The Hydrogen Potential:
Hydrogen Technology and Minnesota Opportunities

Minnesota Department of Commerce, State Energy Office

MINNESOTA
DEPARTMENT OF
COMMERCE

This report is one part of a multi-faceted effort by the State of Minnesota to tap the potential of hydrogen. It is a primer to educate Minnesotans about the background, possibilities, and issues facing hydrogen development in our state.

This is an exciting time to be involved in energy policy in Minnesota. Not only is Minnesota home to some of the best wind energy and bio-fuels resources in the nation, we are home to an incredible amount of quality human capital in our business, academic, government, and non-profit communities. Over the past decade, Minnesota has been a national leader in developing our wind energy and bio-fuels resources and also a national leader in energy efficiency.

A key potential of our long-term energy future centers on hydrogen. As you'll read in the following report, hydrogen is the most abundant natural element in the world and is already being used in a host of applications. Significant time and energy is being invested in developing hydrogen for energy applications, both for power generation and transportation.

In 2003, Governor Pawlenty signed into law an energy bill. Language included in this bill formally states that Minnesota move to hydrogen as an increasing source of energy for our electrical power, heating and transportation needs. This same law also provided the University of Minnesota with millions of dollars for hydrogen research and development.

Hydrogen development and use will help our state in many ways. It could significantly reduce the environmental costs associated with generation and transportation from traditional fossil fuels while creating additional markets for Minnesota's wind and bio-fuels resources. This will keep Minnesota's energy dollars in our state for direct investment in our quality of life.

Minnesota can be a leader in leveraging our indigenous wind and bio-fuels resources to tap the hydrogen potential. In the past year, the State of Minnesota helped spearhead the creation of the Minnesota Renewable Hydrogen Initiative which is bringing together business, government, academia, and non-profits to discuss how our independent strengths can be woven together to create the foundation for a hydrogen economy in Minnesota.

I hope you find this a helpful document as you develop your thoughts on an important component of Minnesota's energy future.

Sincerely,

Glenn Wilson
COMMISSIONER

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INTRODUCTION

HYDROGEN IS ALL AROUND US

Hydrogen is the lightest, most abundant element on earth and makes up approximately 75% of the mass of the universe and 90% of its molecules. Yet, hydrogen isn't readily found by itself, but needs to be freed from other molecular structures, such as water, biomass or petroleum based products, to be used as an energy carrier. Energy carriers transport the energy garnered from an energy source from one place to another. Electricity and gasoline are common examples of energy carriers.

As such, hydrogen can be harvested from many common substances, from natural gas, coal, gasoline, ethanol and methanol (wood alcohol) to methane, biomass and water. However, extracting it requires significant energy in the form of heat, light or electricity. Among the most environmentally benign ways to produce hydrogen is to use a renewable form of energy, such as wind, to split water into its constituent parts – oxygen and hydrogen – in a process called electrolysis.

In addition to its abundance, hydrogen can be used in a number of applications. As an energy carrier, hydrogen can be used for stationary generation of electricity, work like a battery on appliances, or be used to fuel vehicles.

CURRENT USES FOR HYDROGEN

The idea of using hydrogen for energy is not new. Hydrogen was first discovered around the end of the 15th century. It took another 200 years to classify and describe it. But as early as 1923, John Burden Sanderson Haldane gave a now famous lecture at Cambridge University in which he predicted an eventual wind-to-hydrogen energy system. Hydrogen has been used since the late 19th century, when people burned a mixture of hydrogen and carbon monoxide called "town gas." Several countries still distribute this fuel.

The 9 million tons of hydrogen produced annually today are used mainly to make fertilizer, dyes, drugs, electronics and plastics; to hydrogenate oils and fats; and as a fuel for welding. Hydrogen is also used to make gas from coal and to produce methanol. In its super-cooled liquid form, hydrogen powers unmanned rockets and the space shuttle, and is used onboard in alkaline fuel cells that provide astronauts with electricity and potable water.

Today, fuel cells are on the verge of being an economically viable technology for much wider public application as designs improve and unit production costs decrease. NASA has used hydrogen-powered fuel cells to provide electricity and drinking water to astronauts since the 1960s, and the U.S. Department of Defense has called fuel cells a critical technology. Fuel cells are in use at more than 200 military bases, hospitals and office buildings around the world, including an early cold weather demonstration model at Fort Snelling.

In the future, hydrogen can be used for anything that requires energy, including buildings and industrial processes, vehicles and portable uses such as laptops and cell phones. Fuel cells powered by hydrogen derived from domestically produced renewable energy sources have the potential to make the United States an energy independent nation.

HYDROGEN INFRASTRUCTURE

Clearly as the uses for hydrogen increase, the production and distribution system will need to increase as well. However, we currently do not have the hydrogen production capacity or distribution system to match that of gasoline. While we currently have the technology to convert today's internal combustion engines to use hydrogen fuel (as is commonly done for propane and natural gas powered vehicles) we don't have convenient access to hydrogen for refueling. These examples highlight the disconnect that exists between hydrogen's potential uses and the infrastrcture that can make that potential a reality.

When discussing infrastructure, hydrogen safety concerns come to the forefront. The Hindenberg Zepplin accident in 1937 created a number of misconceptions about hydrogen. In actuality, the great fire was caused by the airship's cotton skin that was coated in a flammable material, and not the hydrogen inside, which rapidly flamed and dispersed upward. The majority of deaths in the accident have now been attributed to those who jumped from the ship, versus those who rode the ship to the ground.

Many experts consider hydrogen a safer fuel than gasoline, which as a highly flammable and volatile liquid, flows under a vehicle as it burns. In terms of public health, vapors from gasoline are a known carcinogen. Hydrogen is nontoxic.

PUBLIC POLICY INFLUENCES

The Federal government has shown significantly increased support for developing hydrogen's potential. President Bush discussed the commitment of federal dollars to develop a hydrogen fueled Freedom Car and the importance of moving to increased use of hydrogen fuels with a vision of today's children driving hydrogen powered vehicles 20 years from now. In late 2002, U.S. Energy Secretary Spencer Abraham told business leaders, "The hydrogen economy is within sight," as he unveiled the National Hydrogen Energy Roadmap, charting the course toward a clean, reliable, affordable domestic energy system.

A number of states, including Minnesota (MN Session Laws 2003, 1st Special Session, Chapter 11), have goals and provide monetary support for research and programs that support a hydrogen energy development.

As the potential for hydrogen's energy uses become more real, the role of public policy makers becomes more important. Policymakers get to shape and choose what hydrogen-related issues get attention and which are left to others. They also get to choose from a broad menu of issues. These issues include support for research at state universities, creating markets for hydrogen powered fuel cells, what fuel inputs should create hydrogen, and what aspects of hydrogen development and use best support current economic development needs.

To help Minnesota take advantage of the opportunities hydrogen offers, this initial report will focus on the following issues:

- What is hydrogen and how can it be used to address our national and state electric generation and transportation-related energy issues?
- What infrastructure challenges do we face in moving towards greater reliance on hydrogen as an energy carrier?
- What international and national public policy modifications are being considered to assist hydrogen infrastructure and market development?
- What are the implications of a hydrogen based energy system in Minnesota?

The states that best match their inherent strengths with the emmerging growth in hydrogen use and production will improve their economies, natural environments, and quality of life in ways that will significantly impact life in those states for generations to come.

PRESIDENT WANTS U.S. TO LEAD TRANSITION TO CLEAN HYDROGEN

President George W. Bush, 2003 State of the Union.

"I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles.

A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car – producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."

PRODUCING AND USING HYDROGEN

Producing hydrogen from either hydrocarbons, water, or biomass is energy intensive. For example, the process of reforming natural gas into hydrogen requires 1.2 to 1.4 units of energy for every one unit of hydrogen energy.

HYDROGEN CAN BE DERIVED IN FIVE MAIN WAYS:

1 **Steam reforming**. In the U.S., roughly 95 percent of today's hydrogen is produced by reforming natural gas. Steam reforming uses heat to separate hydrogen from the carbon components in methane and methanol, exposing these fuels to steam on catalytic surfaces at temperatures of 392°F or higher.

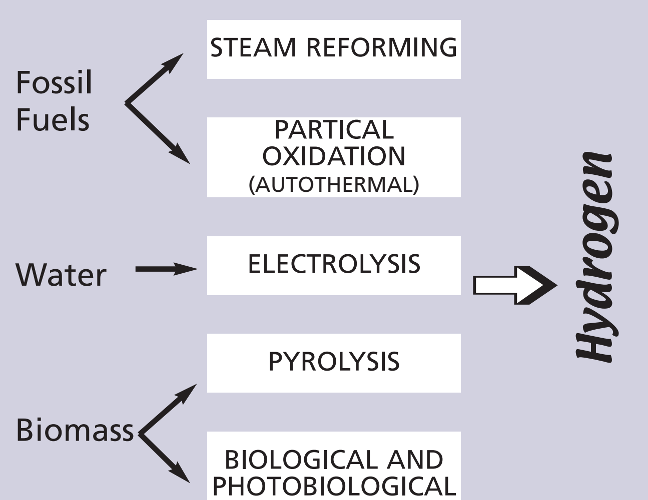
Steam reforming of natural gas does produce some carbon dioxide, a key greenhouse gas, but 99.5 percent of the natural gas consumed in the U.S. is produced in either the United States or Canada, so using it to produce hydrogen would contribute to greater energy independence. Steam reforming is the most energy efficient, commercialized technology at present.

2 **Partial oxidation.** This process involves reacting a fossil fuel with a limited supply of oxygen to produce a hydrogen mixture, which then requires further purification. It generally has a higher capital cost because it demands pure oxygen.

3 **Electrolysis.** Electrolysis has been around for a long time. It separates hydrogen from water by running an electrical current through it. It takes 478 British Thermal Units of electricity (.14 kilowatt-hours) to produce 319 BTUs (or one standard cubic foot) of hydrogen. Put another way, 1 kilowatt-hour of electricity produces 7 cubic feet of hydrogen gas.

The electricity can come from any source, through renewable energy sources, such as wind, photovoltaics, biomass or hydro-power would be the cleanest. Electrolysis is currently not as efficient or cost effective as using fossil fuels to derive hydrogen, and is not practical when using conventional grid electricity, since that is generated at a 30 percent efficiency. However, it could become cost competitive where low-cost power is available (around 1 to 2 cents per kilowatt hour).

HYDROGEN PRODUCTION OPTIONS



4 **Biomass gasification and pyrolysis.** Pyrolysis refers to the chemical decomposition of a substance by heat. This can be done with relatively low temperatures to nearly any type of organic matter (biomass) to produce hydrogen. Hydrogen can also be produced using higher temperatures, by turning these same materials into a gas. Sources of biomass include wood chips, and other forest and agricultural wastes.

5 **Biological and photobiological processes.** The natural photosynthetic activity of bacteria and green algae also produces hydrogen, as does the fermentation of sugars. For example, researchers at the University of Wisconsin in Madison have developed a process that produces hydrogen from glucose, found in everything from corn starch and sugar beets to cheese whey and paper mill sludge.

THE COST OF PRODUCING HYDROGEN

	$ per gigajoule
Hydrogen from coal/gas/oil	*1-5*
Hydrogen from natural gas minus carbon dioxide	*8-10*
Hydrogen from coal minus carbon dioxide	*10-13*
Hydrogen from biomass	*12-18*
Hydrogen from nuclear power	*15-20*
Hydrogen from onshore wind	*15-25*
Hydrogen from solar cells	*25-50*

Note: A gigajoule is a measure of heat. One gigajoule = 948,200 BTUs
Source: International Energy Agency, February 2003

SAFETY CHARACTERISTICS OF HYDROGEN

Like natural gas, hydrogen is odorless and colorless. It is the lightest element on earth and about 14 times less dense than air. As with any other fuel, hydrogen poses risks if not properly handled, but those risks must be compared to existing fuels such as gasoline and natural gas.

Hydrogen has the smallest molecule of any element and therefore is more susceptible to leaking through tiny openings. For example, from low-pressure fuel lines hydrogen might leak at a rate 1.26 to 2.8 times faster than natural gas through the same hole. Hydrogen is more flammable than gasoline and propane, but less flammable than natural gas. In the event of a leak, hydrogen will rise faster and disperse more quickly than any other fuel. It therefore poses less of a hazard.

Unlike a gasoline fire in a conventional auto crash, a hydrogen fire would likely burn around people rather than cling to them. Nearby materials and people would be much less likely to ignite or be hurt by radiant heat. While fumes and soot from a gasoline fire pose a risk to anyone inhaling the smoke, hydrogen fires produce only water vapor unless surrounding materials begin to burn.

A hydrogen explosion is possible, but only under very unusual circumstances. To blow up, hydrogen would have to reach a concentration of 13 percent in a closed space, and only then have an ignition source triggered. If there were an explosion, hydrogen is pound-for-pound the least explosive of any fuel, and is 22 times less explosive than the same volume of gasoline vapor.

A hydrogen flame is nearly invisible, so that people nearby may not even know there is a fire. While this characteristic might pose a danger, it could be solved by adding some chemicals to make the hydrogen flame more visible, much like chemicals are added to natural gas to give it a detectable odor.

Hydrogen poses roughly the same risks as existing fuels. In fact, it is actually a safer fuel than gasoline and natural gas in many ways. But when people think of hydrogen they often think of the Hindenburg dirigible that burst into flames. It turns out that hydrogen was not to blame for the Hindenburg's demise. According to research by NASA scientist Addison Bain, the ship's shell was coated with a close cousin of rocket fuel which ignited and caused the fire. The hydrogen did burn, but because it is so light, it quickly dispersed.

A study commissioned by Ford Motor Company evaluated the probabilities and risks of the most likely hydrogen accidents and concluded that a catastrophic event is highly unlikely. The study also found that in a common open air car collision, a hydrogen fuel cell car should pose less potential danger than either a natural gas or gasoline vehicle. In a tunnel collision, a hydrogen fuel cell vehicle should be nearly as safe as a natural gas vehicle, and both should be potentially less hazardous than a gasoline or propane vehicle.

The greatest potential risk to the public appears to be a slow leak in an enclosed home garage, when an accumulation of hydrogen could lead to fire or explosion if there were no detection or ventilation system in place.

Misperceptions about the safety of hydrogen will need to be overcome if there is to be widespread public acceptance of it. The same fears arose when light bulbs and natural gas were first introduced. The development of public education campaigns, codes and safety standards, field tests and demonstrations will influence public confidence in this technology as they have for previous innovations.

HYDROGEN STORAGE

Hydrogen is already stored and shipped regularly both as a gas and as a liquid. Compared to storing large amounts of electricity, storing hydrogen is relatively easy, though each storage option comes with challenges.

Storing Hydrogen in gas form. In addition to being the most abundant element on earth, hydrogen also has a very low density. This means it is bulky and the only way to store very much of it as a gas is to compress it under very high pressure. High pressure storage in ultra-strong gas tanks is the most advanced storage technology today. QUANTUM Technologies' TriShield composite cylinders can hold up to 3 kilograms (6.66 pounds) of hydrogen at 5,000 pounds per square inch (psi), enough to take a standard sedan about 200 kilometers (125 miles), which the U.S. Department of Transportation says represents about 85 percent of all car trips in the United States. The California Fuel Cell Partnership is demonstrating the tanks in a Hyundai Santa Fe sedan while San Diego is testing a larger version of the tank on a fuel cell bus. QUANTUM Technologies has also developed a tank that can withstand 10,000 psi, but that version awaits certification based on the German Pressure Vessel Code, the most recent and comprehensive standard for hydrogen related components.

In addition to pressurized tanks, large amounts of hydrogen gas could conceivably be stored in caverns, gas fields and mines, then piped to individual homes and businesses the way natural gas is today.

Storing Hydrogen as a liquid. Lawrence Livermore National Laboratory in California is exploring the storage of hydrogen as a liquid in cryogenic vessels for use in vehicles, allowing more hydrogen to be stored in much less space. Five kilograms (11 pounds) of liquid hydrogen used in a high efficiency fuel cell or internal combustion engine could offer a 600 kilometer (375 mile) driving range.

But turning hydrogen into its liquid form means cooling it to -423ºF, which requires 25 to 30 percent of its total energy content. Another drawback is that liquid hydrogen evaporates under low pressure and can only be kept in liquid form at extremely low temperatures inside cryogenic containers. Livermore Laboratory is addressing these barriers by developing highly insulated containers that could use regular compressed hydrogen for short tips and super cold liquid hydrogen for long trips.

HYDROGEN STORAGE ALTERNATIVES

COMPRESSED FUEL STORAGE
- *Cylindrical tanks*
- *Quasi-conformable tanks*

LIQUID HYDROGEN STORAGE
- *Cylindrical tanks*
- *Eliptical tanks*

SOLID STATE CONFORMABLE STORAGE
- *Hydride storage material*
- *Carbon Adsorption*
- *Glass microspheres*

Source: QUANTUM Technologies

Storing Hydrogen in solid state hydrides. Hydrides are chemical compounds of hydrogen and other materials. Chevron Texaco Ovonic Hydrogen Systems is studying the potential for using certain alloyed metals as a storage medium for hydrogen and expects to have a demonstration vehicle on the road by 2003. These alloys are known as metal hydrides. Hydrogen becomes chemically bonded to them and requires heat to release it, such as the waste heat from fuel cells.

The two main benefits of this approach are safety and space. There would be nothing to explode in a crash and metal hydrides can hold 5 kilograms (11 pounds) of hydrogen in one-third the space required for gaseous hydrogen in a 5,000 psi tank. Perhaps the biggest drawback is that metal hydrides are heavy for the amount of hydrogen they carry, which cuts into their fuel efficiency.

Research is also underway on methods of storing hydrogen chemically in tiny carbon structures called nanotubes and in glass microspheres, but these techniques are a long way from full development.

In the future, there will likely be a wide variety of cost competitive storage devices, from pocket-sized containers for laptops and other portable devices, medium-sized containers for vehicles and on-site power systems, and indus-

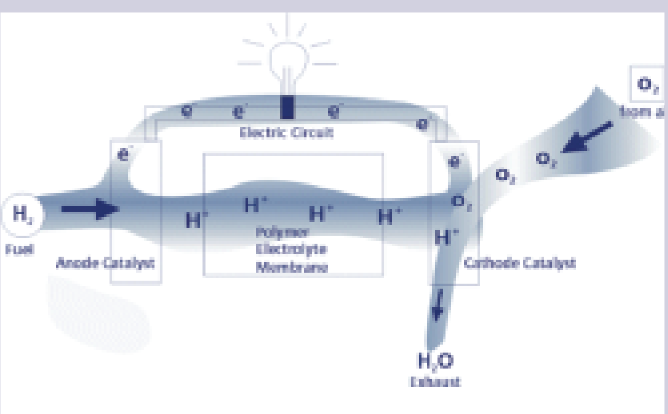
USING HYDROGEN IN FUEL CELLS

Fuel cells create energy not by burning anything, but through an electrochemical reaction between hydrogen, oxygen and a catalyst. Nine different types of fuel cells are under development, each characterized by the electrolyte they use, their operating temperature and the purity of hydrogen they require. These differences make some types better for certain uses than others.

Fuel cells have no moving parts and are nearly silent. They are roughly twice as efficient as traditional internal combustion engines running on gasoline. This is because electrochemical processes are inherently more efficient at capturing the energy in hydrogen. Fuel cells produce energy at about a 35 to 50 percent efficiency rating, and are better than 85 percent efficient when used in situations where both the fuel cell's heat and electric power are used.

The phosphoric acid fuel cell is most developed for commercial applications, and is currently used in buildings and to power large vehicles such as transit buses. Proton Exchange Membrane (PEM) fuel cells appear to be the fuel cell of choice for car manufacturers, and are also being pilot tested in buildings and portable appliances and electronics.

Eventually, fuel cells could be mass-produced for use in everything from homes and computers to wheelchairs, cars and buses.



trial-sized storage technologies for community power parks and utility-scale systems.

CONVERTING HYDROGEN INTO USEFUL ENERGY

Hydrogen can be used for anything that fossil fuels are used for. It can be burned like gasoline or natural gas in internal combustion engines, blended with conventional fuels, or it can be combined with oxygen in a fuel cell to produce heat, electricity and water.

At 52,000 British Thermal Units per pound, hydrogen has the highest energy content by weight of any fuel and is vastly cleaner than burning traditional fossil fuels since water is the main byproduct. An engine burning pure hydrogen produces only water and small amounts of nitrogen oxides and there are no carbon dioxide emissions.

Research continues on using hydrogen as a blend with other traditional fuels as a transition to 100 percent hydrogen use. Adding just 5 percent hydrogen to a tank of gasoline would increase its energy content and reduce nitrogen oxide emissions by 30 to 40 percent. Hydrogen can also be blended with natural gas, up to 20 percent, increasing BTU content. This could be a near term use for early hydrogen production.

USING HYDROGEN TO PRODUCE ELECTRICITY

Hydrogen use in stationary applications that replace traditional battery technology, or grid electricity are likely to be the first applications to overcome the challenges presented by hydrogen fuel. Stationary applications don't have nearly as many obstacles as vehicle applications, and small, portable fuel cells that replace batteries are going to be cost-competitive much sooner than fuel cells that replace engine technologies.

PORTABLE USES FOR HYDROGEN

Companies are also developing fuel cells that can power cell phones, laptops, personal digital assistants and other portable electronics. However, as fuel cells shrink in size their engineering challenges increase. Designers must balance adequate power and convenient refueling while keeping size and cost down. As with fuel cells generally, mass producing them at a low enough cost is the largest remaining barrier to widespread use.

Lawrence Livermore National Laboratory in California has developed a new thin-film fuel cell that will last three times longer, be 50 percent less costly, and 30 percent lighter and smaller than conventional rechargeable batteries. The fuel cell relies on easily replaceable fuel cartridges of concentrated methyl alcohol.

Medis Technologies has developed Direct Liquid Fuel Cell technology that extracts hydrogen from either methanol or ethanol. The cartridge would last up to 20 hours, provide more than twice the power of standard cell-phone batteries and cost about $1. The company expects to focus on ethanol as the base fuel since it is more stable than pure hydrogen and less toxic than methanol. They expect to enter the laptop and cell phone market by 2004.

As quoted in *Scientific American,* editor of *International Journal of Power Sources,* Christopher Dyer predicts that micro fuel cells will "make inroads into markets now dominated by batteries within the next five years," or three years if key breakthroughs come sooner. Indeed, methanol or ethanol fuel cells used in portable applications are likely to be the first type most consumers encounter.

Fuel cells are also being used as portable generators and back-up power, much the way diesel generators are used.

FUEL CELLS IN BUILDINGS AND INDUSTRIES

Hydrogen fuel cells are already providing heat and power for buildings and industrial processes around the world. First National Bank of Omaha uses fuel cells as a secure and reliable power source for its credit card service operations. The New York City Police Department has installed a fuel cell to power its Central Park police station because it was cheaper than extending power lines.

Companies such as Plug Power and Coleman expect to launch fuel cell systems for homes and small businesses by 2004. Initially, for its hydrogen source, these systems would rely on either the natural gas that is already pumped into homes or containerized hydrogen. General Motors estimates that the premium power market (customers who cannot afford to ever be without power) represents a $10 billion per year prospect.

It is difficult to predict whether vehicles or buildings will show the greatest demand for fuel cells in the short run. Some believe that hydrogen fuel cells may be used in buildings before cars, in part because making fuel cells for stationary uses is much easier than for vehicles, which experience extremes in temperature and vibration.

WORLDWIDE FUEL CELL MARKET POTENTIAL

2005 → *$2.4 billion (The Freedonia Group, Inc.)*

2009 → *$7 billion (Business Communications Company, Inc.)*

2020 → *$1.7 trillion (Price Waterhouse-Coopers)*

2030 → *750,000 jobs (U.S. Dept. of Energy)*

FUEL CELL HOME GENERATORS BY 2005

General Motors Corporation announced in 2001 that it could market a fuel cell powered home generator about the size of a refrigerator as early as 2005. The unit would rely on a home's natural gas supply to produce 5 kilowatts of electricity, enough to power the average home or small business. The fuel cell would also produce heat that could be used to provide the building's hot water needs.

According to General Motors officials, within 10 years, homes may become the service station of the future. Natural gas, electricity and water offer all the necessary ingredients to produce hydrogen for fuel cell vehicles and to power homes.

As described in Reuters Financial Report, "run backwards and plugged into an electrical outlet, the fuel cell aboard a car or truck could act as an electrolyzer to create hydrogen from water or natural gas…such technology is already in use on submarines, which create oxygen for their crews to breathe from sea water, with hydrogen released back into the ocean."

HYDROGEN FOR TRANSPORTATION

Many experts believe that mounting pressures on the world's transportation systems will force changes in vehicles first. Fuel cell leaders at General Motors argue in Scientific American that a confluence of factors make a shift toward fuel cell vehicles and hydrogen increasingly likely:

- Engineers cannot make the internal combustion engine much more efficient.
- Internal combustion engines running on fossil fuels raise concerns over climate change; efficiency gains do not solve this problem.

MILLENNIUM CELL INC. HAS NOVEL APPROACH TO HYDROGEN STORAGE

DaimlerChrysler is testing a fuel cell minivan called the Natrium that can travel 300 miles on a single fueling of hydrogen stored in the form of sodium borohydride, mainly used for bleaching paper. When mixed with water, the resulting liquid is neither flammable nor explosive. A catalytic reaction releases hydrogen leaving only sodium metaborate, often known as borax, behind.

The system relies on a proprietary catalyst and special chamber. Recycling the borax back into sodium borohydride starts the process over again. Aside from offering a safe way to carry hydrogen on board vehicles, sodium borohydride can also deliver hydrogen at 100 percent humidity and produces no carbon monoxide, both of which pose problems for fuel cells. Chrysler has yet to figure out how large quantities of borax can be cost effectively transported to filling stations.

Stephan Tang, president and CEO of Millennium Cell Inc., estimates that it would take about 6 percent of the world's borax reserves to completely fill the recycling loop for the equivalent of all new cars on the road today. The economics are not especially favorable for Millennium Cell's technology at present, but their concept reflects the variety of storage methods being explored.

- Fuel cell vehicles are clean and twice as efficient, requiring just half the fuel energy in today's gasoline models.
- The fact that hydrogen can be produced in so many ways means that the U.S. would not need to depend so heavily on one or two energy options.

The GM officials also suggest that introducing hydrogen as a transportation fuel would introduce greater competition into energy pricing, potentially lowering and stabilizing fuel and energy costs in the long run.

HYDROGEN BUSES

In March 1998, the Chicago Transit Authority, second largest in the nation, became the first in the world to operate hydrogen fuel cell buses in a public transit system. Liquid hydrogen was produced at a large centralized plant and then trucked to and stored at a fueling facility near the transit authority's service yard. The liquid hydrogen was then pumped and vaporized for storage on the bus. The 2-year pilot ended, as planned, and the buses returned to Ballard Power Systems in Canada, but Chicago plans to launch another round of three fuel cell demonstration buses soon. This time, the transit authority is working with the State of Illinois and the Illinois Corn Growers Association to develop an ethanol-to-hydrogen fueling station to supply the buses with hydrogen. Other fuel cell buses have been introduced in California, Europe and Canada.

As with car fleets, buses represent a promising initial market for fuel cells because they require relatively little infrastructure, often returning to a central location to refuel. Buses also resolve concerns over the size of hydrogen storage tanks since the tanks can be placed on top of the buses without reducing passenger space.

The Global Environment Facility, which finances international projects that reduce biodiversity loss, climate change, degradation of international waters, and ozone depletion, is providing 46 fuel cell buses for six of the world's most polluted cities: Mexico City, Sao Paulo, Cairo, New Delhi, Shanghai and Beijing.

HYDROGEN AUTOMOBILES

There are many challenges facing the transition from petroleum to hydrogen in vehicle applications. In order to commercialize fuel cell engines for automobiles five key things must happen:

1. **Refine the function and size of engines and storage tanks** so that they do not reduce passenger or cargo space and offer a suitable driving range (300-350 miles). GM has made a breakthrough in hydrogen storage tanks, becoming the first to successfully road test a fuel cell car using 10,000 psi tanks, giving a range closer to that of gasoline vehicles.
2. **Reduce the cost** of fuel cell engines to be competitive with internal combustion engines or have internal combustion engines reflect their true environmental costs. Since fuel cells are inherently more energy efficient, they could out-compete conventional engines even at a somewhat higher cost.

3. **Develop manufacturing processes to mass produce** fuel cells and fuel cell engines in automotive volumes.
4. **Decide on a base fuel** – hydrogen, gasoline, methanol, ethanol, water or natural gas – and whether it will be reformed on-board or on-site.
5. **Make infrastructure investments** to support wide-scale introduction.

According to Thomas Gross, former Deputy Assistant Director of Transportation Technologies at the U.S. Department of Energy, worldwide car ownership is expected to grow from today's 700 million to 3 billion over the next several decades. Only 12 percent of the world's population can afford to own a car or truck today. China's per capita car ownership is about where the U.S. was in 1939 and Latin America is where the U.S. was in 1922. GM officials, among others, see clean fuel cell vehicles as the only politically viable way of seeing those numbers grow in a world increasingly worried about climate instability.

General Motors has promised to have "compelling and affordable fuel cell vehicles on the road by the end of this decade…and significant penetration of fuel cell vehicles between 2010 and 2020."

One obstacle is that automakers have yet to settle on the best way to carry enough hydrogen around in vehicles. One option already discussed is to carry hydrogen in gas form in very high pressure tanks. Compressing the hydrogen gas requires between 6 and 12 percent of the energy in the hydrogen, and carrying it as a gas currently imposes some constraints on vehicle range. At present, this is the most efficient method of carrying hydrogen on vehicles.

Regardless of where the hydrogen comes from, some predict that by the end of this decade, fuel cells cars will become the driving force behind a hydrogen economy. It is perhaps not surprising that auto manufacturers are investing more than any other industry sector in a hydrogen future.

Industry analysts note that automakers are investing $500 million to $1 billion a year in the race to be first with a hydrogen fuel cell vehicle. Virtually all the major auto manufacturers – Ford, General Motors, DaimlerChrysler, Honda, Toyota, Hyundai and BMW – have prototype fuel cell cars and are racing to see who can produce the first commercial vehicles.

Hydrogen fueled internal combustion engines, possibly combined with hybrid vehicle technology, could prove to be an important transitional technology while the costs and performance of hydrogen fuel cells are optimized. This would allow the hydrogen fueling infrastructure to develop, without requiring all customers to pay premiums for fuel cell vehicles. Both Ford and BMW have demonstration vehicles that burn pure hydrogen in internal combustion engines.

For example, Toyota began leasing hydrogen-powered fuel cell vehicles to two University of California campuses at the end of 2002, becoming the first automaker to do so. Honda's FCS fuel cell vehicle is the first to be certified for everyday use by the U.S. Environmental Protection Agency and the California Air Resources Board. Honda is leasing the first of five fleet vehicles to the city of Los Angeles for its use over the next two years. Ford plans to begin fleet sales of its fuel cell hybrid in 2004.

As these examples suggest, the first hydrogen vehicles are likely to be used in government fleets and corporate motor pools, since these require relatively few refueling stations. Of course, even these vehicles may need refueling while on trips, so having only a few stations would limit range and use.

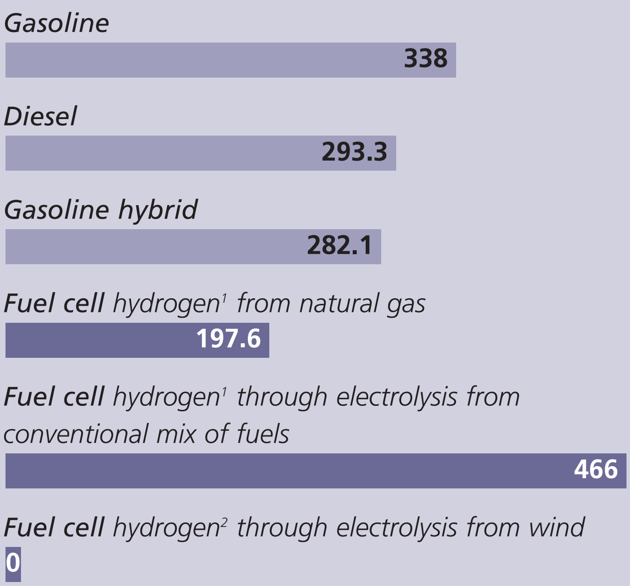
At least one estimate suggests that hydrogen fuel cell vehicles will not make up more than 5 percent of new vehicle sales in the U.S. until after 2008. The U.S. population currently buys roughly 850,000 vehicles a year.

Automakers estimate that hydrogen would have to be available in a third of all fueling stations for a hydrogen-based transportation sector to take hold. The federal government believes the necessary infrastructure will likely not be in place before 2015 at the earliest, but officials from General Motors say that will not delay their goal of mass-producing fuel cell autos by 2010.

General Motors does not see hydrogen infrastructure as the major barrier. It has developed a prototype refueling system that could fit in a home garage. The system relies on natural gas as the source of hydrogen. "Reducing the cost of the fuel cell powertrain by a factor of 10 is a higher

HOW MUCH BETTER?

Emissions for fuel-cell powered vehicles vary depending on how their hydrogen is obtained. The graph shows carbon dioxide emissions from fuel production and car operation, for a Chevrolet Silverado pickup truck running on various engines and fuels. Figures are in grams of carbon dioxide per kilometer.



[1] Compressed hydrogen gas
[2] Liquid hydrogen
Source: Wall Street Journal, March 2003

priority than the fueling issue," according to Larry Burns, GM's vice president for research and development and planning. General Motors' goal is to be the first automaker to produce and sell 1 million fuel cell vehicles at a profit.

Meanwhile, in February 2003 Stuart Energy, based in Ontario, unveiled its first Hydrogen Energy Station able to separate hydrogen from water using electrolysis.

OVERCOMING THE HYDROGEN INFRASTRUCTURE CHALLENGE

It is easy to take today's pipelines, trucks, trains and local power plants for granted. Energy is so central to daily life that few people think much about how the current system arose.

According to the chairman and CEO of Ballard Power systems, one of the world's chief fuel cell producers, there were just 12,000 gas stations in the U.S. in 1921; eight years later the number had jumped to 143,000. The 1,100 percent increase suggests how quickly things can change when economic and cultural forces are pulling in a given direction. Today, there are 175,000 gas stations. What comes first, cars or gas stations?

The National Hydrogen Association argues that government and industry should begin establishing a hydrogen infrastructure by developing refueling stations a few hundred miles apart. These refueling stations could demonstrate several different hydrogen production technologies, including small-scale steam reforming and electrolysis using electricity from the grid or from renewables. Sunline Transit near Palm Springs, California is already demonstrating the latter with its hydrogen station. The transit company uses solar electric panels to electrolyze water and uses the resulting hydrogen to power a fuel cell bus.

A new hydrogen infrastructure is likely to evolve from the existing energy system. Indeed, much of what is needed is already in place, but is designed to support fossil fuels.

Companies such as Praxair of Danbury, Connecticut and Air Products and Chemicals of Allentown, Pennsylvania have a limited but widely distributed hydrogen infrastructure of pipelines, storage terminals, tanker trucks and natural gas reformers. *Fortune* magazine has dubbed this "a kind of hydrogen-economy starter kit."

A central question is whether it will make more sense to produce hydrogen in central locations and distribute it over long distances, or produce the hydrogen at or near the place where it will be used, thereby avoiding the economic and energy cost of transporting and distributing it.

Based on the US DOE *National Hydrogen Energy Roadmap,* the country will likely have a combination of centralized hydrogen power plants and distributed production facilities. The mix will depend largely on the economics of a given region and its particular strengths when it comes to producing hydrogen.

A federal report published in 2000 by the National Renewable Energy Laboratory, *Blueprint for Hydrogen Fuel Infrastructure Development,* attempted to answer the question: "What has to be done, beginning today, to implement a hydrogen fuel infrastructure so that when hydrogen vehicles become market-ready in 3-5 years, the infrastructure needed for on-board direct use of hydrogen will be available?"

The report's findings are based on a consensus among 50 representatives of major energy, auto, industrial gas and hydrogen production companies and representatives from state and regional agencies, national laboratories and universities.

A key finding was that there are no technical showstoppers to establishing a hydrogen fuel infrastructure for direct hydrogen fuel cell vehicles. Despite a great many outstanding issues, "fundamentally the technologies required are available." The main issue is timing and coordination of capital investments among auto, energy and government interests.

The national *Blueprint* outlines several goals for establishing an initial hydrogen infrastructure, including:

- Establishing a process, facilitated by government, for fuel providers and auto companies to launch and grow a hydrogen fuel infrastructure.
- Providing a modular, replicable and consistent design for a hydrogen fuel dispensing station.

The *Blueprint* envisions one of three hydrogen production options for the first fueling stations:

1. Off-site steam reforming of natural gas with tanker-truck delivery of liquid hydrogen to refueling stations with on-site storage of liquid and gaseous hydrogen.
2. On-site electrolysis of water with on-site storage of the resulting hydrogen gas.
3. On-site natural gas reforming with on-site storage of hydrogen gas.

The purpose of having standardized and modular dispensing stations is so they can accommodate both liquid and gaseous hydrogen for storage in either compressed gas form or as a solid in metal hydrides as needs arise and demands change. In addition, a standardized design will make it easier to locate and construct the stations, which in turn will accelerate the expansion of a hydrogen infrastructure.

The lack of a hydrogen infrastructure is among the most obvious and central barriers to a hydrogen economy, but in many respects the challenges are no different than they have been for previous shifts in technology. The first steps will be disproportionately expensive and difficult, but will become easier and more affordable over time.

CHALLENGES TO TAPPING HYDROGEN'S POTENTIAL

Although there are powerful forces behind a hydrogen transition, some significant barriers lie ahead. According to the U.S. Department of Energy National Renewable Energy Laboratory, a hydrogen economy faces four main challenges to tapping the full potential of hydrogen as an energy source:

- Delivering hydrogen to consumers at prices that are competitive with other fuels.
- Increasing the efficiency of hydrogen production
- Improving the methods for storing hydrogen
- Reducing the cost of fuel cells and electrolyzers

A sustainable energy system must ultimately have sufficient supply to meet real-time demand, be nonpolluting, affordable, reliable and be based on an inexhaustible energy source. Hydrogen fits that description, according to Peter Hoffman, author of *Tomorrow's Energy: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet.* However, the single largest barrier to shifting toward hydrogen is that society does not yet place a sufficiently high value on each of these attributes. If it did, he argues, public policies would reflect the true cost of fossil fuels and would establish strong incentives for a hydrogen transition.

The literature also cites a number of other barriers to a hydrogen economy:

Lack of a consistent energy policy. Changing priorities for energy research and development have led to delays and setbacks in pursuing a coherent strategy on hydrogen. In the absence of consistent public policy, private firms are more hesitant to make significant investments. According to the Department of Energy, all the technologies needed to convert to hydrogen exist, but are not yet cost effective. Sufficient private investment is unlikely, or will happen more slowly, without supportive public policies.

Incentives for fossil fuel discovery and production that put hydrogen at an economic disadvantage. The economic playing field is tilted in favor of coal, oil and natural gas. Add to this the extensive infrastructure that supports today's fuels, the economies of scale that those mature industries have achieved, and the largely unpriced costs of pollution, and the collective economic picture does not make a switch to hydrogen attractive in the near term.

The cost of establishing a hydrogen infrastructure. Switching to a hydrogen-based energy system would be expensive. Yet nationally, the cost of maintaining and improving the existing infrastructure is also estimated to be hundreds of billions of dollars over the next several decades. There is a window of opportunity to switch technologies as existing facilities, transmission lines and pipelines reach the end of their useful lives. Policy-makers and others will need to decide whether investments in the existing system or investments in a new hydrogen infrastructure make the most sense.

The national consulting firm, Arthur D. Little, Inc., suggests that fuel cells will only achieve broad market penetration when their price drops below $1,500 per kilowatt for the distributed generation market, less than half the typical cost today. Power from the most widely marketed stationary fuel cells currently costs between $3,000 and $4,500 per kilowatt, as compared to electricity from a diesel generator that costs $800 to $1,500 per kilowatt. Natural gas turbines can produce energy that is cheaper still.

Now being tested are fuel cells that the U.S. Department of Energy estimates will produce power at about $1,200 per kilowatt – comparable to a large-scale coal-fired power plant but still too expensive for most on-site (or distributed) power uses. The department hopes to help cut costs to as low as $400 per kilowatt by the end of this decade, which would make fuel cells competitive for virtually every type of power application.

Depending on how it is produced, a kilogram of hydrogen is four to six times more expensive than a gallon of gasoline or diesel (its energy equivalent). Since fuel cells are twice as efficient as gasoline vehicles, though, GM believes hydrogen will be competitive at twice the cost of gasoline, and that they are within a factor of 1.3 of that competitive price. Many believe that fuel cells must offer power at less than $100 per kilowatt to replace the internal combustion engine.

The lack of low-cost, lightweight storage tanks and cost competitive fuel cells. Hydrogen will need to be stored and used as easily as gasoline or propane if it is to be widely adopted as a fuel. Fuel cell makers and those making high-pressure hydrogen tanks are making rapid progress, and, as with other new technologies, costs will fall as demand rises. Think of the first calculator, the first computer or the first cell phone and compare their original costs to retail costs today.

IDEAS FOR OVERCOMING CHALLENGES TO A HYDROGEN ENERGY SYSTEM

The National Hydrogen Association, representing automobile companies, fuel cell developers, gas producers, chemical companies and others, developed a *Near-term Hydrogen Implementation Plan: 1999 to 2005* that maps out steps for making hydrogen a major energy carrier in three key markets: fleet vehicles, buses and stationary power. Under this scenario, the progression might be:

1. Hydrogen used first in fleet and transit vehicles.
2. Public refueling offered at selected fleet centers.
3. Hydrogen added to existing service stations.

The National Hydrogen Association predicts that the most promising bus markets, for example, will appear first in areas that:

- Are out of compliance with federal air quality standards.
- Have current and potential renewable energy capacity (such as wind)
- Have strict environmental regulations
- Adopt policy statements and incentives that encourage clean vehicles
- Suffer from high transportation costs.
- Have dense populations
- Show strong consumer preferences for environmentally friendly products and practices
- Have leaders who are able to foster and direct the transition

Clusters or corridors of hydrogen transit fleets could represent the beginning of a broader hydrogen infrastructure, particularly as the clusters get closer together.

Another school of thought suggests that the near-term focus should be on establishing a viable hydrogen infrastructure that can serve both vehicles and buildings. For example:

- Use the existing natural gas pipeline system, off-peak electricity, ethanol or methanol to produce hydrogen.
- Install hydrogen appliances at suitably located buildings and gas stations that either electrolyze water or reform natural gas, ethanol or methanol.
- Shift toward producing hydrogen from the state's abundant renewable energy sources, beginning with demonstration.

The logic of using existing natural gas for the electrical and ethanol networks is that it allows production of hydrogen where and when it is needed without having to buy a whole new hydrogen infrastructure first. Hydrogen production could grow as fuel cell sales grow.

Participants in the National Hydrogen Vision Meeting, held in November 2001 in Washington D.C., detailed a four-phase transition to hydrogen. Their conclusions are plausible ways in which the transition might proceed between now and 2040.

FIRST PHASE

Initially, the focus is on refining the technologies necessary for a hydrogen economy and on putting in place the public policies necessary to foster sufficient private investment.

- Research and mass production will bring down the cost of fuel cells.
- High pressure storage tanks of 5,000 and 10,000 pounds per square inch and solid-state storage devices will be refined.
- Natural gas steam reforming will continue to be the main technique for producing hydrogen.
- There will be some initial pilots to demonstrate wind-to-hydrogen production.
- Automakers will deliver cars running on hydrogen fuel cells and hydrogen-powered internal combustion engines to build demand for a fueling infrastructure.
- Fuel cell cars and buses will be demonstrated in fleets first, particularly in areas with the worst air quality.
- Fuel cells will be increasingly used in stationary applications.
- Governments will come under increasing pressure to reduce foreign energy imports, manage greenhouse gases and improve air quality.
- International codes and standards for the safe production, handling and use of hydrogen will be adopted around the world.
- Governments will put in place a predictable and fair framework within which commercial development can proceed, including policies on liability and facility permitting.

SECOND PHASE

This phase will focus on bringing down the cost of hydrogen production, storage and delivery.

- Significant cost reductions in the production of fuel cells will be made possible by the ability to mass produce them for both stationary and mobile uses.
- The beginnings of a hydrogen delivery system will emerge (pipes, trains and tankers).
- Natural gas reforming remains the primary method of producing hydrogen.
- Lighter, cheaper storage devices become more commercially available.
- Local power parks and fueling stations will produce hydrogen on-site, at least some using renewable energies to electrolyze water.
- Hydrogen fuel cells will increasingly be used to provide both heat and power to buildings.
- Governments will play a key role in expanding the markets for hydrogen and fuel cells by being among the first users. Bus fleets, public motor pools, emergency services and military applications will demonstrate the potential.

THIRD PHASE

This phase will see dramatic reductions in the cost of extracting hydrogen and an expansion of hydrogen's market share in the energy system.

- Widespread use of fuel cells in buses and government vehicles.
- Hydrogen will commonly be produced on-site or onboard a vehicle.
- Large-scale biorefineries will produce a range of products including hydrogen, electricity, thermal energy, chemicals, fuels and other industrial products from organic matter.
- Metal hydrides used for hydrogen storage will become commercially viable technologies and enter mass production.
- Other novel storage devices such as carbon nanotubes will be close to commercialization.

- National policies will continue to encourage the transition to hydrogen.
- State and local policies and standards will be in place, including streamlined procedures for siting and permitting hydrogen facilities.

FINAL PHASE

The transition away from fossil fuels in favor of hydrogen will be completed during this phase.

- Hydrogen will become the fuel of choice for most applications.
- It will be produced from renewable sources in an environmentally sound fashion.
- Hydrogen farms that use living organisms such as algae to extract hydrogen from water will be in use.
- To the extent that fossil fuels are still used for energy production, the carbon from those fuels will be captured and put to productive use as industrial feedstocks.
- A national hydrogen infrastructure will be in place.
- U.S. companies involved in the production, storage, distribution or conversion of hydrogen will be exporting their technologies and know-how abroad.
- There will be a diminished government role as the market begins to function on its own.
- Hydrogen-powered vehicles will provide heat and power at places of work during the day and at homes at night.

KEY DRIVERS SUPPORTING A TRANSITION TO HYDROGEN POWER

Against the backdrop of these local opportunities, there are many national and international factors spurring the exploration and development of a hydrogen-powered economy:

National Security

The events of September 11, 2001 placed national security at the top of the country's priority list. According to a November 2001 Newsweek poll, 73 percent of Americans believe the U.S. should develop new energy sources to diminish its dependence on Mideast oil supplies. Hydrogen proponents see a highly decentralized, hydrogen-based system as the best way to decrease U.S. dependence on foreign oil.

In a speech before the National Academy of Engineering, Admiral Richard Truly, director of the National Renewable Energy Laboratory, described the country's energy infrastructure as "extremely vulnerable to disruptive acts of terrorism and nature," adding that energy security has become synonymous with national security.

Since hydrogen can be produced from such a variety of localized sources, relying on it reduces the likelihood of a new hydrogen cartel forming, as happened with OPEC and oil.

Future Oil Prices

As reviewed in the journal Nature, some oil geologists suggest that "the first sign of a permanent downward trend" in world oil production could occur by 2005, or well before the end of the decade at the latest. If these predictions prove accurate, that leaves two or three years to prepare for more price shocks. This by no means signals the end of oil, but may mean the end of cheap oil.

Global Climate Change

The discussion around climate change has become a significant driver for energy alternatives that operate within the earth's natural carbon cycle (plants take up carbon while they grow and release it when they burn or decay). The burning of fossil fuels, in the form of oil, coal and natural gas, has released vast quantities of additional carbon into the atmosphere. Fossil fuel use accounts for 75 to 80 percent of the human-induced carbon dioxide emissions cited as the cause of the climate change.

Climate change has become an international issue with potentially huge economic, environmental and social implications for Minnesota. Long-term changes in temperature can influence the growing season, range of pests, intensity and frequency of extreme weather events, and many other phenomena.

According to the Minnesota Pollution Control Agency, credible scenarios predict that by 2100 the earth's temperature will increase by about 4 degrees Celsius (7.2 degrees Fahrenheit). Over the past 100 years the earth's surface temperature has increased at a rate well outside the range of natural variability for the past 1,000 years. Experts around the world believe that nations must reduce emissions of gases that affect the climate by 60 to 80 percent by 2050.

The National Academy of Engineering believes that climate change and other environmental challenges have become so great that it has launched a new effort dubbed "Earth

Systems Engineering," aimed at finding sustainable solutions to such things as future energy production.

Population and Economic Growth

Another factor influencing hydrogen development is a desire for developing nations to leap-frog past the centralized, capital-intensive energy infrastructure that the U.S. and other industrialized nations have, in favor of more distributed, flexible and cleaner energy options, much as they have done with telecommunications.

The National Research council estimates that by 2050, the world's population will reach 9 billion and eventually level off at even higher levels, with the majority of that growth taking place in the developing world. In 1950, New York was the only city with more than 10 million people. Today there are 20 such mega cities, with more emerging. Many experts predict significant environmental consequences if large and growing populations and economies, such as those in China and India, adopt energy consumption patterns and technologies similar to those in the U.S.

Admiral Truly suggests that if developing countries around the world approach a standard of living anything like that in industrial nations, per capita energy consumption would soar.

Air Quality and Human Health

According to the U.S. Department of Energy and the Environmental Protection Agency, most of the major metropolitan areas in the United States are out of compliance with the Clean Air Act.

The Twin Cities are in compliance, but air quality remains a significant concern in the state. According to the Minnesota Pollution Control Agency, Minnesota exceeded the health benchmarks for 10 toxic air compounds in 1999, and motorized vehicles are responsible for 61 percent of the excess cancer risk that these toxics represent. The agency notes that in 2001 Minnesota experienced the worst ozone levels in 30 years and the worst year ever for fine particulates. The *Journal of the American Medical Association* reported in 2002 that lung cancer deaths increase 80 percent for every additional 10 milligrams per cubic meter of fine particulates in the air.

Renewable Energy and Intermittency

The electricity generated by any renewable energy technology could be used to electrolyze water and produce hydrogen, effectively storing the energy indefinitely until it is either burned directly, blended with other fuels or used in a fuel cell to produce electricity.

Renewable energy sources, such as wind, are often criticized for being intermittent, but hydrogen solves that problem by offering an energy storage solution that allows the energy to be available whenever it is needed.

Legislation requiring zero-emission vehicles.

California has mandated that 10 percent of all new vehicles sold must produce zero emissions of the six federally regulated "criteria" pollutants. In practice, this means electric or hydrogen vehicles. Because California represents 10 percent of the nation's car market, this mandate has become one of the forces behind fuel cell automobiles.

In July 2002, California went a step further by becoming the first state in the nation to require automakers selling vehicles there to limit tailpipe emissions of carbon dioxide, a gas that has gone unregulated until now. The regulations would not take effect until January 2006, but give automakers until 2009 to come up with technological changes or modifications to comply with the new standards.

Significant and rapid improvements in fuel cell technology.

Hardly a day goes by without some new announcement about improvements in the size, power and overall performance and reliability of fuel cells. These advances lend momentum to an already growing industry sector and spur additional interest. According to former U.S. Energy Secretary Federico Pena, "We're going to see fuel cells in homes, cars and other uses much sooner than we had predicted."

KEY FACTORS THAT MAY BOTH DRIVE AND HINDER A SHIFT TO HYDROGEN

Fuel cells are among a fast growing family of technologies that can make a hydrogen-powered future possible. New developments happen so quickly that it is difficult to keep abreast of the technology. The rapid rate of change makes it difficult for investors to make informed decisions, and to know what investments make the most sense.

At the same time that hydrogen-based energy systems are being developed, conventional fossil fuel-based energy systems are becoming cleaner, cheaper and more efficient. Consumers may be reluctant to purchase relatively expensive hydrogen products if they believe that cheaper, more efficient products are just around the corner, or if they feel that the incremental environmental benefits are negligible because of advanced pollution control technology available in fossil-fuel based systems.

When it comes to energy, Americans want minimal environmental impacts and low prices. The public's awareness of how existing technologies compare to hydrogen and fuel cells on cost, performance, availability, safety and environmental impacts, will be crucial to their adoption. Potentially conflicting desires in many of these categories may both drive and hinder the initial move toward hydrogen.

PUBLIC POLICIES PROMOTING HYDROGEN IN THE U.S. AND ABROAD

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Congress has supported hydrogen energy research, development and demonstration since 1990, but more recently the Bush administration has given new momentum to these efforts by scrapping the Partnership for a New Generation of Vehicles – a public-private initiative that produces an 80 miles per gallon sedan but has not led to more efficient vehicles in showrooms – in favor of pursuing a hydrogen and fuel cell energy future.

The President's National Energy Policy directs the U.S. Department of Energy to explore the possibility of a hydrogen economy. In April 2002, the department convened a wide range of business executives, federal and state officials, university leaders, researchers from national laboratories and environmental experts to develop a National Hydrogen Energy Roadmap. The purpose of the roadmap is to allow these diverse interests to identify short, mid-, and long-term actions and to set priorities and roles.

Preceding this roadmapping effort, a broad range of interests met in November 2001 to establish a common vision for a hydrogen-powered economy, along with the time frame for the transition and the key steps required to get there.

Participants in the federally sponsored hydrogen visioning meetings arrived at the following findings and conclusions:

- Hydrogen has the potential to solve two critical energy challenges, reducing U.S. dependence on petroleum imports and reducing pollution and emissions.
- Hydrogen could play an increasingly important role in the energy system, but a complete transition to hydrogen may take several decades.
- The shift toward a hydrogen-powered economy has already begun.
- Key barriers are the current high cost of fuel cells and a lack of infrastructure to support hydrogen. In addition, the nation lacks efficient, affordable hydrogen production and lightweight hydrogen storage options, e.g. high pressure tanks.
- The transition to hydrogen faces a "chicken-and-egg" dilemma should the cars, homes and cell phones that can run on hydrogen come first, or must the network of fueling stations, pipelines and production facilities for hydrogen come first?

These findings, in turn, led to three main conclusions about what will need to happen to make a successful transition to hydrogen.

- Consistent public policy. Federal and state governments must adopt and implement a consistent energy policy that elevates hydrogen as a priority for meeting energy security, energy independence and climate change goals.
- Public-private partnership. Success will require significant and ongoing public-private cooperation. For example, governments could become among the first customers for hydrogen-powered vehicles and stationary fuel cells.

- A clear roadmap. A broad range of interests must collaborate to develop hydrogen roadmaps at the national, regional and state levels.

HYDROGEN INITIATIVES AROUND THE WORLD

Countries and companies around the world are also pursuing a shift toward hydrogen. Amid all this activity, Iceland, Europe and Japan may be leading the way. Each are briefly profiled below.

Iceland

Iceland has ambitious plans for shifting to a hydrogen economy by 2030. In 1999, the small island nation announced a new multi-million dollar public-private venture, New Icelandic Energy, to investigate hydrogen's potential as a clean substitute for fossil fuels. In the next 30 years Iceland expects to convert its bus fleet, its 180,000 cars and 2,500 fishing vessels to hydrogen.

Because Iceland has the luxury of cheap, renewable electricity from geothermal and hydroelectric sources, it has become the ideal laboratory for working out the details of a hydrogen system, from the design of fueling stations to how best to educate the public. Iceland's standards and transportation system are similar to most other developed countries so their results can inform hydrogen initiatives elsewhere.

The Icelandic government not only envisions their country becoming completely energy independent, but turning hydrogen into a lucrative export to other European countries. At an oil price of $20 a barrel, Icelandic hydrogen would currently be two to three times more expensive than gasoline, but fuel cells are also twice as efficient as internal combustion engines running on gasoline, so hydrogen could soon become competitive.

European Union

Begun in 1989, the multinational European Integrated Hydrogen Project aims to establish a coordinated approach to developing the standards, regulations and infrastructure necessary to support a hydrogen energy system.

In October 2002, the European Union announced plans to accelerate its hydrogen and renewable energy program by investing $2 billion between 2003 and 2006, a 20-fold increase over the previous five years. *The Wall Street Journal* reported that this increase is aimed at overtaking the U.S. and Japan in the race to a hydrogen future.

President of the European Commission and former Italian prime minister Romano Prodi made the announcement, saying that shifting to a hydrogen economy (and its technological spinoffs) will be as important to Europe as the space program was for the United States. While acknowledging that a complete transition is years away, he believes that technological advances had made hydrogen "a realistic alternative to fossil fuels."

Prodi sees Europe's public investment focusing on basic development of fuel cell cars and motors and guidelines for establishing a hydrogen infrastructure. According to *The New York Times,* he estimates the cost of converting Europe to a decentralized energy grid based on hydrogen fuel cells at above five times the cost of installing a mobile-phone network. "The cost is enormous," he said, "but it is not out of reach."

Japan

In 1993, Japan launched the $2 billion, 28-year World Energy Network (WE-NET) project aimed at making a transition to hydrogen. It was part of an even larger $11 billion

EUROPE'S FIRST HYDROGEN GAS STATION IS IN HAMBURG

In 2001, the city of Hamburg, Germany, opened the first private fueling station in Europe to deliver hydrogen to vehicles. Today, the station serves six shuttle vans and gets its hydrogen from Hamburg's chemical industry. But in the future hydrogen may well come from Iceland, where it will be made, emission-free, via electrolysis of water using hydropower and geothermal energy. Companies involved in the project, such as Deutsche Shell, expect that up to a quarter of the world's energy production will be delivered to consumers as hydrogen by 2050.

INTERNATIONAL INVESTMENT IN FUEL CELLS AND HYDROGEN

Europe	*$2,000 million (2003 to 2006)*
Japan	*$220 million in 2002 (tripled since 1995)*
China	*$120 million planned investment*
Canada	*$116 million to date (2002)*
U.S.	*$29 million ($40 million proposed for fiscal year 2003)*

effort, the New Sunshine Program, devoted to developing a full range of renewable energy technologies. The hydrogen WE-NET project includes 40 organizations including universities, think tanks and corporations. Funding has increased in most years since its launch.

The first phase, between 1993 and 1999, focused on water electrolysis for hydrogen production, hydrogen as a transportation fuel and on fuel cell development.

Phase two, 1999 to 2003, is focusing on commercialization of a hydrogen fuel cell power plant, hydrogen storage tank systems for fuel cell vehicles and hydrogen refueling stations using natural gas reformers, methanol reforming and Proton Exchange Membrane electrolyzer.

Senior officials are urging the Japanese government to move up its target date for the development and commercial introduction of fuel cells from 2020 to 2005. These officials believe that the consequences of stiff international competition by 2005 "could influence the dominance of future market competition."

As it stands, Japan plans to have 5 million fuel cell-powered vehicles on the road by 2020, with fueling stations totaling 10 million kilowatts of capacity.

HYDROGEN AND FUEL CELL INITIATIVES IN OTHER STATES

At least 18 states have incentives to accelerate the commercialization of fuel cells. Among the common measures are financial assistance for fuel cell projects, tax benefits, and allowing fuel cells to qualify as contributions toward Renewable Portfolio Standards. These laws require electric suppliers to obtain part of their supply from renewable sources.

Five states are profiled below.

California

The California Fuel Cell Partnership is demonstrating a wide range of fuel cell passenger cars and transit buses. Because fuel cell engines have fewer moving parts than traditional engines, the Partnership expects maintenance to be lower. Similarly, while operating costs will depend mostly on the cost of the fuel, the high efficiency of fuel cells is likely to keep operating costs low.

Individual automakers will operate the cars from a headquarters facility in West Sacramento. Automakers will collect data on vehicle performance under a variety of typical driving conditions. The partnership plans to hold regular public outreach events throughout California.

The California Fuel Cell Partnership argues that because they are breaking new ground, specific budget numbers "are somewhat irrelevant to ultimate commercialization and infrastructure costs." However, each member makes an annual contribution of about $85,000 towards facility operating costs, program administration, joint studies, public outreach and education. Automakers and fuel providers are collectively investing several million more dollars in vehicles and fueling stations. Some government agencies contribute in-kind products and services.

Michigan

Michigan will invest $30 to $50 million over the next three to five years to ensure that the state becomes a center of research into alternative energies. "We don't want to be making buggy whips when everyone else is making the horseless carriage," Gov. John Engler told *The New York Times* in April 2002.

Michigan has estimated that it could lose 100,000 to 200,000 jobs if there were a sudden shift away from the internal combustion engine. Before leaving office, Gov. Engler said he believes that such a shift is imminent.

Michigan's *NextEnergy Plan* includes development of a 700-acre alternative energy research center, tax exemptions for businesses that conduct research on alternative energy, a venture capital fund to promote research, and tax breaks for Michigan residents who buy automobiles or power sources that use alternative energy.

The project will also investigate establishing microgrids, or small power networks, to serve clusters of homes and businesses with alternative energy sources, perhaps using the new research center as the first pilot.

New York

A subsidiary of United Technologies Corporation is building eight fuel cell power plants for the New York Power Authority. The $7.6 million project will place 200-kilowatt units at wastewater treatment plants, which produce hydrogen as a by-product. The fuel cells will be installed in Brooklyn, the Bronx, Queens and Staten Island, according to the U.S. Environmental Protection Agency's National Risk Management Research Laboratory.

The fuel cells will represent one of the largest concentrations of fuel cell generators in the U.S., but will generate less than an ounce of pollutants for every 1,000 kilowatt-hours of electricity, compared with as much as 25 pounds of pollutants produced by traditional power generation.

Ohio

Ohio's new three-year, $100 million initiative is designed to position that state as a national leader in the growing fuel cell industry. Gov. Bob Taft hopes to follow this with an even more ambitious $1.6 billion, 10-year effort starting in November 2003. The first, more modest initiative will focus on three core areas:

- Expanding the state's research capabilities among its universities and research labs.
- Launching hydrogen infrastructure demonstration projects.
- Making investments that expand and attract fuel cell industries in Ohio, and the jobs they provide.

The Ohio Department of Development is investing $75 million in financing for various fuel cell projects; $25 million for research, development and demonstration; and $3 million for training.

Texas

The 2001 Legislature established the *Fuel Cell Commercialization Initiative,* which developed a statewide plan to accelerate the introduction of fuel cells in Texas. The State Energy Conservation Office is heading up the effort, enlisting the guidance of the fuel cell industry, energy service companies, utilities and other state and local agencies. Texas sees fuel cells as a potential source of economic development and a market-based opportunity to improve air quality.

IMPLICATIONS OF A HYDROGEN BASED ENERGY SYSTEM FOR MINNESOTA

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The implications and potential of a hydrogen-based energy system are enormous for Minnesota.

Highly distributed production of hydrogen from the state's domestic energy sources may avoid the transmission and distribution costs of traditional, centralized energy production, and could unlock the economic potential of renewable energy.

One way to move towards a hydrogen based energy system is by using large, centralized plants that would reform natural gas or gasify coal to get hydrogen, or use nuclear power to harvest hydrogen from water. While this path may have ancillary benefits for Minnesota, there is an alternative path that will better utilize Minnesota energy resources to produce hydrogen.

A FLEXIBLE, ADAPTABLE ENERGY SYSTEM.

Because hydrogen can be derived from both nonrenewable and renewable energy sources, it can be adopted in ways tailored to a given state's or region's strengths. For example, in Minnesota shifting to hydrogen might mean accelerating development of the state's wind, solar, small-scale hydroelectric and biomass potential. Relying on diverse and geographically distributed energy sources would be inherently more flexible and adaptable to changing circumstances than the centralized, capital intensive energy production of the last century.

A HOMEGROWN SOURCE OF ECONOMIC DEVELOPMENT.

Minnesota's 3M company has been growing a world-class fuel cell materials and components business since the mid-1990s and the state already has established its leadership in wind and other renewable energy technologies. Marrying the state's technical prowess with its renewable resource base could help Minnesota and other Midwestern states become net energy exporters. The same cooperative business model that has worked so well for ethanol could allow groups of small producers to profitably generate hydrogen from widely distributed, renewable energy sources.

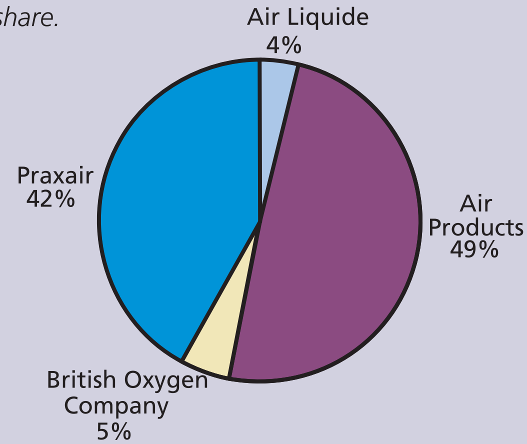
EXISTING HYDROGEN INFRASTRUCTURE IN MINNESOTA

Minnesota already has some experience in developing a new energy infrastructure. In 2001, the U.S. Environmental Production Agency awarded Minnesota for successfully establishing the largest network of gas stations in the nation (more than 85 as of January 2004) offering E85, an alternative fuel blend of 85 percent ethanol and 15 percent petroleum. This alternative fuel is designed for use in many new car models, called flexible fuel vehicles, which can use any combination of E85 and gasoline.

E85 is overcoming many of the same hurdles and barriers that hydrogen is likely to face, from making vehicles that would run on the fuel to getting gas stations to offer it. Minnesota's success in establishing an E85 infrastructure bodes well for the state's ability to lead the nation on hydrogen. The E85 experience also suggests what is possible when public and private interests work together toward a common goal. Finally, if hydrogen could be cost effectively extracted from ethanol, then Minnesota's existing network of E85 stations could quickly become its first hydrogen infrastructure.

LIQUID HYDROGEN

North America liquid hydrogen production capacity market share.



Source: Praxair, 2002

HYDROGEN PRODUCERS

The largest North and South American producer of industrial gases, including hydrogen, is Praxair, Inc. Its closest hydrogen plant is in the Chicago area, so all the hydrogen that Praxair sells in Minnesota is trucked up as a gas in high pressure tube trailers, 180,000 cubic feet at a time, or as a liquid in 13,000 gallon transports.

Costs for liquid hydrogen range from $1.50 to $2.00 per 100 standard cubic foot, while gaseous hydrogen costs between $3.75 and $5.50 per 100 standard cubic foot.

Praxair has the only hydrogen production facility in the Midwest, including a cylinder and tube trailer filling station in Roseville, Minnesota. The company supplies 95 percent of the hydrogen sold in the Midwest. The next closest hydrogen plants, either Praxair's or a competitor's, are located in the Gulf Coast and in the Buffalo, New York area.

Although hydrogen will eventually be produced on-site, either on the consumer's property or at a refueling station, in the interim Praxair has said it could provide hydrogen for feasibility studies or demonstration projects.

END-USERS OF HYDROGEN IN MINNESOTA

Within Minnesota, Flint Hills Resources (formerly Koch Petroleum Group) and Ashland Oil may be the largest users of hydrogen, employed in the refining process and to make fertilizers, but they are also hydrogen producers.

In addition, most power plants use hydrogen for cooling their electrical generation equipment, and powdered metal plants are a growing market, where hydrogen takes the place of dissociated ammonia in the metal coating process.

Renewably produced hydrogen could also be used in the manufacture of anhydrous ammonia, a process that currently uses large quantities of hydrogen produced through the steam reformation of natural gas. The cost of natural gas represents approximately 80% of the cost of the fertilizer. High natural gas costs have significant implications to the entire food production chain in Minnesota, as production costs come down hydrogen produced from renewable energy could provide a cost competitive solution.

According to Praxair, there are currently just six customers for liquid hydrogen in Minnesota, North Dakota and South Dakota, and Praxair services them all.

POSSIBLE HYDROGEN DEMONSTRATIONS IN MINNESOTA

Demonstrating fuel cells and the production and use of hydrogen is not only the best way to prove these technologies and make a start on the infrastructure to support them, but is also the most effective means of educating the general public and decision makers.

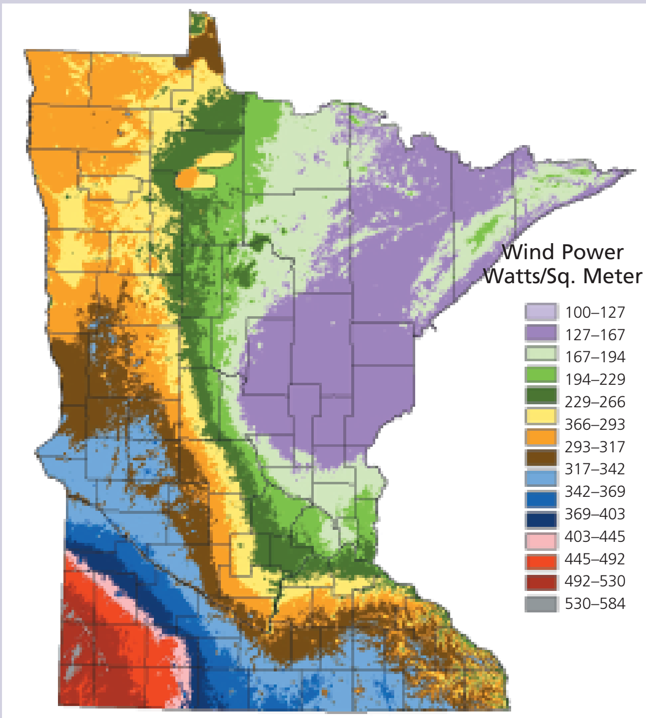
There is no shortage of possible demonstration sites and projects in Minnesota for both hydrogen production and use. The challenge will be to identify the most strategic sites that best demonstrate the various production options and fuel cell applications, while offering the greatest advances in establishing a hydrogen infrastructure in the state. Wherever the pilots are built, they would share four common objectives:

1. Demonstrate the production and storage of hydrogen, preferably from a renewable resource.
2. Demonstrate the flexibility of hydrogen in a variety of settings for a variety of purposes, including as a combustion fuel or in fuel cells for vehicles and buildings.
3. Raise public awareness and acceptance of hydrogen as an energy carrier.
4. Identify barriers to shifting to hydrogen on a broad scale, including infrastructure needs, technical challenges and financing.

No matter where the first demonstrations take place, the state's tradition of effective public and private cooperation,

MINNESOTA'S WIND RESOURCES BY WIND POWER AT 70 METERS

Minnesota's wind potential equals several times its current electricity use.



Source: Minnesota Department of Commerce, www.commerce.state.mn.us

its strong technology base and significant wind and other renewable energy resources place it in a strong position to help lead the nation and take advantage of emerging hydrogen technologies and opportunities. Using Minnesota's indigenous energy resources for the production of hydrogen versus non-Minnesota produced fossil fuel sources will help develop an economic case for hydrogen in Minnesota. Currently Minnesota imports the majority of its energy needs.

Wind

Many see an initial reliance on natural gas as the main source of hydrogen giving way to producing it via renewable energies like solar, wind and biomass. Royal Dutch/Shell predicts that as much as half the world's entire energy supply could come from renewable sources by 2050. The production of hydrogen from electricity generated by wind turbines has significant potential in Minnesota. Hydrogen production provides a level of flexibility in that the hydrogen could be used for either vehicle applications or stationary electric power. Electricity stored as hydrogen would yield a smaller amount of energy due to losses in the conversion process, but the flexibility of the fuel and the ability to deliver the energy during periods that maximize the economics could overcome some, if not all of these losses. Wind to hydrogen plants could serve the hydrogen needs of small communities, or they could be used to firm up wind capacity so as to relieve constraints on our electrical transmission grid.

Biomass

In addition to wind, Minnesota's vast biomass resources offer another potential hydrogen production option. These resources are often characterized as "waste" resources, but it would be more appropriate to characterize them as under-utilized resources.

The U.S. Department of Energy's National Renewable Energy Laboratory reports in *Hydrogen from Biomass: State of the Art and Research Challenges,* that "for the near- and mid-term, generating hydrogen from biomass [of many kinds] may be the most practical and viable, renewable and potentially carbon-neutral (or even carbon-negative in conjunction with sequestration) option."

Biomass conversion to hydrogen is not yet competitive with steam reforming natural gas, but could become competitive if done as part of a biorefinery, where a range of value added products are produced at the same time.

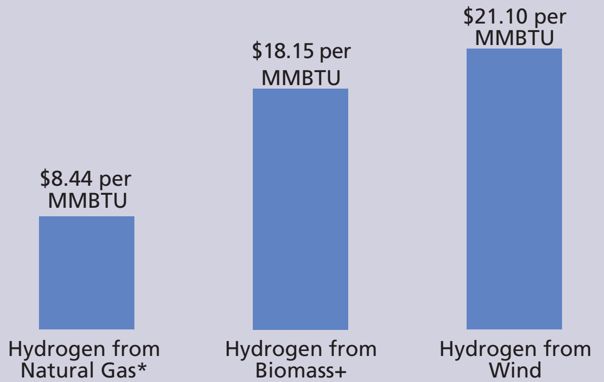
This type of coproduction improves economics because the cost of growing, harvesting and transporting biomass is relatively high and its hydrogen content is relatively low (6 percent versus 25 percent for methane). However, to accomplish the collection and processing of these biomass resources into hydrogen would require the creation of jobs at all levels of the process chain.

Options for biomass-to-hydrogen production will be governed by cost, distribution, mass and physical and chemical characteristics of the organic matter locally available, along with the moisture and energy content of the feedstock.

In addition to biomass, Minnesota could explore the potential of a wide range of other hydrogen production options, including ethanol, methanol, methane from landfills and animal feedlots, hydroelectric power, photovoltaics and even algae.

COMPARING HYDROGEN PRODUCTION COSTS

The cost of hydrogen from biomas may compete with natural gas if produced as one of many products from a biorefinery, close to where the hydrogen would be used. Wind costs are also expected to decline significantly by 2010.



** At a natural gas cost of $2.11 per MMBTU. An MMBTU is a measure of heat equal to 1,000,000 BTUs.*
+ Plant-gate cost of biomass gasification/reforming
Source: Margaret Mann, National Renewable Energy Laboratory, 2003

Ethanol

Ethanol is already a high value product used as an oxygenate for gasoline in Minnesota and many other states. There is no technical reason why ethanol could not be used in fuel cells. Because of its fairly simple molecular structure, it is easier to reform into hydrogen than gasoline and safer to handle than methanol. Using ethanol for the production of hydrogen could solve some of the storage and infrastructure issues faced by pure hydrogen while increasing demand for ethanol from production facilities in Minnesota.

A large ethanol infrastructure already exists in Minnesota, from plants to fueling stations. The size of the ethanol distribution network is second only to gasoline as a vehicle fuel. Tapping this infrastructure as a step toward the hydrogen economy would likely require a much smaller investment than a direct shift to pure hydrogen.

At its 2002 annual convention in Morton, Minnesota, the Minnesota Corn Growers Association displayed a fuel cell running on ethanol. The demonstration represents the association's belief that ethanol as a hydrogen source for fuel cells could be a significant benefit to farmers and rural communities. The association also points out that ethanol is much less toxic than methanol and is produced from a renewable resource. The Corn Growers Association has requested $400,000 from Pacific Northwest National Labs to investigate ethanol's potential as a feedstock for fuel cells.

Methane.

Methane is another source of hydrogen. It is colorless and odorless and makes up 75 percent of the natural gas many people use in their homes. Methane is found widely in nature, can be synthesized, and also is produced from the anaerobic bacterial decomposition of plant and animal matter.

Minnesota has more than 20 landfills and some 561 wastewater treatment facilities that produce methane as a byproduct. Fuel cells running on methane-derived hydrogen are already operating at landfills and wastewater treatment facilities in Connecticut, New York, Boston, Oregon and Japan. Companies across the United States are extracting methane from some 140 landfills and 75 may be tapped in the future according to the Environmental Protection Agency Landfill Methane Outreach Program. Minnesota has a 1.5 cent per kilowatt hour payment for electricity generated from on-farm manure methane digesters that began generating electricity after July 1, 2001 through December 31, 2015. This renewable energy incentive may make it economical to install fuel cells at some of these facilities as well.

Connecticut dairy farm uses methane from manure to run fuel cell. *In 1977. the Freund brothers installed an anaerobic plug flow digester to extract methane from the more than 4,000 pounds of manure produced daily by their cows and calves. They used that methane to run a boiler that heats their house and offices.*

Now, in collaboration with fuel cell manufacturer Tor Energy Company, the Freunds are having a solid-oxide fuel-cell system installed that will provide enough electricity and heat to run the farm without any help from the electrical grid.

The fuel cell will produce about 25 kilowatts of electricity using the methane produced by the manure digester. The energy will power the farm, and the brothers will sell any excess electricity to the grid. In addition, the hot water vapor and carbon dioxide emitted from the fuel cell will each be put to use. The water vapor will heat the buildings, eliminating the need for the existing hot water boiler, and the carbon dioxide will be pumped into greenhouses filled with vegetables and bedding plants, where the gas will revert to oxygen through photosynthesis.

Hydroelectric.

Falling water is another renewable energy source that could be used to electrolyze water to produce hydrogen. Although large dams have become controversial for their economic, environmental and social impacts, they could offer a source of low cost, off-peak electricity for the production of hydrogen through electrolysis. A distributed network of small run-of-the-river hydroelectric facilities may represent another hydrogen opportunity for Minnesota down the road.

Photovoltaics.

Minnesota has a good solar resource despite its northern climate. The solar energy available here in summer is as good or better than that in Jacksonville, Florida. Demonstrating the potential of using solar to produce hydrogen, Humbolt State University's Shatz Energy Research Center in California has operated a photovoltaic array, an electrolyzer and a proton exchange membrane fuel cell without supervision since 1993.

Algae

According to Tasios Melis, a University of California, Berkeley biochemist and founder of Melis Energy in California, "an acre of pond scum...could produce enough hydrogen to power a car from Sacramento to Seattle—and theoretically much farther." His firm hopes to license the technology to power generators, fuel wholesalers and hydrogen producers within two to five years. Melis suggests that this method of hydrogen production has widespread application, in part because it is low-tech. "It won't require fancy equipment or industrial facilities. A farmer could do it." Those hydrogen farmers could potentially be located in Minnesota, though there is some question about whether or not this climate is suitable.

Hydrogen produced from algae is a long way from being competitive in the marketplace since it generates electricity at about 31 cents per kilowatt-hour compared to natural gas at 5 cents and wind power at 4 cents or less.

Sustainable buildings in Minnesota. *In 2003, the Minnesota Department of Commerce gave approval to Xcel Energy to use a portion of their Conservation Improvement Program research and development budget to fund a fuel cell pilot at the University of Minnesota Center for Sustainable Building Research. The project will use electricity from solar panels to power an electrolyzer that will generate hydrogen for a 1.2 KW fuel cell.. The Minnesota Office of Environmental Assistance has also provided a grant towards this project.*

Solar-derived hydrogen and fuel cells offer cheapest option in Hawaii. *Hawaii's first independent hydrogen fuel cell energy system is installed at Maui's Kahanu Garden. The project will employ solar panels, and electrolyzer and fuel cells to produce renewable, pollution-free energy. The electricity generated by the system will be used to run a visitor center and maintenance facility, and my produce enough energy to sell back to the utility grid.*

According to Michael Veith, cheif executive officer of H@ Power systems, "the $150,000 price tag for the system is substantially cheaper than the estimated $200,000 to $400,000 it would cost to tap into Maui Electric Company's electric grid. And we'll continue to save because we won't have to [pay any electric bills,. which would average about $3,000 annually."

Source: http://hydrogenhawaii.com/hydrogenhawaii.org/

CONCLUSION

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Just as the rest of the world looks at the potential of hydrogen, so too is Minnesota. The state already has a strong presence in the fuel cell industry, with companies such as 3M, Tescom, Entegris, Donaldson and ICM Plastics. Companies such as Praxair, Flint Hills Resources, and Marathon Ashland Petroleum have significant experience with handling hydrogen and developing fueling infrastructure.

In addition, legislation passed in 2003 establishes a goal of moving Minnesota towards incorporating hydrogen into its energy mix (MN Session Laws 2003, 1st Spoecial Session, Çhapter 11). The legislation:

- Authorized $10,000,000 for the University of Minnesota Initiative for Renewable Energy and Environment to support basic and applied research and demonstration activities, including hydrogen production and improvements to fuel cell technologies.
- Directed the Department of Commerce and the Department of Employment and Economic Development to issue a request for proposals for the construction of a wind to hydrogen demonstration project that demonstrates all components of a future hydrogen economy, namely, hydrogen production, storage, and distribution.
- Required the Department of Employment and Economic Development to develop a targeted program to promote and encourage hydrogen production.

As Minnesota considers the growing opportunities from hydrogen, the following questions need to be considered:

- How can Minnesota businesses, government and academia work together and leverage their respective strengths and perspectives to address critical issues in hydrogen production, transportation, storage, usage and education?
- What is the best way to produce hydrogen? Using traditional sources such as natural gas and coal with the hope of sequestering the carbon, or from renewables such as wind, photovoltaics and biomass?
- What aspects of hydrogen development relate specifically to current Minnesota businesses and industries? How can transitioning to a hydrogen economy improve economic development throughout the state?

No matter how these issues are resolved, there are significant implications and opportunities for Minnesota.

Hydrogen may solve the intermittancy problems posed by wind power. By storing energy and making it available when needed, hydrogen would allow Minnesota to fully exploit its vast renewable energy potential.

In Minnesota, with its considerable agricultural and natural resource base, biorefineries (the biomass corollary to oil refineries) has the potential to produce a wide range of products including hydrogen, electricity, thermal energy, chemicals, fuels, plastics, animal feed and other industrial products. Other centralized plants may use wind or some other form of renewable energy to split the hydrogen from water.

Because of the enormous investment and long lead times required to take advantage of hydrogen opportunities, public policy leadership is needed. Today's energy and transportation systems would not have evolved without such leadership. The railroads, the interstate highway system and the electrical grid all exist in large part because of government investment on the public's behalf.

The task of moving to hydrogen is large enough that no single sector of society can do it alone. This is where consistent, thoughtful public policies that articulate a clear vision can play a critical role. In addition, there must be serious coordination and cooperation among business, government, academic and non-profit interests to make real progress on a hydrogen-based energy system.

Similarly, a consistent, sustained, and united commitment to hydrogen development by private industry, Minnesota state government, the University of Minnesota and other centers of higher learning, and non-profit groups can help create a transformative new economic sector. A combination of incentives, safety codes and standards and long-term policy goals can provide businesses the predictable investment environment needed to make the potential of hydrogen a reality.

Sources and Resources

Ashley, Steven. "Fuel Cell Phones: Portable Power From Fuel Cells Inches Along." Scientific American July 2001). *www.sciam.com/2001/0701issue/0701scicit4.html. March 1, 2002.*

Banerjee, Neela and Hakim, Danny. "U.S. Ends Car Plan on Gas Efficiency: Looks to Fuel Cells." New York Times. January 9 2002. *www.nytimes.com.*

Barbir, Frano. Safety Issues of Hydrogen Vehicles. International Association for Hydrogen Energy. *www.iahe.org/hydrogen_safety_issues.htm.* March 15, 2002.

Baum, Dan. "Object in Mirror May Be Closer Than it Appears." Wired (August 2002).

Bentley, Jeffrey and Derby, Robert. Ethanol & Fuel Cells: Converging Paths of Opportunity, Renewable Fuels Association, August 2002.

Burns, Lawrence D. McCormick, Byron J. and Borroni-Bird, Christopher E. "Vehicle of Change." Scientific American (October 2002): 66-73.

Business Communications Company, as quoted on Fuel Cells 2000, *www.fuelcells.org/fcbenefi.htm*. June 6, 2002.

California Fuel Cell Partnership, *www.fuelcellpartnership.org/faq.html.* June 2004.

Cherveny, Tom. "Backing King Corn: Growers See Ethanol's Future in Fuel Cell Technology." AgWeek. Feb. 4 2002, p. 23.

Chub, Lucy. "Farm looks to fuel cells to help with the chores." Environmental News Network. September 18, 2000. *www.enn.com*.

Dresselhaus, M.S. and Thomas, I. L. "Alternative Energy Technologies." Nature, Vol. 414 (November 15, 2001): 332-337.

European Integrated Hydrogen Project. *http://www.eihp.org*. May 16, 2002.

Fuel Cells 2000, The Online Fuel Cell Information Center. "Frequently Asked Questions," *www.fuelcells.org/fcfaqs.htm.* June 11, 2002.

Fuel cell home generators by 2005. Vetni: The Global Hydrogen Center, *www.vetni.is/news.asp?ID=149*. May 9, 2002.

Ellis, Michael. "Fill 'er up at home, with hydrogen." Reuters Financial Report. May 29 2002.

Europe's first hydrogen gas station in Hamburg. Vetni: The Global Hydrogen Center, *www.vetni.is/media.asp?ID=129*. May 9, 2002.

GEF Funds 2 Fuel-cell Bus Projects to Ease Air Pollution. Global Environment Facility News Release. May 14 2001. *www.gefweb.org*.

General Motors Invests in Strategic Alliance with General Hydrogen. General Hydrogen Corporation News Release. June 13 2001. *www.generalhydrogen.com*.

Governor Announces Ohio Fuel Cell Initiative: New Initiative to Position Ohio for Leadership in the Third Frontier. New Release, Office of Governor Bob Taft, May 9, 2002. *www.state.oh.us/gov/releases/050902fuelcell.htm*. May 14, 2002.

Hakim, Danny. "Michigan Governor to Offer Energy Research Plan." New York Times. April 18 2002.

Hirschler, Ben. "Hydrogen Puts Iceland on Road to Oil-free Future." Reuters Financial Report. May 29 2002.

Hoffman, Peter. Tomorrow's Energy: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet. Cambridge, Massachusetts: The MIT Press. 2001.

"Japanese Officials Call for Earlier Introduction of Fuel Cells." Kyodo News Service. May 27 2002. *http://home.kyodo.co.jp/*

Lawrence Livermore National Laboratory. "New thin-film fuel cell packs powerful boost for consumer electronics." Newsline. February 14, 2002. *www.llnl.gov.*

McCarthy, Kevin E. Fuel Cell Initiatives in Other States. Connecticut General Assembly, Office of Legislative Research. OLR Research Report Number 2000-R-0581. Hartford, CT: 2000. *www.cga.state.ct.us/2000/rpt/olr/htm/2000-r-0581.htm.* June 14, 2002.

Mechanic, Michael. "It Came From the Swamp: Reengineering Algae to Fuel The Hydrogen Economy." Wired (April 2002), *www.wired.com/archive/10.04mustread_pr.html.* April, 22, 2002.

Meller, Paul. "Europe Pushes for Renewable Energy." New York Times. October 16 2002.

Miller, Scott and Bahree, Bhushan. "For Prodi, Hydrogen is Fuel of the Future." Wall Street Journal Europe. October 16 2002.

Milne, Thomas A. Elam, Carolyn C. and Evans, Robert J. National Renewable Energy Laboratory. Hydrogen from Biomass: State of the Art and Research Challenges. Golden, Colorado, 2002.

Minnesota Corn Growers Association. "Ethanol-powered Fuel Cells." Summary of Biopower Discussions at the Pacific Northwest National Labs, April 15 2002.

Nelson, Mark. Praxair, Inc., E-mail correspondence on May 17, 2002.

Nine cities to run fuel cell buses. Vetni: The Global Hydrogen Center. *www.vetni.is/news.asp?ID=125.* May 9, 2002.

National Hydrogen Association. Near-Term Hydrogen Implementation Plan 1999-2005. *www.hydrogenus.com/impplan.htm.* March 15, 2002.

Ohi. J. Blueprint for Hydrogen Fuel Infrastructure Development. U.S. Department of Energy. Golden, Colorado: National Renewable Energy Laboratory, January 2000.

"Oil: A Dangerous Addiction." The Economist. December 15 2001, pp. 15-16.

Pladsen, Kristian. "Mobility 2001" report. World Business Council on Sustainable Development Press Release. October 11 2001, *www.wbcsdmobility.org.* June 13, 2002.

Rose, Robert. Fuel cells and Hydrogen: The Path Forward, A Comprehensive Strategy for Federal Investment in Fuel Cell Technology and Fuel Infrastructure, *www.fuelcellpath.org.* September 5, 2002.

Minnesota Pollution Control Agency. "Environmental Challenges of Electricity Generation." A presentation at the Minnesota Pollution Control Agency, February 6, 2002.

Sharke, Paul. "Better Storage Through Chemistry." Mechanical Engineering (February 2002). *www.memagazine.org/backissues/feb02/features/storage/storage.html.* March 26, 2002.

Stark, Lisa. "Gasoline Obsolete? Fuel Cell Cars Were Promised, But in Reality They're Far Off." ABC News.Com. *http://abcnews.go.com/sections/wnt/DailyNews/fuelcell_hype020604.html*

Stempel, Robert C. "It's Time We Embrace the Hydrogen Economy." Rochester Post Bulletin. May 4 2002.

Minnesota Department of Commerce. "A presentation on the 2001 State Energy Planning Report at the Minnesota Pollution Control Agency," February 6, 2002.

Truly, Admiral Richard H. How Will We Meet the Future: Transitions to New Energy Frontiers, A speech before the National Academy of Engineers. October 9, 2001. *www.nrel.gov/director/trulyspeech_100901.html* January 16, 2002.

U.S. Department of Energy. Consumer Energy Information: EREC Reference Briefs: Hydrogen Fuel. February 2001. Energy Efficiency and Renewable Energy Clearinghouse. *www.eren.doe.gov/consumerinfo/refbriefs/a109.html.* March 19, 2002

U.S. Department of Energy. Hydrogen: Fuel for the Future. Washington, D.C.: National Renewable Energy Laboratory, DOE/GO-10095-099, March 1995.

U.S. Department of Energy. Hydrogen Program: Technology Overview. Washington, D.C.: National Renewable Energy Laboratory, DOE/GO-102001-1450, October 2001.

U.S. Department of Energy. National Hydrogen Energy Roadmap. Washington, D.C. November 2002.

U.S. Department of Energy. Toward a More Secure and Cleaner Energy Future for America: A National Vision of America's Transition to a Hydrogen Economy To 2030 and Beyond, February 2002. Washington, D.C. (see *www.eren.doe.gov/hydrogen*).

Vaenti, Michael. "Fill'er Up With Hydrogen." Mechanical Engineering (February 2002). *www.memagazine.org/backissues/feb02/features/fillerup/fillerup.html.* March 26, 2002.

Young, Stuart. "Global Energy Prospects: Choices, Challenges and Uncertainties for the Not-So-Distant Future." Nature, Vol. 414 (November 29, 2001): 487-488.

USEFUL LINKS

Fuel Cells 2000: The On-line Fuel Cell Information Center: *http://www.fuelcells.org/*

California Fuel Cell Partnership: *http://www.fuelcellpartnership.org/*

Global Hydrogen Center: *http://www.vetni.is/*

Hydrogen and Fuel Cell Investor: *http://www.h2fc.com/defaultIE4.html*

Minnesotans for an Energy Efficient Economy (ME3): *http://www.me3.org/issues/fuelcells/*

National Hydrogen Association: *http://www.hydrogenus.com/*

National Renewable Energy Laboratory: *http://www.nrel.gov/*

U.S. Fuel Cell Council: *http://www.usfcc.com/*

National Fuel Cell Research Council: *http://www.nfcrc.uci.edu/*

Los Alamos National Lab. Fuel Cells: Green Power: *http://education.lanl.gov/resources/fuelcells/*

Hydrogen Information: *http://www.hydrogenappliances.com/Hydrogendata.html*

How PEM Fuel Cells Wor : *http://www.fueleconomy.gov/feg/fcv_PEM.shtml*

Hydrogen, Fuel Cells, and Infrastructure Technologies Program, U.S. Department of Energy: *http://www.eere.energy.gov/hydrogenandfuelcells/*

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