



Minnesota
**Renewable
Hydrogen**
Initiative

Minnesota Renewable Hydrogen Roadmap

Report to the Minnesota Legislature

Office of Energy Security

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Minnesota Renewable Hydrogen Initiative Roadmap

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Appendix A: Primary References

Executive Summary

The Minnesota legislature requested that the Minnesota Renewable Hydrogen Initiative, an initiative coordinated by the Minnesota Department of Commerce Office of Energy Security (OES), develop a renewable hydrogen roadmap (Minnesota Statute 216B.813).

The legislature stipulated that the roadmap capitalize on the state's existing strengths, be based on an assessment of current energy and fuel marketplace economics and be compatible with the United States Department of Energy's National Hydrogen Energy Roadmap

The Minnesota Renewable Hydrogen Initiative's roadmap process included an assessment of renewable hydrogen within the larger context of clean energy technologies and identified an array of energy technology research and development opportunities that build on Minnesota strengths and will strategically contribute to achieving the state's clean energy goals. The renewable hydrogen roadmap detailed in this report augments the state's renewable hydrogen vision and incorporates a role for renewable hydrogen as an integral part of Minnesota's collective energy-related policies and goals. The primary findings of the Minnesota Renewable Hydrogen Initiative and the scientific advisory committee that assisted in development of the roadmap outline a strategy to guide the state toward prudent investments for renewable hydrogen development with comparatively low risk.

The current stage of the nation's hydrogen economy poses significant technical and economic challenges, particularly in the transportation sector where the nation's hydrogen program has targeted hydrogen fuel cell vehicles as a replacement technology for the nation's current fleet of internal combustion engine vehicles. Yet, despite the challenges, transformation to a hydrogen economy will create economic opportunities and reduce pollutants and greenhouse gas emissions, two important drivers of the national program.

A major finding in this report is that if hydrogen is to achieve environmental advantage over current technologies, hydrogen must be produced using carbon-neutral methods. The critical need for low carbon hydrogen production methods plays directly into one of Minnesota's strengths--renewable energy production. The most prudent investments that Minnesota can make to foster a hydrogen economy are investments to increase efficiency, lower costs, and expand renewable energy production. Investments in development and improvements to Minnesota's renewable energy production systems will position Minnesota to produce renewable hydrogen if and when a hydrogen vehicle market develops.

In addition to development and improvement in renewable energy production in the state, the Minnesota Renewable Hydrogen Initiative found that actions undertaken in the following technical focus areas (see section VI) have potential to further Minnesota economic development while assuring that investments made will benefit renewable energy as well as hydrogen production.

- Electric powered (fuel cell or battery) grounds/off-road vehicles
- Wind power-to-hydrogen and hydrogen storage
 - electricity production
 - off-road vehicles and fueling

- Biomass to hydrogen-rich fuels
 - Gasification-derived hydrogen-rich fuels
 - Methods which produce clean syngas of quality required to produce high-value products
 - Anaerobic digester-derived fuels
 - Methods which incorporate clean biogas to natural gas pipe-line and CNG applications.
- Biomass feedstocks for renewable energy, including hydrogen
- Linking bio-feedstocks with a community's most beneficial conversion technologies

Investments in projects that meet the following criteria have good potential to assure that support is targeted at acceleration of technical and economic viability toward the goal of commercialization.

- Minnesota-based projects that address a particular technical barrier related to commercialization of the production and/or use of renewable hydrogen and/or related technologies.
- Utilize an industry base within the state for support and expertise to build on an area of particular strength within the state's renewable hydrogen research and development community.
- Determine current economic viability and simple payback period of method(s) used for the production and/or use of renewable hydrogen, and identify improvement needed to become cost-competitive with traditional products.

Minnesota's current energy efficiency, renewable energy and greenhouse gas reduction policies place Minnesota on the path toward the hydrogen economy. Staying on course can position Minnesota as a leader in renewable hydrogen production if and when the hydrogen economy emerges.

Minnesota Renewable Hydrogen Initiative Roadmap

I. BACKGROUND

The Minnesota Renewable Hydrogen Initiative (MRHI) is coordinated by the Minnesota Department of Commerce, Office of Energy Security (OES) and is charged to oversee the development and implementation of a renewable hydrogen roadmap as specified in Minn. Stat. 216B.813.

216B.813 Minnesota Renewable Hydrogen Initiative.

Subdivision 1. **Road map.** The Department of Commerce shall coordinate and administer directly or by contract the Minnesota renewable hydrogen initiative. If the department decides to contract for its duties under this section, it must contract with a nonpartisan, nonprofit organization within the state to develop the road map. The initiative may be run as a public-private partnership representing business, academic, governmental, and nongovernmental organizations. The initiative must oversee the development and implementation of a renewable hydrogen road map, including appropriate technology deployments that achieve the hydrogen goal of section 216B.8109. The road map should be compatible with the United States Department of Energy's National Hydrogen Energy Roadmap and be based on an assessment of marketplace economics and the state's opportunities in hydrogen, fuel cells, and related technologies, so as to capitalize on strengths. The road map should establish a vision, goals, general timeline, strategies for working with industry, and measurable milestones for achieving the state's renewable hydrogen goal. The road map should describe how renewable hydrogen and fuel cells fit in Minnesota's overall energy system, and should help foster a consistent, predictable, and prudent investment environment.

II. MINNESOTA STRENGTHS

Although the current stage of the nation's hydrogen economy has significant technical and economic challenges, this roadmap lays out strategies to guide the state toward prudent investments for renewable hydrogen development with comparatively low risk. Rather than considering the hydrogen economy in isolation, the roadmap builds the state's renewable hydrogen vision as an integral part of Minnesota's collective energy-related policies, goals and timelines. A synergistic approach to renewable energy will better leverage opportunities that speed the pace of renewable hydrogen production through identifying partners and projects on which the state can build. This strategy aligns renewable hydrogen projects with a complementary array of low-carbon energy initiatives so that success is not dependant on marked acceptance of one technical pathway. However, should a significant technical and economic breakthrough for the hydrogen economy occur, this strategy places the state in a position to benefit from it.

The critical need for carbon-neutral methods of hydrogen production to achieve a competitive environmental advantage over current fossil fuel-based production methods plays directly into one of Minnesota's strengths--renewable energy production. Any future demand for low-carbon hydrogen will allow Minnesota to capitalize on the renewable energy infrastructure that is currently developing in response to the state's renewable energy goals. The state's renewable producers will be able to expand into hydrogen production if sufficient demand develops. Thus, investments to increase efficiency, lower costs, and expand renewable energy production alone will help position Minnesota to produce renewable hydrogen if and when a hydrogen economy develops. In addition, Minnesota's renewable energy businesses are valuable stakeholders in a future hydrogen economy and are crucial to identifying areas where additional investments can be made to foster greater use of hydrogen in a strategic manner--one that will also help grow the state's economy.

The following provides a discussion of the issues related to hydrogen, the national environment under which hydrogen production, storage and end use technologies are being developed, and the opportunities for Minnesota to play a meaningful role within that environment.

III. HYDROGEN OVERVIEW

A. *HYDROGEN PROPERTIES*

Hydrogen is an extremely valuable element--a critical component of organic life and water. It is the lightest and most abundant element on earth and makes up approximately 75% of the mass of the universe; however, naturally occurring elemental hydrogen is rare on earth. It is commonly bonded to other elements to form molecules and must be freed from molecular structures, such as water, biomass or petroleum-based products, for use in energy applications.

Hydrogen has a long history. It was first identified as an element in 1766, and shortly thereafter, hydrogen and oxygen were identified as the two elements that bonded together to make water. A hundred years later in the mid-19th century, an associated technology, the fuel cell, was discovered when a Swiss chemist found that combining hydrogen and oxygen gases produced water and electricity. It was not until the turn of the 20th century, when German Count Ferdinand von Zeppelin invented the steerable hydrogen-fueled balloon, that hydrogen came to the attention of the general public.

Commercial level production of hydrogen began in Germany during World War I when Allied Forces blockaded nitrate shipments to Germany. Germany used the newly patented Haber-Bosch process, which relies on a reaction of nitrogen and hydrogen gases over an enriched iron catalyst, to produce nitrates from air. The nitrates were used to make explosives. The most common use of manufactured hydrogen today is in chemical processes and reactions (such as breaking down crude oil into gasoline and other fuels), making fertilizer, and making solvents for use in the manufacture of paints, cements, inks and many other products.

After the war, a German engineer converted an internal combustion engine (ICE) to use hydrogen-rich gases and his work stimulated interest in hydrogen as a fuel for vehicles. Few practical applications followed until 1969, when NASA launched the hydrogen-fueled Apollo 11 mission and interest in hydrogen as a fuel grew, particularly as a fuel for the transportation sector.

As with batteries and capacitors, hydrogen is an energy carrier. It is not a primary energy source such as wind, solar, water current, wood, coal or oil. Energy carriers can store the energy obtained from multiple energy sources and then be used to transport it from one place to another. Energy carriers are attractive because they can carry energy obtained from diverse energy sources and deliver it in a consistent form to where it is needed.

B. HYDROGEN PRODUCTION

Virtually all of the hydrogen produced in the United States comes from fossil fuels such as natural gas and coal. The cheapest and most common method of hydrogen extraction is steam-methane reformation (SMR). During this process, heat is added to water and natural gas over a catalyst, producing a hydrogen-rich gas. SMR is used to produce roughly 95% of the hydrogen in use today. It is the predominant hydrogen production method for making fertilizers, dyes, drugs, electronics and plastics; to hydrogenate oils and fats; and for making fuel for welding.

Feedstocks such as biomass and coal can be used to produce hydrogen and hydrogen rich gases. These gases can then be used to make fuels such as dimethyl ether, methanol, or “synthetic” diesel and gasoline which are fully compatible with their petroleum-based counterparts. In its super-cooled liquid form, hydrogen powers unmanned rockets and the space shuttle; and it is used onboard space shuttles in alkaline fuel cells that provide astronauts with electricity and potable water. Demonstration and verification of cost-effective carbon sequestration technologies are needed for fossil fuel methods of hydrogen production in order to achieve greenhouse gas (GHG) reduction benefits in a fuel cell vehicle, compared to alternative vehicle technologies that are currently available

Hydrogen production through carbon-neutral or renewable forms of energy provides the GHG reduction benefit needed for fuel cell vehicles to achieved greater environmental benefits over alternative vehicle technologies. There are many production technologies to make hydrogen from renewable sources of energy that are available today, but the cost of the hydrogen produced by these methods exceeds the marketable price point that would make hydrogen competitive with other low-carbon fuels and efficiency technologies. An example of a renewable hydrogen production process is electrolysis. Electrolysis can be used with wind, solar and hydro power to produce hydrogen from water. Electrolysis relies on electricity to split water (H_2O) into its constituent parts--oxygen (O_2) and hydrogen (H_2). Renewable hydrogen can also be produced from biomass, using a number of thermo chemical and biological processes. Renewable hydrogen, in its purified state, is completely interchangeable with hydrogen produced from fossil fuels and, therefore, can be used to make the same manufactured products.

C. FUEL CELLS

A fuel cell is a device that uses hydrogen (or a hydrogen-rich fuel) and oxygen to create an electric current. When pure hydrogen is used to power a fuel cell, only water and heat are exhausted from the device. Fuel cells are classified by the kind of electrolyte they use. This determines the kind of chemical reactions that take place in the cell, the kind of catalysts that are needed, the temperature operation range, and the fuel required.

According to data assembled by [Fuel Cells 2000](#), a database compiled by the Breakthrough Technologies Institute, a nonprofit educational organization that identifies and promotes environmental and energy technologies, less than 1,000 fuel cell units are in operation or planned worldwide today.¹ Many of the fuel cells that have been installed are in their performance testing or early commercialization stage. Demonstrations of fuel cells are found in the backup power supply and distributed power plant markets. Fuel cells are also in use to provide auxiliary power for manned spacecraft and motive power for submarines. The area with greatest fuel cell penetration and the most commercialization success is the portable device market, including laptop computers and cell phones. Several types of fuel cells, such as Polymer Electrolyte Membrane, Direct Methanol, Alkaline, Phosphoric Acid, Molten Carbonate, Solid Oxide and Regenerative Fuel Cells, exist. Due to their market share, Polymer Electrolyte Membrane and Solid Oxide are summarized below.

Proton-Exchange-Membrane (PEM) fuel cells are the type of fuel cell best suited to power vehicles. They use a solid electrolyte, have high power density, and operate at lower pressure ranges and at temperatures below the boiling point of water than other fuel cells. The low operating temperature enables the fuel cell to warm up and begin generating electricity quickly, an important feature for use in vehicles.

Solid oxide fuel cells (SOFC) have a solid oxide, or ceramic, electrolyte, which makes them particularly well suited for stationary applications. They can convert a wide variety of fuels to power and do so with high efficiency (40-60% unassisted, up to 70% in pressurized hybrid system) in comparison to engines and modern thermal power plants (30-40% efficient).² But SOFC, like other types of contaminant-tolerant, higher-temperature fuel cells, are relatively slow to start up and are not suited to meet consumer demands for vehicle applications. A major advantage of SOFC and other contaminant-tolerant fuel cells is that they can operate on hydrogen without full removal of impurities, while PEM and some other fuel cell technologies require pure hydrogen, a difficult molecule to extract.

IV. NATIONAL HYDROGEN AND FUEL CELL DEVELOPMENT PROGRAM: BACKGROUND AND TECHNOLOGY DEVELOPMENT TARGETS

During the 1960s and 1970s, hydrogen research was divided between two U.S. government agencies. Fundamental research was primarily sponsored by the National Science Foundation,

¹ The Breakthrough Technologies Institute, Fuel Cells 2000 Database, <http://www.fuelcells.org/db/>, December, 2009

² Singhal, S.C., *Science and Technology of Solid-Oxide Fuel Cells*, Materials Research Society Bulletin. Vol.25, No.3, 2000, p.16-21

while applied hydrogen research was conducted by the National Aeronautics and Space Administration (NASA). In 1978, the National Science Foundation transferred the Federal Hydrogen Research and Development (R&D) Program to the U.S. Department of Energy (U.S. DOE), a transfer that signaled the development of hydrogen for energy applications was entering a commercialization stage of research and development.

In the 1990s, U.S. DOE began a concentrated effort to develop advanced vehicle technologies that would reduce oil dependence and pollution. It established a cooperative research and development program, the Partnership for a New Generation of Vehicles, specific to advanced vehicles technologies and alternative fuels. This partnership was established as a joint effort between the government and automobile manufacturers. In 1992, the program identified hydrogen and fuel cells as one of the eligible technologies to receive R&D funding, an early indication that the U.S. auto industry considered hydrogen fuel cell vehicles to have commercialization potential.

In 2002, U.S. DOE coordinated the development of the nation's first National Hydrogen Energy Roadmap, *National Hydrogen Energy Roadmap: Toward a More Secure and Cleaner Energy Future for America*.³ The national hydrogen roadmap outlines the main issues regarding hydrogen development, particularly as a vehicle fuel, and maps out a general direction for government and industry to expand the use of hydrogen-based energy. The major drivers for development of hydrogen fuel cell transportation systems identified in the roadmap remain the primary drivers today. These are:

- National security and the need to reduce oil imports
- Global climate change and the need to reduce and ultimately stabilize GHG emissions and pollution
- Global population and economic growth
- The need for new, clean energy supplies at affordable prices
- Air quality and the need to reduce emissions from vehicles and power plants⁴

The program to develop hydrogen fuel cell vehicles was expanded in 2003, and the National Hydrogen Fuel Initiative, a group representing 30 lead organizations and more than 100 competitively selected partners, was given the responsibility for strategically guiding program expenditures toward commercialization of fuel cell vehicles. The program was allocated a total of \$1.15 billion over a five-year period through fiscal year 2008, with the budget escalating from \$159 million in the first year to \$279.2 million in the last. National Hydrogen Fuel Initiative's main goal was to make incremental improvements to the hydrogen system and fuel cell technologies so that by the year 2020 these technologies would be market ready and would become the power generating technology in future passenger vehicles.

³ United States Department of Energy, *National Hydrogen Energy Roadmap: Toward a More Secure and Cleaner Energy Future for America*, November 2002.

⁴ U.S Department of Energy, *National Hydrogen Roadmap, Toward a More Secure and Cleaner Energy Future for America*, 2002. http://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf, Page 1.

Within the spectrum of uses for hydrogen and fuel cell technologies, the transportation sector is the primary focus of U.S. DOE's hydrogen program because of two reasons: 1) market size and impact of the transportation sector, and 2) the potential to eliminate all emissions of regulatory concern from vehicle exhaust and fueling stations. However, it is also one of the higher risk and more costly sectors to transform into a hydrogen economy. Converting the light-weight passenger vehicle sector to run on hydrogen fuel cells involves not only conversion of the vehicle itself, but also the entire gasoline production, distribution and refueling infrastructure as well. Financial risk is high because the net environmental benefits of such a transition are dependent on how the hydrogen is produced and because significant technical challenges remain. Also, due to the infrastructure conversion required, the transition is a long-term task projected to cost billions of dollars. Consequently, it is appropriate for federal efforts to address these risk and for states (as is the case for Minnesota) to determine the level of risk that is appropriate for them and make investments that are commensurate with that risk.

One of the most compelling reasons for using hydrogen fuel cells in passenger vehicles is the potential for the technology to reduce tailpipe GHG and priority air pollutant emissions.⁵ Estimates of GHG emission reductions that the nation could achieve through transformation of its current petroleum-fueled fleet of light-duty vehicles over to hydrogen-powered fuel cells can be quite substantial because hydrogen fuel cell vehicles emit only water vapor and some hydrogen--neither of which is a concern for local air pollution. However, comparison weakens when two factors are taken into consideration.

The first is dependant upon how the hydrogen is produced. Significant GHG emissions result when hydrogen is produced from fossil fuels--by far the most common means of producing hydrogen today.

The second is that alternative vehicle technologies compete with hydrogen and fuel cell vehicles. Gasoline and diesel electric hybrid engines are commercially available, as are fully electric vehicles. Although these technologies are still maturing, they are currently for sale to the general public which is not the case for hydrogen fuel cell vehicles. They are also achieving many of the same benefits targeted by hydrogen fuel cell technologies without the need for very substantial infrastructure investments. This issue was assessed in 2008 by the Board on Energy and Environmental Systems of the National Research Council (NRC) of the National Academies in a study titled *Transitions to Alternative Transportation Technologies--A Focus on Hydrogen*.⁶ The finding of NRC highlighted some low-risk avenues within the universe of hydrogen economy development. Some of these low-risk avenues match well with the strengths of Minnesota and coincide with recommendations found in section VII of this roadmap.

⁵Criteria pollutants are air pollutants for which the U.S. Environmental Protection Agency has established National Ambient Air Quality Standards are [carbon monoxide \(CO\)](#), [nitrogen oxides \(NO_x\)](#), [lead \(Pb\)](#), [total particulate matter \(PT\)](#), [particulate matter less than 10 microns in diameter \(PM₁₀\)](#), [sulfur dioxides \(SO₂\)](#), [volatile organic compounds \(VOC\)](#) due to reactions with sunlight in air to produce NO_x. <http://www.pca.state.mn.us/air/criteria-emissioninventory.html>

⁶ Board on Energy and Environmental Systems of the National Research Council (NRC) of the National Academies, *Transitions to Alternative Transportation Technologies — A Focus on Hydrogen*, National Academies Press, 2008.

NRC's study was conducted at the request of Congress to assess the current status of the national hydrogen fuel cell vehicle program. It provides an estimate of the investments that would be needed for the national hydrogen vehicle program to meet a goal of two million vehicles on the road by 2020 (cumulative total from government and industry including R&D estimated at \$200 billion for the period 2008-2023). This work also assessed GHG emission reductions that are estimated at various market penetration rates for current alternative vehicle technologies and compared those to estimated GHG reduction levels that are expected from hydrogen fuel cell vehicles. It concludes that the main advantage of a transition to hydrogen fuel cell vehicles is the potential for reducing the use of oil and emissions of CO₂. It projected that further penetration of other current alternative vehicle technologies in the market could deliver significantly greater reductions in U.S. oil use and CO₂ emissions than the use of hydrogen fuel cell vehicles over the next two decades, but that the longer-term benefits of such approaches were likely to grow at a smaller rate thereafter, even with continued technological improvements, whereas hydrogen offers greater longer-term potential.⁷ But the study also acknowledges that the ability of hydrogen fuel cell vehicles to achieve significant GHG reductions over current alternative vehicle technologies assumes that hydrogen and electric energy **can be made in a way that does not release greenhouse gases over the long term.**⁸

In February 2004, the National Hydrogen Fuel Initiative issued its first *Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan* that identified performance and cost goals and developed strategies and a timeline to accelerate the pace of fuel cell vehicle commercialization. The plan was updated in 2006. Milestones in the 2006 plan covered the following areas:

- Hydrogen production
- Storage
- Hydrogen conversion (fuel cells)
- Delivery
- Technology validation demonstrations
- Systems analysis milestone

The Hydrogen Posture Plan laid out the technical targets needed for each system component. The plan envisioned an integrated roll-out of fuel cell vehicles and an associated refueling infrastructure that was aimed at attaining the performance from a fuel cell vehicle and refueling system that today's drivers get from their gasoline-powered vehicles in terms of driving range, durability, and costs. The plan includes interim milestone target dates intended to keep technology development on schedule.

An assessment of the national hydrogen vehicle program was conducted in 2008 by the Government Accounting Office (GAO). Their report, *A Report to Congressional Requesters, Hydrogen Fuel Cell Initiative*, concluded that U.S. DOE has made significant progress toward

⁷ Board on Energy and Environmental Systems of the National Research Council (NRC) of the National Academies, *Transitions to Alternative Transportation Technologies — A Focus on Hydrogen*, National Academies Press, 2008, pg 24.

⁸ Board on Energy and Environmental Systems of the National Research Council (NRC) of the National Academies, *Transitions to Alternative Transportation Technologies — A Focus on Hydrogen*, National Academies Press, 2008.

achieving many targets.⁹ It also found that a few key deadlines, particularly in the hydrogen storage and delivery system areas, have been delayed or not met. The GAO report and U.S. DOE program status documents are summarized in the next section to provide an overview of the technical program targets and summarize the status toward commercialization. Although the majority of the national hydrogen targets are directed at development of an integrated hydrogen system for light-duty vehicles, components of such a system, like the target for renewable hydrogen production, are applicable to other avenues for hydrogen commercialization.

A. SUMMARY OF NATIONAL FUEL CELL PROGRAM

Cost and durability are the major challenges to fuel cell commercialization. The national *Hydrogen Posture Plan* identifies the costs and performance targets needed for its transportation and stationary fuel cell programs to develop technologies that are competitive with the current technologies they are to replace. It includes interim technology goals and milestones by which to measure progress and specifies decision points at which a determination is to be made on the feasibility of that area in technology development. For the transportation sector the target was set to develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system at a cost of \$45/kW and \$30/kW by 2010 and 2015, respectively. It also targeted PEM stationary power fuel cells that operate on natural gas or LPG to achieve an electrical efficiency rate of 40% and 40,000 hours durability at \$750/kW by 2011.¹⁰

These targets provide the direction and final goal for commercialization. To compete with today's internal combustion engines, for example, PEM fuel cells must have competitive lifecycle performance and cost. For automotive applications, this means a fuel cell system must be able to withstand a widely varying duty cycle with thousands of stops and starts, and it must be able to operate for approximately 5,000 hours (150,000 miles).¹¹ The cost must also be comparable to that of internal combustion engines (ICE). Current automotive ICE power plants cost approximately \$25-35/kW, which translates to a cost of less than \$50/kW that must be met by a fuel cell.¹²

In 2009, the cost of an 80kW automotive PEM fuel cell system operating on direct hydrogen was estimated at \$61/kW (or \$51/kW in 2002 dollars).¹³ This projection was based on a manufacturing volume of 500,000 units per year. A significant portion of this cost comes from

⁹ United States Government Accountability Office, Report to Congressional Requesters, *Hydrogen Fuel Cell Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target*, GAO-08-305, 2008.

¹⁰ U.S. Department of Energy, Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015, Section 3.4 Fuel Cells, Updated in 2007. <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>

¹¹ U.S. Department of Energy, *Fuel Cell School Buses: Report to Congress*, December 2008, http://www.hydrogen.energy.gov/pdfs/epact_743_fuel_cell_school_bus.pdf

¹² U.S. Department of Energy, Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015, 2005. <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>

¹³ Jacob Spendelow and Jason Marcinkoski, Originators, U.S. Department of Energy, DOE Hydrogen Program Record # 9012, *Fuel Cell System Cost – 2009*, October 7, 2009, 3 pages. http://www.hydrogen.energy.gov/pdfs/9012_fuel_cell_system_cost.pdf

the expensive precious metal catalyst. Although the estimates for high volume production costs indicate steady progress, the accuracy of these estimates is limited because many of the final technologies and manufacturing processes are still evolving or are unproven.¹⁴

The durability of fuel cells operating under conditions that automobiles experience has not yet been established. The problem of durability arises because the fuel cell is exposed to wide ranging temperatures (+40°C to -40°C) and climate conditions, along with many starts and stops, and varying fuel composition. The tolerance of a fuel cell stack to impurities under such variable conditions remains a significant factor for the technology to overcome in achieving expected performance and durability.¹⁵ Although steady progress in fundamental research on polymers and catalysts has been demonstrated, the national hydrogen experts believe that it will be difficult to assess this progress in terms of achieving program targets until the technologies are demonstrated on-board a vehicle or in a laboratory situation where vehicle operation can be accurately simulated.¹⁶

The national hydrogen program's fuel cell R&D efforts have advanced the technology to a great degree and are now primarily aimed at reducing cost and improving durability of fuel cells. The key objectives are to develop a vehicular polymer electrolyte membrane (PEM) fuel cell power system with 60% peak efficiency and a 5,000-hour lifespan (150,000 miles) at a cost of \$30/kW (at large manufacturing volumes), and to develop a stationary PEM fuel cell system with 40 percent efficiency and a 40,000 hour lifespan at a cost of \$750/kW. Current stationary fuel cell performance has reached 20,000 hours, but significant improvement is still necessary.

Table 1 shows the current fuel cell durability, cost, and efficiency status and the 2010 and 2015 U.S. DOE targets for automotive applications. The program improved the durability of fuel cell systems for vehicles from 950 hours in 2006 to 1,900 hours in 2008 and are on track to reach the target of 5,000 hours durability by 2010 (approximately 150,000 miles of driving) if progress continues. The cost targets are also in range with the successful conversion to low platinum catalysts.¹⁷

¹⁴ Board on Energy and Environmental Systems, Transportation Research Board and Engineering and Physical Sciences Division of the National Research Council (NRC) of the National Academies, *Review of the Research Program of the FreedomCar and Fuel Partnership: First Report*, 2005, 146 pages http://www.nap.edu/catalog.php?record_id=11406

¹⁵ U.S. Department of Energy, Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015, 2005. <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>

¹⁶ Board on Energy and Environmental Systems, Transportation Research Board and Engineering and Physical Sciences Division of the National Research Council (NRC) of the National Academies, *Review of the Research Program of the FreedomCar and Fuel Partnership: First Report*, 2005, 146 pages http://www.nap.edu/catalog.php?record_id=11406

¹⁷ K. Wipke, "Completed Learning Demonstration Composite Data Products as of December 1, 2006," National Renewable Energy Laboratory, December 2006, slide 5, www.nrel.gov/hydrogen/docs/cdp/41090.ppt; and K. Wipke, et al., "Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, slide 4, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

Table 1: Technical Targets for Automotive Applications: ¹⁸

80kW (net) Integrated Fuel Cell Power Systems Operating on Direct Hydrogen ¹⁹					
Characteristic	Units	2003 Status	2005 Status	2010	2015
Energy efficiency ²⁰ @ 25% of rated power	%	59	59	60	60
Energy efficiency @ rated power	%	50	50	50	50
Power density	W / L	440	500	650	650
Specific power	W / kg	420	470 ²¹	650	650
Cost ²²	\$ / kW ²³	200	110 ²⁴	45	30
Transient response (time from 10% to 90% of rated power)	seconds	3	1.5	1	1
Cold start-up time to 50% of rated power					
@-20°C ambient temp	seconds	120	20	30	30
@+20°C ambient temp	seconds	60	<10	5	5
Start up and shut down energy ²⁵					
from -20°C ambient temp	MJ	N/A	7.5	5	5
from +20°C ambient temp	MJ	N/A	N/A	1	1
Durability with cycling	hours	N/A	~1,000 ²⁶	5,000 ²⁷	5,000 ²⁸
Unassisted start from low temperatures ²⁹	°C	N/A	-20	-40	-40

To specifically address the cost and durability issues, a significant amount of fuel cell research has been devoted to improving fuel cell membranes, reducing expense of catalysts, and decreasing the effect of impurities on the fuel cell durability. Improvements are continually being achieved in these areas, but there is a lag time before these achievements are verified and reported. Some breakthroughs have been made that are not yet reflected in summary reports. For example, a notable success, announced in June 2008, was achieved in the area of PEM catalysis materials and fuel cell durability. Through the use of ternary platinum alloys and with the help of mechanical stabilization techniques, durability for membrane electrode assemblies has improved from 2,000 hours in 2005 to more than 7,300 hours under cycling conditions, while at the same

¹⁸ U.S. Department of Energy, Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015, Section 3.4 Fuel Cells page 14, Updated in 2007.

<http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>

¹⁹ Targets exclude hydrogen storage, power electronics and electric drive.

²⁰ Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

²¹ Based on corresponding data in Table 3.4.3 divided by 3 to account for ancillaries.

²² Based on 2002 dollars and cost projected to high-volume production (500,000 systems per year).

²³ Status is from 2005 TIAX study and will be periodically updated.

²⁴ Status is from 2005 TIAX study and will be periodically updated.

²⁵ Includes electrical energy and the hydrogen used during the start-up and shut-down procedures.

²⁶ Durability with cycling is being evaluated through the Technology Validation activity. Steady-state stack durability is 20,000 hours.

²⁷ Based on test protocol to be issued by DOE in 2007.

²⁸ Based on test protocol to be issued by DOE in 2007.

²⁹ 8-hour soak at stated temperature must not impact subsequent achievement of targets.

time major improvement in the use of platinum group metals were reduced to 0.2 mg/cm². This exceeds the national hydrogen program's 2010 durability target requiring 5,000 hours as well as the platinum reduction target of 0.3 mg/cm² platinum loading³⁰.

A novel approach to the design and fabrication of the fuel cell membrane electrode assembly, reported by 3M, eliminates the corrosion-prone carbon support structure and utilizes nanoscale metallic whiskers and a vacuum-deposited, thin film of catalyst. This approach, while not yet proven commercially viable, offers the potential for simultaneously increasing fuel cell durability and reducing costs, a large step toward achieving the necessary performance and cost goals for commercialization.

The national deployment goal of 100,000 hydrogen-fueled vehicles by 2010, as specified in Environmental Protection Act, section 811(a)(4), will not be met because the cost of PEM fuel cells still remains too high and durability too low for commercial-scale production. Although research is promising, too many uncertainties remain to determine whether the industry can achieve the 2020 vehicle deployment goal of 2.5 million hydrogen-fueled vehicles identified in section 811(a)(4) of the Environmental Protection Act. However, the 2009 U.S. Department of Energy, Report to Congress regarding fuel cell vehicles notes that market entry on that scale by that date is doubtful.³¹

B. NON-VEHICLE MARKETS FOR FUEL CELLS

The development of niche-market applications for hydrogen fuel cells has been identified as the quickest way to achieve early market penetration. A study conducted for the national hydrogen program by the Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen PEM Fuel Cell Markets*,³¹ identifies fuel cells to power forklifts and to provide backup power for telecommunications and emergency response as promising near-term opportunities. The most promising near-term opportunities for PEM fuel cells in this size range are in specialty vehicles and backup power applications. PEM fuel cell systems are commercially available to support these applications and offer several potential advantages over current technologies. However, PEM fuel cells were found to be much less attractive than alternatives when longer backup power runtimes are required (one week or more) due to the high cost of hydrogen storage and use.

For a brief summary of early market opportunities for PEM fuel cells, see the program's fact sheets on forklifts and backup power at:

www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/early_markets_forklifts.pdf and www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/early_markets_backup_power.pdf. For the full report by the Battelle Memorial Institute, see: www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

³⁰ Garland, Nancy, *Fuel Cells*. U.S. Department of Energy Hydrogen Program Presentation presented at the 2008 DOE Hydrogen Program Merit Review and Peer Evaluation Meeting June 9, 2008. (2008)

³¹ U.S. Department of Energy, Report to Congress, *Hydrogen and Fuel Cell Activities, Progress, and Plans: Report to Congress*. (2009, U.S. Government) http://www.hydrogen.energy.gov/pdfs/epact_report_sec811.pdf

U.S. DOE has research efforts in stationary and distributed generation fuel cell systems as well as automotive fuel cells, although funding has been significantly lower. Stationary and distributed generation fuel cells are typically contaminant tolerant and operate at higher temperatures than PEM fuel cells. In the stationary market, where applications such as combined heating and power are targeted for fuel cell systems, the acceptable price point and also the durability standards are considerably higher than for transportation applications. Although progress had been made towards achieving the original goals of the program, some key target dates have not yet been met. U.S. DOE and the stationary and distributed generation fuel cell industry are currently in the process of updating targets and milestone dates in line with more realistic commercialization expectations. The following table, Table 2, shows the new preliminary targets that U.S. DOE and the industry are proposing, using information submitted in response to a U.D. DOE Request for Information from the fuel cell developer and R&D community. (<http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/systems.html>).

Table 2

Preliminary Technical Targets: 1–10 kW Residential Combined Heat and Power Fuel Cells Operating on Natural Gas³²				
	2008 Status	2012	2015	2020
Electrical efficiency at rated power ³³	34%	40%	42.5%	45%
CHP energy efficiency ³⁴	80%	85%	87.5%	90%
Factory cost ³⁵	\$750/kW	\$650/kW	\$550/kW	\$450/kW
Transient response (10%- 90% rated power)	5 min	4 min	3 min	2 min
Start-up time from 20°C ambient temperature	60 min	45 min	30 min	20 min
Degradation with cycling ³⁶	< 2%/1000 h	0.7%/1000 h	0.5%/1000 h	0.3%/1000 h
Operating lifetime ³⁷	6,000 h	30,000 h	40,000 h	60,000 h
System availability	97%	97.5%	98%	99%

C. NATIONAL HYDROGEN STORAGE TARGETS

Significant advancement and innovation will be needed to make hydrogen storage technology economically feasible by U.S. DOE's 2015 target date. Table 3 shows the current status of various hydrogen storage technologies and the targets.³⁸

³² Standard utility natural gas delivered at typical residential distribution line pressures.

³³ Regulated AC net/lower heating value of fuel.

³⁴ Only heat available at 80°C or higher is included in CHP energy efficiency calculation.

³⁵ Cost includes materials and labor costs to produce stack, plus any balance of plant necessary for stack operation. Cost defined at 50,000 unit/year production (250 MW in 5-kW modules).

³⁶ Based on operating cycle to be released in 2010.

³⁷ Time until >20% net power degradation.

³⁸ Sunita Satyapal, U.S. Department of Energy Presentation, *Hydrogen Program Overview: 2009 DOE Hydrogen Program and Vehicle Technologies Program*, presented at the Annual Merit Review and Peer Evaluation Meeting May 18, 2009, Slide 41. http://www.hydrogen.energy.gov/pdfs/review09/program_overview_2009_amr.pdf

Table 3

Current Hydrogen Storage Status and Targets					
Test Metrics	Current Status				2015 Target
	<i>350 bar</i>	<i>700 bar</i>	<i>Mat.-based</i>	<i>Liquid H2</i>	
System Gravimetric Density (wt%)	2.8 -3.8	2.5 -4.4	0.03	5.1 -6.5	5.5
System Volumetric Density (g/L)	17 -18	18 -25	14 -19	22 -36	40
System Cost (\$/kWh)	~15.5	~23	~15.6	~8	2

The main technical challenge for hydrogen storage for transportation applications is how to store the necessary amount of hydrogen required for the conventional driving range (greater than 300 miles). Table 3 shows that although the energy density requirements achieved through the Hydrogen Vehicle program seem to be within reach for some of the storage methods, the system cost is at least 4 to 11 times higher than the 2015 target. U.S. DOE is focusing research on identifying new materials that may increase storage capacity, while reducing cost. It may take a significant technical breakthrough to develop needed new materials, which adds to the uncertainty about whether hydrogen storage can meet the 2015 program target.

D. NATIONAL HYDROGEN DELIVERY TARGETS

In a scenario where demand for hydrogen fuel cell vehicles increases, a hydrogen distribution system and refueling network will need to be developed and to expand in tandem, eventually replacing the world's vast petroleum refueling infrastructure. Due to the ease in which the small hydrogen molecule can escape through a surface, transporting hydrogen without large losses requires more costly materials. Current costs for the transport of hydrogen range from \$3 to \$9/gasoline gallon equivalent (gge). This is based on transport by gaseous tube trailers or cryogenic liquid tank trucks and is dependent on the quantity of hydrogen and distance that the hydrogen is transported. Pipeline transport costs are at the lower end of the cost range and are also dependent on transport distance and quantities. These transport costs do not include the delivery costs associated with compression, storage and dispensing at fueling sites. These additional costs could be as high as \$2-\$3/gge of hydrogen.³⁹

There are some strategies for hydrogen delivery systems that may not be as costly as replacing or duplicating the extensive petroleum fuel delivery network that is in existence today. The National Academies study suggests that a national hydrogen distribution system may never be as centralized as the current petroleum refueling system, and, in fact, may develop along lines which connect nodes of smaller distributed hydrogen production facilities. This model complements the model for development of renewable energy and provides one reason for

³⁹ Gardiner, Monterey, *FY 2009 Annual Progress Report, U.S. DOE Hydrogen Program*, Chapter III, page 285

Minnesota to take production of renewable hydrogen into consideration as it moves forward on its path toward achieving its goal of obtaining 25% percent of its energy from renewable sources by 2025

The main challenge for hydrogen delivery is reducing the cost of the technology so that stakeholders can achieve a return on the investment required for this infrastructure. The energy efficiency of delivery also needs to be improved. Table 4 shows the current status of various hydrogen delivery methods.

Table 4
Current Hydrogen Delivery Status and Target⁴⁰

Delivery Method	Current Status	Target
Pipeline to Station (350 bar)	\$3/gge	< \$1/gge, from point of prod. to point of use
Pipeline & Truck to Station	\$5/gge	
Liquid Truck to Station	\$3.2/gge	

There are approximately 700 miles of hydrogen pipeline in the United States today, primarily for the refinery industry in Texas and Louisiana. Significant cost reductions and performance improvements are required in hydrogen distribution systems. The national program set a long-term target of <\$1.00/gge in 2015, including the operation costs at the refueling site. Pipelines generally offer the least cost alternative for petroleum, ethanol and natural gas. But pipelines have leakage and embrittlement problems when used for transporting hydrogen. Pipeline planners are hesitant to give a generalized estimation for pipeline construction cost because it is very dependent on the location. A pipeline through a rural area without special environmental concerns can cost five times less than a pipeline of the same length and diameter through a dense urban area. The following table, Table 5, from Argonne National Laboratory estimates that hydrogen pipelines will cost an additional 45-75% more than natural gas pipelines, depending on method used.⁴¹

⁴⁰ Gardiner, Monterey, *FY 2009 Annual Progress Report, U.S. DOE Hydrogen Program*, Chapter III, page 285-286

⁴¹ Mintz , Marianne; Folga, Stephen; Molburg, John; Gillette, Jerry; U.S. Department of Energy, Argonne National Laboratory, Transportation Technology R&D Center, Presentation to the Transportation Research Board, *Cost of Some Hydrogen Fuel Infrastructure Options*, Slide 21, January 16, 2002



Table 5
Unit Cost of NG & H₂ Pipelines Vary with Pipe Diameter & Installation Technology

Diameter (inch)	Capital Cost of Natural Gas Pipeline (\$/mi)	Capital Cost of H ₂ Pipeline, Cut/Cover (\$/mi)	Capital Cost of H ₂ Pipeline, Trenchless (\$/mi)
3	\$200,000	\$400,000	\$300,000
9	\$500,000	\$900,000	\$700,000
12	\$600,000	\$1,000,000	\$900,000
14	\$800,000	\$1,400,000	\$1,150,000

Argonne National Laboratory
Transportation Technology R&D Center

Hydrogen compression technology is another component of the hydrogen delivery system that was identified as needing reliability improvements and cost reductions to meet the goals of the national hydrogen program. If liquefaction and cryogenic liquid transport, a frequently cited delivery method, is to be used, the capital cost and energy efficiency of liquefaction needs to be improved by about 15%.⁴² The challenges associated with reducing delivery cost would also benefit by the cross-cutting efforts of reducing the cost of hydrogen storage. National hydrogen program experts also point to the use of gaseous tube trailers as an attractive method of delivery if their carrying capacity could be significantly increased through the use of higher pressure, cooled gas, and/or the use of a novel solid carrier in the tubes.

E. NATIONAL HYDROGEN PRODUCTION TARGETS

Hydrogen can be harvested from many common fossil fuels, such as natural gas, coal, gasoline and diesel fuel, or from renewable resources such as biomass and water. Depending on size and scale of production facility, hydrogen production systems, like other energy systems, are frequently referred to as either distributed production systems or centralized. Distributed production is loosely defined as small-scale energy production or generation from sites that are dispersed around a region, typically located near the resource that will be used to produce the energy. Distributed hydrogen production systems are frequently modular natural gas reformers, but examples of renewable hydrogen produced from wind, solar, hydro or biomass resources exist. Given the availability of renewable energy resources for hydrogen production, they can be ideal for many rural communities where the renewable energy sources or biomass feedstock is abundant. Because this approach serves as a smaller point-of-use production plant and is not designed for production of large quantities of hydrogen, it requires lower capital investment. It is typically distinguished from centralized production methods by size of facility and amount of

⁴² U.S. Department of Energy, *Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015*, 2005.
<http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>

power produced--although there are no specific criteria to which either type of generation must conform. Distributed systems are also frequently scalable, with new modules added only when needed, another feature that reduces investment costs.

Distributed hydrogen generation may be the method suited best for the early stages of transition to a hydrogen economy. It requires less capital investment for development of the production facility. It does not require substantial hydrogen transport or delivery infrastructure. Two distributed hydrogen production technologies that have good potential for development are (1) reforming of natural gas or liquid fuels, including bio-derived liquids, such as ethanol and bio-oil, and (2) small-scale, solar or wind powered water electrolysis. Future research is focusing on applying the latest small-scale natural gas reforming systems, which are meeting the U.S. DOE cost targets, and reforming renewable liquid feedstocks, such as ethanol, at a competitive hydrogen cost. Using a renewable feedstock can dramatically decrease the GHG emissions, compared to using fossil natural gas. But renewable hydrogen need not all be distributed. Biomass processes are expected to be distributed at sites near the resource, while wind-based water electrolysis processes may find that the cost of capital equipment is reduced in larger, centralized projects.

For both methods, centralized or distributed, the main challenge to hydrogen production is cost. The national hydrogen cost targets, \$2-\$3 per gallons of gasoline equivalent (gge) were set by U.S. DOE to be competitive with current advanced gasoline-electric hybrid vehicles.⁴³ These targets are independent of production pathways. The national program anticipates these targets will be met in 2017 through continual improvements in production process methods and technologies. The targets are based on current prices for gasoline. If the price of gasoline increases, the national program may also increase its cost targets for hydrogen production accordingly, and hydrogen production may be cost competitive earlier.

The national hydrogen vehicle program has made significant progress in improvement efficiencies to today's dominant production method, SMR from natural gas. It has also made progress in renewable production methods. Table 6 shows how hydrogen produced from distributed natural gas reforming has met the upper target of \$3/gge. The table compares natural gas production with the most likely methods that are used for production using renewable sources. The comparison for the anticipated target is based on many assumptions, including that a sufficient volume is produced to achieve economy of scale and that projected technology advancements are expected to reduce costs.

⁴³ Garland, Roxanne, U.S. Department of Energy, *Hydrogen Cost Goal Item: \$2.00 - \$3.00/gge*, U.S. Department of Energy Hydrogen Program Record #: 5013, page 11. December 21, 2005

Table 6 ⁴⁴

Current Hydrogen Production Status and Target		
Production Method	Current Cost (\$/gge)	Target (\$/gge)
Distributed NG	\$3/gge	\$2-\$3/gge delivered at the pump
Distributed Bio-derived Liquids	\$4.4/gge	
Distributed Electrolysis	\$4.8/gge	
Central Wind Electrolysis	\$5.9/gge @ plant gate	
Central Biomass Gasification/ Pyrolysis	<\$2/gge @ plant gate	
Solar High-temp. Electrochemical	

The 2008 GAO report states that because the upper target for natural gas reformation has been met, the U.S. DOE will be phasing out R&D in that area and will focus resources in higher priority areas, such as reducing costs of hydrogen produced from renewable sources.

Over the last three years, U.S. DOE has identified a number of potential methods to reduce costs of hydrogen production for other production methods and has awarded grant contracts to further research in this area. The research focus for the near term is on distributed reformation of natural gas and renewable liquid fuels, and on electrolysis to meet initial lower volume hydrogen needs with the least capital equipment costs. For the long term, national research is focused on renewable feedstocks and energy sources, with emphasis on centralized options to take advantage of economies of scale when an adequate hydrogen delivery infrastructure is in place. Information about these projects and more detailed cost estimates for various hydrogen production pathways can be found in U.S. DOE's *Hydrogen, Fuel Cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015*.⁴⁵

Recently, U.S. DOE extended the target dates for producing hydrogen from renewable resources from 2015 to 2017.⁴⁶ Renewable hydrogen production methods still face many economic challenges. The costs of producing hydrogen using distributed or centralized water electrolysis

⁴⁴ Sunita Satyapal, US Department of Energy Presentation, *Hydrogen Overview: 2009 DOE Hydrogen Program and Vehicle Technologies Program*, presented at the Annual Merit Review and Peer Evaluation Meeting, May 18, 2009. Slide 41.

⁴⁵ Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015. U.S. Department of Energy (Updated in 2007)

⁴⁶ United States Government Accountability Office, Report to Congressional Requesters, *Hydrogen Fuel Cell Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target*, GAO-08-305, 2008.

units at wind power sites must be reduced by over 35 percent for distributed systems to be competitive with gasoline and by about 65 percent for centralized production (targets set at \$3/gge and \$2/gge, respectively).⁴⁷

Use of biomass crops for hydrogen encounters the same market issues that using agricultural crops for other fuels and energy sources encounter--their price is dependent on the market price of the crop. For example, reformation of bio-derived liquids, such as ethanol, for hydrogen is expensive because the cost of corn feedstock to make ethanol is currently high. Technology and process improvements may bring production costs down but will not affect the market price of the very feedstock on which they depend. Thus, methods of production (such as through gasification or anaerobic digestion, which can more easily use bio-waste or non-cash crops such as switchgrass) are being pursued. But advances are needed in areas such as the efficiency of biomass gasification technology or in reducing the capital costs of the gasifier for these methods to be widely adopted and cost competitive. As described in section VII of this roadmap, there may be opportunities for the state to support projects that are directed at advancing a technology toward meeting national hydrogen program goals, particularly in areas that also present economic or business opportunities in the state.

Large hydrogen production facilities can more easily take advantage of economies of scale, especially in the long term, to meet increases in hydrogen fuel demand. Central hydrogen production allows management of GHG emissions through strategies like carbon sequestration. U.S. DOE is pursuing central production of hydrogen from a variety of resources--fossil, nuclear and renewable, in parallel with their distributed production efforts.

V. HYDROGEN PRODUCTION: TECHNICAL AND ECONOMIC CHALLENGES

The following provides an overview of the primary technical and economic challenges for hydrogen production from wind, solar, hydro and biomass energy, and small-scale natural gas.

A. RENEWABLE HYDROGEN PRODUCTION

The overarching technical and economic challenge to hydrogen as an energy carrier is achieving system cost efficiencies to make hydrogen costs competitive with current fuels. There are a number of strategies within the national hydrogen program to lower costs. The strategies from US DOE's research and development plan,⁴⁸ briefly outlined below, are ones that target or are applicable to renewable hydrogen.

⁴⁷ United States Government Accountability Office, Report to Congressional Requesters, *Hydrogen Fuel Cell Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target*, GAO-08-305, page 15, 2008.

⁴⁸ U.S. Department of Energy, *Hydrogen, Fuel cells, and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015, Section 3.4, Updated 2007*.

Wind, Solar and Hydro Resources. Electrolysis is the primary method to produce hydrogen from wind, solar or hydro power. The capital costs of current water electrolysis systems, along with the high cost of electricity in many regions, limit widespread adoption of electrolysis technology for hydrogen production. Water electrolyzer capital cost reductions and efficiency improvements are required along with the design of utility-scale electrolyzers capable of grid integration and compatible with low-cost, near-zero emission electricity sources.

Biomass Resources. Hydrogen can be produced from biomass either by distributed reforming of bio-derived liquids or through gasification or pyrolysis of biomass feedstocks. Although technically feasible, the costs of currently available bio-derived liquids such as ethanol or sugar alcohols (e.g., sorbitol) need to be reduced before nearing economic feasibility. Significant improvements in ethanol reforming and improved technologies need to be developed for other bio-derived liquids to reduce the capital and operating costs for this distributed production option to become competitive. The efficiencies of biomass gasification, pyrolysis and reforming need to be increased and the capital costs need to be reduced by developing improved technologies and approaches.

B. DISTRIBUTED HYDROGEN PRODUCTION FROM NATURAL GAS OR RENEWABLE LIQUID FEEDSTOCKS

Reformer Capital Costs. Current small-scale distributed natural gas and renewable liquid feedstock reforming technologies have capital costs remain too high to achieve the targeted hydrogen production cost. Multiple-unit operations and low energy efficiencies are key contributors to the high capital cost. Improved reforming and water-gas shift catalysts are needed to increase yield and improve performance. Water-gas shift and hydrogen separation and purification costs need to be reduced. Process intensification by combining unit operations could significantly reduce costs. For example, combining the current two step water-gas shift reactor and pressure swing adsorption (PSA) separation into a single unit operation could significantly reduce capital costs.

Reformer Manufacturing. Distributed reforming units are currently designed and built one at a time. Efforts such as Design for Manufacture and Assembly (DFMA) need to be applied to develop more compact, skid mounted units that can be produced using currently available low-cost, high-throughput manufacturing methods (see the Manufacturing section of this plan).

Operation and Maintenance (O&M). O&M costs for distributed reforming hydrogen production from natural gas and renewable feedstocks are too high. Robust systems that require little maintenance and that include remote monitoring capability need to be developed.

Feedstock Issues. Availability of some feedstocks is limited in certain areas. Feedstock-flexible reformers are needed to address location-specific feedstock supply issues. Effects of impurities on the system from multiple feedstocks as well as the effects of impurities from variations in single feedstocks need to be addressed in the reformer design.

Greenhouse Gas Emissions. Distributed natural gas reformers emit greenhouse gases. Feedstocks and/or technologies that can approach near zero net GHG emissions are needed.

Control and Safety. Control and safety issues are associated with natural gas and renewable feedstock reforming, including on-off cycling. Effective operation control strategies are needed to minimize cost and emissions, maximize efficiency, and enhance safety. Hydrogen safety is a part of U.S. Department of Energy's Hydrogen Delivery and Safety Program elements.

C. *HYDROGEN GENERATION BY WATER ELECTROLYSIS*

Capital Cost. The capital costs of water electrolysis systems are prohibitive to widespread adoption of electrolysis technology for hydrogen production. R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital while improving the efficiency and durability of the system. Development of larger systems is also needed to take advantage of economies of scale. Technically viable systems for low-cost manufacturing need to be developed for this technology.

Hydrogen System Efficiency. New membrane, electrode and system designs are needed to improve system efficiency and durability. Mechanical high-pressure compression technology exhibits low energy efficiency and may introduce impurities while adding significantly to the capital and operating cost. Efficiency gains can be realized using compression in the cell stack. Development is needed for low-cost cell stack optimization addressing efficiency, compression and durability.

Grid Electricity Emissions (for distributed). The current grid electricity mix in most locations results in GHG emissions in large-scale electrolysis systems. Low-cost, carbon-free electricity generation is needed. Electrolysis systems that can produce both hydrogen and electricity remain at pilot scale. (The U.S. DOE's Office of Energy Efficiency and Renewable Energy's programs for solar, wind, geothermal, biomass and hydro power includes research to reduce cost of renewable electricity, including from hydrogen fuel cell systems.)

Renewable Electricity Generation Integration (for central). More efficient integration with renewable electricity generation is needed to reduce costs and improve performance. Development of integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production.

D. *BIOMASS GASIFICATION/PYROLYSIS HYDROGEN PRODUCTION*

Feedstock Cost and Availability. Improved feedstock/agriculture technology (higher yields per acre, etc.), lower cost feedstock collection, and improved feedstock preparation are required before economic viability is approached. Because biomass feedstocks are seasonal in nature, feedstock-flexible processes and cost-effective feedstock storage are needed. (Tasks to overcome these barriers are undertaken by both the U.S. DOE Biomass Program and the U.S. Department of Agriculture.)

Capital Cost and Efficiency of Biomass Gasification/Pyrolysis Technology. The capital cost for biomass gasification/pyrolysis needs to be reduced. Process intensification by combining unit operations can significantly reduce capital costs. This could range from combining the current

two step water-gas shift and PSA separation to a one step water-gas shift with integrated separation, to integrating gasification, reforming, water-gas shift and separation all in one unit operation. Improved process efficiency and higher hydrogen yields and selectivities through catalyst research, better heat integration, and alternative gas clean-up approaches are needed. Improved catalysts or engineering approaches for tar cracking are also needed.

Minnesota-Specific Opportunities

Sections VI, VII, VII, and XI provide Minnesota-specific information on opportunities for the state to help foster a consistent, predictable and prudent investment environment in the renewable hydrogen and fuel cell industries.

VI. MINNESOTA RENEWABLE HYDROGEN INITIATIVE--OPPORTUNITIES

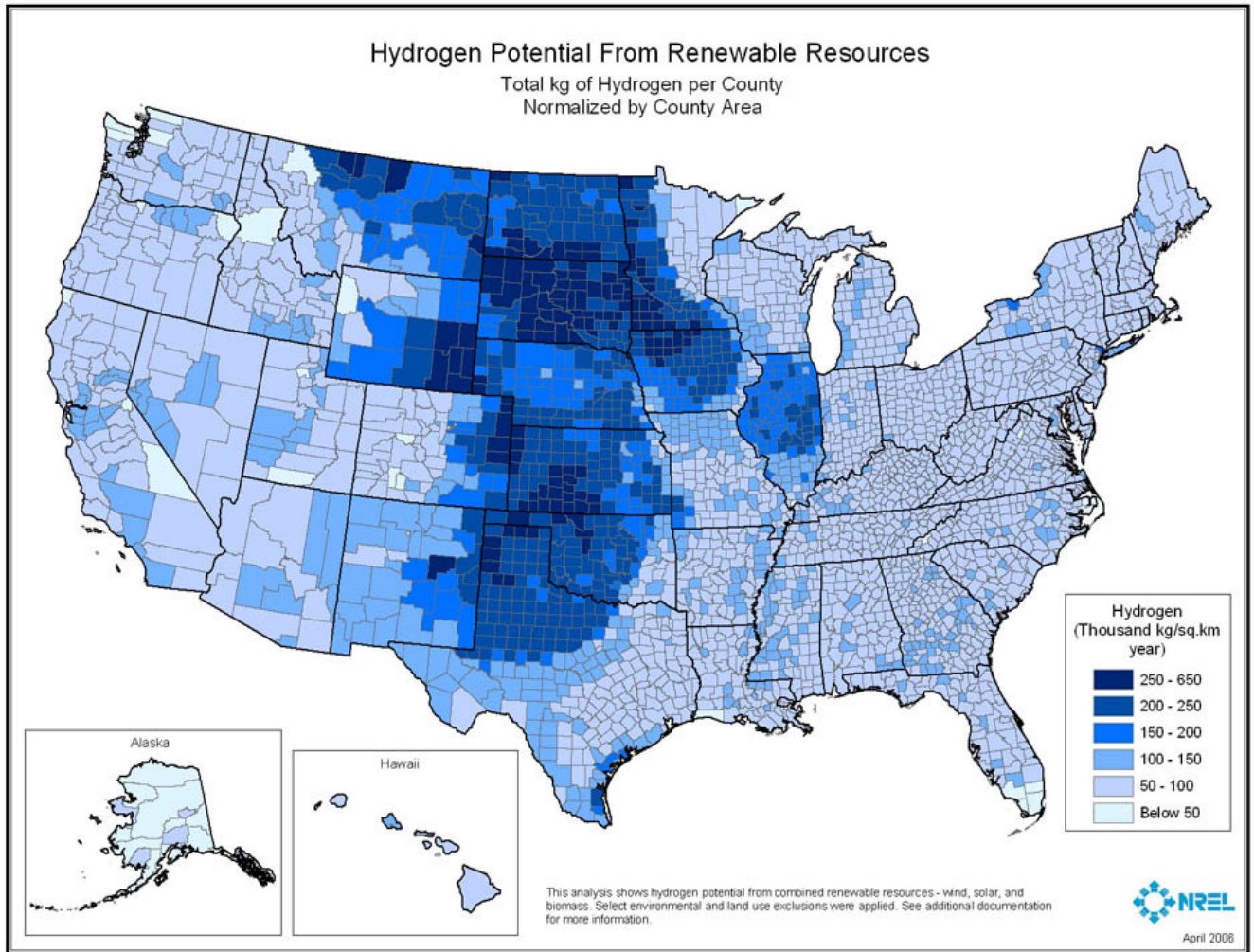
A. *STRATEGIC DEMONSTRATION PROJECTS TO ACCELERATE THE COMMERCIALIZATION OF RENEWABLE HYDROGEN IN MINNESOTA*

The Minnesota Renewable Hydrogen Initiative within OES has been monitoring renewable hydrogen research and projects in the state since 2005. It has authored three reports to the Minnesota Legislature on opportunities for demonstration projects that would contribute to realizing Minnesota's hydrogen economy goal enacted in 2003 (§ [216B.8109](#)), which proposes that hydrogen become an increasing source of energy for its electrical power, heating, and transportation needs. These reports, *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota*,⁴⁹ identify demonstration projects for renewable hydrogen production processes and related end use technologies that are compatible with the U.S. DOE's national hydrogen program goals and are based on an assessment of marketplace economics and the state's opportunities in hydrogen, fuel cells, and related technologies, so as to capitalize on the state's strengths. These reports are available at: [Hydrogen Strategic Demonstration Projects](#).

The 2005 *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota* report concluded that, due to the state's strength in renewable energy, Minnesota has an opportunity to spawn the emergence of a new homegrown industry based on the production of renewable hydrogen. Because of Minnesota's geographic location, as portrayed in the National Renewable Energy Laboratory's map (Figure 1), it is uniquely positioned to capitalize on a number of renewable energy resources--wind, solar and biomass--for hydrogen production.

⁴⁹ *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen in Minnesota*, Office of Energy Security, Minnesota Department of Commerce, State of Minnesota (2005, 2007, 2009)

Figure 1



Given that the cost of producing renewable hydrogen is directly related to the cost of wind, solar and bioenergy, the report recommended that the state build on the success of its existing renewable energy industries as a means to address not only hydrogen, but the state's GHG reduction and renewable energy goals. The first report also recommended that the state focus on demonstration projects that target technology involving a Minnesota innovation or Minnesota-made components to maximize the potential economic benefits from support.

Findings in the *2007 Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota* report focused on emerging Minnesota technologies, business development opportunities, new Minnesota markets for renewable hydrogen, and near term commercialization of hydrogen and related technologies. The 2007 focus was more targeted than the 2005 report and included:

- Areas in which Minnesota researchers and businesses have made advancements, have met project performance goals, and have begun development of a business plan with identification of markets and price points to guide the next project work phase.

- Technologies and opportunities that offer other attractive co-benefits for the state, such as economic development, and provide for value-added use of a low-value resource or waste product, or an environmental benefit, etc.
- Projects that offer opportunities to leverage state funds with private and/or federal funds toward commercialization of a technology, particularly ones where Minnesota interests play a role, either as an original equipment manufacturer or balance of parts, or as a provider of feedstock.

The 2009 *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota* report reconfirmed many of the criteria in the earlier reports and also emphasized:

- Support for the state's fuel cell component suppliers.
- Utilization of existing commercial markets for fossil fuel based hydrogen as a critical market entry point for renewable hydrogen.
- Support for efforts by Minnesota manufacturers of off-road and service vehicles to develop the electronics and control systems needed for either battery or fuel cell powered systems.
- Building on the success of the state's existing renewable energy industries as a means to address not only hydrogen, but the state's GHG reduction and renewable energy goals.

In keeping with the charge to foster consistent, predictable and prudent investment in renewable hydrogen-related opportunities, the types of projects included in these reports are ones that could be implemented without requiring costly infrastructure changes and development, could produce results in the near term, and also provide benefit to the state regardless of whether hydrogen fuel cells become the dominant technology for light duty passenger vehicles. Minnesota opportunities fall into some of the areas that were referred to in recent reports by the U.S. Fuel Cell Council⁵⁰ and the GAO⁵¹ as underfunded and also ones that would benefit from the funding changes first proposed by the current Secretary of Energy, Steven Chu. Minnesota opportunities generally fall into the areas of production of hydrogen from renewable energy source; niche fuel cell vehicles markets such as small engine vehicles and grounds equipment; and stationary applications for contaminant tolerant fuel cells. These are areas where strategic, prudent and potentially small investment can grow an industry.

B. RELATED HYDROGEN PROJECTS AND ACTIVITIES

University of Minnesota West Central Research and Outreach Center's Wind to Hydrogen for Anhydrous Ammonia Fertilizer Project: Currently some of the better opportunities for renewable

⁵⁰ *Fuel Cell Connections*, US Fuel Cell Council (2009)

⁵¹ United States Government Accountability Office, Report to Congressional Requesters, *Hydrogen Fuel Cell Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target*, GAO-08-305, page 31, 2008.

hydrogen in Minnesota are in production of high-demand, value-added products such as anhydrous ammonia fertilizer. Products, such as renewably produced anhydrous ammonia, have easy market entry because they fit into an extensive distribution and use system that has been in place for decades. These kinds of products do not depend on the development of new networks like most applications that involve use of hydrogen for fuel. Products produced from renewable hydrogen may even have a higher value than similar fossil fuel produced products because of the local jobs produced and the premium that the label renewable carries in the marketplace. If carbon reduction policies are implemented, there will be further value.

The University of Minnesota Department of Bio-products and Bio-sciences has developed a laboratory-scale prototype which produces ammonia from hydrogen and nitrogen via a catalytic assisted NTP process at atmospheric temperature and pressure. Currently Minnesota corn farmers spend over \$300 million a year to purchase ammonia fertilizers from other states and countries, where the ammonia is produced at high temperatures and pressures (300–600°C and 150–300 x 10⁵ Pa), which is not feasible for a distributed system. This prototype is designed for use on farms and distributed areas where a wind turbine would power an electrolyzer to produce the hydrogen needed and would also provide the needed energy to power the plasma. The lab-scale plasma has shown ammonia output concentrations of up to 12%. Further funding is needed to scale up the project.

The University of Minnesota was awarded grant funds and received bonding authority for the West Central Research and Outreach Center to design and build a refinery to produce anhydrous ammonia from the renewable hydrogen. The commercial opportunities for production of anhydrous ammonia from renewable wind power are promising. Due to the rural benefits possible, use of renewable hydrogen to produce anhydrous ammonia is a priority area for Minnesota. The concept is technically feasible but the economics are uncertain. Minnesota's strategy to use wind power when it is at a low value (not useable by the grid) to produce the hydrogen needed for fertilizer could produce the economics needed for renewably produced anhydrous to be price competitive with current market prices and apply to other renewable products as well. The project has experienced delays due to unforeseen issues, including recently unresolved negotiations over royalty payments. Project success will also allow the investment to further serve the state as a research platform while producing performance data so that the process can be tested, optimized and measured.

The economic viability of producing anhydrous ammonia from renewable hydrogen is a frequently overlooked but important component to assessment of the WCROC's anhydrous project. Included in this slate is a plan that would provide financial analysis, market analysis, pricing, technology, maintenance and operator requirements, and regulatory assessment to support the WCROC's anhydrous ammonia project. The study should provide detailed information on the manufacturing and transportation costs of production of anhydrous ammonia and identify components within renewable hydrogen production systems that can be improved to meet market price point goals for renewable anhydrous ammonia fertilizer.

Status of Hydrogen Code and Standards in Minnesota Report: In May 2007, the Minnesota Legislature adopted legislation requiring that the Minnesota Departments of Commerce and Labor and Industry develop recommendations to facilitate the adoption of uniform codes and

standards for hydrogen infrastructure, fuel cells and related technologies. The departments conducted a review of the status of existing hydrogen codes and standards in the state and the results of that effort are included in a 2008 report to the Minnesota Legislature, *Recommendations for the Adoption of Uniform Hydrogen and Fuel Cell Codes and Standards*.⁵² This report found that the State of Minnesota regulates codes and standards in such a way that all regulatory jurisdictions in the state have the same safety standards with regard to the production, storage, transportation, distribution, use of hydrogen, fuel cells, and related technologies. Except where amended, Minnesota codes and standards cover hydrogen and fuel cells by adoption of national codes and standards developed by the International Codes Council (ICC) and the National Fire Protection Association (NFPA). In 2009, the Minnesota Department of Labor and Industry incorporated the International Mechanical Code and International Fire Gas Code into the Minnesota State Building Code, which included hydrogen provisions that had previously been excluded from Minnesota codes (IMC 304.4 and IFGC 703).

The Minnesota Department of Labor and Industry has an existing annual training program for building officials. As this is already a part of the Minnesota Department of Labor and Industry's business plan, no additional funding would be anticipated to present a seminar about hydrogen codes. Additionally, U.S. DOE can provide free training for local code officials and hydrogen facility developers who are working on permitting of specific proposed hydrogen fueling station or back-up power projects. To formalize the use of the existing hydrogen codes, the state of Minnesota should evaluate the adoption of the NFPA's comprehensive Hydrogen Technologies Code (NFPA 2), once it becomes available in 2010.

VII. MINNESOTA RENEWABLE HYDROGEN COMMERCIALIZATION GRANT PROJECTS

The Minnesota Legislature allocated funding to OES for a competitive grant funding program to provide financial assistance for demonstrations of renewable hydrogen production processes and related end-use technologies to assist the state in attaining its renewable hydrogen energy goals in accordance with Minnesota Statute 216B.813 Subd 2 (b). The Legislature specified that OES give preference to project concepts included in the department's most recent biennial report: *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota*. In fulfillment of this charge, OES convened an industry advisory committee of hydrogen experts to assist OES in developing criteria for the request for renewable hydrogen pilot project proposals. To assure that grant awards advance a technical concept within both the *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota* and national hydrogen commercialization efforts, the advisory committee developed the following goals that proposed projects must address.

⁵² Report submitted to the Minnesota Legislature by the Minnesota Department of Labor and Industry, in consultation with the Minnesota Department of Commerce Office of Energy Security, *Recommendations for the Adoption of Uniform Hydrogen and Fuel Cell Codes and Standards*, (State of Minnesota, 2008).

Goals for Minnesota Hydrogen Grant Projects:

- Address a particular technical barrier related to commercialization of the production and/or use of renewable hydrogen and/or related technologies.
- Utilize an industry base within the state for support and expertise to build on an area of particular strength within the state's renewable hydrogen research and development community.
- Determine current economic viability and simple payback period of method(s) used for the production and/or use of renewable hydrogen, and identify improvement needed to become cost competitive with traditional products.

Proposals were requested in the following areas that were previously identified as areas of potential opportunities for the state:

Renewable Hydrogen Technology Areas of Opportunity:

- Wind power-to-hydrogen and electricity production
- Biomass to hydrogen
- Gasification-derived hydrogen-rich fuels
- Demonstrate high-pressure gasification for high value products
- Improve syngas carbon dioxide removal
- Anaerobic digester-derived fuels
- Biomass feedstocks for renewable hydrogen
- Bio-feedstocks and conversion technologies

OES notified over 200 interested parties through the Minnesota Renewable Hydrogen Initiative list serves and an additional 700 parties through its grant opportunities notification service. OES received four proposals in response to its request for proposals, of which three were selected to receive a grant award. The small number of proposals received indicates a decline in renewable hydrogen-related research in Minnesota. That trend was also observed by the University of Minnesota Institute for Renewable Energy and Environment (IREE), which reported that in 2004 and 2005 almost 25% of proposals submitted to IREE for funding were hydrogen related. However, since 2005, IREE has not received any hydrogen-related proposals for their funding cycle.

VIII. ROADMAP DEVELOPMENT PROCESS

A. INTRODUCTION

The success of Minnesota's renewable hydrogen efforts is due in large part to the success of meeting the state's other energy-related statutory goals and requirements. It is critical that the state's hydrogen-economy efforts are undertaken in concert with, as opposed to in isolation from, these other efforts. Consequently, OES adopted a holistic approach in development of a

hydrogen roadmap. Rather than isolate hydrogen from other energy sources to develop a roadmap, OES approached hydrogen as only one energy option in a suite of energy options for the state.

In November 2008, OES began to facilitate a process to develop a Clean Energy Technology Roadmap (CETR) which incorporated this need.⁵³ CETR outlines Minnesota's clean energy research and development vision, along with an action plan and related milestones, to ensure that Minnesota achieves the energy-related goals--including hydrogen--passed into law by the Legislature.

A clean energy technology roadmap is essentially a plan for an emerging technology that matches short-term and long-term goals with specific technology solutions to help meet those goals. It provides not only a direction toward commercialization but also identifies the critical system requirements and their targets, specifies the technology drivers, identifies technology alternatives, and assesses the emerging technology against the alternatives to assure that the emerging technology provides benefits over and above what is currently available at an appropriate market price.

The CETR process took into consideration significant energy-related policies that have recently been enacted into law in Minnesota and have milestones and targets of their own. Examples include:

- The Minnesota Renewable Energy Standard (Minn. Stat. 216B1691), which requires utilities to produce 25 percent of the state's energy from renewable sources by 2025, with the exception of Xcel Energy, which is required to produce 30 percent of its energy from renewable resources by 2020.
- The Minnesota Greenhouse Gas Reduction mandate (Minn. Stat. 216H.02), which requires statewide GHG emissions are reduced across all sectors producing those emissions to a level at least 15 percent below 2005 levels by 2015, to a level at least 30 percent below 2005 levels by 2025, and to a level at least 80 percent below 2005 levels by 2050 (216H.02).
- Fossil fuel and renewable energy consumption goals (Minn. Stat. 216C05 Subd.2), which state per capita use of fossil fuels are reduced by 15 percent by 2015, and total energy derived from renewable energy sources is 25% by 2025.
- The Biodiesel Content Mandate (Minn. Stat. 239.77).
- The Oxygenated Gasoline Ethanol Content Mandate (Minn. Stat. 239.791 Subd. 1a).
- The Energy Conservation Mandate (Minn. Stat. 216B.241), which sets aggressive energy conservation goals and transitioned Minnesota's utility Conservation Improvement Program from a spending requirement to a savings requirement of

⁵³ *Clean Energy Technology Roadmap: A Project to Identify Minnesota's Most Promising Research and Development Opportunities for Achieving the State's Clean Energy Goal*, November 2009; Office of Energy Security, Minnesota Department of Commerce. In January 2008, Governor Pawlenty issued an Energy Initiative to create the "Clean Energy Technology Collaborative" charged to develop the *Clean Energy Technology Roadmap*.

- 1.5% of annual retail energy sales for each utility--essentially doubling the amount of energy saved by Minnesota's utilities.
- The Minnesota's Hydrogen Economy Goal (Minn. Statute 216.B8109).

The CETR process assessed areas of research and demonstration related to these interdependent legislative initiatives as a means to determine which activities within them had the highest potential for significant environmental and economic benefit for the state.

Nineteen experts, primarily scientists and engineers, were asked to participate in a facilitated process to develop the roadmap. This group, referred to as the Clean Energy Technology Collaborative (CETC), held six meetings between November 2008 to April 2009 to assess technologies and identify opportunities within the scope of those technologies that could help achieve the statutory goals. The CETC plan identifies specific technology solutions to help meet state goals. CETC's plan is broad and includes an assessment of a suite of technologies in each of the areas targeted by legislation. As an important part of the states clean energy-related goals, CETC assessed the technical challenges facing the development of renewable hydrogen and related technologies and identification of areas within a hydrogen energy system development where Minnesota may best be positioned to advance technological solutions.

To reduce costs, avoid duplication, and leverage previous work, OEA and CETC reviewed existing roadmaps and published research as a means to effectively accomplish the task. Reviewers proceeded to:

- Identify high-level research categories in which the state could potentially play a leadership role.
- Survey and review existing roadmaps and published research regarding those categories.
- Identify specific research topics about which the state has a competitive industrial or academic strength, as well as the ability to influence development of a product that would help achieve state goals.

B. INCLUSIVE CLEAN ENERGY VISION

Results of Minnesota's priority energy efficiency and renewable energy research technologies provide for improved quality of life, economic and environmental benefits, and reliable and competitively priced heat, power and fuels for current and future generations.

C. RANKING GUIDELINES

Ranking guidelines were developed for prioritizing research and development needs for the technologies under consideration. These included the impact the technology would have on Minnesota, the time frame necessary for its commercialization, and the product development stage of the technology under consideration.

The process not only mapped out Minnesota’s opportunities for development of renewable hydrogen but also offered OES an opportunity to check the criteria and opportunities developed for its slates of renewable hydrogen reports against the opinions of impartial experts. The strategies detailed below by CETC were used to help assure that the state is headed in a direction to capitalize on the opportunities within the state, and thus reduce the risks inherent in new technologies.

D. IMPACT

The impact the proposed technology will have on Minnesota, including:

- Economics--The likelihood of the technology to be economically competitive, create green jobs, and result in economic development for the state.
- Environmental--The likelihood the technology will allow for sustainable use of air, water, land, and ecosystems in the state, including indirect benefits.
- Mandates--The potential for the technology to provide measurable results toward achieving state-mandated energy-related goals.
- Ability to influence--The scope and ability that units-of-government and private and public expertise have to competitively influence commercialization and use of the technology.

E. TIME FRAME

The time frame considered realistic for the technology to become economically competitive, as follows:

- Five years--Solution is already identified and experts are confident that the required commercial capabilities will be demonstrated within five years.
- Ten years--Research indicates high scale-up potential; improvement is expected to close any gaps for required commercial production performance and capabilities within 5 to 10 years.
- Fifteen years--Unknown manufacturability solutions; industry doesn’t have much confidence that scale-up potential of currently proposed solution(s) will be viable within the next 10 to 15 years.

F. PRODUCT DEVELOPMENT STAGE

The stage of development or maturity for a given technology, as follows:

1. *Idea*--The thought or revelation...“I wonder if...”
2. *Preliminary Investigation*--Back-of-the-envelope technical and market niche assessment.
3. *Initial Laboratory Investigation*--Basic assumptions and principles observed and evaluated in a laboratory setting.
4. *Laboratory Detailed Investigation*--Practical application of the technology formulated, and detailed analysis conducted to discover validity of assumptions.

5. *Laboratory scale-up*--Options narrowed down to most feasible line of investigation.
6. *Prototype Project*--Demonstration of scale-up prototype with performance of integrated components in a relevant, operational environment.
7. *Commercial-scale Demonstration Project*--Commercial-scale demonstration project providing actual operating conditions, testing and evaluation.
8. *Commercial Production*--Detailed engineering, production data, manufacturing processes, and performance and market metrics providing justification for commercial production.
9. *Market Entry*--Leading-edge customers determine that it is good practice to purchase the technology and implement change.
10. *Market Penetration and Diversification*--Proven results create additional sales, increasing market penetration.

IX. FOCUS AREAS

Renewable energy technology research, development and deployment, including for renewable hydrogen, is extensive and evolving rapidly. A comparison of global-scale opportunities with those in which Minnesota can play a leadership role require a great deal of candid evaluation. The opportunities identified for Minnesota do not represent a comprehensive list of all important projects. Rather, the actions listed represent conclusions reached through using the criteria-driven process described. They offer guidance, not prescription, for the deployment of research, development and deployment dollars in the state's effort to advance renewable hydrogen and create economic opportunity for all Minnesotans.

A. HYDROGEN PRODUCTION

Most of the hydrogen produced today is made from natural gas in large, centralized facilities. Commercial operations commonly use an energy intensive process to obtain hydrogen from natural gas via steam methane reforming. However, technologies to produce hydrogen from non-fossil sources such as biomass, wind and solar also exist. Minnesota has already invested in demonstration projects using wind and solar power to obtain hydrogen and oxygen from water. The state is also a leader in biomass gasification technology that also has potential to serve as another source of renewable hydrogen. There exists an opportunity to leverage this research and identify technical and economic barriers specific to the state.

1) *Wind Power-To-Hydrogen and Fuel Cells*

Issue: The high cost of hydrogen production, low availability of hydrogen production systems, and the challenge of providing safe production and delivery systems are all barriers to market penetration. There is little operational, durability, and efficiency information for renewable hydrogen production systems. Hydrogen delivery options need to be determined and assessed as part of system demonstrations for production and delivery technologies. Validation of integrated systems is required to optimize component development. There are no manufacturers of fuel cells located in the state. However, there are component suppliers providing products to

manufacturers of polymer electrolyte membrane (PEM) and solid oxide fuel cells. Participation in a demonstration project specifically designed to use Minnesota-made components would provide value to these suppliers, provide for system performance evaluation, and highlight economic development opportunities regarding use of fuel cells in the state.

Between 2005 and 2007, the University of Minnesota West Central Research and Outreach Center (WCROC) was awarded funding from various state sources to design and build a large scale wind-to-hydrogen demonstration project. The ability to integrate energy from variable-speed wind turbines directly to the hydrogen-producing stacks of commercially available electrolyzers is a challenge. There are system-level integration issues related to multiple electrolyzers that produce hydrogen gas at different pressures that must be resolved for these systems to operate efficiently. One of several research areas of the WCROC project includes evaluation of the effectiveness of storing hydrogen and using that hydrogen to produce electricity during periods of low wind. The stored hydrogen will be used in an internal combustion generator to produce electricity. Fuel cells provide another means to produce electricity from hydrogen.

For fuel cells to be competitive in the power generation market, the cost of manufacturing must be reduced. Fuel cell makers often cite a commercial entry price of about \$1,200 per kW as the price point where fuel cells could compete successfully with other small power generators such as peak power microturbines and engine/generators. The WCROC project represents a key opportunity to develop operational, durability, efficiency and cost information for a water electrolysis-to-hydrogen production system and use of renewable hydrogen as a means to produce electricity during periods of low wind.

Research: Adding PEM and solid oxide fuels to the analysis planned for the internal combustion generator at WCROC would allow comparison of hydrogen-to-electricity production costs and efficiencies of all three technologies. Total costs per kWh for the renewable hydrogen production, storage and electricity generation systems would be compared to those obtained from Xcel Energy's wind power battery storage project in Luverne, Minnesota. The research would provide the specific information needed to identify technical, cost and performance improvements and parameters needed for commercially viable, utility-scale energy storage systems.

Milestones: Development and testing of complete integrated fuel cell power systems is benchmarked and performance parameters needed for cost-competitive component development are validated. The ability of existing electrolyzer technology to accommodate the varying energy input from wind turbines is determined and alternative electrolyzer technologies that may provide superior performance are identified. The system-level efficiency improvements and cost reductions needed by designing, building, and integrating dedicated wind-to-electrolyzer stack power electronics that enable closer coupling of wind-generated electricity and electrolyzer stack requirements is determined. Safety systems and system controls for the safe operation of hydrogen production technologies with varying wind input are evaluated. Demonstrated operation of a wind-to-hydrogen system enables evaluation of actual system costs and identifies

areas for cost and efficiency improvements as compared to energy storage battery systems. Operational challenges and opportunities related to energy storage systems and potential for addressing electric system integration issues are identified.

Timeline: Less than five years

U.S. DOE and National Program Alignment: The U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE) are leading the technology development for water electrolysis and centralized wind power generated water electrolysis. The near term 2014 hydrogen cost targets are \$3.70 and \$4.80 per gasoline gallon equivalent, for distributed and centralized production, respectively.⁵⁴ The most significant contributor to hydrogen costs produced via electrolysis is the cost of electricity to run the electrolyzer, which ranges from 60-70% of the total cost.⁵⁵ The capital costs roughly make up the rest.

EERE began a wind power generated water electrolysis project in 2003, which is being conducted by DOE's National Renewable Energy Laboratory (NREL) in collaboration with Xcel Energy. The current U.S. DOE-funded project is set to be completed in 2010. The main goals of this project include: 1) demonstration of a renewable electrolysis system, 2) exploration of system-level integration issues, 3) optimization of renewable energy sources for stack use, and 4) investigation of challenges related to storage.⁵⁶ (NREL 95-page report of wind2H2 project 2009). A PEM and an alkaline electrolyzer technology are being tested for stack efficiency. The data gathered from this work will be used in economic models to identify potential improvements that may reduce the overall cost of hydrogen produced through renewable electrolysis.

The close collaboration between the utility industry and NREL combines NREL's expertise in renewable hydrogen production with Xcel Energy's expertise in energy transmission and distribution. This type of collaborative effort should be encouraged in Minnesota. Also, collaboration with NREL to take advantage of the lessons learned from their ongoing project should be encouraged for the WCROC. Minnesota's electrolysis focus should be on research areas that have not yet been demonstrated or investigated at NREL, such as ammonia production from the wind generated renewable hydrogen. Also, fundamental electrolyzer stack research conducted at the University level should also be encouraged.

The DOE Fuel Cell Technologies Program is heavily invested in reducing the cost and increasing the durability of fuel cells. The major focus from the national level has been on fuel cells and fuel cell components for vehicular applications. The DOE has reported that the development of niche-market applications for hydrogen fuel cells, such as fork lifts and landscaping equipment,

⁵⁴ Satyapal, Sunita, *The 2009 Progress Report for the DOE Hydrogen Program*, U.S. Department of Energy Report number DOE/GO-102009-2950 (November 2009)

⁵⁵ Kroposki, B., Levene, J., Harrison, K., Sen, P.K., and Novachek, F., *Electrolysis: Information and Opportunities for Electric Power Utilities*, National Renewable Laboratory, Technical Report NREL/TP-581-40605. (2006)

⁵⁶ Harrison, K.W., Martin, G.D., Ramsden, T.G., and W.E.Kramer, *Wind-to-Hydrogen Project: Operational Experience, Performance Testing, and Systems Integration*, National Renewable Laboratory. Page 95. (March 2009)

is the quickest way to achieve early market penetration (Hydrogen and fuel cell activities, progress and plans: report to Congress Jan 2009). The state of Minnesota has little economic influence in the passenger car industry. It does, however, have a fuel cell component manufacturing industry. Funding local fuel cell component and niche market manufacturers places the state at a competitive advantage in drawing more component manufacturers, increases the potential of creating a fuel cell component technology hub in the region, and is in alignment with the national goals and objectives. More information about the DOE Fuel Cell Technologies Program can be found at: <http://www1.eere.energy.gov/hydrogenandfuelcells/>.

2) *Biomass to Hydrogen*

Production of hydrogen from renewable biomass feedstocks has several advantages compared to fossil fuels, with a significant list of plant species, byproducts and waste materials that can potentially be used. However, biomass is a limited resource, and care must be taken to assure that sustainable production, harvest and processing is provided, while assuring optimum value for the state. Minnesota is well positioned to be a leader in the development and production of hydrogen-rich gas from gasification and anaerobic digestion of biomass.

Issue: Both the gasification of biomass to produce syngas and the anaerobic digestion of biomass to produce biogas promise to be comparatively near-term, technically and economically viable sources of renewable hydrogen. Costs for producing pipeline quality biomethane from biogas have declined sharply in recent years. However, the cost of cleaning syngas to the level needed to produce high-value products currently produced from fossil fuel-based hydrogen remains a significant challenge. The U.S. DOE has a 2012 biomass gasification-to-hydrogen target of \$1.60 per gasoline-equivalent gallon., the amount of alternative fuel it takes to equal the energy content of one gallon of gasoline. The environmental and economic benefits the state can receive from producing cost-competitive renewable hydrogen and the leadership position the state can obtain represent significant and timely opportunities for Minnesota.

Research: Biomass-to-hydrogen research should address four main areas: anaerobic digester and gasification plant and system design; catalyst and/or reformation of resultant biogas or syngas to produce hydrogen; evaluation of highest value use of that hydrogen; and proof of concept demonstration projects. Demonstration projects using optimized systems would allow for use and testing of multiple bioenergy feedstocks. They would also employ plug-and-play gas clean-up methods needed to identify the most cost-effective processes appropriate to local biomass. Objectives would include development of optimum reactor and system design with cost projections for a biomass conversion and reforming process for hydrogen production. Economic analysis would include identification, on a regional basis, of the highest value use of the hydrogen or hydrogen-rich gas.

Milestone: Improving cost effectiveness of biogas and syngas production and clean-up greatly expands biomass utilization, as well as related economic development and jobs, to produce high-value products from hydrogen. The demonstration project confirms the state's leadership role in development of the technology and supports near-term job growth in manufacturing, operations, maintenance, feedstock production and processing. The highest value use in local economics for the hydrogen produced is identified.

Timeline: Less than five years

U.S. DOE and National Program Alignment: The U.S. DOE has efforts in biomass gasification, reformation, syngas cleaning and CO₂ removal, which is being led by the EERE biomass program (<http://www1.eere.energy.gov/biomass/>). One project is being conducted by the Gas Technology Institute (GTI). Researchers at GTI are trying to develop a membrane reactor that combines biomass gasification, reforming, shift reaction, and hydrogen separation in one step. Some problems faced have been due to impurities and hydrogen selectivity. U.S. DOE has also funded work out of NREL to verify the technical and economic performance of an integrated biomass steam gasification-based hydrogen production system. The project consists of experimental testing of a gasification unit, along with updating a gasification simulation model with the experimental data. The NREL gasifier has been tested using oak and pine biomass. This project shares many similarities and is in alignment with the WCROC gasifier project being conducted at the University of Minnesota-Morris. The WCROC is planning on utilizing waste corn stover as a gasification fuel which researchers from NREL have also investigated. More information on this can be found at (<http://www1.eere.energy.gov/biomass/>).

3) Gasification-Derived Hydrogen-Rich Fuels

Burning a match provides a good demonstration of the common, open-air combustion process. The heat generated by the flame drives flammable gases out of the matchstick, which are continually ignited by the flame. The process continues until gases have been depleted and the flame goes out. Char, the burned matchstick, is the primary substance that remains after the gases have been expelled.

Gasification systems, rather than igniting these gases as they are released, serve to capture them for later use. To accomplish this, gasification restricts the amount of oxygen present by heating the biomass inside a chamber. This results in incomplete combustion of the flammable gases (commonly called syngas) that are contained. Depending on the amount of oxygen and temperature inside the chamber, many different products can be produced from the syngas. Renewable alcohols, diesel and jet fuel are examples. Wood chips, distiller grains, agricultural or forest product based pellets, food processing by-product, corn cobs, torrefied biomass, refuse-derived pellets, as well as residuals from the state's paper and wood products industries can provide for a consistent supply of feedstock.

Most commercial biomass gasifiers today are low-pressure systems that use the syngas to replace natural gas or coal as heating fuel for a variety of furnaces, boilers or process heating needs. Projects in Minnesota have demonstrated the value of using renewable syngas to minimize a facility's demand for fossil heating fuel.

Fuel production process: Biomass derived syngas, when cleaned and supplied at pressure can be used to make gasoline and diesel fuels. Gasoline is produced by first making di-methyl ether (DME) from syngas and then converting the DME to gasoline. The gasoline is full specification (ASTM-4814) fuel with an octane number >92. Alternatively, the Fischer-Tropsch (FT) process converts syngas into long chain carbon-hydrogen (CH₂) molecules. The resulting paraffinic liquid is reacted with hydrogen to increase yield of the renewable, full specification (ASTM-975) diesel. These renewable fuels are fully compatible with their fossil fuel counterparts, but are free of sulfur and nitrogen; an additional environmental benefit. Use of multiple biomass feedstocks allows for broad participation by communities across the state.

These efforts merit continued support. Due to progress made with gasification technologies, converting syngas into renewable transportation fuel now represents a pivotal research opportunity. Since the fuel can be made from a wide variety of biomass feedstocks (including residuals related to the ethanol and biodiesel industries) this opportunity can improve economics and participation across the state.

Due in large part to state support for technical innovation, five Minnesota facilities are advancing use of low-pressure gasification as a means to replace fossil fuel-based natural gas with renewable syngas for process heating needs. As is currently possible with natural gas, if syngas is cleaned to beyond pipe-line quality methane standards, it can also be used to produce high-value alcohols, diesel and jet fuels. The key barrier to competitive production of these fuels from gasified biomass is the cost of syngas clean up: 60% of the transportation fuel production cost is related to syngas clean-up for low pressure systems.

Issue: Very clean syngas is needed to produce high-value, renewable transportation fuels. Improving cost effectiveness of syngas clean-up would greatly expand biomass utilization, related economic development and jobs to produce high-value renewable fuels and chemicals. As a result of research targeted for the coal industry, a timely opportunity exists. Large investments (in the billions of dollars) have been made in the coal industry to use high-pressure gasification as a means to reduce clean-up costs of gases produced from coal gasification. Adapting proven high-pressure gasification systems to utilize Minnesota biomass can reduce net costs required for syngas clean-up, opening the opportunity for statewide renewable fuel production.

Low-pressure gasifiers typically operate at or near atmospheric pressure. High-pressure gasifiers operate above 300 psi. Biomass conversion to high-value liquid fuels is achieved by catalytic means at high pressure, commonly between 750 and 1500 psi. Due to this difference in operating pressure, the compressor package required to achieve the required pressure for a low-pressure gasifier system would be about six times larger than that required for a high-pressure gasifier. This equates to energy savings of about 20%, with a 70% reduction in capital costs due to the smaller compressor system needed for a high-pressure gasifier. This, combined with savings resulting from a smaller gasifier, has the potential to decrease overall capital costs by as much as 33%. In addition to potential net energy savings, syngas clean-up system efficiencies can be improved to more cost-effectively obtain the gas purity needed for high-value fuel production.

Research: Due to expertise in the state, Minnesota is uniquely positioned to leverage what has been learned through low-pressure biomass gasification projects with the techniques commonly used in high-pressure gasification systems by the coal industry. A demonstration project using a high-pressure gasification system would allow for use and testing of multiple bioenergy feedstocks, and also employ plug-and-play syngas clean-up methods. A demonstration project of this type would confirm the state's leadership role in development of the technology and support of near-term job growth in the manufacturing, operations, maintenance, feedstock production and processing, and high-value fuels industries.

Milestone: Timely integration of high-pressure gasification technology provides Minnesota with a competitive, non-food-based route to production of renewable ethanol, gasoline, diesel and jet fuel from a wide variety of statewide biomass feedstocks.

Timeline: Less than five years

U.S. DOE and National Program Alignment: The U.S. DOE Office of Fossil Energy is focused on the research, development and demonstration of producing hydrogen from coal and natural gas. U.S. DOE currently has an industry partnership at the Power Systems Development Facility (PSDF) in Alabama to develop clean, economical and reliable processes for power and chemical production from coal. The Office of Fossil Energy is also supporting research into new types of pollutant-capturing sorbents that work at elevated temperatures and pressures and do not degrade under the harsh gasification conditions. The U.S. DOE goal is to produce both hydrogen and electric power employing a modern gasification system; however, there are currently none in operation. The modern coal gasification systems, on which U.S. DOE is working, operate at high pressures to minimize the cost of the gas clean-up system. Although coal is a very different feedstock from biomass, similar issues concerning sulfur, char, and tar clean-up with a high-pressure syngas stream are observed. Significant for the state, Minnesota is positioned to become a national leader in high-pressure biomass gasification systems by integrating the DOE's recent high-pressure gasification technologies with Minnesota's biomass gasification knowledge. More information about the DOE's Hydrogen from Coal Program can be found at: http://fossil.energy.gov/programs/fuels/hydrogen/Hydrogen_from_Coal_R&D.html.

4) Improve Syngas Carbon Dioxide Removal

The carbon dioxide (CO₂) released due to combustion or gasification of biomass does not add a net increase to global CO₂ concentrations because, unlike fossil fuels, biomass is an integral part of the biosphere. In addition, the char produced through biomass gasification is increasingly being considered for use as a soil amendment and carbon sequestration tool. Syngas produced from biomass typically contains 40 percent CO₂ by volume. However, the presence of this CO₂ in syngas significantly reduces the yield of desired products; thus, costly processes are currently used to chemically remove it from the syngas prior to conversion of the syngas into high-value products.

Issue: Syngas that contains more hydrogen as compared to carbon monoxide (known as the H₂:CO ratio) is preferable. Syngas produced from biomass contains significantly more CO₂ at a given H₂:CO ratio than syngas produced from fossil fuels. This causes a competitive problem when high-value biofuels are desired because the presence of CO₂ limits yield. Commonly available technologies, such as amine or methanol absorption systems as used by the fossil fuel industry, reduce CO₂ levels but require significant capital, operating and disposal costs.

Research: A cost-effective technology that would remove CO₂ from biomass-derived syngas would further improve the economics of both high- and low-pressure biomass gasification. Due to its need for clean hydrogen-rich fuel, the fuel cell industry has invested heavily in membrane technology to selectively remove CO₂ from natural gas. There is an opportunity to leverage this

and related research and apply it to reduce CO₂ levels in biomass-derived syngas. This would significantly improve the economic performance of renewable fuels produced by gasification from a wide range of biomass feedstocks.

In addition, with cost-effective removal and resultant capture of CO₂ from syngas, the CO₂ can be used to produce urea, a more environmentally friendly fertilizer. Urea, as compared to anhydrous ammonia, decomposes more slowly, resulting in less nitrous oxide (NO_x) production and more effective delivery of nitrogen to plants. Given available expertise in the state and the ability to influence development, research that tests, evaluates, and adapts membrane separation technology to address this economic issue represents an important and timely opportunity for the state.

Milestone: Optimum membrane separation technologies are adapted to clean syngas from biomass gasification systems and provide for increasingly cost-effective production of renewable fuels and fertilizer, as compared to those currently provided from fossil fuels.

Timeline: 5-10 years

U.S. DOE and National Program Alignment: In high-temperature, high-pressure applications such as chemical synthesis processes, the removal of contaminants ideally would occur at the same temperatures and pressures as the gasification process. This method of contaminant removal, referred to as hot gas cleanup, retains the thermal energy of the gases and, in the case of pressurized gasification, may eliminate the necessity of a costly and power intensive gas compressor. At present, however, there has been little commercial demonstration of successful hot gas cleanup. Most of the national level work on hot gas cleanup is conducted by U.S. DOE's Office of Fossil Fuels as part of the nation's clean coal initiative. Many of the conversion technologies used for coal apply similarly to biomass-derived syngas, although because of the smaller scale of biomass facilities, they are not yet cost effective.

The majority of biomass gasification projects employ low-temperature (< 100 F) contaminant removal, known as cold gas cleanup. U.S. DOE's Office of Energy Efficiency and Renewable Energy's Biomass Program conducts ongoing research and development on cold gas cleanup within the program's Processing and Conversion area. Research is primarily focused on identification and testing of selective catalysts that work under heat and pressure to convert the carbon monoxide and hydrogen into larger more useful compounds. Some of the strategies currently be assessed include cleanup methods such as using a fluidizable reforming catalyst, CO₂-scrubbing and methanation, new membrane technologies, catalysts embedded into platinum nanoparticles, solvents, and use of novel intensified equipment for syngas cleaning and high-temperature hydrogen separation.

In Minnesota, there are a number of syngas cleanup technologies under development. Funded by an OES Renewable Energy Research and Development grant, Gradient Technologies developed and evaluated a high-pressure biomass gasification and clean-up process, the success of which resulted in formation of a new company, Syngas Technology Inc. in Elk River, Minnesota. Funded by Xcel Energy, the Gas Technology Institute, and the Natural Resources Research Institute, the University of Minnesota-Duluth recently completed demonstration of direct

hydrogen production from a down draft biomass gasifier using a hydrogen-selective membrane. The project team identified palladium-copper as preferred candidate materials for hydrogen separation applications under the conditions of the biomass gasification that have temperatures above 700°C and pressures above 20 atm. The membrane module consisted of a gas conditioning/cleaning reactor, a booster compressor, and a water gas shift reactor to enhance the hydrogen generation from the producer gas followed by the selective membrane. Researchers found that their direct production concept could potentially improve the hydrogen production efficiency by more than 40% based on a preliminary analysis. They also identified a number of areas for future work.

5) *Anaerobic Digester-Derived Fuels*

Biomethane (renewable gas) is a hydrogen-rich fuel that is produced by cleaning and upgrading biogas. Biogas is a mixture of methane (CH₄) and carbon dioxide created from anaerobic digestion of organic waste. The process that produces biogas is an integral part of the natural decomposition cycle of organic material. Biogas was captured and used for heating bath water in Assyria during the 10th century BC. Seven hundred years ago, Marco Polo noted its use from covered sewage tanks in China. Biogas was produced commercially in England in the 1890s to provide for lighting. Today, technically optimized systems are being used to produce biogas from anaerobic digestion of food processing waste, livestock manures, wastewater treatment biosolids, agricultural and forest product residues, municipal solid waste, and landfills.

Issue: Anaerobic digestion of livestock manure wastes has been used with success as a means to address environmental concerns, particularly the problem of nutrient runoff into waterways. It has also been used successfully to address odor management concerns by owners of wastewater treatment and food processing facilities. Typically, the biogas is used as fuel for a generator to produce electricity or for a boiler to produce heat. A Minnesota utility can also use the renewable electricity produced to help meet state renewable energy standards. Given that systems are typically above the state's 40 kW net metering threshold, the price the producer obtains for the electricity is non-public; it is independently negotiated through a power purchase agreement. However, it is evident that the environmental benefits and income derived from the sale of this electricity is not sufficient to prompt widespread adoption of the anaerobic digestion technology in Minnesota.

Cleaning biogas for use as a fuel to replace natural gas or propane is another avenue for using anaerobic digestion technologies. Commercialized technologies now exist to clean biogas to meet pipeline-quality, natural gas standards. Once cleaned to quality-assured natural gas standards, the biomethane is injected into a commercial pipeline. An advantage of this approach is that multiple small local producers of biogas can connect by pipeline and jointly send their biogas to a facility for conditioning and central-point injection into a natural gas pipeline. Given that a natural gas utility must facilitate interconnection into their pipeline, active participation by natural gas carriers is vital to the success of a significant biomethane industry in the state.

In addition to the purchase of biomethane by a natural gas utility for sale to its customers via existing pipeline infrastructure, it can also be used directly at the production site to offset natural gas or propane consumption, purchased by large users directly, or used in the transportation

sector as compressed gas fuel, or used in fuel cells. When compressed and used as fuel for transportation, biomethane dramatically decreases the carbon footprint compared to the fuels it replaces (gasoline or diesel). Kits to retrofit existing diesel or gasoline engines to run on biomethane are commercially available. Given the technical maturity of the natural gas vehicle and fueling industry, the potential to substitute biomethane for use in these vehicles represents a significant opportunity for the state.

Although of proven technical and economic viability, biomethane of commercial natural gas quality is not currently available for distribution in Minnesota. Consequently, the degree to which the economic performance of operations in other states and Europe correspond to the state remains uncertain. Minnesota-specific information is needed to more accurately determine the optimal use of biogas for local projects and economics.

Research: Whether for electricity or biomethane production, there are vast differences between designs and approaches used in anaerobic digestion systems for similar feedstocks. The range of design considerations further expands when different feedstocks are considered, such as from dairy manure, swine manure, wastewater treatment works, food processing facilities, mixed, or municipal solid wastes. Further, systems are often poorly maintained and operated once installed. Nationally, use of process control metering and dedicated third-party operation is increasing, so that consistent feedstock input and robust operations are maintained. Given technical and management advancements, best available and most recent information should be researched and made public so that the state's current and future facilities can operate more cost-effectively. This will provide for an accurate assessment of today's potential for economically viable biogas production and use in the state.

This research includes identification of barriers to commercialization that are present in Minnesota, and analysis of whether these barriers are unique to the state. With economic barriers identified, a demonstration project that cleans biogas to biomethane standards and best utilizes that gas is needed to demonstrate actual performance in Minnesota. This hard data--and resultant problem solving--will allow for methodical and fact-based funding and investment decisions. Absent such a demonstration project, the state remains at a disadvantage when competing for private sector investments needed to develop the opportunity in Minnesota.

Milestones: Guidelines on the optimal conditions, system designs, and the minimum capacity needed for successful biogas electricity and biomethane projects in Minnesota are determined. Minnesota optimizes use of organic waste as available from the food sector (processing, distribution and retail); dairy, swine and livestock industries; wastewater treatment plants; municipal solid waste; and agricultural and forest product industries to produce cost-effective biogas. Depending on economics of a specific project, the biogas is conditioned for use in electricity production, for use as a process heating fuel, or cleaned to pipeline-quality renewable gas standards for use in natural gas consuming engines, equipment, appliances or fuel cells. The state creates a multi-feedstock biogas and biomethane industry comprised of anaerobic digester engineers, construction, operation, system quality control, and gas cleaning specialists that perform as a national hub for the industry.

Timeline: Less than five years

U.S. DOE and National Program Alignment: The United States Department of Agriculture (USDA) and the US Department of Defense (USDOD) are leading the efforts in anaerobic digester demonstration projects. In December 2009, USDA Secretary Tom Vilsack announced an agreement with U.S. dairy producers to curb their GHG emissions by 25 percent by 2020. The USDA plans on utilizing anaerobic digesters to produce biomethane, which will then be utilized in a generator to produce electricity. The DOD is investigating using waste energy from wastewater treatment plants via an anaerobic digester, which will then feed a fuel cell power plant. Although the main fuel produced from anaerobic digesters is biomethane, digesters still have applications to hydrogen related technologies and this roadmap, because biomethane can be utilized in solid oxide fuel cells (SOFCs) like renewable hydrogen. Having Minnesota focus on anaerobic digesters would be in alignment with the USDA national goal of increasing use with U.S. dairy farmers and has the potential of increasing SOFC use.

Gas Technology Institute (GTI), a national, not-for-profit research and development organization with more than 65 years of service, recently published *Pipeline Quality Biomethane: North American Guidance Document for Interchangeability of Dairy Waste Derived Biomethane*. Findings support Minnesota's direction as outlined above.⁵⁷

6) *Biomass Feedstocks for Renewable Hydrogen*

Bio-feedstocks and conversion technologies: Each Minnesota community has a particular mix of accessible, low-value biomass feedstocks. The supply and cost of available feedstock--such as those from wastewater treatment, food processing, agricultural and forest product residues, municipal solid waste, livestock manures and processing waste, tree and landscape management, and energy crops--vary greatly. As research to optimize energy conversion technologies to produce cellulosic ethanol, renewable diesel and gasoline, biomethane or other high-value products proceeds, it is important that technology demonstration projects evaluate feedstock availability and local cost from a variety of Minnesota communities. Without these considerations, assumptions used could inadvertently limit participation among many communities around the state.

⁵⁷ Pipeline Quality Biomethane: North American Guidance Document for Interchangeability of Dairy Waste Derived Biomethane. GTI project number 20614, October 2009, provides guidance needed for the introduction of biomethane from dairy waste into existing pipelines.
http://www.gastechnology.org/webroot/app/xn/xd.aspx?it=enweb&xd=1ResearchCap/1_4EnvironSci/DairyWasteBiomethane.xml

To support this effort, three areas of focus have been captured, with independent reports:

- [Executive Summary and Acknowledgments](#) – (GTI-09/0011)
- [Task 1 Final Report: Technology Investigation, Assessment, and Analysis](#) – (GTI-09/0012)
- [Task 2 Final Report: Laboratory Testing and Analysis](#) – (GTI-09/0013)
- [Task 3 Final Report: Guidance Document for Introduction of Dairy Waste Biomethane](#) – (GTI-09/0014)

GTI is also implementing a similar gas testing and quality program for biogas/biomethane derived from landfills and waste water treatment plants to provide guidance for a growing green energy market from these biomass sources. Results from this project are anticipated at the end of 2009.

Scale of facility and feedstock required for the competitive production of high-value products is a consideration that crosses all bioenergy conversion technologies. Conversely, investing in feedstocks for which there is not a feasible bioenergy-conversion technology is also problematic. The optimum energy conversion technology for a given community varies across the state. Effective, sustainable, and regional economic development is dependent upon aligning a community's least-cost renewable resources with their most advantageous energy conversion technologies. It is particularly important that bio-feedstock research include current and anticipated technical, economic and environmental considerations

In general, a community's feedstocks, conversion technologies, and highest value products must be considered as a whole to avoid the risk of creating siloed research projects that are neither consistent nor responsive to community benefits and needs.

In terms of economic development, the higher the value of products made from biomass, the greater the positive impact on jobs, wages and revenues. While the amount and type of biomass that can be harvested or removed from land can be optimized, its supply is limited. Biomass is being used to produce a range of quality wood products, high-value fuels, food and feed, and heat and power. Basic economic principles assert that competing interests for a limited resource drives up the price and the supply of available biomass; Minnesota is no exception to this principle.

Issue: A bidding war for biomass is emerging in the state between, for example, the need for manufactured wood products and the need for renewable electricity; or the need to supply wood pellets to a local gasifier or to ship them to out-of-state markets. No markets are mutually exclusive. To maximize economic development opportunities for communities, the economic value of available, sustainably harvested biomass resources must be evaluated.

Research: Research that inventories Minnesota biomass (including biomass from forest and agriculture, wastewater biosolids, plant and animal-based food processing, municipal solid wastes, and livestock operations) should be expanded to include research on: the cost of collection and processing of biomass for use as a feedstock; economically and environmentally viable collection distances given market pricing for the feedstock; and the jobs and economic development impact resulting from different uses of the biomass. Once established, the information should be in the public domain so that communities can use defaults or change variables to fit their unique situation, and gain critical information needed for strategic biomass-related economic development projects.

Milestone: The interdependence of current biomass availability, market price, and environmental and economic impact pertaining to its use is understood, enabling strategic implementation of the most beneficial projects by public and private sectors.

Timeline: Less than five years

U.S. DOE and National Alignment: The national biomass energy program is a result of the Biomass Research and Development Act of 2000 (Biomass Act) [Pub. L. No. 106-224], which requires cooperation and coordination in biomass R&D between the U.S. Department of

Agriculture and U.S. DOE. It has been amended and strengthened a number of times, most recently in 2008 by the Food, Conservation and Energy Act. It established a Biomass Research and Development Board to coordinate research and development activities relating to biofuels and biobased products and an independent panel of experts, the Biomass Research and Development Technical Advisory Committee, to serve as objective, scientific advisors on technology development. The biomass energy program has developed aggressive goals for biomass to be integrated into the nation's energy systems. The end targets for the program specify that by 2030 20% of the nation's fuels will be biofuels; 7% of the nation's power will be produced from biomass feedstocks and 55 billion pounds of byproducts will be produced.⁵⁸ Feedstocks development is an important component of this program and includes research, development, and demonstration activities regarding feedstocks and feedstock logistics (including the harvest, handling, transport, preprocessing, and storage) relevant to production of raw materials for conversion to biofuels and biobased products. Feedstock issues were identified early after the establishment of the national bioenergy program as barriers to widespread growth of bio-energy, particularly in relation to the expansion of the ethanol industry, and a roadmap developed in 2003 that identified areas within the feedstock chain that could help make the biorefinery industry more sustainable.⁵⁹ Because agriculture and biomass is geography dependent, the Biomass Research and Development Board is actively identifying specific regional opportunities and identifying the technical challenges and research needs for each region. The regional issues for the Central Region, which includes Minnesota, were identified in a series of workshops among area experts in 2007. The draft report specifies research needs in the areas of small scale decentralization and distributed resources storage and handling, ecosystem services, crop yields, and farm profitability. Many Minnesota biomass research projects are already in alignment with the national program. Minnesota projects tend to focus on land use management practices for sustainable biomass, including use of community organic waste as well as native plants and cellulosic materials, efforts to improve soil carbon sequestration and mitigate other environmental issues with native plantings, crop yields for biomass energy crops and densification of biomass for ease of transport.

⁵⁸ *The Vision for Bioenergy and Biobased Products in the United States: Bioeconomy for a Sustainable Future*, Biomass Research and Development Technical Advisory Committee, U.S. Department of Agriculture. Page 12. (2006)

⁵⁹ *Roadmap for Agriculture Biomass Feedstock Supply in the United States*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program. November 2003.

The national program's draft document, *Central Regional Roadmap Workshop Summary*, provides a summary of strategies pertaining to Minnesota as well as the much of the Midwest.⁶⁰

B. END-USE APPLICATIONS

Vehicles: High-performance batteries/capacitors represent the largest competitor to hydrogen as an energy carrier. Worldwide concern about the security, availability, cost and environmental impacts of petroleum have greatly accelerated energy storage research and development. Whereas use of hydrogen in vehicles requires significant changes in existing delivery, storage and conversion technologies, such as for fuel cells, high-performance batteries are being commercially integrated into vehicle engines that use existing fuels and distribution systems. Although breakthroughs may occur that could shift current viability of fuel cell vehicles and hydrogen refueling infrastructure, Minnesota is not well positioned to take a leadership role in the research required to achieve needed breakthroughs for use of hydrogen in vehicles.

University of Minnesota Hydrogen Research Platform: Two projects, currently being built on the Morris campus of the University of Minnesota and involve both the campus and the WCROC, are serving a broader purpose than their original goal. The first project, being developed by WCROC and discussed in a previous section of this roadmap, intends to convert wind energy into hydrogen and use the hydrogen to produce anhydrous ammonia fertilizer. The second project, also underway but initiated by the University of Minnesota- Morris campus, in partnership with the City of Morris, is attempting to install a biomass gasifier as a district heating system for the community. Although there have been obstacles to implementing both systems, components of each are currently operating and also serving as educational tools and research platforms. Completion of these projects will provide the state with a potential research platform at which pilot scale projects and near-commercial end-use technologies can be deployed and tested.

Vehicle strategy: The state is in a competitive position to influence development of the electronics and control systems needed for vehicle niche markets for both hydrogen fuel cell and battery/capacitor powered systems. Vehicle manufacture niche markets of particular strength in Minnesota are in the landscape maintenance, local transportation cart, off-road, and water recreational vehicle markets. Supporting efforts by such manufacturers to develop the electronics and control systems needed for either battery or fuel cell powered systems would position the state for successful participation in vehicle-related opportunities that are not dependent on an ultimate end-use product.

One project at the University of Minnesota Morris that has the potential for both research and commercial application is the utilization of biomass gasifier derived syngas in an internal combustion engine generator. Although there well documented use of syngas in IC engines from the 1940s to present, comparatively little research and evaluation has been done to determine how the composition of the biomass affects performance and emissions. The syngas composition can vary greatly depending on the feedstock and also the production method. It is also unclear which engine platform (diesel or gasoline) is best suited for biomass gasifier derived syngas use.

⁶⁰ *Central Regional Roadmap Workshop Summary, Draft for Participant Comment.* Central Roadmap Workshop, Argonne National Laboratory, for Biomass Research and Development Technical Advisory Committee, National Biomass Research and Development Initiative, Biomass Research and Development Board (2007)

This project hopes to answer some of these fundamental questions, while also developing a fully functional integrated gasifier + engine generator combination that can be used in urban or rural settings.

Combining the renewable hydrogen demonstration project with fuel cell-capable on-campus vehicles, and the biomass gasification-to-syngas project with IC engine on-campus vehicles, would provide valuable information and experience needed for hydrogen-rich gas storage and fueling. Although of comparatively small scale, the experience and expertise gained through researching, selecting and operating such systems would provide for active participation with these technologies, yet in a manner that does not expose the state to the high levels of risk associated with public highway, passenger vehicle, refueling stations which rely on non-renewable sources of hydrogen. This strategy of leveraging assets and core capabilities in order to successfully interface with federal efforts is critical for achieving state goals. In this example, one part of Minnesota's hydrogen initiative (the production of renewable hydrogen) with another (the state's vehicle strategy) allows for expansion into a third area (storage and hydrogen fueling).

Some of the end-use research areas that have been identified for the Morris location include:

- a. Ammonia Production from Wind Energy
 - i. Background and Overview
 - ii. Current Status
 - iii. R,D,D, and D
 - iv. Bottlenecks
 - v. Opportunities
 - 1. Refrigerant, H₂ Delivery, and Other Ammonia Markets
- b. Use of electrolysis hydrogen production by-products
 - i. Oxygen
 - ii. Heat
- c. Electrical Energy
 - i. NH₃ and H₂ Fuel Cells
 - ii. NH₃ and Syngas ICE Gensets
- d. Transportation
 - i. Service Vehicles
 - 1. H₂ Fuel Cell
 - 2. Syngas ICE
 - iii. Refrigeration
 - iv. NO_x Mitigation
 - v. CO₂ Mitigation

X. CONCLUSIONS:

The Minnesota renewable hydrogen roadmap, as outlined in this report, is intended as a guide for the state to foster predictable and prudent investments in renewable hydrogen and related technologies. This roadmap is designed to be both consistent with the national hydrogen program and complements Minnesota's overall energy system. It builds upon one of the state's competitive strengths--renewable energy production.

The most prudent investments that Minnesota can make to foster a hydrogen economy are investments to increase efficiency, lower costs, and expand renewable energy production. Production of hydrogen from renewable energy sources is crucial for a hydrogen economy to achieve environmental benefits greater than those that current marketplace alternative technologies can achieve. Investments in development and improvements to Minnesota's renewable energy production methods will position Minnesota to produce renewable hydrogen if and when a hydrogen vehicle market develops.

In a future low-carbon economy, low-carbon hydrogen production capacity will become the backbone of the hydrogen economy. Development of renewable energy projects that can provide such capacity offers the state an avenue toward playing a significant role in the hydrogen economy.

A. POLICY

Due to interdependence of Minnesota's renewable hydrogen goal with other energy-related goals, actions undertaken in support of the following statutes will particularly help position the state's renewable energy industry to play a major role in a potential hydrogen economy.

State Greenhouse Gas Reduction Goal. 2007 Minn. Stat. 216H.02: It is the goal of the state to reduce statewide GHG emissions across all sectors producing those emissions to a level at least 15% below 2005 levels by 2015; 30% percent below 2005 levels by 2025; and 80% below 2005 levels by 2050.

<https://webrh12.revisor.leg.state.mn.us/statutes/?id=216H.02>

Renewable Energy Standard (RES): 2007 Minn. Stat. 216B.1691: Requires that the state's electric utilities obtain the following percentages of energy from renewables by the following dates:

Year	Utilities	Xcel
2010	7% (goal)	15% req.
2012	12% req.	18% req.
2016	17% req.	25% req.
2020	20% req.	30% req.
2025	25% req.	30% req.

Total 27% renewable electricity by 2025

<https://www.revisor.leg.state.mn.us/statutes/?id=216B.1691>

Energy Policy Goals: 2007 Minn. Statute 216C.05 Subd. 2: It is the energy policy of the state of Minnesota that the per capita use of fossil fuel as an energy input be reduced by 15 percent by the year 2015, through increased reliance on energy efficiency and renewable energy alternatives, and 25 percent of the total energy used in the state be derived from renewable energy resources by the year 2025.

<https://www.revisor.leg.state.mn.us/statutes/?id=216C.05>

B. TECHNICAL FOCUS AREAS

Actions undertaken in the following technical focus areas, as itemized in section VI of this roadmap, will help assure that expenditures will benefit renewable energy as well as hydrogen production.

- Electric powered (fuel cell or battery) grounds/off-road vehicles
- Wind power-to-hydrogen and hydrogen storage
 - electricity production
 - off-road vehicles and fueling
- Biomass to hydrogen-rich fuels
 - Gasification-derived hydrogen-rich fuels
 - Methods which produce clean syngas of quality required to produce high-value products
 - Anaerobic digester-derived fuels
 - Methods which incorporate clean biogas to natural gas pipe-line and CNG applications.
- Biomass feedstocks for renewable energy, including hydrogen
- Linking bio-feedstocks with a community's most beneficial conversion technologies

C. PROJECTS

In particular to renewable hydrogen and fuel cells, support for projects that meet the following criteria will accelerate technical and economic viability:

- Minnesota-based projects that address a particular technical barrier related to commercialization of the production and/or use of renewable hydrogen and/or related technologies.
- Utilize an industry base within the state for support and expertise to build on an area of particular strength within the state's renewable hydrogen research and development community.
- Determine current economic viability and simple payback period of method(s) used for the production and/or use of renewable hydrogen, and identify improvement needed to become cost-competitive with traditional products.

XI. NEXT STEPS

Minnesota's current energy policies provide the catalysts for the state to play a significant role in the nation's transition to a hydrogen economy. Development of renewable energy facilities within the state can serve both an immediate purpose--locally produced renewable energy--as well as an important role in the future as sites for the production of renewable hydrogen and, eventually, as the backbone of the nation's hydrogen economy's infrastructure. The goals and timelines built into current policies will position the state for production of hydrogen, if and when demand for hydrogen develops. Investments to increase efficiency, lower costs, and expand renewable energy production within the state offer the state a low-risk strategy to play a crucial role within the national hydrogen economy.

Future activities of the Minnesota Renewable Hydrogen Initiative and updates to this renewable hydrogen roadmap will focus on:

- Compilation of research items in the areas of renewable hydrogen into a Minnesota Renewable Hydrogen Initiative electronic newsletter for dissemination to the Minnesota Renewable Hydrogen Initiative Listserve.
- Reports on the progress of hydrogen projects that were selected for state grant awards.
- Tracking and reporting on new projects funded by the University of Minnesota Institute for Renewable Energy and Environment.
- Tracking of hydrogen-related projects in Minnesota that win competitive grant awards.
- Updates on the University of Minnesota West Central Research and Outreach Center's wind to hydrogen via electrolysis project.
- Updates on the University of Minnesota-Morris's and City of Morris's district heat gasification system and related projects.

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