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Prospects for Hydrogen in the Future Energy System

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Abstract
Hydrogen is a high quality energy carrier that could be produced at global scale, via thermochemical processing of hydrocarbons, such as natural gas, coal or biomass, or water electrolysis using any source of electricity including renewables, such as wind or solar, or nuclear power. Hydrogen is receiving renewed attention driven by growing concerns about climate change, air quality and integration of variable renewable energy into the energy system. Recent energy/economic studies suggest that hydrogen and fuel cells could be important technologies for simultaneously addressing these challenges in a future renewable-intensive, low carbon energy system. In this paper, we review the technical and economic status of hydrogen and fuel cell technologies, progress toward commercialization, and the role of policy. We discuss timing, barriers, costs and benefits of a hydrogen transition, focusing on vehicle and energy storage applications. Finally, we suggest guidelines for future policies guiding a hydrogen transition.

1 Motivation for Hydrogen and Fuel Cells

The concept of a "hydrogen economy" has been analyzed many times [1] [2] [3] [4]. Hydrogen is receiving renewed attention driven by growing concerns about climate change, air quality, integration of variable renewable energy into the energy system and rapid technical progress in fuel cell systems. Recent energy/economic studies suggest that hydrogen and fuel cells could be important technologies for simultaneously addressing these challenges in a future renewable-intensive, low carbon energy system [5] [6] [7] [8] [9]

Hydrogen is a high quality energy carrier that could be produced at global scale from widely available resources, via thermochemical processing of hydrocarbons, such as natural gas, coal or biomass, or water electrolysis using any source of electricity including renewables, such as wind or solar, or nuclear power. Hydrogen can be converted to electricity and heat in fuel cells at high efficiency with zero end-use emissions. There is a strong technical base for hydrogen, and rapid progress across a range of emerging hydrogen technologies.[10] Today, hydrogen is produced commercially from fossil fuels as a feedstock for oil refining and other industrial uses, accounting for 1-2% of global primary energy use. In the future, hydrogen might be produced from a variety of low carbon sources, stored, distributed and widely utilized throughout the energy system, including power plants, buildings and vehicles. Further, hydrogen could serve as flexible energy storage for intermittent renewable electricity that might otherwise be curtailed, opening the possibility of "greening" both electricity and fuels.[9, 11] Hydrogen is increasingly seen as a key energy carrier for a future low carbon energy system, complementing electricity and renewable biofuels, and enabling new linkages between energy sectors such as transportation and power generation.

In this paper, we review the technical and economic status of hydrogen and fuel cell technologies, progress toward commercialization, and the role of policy. We discuss timing, barriers, costs and benefits of a hydrogen transition, focusing on hydrogen as a transport fuel and the role of hydrogen in a low carbon emitting energy system. Balancing insights from past energy transitions and climate imperatives for rapid change, we suggest guidelines for future policies guiding a hydrogen transition.

2 Status of Hydrogen Supply Technologies

Like electricity, hydrogen can be produced from diverse, widely available primary energy resources including fossil fuels, renewables and nuclear power. (Various options for producing, storing, distributing and using hydrogen are shown in Figure 1).

Today most hydrogen is derived "thermochemically" when a hydrocarbon feedstock (such as natural gas, coal or biomass) is chemically processed at high temperature, producing a synthetic gas or "syngas" that can be further processed to increase the hydrogen content. The technical status and cost of hydrogen production, storage and delivery technologies are summarized in Table 1 and discussed below.

Large scale production of hydrogen from natural gas via steam methane reforming is a mature commercial technology, widely used in the chemical and refining industries. Steam methane reforming (SMR) accounts for about 95 percent of hydrogen made in the United States today and availability of low cost natural gas has helped motivate recent US interest in hydrogen. Typical industrial SMRs produce 50-500 tonnes of hydrogen per day (equivalent to 80-800 MW of continuous hydrogen energy output, on a higher heat value basis). This is enough energy to support a fleet of tens to hundreds of thousands of fuel cell cars. (As a rule of thumb, a mid-sized fuel cell car driven 15,000 miles per year would consume an average of 0.7 kilogram of hydrogen per day.) Smaller reformers (in the range 0.16-16 tonne per day) have been developed as components of natural gas fueled fuel cell power systems, such as those now being introduced in Japan and Europe for combined heat and power applications. Small scale reformers have also been employed for distributed hydrogen production at refueling stations.

Coal gasification is another well-established pathway for large scale production of hydrogen. As shown in Table 1, it is more capital intensive and less energy efficient than steam methane reformation, although feedstock costs are generally lower for coal than for natural gas and the levelized cost counting both capital and operating costs are similar. Biomass gasification is an early commercial stage hydrogen production technology. Biomass gasification systems are typically smaller than those for coal, because of a trade-off between plant scale economies and the costs of transporting biomass long distances to a large production plant.

Depending on the process, hydrogen production from hydrocarbons can emit significant amounts of CO_2. This can be of concern, if one of the major motivations for adopting hydrogen is reducing carbon emissions. Although a hydrogen fuel cell vehicle has no tailpipe emissions of carbon or air pollutants, there can be “upstream” emissions from producing hydrogen. (This is analogous to electric battery vehicles, where the vehicle is zero emission, but there emissions associated with generating the electricity.) Although the full fuel cycle or “well to wheels” greenhouse gas emissions are less for a fuel cell car using hydrogen made from natural gas than for a comparable conventional gasoline car, they are not zero.[12]

One possible technical “fix” is carbon capture and sequestration (CCS). When hydrogen is produced thermochemically from a hydrocarbon feedstock, a concentrated stream of CO_2 is created, which can be captured and stored, reducing carbon emissions to the atmosphere at relatively low incremental cost, with only a small energy penalty. As shown in Table 1, carbon capture adds about 10-20% to the capital cost of a large hydrogen plant and 10-30% to the levelized cost of producing hydrogen, while reducing carbon emissions by 80-90%. CCS is often suggested as an enabling technology allowing continued use of low cost fossil fuels to make hydrogen, while avoiding most of the CO_2 emissions. Hydrogen production from renewable biomass with CCS opens the possibility of “net negative carbon” fuels,[13] [14] a strategy invoked in many energy scenarios for climate stabilization.[6]

Water electrolysis is used commercially today in a few regions with low cost hydro-electricity. However, a broader role for electrolytic conversion is envisioned in a future hydrogen economy which utilizes vast renewable wind and solar resources. Development of lower cost, more efficient electrolyzers for use with variable renewable electricity is an active area of research.[15] [16]

Hydrogen energy supply pathways are categorized as “centralized” production, where hydrogen is produced at large scale and distributed to users via truck or pipeline, and “onsite” or “distributed” production, where hydrogen is produced at the end-use site, typically via small scale electrolysis or steam methane reforming. Hydrogen supply pathways are illustrated in Figure 1, for hydrogen production from fossil, renewable and nuclear resources with storage and delivery via truck or pipeline. Hydrogen can also be converted to other energy carriers such as electricity, methane or liquid fuels, which entails conversion costs and efficiency losses, but enables access to existing energy distribution networks, without having to build an extensive hydrogen distribution system. Indeed, hydrogen is an important feedstock in refining crude oil to make today’s petroleum based fuels like gasoline and diesel.

Choosing the best hydrogen supply pathway depends on the scale and location of demand, the relative cost of regional primary resources for hydrogen production, policy (for example, a requirement for renewable hydrogen) and technology developments.[17]

Comparing hydrogen production costs for different technologies (Table 1), several trends are apparent. Large scale thermochemical conversion of fossil fuels (natural gas or coal) is currently the least costly way to make hydrogen in terms of both the specific capital cost ($/kW) and the levelized cost of hydrogen ($/kg). With carbon capture, greenhouse gas emissions can be significantly reduced, at relatively modest cost. Renewable pathways like biomass gasification and electrolysis are typically more expensive. Distributed hydrogen production via steam methane reforming or water electrolysis is more expensive than large scale central production, but avoids the costs of hydrogen distribution.

The cost of hydrogen storage and distribution depend sensitively on the amount of hydrogen delivered, the distance, the storage method (compressed gas or cryogenic liquid) and the delivery mode (truck vs. pipeline).[18] Hydrogen can be delivered by gas pipeline, similar to natural gas, and over 1000 miles of commercial hydrogen pipelines exist today, serving refinery and large chemical users. However, hydrogen pipeline delivery only makes economic sense for large energy flow rates and geographically concentrated demands (like a large refinery or a full blown hydrogen energy economy in a large city). Today, hydrogen demands for fuel cell cars and stationary power systems are small and geographically dispersed, so pipelines would be too costly. For these applications, hydrogen would be delivered by truck or made onsite from natural gas or electricity. It is more energy efficient and costs less to compress hydrogen than to liquefy it, but liquid hydrogen has a much higher energy density. Because of this, compressed gas is preferred for short distance truck delivery of small quantities of hydrogen, while liquid hydrogen is delivered in larger quantities over longer distances.

Clearly, no one hydrogen supply pathway is preferred in all cases, and the best option can change over time, for example starting with onsite production and moving toward large scale central production with delivery as demand grows, so that planning a hydrogen infrastructure is a complex design problem.[18] [19]

3 Overview of Hydrogen and Fuel Cell Applications

Here we review the technical status and progress toward commercialization for hydrogen and fuel cells in stationary, transportation and energy storage applications. Several fuel cell technologies are being introduced, based on different electrolytes: proton exchange membranes (PEMFC), for both mobile and stationary applications, and phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC) for stationary applications. In Table 2, we summarize the technical status and cost of fuel cell systems for various applications. [7,] [20] [21]

Stationary Power

Fuel cell stationary power applications include power plants in the kilowatt to multi-megawatt range, combined heat and power systems for residential and commercial buildings, back-up power and off-grid power in remote locations. Stationary markets represent about half of fuel cell applications today and the number of units shipped grew about 20% in 2016.[22]

Residential fuel cell combined heat and power systems based on PEMFC and SOFC technologies have been widely adopted with about 190,000 0.7-1.0 kW units installed in Japan subsidized by government support under the Enefarm program, and thousands planned in Europe under the Enefield program.[22, 23] These residential units are currently expensive ($20,000/kW or about $15,000-20,000 per unit), but the market is growing with government support, and it is anticipated that costs will fall to $3500/kW by 2020-2030 (see Table 2) as more units are manufactured. Larger stationary fuel cell installations in the 100 kW to multi MW range are produced by FuelCell Energy (FCE) Inc. and POSCO using MCFC technology, Doosan Fuel Cell using PAFC systems and Bloom Energy with SOFC plants. A 59 MW power plant is planned in Connecticut and another is being built in South Korea. The reliability of fuel cell cogeneration systems during power system outages, such as those experienced in the Northeastern US during Hurricane Sandy is a selling point for these systems.[7]

Hydrogen Fuel Cells for Zero Emissions Transportation

Hydrogen has been proposed as a future transportation fuel for zero emission vehicles, because of its potential to reduce greenhouse gas emissions in the transport sector as well as air pollutant emissions. (Two technologies could provide zero tailpipe emissions, hydrogen fuel cell vehicles and electric battery vehicles.) Recent studies of low carbon futures suggest that a variety of electric drive vehicles could play a major role in the future light duty vehicle fleet. [6, 8] In the International Energy Agency's "2 degree scenarios", corresponding to 80% GHG emissions cuts by 2050, hydrogen fuel cell (FCVs) and plug-in electric vehicles (PEVs) account for nearly 75% of on-road passenger cars by 2050.[6]

Hydrogen fuel cell vehicles began commercial introduction in Japan, Europe and the US (notably California), in 2013. Major automakers including Hyundai, Toyota and Honda have entered the market. Nissan, GM and Daimler have announced plans to commercialize FCVs within the next few years.[22] Hydrogen is also being demonstrated in fleet vehicles such as transit buses (where there are currently a few dozen in operation with a few hundred planned over the next few years), trucks, and specialty vehicles, notably forklifts, where hydrogen fuel cells offer operational advantages over batteries.[22] Markets for transport fuel cells are growing rapidly, more than doubling in 2016. [22]

Fuel cell vehicles are potentially attractive to buyers of zero emission passenger vehicles, because of their fast refueling time (3-5 minutes), long range (>500 km), large size and good performance. Most automakers are developing both PEVs and FCVs, seeing future roles for both types of zero emission vehicles. While further development is needed for hydrogen technologies such as proton exchange membrane (PEM) fuel cells' cost and durability, and cost of hydrogen storage on vehicles, it is anticipated that hydrogen FCVs will meet these goals over the next few years.[21] Although current fuel cell vehicles are costly, projections by the National Academies [8] suggest that mass produced FCVs could become competitive with incumbent technologies over next few decades. Developing hydrogen refueling infrastructure for light duty vehicles is a challenging logistical problem, which is seen as a key barrier to its wide scale use.

Fuel cell vehicles are approaching their goals, and costs for fuel cell vehicles are expected to drop with high level mass production (see Table 3).

Hydrogen as storage for renewable energy (power to gas)

As renewable portfolio standards and carbon policies are being implemented, power grids in Europe and North America are incorporating an increasing fraction of variable renewables (wind and solar power), which are not coincident with demand, creating significant amounts of excess generation and driving a growing interest in energy storage.[9, 24 25] Hydrogen is being widely discussed as a flexible energy carrier for integrating intermittent renewables into the energy system. Power that would otherwise be curtailed is used to make hydrogen electrolytically. 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 very low-cost, off-peak power to make hydrogen transport fuel.[26 27] More than 30 "power to gas" projects are under way in Europe, primarily in Germany, including at least two that feed hydrogen into the natural gas pipeline grid.[28] The first power to gas system went into operation in the US in 2016.[29]

4 **Designing a Transition to Hydrogen**.

Lessons from Past Energy Transitions

Historical studies of energy transitions provide interesting insights for a future hydrogen transition.[30 31 32 33] Researchers at the International Institute of Applied Systems Analysis (IIASA) found that successful energy transitions go through a series of characteristic stages: an extended period of experimentation and learning, scale up and cost reduction at both the individual technology and network level, and co-evolution of long lived infrastructures and technological clusters due to network effects.[30 32] Energy transitions typically take decades, but the rate of change is influenced by several factors.

1) Scale. It is more difficult to transform a large market than a smaller system. Further, energy transitions tend to begin at small, local scales that spread to national and eventually global scale.[31]
2) Complexity. The more complex and infrastructure-intensive the system, the slower the transition.

3) End-use innovation is a major driver of energy transitions, and new technologies may be adopted for reasons not emergent from traditional economics.
4) Although a successful transition depends on consumer adoption, it also requires coordination among multiple stakeholders, and institutional and policy support.
5) Risk reduction. Uncertainty about technology and policy can lead to risk averse behavior. Reducing risk to investors is a precondition for success, as demand grows and technology changes
6) Having a comparative advantage across multiple dimensions can accelerate transitions.

Grubler cautions against cutting short the time needed for experimentation and learning and notes that premature “Manhattan project” style attempts at energy transitions have failed[30 32].

In contrast, integrated assessment models suggest that climate change introduces a new and urgent need for rapid energy transitions.[6] Meeting 2050 GHG reduction emissions goals consistent a 2 degree scenario implies multiple energy transitions that start immediately and proceed at a very rapid rate compared to historical changes.

Implications for a Future Hydrogen and Fuel Cell Transition

We now discuss how these general insights on past energy transitions, might apply to large scale introduction of hydrogen and fuel cells. Drawing on research at UC Davis,[34 50] and studies by the NRC[4 8] and the IEA[7], we discuss transitions for two important potential applications, fuel cell vehicles, and “power to gas” systems for capturing the energy in variable renewable electricity.

For hydrogen to become a major energy carrier in a low carbon future, three interdependent transformations will be required: 1) consumer adoption of hydrogen end-use technologies, especially fuel cells, for transportation, buildings, power generation, and energy storage, 2) development of a widespread hydrogen supply system that delivers fuel reliably and at low cost and 3) a shift from fossil based hydrogen production toward large scale hydrogen from renewables and other low carbon pathways.

Transition 1 depends on consumer adoption, enabling fuel cell system manufacturing scale-up and lower vehicle costs, which in turn lead to more consumer adoption. Transition 2 depends on scaling up hydrogen infrastructure, to supply fuel conveniently and bring down fuel costs. Infrastructure scale up is a complex problem that depends on regional/spatial characteristics like the type of demand and available primary resources. These transitions in hydrogen demand and supply are closely coupled in both space and time. For example, consumer markets for fuel cell vehicles will not flourish without a network of hydrogen stations and hydrogen suppliers will not build stations without vehicles to use them.

As an example, we present a hypothetical hydrogen fuel cell vehicle transition scenario research, [34 50]In this scenario, a growing number of fuel cell vehicles (FCVs) is introduced in the US, and regional networks of hydrogen stations are built to refuel them in a series of early adopter or “lighthouse cities”. Figure 2 shows results from this US scenario for the cumulative number of vehicles sold and the hydrogen fuel cell vehicle retail price equivalent (RPE) as a function of year[50]. The RPE of the hydrogen car is estimated to decrease over time, as vehicle manufacturing scales up and the technology improves. (We employ a "learning by doing" model, based on a recent NRC studies of hydrogen transitions [4 8 50]). For reference, the RPE of a comparable gasoline car is also shown[8]. (The RPE of the gasoline car increases slightly over time to reflect costs for increasing fuel economy.) At first, hydrogen cars are much more expensive than gasoline cars, but as more hydrogen cars are produced, the cost gap narrows. After about 10-15 years hydrogen cars are only about 5-10% more expensive than gasoline cars and 20 years out the cost difference is approaching zero.

An important question facing widespread adoption of hydrogen fuel cell vehicles is potential competition with the other leading zero emission vehicle (ZEV) technology, plug-in battery electric vehicles (PEVs). PEVs entered the light duty vehicle market in 2010, roughly 5 years before the first commercial FCVs, and sales have been growing rapidly. The on-road fleet of PEVs is now over 1 million vehicles worldwide. However, most automakers see roles for both PEVs and FCVs, serving different segments of the future light duty market. [22]

In Figure 3, we estimate the required US hydrogen supply capacity over time assuming FCVs are adopted according to Figure 2.[50] The US average cost of fuel is shown for hydrogen fuel cell and gasoline cars. (Fuel costs expressed in cents per mile, to account for the higher efficiency of the fuel cell cars compare to a gasoline ICEVs). At first, hydrogen is much more expensive than gasoline, because the first hydrogen stations are small and underutilized.[34 50] As the hydrogen supply network scales up and matures, we find that the cost of hydrogen decreases. After about 10 years, the fuel cost becomes less expensive for hydrogen than gasoline (on a cent per mile basis).

Building an extensive new hydrogen infrastructure is costly, especially during early commercialization when demand is small, market growth is uncertain and technologies are still evolving rapidly. To mitigate risk, early hydrogen fuel supply might "piggyback" on existing energy infrastructures. For example, hydrogen might be produced at small scale at the point of use from widely available energy carriers such as natural gas or electricity, obviating the need for a hydrogen delivery system. Onsite methane reforming is widely employed to produce hydrogen for fuel cell stationary power systems[22] and several hydrogen vehicle refueling stations use onsite reforming or electrolysis.[35] Alternatively, the existing industrial gas system, which supplies hydrogen today for oil refining and chemicals, might deliver hydrogen by truck or pipeline to early hydrogen stations. Eventually, purpose built hydrogen production and delivery systems could be built to meet growing demand for hydrogen energy and to capture variable renewable energy at scale.

During the early stages of a hydrogen transition, one of the major challenges is providing a convenient and low-cost distribution network to bring hydrogen to many dispersed users. This is particularly crucial for light duty transport where lack of refueling infrastructure is a potential barrier to consumer acceptance of fuel cell vehicles, and slow adoption of vehicles inhibits hydrogen infrastructure investment; the so-called “chicken and egg” problem. Current thinking suggests that an early hydrogen refueling infrastructure should offer: 1)“coverage”: enough stations to provide convenient fuel accessibility for early vehicles and enable travel; 2) capacity to meet hydrogen demand as the fuel cell vehicle fleet grows; 3) a plausible path to positive cash flow for individual station owners and for network-wide supply; and 4) a path to offering hydrogen fuel to consumers at a competitive cost with gasoline on a cent per kilometer basis, estimated to be $10/kg initially, and $5-8/kg for the longer term[21 34].

To meet these goals, rollout plans must coordinate the deployment of FCVs and hydrogen infrastructure, geographically and over time. Such plans are being developed by public-private partnerships around the world including California, Japan, and the EU (notably Germany).[22 35]

Recent studies by UC Davis, UC Irvine, the National Renewable Energy Laboratory, the California Energy Commission, and the California Air Resources Board suggest that there will be a period of regional infrastructure scale up where support will be needed to build stations.[34 35 36 37 38] These calculations suggest that regional hydrogen infrastructure investments totaling several hundred million dollars spent over perhaps 7-10 years to build a few hundred stations could launch a cost-competitive regional hydrogen fuel supply infrastructure.[34] Launching infrastructure on a US national scale will likely take longer and cost tens of billions of dollars[4 8 34 50].

Switching to low carbon hydrogen pathways is the third key transition. This can be seen as part of an economy-wide shift, driven by climate concerns, toward higher efficiency, electrification and low to zero net carbon energy supply pathways. Although initial hydrogen supply might come from fossil fuels, eventually production must transition to low to zero emissions energy pathways.

It is uncertain how moving to “green hydrogen” might affect early market growth. Renewable hydrogen will probably cost more than fossil hydrogen, absent policy, so switching too early, without policy support, might impose higher fuel costs that could inhibit early vehicle sales and station development. On the other hand some early adopters might prefer zero carbon fuels and there is policy support for developing zero carbon hydrogen pathways.

Implementing renewable hydrogen could mean complex interactions with the evolving electric grid. In particular, hydrogen has been proposed as a storage medium for excess intermittent renewable electricity that would otherwise be curtailed. There is growing interest in adapting the current fossil natural gas grid to eventual use of “green” fuels including hydrogen. One proposed idea for starting a transition to “greener” gaseous fuels is blending electrolytic hydrogen produced from curtailed wind or solar power into natural gas pipelines or “power to gas”. The introduced hydrogen essentially stores renewable energy within the natural gas pipeline and contributes to making the blend gas a lower carbon fuel. The natural gas/hydrogen blend delivered through the gas grid would be combusted as usual in burners and boilers designed for natural gas, but the primary source is now partly renewable. Over time, an increasing fraction of hydrogen might be added to natural gas, increasing the renewable content.

However, the blending approach has limits. Because of natural gas pipeline materials compatibility and end-use operational concerns, there is a technical limit of perhaps 5-15% hydrogen by volume that could be safely blended with natural gas. (The allowable fraction depends on the particular equipment, and current regulations in Europe allow 0.1-12% hydrogen by volume in the natural gas system. [9 10 39]) It would be difficult to move beyond these limits without expensive retrofits to the existing system. Before injecting hydrogen into any natural gas network, it would be important to understand the components in that natural gas system and adjust for incompatibilities. In theory, hydrogen could be separated from the blend and used in a fuel cell, but this adds costs and energy use. [39] By combusting natural gas/hydrogen blends for end-uses like transportation, the higher end-use efficiency of pure hydrogen fuel cells would be foregone.

The economics of the "power to gas" as a transition strategy are complex and system dependent, but appear promising if there is a nearby use for large quantities of pure hydrogen.[9 11 26 27 40] In a recent German case study Bunger et al. found that transportation was the most economically promising end-use for electrolytic hydrogen produced from curtailed solar and wind power[10].

5 The Role of Hydrogen Policy

Launching a hydrogen transition involves surmounting an array of challenging economic and logistical barriers, which suggests a role for policy. Although there has been progress, the costs of fuel cell vehicles are still high, consumer adoption and market growth are uncertain, and building a new hydrogen infrastructure will be costly and risky. Further, hydrogen must be derived from low net carbon pathways to reach its full potential as a climate friendly fuel, which means switching the energy source away from fossil fuels. Although hydrogen and fuel cell technologies have begun commercialization, and several energy economic studies suggest that the long term prospects for a fully realized hydrogen energy system are promising, it will likely take 15-20 years to buy down costs to competitive levels.[4 8 34]

A crucial question for hydrogen is the role of policy and public support in financing the early markets. Most hydrogen fuel cell markets today rely on government incentives, and it is likely that public support will be needed for some time.[7 8] Policies will play an essential role in supporting early markets for fuel cells and hydrogen infrastructure and shaping the environmental benefits realized by a hydrogen transition.

Current Hydrogen and Fuel Cell Policies

Various policies support hydrogen and fuel cells around the world, targeting different markets and stakeholders. These include direct subsidies for purchasing vehicles and support for building hydrogen infrastructure, tax exemptions, zero emission vehicle regulations, and low carbon and renewable fuel standards. "Perqs" for hydrogen vehicle owners such as High Occupancy

Vehicle lane access, free parking and free fueling exist in Norway, Denmark[10] and California[35], similar to policies that have incentivized adoption of plug-in electric battery vehicles. Subsidies for stationary power systems and niche markets such as forklifts have also helped drive market adoption of fuel cells.[21]

National policies differ depending on the fuel cell and hydrogen markets targeted and the needs addressed. For example, in Japan, there is an extensive government program to support adoption of PEM fuel cell residential heat and power systems for single family homes, as well as a thriving fuel cell vehicle program. In North America and Europe the emphasis has been more on large stationary power systems and fuel cell light duty vehicles, although hydrogen fueled buses and trucks are also being demonstrated. There is strong interest in "power to gas" concepts in Europe. In China, there is interest in long-distance zero emission intercity transit via fuel cell buses, while urban light duty vehicles rely more on batteries.[41]

Stated national goals for FCV adoption could amount to millions of FCVs on the road globally by 2025-2030. Japan has a goal of 2 million by 2025; Germany 1.8 million by 2030; UK 1.8 million by 2030; and 8 US states 3.3 million ZEVs by 2025, including 1.5 million ZEVs in California (Zero Emission Vehicles or ZEVs can be either plug-in battery electrics or FCVs.) In order for these ambitious goals to be reached, a series of regional hydrogen vehicle rollouts would need to begin over the next few years, and ramp up quickly.[22 41]

Public funding for hydrogen and fuel cells currently exceeds $1 billion per year globally. Japan, Germany, the European Union, South Korea and the United States each have programs of at least $100 million per year, with Japan recently announcing a $500 million program[22]. Public investment and strong policy spurs additional industry investment. The US Department of Energy estimated that its public investment in fuel cells and hydrogen led to perhaps 5 times more in private investment.[42] In January 2017, a group of 13 companies formed the Hydrogen Council, committing to global private investments of over $10 Billion over the next 5 years in hydrogen and fuel cell technologies.[43] Studies by the National Academies estimated that in the US, annual subsidies of a few Billion dollars might be needed over the next 10-15 years to bring hydrogen fuel cell vehicles and hydrogen infrastructure to cost competitiveness. [4 8]

Plug-in electric vehicles (PEVs) offer an interesting point of comparison for fuel cell vehicles. During their early commercialization (2008-2014), the IEA estimated that PEVs received about $5 Billion in fiscal incentives (such as direct subsidies for vehicles) globally, subsidizing rollout of about 0.67 million vehicles (an average of about $7500 per vehicle). Counting R&D ($7.2 Billion) and infrastructure support ($2.4 Billion), the total between 2008 and 2014 was about $15 Billion or $22,000 per vehicle.[44] These subsidies are of the same order as those estimated for the early years of a hydrogen fuel cell vehicle rollout.[50]

Another point of comparison is energy supply subsidies. Global subsidies for renewable energy supply (including solar, wind and biofuels), are estimated at about $100 Billion per year, (including annual subsidies about $15 Billion in the US and over $20 Billion in Germany), while fossil fuels receive global subsidies of perhaps $500 Billion a year, mostly as support for low energy prices in oil-producing countries[45]. Fossil subsidies are considerably higher than those envisioned for launching hydrogen and fuel cells.

Policies Tools for Managing the Transition

One of the signature challenges of a hydrogen transition is the high degree of spatial and temporal coordination required among disparate stakeholders: consumers, automakers and fuel providers. A successful transition requires policies that effectively target these different stakeholders throughout the various stages of commercialization.[22 37] In many places, notably California, Germany and Japan, multi-stakeholder public-private partnerships have developed to map coordinated regional rollouts.[9]

To illustrate the types of policies that might be required, a hypothetical transition timeline for fuel cell vehicles is presented in Figure 4. Different stages of commercialization are shown in a timeline from left to right, starting with R&D, and progressing to "DEMO" (one of a 1 kind demonstrations), "PRE-COMMERCIAL", "EARLY COMMERCIAL" and "COMMERCIAL" stages. Transition dynamics are sketched for the "three transitions" described in section 4: vehicle adoption, infrastructure build out and switching to low carbon hydrogen pathways. Relevant policies are shown, by stakeholder, for each of these three transitions and are discussed below. The graphs are based on recent research at UC Davis on transition costs.

The three parallel "hydrogen transitions" are shown as horizontal graphs in figures (a)-(c). Graph (a) at the top of figure 4 illustrates progress in adoption of fuel cell vehicles. The numbers of vehicles in each stage are shown, and the estimated FCV retail equivalent price is sketched over time, based on scenarios by UC Davis researchers[50]. Graph (b), shows the corresponding time development of hydrogen infrastructure needed to support the rollout of vehicles in graph (a). Numbers of hydrogen stations and numbers of "lighthouse cities" are indicated, along with the incremental cost of hydrogen fuel compared to gasoline (in cents per km). In graph (c), the transition from fossil-based hydrogen to renewable hydrogen is shown. As commercialization progresses, increasing fractions of hydrogen come from renewables, and the well to wheels greenhouse gas emissions decrease (gCO2 equivalent per km). For each of the 3 transitions, policies targeted at different stakeholders are shown, as well as economy wide carbon policies. "Starred" policies are phased out once commercialization is well established; environmental policies are made increasingly stringent.

The final graph (d) at the bottom of the page indicates the fractions of support from public and private investment over time. Initially, public investments and subsidies are important, but as commercialization progresses, and hydrogen and FCVs become competitive, private investment dominates. The overall transition proceeds from policy-driven to market-driven.

Policies targeting adoption of fuel cell vehicles: A successful transition requires rapid consumer adoption of fuel cell vehicles[34 35 37]. What might make a consumer choose a hydrogen vehicle and which policy levers are most effective to enable hydrogen FCVs to reach mass markets? Several recent studies have examined the factors that go into consumer choice of one type of vehicle over another.[8] [46] Automobile buyers consider not only the first cost of the vehicle and the fuel cost, but the overall "utility" of the vehicle including factors like fuel availability, refueling time, range, vehicle size and environmental performance. Some important factors like vehicle first cost could be addressed by direct vehicle subsidies or tax credits to consumers, as well as fuel price subsidies. These policies, as well as "perqs" such as high occupancy vehicle lane access and free parking are being offered to fuel cell vehicle customers. Another key consumer requirement is fuel availability, which depends on complementary policy support for fuel suppliers to build a reliable hydrogen station network. Vehicle subsidies and perqs would be designed to phase out once large scale commercialization is established.

Strong market growth requires automakers to rapidly scale up vehicle production. Policies affecting automakers include regulation and/or incentives. For example, automakers are regulated to produce a growing number of zero emission vehicles in California and some other US states, and to meet fuel economy standards. Unlike vehicle purchase subsidies, which would eventually be phased out, ZEV regulations and fuel economy standards might become more stringent over time in a low carbon world.

Policies targeting infrastructure buildout: Policy support for hydrogen infrastructure buildout could be provided as subsidies for station developers, and targeted via incentives to build in key "early adopter" areas to encourage market growth. In addition, codes and standards for hydrogen fuel stations have been developed with public support. Low carbon fuel credits are another possible policy support for hydrogen fuel providers.

Early hydrogen infrastructure development is inherently regional. Geographic focus is needed to rapidly scale up infrastructure, bringing down costs. Support for building initial hydrogen station networks is being provided in several "lighthouse" regions such as California, Japan, and Germany. Often this is being accomplished through regional public-private partnerships. For example, the state of California has committed up to $200 million to build the first 100 stations through the early 2020s, seen as a viable start-up statewide network[35]. This is a cost-shared initiative, with public funding incentivizing industry hydrogen suppliers. California's support of building the first 100 hydrogen stations in that state seeks to address a key precondition for successful launch of hydrogen vehicles. Because both new types of vehicles and a new fuel are needed, hydrogen will require policies that encourage a high degree of coordination across the whole pathway from production through end-use and network level demonstrations of the whole system, as well as individual technologies.

Polices for switching to low carbon emissions hydrogen supply pathways: In the long term, switching from fossil based hydrogen to low to zero net carbon hydrogen pathways will be required. Policies to accomplish this transition might target fuel providers. The state of California requires that a growing fraction of hydrogen transportation fuel be produced from renewable sources. In addition, economy wide environmental policies such as carbon tax (or cap and trade systems), low carbon fuel standards, renewable fuel standards will encourage lower carbon pathways.

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. [6] [8]

Intersection of Hydrogen and Other Policy Goals

While our discussion has centered on the climate imperative, hydrogen can help meet multiple other policy goals. Improving air quality and public health is an important driver for ZEVs, hydrogen fuel cells as well as battery vehicles, in California and other US states. Hydrogen might play a role in zero emission heavy duty and medium duty trucks, applications which are more difficult for batteries. Renewable portfolio standards that incorporate large fractions of variable renewable energy are driving interest in hydrogen as energy storage, especially in Europe and North America.

Policies supporting industrial development of critical technologies could help hydrogen and fuel cells progress. (In 2009-2012 US battery manufacturers received large subsidies to scale up mass production under the American Reinvestment and Recovery Act, which contributed to lower battery costs and battery vehicles' success in early commercialization. Strong policy support in Europe for solar energy encouraged scale up of solar panel production and reduced costs.)

Toward a fully commercial market

Public funding should be a temporary aid to commercialization. Some key policies suggested above, such as vehicle and fuel station subsidies, could be designed to "sunset" once fuel cell vehicles and hydrogen became competitive with other fuels, even though this might take some time. [35] However, policies aimed at GHG emissions reductions, improved efficiency and low carbon fuels would likely become more stringent over time to drive great reductions in carbon emissions. In Figure 4-d, we sketch a transition timeline moving from early phases (mainly public support) to full commercialization (mainly private investment). Assurance of long term (multi-decade), consistent public policy support for hydrogen and fuel cells is critical for industry involvement in early commercialization to get through the innovators' "valley of death".[35 37]

6 Conclusions and Future Policy Guidelines

Hydrogen and fuel cell technologies are at a critical phase of development, as they approach technical goals and begin to appear in stationary power markets, zero emission vehicles and power to gas projects. Energy economic studies suggest paths to commercial viability, under certain conditions, but the timescale for widespread adoption of hydrogen and fuel cells is uncertain.

A hydrogen transition is inherently complex, requiring many major changes at once and coordination among diverse stakeholders with differing motivations (fuel suppliers, vehicle manufacturers, consumers and policy makers). This is especially true in the early stages when costs for fuel cells are high and hydrogen infrastructure is sparse. Factors that could ease transitions, like compatibility with the existing fuel infrastructure, are more complex for hydrogen than for electricity or biofuels (or other liquid synthetic fuels).

Hydrogen infrastructure is seen as a daunting barrier, more because of logistics and scale up issues than technology. After a decade of exploration, workable regional strategies for hydrogen infrastructure rollout are emerging with buy-in from key stakeholders: the automakers, hydrogen suppliers and regulators, including public and private funding to support building early networks of stations. [34,35] Hydrogen will likely appear in a series of regional rollouts, so that infrastructure scale-up can be concentrated and lower costs achieved. A recently formed industry group the Hydrogen Council has committed $10 Billion to building hydrogen infrastructure.

A potential stalling point is that the funding required to launch hydrogen infrastructure is more than the usual amount for energy R&D projects, though vastly less than for current expenditures on the energy system. The risks involved in getting through the "valley of death" have daunted investors. (The "valley of death" refers to the market entry cost barrier facing new technologies that must scale up production in order to compete economically.) Energy economic analyses suggest that the long term rate of return (and societal benefits) are potentially attractive in a range of applications, but the path is not certain. Not surprisingly, some potential infrastructure investors want to wait until fuel cell market is more secure and they could build large, fully utilized stations with confidence. There is a clear need for a strong and consistent policy framework to give predictable support to emerging technologies.

Despite these uncertainties there are strong reasons to take a long view in supporting continued development of hydrogen and fuel cell systems at a network scale. The long-term payoff could be large. In the IEA's Energy Technology Perspective reports and the 2013 NRC study on light duty vehicle transitions, hydrogen fuel cell vehicles played an important role in meeting GHG reduction goals for light duty vehicles in 2050. In the NRC studies, the long-term benefits of hydrogen fuel cell vehicles are large [4,8] 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 ten.[8] A recent study by the IEA notes, more generally, the benefits of transitioning to a sustainable energy future outweigh costs as long as flexibility and adaptation is ensured within policy frameworks.[7]

We are entering a new era of climate change driven policy, bringing with it a tension between cautionary experiences of past energy transitions and an imperative for rapid change. Meeting emissions reduction goals for a "2 degree scenario" may mean a faster energy transition than historical rates, with more systems level, network demonstrations, more willingness to experiment at scale, and flexible policy frameworks. Hydrogen and fuel cells could play a role throughout a future low carbon energy system, and help enable wider use of renewables in fuels markets. The early steps in a hydrogen transition have begun. Consumer preferences, technology progress, system issues and policy will determine how fast it progresses.

We suggest the following guidelines to navigate the transition:

- Persistence, alignment and continuity of policies will be needed over many decades.
    - Industry confidence is built on signals that there will be consistent policies over the long term and that they will adapt to reflect experience.
    - It will be important to incorporate externalities into economics through policies or regulations.
- Hydrogen and fuel cells should be seen as part of a portfolio approach to decarbonizing the energy system and moving to zero net emissions.
    - A portfolio of future transportation fuels is likely in a low carbon world, unlike today's petroleum monoculture. It is important to keep a range of options open for a while, rather than selecting a single "winning" vehicle technology or fuel too soon.
    - "Black swan" issues may arise, such as changes in technology (e.g. a very low cost electrolyzer or battery), or new consumer patterns of using energy (e.g. automated vehicles or ride sharing) that alter the future transportation landscape.
- Keep transition costs in perspective. Various studies estimate investments to bring the cost of hydrogen and fuel cells in the US down to competitiveness with incumbents might average a few billion dollars a year for 10-20 years.[4 8] While this is more than typical R&D expenditures, it is much less than the money flows in the energy system, which amounts to hundreds of billions per year[6], and is roughly comparable to the amount spent on launching other clean technologies such as plug-in vehicles and renewable energy supply technologies.

- System level learning is needed. It is important to experiment at the network scale, rather than with one of kind component level demonstrations and to focus efforts geographically. These could include:
    - City scale demonstrations of hydrogen infrastructure and fuel cell vehicle technologies as a networked system tens to hundreds of thousands of vehicles and 100s of stations in a region to start.
    - Use of hydrogen storage to capture variable renewable electric energy (solar, wind).

Finally, expect a period of experimentation at the system level. Not everything will work immediately. But the potential net benefits are large, and given the urgency of climate change, it is worth making the bet.

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Table 1. Technology Status and Costs for Hydrogen Production, Storage and Distribution Infrastructure

Table 2. Current Status and Goals for Hydrogen and Fuel Cells in Stationary Power Applications

Table 3. Current Status and Goals for Hydrogen and Fuel Cells in Transportation and Energy Storage Applications

Table 1. Technology Status and Costs for Hydrogen Production, Storage and Distribution Infrastructure

	Technology Status	***Capacity***	***Conversion efficiency*** ***H2 out /energy in (HHV)***	***Capital cost***	***Levelized H2 Cost ($/kg H2)***
HYDROGEN PRODUCTION (in MW of H2 output on HHV basis)					
Steam methane reforming (SMR) Central production [20] SMR w/CCS (central) [20] Distributed production [7]	Commercial CCS Early Market Early market	400-700 MW “ 0.16-16 MW	72% 71% 51%	$380-480/kW $450-560/kW $3000-5000/kW	$1.7/kg $2.1/kg
Coal Gasification (central) [20] Coal gasification w/CCS [20]	Commercial CCS Early market	160-820 MW “	56% 54%	$940-1780/kW $1200-2200/kW	$1.3-1.7/kg $1.8-2.4/kg
Biomass gasification (central) [20] Biomass gasification w/CCS [20]	Early market CCS Early market	32-320 MW “	48% 47%	$700-1200/kW $800-1300/kW	$2.1-2.3/kg $2.7-2.9/kg
Water Electrolysis Alkaline Proton exchange membrane Solid Oxide	Commercial Early market R&D	Up to 150 MW[7] Up to 1 MW[7] Laboratory scale[7]	65-82%[7] 65-78%[7] 80-90%[7]	$800-1500/kW[7] $1500-3800/kW[7]	$4.1-5.5/kg [20] $4.1-5.5/kg[20] $2.8-5.8/kg[20]
HYDROGEN STORAGE AND DELIVERY INFRASTRUCTURE					
H2 BULK STORAGE Compressed gas (180-340 atm) Compressors[20] Above ground pressure vessels Geologic formations Liquid hydrogen (LH2) (-253 C)[20] Liquefiers LH2 Storage tanks	Commercial	-250 kg/h (small) 1-16 MW (large) 2.5-250 kg [7] 20-200 million m^3 [20] 25-200 t/d 500-3500 m^3 (3.5-24.5 t LH2)	Compression Elec input= 5-10% of H2 HHV Liquefaction Elec input =36% of H2 HHV <1% loss/day	$0.15-1.1 million $1.4-8 million $250-700/kg[20,7] $6-30 million[20] $7/kg [7] $50-250 million $2-6 million	Levelized costs for storage range from $1-10/kg depending on conditions
H2 TRANSMISSION AND DISTRIBUTION [20] H2 Gas pipelines Long distance transmission Local distribution H2 Delivery Trucks Capacity Gaseous H2 Liquid H2	Commercial (>1000 mi in use) Commercial	10-10000 t/d 10 t/d 0.5 t/truck 3 t/truck		$1-2 M/km $0.6-1.2 M/km $0.3-0.4 million $0.7 million	$1-10/kg[7,20]
H2 REFUELING STATIONS[34,35,38,48] (see Table 2 for more details)	Early market intro networks w/ 10s of stations in California, EU, Japan. 100s of stations planned by 2020[35,51]	0.1-0.35 t/d (now) 0.5-1 t/d (2020)		$1-4 million $1.5-4 million	Dispensed levelized cost of H2 to vehicles ranges from $5-10/kg

Table 2. Current Status and Goals for Hydrogen and Fuel Cells in Stationary Power Applications

STATIONARY POWER APPLICATIONS		
	Current Market Status	***Cost and Performance***
Residential combined heat and power (CHP) PEM fuel cell systems (~0.7-1 kW)	Early commercial >190,000 PEMFC units operating in Japan[22]; Goals for 1.4 million micro-CHP units (2020); 5.3 million (2030)[48]	$20,000 (now)[7, 47] $3500 (2020-2030 goal) [47] 35-50% elec eff.; 95% cogen eff. [7] 60,000-90,000 hours lifetime [47]
Commercial Bldg. CHP (20-100 kW) PAFC systems	Mature market	$3000-4000/kW [7] 30-40% elec eff; 75-80% cogen. [7]
Stationary power (0.1-100 MW)	>1000 MW in use globally [22]	

Table 3. Current Status and Goals for Hydrogen and Fuel Cells in Transportation and Energy Storage Applications

TRANSPORTATION APPLICATIONS		
	2015 Status	***USDOE 2020 Goals***
	Fuel Cell Light Duty Vehicles	
Fuel Cell Vehicles in Use [22]	>1000 worldwide	Projections of 10s of thousands in each of several lighthouse regions by 2020 (California, Germany, Japan)
Fuel Cell In-Use Durability (h)[21 ,49]	2500 (average on-road) 4100 (best on-road) 4000-12,000 (in lab)	5000 8000 (long-term goal)
Vehicle range (miles)[21,42]	200-320 (on-road)	300
Fuel Cell Efficiency (LHV basis)[21,42]	57%	65%
Fuel Cell System Cost in large scale mass production ($/kW)[21,53]	53 (500K unit/y) 280 (20K unit/y)	40 30 (long term goal)
H_2 Storage Cost on vehicle in large scale mass production ($/kWh) pressurized H2 @350-700 bar[21,42]	15 (500K unit/y) 33 (20K unit/y)	10 (DOE 2020 goal)
	Hydrogen Refueling Infrastructure	
H2 station deployment [22,48]	29 stations operating in US	100s planned in US, Japan, EU by 2020.
Fuel Dispensing rate (tank 5-6 kg)[48]	0.58 kg/min average	1.5 kg/min
Station capacity (kg H2 dispensed per day)[21,35,48]	700 bar Stations ranging from 100 – 350 kg/d have been built	Validate H2 station producing and dispensing 200 kg H2/day (@ 5 kg H2 per 3 min @ 700 bar) (2019 goal)
Availability (% of time)	varies	70%
Average time to build station (y)	1.6 years in 2014, down from 4.9 years in 2009 [35]	1 year
H2 cost delivered to vehicle ($/kg) [21]	>$10 kg	$5-7/kg
HYDROGEN AS ENERGY STORAGE FOR RENEWABLE ELECTRICITY.		
Power to gas systems	30 power to gas demonstrations ongoing in Europe[11,35]. Southern California Gas beginning 2 US projects with UC Irvine and NREL in 2016/7. [50]	Validate large-scale systems for grid energy storage that integrate renewable hydrogen generation and storage by operating for more than 10,000 hours with an electrolysis system eff. of 60% on LHV basis (2021 goal) [21]

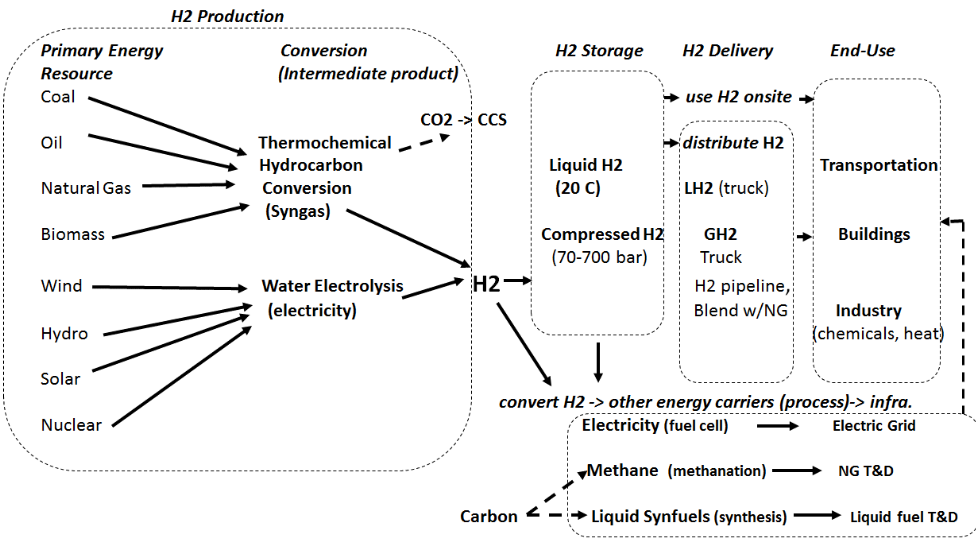
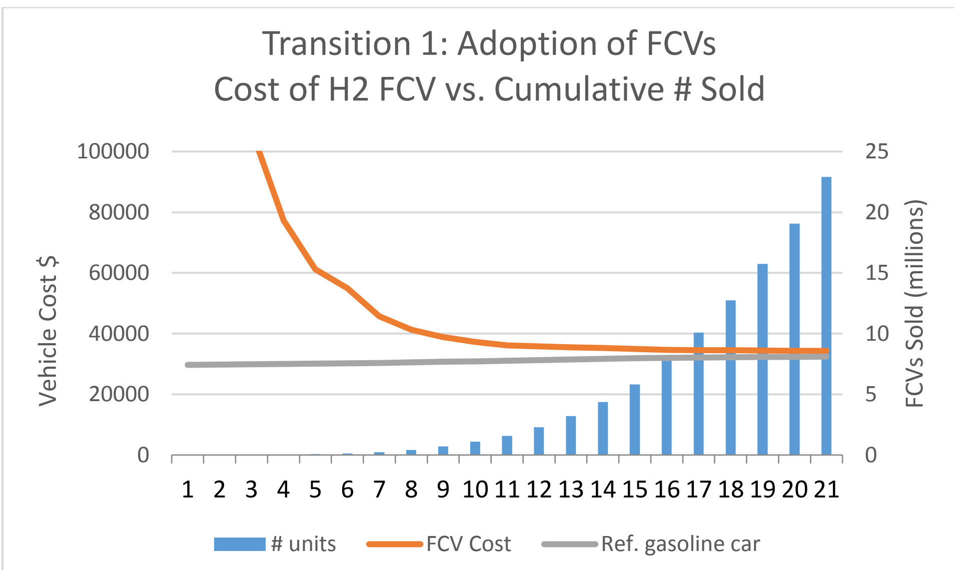


Figure 1. Pathways for hydrogen production, storage, delivery and end-use.



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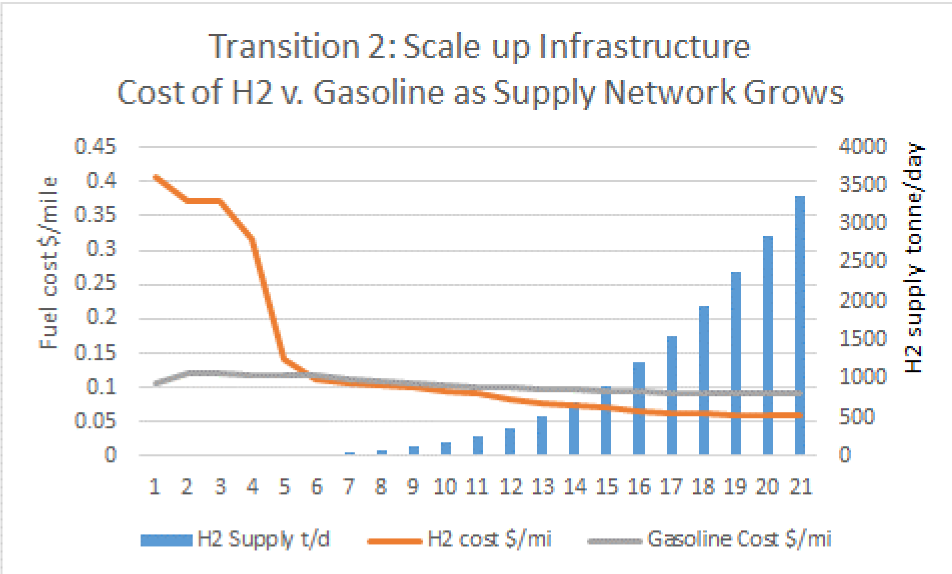

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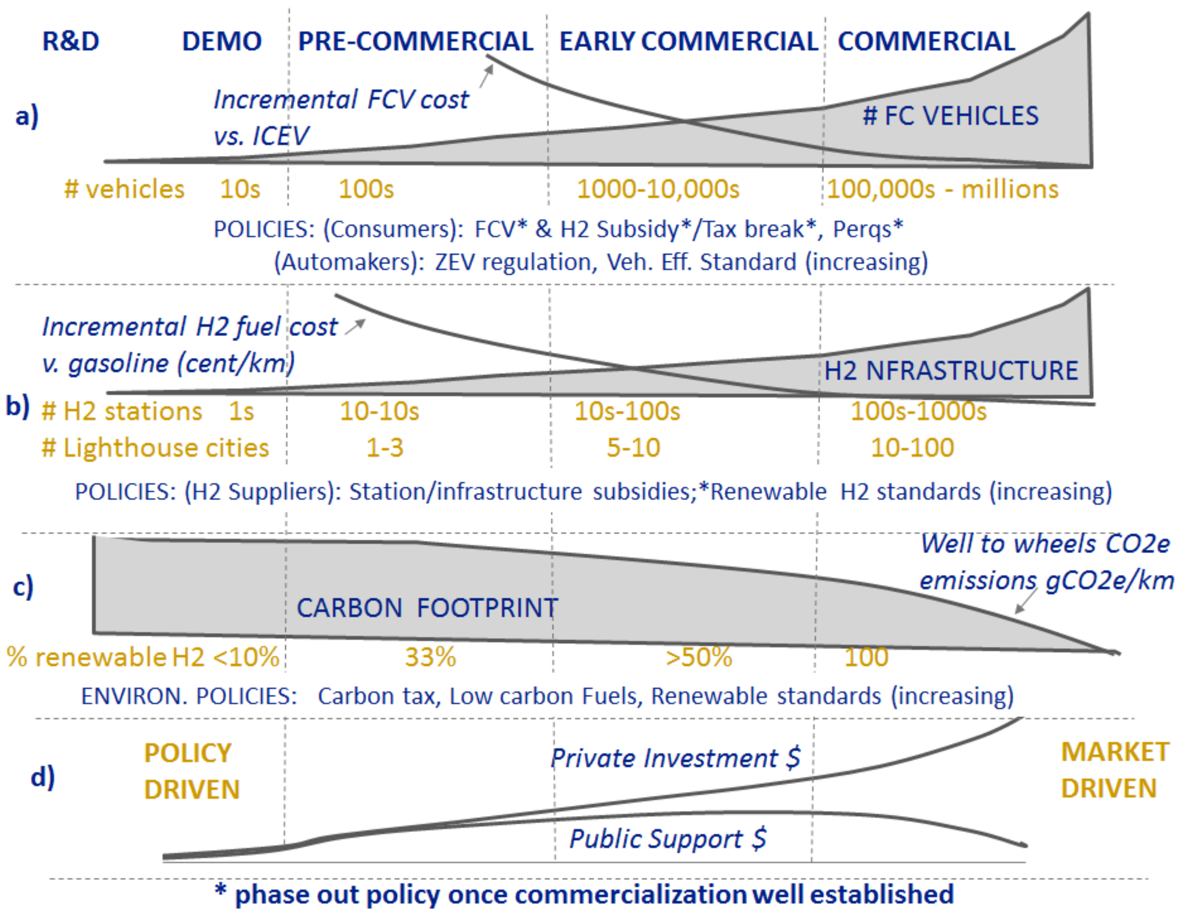

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