

Stated national goals for FCV adoption could amount to almost 9 million FCVs on the road globally by 2025-2030 (Japan: 2 million by 2025; Germany 1.8 million by 2030; UK 1.8 million by 2030; 8 US states 3.3 million ZEVs by 2025, including 1.5 million ZEVs in California[18]). In order for these goals to be reached, regional launches need to occur over the next few years and ramp up fairly quickly. As NRC studies have shown, the long-term benefits of H2 FCVs are large (NRC 2013, NRC 2009) in terms of fuel cost savings, and reduced costs of climate change, air pollution and oil dependence. By 2050, the total benefits outweigh transition costs by a factor of 10 (NRC 2013).

Table 9. Public Policies Related to Hydrogen and Fuel Cell Vehicles

		Canada	USA	California	EU	Denmark	France	Germany	Netherlands	UK	Iceland	Norway	China	Japan	S. Korea
Consumer	Vehicle purchase Subsidy		X	X		X		X		X		X	X	X	
	Vehicle purchase tax exemption					X		X		X	X	X			
	Vehicle "Perks" (HOV lanes, free parking, etc.)			X								X			
	H2 fuel subsidy		X	X		X						X			
Automaker	Zero emission vehicle reg.			X				X		X		X			
	Fuel economy targets	X	X	X	X								X	X	X
Energy/Fuel Supplier	H2 Infrastructure subsidy		X	X		X		X						X	
	Renewable H2 reg.			X											
	Low Carbon Fuels Reg.			X											X
	Renewable Fuels Reg.		X								X				X
	Subsidy stationary power FCs		X	X				X		X			X	X	X
Other	Public/private partnerships for H2/FCVs	X	X	X	X	X	X	X	X	X		X		X	
	H2/FC R&D	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Nat'l Goals #FCVs		X	X				X		X				X	X
	Renewable Portfolio Standard			X											
	Carbon policy			X	X		X	X	X	X	X	X	X	X	X
	Goal to end fossil fuel use by 2050					X									

[18] Note that ZEVs could be either battery electric or fuel cell vehicles.

CONCLUSIONS AND RECOMMENDATIONS

We seem to be tantalizingly close to the beginning of a hydrogen transition. But energy decision-makers have heard this before. Is it different this time?

Fuel cell vehicles are technically ready and there appears to be a path to cost competitiveness with incumbent gasoline vehicles.

After a decade of controversy and exploration, workable strategies for hydrogen infrastructure rollout are emerging with buy-in from key stakeholders: the automakers, hydrogen suppliers and regulators. And with public funding to support building early networks of stations.

The stalling point has been that the funding required to launch hydrogen infrastructure is more than the usual amount for R&D projects, though vastly less than for current expenditures on the energy system. The risks involved in getting through the "valley of death"[19] have daunted investors. The long term rate of return (and societal benefits) are potentially attractive, but the path is not certain. How to get across the valley of death? The first mover disincentive has made it tougher to get private investment. Not surprisingly, some potential infrastructure investors want to wait until the FCV market is more secure and they could build large, fully utilized stations with confidence.

But the good news is that it might not take that much investment to build up infrastructure to that point where new investments are profitable and less risky for infrastructure providers. Out estimates indication that perhaps 50,000 FCVs in a region with 100 stations would be enough to bring hydrogen costs to competitiveness with gasoline on a cost per-mile basis. The station investment cost would be $100-200 million. There appear to be at least 3 locations where public and public/private partnerships have made commitments on that order (California, Japan, Germany).

If these regional rollouts are successful, hydrogen FCVs may be just a few years behind battery EVs, not decades. It appears that these efforts may jump start the hydrogen economy at last.

[19] The "valley of death" refers to the market entry cost barrier facing new technologies that must scale up production in order to compete economically.

Acknowledgements

The authors would like to acknowledge the sponsors of the Sustainable Transportation Energy Pathways research program at UC Davis for research support. We also thank Dan Sperling, Anthony Eggert, and Gustavo Collantes (UC Davis), Thomas Briggs, Rosemary Albinson, and Michael Desmond (BP), Tom Cackette (CARB, ret.), Sujit Das (ORNL), Catherine Dunwoody (CARB), Bill Elrick (California Fuel Cell Partnership) Alan Lloyd (ICCT), Tien Nguyen (USDOE), Jesse Schneider (BMW) and Ian Sutherland (GM) for helpful comments on earlier drafts of this paper.

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