2007 Report on Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota

Recommended Projects

Report to the Minnesota Legislature
November 2007

Minnesota Department of Commerce
State Energy Office

Background

In 2005, the Minnesota legislature requested that the Minnesota Department of Commerce, "in consultation with appropriate representatives from state agencies, local governments, universities, businesses, and other interested parties,… report back to the legislature by November 1, 2005, and every two years thereafter, with a slate of proposed pilot projects that contribute to realizing Minnesota's hydrogen economy goal as set forth in section 216B.013." That goal, enacted in 2003, states "It is a goal of this state that Minnesota move to hydrogen as an increasing source of energy for its electrical power, heating, and transportation needs."

The first report, *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota, 2005* concludes that Minnesota has an opportunity to spawn the emergence of a new home-grown industry based on the production of renewable hydrogen. Given that the cost of producing renewable hydrogen in Minnesota is directly related to the cost of wind, solar and bioenergy, it recommends that the state build on the success of its existing renewable energy industries. Targeting products or end-use technologies that maximize use of existing infrastructure and renewable energy investments recognizes the importance of leveraging renewable energy technologies while working in paralleled to create value added renewable hydrogen production strategies. Not only will this functionally advance the state toward its goal of increasing the use of hydrogen within the state in the near term, but it will also place Minnesota in a competitively advantageous position as a major producer of renewable hydrogen for a future hydrogen economy without incurring the risk and costs of pursuing projects that will only be successful if and when the infrastructure for a hydrogen economy develops.

The first report recommends that the state focus on demonstration projects that help convert a targeted technology, particularly one involving a Minnesota innovation or Minnesota-made components, into successful products. The emerging phase of a technology offers the best chance for a state government to influence business formation, and many renewable hydrogen and corollary system technologies are currently at their emerging stage. Support for homegrown innovations offers the potential to develop new business opportunities in the state and thus, may impact the state's economic performance. The first report concludes, "With strategic policy targeted at the development of cost-effective processes to produce hydrogen and other products from renewable fuels, Minnesota can translate its competitive edge into the expansion of its renewable fuels industry." (The Minnesota Department of Commerce's report on the first slate of projects is available on the Minnesota Department of Commerce web site at www.commerce.state.mn.us > Energy Info & Services > Hydrogen Fuel Cell > General Hydrogen Information > *Hydrogen Demonstration Projects.)*

The projects included in the first report concentrate on identifying renewable hydrogen production methods and hydrogen end use applications—the components around

which an integrated system would be designed – that would put Minnesota in a position to have a competitive advantage over other states. The state did not offer funding for the first slate of projects but many of the projects recommended in the first report found funding sources on their own that helped them advance to their next phase. The following is a short update on the status of some of Minnesota's renewable hydrogen and end use technology projects.

2005 Recommended Projects Update

Current Status of Renewable Hydrogen Production and Related End Use Projects in Minnesota

- *Wind to Hydrogen by Electrolysis for Electricity and Reacted with Nitrogen to Produce Anhydrous Ammonia Fertilizer-* the University of Minnesota West Central Research and Outreach Center (WCROC) was awarded $3,750,000 from various sources, including a Minnesota legislative appropriation, and grants from the Legislative Commission on Minnesota Resources and the University of Minnesota's Institute for Renewable Energy and Environment (IREE), over the last 3 years to build a wind to hydrogen demonstration project. This project includes research on the effectiveness of storing hydrogen and using that hydrogen to produce electricity during periods of low wind. One of the main end uses of the hydrogen for this project will be to react it with nitrogen to produce anhydrous ammonia, a fertilizer that will be spread on research farm fields. Phase 1 of this project, the installation and configuration of a 1.65 MW wind turbine is complete, and the turbine currently supplies electricity to the UMN-Morris campus. The remaining components of the system, including use of stored renewable hydrogen in an internal combustion generator to produce electricity, will be operational in September 2008. The wind-to-hydrogen-to-ammonia system will be the first of its kind in the world. The capacity to produce renewable anhydrous ammonia fertilizer could provide for an effective market entry point for renewable hydrogen produced in the state.
  http://wcroc.cfans.umn.edu/Renewable_Energy2.html

- *Solar to Hydrogen by Electrolysis* – A hydrogen production demonstration project that used recycled photovoltaic panels and a small electrolyzer operated temporarily at the University of Minnesota School of Architecture building. About $200,000 in total funding was provided for this system through collaboration of the Minnesota Office of Environmental Assistance, Xcel Energy and IREE. The project operated as a popular, on-site, technical education tool to build knowledge of the systems and engineering required for effective renewable hydrogen production from solar energy. Although the system provided a platform for effective applied research, components had to be removed in the winter because budget limits only allowed for installation in a secure, though

unheated structure. The University is currently storing the equipment in a heated area. http://www.buildingphysics.umn.edu/h2pvwww/

- *Catalytic Conversion of Water-Rich Ethanol to Hydrogen from an Autothermal Reforming Process* – IREE provided a seed grant, with a match from the Corn Growers Association of $50,000 in 2003-04 to help fund research in the efficacy of using autothermal catalytic reforming of water-rich ethanol to produce hydrogen at the laboratory of Dr. Lanny Schmidt at the University of Minnesota. After detailed research, Dr. Schmidt determined that a more economically viable and near-term use for the technology was production of high value syngas rather than hydrogen. The reactive flash volitization of the autothermal reforming process can be modularized to produce syngas from such feedstock as cellulose, starch, soy oil and sugar-water. This renewable syngas can easily replace natural gas in a process heat application. IREE provided $20,000 in 2005, with matching amount from GE Power and Argonne National Laboratory to develop a refueling reformer; IREE subsequently provided $20,000, with $240,000 from U.S. DOE (with GE as the prime contractor) to build a compact and robust unit. The technology is laboratory scale at this time. An early commercial scale-up is planned after further optimization of feedstocks, feed rates, catalyst and system performance, and end product.
  http://www1.umn.edu/iree/docs/sg_h1_2004_final.doc
  http://www1.umn.edu/iree/docs/m6_2004_final.doc
  http://www1.umn.edu/iree/docs/m8_2004_final.doc
  http://www1.umn.edu/iree/docs/sg_h1_2004_final.doc

- *Hydrogen from Biodiesel By-product* –Virent Energy, a Wisconsin company, uses catalytic techniques to convert biologically derived sugars or cellulose to liquid or gaseous fuels. The company's initial research on hydrogen has evolved to producing replacements for gasoline, diesel and natural gas. Shell Hydrogen and Virent Energy Systems joined a five-year joint development agreement to further develop and commercialize the technology in Wisconsin. Virent has obtained a $21 million second round of venture financing. Virent has received grants and venture funding totaling nearly $40 million since its founding in 2002. The technology is pre-commercial.
  http://www.virent.com/Platforms/platforms.html

- *Hydrogen from the Gasification of Wood, Crop, Food or Other Biomass Waste* – The University of Minnesota's Natural Resource Research Institute (NRRI) is currently working with Gas Technology Institute to produce hydrogen through gasification of residual biomass. The gasifier for this project was procured this year and has begun to analyze emissions and performance using various biomass feedstocks. Hydrogen reports from NRRI include:

- Direct Hydrogen Production from Biomass Gasifier Using Hydrogen-Selective Membrane http://www.nrri.umn.edu/default/pt.asp?id=1444
- Hydrogen Production from Biomass Gasification Processes http://www.nrri.umn.edu/default/nrri.asp?pageID=315
- Direct Hydrogen Production from Biomass Using a Novel Membrane Gasifier: http://www.nrri.umn.edu/default/pt.asp?id=1478

- *Purified Biogas from Anaerobic Digestion* –University of Minnesota's Dr. Phil Goodrich developed a simple process for purifying methane to be reformed into hydrogen and used in a fuel cell. The fuel cell tested was a PEM. Research results suggest that hydrogen produced from bio-methane may be more economically suited for use in higher temperature, contaminate tolerant fuel cells. Additional information: http://www.bbe.umn.edu/annrpt/2003/research/livestock15.html

  Note: The Environment and Natural Resources Trust Fund through the Legislative Commission on Minnesota Resources provides $200,000 for the hydrogen fuel cell at the Haubenschild farm. http://www.hometownsource.com/2005/February/14farmers.html

  Other information and funding for this front end of this project include: $107,000 from the Legislative Commission on Minnesota Resources and $45,000 from John Deere for Advancing Utilization of Manure Methane Digester. http://www.jgpress.com/archives/_free/000455.html

- *Solid Oxide Fuel Cell Development*- With partnership funding from U.S. Department of Energy, Cummins Power Generation led an industry team in the successful development and performance testing of one of the first solid oxide fuel cell prototypes that can be manufactured at costs approaching those of conventional stationary power-generation technology. The project's next phase will be to demonstrate the solid oxide fuel cell in a real world application with hydrogen rich, versus pure hydrogen, gas.

- *Hydrogen End Use Technologies - Fuel blended hydrogen* -Blending hydrogen with methane (or natural gas) represents a near-term opportunity to introduce hydrogen into the nation's fuel mix, typically reducing emissions, improving turbine or engine performance, and creating a near-term market for renewable hydrogen.

  - *Gas Turbines* - Burning a mixture of 12% hydrogen and 88% natural gas, with water injection to limit NOx to 25 ppmv. No current projects in Minnesota.

  - *Internal Combustion Engines (ICE)* – University of Minnesota's Dr. David Kittelson and the staff at the Diesel Research Center developed a device

to inject and test performance of various fuels with hydrogen blends into spark-ignited internal combustion engines. Results include:

- Reductions in both NO and NOx emissions were observed at all load conditions with 5% hydrogen energy input
- Significant (>20%) reduction in PM emissions were observed at low and medium load conditions
- An increase in PM emissions was observed with any hydrogen energy input at the high load condition
- An apparent increase in NO2 emissions with the addition of hydrogen

- *Methane/Syngas Powered Fuel Cells* -Methane produced through the anaerobic digestion of organic matter, particularly as produced from manure or by sewage treatments plants, can be reformed or filtered to obtain hydrogen. University of Minnesota's Dr. Phil Goodrich project *Purified Biogas from Anaerobic Digestion* as noted above, documented the challenges of obtaining pure hydrogen needed for PEM fuels. Research showed that the state of current purification technology for biomethane is better suited for use in high-temperature, contaminate tolerate types of fuel cells.

Status of Fuel Cell Projects in Minnesota that Received Grants from the State of Minnesota

The following projects were undertaken, in part, to determine real world performance and durability of PEM fuel cells available in 2004.

Commercial hydrogen fuel: In 2004, H. G. Cragg, Minnesota's first commercial fuel cell distributor, received a $20,000 grant from the Minnesota Department of Commerce to help them identify and provide incentives to appropriate business partners for a demonstration of the first commercial fuel cells in Minnesota. The fuel cells were U.S. manufactured PEM fuel cells developed to provide back up power at remote sites using pure hydrogen fuel. Two fuel cells were installed, one of which performed to specifications and remains operational, while the other failed to perform as designed and is not in operation.

- Natural gas fuel: In 2004, Hennepin County received a $50,000 from the Office of Environmental Assistance and additional funding from CenterPoint Energy and 3M to install and demonstrate use of a 5 kW PEM fuel cell designed to provide the electricity for an average home. Natural gas lines supplied the fuel, which

will be reformed into hydrogen as it enters the fuel cell. The fuel cell operated for one year, at which time its membrane required replacement. 2004 benchmark operation life and performance of commercial natural gas fueled PEM was established. Although not currently operating, the fuel cell and its exhibit remain popular with citizens and continue to serve as an educational resource. http://wwwa.co.hennepin.mn.us/portal/site/HCInternet/menuitem.3f94db53874f9b6f68ce1e10b1466498/?vgnextoid=1a29b70a699fc010VgnVCM1000000f094689RCRD

- Biogas Fuel: In 2004, the Environment and Natural Resources Trust Fund through the Legislative Citizens Commission on Minnesota Resources provided $200,000 for a biogas fueled PEM fuel cell at the Haubenschild farm. The research was to evaluate the efficacy of using conventional biogas cleaning technology to produce hydrogen for use in the PEM fuel cell to generate electricity. Contamination levels resulted in decrease life of the fuel cell membrane. With research outcomes accomplished, replacement of the membrane was not deemed appropriate and it is no longer in operation.

- Pure hydrogen from water electrolysis fuel: In 2004, the Office of Environmental Assistance provided a $50,000 grant to the University of Minnesota to assist with the installation of a 1.2 kW PEM fuel cell fueled by pure hydrogen produced by using solar PV electrolysis of water. The fuel cell operated as expected for the duration of the project in an unheated structure, and is currently stored in a heated area until further testing can occur. The pure hydrogen fueled PEM remains operational.

2007 Input to Develop Recommended Projects that Contribute to Realizing Minnesota's Hydrogen Economy Goal

The 2007 slate of projects that will contribute to realizing Minnesota's hydrogen goals, which will be the subject of this report, will have a similar focus, as described in the2005 report, on emerging Minnesota technologies, business development opportunities, new Minnesota markets for renewable hydrogen and near term commercialization of hydrogen and related technologies, but will also target areas:

- areas in which Minnesota researchers and businesses have made advancements, have met project performance goals, and have begun development of 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, provide for value-added use of an low-value resource or waste product, or an environmental benefit, etc.; and

- projects that offer opportunities to leverage state funds with private and/or federal funds toward commercialization of a technology, particularly ones where Minnesota interests plays a role, either as OEM or balance of parts, or as a provider of feedstock.

In drafting this second list, the Department of Commerce was asked by the 2007 Minnesota legislature to consider the following nonexclusive list of priorities:

(1) deploy "bridge" technologies such as hybrid-electric, off-road, and fleet vehicles running on hydrogen or fuels blended with hydrogen;
(2) lead to cost-competitive, on-site renewable hydrogen production technologies;
(3) demonstrate non-vehicle applications for hydrogen;
(4) improve the cost and efficiency of hydrogen from renewable energy sources; and
(5) improve the cost and efficiency of hydrogen production using direct solar energy without electricity generation as an intermediate step.
(b) For all deployment projects that do not involve a demonstration component, individual system components of the technology should, if feasible, meet commercial performance standards and systems modeling must be completed to predict commercial performance, risk, and synergies.

In addition, the proposed pilots should meet as many of the following criteria as possible:
(1) advance energy security;
(2) capitalize on the state's native resources;
(3) result in economically competitive infrastructure being put in place;
(4) be located where it will link well with existing and related projects and be accessible to the public, now or in the future;
(5) demonstrate multiple, integrated aspects of renewable hydrogen infrastructure;
(6) include an explicit public education and awareness component;
(7) be scalable to respond to changing circumstances and market demands;
(8) draw on firms and expertise within the state where possible;
(9) include an assessment of its economic, environmental, and social impact, and
(10) serve other needs beyond hydrogen development

With these priorities, criteria, and issues taken into consideration, the Minnesota Department of Commerce began a public process to help identify renewable hydrogen and fuel cell technologies that are close to commercial readiness or emerging into the market such that the performance and cost data resulting from a project will accelerate progress toward achieving Minnesota's hydrogen economy goal. In August 2007, a request for information was sent out to over 500 stakeholders, including over 200 who are participants in the Minnesota Renewable Hydrogen Initiative, with instructions to pass the request along to other interested Minnesotans. The input process was

deliberately designed to be simple, requesting that submitters include their names, potential partners, location (if already determined), a description of potential co-benefits for the state and a succinct two-page project description. The Department received twelve project submissions from eight different entities in response to the request.

Many of the submissions to the 2007 slate of projects propose a new stage of development to an existing renewable hydrogen production process or related end use technology where the original project met its performance goals and was ready for further development. Some of the projects include multiple new stages within one proposal. For these project ideas, each new stage was considered as a separate project idea. In a competitive process, each of these stages would be assessed on its own merits, and well as would be assessed on whether the main project was at a stage to incorporate new components. The following is a short description of the project ideas that were submitted to the Minnesota Department of Commerce in response to its request for project ideas.

- Demonstrate renewable hydrogen production by installation of a 1.56 MW wind turbine and hydrogen manufacturing system to produce hydrogen for a fueling station to power a vehicle that will be converted to run on a fuel cell.

- Produce renewable hydrogen by one of the following three processes :
    - Production of hydrogen from vegetative biomass
    - Production of hydrogen from gas (methane) produced by animal, human, or landfill digestion
    - Production of hydrogen via reformation from ethanol or E85, either singularly or in combination.

  The selected hydrogen production processes will produce a dependable process stream to support either a:
    - Proton Exchange Membrane fuel cell (PEM), or a
    - Solid Oxide Fuel Cell (SOFC) technology

  The output of the fuel cell will be used to produce the base load electrical power for a small hybrid (prime mover plus energy storage) power system producing 120V, 60 Hz single phase and/or 120/240V, 60 Hz single phase electrical power, primarily targeted towards off-grid applications such as remote residences, farm facilities, telecommunications, scientific research, and state facilities (e.g. parks).

- Demonstrate the economical production of renewable hydrogen, electricity and anhydrous ammonia fertilizer from non-food renewable agricultural material. This project will use a solid oxide fuel cell to convert methane that is obtained from an existing anaerobic digester into electricity and fertilizer.

- Demonstrate on-farm production of hydrogen, electricity and anhydrous ammonia fertilizer from energy crops and manure. This is a two-phase project.

Phase one will configure a molten carbonate fuel cell to operate off the biogas from the dairy's anaerobic digester. Phase two will install a small refinery to convert the excess hydrogen into ammonia, a product more valuable than electricity.

- Demonstrate the reformation of glycerol or other biomass material to produce hydrogen-rich gases, and introduce these gases and a biodiesel fuel blend into a diesel engine. The hydrogen rich gases will be mixed with air entering the engine while the biodiesel blend will be injected normally with a goal of obtaining 40% of the fuel energy input from renewable energy sources. This project is phase two of a three phase project, where phase one successfully proved an automotive engine can be operated at 60% of rated torque on a fuel where 80% of the energy is produced from biodiesel and 20% from hydrogen. This phase would solve the mechanical and chemical engineering problems associated with operating a diesel engine on a mixture of hydrogen rich gases (similar to gas produced from a reformer) and a biodiesel blend, a mixture of gases including mainly H2, CO, N2, water vapor, and CO2.

- Demonstrate the technical and economic viability of producing renewable hydrogen by efficiently and economically converting lignocellulosic biomass to purified hydrogen in a distributed small-scale conversion plant that has the potential to be mass-produced. This project would address two major limiting factors of biomass to hydrogen conversion: 1, reliably enhancing the portion of hydrogen generated from the biomass; and 2, cost-effectively cleaning the impurities from hydrogen to a degree acceptable for its three major uses (direct use for combustion, conversion to electricity in a fuel cell, and use in downstream processes for liquid fuel and chemical production).

- Examine the performance and emissions of a second-generation biofuel, dimethyl ether (DME), which has the highest well to wheel energy efficiency and lowest GHG emissions of the biomass to liquid fuels. Also examine the potential to use DME as a replacement for propane by measuring performance and emissions of DME/propane blends.

- Integrate contaminate tolerant solid oxide fuel cell with a gas to create a base-load, cogeneration system that has multiple fuel capability (hydrogen, methane and biogas) and deploy it on a green microgrid. This proposal is part of a larger project that focuses on the configuration and optimization of a control system for a green microgrid that has the potential to balance different renewable energy sources, some of which would be base load and others intermittent, to achieve a mix of 50% renewables on the grid. The hybrid micro turbine/fuel cell technology would provide appropriate hardware for full testing of the green

microgrid and proprietary control system that operates it. The focus of this project is on full commercial systems deployment.

- Enhance the performance and make long-term use of the PV arrays and pilot hydrogen production demonstration system (performance is proven) at the University of Minnesota, School of Architecture building to assess commercial viability of solar PV-water electrolysis, hydrogen production and use the hydrogen in a pilot hydrogen-gasoline co-fueled internal combustion engine (ICE) vehicle. This project is located at a research university and will help build awareness and provide educational opportunities for Minnesota's future architects, engineers and citizens.

- Convert and demonstrate an ICE for a school bus to run to hydrogen with focus on solving fueling, storage and safety concerns about the operation of the fueling station.

- Demonstration of fuel cells in targeted specialty markets where fuel cells offer tangible advantages over current technologies and are at a price point to be cost competitive in the very near term, particularly those involving electric powered technologies, such as forklifts, or other such technologies where a fuel cell retrofit would be relatively inexpensive and easy.

- Vast wind energy resources in the Midwest can be enhanced through the production of value added products and the subsequent use of these products to regenerate electrical energy. Using hydrogen to produce electrical energy alone is not very economical. However when utilizing hydrogen for production of anhydrous ammonia it may be possible to have ICE gensets or fuel cells produce peaking power as a secondary hydrogen use. This proposal plans to develop and test combinations of technology (technology bundles) that can improve the efficiency of the production and utilization of hydrogen. Those technologies could be:

    - Incorporating a novel 120 kW hydrogen and ammonia fuel cell into an operating wind to hydrogen to anhydrous ammonia system.
    - Production testing and subsequent optimization of the hydrogen and anhydrous ammonia production system for commercialization with a focus on testing various catalysts, pressure, and temperature parameters.
    - Incorporating a 120 kW anhydrous ammonia internal combustion generator set into the system and conducting related performance tests.

In addition to the projects submitted to the Department in its request for information, the Department also held an input session for the Upper Midwest Hydrogen

Association, an association that includes many Minnesota members, to elicit projects ideas that would fit the legislative criteria. Projects proposed in response to this session are:

- Development and deployment of two fuel cell hybrid ice resurfacers and a hydrogen fuel dispenser at an ice arena to eliminate emissions with the current propane power units. The units will be integrated at a local community college and will be part of a training program developed with them to also support the machines and the dispensing system.

- Development of two fuel cell powered neighborhood electric vehicles (NEV) and a hydrogen dispensing system and deployment at a educational institution campus. The NEVs will be integrated and then put into daily service with the campus security forces to provide clean, quiet, all-weather patrol capability. A local community college could be brought in as a partner to provide maintenance to the vehicles and fueling system as part of a vocation development program.

- Development and deployment of four pieces of hydrogen powered ground service equipment (2 baggage tractors and 2 forklift trucks) at an airport along with a hydrogen dispensing station. These vehicles could be integrated locally and serve in programs to reduce airport vehicle emissions.

- Acquire and deploy hydrogen ICE powered shuttle bus and hydrogen dispenser to shuttle people to and from the airport or Mall of America.

- Installation of a hydrogen fueling station suitable for refueling vehicles that are part of public or private passenger fleet, turf maintenance service or bus service in Minnesota. Preference will be given to a refueling station that intends to initially or eventually use hydrogen produced through a renewable electrolysis method.

- Acquisition of a hydrogen internal combustion or fuel cell passenger vehicle or bus for long-term (minimum of 5 years) use within the state.

- Demonstration of current or 'near market ready' hydrogen technologies including fuel cell conversion and demonstration of a forklift or turf maintenance vehicle; fuel cells used for uninterrupted power backup systems (UPS); internal combustion engine transport trucks retrofitted for hydrogen.

- Implementation and demonstration of fuel cell application in recreational vehicles such as snowmobiles and all terrain vehicles (ATVs).

- Demonstrate a single turbine Wind/Hydrogen/Fuel Cell Power Plant system that would allow for firm capacity energy to be delivered to the grid during peak

hours or when scheduling the power would alleviate transmission constraints. The heat from the fuel cell would also be used to supply heating loads at the power plant location.

- Demonstrate a neighborhood wind/hydrogen generation station where the hydrogen would be trucked periodically from the neighborhood H2 generating plant to multiple local residential homes. A co-gen ICE engine run on hydrogen (located outside the home) would supply heat to each home and power to the grid at each location. The target homes would ideally be ones that are currently using fuel oil as a heating source.

- Demonstrate use of fuel cells to deliver customer desired and/or superior performance in electric off-road/mobile equipment, such as turf or grounds maintenance equipment and recreational vehicles, which already have customer-valued attributes such as low noise, easy use & maintenance, and reduced emissions. Battery technology for this kind of equipment is often not viable due to weight, range and refueling (recharging) issues. Hydrogen powered fuel cells are an ideal solution to this problem because they are relatively light and easy to refuel quickly.

- Renewable hydrogen for production of nitrogen fertilizer, biofuel enhancers/additives and other applications in which hydrogen is already a key component offer many near term opportunities to advance hydrogen use. Minnesota has already taken the first step to build a system to produce nitrogen fertilizer. Minnesota's challenge is to simultaneously create a large market for fertilizer and other products made with renewable hydrogen while developing efficient manufacturing systems (i.e. production lines) for renewable hydrogen systems. To meet this challenge, ancillary studies on the financial, business level and economic feasibility for optimized hydrogen production and manufacturing are needed. Studies should include discussion of the effect of carbon pricing on fossil fuel produced fertilizer

2007 Recommended Pilot Hydrogen Projects

Project ideas submitted in response to the Department's request helped the Department identify a wide range of demonstration project concepts that will help move the state toward its goal of increasing renewable hydrogen's use in the state. In addition to this input, the Department reviewed status reports and information from U.S. DOE, industrial, academic and international sources. This input guided the Department in development of its 2007 slate of recommended projects.

Projects that the Minnesota Department of Commerce recommends concentrate on emerging technologies that offer near term commercial potential, particularly ones being developed in Minnesota, and that also provide opportunities to influence the state's economic performance. Given that statutory criteria are comparable, the slate of projects that the Minnesota Department of Commerce recommends in its 2007 report has a similar focus as the ones in the 2005 report. Both emphasize emerging Minnesota technologies, business development opportunities, new Minnesota markets for renewable hydrogen and projects in early stages of commercialization. Given technological progress, as well as the progress made in implementing projects recommended in 2005, this report will also target:

- areas in which Minnesota researchers and businesses have made advancements, have met project performance goals, and have begun business plan development 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, provide for value-added use of low-value resource or waste product, or an environmental benefit, etc.; and
- projects that offer opportunities to leverage state funds with private and/or federal funds toward commercialization of a technology, particularly ones where Minnesota stakeholders play a role, either as OEM or balance of parts, or as a provider of feedstocks.

Hydrogen Production Processes

The 2007 slate of recommended renewable hydrogen and related technology includes the following list of renewable hydrogen production processes and end use applications.

- **Solar to Hydrogen by Electrolysis**.
  As documented in this report, notable progress is being made in the state to produce pure hydrogen from wind power. Although opportunities continue to exist for wind, there are currently no facilities that demonstrate hydrogen production from solar photovoltaic (PV). Given the viability of solar throughout the state as opposed to the more geographically limited locations for commercially viable wind, the Department recommends a project that produces renewable hydrogen from solar PV. Solar PV can be a valuable way to build local awareness, further technology commercialization and lay the groundwork for Minnesota's future architects and engineers to solve the problems associated with renewable hydrogen development and market acceptance. With appropriate location, sizing and configuration, such projects can provide on-going research platforms for development and demonstration of promising new, hydrogen end-use technologies, such as gasoline/hydrogen co-fueled ICE vehicles or fuel cells. As with existing wind-to-hydrogen, production of

hydrogen from solar provides good potential for future, renewable hydrogen fueling installations. Educational institutions provide unique settings to build awareness and stimulate technology development, especially if demonstration projects are integrated into a program where they become a visible and important educational tool and curriculum in advancing the technology.

- **Hydrogen from low-value by-products.**
  The Department encourages hydrogen production projects that rely on use of low value, renewable by-products from commercial or industrial processes. A notable example is glycerin, a byproduct of the biodiesel industry. The Department considers significant benefit to the state may be derived from producing hydrogen or hydrogen rich gas from low value, renewable by-products produced, converted and used on-site for the thermal or energy needs of the facility, eliminating transport and storage costs.

- **Hydrogen from Gasification of Wood, Crop, Food or Other Biomass Waste.**
  There are currently five biomass gasification facilities in the state that can use syngas in place of natural gas to provide for process heating needs. A major problem regarding renewable hydrogen production from syngas is the need for improved hydrogen gas separation and purification. The problem is compounded when multiple feedstocks are used. The Department recommends a project that focuses on the separation and purification of hydrogen from gasification syngas produced from a variety of feedstocks so that technical issues regarding production of hydrogen and value-added products are benchmarked and identified.

- **Biogas from Anaerobic Digestion.** Minnesota has significant potential to produce biogas from anaerobic digestion of manure. Although removing sulphur, the major contaminate, is commercially viable, cleaning the biogas to the hydrogen purity recommended for a PEM fuel cell is problematic given the specifications needed for PEMs today. More contaminate tolerant fuel cells, such as solid oxide fuel cells, can more cost effectively use cleaned biogas as fuel and operate at much higher temperatures to provide opportunities for heat recovery.

  The Department supports projects that evaluate the optimization of the production and use of hydrogen from anaerobic digestion; particularly ones that would help reduce hydrogen production costs, accommodate mixed streams of waste biomass such as different types of manures, crop or food waste, improve hydrogen quality, create new markets for renewable hydrogen, and/or lead to turnkey systems for the marketplace.

  Wind to Hydrogen by Electrolysis. A large-scale demonstration project for the production of hydrogen from wind-powered electrolysis is underway.

The Department is interested in a smaller scale project that uses an existing wind turbine with best available electrolyzer and storage technology. The turbine must use wind power when it is at a low value (not useable by the grid). Hydrogen may be used for any value added product or purpose.

Value-Added Products and End Uses for Hydrogen

- **Anhydrous Ammonia**
  Currently some of the better opportunities for renewable hydrogen in Minnesota are in production of high demand value-added products such as anhydrous ammonia fertilizer. Products, like 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 polices are implemented, there will be further value. Anhydrous ammonia produced from renewable hydrogen may also offer Minnesota another important opportunity in addition to the prospect of developing the first system to produce it – an opportunity to influence the development of a new manufacturing sector in the state.

  The University of Minnesota received bonding authority from the Minnesota legislature 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 look hopeful enough that the Department recognizes the need for ancillary market and economic studies to assess commercial opportunities and determine cost goals for market entry. Such a study should also evaluate the economics from smaller scale hydrogen production processes, like those proposing to use manure anaerobic digestion to produce hydrogen feedstock for anhydrous ammonia.

  - 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 apply to other renewable products as well. The Department encourages projects that would develop this and other processes to produce anhydrous ammonia from renewable hydrogen but it recommends any

new projects be developed on a small scale at this point in time. It also recommends that hydrogen reactor technology projects are coupled with existing renewable energy projects that have an established track record in which under-valued or surplus energy is produced.

To determine the economic viability of this technology, the Department recommends a Front End Engineering and Design (FEED) study incorporating business plan, financial analysis, market analysis, pricing, technology, maintenance and operator requirements, and regulatory assessment. The study would 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. This project would determine the opportunity for renewable hydrogen anhydrous ammonia production in the State; expanding use of use of renewable hydrogen, while also reducing emissions and opening a new avenue for development of a new manufacturing sector.

- **Fuel Blended Hydrogen**. Blending hydrogen with methane, gasoline, diesel and other fuels represents a near-term opportunity to introduce hydrogen into the nation's fuel mix, typically reducing emissions, improving turbine or engine performance, and creating a near-term market for renewable hydrogen. Hydrogen blend projects that would be of particular interest to the state are:

    - Gas turbines where the hydrogen/natural gas blending would play an important role in the generation of efficient, low cost electric power and process heat for applications ranging from small 75-kilowatt (kW) distributed power systems up to 200 megawatt (MW) utility combined cycle power plants.

    - Diesel Generators. In the Twin Cities Metropolitan area alone, stationary generators produce about 300 MW of power for peak shaving purposes. The largest of these generators is about 2 MW and many are in the range of a few hundred kW. Hydrogen blends for diesel generators could reduce emissions while increasing use of renewable fuels to help meet the state's renewable electricity goal.

- **Fuel Cell Niche Markets.** The Department supports projects that would demonstrate fuel cells in targeted specialty markets where fuel cells have the potential to offer tangible advantages over current technologies. The Department is particularly interested in projects that could reach a competitive price point and be commercialized in the near term.

- PEM fuel cells**.** The Department recommends support for PEM fuel cell projects related to neighborhood electric vehicles, forklifts or other such niche applications where a fuel cell retrofit would be relatively inexpensive and would provide a tangible market advantage, such as greater functionality, reduced emissions, or economic competitiveness with battery or small ICE powered equipment.

- Solid Oxide Fuel Cells (SOFC) or other contaminant tolerant fuel cells**.** Methane produced through the anaerobic digestion of organic matter, particularly when produced from manure or by sewage treatments plants, can be reformed or cleaned to obtain hydrogen. The same is true for syngas produced by the gasification of organic matter such as wood waste and agricultural residue. The Department recommends demonstrations of contaminant tolerant fuel cells with bio-fuels but, due to maturity of the technology at present, would prefer projects that involve evaluation of relatively small fuel cells.

End-Use Technology System Integration Components and Distribution Technologies

Many of the hydrogen production processes and end-use technologies that the state considers most promising in the near term need to be further developed, tested and demonstrated independently before it is known which can be most successfully combined into integrated renewable hydrogen systems. For this reason, the Department supports separating the development of renewable hydrogen production processes from end use technologies until such time when both elements have reached their progress and performance goals, increasing the chance for successful integration. The Department recognizes that a selected production method and end use application would determine what system integration components, including storage, transport, distribution and balance of systems components, are needed. The Department supports projects that propose to integrate end-use technologies with renewable hydrogen production systems, but recommends that the components of such projects have first met stand-alone performance goals before their use in an integrated system.

Conclusion

The Minnesota Legislature requested that the Minnesota Department of Commerce compile a slate of proposed projects that contribute to realizing Minnesota's hydrogen economy goal and report back every two years on such projects. The 2007 slate of projects developed by the Minnesota Department of Commerce target projects that not only have the ability to contribute to the goal of increasing hydrogen use in the state but also provide an opportunity to influence business and rural economic development. The

2007 slate, as described in this report, focuses on projects that have demonstrated proof of concept, are at a pre-commercial stage of development and are entering a stage where market economics can be assessed and will likely be developed in Minnesota, by or in partnership with, Minnesota institutions or businesses that have an economic stake in their success.