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Hydrogen as an Energy Carrier: Outlook for 2010, 2030 and 2050

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Introduction: Why consider hydrogen as a future energy carrier?

Globally, direct combustion of fuels for transportation and heating accounts for about two thirds of greenhouse gas (GHG) emissions, a significant fraction of air pollutant emissions and about two thirds of primary energy use. Even with continuing incremental progress in energy technologies; primary energy use, and GHG and air pollutant emissions from fuel use will likely grow over the next century, because of increasing demand, especially in developing countries. To stabilize atmospheric CO_2 concentrations at levels that avoid irreversible climate changes,[1] integrated assessment models suggest that it will be necessary to reduce carbon emissions from fuel combustion several-fold over the next century, as compared to a "business as usual" scenario, even if the electric sector completely switches to non-carbon emitting sources by 2100 (Williams 2002). Air quality remains an issue in many parts of the world. Moreover, fuel supply security is a serious concern, particularly for the transportation sector.

A variety of efficient end-use technologies and alternative fuels have been proposed to help address future energy-related environmental and/or supply security challenges in fuel use. Alternative fuels include reformulated gasoline or diesel; compressed natural gas; methanol; ethanol; synthetic liquids from natural gas, biomass or coal such as Fischer-Tropsch liquids or dimethyl ether (DME); and hydrogen. Recently, hydrogen has received increased attention worldwide, because it offers perhaps the greatest long-term potential to radically reduce several important societal impacts of fuel use at the same time.

Hydrogen can be made from widely available primary energy sources including natural gas, coal, biomass, wastes, solar, wind, hydro, geothermal or nuclear power, enabling a more diverse primary supply for fuels. Hydrogen can be used in fuel cells and internal combustion engines (ICEs)[2] with high conversion efficiency and essentially zero tailpipe emissions of GHGs and air pollutants. If hydrogen is made from renewables, nuclear energy, or fossil sources with capture and sequestration of carbon, it would be possible to produce and use fuels on a global scale with nearly zero full fuel cycle emissions of GHG and greatly reduced emissions of air pollutants.

Most analysts believe that hydrogen will only become viable if public policy more aggressively addresses the societal impacts of fuel use. However, the intriguing possibility has been raised that hydrogen and fuel cells might enable improved energy services and new features, such as clean, quiet, mobile electricity generation, that would make them attractive to consumers, even without policies considering external costs of energy (Burns et al. 2002). Some see hydrogen and fuel cells as "disruptive technologies" that could change how we produce and use energy in profound ways.

Hydrogen also poses the greatest challenges of any alternative fuel: there is an array of technical, economic, infrastructure and societal issues that must be overcome before it could be implemented on a large scale. Technologies for hydrogen production, storage and distribution exist, but need to be adapted for use in an energy system. Building a new hydrogen energy infrastructure would be expensive and involves logistical problems in matching supply and demand during a transition. Hydrogen technologies such as fuel cells, and zero-emission hydrogen production systems are making rapid progress, but technical and cost issues remain before they can become economically competitive with today's vehicle and fuel technologies.

This report examines the current status of hydrogen technologies, possible paths forward and the issues associated with a transition toward large-scale use of hydrogen. It discusses technical milestones, actions and policies that might be needed for successful development of hydrogen energy systems. There are still major uncertainties about the future performance and cost of hydrogen technologies versus competitors, and in the future policy landscape, making it difficult to project future markets over a 50-year time frame. Because of these uncertainties, this report discusses hydrogen transitions in the context of a possible future where externalities begin to receive serious attention and where hydrogen technologies reach their technical and cost goals, both within the next decade or so. A possible timeline for hydrogen energy systems is sketched, and near to mid-term "no-regrets" actions are suggested.

Overview of Hydrogen Technologies: Present Status, Challenges and Policy Implications

Today's Industrial Hydrogen System

Technologies to produce, store and distribute hydrogen for industrial markets are well established. Hydrogen is widely used for a variety of applications such as the refining of crude oil, production of ammonia and methanol, production of semiconductor chips, processing of edible oils, surface treatment of machined metal parts and other chemical uses. The annual worldwide production of hydrogen is about 50 million (metric) tonnes (equivalent to about 2% of global primary energy use), the vast majority (95%) of which is made from fossil fuels and used within large refineries and ammonia and methanol plants. There is also a smaller but rapidly growing merchant hydrogen industry, which makes and supplies about 2.5 million tonnes of hydrogen per year to customers (enough to fuel about 14 million hydrogen cars if they filled up once every 8 days with 4 kilograms of hydrogen each time.) (See Raman.) Hydrogen is delivered in trucks as a high-pressure compressed gas or cryogenic liquid or by gas pipeline (there are more than 1,000 miles of hydrogen pipelines serving large refineries and chemical plants in several locations around the world). The current industrial hydrogen system provides a technical starting point for building a future hydrogen refueling infrastructure, although new engineering (and new or at least updated regulatory regimes) would be needed to adapt industrial hydrogen technologies to an energy system serving mass consumer markets with near zero emissions of GHGs and air pollutants.

Hydrogen Production

Current Status

Hydrogen Production from Hydrocarbons: About 95% of hydrogen today is produced from fossil fuels using high-temperature chemical reactions that convert hydrocarbons to a synthetic gas, which is then processed to make hydrogen. In many areas of the world, including the United States, large-scale natural gas reforming is currently the lowest cost method for hydrogen production. Systems are being developed for small-scale production of hydrogen from natural gas, at a size appropriate for vehicle refueling stations or fueling stationary fuel cells in buildings. Hydrogen could also be produced at large scale by gasification of feedstocks such as coal, heavy oils, biomass, wastes or petroleum coke. In regions with plentiful, low-cost biomass resources, biomass gasification could become an economically attractive method of hydrogen production. Limiting factors are likely to be land availability and competing uses for low-cost biomass feedstocks in the electricity sector.

Fossil Hydrogen and CO_2 Sequestration: When hydrogen is made from fossil fuels, carbon dioxide can be separated, compressed, transported by pipeline and “sequestered” in secure underground storage sites such as deep saline aquifers or depleted oil and gas fields. Carbon capture and sequestration are key enabling technologies for fossil hydrogen as a long-term, low carbon-emitting option. (For example, without carbon sequestration, vehicles using hydrogen from natural gas would offer modest [10-40%] reductions in GHG emissions,[3] compared to advanced ICE vehicles fueled with natural gas, gasoline or diesel [Wang 2002]. With CO_2 sequestration well-to-wheels GHG emissions might be reduced by 80-90%.) Technologies for CO_2 capture, transmission, and sequestration are used for enhanced oil recovery today, and several large-scale demonstrations of CO_2 capture and sequestration are ongoing or planned in the United States and Europe. However, there are still many unanswered scientific and cost questions about long-term storage of carbon dioxide (See companion workshop papers on Carbon Sequestration).

Hydrogen Production via Electrolysis: Water electrolysis is a mature hydrogen production technology, in which electricity is passed through a conducting aqueous electrolyte, "splitting" water into hydrogen and oxygen. Electrolysis is a modular technology that can be used over a wide range of scales from household to large central hydrogen plants serving a large city. Research is ongoing to reduce capital costs and improve efficiencies of electrolysis. The production cost of electrolytic hydrogen strongly depends on the cost of electricity. Today, electrolytic systems are generally competitive with steam reforming of natural gas only where very low cost (1-2 cent/kWh) power is available (Thomas et al. 1998, Ogden 1999, Williams 2002).

Depending on the source of the electricity, the full fuel cycle carbon emissions from electrolytic hydrogen production could range from zero (for hydropower, wind, solar, geothermal or nuclear power) to quite large (for coal-fired power plants without CO_2 sequestration). Off-peak power could be a locally important resource for electrolytic hydrogen production, particularly in areas where low-cost excess hydropower or geothermal power is available. Solar and wind power are potentially huge resources that could produce enough electrolytic hydrogen to satisfy human needs for fuels, with zero emissions of GHG and air pollutants. At large scale, electrolytic hydrogen from intermittent renewable sources is projected to be more costly to produce than hydrogen from fossil fuels, even if future cost goals are reached for wind and solar electricity (Myers et. al 2003), and even when the costs of CO_2 sequestration are added to the fossil hydrogen production cost (Williams 2002). Nuclear electrolytic hydrogen would be high cost as well, unless low-cost off-peak power from a nuclear plant were used. In addition there are issues of weapons proliferation and waste disposal associated with nuclear energy. (See companion workshop paper on nuclear energy.)

Advanced hydrogen production methods using renewable or nuclear energy: Water splitting can also be accomplished through a complex series of coupled chemical reactions driven by heat at 400-900 degrees C from nuclear reactors or solar concentrators. Thermo-chemical water splitting cycles are still undergoing research, and are not as technically mature as hydrogen production systems such as steam reforming, coal or biomass gasification, or water electrolysis, and should be considered a longer-term possibility. Fundamental scientific research is being conducted on a variety of other experimental methods of hydrogen production including direct conversion of sunlight to hydrogen in electrochemical cells, and hydrogen production by biological systems such as algae or bacteria. These methods are far from practical application for commercial hydrogen production.

Summary of Hydrogen Production Costs

How does hydrogen compare in cost to other fuels? In Figure 1, we estimate the delivered cost of hydrogen for several supply options. These include both near-term options (truck delivery of liquid hydrogen, onsite production of hydrogen in small electrolyzers or steam methane reformers) and long-term centralized options (central fossil hydrogen production with and without CO_2 sequestration, nuclear thermo-chemical water splitting and central electrolysis using electricity costing 3 cents per kwh). The delivered cost of hydrogen including production, delivery and refueling stations is approximately \$2-3.5 per kg of hydrogen. (The energy content of 1 kg of hydrogen is about the same as 1 gallon of gasoline, although hydrogen can be used more efficiently.)[4] In the near term, onsite production of hydrogen from natural gas is the most attractive option. In the longer term, zero GHG emission hydrogen supplies will presumably be phased in, but have a higher cost. At large scale, CO_2 sequestration is projected to add relatively little to the delivered cost of hydrogen (Williams 2002, Ogden 2003). A recent assessment of the potential for renewable hydrogen production in the United States found that it was technically feasible to make 10 Quadrillion Btu of hydrogen per year (enough hydrogen for more than 100 million light duty vehicles), with delivered hydrogen costs ranging from \$3-4.5/kg for various renewable sources such as wind-powered electrolysis and biomass gasification (Myers et al. 2003).

Policy Implications

Fossil-derived hydrogen (without CO_2 sequestration) is likely to be the lowest cost hydrogen supply in many places over the next few decades, offering modest societal benefits (e.g. significant reductions in air pollutant emissions and oil use per mile of vehicle travel, but modest reductions in well to wheels GHG emissions per mile as compared to advanced ICE vehicles using conventional fuels [Wang 1999, Weiss et al. 2000, Ogden, Williams and Larson 2004]). Renewable hydrogen could be locally important in the near term, where low-cost renewable resources are available. In the long term, to fully realize hydrogen's benefits, it will be important to widely implement zero-emission hydrogen production systems. As discussed above, each of these options faces significant challenges before it could be implemented on a global scale. Vigorous support for RD&D on zero-GHG emission hydrogen production technologies is needed, even if hydrogen is made from fossil sources such as natural gas in the near term. Many of the enabling technologies (such as gasification, CO_2 sequestration and wind power) have potential applications in the electric sector as well, and are being developed for electric markets.

Hydrogen Storage

Present Status

Unlike gasoline or alcohol fuels, which are easily handled liquids at ambient conditions, hydrogen must be stored as a compressed gas (in high-pressure gas cylinders), as a cryogenic liquid at -253°C (in a special insulated vessel or dewar) or in a hydrogen compound where the hydrogen is easily removed by applying heat (such as a metal hydride). Commercial, large-scale bulk storage of industrial hydrogen is typically done as a compressed gas or a cryogenic liquid. Very large quantities of hydrogen can be stored as a compressed gas in geological formations such as salt caverns or deep saline aquifers

Hydrogen onboard storage systems now under development for vehicles are bulkier, heavier and costlier than those for liquid fuels (like gasoline or alcohols) or compressed natural gas, but are less bulky and heavy than electric batteries. Automotive manufacturers have identified hydrogen storage for light duty vehicles as a key area for RD&D, as none of the existing hydrogen storage options simultaneously satisfy the manufacturers' goals for compactness, weight, cost, vehicle range and ease of refueling. Current hydrogen vehicle demonstrations are focused on compressed gas storage, because of its simplicity. Innovative storage methods such as hydrogen adsorption in advanced metal hydrides, carbon nano-structures and chemical hydrides are being researched, but none are near commercialization.

Challenges and Policy Implications

Support for R&D on hydrogen storage could have a large payoff. Development of a novel hydrogen storage medium that required neither high pressure nor low temperature would not only facilitate use of hydrogen in vehicles, but could reduce hydrogen infrastructure costs and complexity as well. (Over half of the capital cost of a hydrogen refueling infrastructure with pipeline distribution of gas to refueling stations is due to compressors and pressure storage vessels. [Ogden 2003]). Compressed gas storage and refueling are relatively simple technically, and could work in the long term, even without a storage breakthrough, although there is considerable cost and energy use involved in hydrogen fuel distribution compared to liquid hydrocarbon fuels. Also, if large amounts of bulky above-ground compressed hydrogen gas storage were needed, this might require creative use of space at refueling stations. Too early an investment in an extensive compressed gas hydrogen infrastructure might result in "stranded assets" if a breakthrough in hydrogen storage materials occurred later. Over time, incremental infrastructure decisions could take advantage of improvements in hydrogen storage technologies.

Hydrogen Delivery Infrastructure: Hydrogen Transmission, Distribution, Refueling

Present Status

Long-Distance Hydrogen Transmission: The technologies for routine handling and delivery of large quantities of hydrogen have been developed in the chemical industry (see Raman). Liquid hydrogen is delivered by truck or rail over distances of up to several hundred miles. Compressed gas hydrogen pipelines (up to several hundred kilometers in length) are used commercially today to bring hydrogen to large industrial users like refineries. For a large-scale hydrogen energy system, it would probably be less expensive to transport a primary energy source (like natural gas or coal) to a hydrogen plant located at the "city gate," rather than making hydrogen at the gas field or coal mine and piping it to the city. In the long term, transcontinental hydrogen pipelines seem unlikely, unless there were a compelling reason to make hydrogen in a particular location far from demand.

Local Distribution and Refueling: For local distribution of hydrogen from the city gate to users such as refueling stations, compressed gas or liquid hydrogen trucks or high-pressure, small-diameter pipelines analogous to natural gas utility "mains" might be used. The cost of building local distribution pipelines through an urban area is likely to be quite high, on the order of $1 million/mile, depending on the area. A large and geographically dense demand would be required for cost-effective local hydrogen pipelines. This might not occur until 10-25% of the cars in a large urban area used hydrogen.

There are currently about 60 hydrogen refueling station demonstrations worldwide for experimental vehicles, using a variety of approaches, including truck delivery and onsite production from small-scale electrolysis or steam reforming of natural gas.

The cost of building a full-scale hydrogen refueling infrastructure (assuming a large fraction of future vehicles use hydrogen) has been estimated at hundreds to thousands of dollars per vehicle, depending on the level and geographic density of demand and the hydrogen production technology required (Ogden 1999, Mintz et al. 2002, Thomas et al. 1998) Early infrastructure will be more costly per vehicle, because of economies of scale and low density of demand. In the longer term, zero-emission hydrogen supplies are likely to have a higher capital cost per car.

Challenges and policy implications

For implementing a future hydrogen delivery infrastructure, the major challenges are likely to be more economic and logistical than technical. In particular, matching supply and demand during a transition at low cost is a key issue. To address the associated "chicken and egg" problem, coordination between fuel suppliers and fuel users will be needed during infrastructure growth. In addition, government support may be needed to encourage early infrastructure investments, before economies of scale can be realized.

A possible development path for hydrogen infrastructure is sketched below (see also Raman and Nemanich). Initially, when demand for hydrogen energy is small, hydrogen will be delivered by truck from centralized plants, similar to today's merchant hydrogen system. Excess capacity in the merchant hydrogen system could be used for early demonstration projects. Mobile refuelers might be used (a compressed hydrogen gas storage system and dispenser mounted on a small trailer that could be delivered by truck to refueling sites and replenished at a central hydrogen plant). Alternatively, hydrogen could be produced at the end-user site (e.g. a refueling station or building) by small-scale electrolysis or steam reforming of natural gas. Onsite production avoids the cost of hydrogen distribution, and allows supply to grow incrementally with demand. One of the benefits of central production is that zero-emission sources can be more easily used and control of emissions including CO_2 is easier to accomplish. (It might also be possible to make hydrogen at refueling stations, for example, from renewable electricity, such as off-peak hydropower.) As hydrogen demand increases, pipeline distribution could be considered for large, geographically dense demands. Local distribution pipelines are most likely to make economic sense where a large demand is located near an existing supply, or in large cities with geographically dense demand and a high fraction of hydrogen vehicles (probably at least 10% [Ogden 1999]).

The existing energy infrastructure could strongly influence how hydrogen supply evolves in the near term. In the long term, some sites used for energy infrastructure today might remain in use for hydrogen systems, but new development might also be required, and new fuel delivery locations to allow refueling at home or at work. Infrastructure considerations might be different for developing countries, where relatively little fuel supply infrastructure currently exists.

Hydrogen End-Use Technologies

Present Status

Hydrogen Use in Transportation: Hydrogen vehicles are undergoing rapid progress. Experimental fuel cell vehicles have been developed by most automotive manufacturers, and are being tested in small fleet trials of buses and light duty vehicles. However, current automotive fuel cell costs are still perhaps 30-100 times higher than ICEs that cost perhaps $35-45/kW. Further, reliability and durability of fuel cells needs to be improved several-fold. The U.S. government's Freedom Car program with industry has established goals for fuel cells, hydrogen storage and auxiliaries (see Ford Motor Company paper). In the near to mid term, hydrogen internal combustion engines could offer a near-zero GHG emission technology,[5] with lower cost than fuel cells, and high efficiency when used in a hybrid configuration. Hybrid technology development is relevant to future prospects for fuel cell vehicles, because many of the electric drive technologies are similar.

Hydrogen for Heat and Power in Buildings: Although much of the attention has been on hydrogen vehicles, hydrogen might find earlier applications in providing heat and power for buildings, where cost goals are less daunting than for vehicles. Fuel cell cogeneration systems using reformed natural gas are being developed to provide heat and power in buildings. Several hundred natural gas fueled fuel cell cogeneration systems have been installed worldwide. There is growing interest in the "energy station" concept, where natural gas is reformed to power a fuel cell providing building energy plus hydrogen for vehicles.

Early Niche Applications: It has been proposed that hydrogen might be used first in heavy vehicles, including ships and locomotives that currently rely on heavily polluting diesel engines (Farrell et al. 2004). Hydrogen fuel cells might be used in applications where battery electric power trains are used today, and zero air pollutant emissions are required (e.g. vehicles used indoors or mine vehicles). Other early niches for fuel cells might include use as zero-emission mobile auxiliary power units (for auxiliary electrical loads on idling vehicles or at work sites, military "backpack" power, etc.) and as battery replacements (e.g. in laptop computers, power tools).

Challenges and Policy Implications

For hydrogen vehicles to compete in automotive markets they will have to offer the customer comparable or better performance at a similar cost to competing vehicles. Or they must offer societal benefits that are accounted for in policies that help to close the gap between private and public costs/preferences for the vehicles. Incentives would likely be needed to make up any difference in costs, until mass production brought hydrogen vehicles to a competitive level. Clearly, continued RD&D on hydrogen vehicle and fuel cell technologies is key to the success of hydrogen in transportation. Initially, use of hydrogen in heavy vehicles and/or fleet vehicles may be preferred. Demonstrations of hydrogen vehicle technologies over the next decade or so should provide answers to some of these technical and cost questions. Because of the need for coordination between fuel suppliers, auto manufacturers and end-users, public/private partnerships among stakeholders will be needed.

The business case for hydrogen depends on how society values external costs of energy. A "wild card" is the possibility that hydrogen and fuel cells might enable new products and services that would create significant market pull even without considering societal benefits (Burns et al, 2002, Kurani et al. 2004).

Hydrogen Safety

Safety is an assumed precondition for hydrogen energy use by consumers. Hydrogen has been used safely in industrial settings for many decades, and there are efforts underway worldwide to extend this knowledge to general use of hydrogen as a fuel. To this end, it will be important to develop appropriate safety procedures and codes and standards for hydrogen use in energy applications. (See Ringland et al. 1994, Ford Motor Company 1997, Linney and Hansel 1996 for reviews of safety issues for use of hydrogen as a vehicle fuel.) The United States Department of Energy and the National Hydrogen Association are involved in developing codes and standards (USDOE Hydrogen Program website).

Resource Issues for a Hydrogen Economy: Where will hydrogen come from?

A major long-term question for hydrogen is the primary resource used for supply.

Natural gas is widely seen as a transitional source for hydrogen production in the United States over the next few decades, in terms of low cost and low emissions. Several studies have estimated a modest wells-to-wheels GHG benefit in using hydrogen from natural gas in advanced hydrogen vehicles, compared to using liquid fossil fuels in improved ICE hybrid vehicles. (Wang 1999, Weiss et al. 2000, Wang 2002, GM et al. 2001) Moreover, there would be reduced emissions of air pollutants and reduced oil use (although greatly expanded use of natural gas in the United States might come from imports, bringing its own security issues). It might be possible to develop hydrogen end-use technologies (for vehicles and buildings) and bring them to technical readiness over the next few decades, fueled with hydrogen from natural gas, while achieving a reduction in the societal impacts of energy, as compared to what might be achieved with advanced ICE vehicles. The impact on U.S. natural gas supply of making hydrogen for the next decade or so would be relatively small - even under the most optimistic hydrogen demand scenarios, natural gas use would be increased only a few percent by 2025 (Ogden 2004).

Beyond a few decades, in order to realize the low-carbon benefits of hydrogen technologies it would be necessary to change from natural gas without CO_2 sequestration to hydrogen supplies with nearly zero GHG emissions. There is a debate about whether using natural gas to make hydrogen in small reformers for the next few decades would impede a later switch to lower-carbon sources, or would constitute a bridge, allowing development of end-use systems using low-cost hydrogen (Thomas 2003). Promising long-term options that have the potential to reach both low-cost and zero or nearly zero carbon emissions include fossil hydrogen production with CO_2 sequestration, renewable hydrogen (from biomass gasification or possibly wind-powered electrolysis), and hydrogen from off-peak power based on carbon-free electricity. There are ample resources for hydrogen production in the United States, and in most areas of the world. In Table 1, we summarize the primary energy requirements to fuel 100 million hydrogen vehicles (about half the number of light duty vehicles in the United States today), assuming these vehicles are 2 to 3 times as efficient as today's 20 to 30 mile per gallon gasoline light duty vehicles (or 40-60 mpg equivalent).[6] There are clearly many resources that could contribute to hydrogen production in the United States, including renewable resources (Myers 2003).

There are likely to be many solutions for hydrogen supply depending on the level of demand, resource availability, geographic factors, and progress in hydrogen technologies. In the long term, there will be a mix of primary resources for hydrogen supply and hydrogen distribution modes. The mix will probably change as demand grows, and as the cost and availability of primary resources change over time. Depending on the region, different primary resources might be used to make hydrogen. Where external costs of energy are highly valued, this will tend to favor nearly zero GHG emission hydrogen options. Hydrogen will develop first in regions where the case seems compelling on a policy/societal or economic basis; for example in large cities with air pollution problems[7] or island nations with high imported fuel costs (such as Iceland).

Long-term visions of the hydrogen economy, transition paths, and a timeline

Long term visions

Alternative long-term visions of a hydrogen economy have been articulated based on large-scale use of renewables, fossil energy sources (with carbon sequestration) or nuclear energy. These visions share the goal of a zero-GHG emission, more secure fuel supply system using widely available resources. Challenges face each of these zero-emission hydrogen pathways

- For hydrogen from renewables, the issue is primarily cost rather than technical feasibility. Electrolyzers using solar,wind, hydro or geothermal power, and biomass gasification systems could be built today using commercial or near-commercial technology, but, generally, in the United States, delivered hydrogen costs would be higher than for the near-term supply options like steam reforming of natural gas (See Figure 1). For biomass hydrogen the limiting factors might be land availability and competing uses for low-cost biomass feedstocks in the electricity sector.

- Nuclear electrolytic hydrogen suffers from high cost, unless low-cost off-peak power were used. Water splitting systems powered by nuclear heat are still in the laboratory stage, face a number of technical issues, and are less technically mature than renewable or fossil hydrogen systems. Nuclear hydrogen would have the same societal issues as nuclear energy (see companion papers in this workshop on nuclear energy).

- Fossil hydrogen with CO_2 capture and sequestration holds the promise of nearly zero emissions and a relatively low hydrogen production cost, assuming that nearby suitable CO_2 disposal sites are available, and that hydrogen is produced at large scale. (It is not economically feasible to collect CO_2 from small hydrogen production systems such as fueling stations or buildings with onsite reformers.) Much remains unknown about the potential environmental impacts and feasibility of this concept. (See companion workshop papers on geological sequestration.)

In the long term, a hydrogen energy system would use a variety of zero emission supply pathways, depending on regional resources, technical progress, economics, and policies that might favor one resource over another. Hydrogen would be distributed to users by pipeline or truck depending on the level and density of demand (or perhaps via some new method, if there is a breakthrough in hydrogen storage), or produced onsite. There might still be multiple fuels (as today) for different applications (see Greene). Unlike the current transportation fuels, hydrogen might be produced from regionally available primary sources, and the production of fuels, electricity and chemicals could become more closely coupled. A future hydrogen energy supply system will be interdependent with other parts of the energy system. It is important to understand how hydrogen might fit, especially its interactions with the electricity and natural gas systems.

A Timeline for Transition

Setting a precise timeline for a transition to hydrogen is complicated by large uncertainties in projecting technological progress, policies, and future hydrogen markets, and by the site specific nature of hydrogen transitions.[8]To deal with these uncertainties, we set forth a possible scenario for introduction of hydrogen into the energy system.[9] The author first describes a context (in terms of policy, technology and economics), where hydrogen might come into wide use over the next 50 years. The author assumes a high level of societal willingness to address external impacts of energy through policy, and technical and economic success for hydrogen technologies. Absent such a convergence of both political will and technological progress, it is much less likely that hydrogen will play a major role as a future energy carrier. The author then sketches a possible evolution for a hydrogen energy system over the next 50 years within this context, considering likely hydrogen markets, production sources, and delivery infrastructure, and assuming certain technical goals are met. This timeline is summarized in Table 2.

Assumed Potential Scenario for Hydrogen

Policy Context (General):

There is growing will to address climate change issues, and in the 2010 to 2030 timeframe, policies will be enacted at the regional and national level to regulate CO_2 emissions. Air pollution regulations will become increasingly strict in urban areas around the world. Security of energy supply will become an increasingly difficult issue, especially for the transportation sector. Energy policy in the United States will be guided by a continuing debate about the best way to achieve societal goals related to energy, environment and security. Policies to address GHG emissions, air pollutant emissions and national security will send a consistent, strong signal to consumers, vehicle manufacturers, and energy producers to encourage use of cleaner domestic fuels. Beyond 2030, international agreements will be in place to address GHG reductions, including carbon taxes or a carbon cap and trade system. GHG emissions and air pollutants will be strongly regulated in most parts of the world, including developing countries.

Policy Context (Hydrogen specific):
Over the next 10-20 years, vigorous government-supported RD&D programs on hydrogen and fuel cell technologies will be pursued in the United States, the European Union, and Japan, including local and regional demonstration projects, where national and local governments will act as early adopters of hydrogen and fuel cell technologies. Demonstrations of fuel cell buses will also occur in developing countries. Public/private partnerships will be a key aspect of the demonstrations. Policies to implement hydrogen will be enacted in island countries, and in urban areas with high air pollution emissions. Codes and standards for hydrogen will be established and harmonized throughout the world. Where appropriate, incentives may be put in place to support nascent hydrogen and fuel cell industries, including financial incentives for hydrogen vehicles and hydrogen fuel suppliers to reach commercial viability. Beyond 2030, national policies on hydrogen will be in place, including regulations to facilitate hydrogen infrastructure building.

Technology context: A range of hydrogen technologies will be tested and evaluated over the next 15 years. For hydrogen to go forward, a number of hurdles must be passed. The author makes the following assumptions: Hydrogen and fuel cells meet technical and cost goals for a variety of applications. A decision is made in the 2015-2020 timeframe to commercialize hydrogen fuel cell vehicles in light duty markets. Onsite hydrogen supply systems based on small-scale natural gas reformers and electrolyzers are commercialized. Enabling technologies for zero-emission hydrogen such as wind power, gasification technologies, and CO_2 sequestration appear in the electricity sector. Beyond 2030, there are further advances in zero emission hydrogen production technologies, and in hydrogen storage. Beyond 2050, a variety of low-cost, zero-carbon hydrogen production, storage and delivery technologies are available. Within the policy context described above, there is a business case for hydrogen and fuel cell technologies, when externalities are considered, leading to commercialization in the 2010-2030 timeframe, and profitable self-sustaining companies beyond this.

Development of a hydrogen energy system

Table 2 sketches a possible evolution for hydrogen markets and infrastructure over time. Beginning with today's chemical markets, hydrogen moves through a succession of niche applications, followed by heavy vehicles, bus and light duty fleet vehicle demonstrations, culminating with introduction into general transportation markets in 2015-2020. In parallel, fuel cell technologies are successful in distributed electric generation markets, providing heat and power in buildings. Over the next decade or so, hydrogen use begins in cities with poor air quality or other locations such as islands with multiple drivers for zero emission technologies and domestic fuels. Hydrogen infrastructure builds on the existing energy system at first, with distribution to early small demands by truck or mobile refueler, followed by onsite production and central production with pipeline distribution. There is a strong trend toward zero-emission supplies of hydrogen sources by 2030, as technologies (such as wind) move from the electric sector to hydrogen production. Between 2030 and 2050, hydrogen captures a growing fraction of vehicle markets, and is distributed to buildings. Regional distribution networks including hydrogen pipelines in cities are developed. Beyond 2050, there is general use of hydrogen in the energy sector, and a large suite of zero-carbon supplies and end-use options.

A No-Regrets Action Agenda

To set out a 50-year action agenda for hydrogen is immensely complicated by the uncertainties. The following "no regrets" actions with regard to hydrogen might be pursued over the next decade or so.

Hydrogen-specific actions over the next decade

- Strong support of RD&D on hydrogen technologies, especially fuel cells, zero-emission hydrogen production (including hydrogen from renewables and research on carbon sequestration) and hydrogen storage.

- Public/private partnerships that bring all the stakeholders together for demonstration of hydrogen technologies. The California Fuel Cell Partnership, the U.S. Department of Energy's FreedomCAR hydrogen program, Icelandic New Energy Ltd. , the European Union's CUTE project, and the United National Development Program demonstrations of fuel cell buses are examples of such efforts. Other regional public/private partnerships are under development worldwide.

- Federal and state governments play a role as early adopters of hydrogen technologies. This could involve demonstration of hydrogen technologies in government buildings and vehicle fleets over the next 5-10 years.

- Establishment of codes and standards for safe hydrogen operation in energy applications. Thus far, national and international standards organizations, industry and professional societies have been developing standards with support from the United States and other governments. The need for harmonized hydrogen codes and standards has been highlighted in the National Hydrogen Roadmap (2002) and in the recent National Academy study of the hydrogen economy (NAE 2004).

- Analysis to better understand the external costs of energy and role of hydrogen in the future energy system. As noted above, not all pathways for hydrogen production and use have the same full fuel cycle emissions of greenhouse gases and air pollutants, the same availability of primary resources or the same implications for security. There is a need for continued analysis and societal debate to understand alternatives for reducing societal impacts of energy, and hydrogen's role. (Or as David Greene posed this question, "Is hydrogen THE answer?") This point is emphasized in a recent report by the National Academy of Engineering on the Hydrogen Economy (NAE 2004), which suggested development of a systems analysis effort to understand the implications of hydrogen.

General Actions over the next 10-20 years.

- Development of a consistent national energy policy to address societal problems of climate change, air pollution and national security. This includes action on near-term technologies that could help address these problems now (such as energy efficiency and hybrid vehicles), and simultaneously developing hydrogen and other longer-term technologies that will be needed for deep cuts in carbon emissions.

- RD&D on efficient vehicle technologies with applications in a wide range of advanced vehicles (including hydrogen vehicles). These include electric drive train components being developed for hybrid vehicles, and advanced lightweight materials for vehicles.

- RD&D on clean energy technologies with applications in both electricity and hydrogen production. These include wind, solar, gasification technologies, CO_2 sequestration, and biomass energy.

How soon could hydrogen make a major difference in environmental and supply problems?

Even under a scenario of technical success, and strong policy, it will probably be 10-15 years before hydrogen energy technologies start to enter mass markets such as light duty vehicles. Given the time needed to bring hydrogen technologies to commercialization and the long time constants inherent in changing the energy system, most analysts do not see a major role for hydrogen in reducing emissions or oil use on a global scale for several decades. (Local benefits might be felt before this, if hydrogen is used in fleet vehicles in cities, for example.) Beyond 2025, most analysts agree that there is the possibility that use of hydrogen could make a large impact on reducing emissions (NAE 2004). In the mean time, as discussed in David Greene's contributing paper, many other effective approaches (such as higher efficiency vehicles) should be pursued both to address the energy-related problems in the near-term and to drive a long-term shift towards low-carbon energy carriers such as hydrogen. Implementing policies to encourage energy efficiency is not in competition with conducting RD&D on hydrogen: a comprehensive approach should include both near-term and long-term strategies. In fact, promoting energy efficient technologies is synergistic with long term use of hydrogen.

Hydrogen is potentially very important for our nation's energy future.[10] Hydrogen is one of the few widely available, long-term fuel options for simultaneously addressing energy security and environmental quality (including both deep reductions of greenhouse gases and pollutants).[11] Use of hydrogen could transform the ways we produce and use energy. But is future large-scale use of hydrogen a foregone conclusion? Although the potential is tremendous, in the author's view, it is still too early to tell exactly how large hydrogen's role will become over the next 50 years. While a large scale hydrogen economy by 2050 cannot be considered inevitable at this point, a vigorous program of RD&D on hydrogen can be considered a prudent insurance policy against the need to begin radical decarbonization of the fuel sector within a few decades, while simultaneously addressing energy security and pollution problems. Given the promise of hydrogen, the long lead time in accomplishing transitions in the energy system, and the challenges posed by hydrogen, it is important to provide significant support now, so that hydrogen technologies and strategies will be ready when needed.

Table 1. Primary Resources To Make H_2 For 100 Million Light Duty Vehicles in the US, Assuming H_2 Vehicles are 2-3 times as Efficient as Today's 20-30 mpg Gasoline Light Duty Vehicles (40-60 mpg equivalent).[12]

- **Natural Gas:**
  - Current U.S. NG use = 22 EJ/y
  - Projected NG use to make H_2 for 100 million light duty vehicles, if H_2 is made at 80% conversion efficiency
    = 3.8-5.7 EJ/y **(17-26% of total NG use today)**
- **Coal:**
  - Current U.S. coal use = 20 EJ/y
  - Projected coal use for 100 million light duty vehicles, if H_2 is made at 65% conversion eff. = 4.7-7.0 EJ/y **(23-35% of total coal use today)**
- **Biomass:**
  - Current cropland = 1.7 million km^2;
    rangeland + pasture = 2.25 million km^2;
  - biomass production = 15 dry tonnes/y/hectare; 1 dry tonne = 18 GJ;
  - Land for biomass for H_2 (at 60% biomass → H_2 conv. Eff.)
    = 0.19-0.28 million km^2 **(8-13% of current range and pastureland)**
- **Wind:**
  - U.S. wind power potential > 10,000 billion kWh, from resources > class 3.
  - At 75% electrolysis efficiency, **11-17% of good to excellent wind resources** would be needed for H_2
- **Off-peak power used in 75% efficient electrolyzers:**
  35-53% of total U.S. installed electric capacity, used 12 hours per day

1 EJ = 1 Exajloule = 10^{18} Joules (the U.S. uses about 100 EJ/year of primary energy)

These are values that would be needed if all the hydrogen is made from one resource only.

References:

Burns, L, McCormick, J, and Borroni-Bird, C, “Vehicle of change,” Scientific American Vol. 287, No. 4,:pp. 64-73, 2002.

Directed Technologies, Inc., Air Products and Chemicals, BOC Gases, The Electrolyser Corp., and Praxair, Inc., prepared for Ford Motor Company Under USDOE Contract No. DE-AC02-94CE50389, Purchase Order No. 47-2-R31148, “ Hydrogen Infrastructure Report,” July 1997.

Energy Information Administration, “Energy Outlook with Projections to 2025,” United States Department of Energy, 2003.

E. Farrell, D. W. Keith and J.J. Corbett, “A Strategy for Introducing Hydrogen into Transportation,” preprint, to appear in Energy Policy 2004.

Ford Motor Company, "Direct Hydrogen Fueled Proton Exchange Membrane Fuel Cell System for Transportation Applications: Hydrogen Vehicle Safety Report,” Contract No. DE-AC02-94CE50389, May 1997.

General Motors Corp., Argonne National Laboratory, BP, ExxonMobil, and Shell, “Well to Wheels Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems: North American Analysis, Executive Summary Report,” April, 2001.

Kurani, K., T. Turrentine, R. Heffner, and C. Congleton, “Prospecting the Future for Hydrogen Fuel Cell Vehicle Markets,” to appear in Hydrogen Transitions, ed. D. Sperling and

J. Cannon, the Proceedings of the 9th Biennial Conference on Transportation and Energy, Asilomar, California, July 30-August 1, 2003.

Linney, R.E. and J. G. Hansel, “Safety Considerations in the Design of hydrogen-powered vehicles,” Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, June 23-28, 1996, pp. 2159-2168.

M. Mintz et al, "Hydrogen: On the Horizon or Just a Mirage?" Society of Automotive Engineers paper No. 02FCC-155, 2002.

Mintz, M. (Argonne National Laboratory), and M. Singh (Oak Ridge National Laboratories), private communications, 2003.

D. Myers, G. Ariff, B. James, R. Kuhn, “Hydrogen from Renewable Energy Sources: Pathway to 10 Quads for Transportation Uses in 2030 to 2050,” Task 3, draft report to the USDOE. Hydrogen Program Office, under grant No. DE-FG01-99EE35099, February 2003.

National Academy of Engineering and the Board of Energy and Environmental Systems, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Academy Press, Washington, DC, 2004.

Ogden, J., "Prospects for Building a Hydrogen Energy Infrastructure," Annual Review of Energy and the Environment, Vol. 24, pp. 227-279, 1999.

J. M. Ogden, M. Steinbugler and T. Kreutz, "A Comparison of Hydrogen, Methanol and Gasoline as Fuels for Fuel Cell Vehicles," Journal of Power Sources, vol. 79, pp. 143-168, 1999.

Ogden, J.M. "Modeling Infrastructure for a Fossil Hydrogen Energy System with CO_2 Sequestration, "Proceedings of the GHGT-6 Conference, October 2002, http://www.rite.or.jp/GHGT6/.

J.M. Ogden, "Where Will the Hydrogen Come From? Systems Considerations and Hydrogen Supply," to appear in Hydrogen Transitions, ed. D. Sperling and J. Cannon, the Proceedings of the 9th Biennial Conference on Transportation and Energy, Asilomar, California, July 30-August 1, 2003.

Ogden, J.M., R.H. Williams and E.D. Larson, 2004, "A Societal Lifecycle Cost Comparison of Alternative Fueled Vehicles, Energy Policy, Vol. 32, pp. 7-27.

J. T. Ringland et.al. "Safety Issues for Hydrogen-Powered Vehicles," Sandia National Laboratories, March 1994.

Thomas, C.E., I.F. Kuhn, B.D. James, F.D. Lomax, and G.N. Baum, "Affordable hydrogen supply pathways for fuel cell vehicles," International Journal of Hydrogen Energy, v. 23, No. 6, 1998.

Thomas, C.E., B.D.James, F.D. Lomax, and I.F. Kuhn, 1998b: Draft Final Report, *Integrated Analysis of Hydrogen Passenger Vehicle Transportation Pathways*, report to the National Renewable Energy Laboratory, U.S. Department of Energy, Golden, CO, Under Subcontract No. AXE-6-16685-01, March.

C.E. Thomas, H2Gen Innovations, private communications, 2003.

United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen Fuel Cells, and Infrastructure Technologies Program, website, 2003. http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/

United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen Fuel Cells, and Infrastructure Technologies Program, website, 2003. http://www.eere.energy.gov/hydrogenandfuelcells/

Wang, M.Q., 1999a: GREET 1.5 – Transportation Fuel-Cycle Model, 1, Methodology, Development, Use and Results, Report No. ANL/ESD-40, Center for Transportation Research, Argonne National Laboratory, prepared for the Office of Transportation Technologies, U.S.Department of Energy, Washington, DC, December.

Wang, M., "Fuel choices for fuel cell vehicles: well-to-wheels energy and emission impacts," Journal of Power Sources, Vol. 112, pp. 3017-321, 2002.

Weiss, M., J. Heywood, E. Drake, A. Schafer, and F. AuYeung, 2000: On the Road in 2020, MIT Energy Laboratory Report # MIT EL 00-003, Cambridge, MA, October

Wigley, T.M.L., R. Richels, and J.A. Edmonds. 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations." Nature 379(6562):240-243.

Williams, R.H., "Decarbonized Fossil Energy Carriers And Their Energy Technological Competitors," Prepared for the IPCC Workshop on Carbon Capture and Storage, 18-21 November 2002, Regina, Saskatchewan, Canada.

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[1] This is often discussed as 450-550 parts per million CO_2 concentration in the atmosphere. (Wigley et al. 1996)

[2] Hydrogen can be used in internal combustion engine vehicles with high efficiency, zero emissions of greenhouse gases and low air pollutant emissions. When hydrogen is burned in air the only air pollutant is NO_x, which can be controlled to low levels. Hydrogen ICE hybid electric vehicles (ICE/HEVs) can be almost as efficient as hydrogen fuel cells. Efficiency of a hydrogen ICE/HEVis typically 80% that of a comparable hydrogen FCV (Thomas et al. 1998).

[3] Well to wheels or "full fuel cycle" emissions refer to all the emissions involved in producing and using a fuel including: primary feedstock extraction, transport of the feedstock to a fuel production plant, fuel production, storage and distribution of fuel, and use of the fuel (for example, in a vehicle). For an excellent description of well to wheels emissions see Wang (1999)

[4] Hydrogen can be used with 2-3 times the efficiency of today's gasoline vehicles in fuel cell vehicles (see endnote vi below). Even though hydrogen is more costly than gasoline ($2-3.5/kg delivered), it might be used with similar fuel costs per mile to today's vehicles.

[5] As with any hydrogen end-use technology, the degree to which H_2 ICEs will be "zero-emission" on a well to wheels basis will largely depend on the source of the primary energy used to make the hydrogen.

[6] Efficiencies for hydrogen vehicles as compared to internal combustion engine vehicles have been modeled in (Thomas et al. 1998, Weiss et al. 2000, GM et al. 2001). These studies indicate that the energy efficiency of a hydrogen fuel cell vehicle might be 2-3 times that of today's gasoline vehicles, or

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about 40-60 miles per gallon equivalent on an energy basis. Some studies (Thomas et al. 1998, Weiss et al. 2000) have projected even higher fuel economies for advanced lightweight hydrogen vehicles.

[7] There is a question whether local air pollution concerns will drive a push towards hydrogen or whether evolution of conventional pollution control vehicle technologies (e.g. SULEVs) will be sufficient to address such concerns. In particular, there is a question whether Diesel hybrid will reach SULEV standards and high fuel economy to give a similar combination of environmental benefits as H_2 FCVs

[8] Despite rapid progress and promising results, there is still uncertainty in the future cost and performance of hydrogen technologies (How soon and how well will hydrogen vehicles meet their goals? How much will hydrogen from zero emission sources cost?) and in understanding possible new markets for hydrogen driven by new products or services like mobile electricity.

It is uncertain how soon and where policies will be enacted to address the external costs of energy (not only greenhouse gases but also air pollutants and national security), and what this will mean for hydrogen demand. Integrated assessment models suggest that within a few decades we will need to start dramatically reducing GHG emissions from the energy supply. There is a growing body of analysis on the lowest cost ways to do this. However, the best timing for radical decarbonization of the fuels sector and the potential for energy efficiency and alternative fuels to contribute are still unknown. The fact that hydrogen offers strong multiple benefits complicates the question of timing, as GHG reduction is not the only driver for hydrogen.

Depending on the location, a hydrogen transition will happen in different ways and at different times There is no one solution for designing a hydrogen infrastructure or a hydrogen transition that is preferred under all conditions. The most attractive option in terms of cost and/or emissions depends on a complex set of factors related to the size and type of demand, technology progress, the availability of resources for hydrogen production, and existing infrastructure.

The current lack of knowledge about future demand and markets for hydrogen energy makes it difficult to make projections about the timing for using various hydrogen supply options. Future hydrogen demand scenarios that have appeared in recent years vary widely, projecting between 1% and 100% hydrogen use in transportation by 2050 (EIA 2003, Mintz 2003).

[9] Of course, the scenario described in Table 2 is only one possible future. The author does not consider futures where hydrogen technologies are unsuccessful as hydrogen energy use would be minimal in this case, or only partly successful (see Greene). Nor does the author consider futures where society does not muster the will to address external impacts of energy, although it is conceivable that market pull for new products might lead to large markets for hydrogen even in that situation.

[10] The author's views are similar to those voiced by the National Academy of Engineering about the potential importance of hydrogen to the nation's energy future (NAE 2004).

[11] Near-term technologies (such as hybrid internal combustion engine vehicles using conventional fuels) could provide some level of these benefits sooner and at a lower cost, while hydrogen technologies are being developed. But ultimately, greater emissions reductions from fuels use will likely be needed to achieve societal goals. The long-term contenders for deep emissions reductions in the transport sector are vehicles using renewable biofuels, electric batteries or and hydrogen. Biofuels could potentially give net zero carbon emissions well to wheels (assuming that fossil fuels now used in cultivation, fertilizers or harvesting were replaced with renewable substitutes), but availability of resources, land-use constraints and environmental concerns might limit their use on a global scale. Battery-powered electric vehicles using renewable electricity would offer similar environmental advantages to hydrogen vehicles, but battery costs, recharging time, and range are issues.

[12] NG, Coal, Biomass energy use is from the EIA Annual Energy Outlook. Wind potential is from Myers et al. 2003. H_2 use is calculated for this paper.

Table 2. Context for hydrogen transition, and possible timeline for a hydrogen transition

CONTEXT FOR TRANSITION			
	2010-2030	**2030-2050**	**>2050**
POLICY CONTEXT **General**	**GHG Emissions Policy** U.S. National Debate ⇒ State and Regional Policy ⇒ National Policy **Air pollution regulation, increasingly stringent, zero-emission technologies** State and Regional Policies ⇒ National Policy **International Regulations on GHG in several -countries** **National energy security concerns ⇒ Policies encouraging domestic fuels** **Consistent energy policy including RD&D on key technologies for energy future** RD&D on range of energy technologies including H2 and enabling technologies like CO_2 seq, wind power **Ongoing debate: which energy alternatives best achieve societal goals**	Increased regulation of GHG worldwide; Broader International agreements on GHG reductions, carbon taxes or cap and trade; Developing country regulations on GHG and pollution; National security concerns encourage use of diverse, secure primary supplies	Regulations on GHG, air pollutants in place worldwide; National security concerns remain important
H_2 specific	Vigorous RD&D programs on H_2 and FC technologies in U.S., EU, Japan; Local and Regional H_2 demonstration projects; Federal and state government early adopter fleets and buildings use H_2. Regional policies to implement hydrogen in urban areas and island countries (Iceland); Public/private partnerships facilitate cooperation between stakeholders; H_2 codes and standards established by 2010; Support nascent high tech H_2 and FC industries; Financial incentives for H_2 vehicles and H2 fuel suppliers to bring to commercial viability; Tax incentives for H_2 fuel.	National policies to use H_2	
TECHNOLOGY CONTEXT	H_2 fuel cells meet durability and performance goals ⇒ H_2 FCs meet cost goals Hybrid electric vehicles provide basis for FCV developments H_2 storage goals met for vehicles with incremental improvements Small-scale reformers and electrolyzers successfully commercialized Geological CO_2 sequestration successfully demonstrated Wind power costs reduction	Advanced renewable, fossil w/CO2 seq. and/or nuclear H_2 production option successful; Advanced onboard H_2 storage systems using metal hydrides or lower energy use liquefaction	Variety of efficient, low cost H_2 production, storage delivery technologies available
BUSINESS CONTEXT	H_2 end-use technologies are proved viable and move to commercialization; low- cost, zero emission production technology proves viable; establish coordination among fuel suppliers, vehicles suppliers and users, and governments; H_2 and fuel cells enable new products and services	H_2 and FC businesses self-sustaining	H_2 and FC businesses include well established players in energy field.

MARKETS AND INFRASTRUCTURE DURING TRANSITION

	2010-2030	2030-2050	>2050
H_2 MARKETS Industrial Vehicles Buildings/ Sta. Power	Oil Refining; Chemical Aerospace and military; Niche Electric vehicles; Battery replacement Demonstration Fleets Controlled small fleets ⇒ Larger fleets ⇒ General vehicle intro (2005-2009) (2009-2015) (market intro 2015-2020) Heavy vehicles (buses, ships) Fuel Cell Cogeneration, possibly with hydrogen co-production	Centrally refueled fleets and public use in automobiles; H2 FCVs capture significant fraction of light duty vehicle market Hydrogen distribution to buildings/commercial/industrial sector?	General use of H2 in energy sector
Production/ Primary Supply	Excess capacity existing H2 infrastructure Steam reforming of natural gas; Partial oxidation of oil; coal gasification; electrolysis; CO2 sequestration demos; Renewable H2 demos;	Fossil with CO2 sequestration; electrolysis powered by zero emission electricity; Biomass gasification Adv. renewable demos Adv. nuclear demos	Fossil with CO2 sequestration; electrolysis powered by zero emission electricity; Biomass gasification; advanced renewable or nuclear
Delivery Infrastructure	Delivery by truck; Mobile refuelers; ⇒ onsite production via steam reforming or electrolysis ⇒Pipelines; Infrastructure design site specific; progression from truck delivery to onsite production to central production to use of renewable sources.	Development of regional networks of hydrogen fueling systems, including pipelines in some cities; interaction with electricity system begins; developing country applications	National networks for hydrogen energy; New paradigm for energy production and use; H2 integrated with rest of energy system
Where Will H_2 Be Used?	Local and Regional H2 demonstration projects ⇒ small networks in a few cities	Citywide or regional networks; island H_2 systems	National network in large countries like US and in developing countries

Delivered Cost of H_2 (\$/kg H_2)

\$1/gallon gasoline - \$1/kg