Clean Energy Technology Roadmap

a project to identify Minnesota's most promising research and development opportunities for achieving the state's clean energy goals

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Clean Energy Technology Collaborative

Introduction

In January, 2008, Governor Pawlenty issued an Energy Initiative to create the Governor's Clean Energy Technology Collaborative (CETC). Nineteen members were appointed to CETC in September, 2008. The group was asked to develop a Clean Energy Technology Roadmap outlining Minnesota's research and development vision, along with an action plan and related milestones, to ensure that Minnesota achieves the clean energy goals passed into law by the Legislature in 2007. CETC held six meetings from November, 2008 to April, 2009 in order to carry out this task.

While "clean energy" is not defined in Minnesota law, the state's energy-related statutes provided useful guidance. Provisions passed and signed during the 2007 legislative session outlining Minnesota's energy goals include:

- Reduce per capita use of fossil fuel as an energy input by 15 percent by 2015.
- Derive 25 percent of the total energy used in the state from renewable energy resources by 2025.
- Reduce Utility Conservation Improvement Program electricity and natural gas consumption by 1.5 percent per year.
- Reduce greenhouse gases by 15 percent below 2005 emission levels by 2015, 30 percent by 2025, and 80 percent by 2050.
- Establish a Renewable Energy Standard for electric utilities, totaling 27 percent by 2025.

CETC's project timeline precluded development of original research. Moreover, comprehensive technical roadmaps can take months or years to develop. Given the time commitment agreed upon for this project, members chose to leverage use of existing roadmaps and published research as a means to effectively accomplish the task. As such, CETC members 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.

To guide the Roadmap creation process, members developed ranking guidelines for prioritizing research and development needs for the technologies under consideration. These included the impact the technology would have on Minnesota, the timeframe necessary for its commercialization, and the product development stage of the technology under consideration.

As a result, the Clean Energy Technology Roadmap describes the most promising clean energy technology research and development opportunities with the greatest potential benefit for Minnesota. The opportunities identified do not represent a comprehensive list of all important or relevant projects; absence of a particular technology does not mean research regarding it should be excluded. Rather, the technologies listed represent conclusions reached by CETC based on the spectrum of publications reviewed and discussed by members in comparing research projects and opportunities.

Clean energy technology research and development is extensive and evolving rapidly. A comparison of global-scale opportunities with those in which Minnesota can play a leadership role required a great deal of candid reflection. It is CETC's hope that this Roadmap will be a tool to help guide the deployment of research and development dollars in the state's effort to advance the clean energy technology revolution and create economic opportunity for all Minnesotans.

Clean Energy Technology Collaborative Members

- Ulrich Bonne (Chief Technology Officer and Consultant, MinneFuel, LLC)
- Lou Cristan (Business Director, 3M Energy and Advanced Materials Division)
- Jane Davidson (Professor of Mechanical Engineering, University of Minnesota)
- John Drown (Partner and Owner, Solar Skies, LLC)
- Don Fosnacht (Director, Center for Applied Research and Technology Development, University of Minnesota –Duluth Natural Resources Research Institute)
- Camille George (Associate Professor, School of Engineering, University of St. Thomas)
- Duane Goetsch (President and CEO, Gradient Technology)
- John Goodman (Senior Vice-President and Chief Technology and Innovation Officer, Entegris)
- Dan Henry (Chief Technical Officer, Hearth and Home Technologies)
- Ralph Imholte (President and CEO, Bepex International, LLC)
- Paul Plahn (Director of Advanced Product Development, Cummins Power Generation, Inc.)
- Lanny Schmidt (Regents Professor, Department of Chemical Engineering and Materials Science, University of Minnesota)
- Claudia Schmidt-Dannert (Associate Professor, Department of Biochemistry, Molecular Biology and Biophysics, University of Minnesota)
- Vincent Winstead (Assistant Professor, Department of Electrical and Computer Engineering Technology, Minnesota State University-Mankato)
- Luca Zullo (Principal Chemical Engineer, Cargill Inc. and Technical Director, Cargill Environmental Finance)
- Ex-officio members:
- Pollution Control Agency Commissioner Paul Eger, assisted by Agriculture Marketing & Development Director Wayne P. Anderson
- Office of Energy Security Director William Glahn, assisted by Department of Commerce Assistant Commissioner Jim Pearson
- Department of Agriculture Commissioner Gene Hugoson, assisted by Director of Policy Development Quinn Cheney and Biofuels Manager Christina Connelly
- Department of Employment and Economic Development Commissioner Dan McElroy, assisted by Deputy Commissioner Paul A. Moe

Project staff:

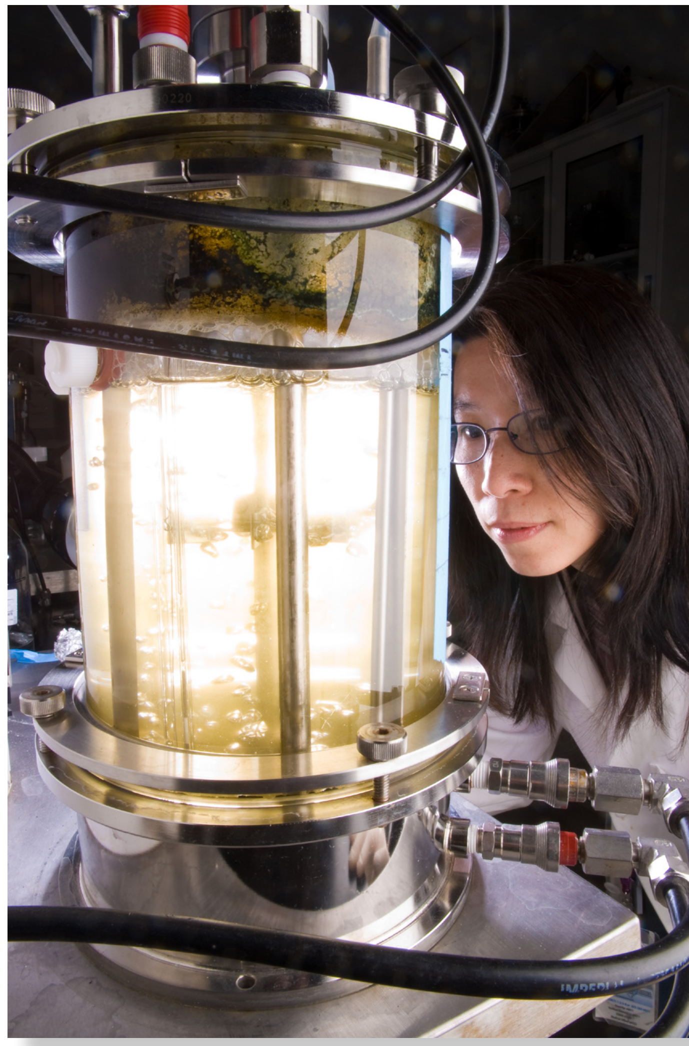
- Ken Brown and Georgie Hilker, Office of Energy Security

Clean Energy Technology Roadmap

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.

Technology Ranking Guidelines



To successfully develop this Roadmap, members reviewed existing roadmaps and published research as a means to identify the spectrum of opportunities available to the state. To ensure consistent review and ranking, CETC developed ranking guidelines to provide for balanced decision-making as technologies were compared. These included the impact, time frame, and product development stage of the technologies (described below).

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 (see Appendix A).
- 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.

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 5 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.

Product Development Stage

The stage of development or maturity for a given technology (see Appendix B), as follows:

- Idea - The thought or revelation. "I wonder if…"
- Preliminary Investigation - Back-of-the-envelope technical and market niche assessment.
- Initial Laboratory Investigation – Basic assumptions and principles observed and evaluated in a laboratory setting.
- Laboratory Detailed Investigation – Practical application of the technology formulated, and detailed analysis to discover validity of assumptions.
- Laboratory scale-up - Options narrowed to most feasible line of investigation.
- Prototype Project - Demonstration of scale-up prototype with performance of integrated components in a relevant, operational environment.
- Commercial-scale Demonstration Project - Commercial-scale demonstration project providing actual operating conditions, testing and evaluation.
- Commercial Production - Detailed engineering, production data, manufacturing processes, performance and market metrics providing justification for commercial production.
- Market Entry - Leading-edge customers determine that it is good practice to purchase the technology and implement change.
- Market Penetration and Diversification - Proven results create additional sales, increasing market penetration.

Summary

High-level research categories & priority projects

High-level categories are listed in the order prioritized by CETC on the basis of the state's ability to influence development and impact the proposed technology will have on Minnesota.

Energy Efficiency

Use exergy to optimize building efficiency

Recovering and using "wasted" energy from one component to supply another reduces external energy inputs needed for building systems as a whole. The next big advance in energy efficiency technology will likely come from evaluating building thermodynamics to optimize use of "exergy."

Bioenergy

Feedstocks

Establish existing sustainable biomass availability, price and economic impact

Establishing the interdependence of current biomass availability, market price, and community economic impact pertaining to its use will enable strategic implementation of the most beneficial projects for the state.

Evaluate future sustainable biomass availability for energy production

There is a critical need to evaluate potential feedstocks to determine which hold the greatest promise for an economically viable, sustainable expansion of biomass so that strategic development of priority feedstock infrastructure can occur.

Optimize feedstock processing

Effective use of biomass resources is constrained by the ability to deliver it cost-effectively and in a useable form to an energy conversion facility. Composition, energy content, storage, and use characteristics of biomass vary widely. Feedstock processing research will determine the most economical and environmentally preferable processes needed to deliver biomass in useable forms for effective conversion into high-value fuels and products.

Bioenergy conversion

Fermentation-derived fuels

Improve ability to obtain cellulose and hemicellulose sugars from biomass

Additional research will improve our ability to release all sugars from biomass as a means to enable cost-competitive use of cellulosic feedstocks by the state's evolving ethanol industry.

Gasification-derived fuels

Demonstrate high-pressure gasification for high value products

Reducing the cost of cleaning syngas is the chief barrier to competitive, non-food-based production of renewable alcohols, gasoline, diesel and jet fuel. Leveraging what has been learned through the state's low-pressure biomass gasification projects with the techniques used in high-pressure gasification systems by the fossil fuel industry promises significant improvements in syngas clean-up needed for biomass.

Improve syngas Carbon Dioxide removal

The presence of CO_2 in biomass gasification syngas significantly reduces the yield of desired products. There is an opportunity to leverage CO_2 membrane-separation technologies developed by the fuel cell industry and apply it to reduce CO_2 levels in biomass-derived syngas. Adapting these technologies to reduce CO_2 in syngas can provide for increasingly cost-effective production of renewable fuels and high-value products in the state.

Employ thermal biomass pre-treatment to produce uniform feedstock

Pre-treating biomass to ensure a more uniform feedstock for gasification systems can reduce the syngas clean-up cost of producing other high-value products from renewable fuels. Pyrolysis bio-oil and torrefied biomass are two pre-treatment methods that offer opportunity for the state to produce a much more uniform feedstock from the wide spectrum of non-food biomass.

Anaerobic digester-derived fuels

Maximize biogas-to-electricity, process heating and biomethane production

Noteworthy improvements have recently been made in the production of biogas from anaerobic digestion of biomass. Guidelines on the optimal conditions, system designs and minimum capacity needed to deploy successful biogas-to-electricity and biomethane projects in Minnesota will provide information needed for the state to realize the significant benefits available from these innovations.

Wind Power

Improve efficiency of wind turbine blades

Energy efficient airflow control products developed for the aerospace industry may be transferable to the wind power industry. The greater the frictional drag of air on airplane wings or wind turbine blades, the less beneficial the airflow. Leveraging research and products that reduce frictional drag on airplanes by applying it to wind turbine blades presents an opportunity for the state to play a leading role in reducing costs of wind power generation.

Solar Energy

Establish multi-purpose solar research and testing lab

Due to the international need for understanding cold weather effects on solar materials, systems and system efficiency, as well as the presence of significant industrial and academic expertise, the state is positioned to benefit significantly from increasing demand for distributed solar technologies. Academic / private sector collaboration focused on materials research, development and evaluation to develop higher efficiency / lower cost systems can place Minnesota in a position of national prominence.

Energy Storage

Determine the highest value energy storage systems for electric utility applications

The ability to respond to fluctuating demand on the electric grid promises significant environmental and economic benefits for use of bulk energy storage. The various applications for energy storage can be generally classified, but regional differences affect the desired level of energy storage, discharge duration, and number of cycles needed per day. The state is well-positioned to influence development of the technology that provides greatest cost-savings and improved reliability for Minnesota ratepayers.

Hydropower

Update hydropower potential for Minnesota

Significant improvements have been made over the last 25 years to the design and performance of low-head dam as well as current-flow (non-dam hydrokinetic) powered turbines. Evaluation of the state's current opportunity for cost-effective use of low-head and hydrokinetic distributed power generation will prioritize use of technologies with the greatest potential for hydropower expansion in the state.

Renewable Hydrogen

Evaluate wind power-to-hydrogen, energy storage and electricity production

Like batteries, hydrogen is an energy storage medium. Evaluation of wind-to-hydrogen production, storage, and electricity production costs (compared to other technologies) would provide the specific information needed to identify technical cost and performance improvements and parameters needed for commercially viable, hydrogen-energy storage systems.

Identify biomass-to-hydrogen opportunities

Minnesota is well-positioned to be a leader in the development and production of hydrogen-rich gas from the gasification and anaerobic digestion of biomass. Research addressing four main areas – (1) anaerobic digester and gasification plant system design; (2) catalyst and/or reformation of resultant biogas or syn-gas to produce hydrogen; (3) evaluation of highest value use of that hydrogen; and (4) proof of concept demonstration projects – would expand biomass utilization, related economic development and jobs to produce high-value products from renewable hydrogen-rich gases.

Coal

Use pre-treated biomass to meet coal-fired power plant performance targets

Co-firing biomass with coal has proven to be a near-term method to reduce CO_2 emissions per kilowatt hour, and has helped utilities meet renewable energy portfolio standards. Research that determines cost-effective biomass pre-treatment options for existing coal-fired plants to continue production of electricity while meeting renewable energy and CO_2 emissions reduction targets will develop long-term, stable markets for biomass.

Geothermal Power

Update geothermal heat-flow map for Minnesota

A generalized map for Minnesota, created more than 20 years ago by the U.S. Department of Energy, relied very heavily on shallow measurements under Lake Superior and used only four data points from bore-holes in the state. A determination that the state was not well-suited for development of geothermal electric power generation[1] relied on scarce data of doubtful reliability. Research that uses in-field sampling will develop a Minnesota-specific heat flow map to better provide for comprehensive renewable energy resource planning in the state.

Detailed findings regarding the high-level research categories and research and development projects determined to be most promising and beneficial to the state.

1 *Geothermal power production should not be confused with ground source (or geothermal) heat pumps; a heat exchange system that actively pumps heat to or from relatively shallow ground as a means to support the heating and cooling needs.*

ENERGY EFFICIENCY

Use exergy to optimize building efficiency

"Exergy" is the component of a building's energy stream that can be recovered and used in place of additional energy inputs such as additional heat, power or fuel. The next major progression in energy efficiency will likely come from evaluating building thermodynamics as a whole to optimize exergy. This approach incurs savings much larger than the sum of the system's energy efficient components.

Approximately 40 percent of energy consumption in the U.S. is used to heat, cool, light and operate buildings. Because 70 to 85 percent of the buildings that will be in use in the year 2030 already exist today, significant energy savings and greenhouse gas emission reductions will occur through retrofitting of existing structures. A recent McKinsey report[2] predicted that U.S. carbon dioxide emissions can be reduced by up to 1 gigaton per year by the year 2030 primarily due to the retrofitting of existing buildings with energy efficient systems.

A great deal of research and product development has occurred in regard to building envelopes, lighting, heating and cooling appliances, and systems and materials. Due to historical industrial and academic expertise regarding building system energy efficiency, Minnesota has demonstrated leadership in development and implementation of many of these products, and is well-positioned to benefit from this next level of building efficiency development. Even if a building has energy efficient components, however, not incorporating them into an integrated energy system can result in significant waste.

Matching the load to the energy available from a thermodynamic system is known as proper use of exergy. Optimizing exergy maximizes the amount of work that can be done in a given system by using "wasted" energy from one component to supply another – reducing net energy inputs needed for the system as a whole.

Today, emerging work shows that commercial facilities can reduce net energy use for space heating and cooling by 50 percent by maximizing opportunities to combine heating and cooling components (including distributed solar) into an integrated, thermodynamic system. As an example, chillers are commonly large units situated on the roofs of commercial buildings that provide for climate control needs (temperature, humidity and ventilation). By piping warmer or cooler water available from other areas of the building to the chiller, energy inputs are decreased and energy efficiency can be increased for the system as a whole. Similarly, warm "wasted" water available in one part of the building can be piped to another part to supply warm water for boilers. This concept can be extended to multiple buildings that operate interdependently with a variety of energy sources to improve energy efficiency and economic vitality.

- ISSUE: Minnesota is a world leader in the area of building efficiency, driven in part by its harsh northern climate and the fact that nearly one-half of the state's annual energy consumption is in buildings. Exterior wall, roof

2 *"Reducing U.S. Greenhouse Gas Emissions: How much at what cost?" U.S. Greenhouse Gas Abatement Mapping Initiative, McKinsey & Company*

and window construction innovations have been fostered by Minnesota's wealth of forest and mineral resources, which have led to creation of some of the largest forest products, window and glass manufacturers in the country. Several large mechanical equipment manufacturers are headquartered in the state that design and produce the hardware and software needed to provide the space heating and cooling, humidity control, ventilation and air cleaning necessary to maintain comfortable, safe, and healthy indoor environments. Numerous small companies provide components and subsystems such as heat recovery ventilators, thermodynamic system design and installation expertise necessary for proper implementation of exergy. Demonstrating efficiency gains by matching forms of "wasted" energy available from some components with energy demand from others will build upon Minnesota's leading role in energy efficiency, derive measurable economic and environmental benefits, and attract additional investment to the state.

- RESEARCH: Building upon long-standing partnerships between academic and private sector researchers and local manufacturers, collaboration should be broadened to include major commercial/industrial end users and electric and natural gas utilities. Collaborative research will identify and evaluate energy systems and control strategies to benefit from optimizing use of exergy. Targeted industrial and commercial demonstration projects will provide data to document net energy and cost changes. Information will be used to apply the practice to other systems which, as documentation merits, will be applied to the residential sector and multiple-use building complexes.
- MILESTONE: The most promising alternatives for use of exergy are identified and quantified. Due to availability of this data, the state moves forward with the best options for rapid implementation. Use of exergy applied to the manufacturing and commercial sectors makes Minnesota more competitive in a global market. Significant cost benefits and energy savings result in more cost-effective energy efficiency efforts, job retention and job creation. Lessons learned are applied to residential sector and multiple-use building complexes.
- TIMELINE: Less than 5 years

Algae oil: Algae oil currently costs more than $25 per gallon to produce. It's conversion into a commercial transportation fuel requires additional expense. Hence, the economics of producing transportation fuel from algae are quite unfavorable today. Resolution of complex issues needed to reduce costs regarding system integration, energy, and land and water usage per gallon remain. However, rather than producing fuel, Minnesota is well positioned to use algae as a means to remove phosphorous, nitrogen and CO2 from wastewater. The resulting algae biomass can be land-spread as a fertilizer, anaerobicaly digested to produce biogas, or used as livestock or aquaculture feed. Leveraging economics of such existing business opportunities can allow for participation in development of the technology without the risk associated with resolution of the complex issues specific to algae oil fuels production, and presents an important opportunity for the state.

BIOENERGY

Because plants so efficiently convert sunlight into sugars and fibers, biomass is an outstanding, perpetual, and effective energy storage medium. Minnesota has very significant biomass resources; however, key research is needed to enable the state to achieve the long-term economic and environmental benefits available from biomass.

In general, all biomass produced in the state is converted into usable products or energy, or decomposed through natural processes to replenish ecosystems. Whether used by humans to produce product or microbes to build soil, all biomass has value. The lack of understanding concerning the interrelationship of such end-uses for biomass represents a significant threat to the creation of a thriving, economically sustainable bioenergy industry in the state.

Minnesota has historically supported research to determine which types of biomass provide for optimum growth rates, the most effective conversion to useable energy, and the best environmental and economic benefits. This research and investment has shaped the state's sizable bioenergy industry. However, increased demand on lands and ecosystems to meet multiple needs for energy, recreation, agricultural, and forest products in an economically and environmentally sustainable manner requires increased focus within two key research areas: the need to optimize feedstocks, and energy conversion processes.

Feedstocks

Establish existing sustainable biomass availability, market price and economic impact

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 5 years

Evaluate future sustainable biomass availability for energy production

There is general agreement that the amount of biomass collected from managed lands has the potential to be increased for sustainable energy production. However, the amount of that increase remains uncertain.

- ISSUE: Different varieties of annual and perennial grasses, woody biomass and polycultures require different soils, nutrients, and environmental conditions to grow. Varying species also require different collection and processing infrastructures. In addition, energy densities vary among species and a wide range of energy inputs for collection, processing, storage, and energy conversion are required for each. To help determine which feedstocks hold the greatest promise, the state has supported a range of energy-crop development and evaluation projects. Based on this research, there is a critical need to evaluate which of these potential feedstocks holds the greatest promise for the most economically viable, sustainable expansion of biomass availability. This analysis will allow subsequent research and economic development to focus on Minnesota's priority bio-energy feedstocks.
- RESEARCH: Based upon previous and current research supported by the state, future research and demonstration projects should focus on evaluation of the best management and harvesting techniques (including yield potentials) for the most likely successful bioenergy crops on different soils and in different agro-regions. Landscape-scale projects should determine the following: (1) best practices for yield optimization; (2) environmentally-sustainable removal rates; (3) understanding of costs and benefits of each feedstock option (including forest residuals and recovered brushland materials); and (4) estimated costs for material collection, preparation and logistics.
- MILESTONE: Future sustainable and economically viable biomass supply is forecast, enabling long-range strategic implementation of priority feedstock and infrastructure development.
- TIMELINE: Less than 5 years

Optimize feedstock processing and pretreatment

Even with available feedstock, effective biomass utilization is constrained by the ability to deliver it cost-effectively and in useable form to an energy conversion facility. Biomass must contain sufficient energy per ton, preserve its energy content and integrity during storage, and maintain a form suitable for use with energy conversion technologies.

- ISSUE: The range of optimum feedstock sizes, characteristics and chemical content for gasification, anaerobic digestion, and combustion technologies is reasonably well-defined. However, compositions and characteristics of the chips, pellets or briquettes (which can contain different compositions of woody, perennial or annual plant material), and torrefied (carbonized) biomass or pyrolysis oil vary widely. Energy conversion facilities require a consistent and uniform on-going supply of feedstock to operate successfully. Today, it is not uncommon for non-optimized feedstocks to be used in fuel energy conversion facilities, causing inferior performance and even failure of system components.

- RESEARCH: Feedstock processing and pretreatment research should determine the most economical and energy efficient characteristics of biomass-derived fuel either delivered for use in leading energy conversion systems or needed to produce specific products. For example, the physical and chemical characteristics of biomass used to produce heat from combustion vary from those needed to produce transportation fuels through gasification. Hence, identifying the most optimum range of fuel forms and characteristics for a given technology and end-use will enable public and private feedstock processing investments to better target their most profitable market, reduce risk, and deliver needed feedstock products.
- MILESTONE: Minnesota feedstocks are processed into forms that provide for the highest sustainable economic value for the producer. State energy conversion facilities procure long-term feedstock supply contracts that provide uniform storage, handling, feeder system and performance characteristics needed for superior performance of their process. Public and private investments improve access to information that links optimum form and characteristics of feedstocks with conversion technologies, which reduces risk and increases cost-effectiveness of projects.
- TIMELINE: Less than 5 years

Bioenergy conversion

Bioenergy conversion research focus areas include those for fermentation, gasification, and anaerobic digester-derived renewable fuels.

Fermentation-derived fuels

Improve ability to obtain cellulose and hemicellulose sugars from biomass

The intentional production of alcohol is one of civilization's earliest innovations. The discovery of late Stone Age beer jugs established the fact that purposely fermented alcohol existed at least as early as 10,000 BC. It is known that pure distilled alcohol was being produced 1,200 years ago. More than 200 years ago, American farmers were fermenting crop waste to make lamp oil and stove fuel. In 1826, Samuel Morey built on his knowledge of steam engines and used alcohol to fuel the first American internal combustion engine prototype. Today, the Indy Racing League uses an all-alcohol formula for its cars, and because it is rich in oxygen, a 10 percent blend of ethanol in gasoline is very commonly used to increase the octane level of gasoline and reduce carbon monoxide emissions. Due to in-depth knowledge and experience regarding its production and use, alcohol has predictably become a very significant renewable transportation fuel.

- ISSUE: Availability of fermentable sugars from biomass forms the basis for cost-effective alcohol production. However, biomass is a complex material composed of cellulose, hemicellulose, and lignin. Cellulose contains the most "accessible sugar" – the same six-carbon (C6) sugar that is found in cornstarch which is commonly fermented to ethanol using conventional yeasts. Hemicellulose contains mainly non-glucose sugars – five-carbon (C5) sugars. Lignin provides the support and strengthening of plant cells, stems and branches. What is digestible by one animal or insect compared to another depends upon the type of microbe, or enzyme, present in its digestive system. Traditionally, people have used starches and sugars commonly found in foods as feedstock for alcohol production. Research is ongoing to expand use of alcohols obtained from non-food sources; progress has been significant in the ability to ferment both C6 and C5 sugars. However, the single largest challenge to production of non-food-based ethanol is the need for cost-effective deconstruction of cellulosic feedstocks into C5 and C6 sugars so that they are available for fermentation. Processes and enzymes exist in animals, insects and microbes that can obtain these sugars from cellulosics. Identifying and emulating these processes and enzymes so they can be used by Minnesota's ethanol industry is necessary for the industry's continued growth.

- RESEARCH: Unlike the many proprietary biofuels fermentation processes, development of biomass deconstruction and hydrolysis technologies needed to release C5 and C6 sugars provides a considerable opportunity for state academic and industrial research. Research should investigate and optimize the effectiveness of different non-biological chemical, pressure and thermal pretreatment processes tailored to a specific blend of biomass that yields a material suitable for subsequent biological enzymatic breakdown into sugar molecules. Once obtained, separation of the sugars from other compounds will then allow for fermentation.
- MILESTONE: Research partnerships focused on improving biomass conversion into sugars enable cost-competitive use of Minnesota cellulosic feedstocks by the state's ethanol industry.
- TIMELINE: 10 years

Gasification-derived 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") which 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, distillers 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. 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

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 dimethyl 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 (CH_2) 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.

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.

Demonstrate high-pressure gasification for high value products

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 percent 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 percent, with a 70 percent 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, have the potential to decrease overall capital costs by as much as 33 percent. 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 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 5 years

Improve syngas carbon dioxide removal

The carbon dioxide (CO_2) released due to combustion or gasification of biomass does not add a net increase to global CO_2 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 CO_2 by volume. However, the presence of this CO_2 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 CO_2 at a given H_2:CO ratio than syngas produced from fossil fuels. This causes a competitive problem when high-value biofuels are desired because the presence of CO_2 limits yield. Commonly available technologies, such as amine or methanol absorption systems as used by the fossil fuel industry, reduce CO_2 levels but require significant capital, operating and disposal costs.
- RESEARCH: A cost-effective technology that would remove CO_2 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 CO_2 from natural gas. There is an opportunity to leverage this and related research, and apply it to reduce CO_2 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 CO_2 from syngas, the CO_2 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 (NOx) 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

Optimize bio-oil and torrefied biomass for renewable fuel production

The production of high-value transportation fuels from biomass gasification requires very clean syngas. Net processing costs can be reduced though optimizing gasification processes and clean-up options; however, using feedstock that decreases clean-up cost and complexity is a potential "front-end" solution to achieve cost-effective production of renewable fuels from non-food based biomass.

In contrast to biomass gasification systems that heat biomass in a low oxygen environment to maximize production of syngas, production of either torrefied biomass or bio-oil is maximized when biomass is heated in a zero oxygen environment. Slow pyrolysis (slow heating without oxygen) is used to "roast"—or torrefy—biomass and create a renewable coke-like solid fuel. Fast pyrolysis (rapid heating without oxygen) serves to maximize bio-oil production. Both torrefied biomass and bio-oil could be produced and used in a local energy conversion facility, or shipped to a distant one.

Bio-oil

Fast pyrolysis bio-oils are usually dark brown, somewhat viscose liquids that have a distinct "smoky" odor. Today's fast pyrolysis reactors incorporate the high heating and rapid heat transfer rate, carefully controlled temperature, and very rapid cooling of the pyrolysis vapors required to maximize bio-oil production. The resultant unrefined oils are highly acidic, water soluble, have short shelf-life due to a chemically unstable mixture of oxygenated organic compounds, and are incompatible with conventional transportation fuels. Hence their use is primarily limited to boiler fuel, sometimes co-burned with coal, for stationary power and heat production.

- ISSUE: Significant upgrading of the bio-oil must occur if it is to be used as a renewable replacement for diesel or gasoline fossil fuels. One method, hydrotreating, upgrades bio-oil using high-pressure hydrogen in combination with catalysts to remove sulfur, nitrogen and oxygen. The chief disadvantage of hydrotreating is that high-pressure hydrogen is costly. Bio-oil is also being upgraded using zeolite catalysts to reduce oxygen content and improve chemical stability. However, poor hydrocarbon yield and catalyst contamination by coke limits effectiveness. Injecting steam with bio-oil into a gasifier, as is done with biomass, produces syngas that can then be used to produce fuels. However, steam-gasification of bio-oils is complicated because bio-oil components decompose upon heating. In addition, some resulting compounds are difficult to reform and high amounts of CO_2 are produced. All of these processes are successfully in use by the petrochemical industry. However, because bio-oils have more instability and variable chemistry compared to petroleum, direct transfer of technology is neither straightforward nor assured.
- RESEARCH: New catalysts need to be developed for bio-oil derived transportation fuels to become viable. The challenges are not trivial, and fundamental research for bio-oil upgrading through catalytic cracking and condensation chemistry is needed. Significant research is underway nationally and internationally to develop a cost-effective means to fractionate and convert bio-oil to high-value chemicals and transportation fuels. The state should support research partnerships that can achieve this goal.
- MILESTONE: Bio-oil is upgraded through use of new catalytic cracking and condensation chemistry processes to produce competitive, chemically stable, high hydrocarbon yield, blendable supplements and replacements for petroleum.
- TIMELINE: 10 years

Torrefied biomass

Many types and qualities of biomass can be gasified to produce syngas for use as an effective heating or transportation fuel. However, very clean syngas is required to produce transportation fuel. Gasifying torrefied biomass, as opposed to feeding "raw" biomass, promises to significantly reduce syngas clean up costs. When biomass is torrefied—slowly heated in a zero oxygen environment—its volatile, low-energy components are largely removed, resulting in a more dense and uniform form of biomass that is less costly to transport and easier to process. Typically, 70 percent of the mass remains—but that mass retains 90 percent of the initial energy content. Since components in biomass that increase costs for syngas clean up are removed—principally water, methanol, CO_2 and acetic acid—syngas produced from torrefied biomass contains less CO_2 and methane than syngas produced from untreated biomass. Because CO_2 limits yield and methane does not reform into liquid fuel, this process increases carbon efficiency and decreases clean-up costs for renewable transportation fuel. Torrefied biomass is a brittle crumble or powder which can either be fed directly into a gasifier or be pelletized for convenient pulverizing at a later time. Either form can improve transportation, handling and feeding characteristics compared to the use of "raw" biomass in a gasifier. Aspects are further improved by the fact that torrefied biomass does not readily absorb water. (Water in biomass decreases its heating value and increases its processing cost.)

- ISSUE: The primary research and commercialization regarding torrefied biomass has focused on its use as a renewable supplement for coal. As with bio-oil, it may be readily co-burned with coal in current coal-fired boilers, and so provides an additional means for electric utilities to meet their renewable energy or greenhouse gas reduction requirements. Although understandably attractive for the international coal power industry, using Minnesota biomass to produce community-based high-value transportation fuels through biomass gasification may provide for broader economic development for the state. Due to competing needs for limited biomass, there exists a timely opportunity for the state to demonstrate and evaluate this pretreatment technology for use in non-food-based, renewable fuel production.
- RESEARCH: Early commercial processes that currently torrefy biomass for use in coal-burning power plants should be evaluated for use with a variety of Minnesota biomass feedstocks. Most optimum torrefaction processes for selected Minnesota biomass should be identified and piloted in the state. Torrefied biomass should then be used in a Minnesota gasifier designed to produce renewable transportation fuels. The change in performance and net costs of the gasifier and its syngas clean-up system due to use of a variety of torrefied versus non-torrefied feedstocks should be compared.
- MILESTONE: Performance and cost of using torrefied compared to non-torrefied biomass determines the most cost-effective means to produce clean syngas needed to produce high-value fuels from a variety of feedstocks. The production of competitive, non-food-based, renewable transportation fuels is maximized for communities across the state.
- TIMELINE: Less than 5 years

Anaerobic digester-derived fuels

Biomethane (Renewable Gas) is produced by cleaning and upgrading biogas. Biogas is a mixture of methane 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 run-off 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 systems are typically above the state's 40 kW net metering threshold, the price the producer obtains for the electricity is non-public; 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. 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.
- Although technically viable, biomethane is not currently (April 2009) produced 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 publicly available 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.
- MILESTONE: 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. 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 5 years

WIND POWER

Improve efficiency of wind turbine blades

Reducing the cost of wind power generation is one of the main challenges confronting the wind turbine industry today. The most common and cost-effective approach for reducing cost is to increase the rotor diameter of a given machine. However, as rotor size increases, so does its mass—and the greater the mass, the more the load and fatigue on components. To solve this problem, designers must devise innovative approaches to reducing the loads encountered during both normal operation and during high-wind, parked conditions so that structural integrity is not compromised and the cost of wind power is further reduced.

Turbine blade manufacture and transport: Turbine blades are relatively lightweight but unusually long, some longer than 120 feet. Shipping blades is a complex, expensive, and time consuming process. Minnesota has noteworthy private-sector expertise in the high-strength composite industry. Due to its historical and on-going support of wind power, the state has significant opportunity to successfully locate additional wind turbine blade manufacturing facilities in the state and reduce cost of local wind power, leverage use of composite expertise, and provide high-skilled jobs.

One of the most promising approaches involves using air flow control strategies that can either passively or actively manipulate air flow to achieve desired aerodynamic objectives. Such objectives typically involve eliminating flow separation and stall, thereby broadening the operational parameters of the turbine; reducing the drag force and increasing lift on the blade; and suppressing large-scale unsteady vortices (which induce noise and cause large fluctuating forces on the blades).

Both passive and active flow control strategies have been deployed in the aircraft industry with a great deal of success—significant potential exists for their use in wind turbines as well. To date, however, very little work has been done to systematically explore the potential of various flow control strategies in wind turbines and demonstrate their performance in a full-scale installation.

Passive flow

Passive flow control strategies typically modify the geometry of the blade by small-scale protrusions into the flow; common approaches involve vortex generators and riblets.

Vortex generators are small protrusions (typically shaped like tiny delta wings) ranging in size from a few millimeters to a few centimeters. When applied to wind turbine blades, vortex generators delay separation of flow from the blade, increase the maximum lift coefficient, and reduce unsteady aerodynamic loads over a range of turbine sizes and operating conditions. By keeping airflow attached to the blade, they can be tuned to maximize the ratio between the lift and drag coefficients, which directly influences the aerodynamic efficiency of the blade.

Riblets structures are much smaller than vortex generators, ranging in height from a few up to hundreds of micrometers. They operate very near the surface of the blade where viscous forces dominate and reduce drag by preventing lateral movement of airflow. Riblet structures applied to airfoils have been shown to provide a significant benefit to aerodynamic efficiency by reducing skin frictional drag and/or increasing lift, and have been successful in a variety of applications—aircraft wings, compressor blades, an entire aircraft, and the winning boat in the 1987 America's Cup competition. Riblets should be expected to work well for a range of wind turbine sizes and operating conditions when the flow remains attached on the turbine blade. With airflow attached, they increase the torque on the rotor due to increasing lift versus drag on the blade. However, riblets become largely ineffective upon airflow separation. Thus, a combination of riblets and vortex generators should be explored to ensure that a turbine blade is equipped with passive flow control strategies that work over a range of operating conditions.

Active flow

Active flow control strategies typically involve some kind of actuators that add energy to the flow locally (in the vicinity of the blade). Concepts range from relatively simple mechanical actuators, such as flaps, to various forms of boundary layer manipulation via steady/pulsed/oscillatory blowing and/or suction, and on up to even more advanced methods of wing/blade and airfoil geometry morphing. Application to wings and airfoils have shown that, although such actuators modify the small scales of the airflow, they have a profound impact on large-scale flow features. For example, such approaches have been shown to completely eliminate separation and vortex shedding from poorly streamlined shapes, reduce drag, enhance lift, and reduce noise.

- ISSUE: While many passive and active flow control technologies have been sufficiently studied and validated, none have been integrated into a wind turbine product. Consequently, cost-benefit in regard to application to wind turbines remains unknown. The impact of these technologies on the cost of wind power encompasses a wide variety of issues such as: optimum use of air flow control and sensing technologies; manufacturing cost; measurable change in maintenance cost due to impacts of lightning, rain, ice, UV light, etc. common in the operating environment; minimized blade soiling and blade erosion; and ultimately the robustness and durability of the system over a 20-year life. However, the potential gains in energy capture on the order of roughly 10% creates significant incentive for investigation.

- RESEARCH: In order to implement flow control technologies into a wind turbine blade design, various available strategies must be investigated using a combination of computational fluid dynamics tools, detailed wind tunnel experiments, and field testing. The optimal solution will likely involve a combination of riblets, vortex generators, and actuators, each applied at different sections of the blade but acting together to suppress aerodynamic noise, reduce structural loading of the turbine blades by air flow imparted forces, and drastically enhance the energy captured by the rotor over a wide range of operating conditions.
- MILESTONE: A cost-effective means to improve efficiency of small and large wind turbines, and reduce the cost per megawatt-hour of wind electricity generated though use of air-flow control technologies for existing and new installations, is determined. Minnesota is recognized as a leader in development and commercialization of the technology.
- TIMELINE: Less than 5 years

SOLAR ENERGY

Establish multi-purpose solar research and testing lab

Options for harnessing solar energy span a broad range of technologies. In Minnesota, the technologies most likely to provide significant offset of electricity and natural gas are distributed non-concentrating solar thermal and photovoltaic (PV) systems. Distributed systems allow for energy production at the location where solar energy is used as well as broad participation from building owners. Buildings account for about 41 percent of primary energy consumption in the state. The use of distributed solar in Minnesota is most common in residential and commercial buildings, followed by agricultural and light industrial facilities.

- ISSUE: There are two manufacturers of solar thermal collectors in the state. Minnesota's academic sector is a recognized leader in solar hot water and space conditioning research. Due to available manufacturing and academic expertise, Minnesota has considerable ability to influence further development of solar heating and cooling technology, especially in regard to systems design, materials performance, demonstration projects, and evaluation.
- Minnesota is not currently home to any major system manufacturers and/or manufacturing facilities of PV systems. However, companies that install, service and manufacture some PV components form a strong nexus in the state.

Because the manufacturing and research base for solar PV is located in other areas of the nation, less opportunity exists to influence development of this technology as compared to solar thermal. However, cold-climate testing and evaluation of PV materials, subsystems and systems represents an opportunity to increase visibility and draw additional investment to communities.

- Minnesota's weather conditions and latitude may uniquely position the state to evaluate how systems perform in variable weather and seasonal change conditions. These conditions are already being capitalized upon: cold climate testing in nine Minnesota cities (including International Falls, Bemidji, Thief River Falls and Baudette) attracts auto engineers from around the globe. Most solar system testing facilities are located in the southwest, and DOE's National Renewable Energy Laboratory has a testing site located near Denver for high elevation testing. Due to available expertise and its climate, Minnesota may have the unique ability to influence product development by serving as a qualified research partner to evaluate performance and economics associated with solar.
- RESEARCH: Due to the need for understanding the environmental effects on materials, systems and system efficiency, as well as the presence of significant industrial and academic expertise, the state is positioned to benefit significantly from increasing demand for distributed solar technologies. Academic/private sector collaboration focused on materials research, development, and evaluation to help commercialize more efficient and lower cost systems would place Minnesota in a leadership position. As such, the state should consider establishing a multipurpose laboratory for research, product development, testing, teaching, and demonstration of solar technologies. Such a facility would provide vertical integration of academic and industry development of new solar technologies and materials. It would also serve as a unique laboratory for northern climates and development of systems for solar thermal space conditioning and PV systems. Such a facility would position the state to serve as a commercial research hub for solar thermal technologies, thereby increasing the profile of the state in regard to solar technologies. Based on a market assessment demonstrating economic viability, such a laboratory could also serve as a nationally accredited product certification facility with minimal additional investment.
- MILESTONE: Research, testing, and educational facility(ies) focused on understanding the climatic and environmental effects on solar systems, subsystems, components, economics and system reliability provides data and information that successfully optimizes solar technologies for a variety of uses in northern climates.
- TIMELINE: Less than 5 years

ENERGY STORAGE

Determine the highest value energy storage systems for electric utility applications

Bulk utility class electrical energy storage systems can be applied in a wide spectrum of applications that have unique requirements and economic benefits. The ratings for such systems are typically 200 kilowatts (kW) to 2 MW in power and 50 kilowatt hours (kWh) to 13 MWh in energy capacity.

Application requirements range from under a minute of power to stabilize voltage and frequency due to power surges, or for up to eight hours to reduce peak consumption, follow changing demand, or defer upgrade transmission investments. Fast transient power demands (within fractions of a second) favor use of technologies that can transfer stored energy at a high rate, such as capacitors, superconducting magnetic storage, flywheels, and NiCd, Li-Ion, NaS and lead-acid batteries. Long period power demands (minutes to hours) favor technologies with a higher level of energy capacity, such as PSB, VRB, NaS, ZnBr flow batteries, pumped hydro storage, or compressed air.

A recent report from the market analysis firm Lux Research, "Making Sense of the Next Big Thing," predicts that the $41 billion energy storage market will grow $64 billion by 2012, but entrants struggle with a complex and competitive market. Of all the markets studied—portable device, vehicle, residential and commercial—bulk energy storage for utilities was identified as holding the biggest potential.

The market size for bulk energy storage is currently small, about $500 million, and large-scale manufacturing hubs have yet to be established. States that take a leadership role in collaboration with their utilities can significantly influence development of the technology. Bulk energy storage offers an array of benefits for utilities and ratepayers, and these benefits will continue to improve, especially as smart grid initiatives (designed to allow for broader transmission and distribution power system flexibility and functionality) move forward.

Bulk energy storage allows for:

- System-wide predictability;
- Reduced need to invest in new capacity by providing for more flexible use of existing generation capacity;
- Minute-by-minute generation/load balance;
- Reduced need to purchase electricity on the spot market (utility issue) or during high peak price times of the day (consumption issue);
- Ability to store inexpensive electricity when demand is low to offset higher cost electrical when the demand is high;
- Avoided use of relatively high cost peak generation plants;
- Increased line-carrying capacity by improved dynamic stability;
- Reduced transmission congestion in areas where systems are becoming congested during periods of peak demand;
- Reduced or deferred utility investments for transmission and distribution system upgrades; and,
- Improved power quality and reliability.

The benefits of energy storage are significant when they are fully integrated into the grid so that multiple stakeholders can benefit from it as a system resource. System ownership may be with the utility, independent power producer, or large power consumers. Energy storage, as a part of Smart Grid implementation, will allow all parties connected to the grid to either directly or indirectly share benefits.

- ISSUE: Previous analysis performed nationally and internationally promises significant environmental and economic potential for the use of bulk energy storage. The various applications for energy storage can be generally classified, but regional differences affect the desired level of energy storage, discharge duration, and number of cycles needed per day. Bulk energy storage, as a part of a Smart Grid strategy, can optimize Minnesota's contri-

Energy storage and Smart Grid: Evolving energy storage technologies vary by their energy storage capacity (MWh), energy density, cycle efficiency, cycle service life and the sustainable power levels (kW) during charge and discharge. To research the use of large-scale batteries as a part of its Smart Grid strategy, Xcel Energy has installed a NaS battery for energy and power storage rated by the manufacturer, NGK, at 6-7 MWh in energy capacity and 1 MW in power. Evaluation is in progress to determine the large-scale battery's ability to store energy generated from the Minwind Energy site in Luverne MN and provide power to the grid when needed. The research will characterize this energy storage system's ability to stabilize line voltage and decrease the need for fossil fuel peak power by maximizing use of variable wind power. This type of research is critical for the state to best benefit from emerging Smart Grid-energy storage technologies.

butions for distributed generation provided by residential and commercial sources. Performing an analysis using the economics unique to Minnesota will allow the determination of system capital costs, the system benefits for identified applications, and installation potential in Minnesota. Without this information, the optimum technical and economically beneficial energy storage technology cannot be determined. States that determine the most cost effective energy storage technology for unique conditions and needs will enable effective decision making, and will be better positioned to effectively influence development of the technologies, compete for funding and deployment, and create associated high-skilled jobs.

- RESEARCH: The research should identify high potential bulk energy storage technologies and applications that provide the greatest economic benefits to owners and ratepayers based on state regional power production and application economic conditions. This work should build upon similar research done in other geographic locations. Factors unique to Minnesota are: the mix and amounts of power generation; the type and cost of base load and peaking power production; the type and cost of distribution; and the type of commercial loads and their attendant power quality issues. Energy storage applications with the highest potential should be piloted for use in the state such that the data collected can be used to verify the economic models developed and the level of opportunities and benefits previously estimated. This research will position the state for a leadership role in influencing development and siting of the technology
- MILESTONE: Minnesota power producers and the state identify: the most cost-effective and cost-competitive bulk energy storage systems and applications; pilot projects demonstrating significant cost-savings and improved reliability for stakeholders; and developers of selected technologies seeking partnerships to locate manufacturing facilities in the state.
- TIMELINE: Less than 5 years

HYDROPOWER

Update hydropower potential for Minnesota

The first hydroelectric power generation facility in the United States went into operation on September 6, 1882 at St. Anthony Falls in Minneapolis, marking the beginning of a new era. In 1960, 39 Minnesota hydropower plants with 210 MW of total installed capacity were in operation. Today, around 32 plants with about 150 MW of installed capacity are active, as economies of scale and improved technology have allowed centralized coal fired and nuclear power plants to produce electricity more cheaply and consistently than distributed hydropower stations.

- ISSUE: A 1996 assessment report released by the U.S. Department of Energy (DOE) lists 40 sites in Minnesota with an additional 137 MW of hydropower potential (primarily available from upgrades to existing power generation sites and redevelopment of existing dam sites from which turbines have been removed). Significant improvements have been made over the last 25 years to the design and performance of low-head dams as well as to current-flow (non-dam) powered turbines. In addition, incentives to provide for distributed renewable electricity have changed significantly over this time period. Consequently, today's potential for environmentally and economically viable distributed hydropower in the state is unclear.
- RESEARCH: The historical use of river systems for distributed power generation created a nexus of expertise in the state. Today, noteworthy aca-

First in the nation again: in January 2009, the Federal Energy Regulatory Commission (FERC) approved installation of the nation's first hydrokinetic river installation in Hastings, Minnesota. FERC members voted 5-0 in favor of the project for two Hydro Green Energy 35-kilowatt turbines to generate a total of 70 kilowatts of power. The hydrokinetic turbines will be mounted on a barge just downstream from the City of Hastings' existing hydropower plant, generating power from the dam's tailrace current.

demic and industrial sector expertise continues regarding both low-head and current-flow (hydrokinetic) power generation. The presence of this expertise creates a key opportunity for the state.

Costs for reopening an existing small dam or installing hydrokinetic turbines vary widely from site to site. Hydrokinetic turbines did not exist when the 1996 assessment was performed. Based on present costs and turbine performance, an updated high-level investigation is needed for (1) existing hydropower sites, (2) dam sites from which turbines were removed, and (3) of sites for which hydrokinetic power generation potential exists. Collaborative research regarding the mechanical and environmental design and implementation of these power generation technologies would serve to identify the optimum sites for successful low-head dam and hydrokinetic turbine investment in the state.

- MILESTONE: Evaluation of the state's current opportunity for cost-effective use of low-head and hydrokinetic distributed power generation provides information required for methodical decision making. Outreach and assistance is prioritized toward the sites and technologies that have the greatest potential for additional hydropower in the state.
- TIMELINE: Less than 5 years

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.

RENEWABLE HYDROGEN

Hydrogen (H_2) is an extremely valuable element—a critical component of organic life and water. The most common use of manufactured hydrogen 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. Hydrogen is also being burned in engines to produce power and in fuel cells to produce electricity. Renewable hydrogen is completely interchangeable with hydrogen produced from fossil fuels and, therefore, can be used to make the same manufactured products.

Hydrogen, like batteries, is an energy carrier—not a fuel. While the most abundant element on earth, it is commonly bonded to other elements to form molecules. Finding cost-competitive methods to produce, store, and deliver elemental hydrogen for use by the transportation and power generation industries, represent the most significant barrier to widespread use in those industries.

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 it 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 which 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.

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.

Power generation industry

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.

Wind power-to-hydrogen and electricity production

- ISSUE: The high cost of hydrogen production, low availability of hydrogen production systems, and 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. 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. 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 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.
- MILESTONE: Development and testing of complete integrated fuel cell power

systems is benchmarked and performance parameters needed for cost-competitive component development is 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 5 years

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, as described in the recommendation for feedstocks, 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. As described in the biomass gasification and anaerobic digester sections of this roadmap, 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. Department of Energy has a 2012 biomass gasification-to-hydrogen target of $1.60 per gasoline-equivalent gallon (GEG), 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, and 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

Pre-treatment of coal: Billions of dollars from the coal industry and federal government have been spent, primarily in coal-rich states, to develop coal pre-treatment technologies to make the emissions and ash from coal combustion less problematic. Minnesota has no coal deposits, hence, the priority for the state to focus on pre-treatment of biomass as a means to reduce environmental impact per kWh. However, given the scope of national and international research to remove sulfur, mercury and components that result in problematic ash from the coal prior to its combustion, there may be opportunity for the state to obtain advantage from these investments. Enabling Minnesota utilities to evaluate opportunities to partner with coal-producers that apply pre-treatment to coal prior to its shipment could help determine viability, cost and environmental impacts for using pre-treated coal in the state's existing power plants.

Carbon capture and sequestration (CCS) also qualifies in the state as a method to reduce GHG emissions. Cost estimates to develop a sequestration site, capture, and pipe and inject the CO_2 into suitable geologic formations range from about $40 to $90 per ton CO_2. Minnesota power plants currently release approximately 1,350,000 CO_2-equivalent tons per year. Regionally, the states of North Dakota and Illinois have confirmed formations suitable for sequestration. Formations in the Midcontinent Rift System which runs from south central through northeastern Minnesota, as well as mineral by-products from non-ferrous mining operations, may have characteristics required for successful sequestration. If confirmed, the costs for sequestration would be decreased for the state, due to decreased piping and transfer expenses.

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 5 years

COAL

Use pre-treated biomass to meet coal-fired power plant performance targets

More than 60 percent of electricity generated in Minnesota comes from coal-fired power plants. Given the long time-horizon required for major changes in power supply infrastructure, the state will need existing plants to continue to supply a high percentage of its electricity for the foreseeable future. Minnesota electric utilities are required to meet state renewable energy portfolio standards, and it is anticipated that amounts of CO_2 emissions per kWh generated will become regulated. Given the large investment and reliance on coal-fired power production in Minnesota, it is important that the state seek ways to most cost-effectively reduce the expense of meeting renewable energy and CO_2 reduction targets through optimizing use of existing power plants.

Co-firing biomass with coal has proven to be a near-term method to reduce CO_2 emissions per kWh, and has helped utilities meet renewable energy portfolio standards. However, the direct co-firing of wood with coal requires significant expense due to the need to add auxiliary combustion equipment and dual burner control technology as well as to re-permit current facilities. Additionally, it is difficult to control the results of co-firing because of the variable nature of the biomass materials relative to the coal fuels that they displace. Uniformity in biomass fuel properties would minimize need for separate combustion technologies and would greatly facilitate wider use of the biomass for displacement of coal in power generation.

Biomass pretreatments that would allow for a uniform renewable combustion product are needed. Such pretreatments should be targeted to reduce the moisture content of the biomass, increase its caloric value relative to coal, and allow its use in existing coal-based combustion systems. Use of pretreatments for biomass promises a means for the state's existing coal-fired power plants to meet renewable energy and CO_2 reduction requirements without incurring high equipment and permit costs. At the same time, it will provide for a long-term stable market for biomass residuals without large increases in rates charged for electricity anticipated for implementation of other methods to reduce CO_2 per kWh.

- ISSUE: The need to prepare biomass feedstocks in a fashion that will make it possible to cost-effectively utilize biomass in existing pulverized coal systems is the key problem in need of resolution. Several biomass pretreatment options exist that have potential to accomplish this need.[3]
- RESEARCH: Determine the utility of various biomass pretreatments (e.g., moisture reduction, consolidation, torrefaction, fast pyrolysis) to enable large amounts of biomass to be routinely used as a substitute for coal in current and Integrated Gasification Combined Cycle (IGCC) power plant burner

3 As with all recommendations for use of biomass feedstocks provided in this roadmap, care must be taken to assure that sustainable production, harvest, processing, and optimum value for use of this resource in the state is achieved.

technology applications (either as a treated solid or as a bio-oil injectant). Each pretreatment option would be tested with present and IGCC power plant technologies to determine net change in CO_2 emissions per kWh generated and net change in cost per kWh generated. Based on this research, the quantity, amount, type and cost of obtaining the biomass required to provide for reductions needed in CO_2 emissions for a typical Minnesota coal-fired power plant should be determined.

- MILESTONE: The most cost-effective biomass pre-treatment options for existing coal-fired plants to continue production of electricity while meeting renewable energy and CO_2 emissions reduction targets though use of biomass is determined. As compared to other markets, the economic value to the state for use of the quantity, amount and type of biomass needed to provide for cost-effective reductions in CO_2 emissions for a typical Minnesota coal-fired power plant is determined.
- TIMELINE: Less than 5 years

GEOTHERMAL POWER

Update geothermal heat-flow map for Minnesota

Indigenous, renewable energy is increasingly relied upon to address a range of environmental, security and economic needs for our nation. Efforts to implement wind, solar and bioenergy technologies for heat, power and fuel are well-publicized; this is not the case for geothermal power. However, due in large part to its potential to serve as a large and well-distributed national energy source, funding for the U.S. Department of Energy's geothermal program has doubled over recent years.

Whereas solar, wind and bioenergy technologies rely on energy directly from the sun, geothermal energy consists of utilizing heat from the Earth's crust. This heat flow is due to two primary processes: 1) Upward movement of heat from the Earth's mantle and core, and 2) Heat generated by the decay of radioactive elements in the crust.

In contrast to ground-source heat pumps (also mistakenly called geothermal heat pumps) that use the thermal mass of the ground as a heat-transfer medium for heating and cooling of buildings, geothermal reservoirs use hydrothermal geologic systems to produce large amounts of heat and electricity for communities or larger scale regions.

There is widespread perception that geothermal power must be associated with relatively few high-grade hydrothermal systems. Indeed, most of today's commercial systems are located in high-temperature (>200º C) high heat flow rate (>100 milliWatt per square meter) rock formations that are present within 1,000 feet of the surface. However, improvements in heat-transfer and power generation technologies are being demonstrated at several U.S. sites—in California, Nevada, and Alaska—where inlet temperatures are just above 100º C. Power generation using low inlet temperatures may also be possible in Minnesota.

- ISSUE: Although Minnesota has renewable energy resource maps for wind, solar and biomass, the state does not have a detailed geothermal heat-flow map. A generalized map for Minnesota, done more than 20 years ago by the U.S. DOE, relied very heavily on shallow (>10 ft.) measurements under Lake Superior and used only four data points from bore holes in the state. That data was used to model results for Minnesota that indicated 50º C at 1,000 feet depth and a heat flow rate of less than 50 milliWatt per square meter.

Binary plants convert medium-temperature resources into electricity more efficiently than other technologies. In the binary process, a closed-loop system uses hot water from the well to heat another liquid, such as isobutane, through use of a heat exchanger. The secondary fluid vaporizes into gaseous vapor and (like steam) the force of the expanding vapor turns the turbines that power the generators. The main economic challenge in engineering binary systems is not technical, but rather in the need for an adequately sized reservoir with sufficient permeability to sustain long-term flow rates at temperature.

Since these estimates were too low for a viable geothermal power system, no state or federal resources have been directed toward further investigation since that time. Unfortunately, this important determination relied on scarce data of doubtful reliability. In addition, the study used no samples from Minnesota's large and relatively shallow granitic formations—rock types known to provide for significant geothermal reservoirs in other states.

- Given on-going improvements in binary geothermal power generation technology that have occurred over the last couple of decades, as well as recent increased investment by the federal government and private sector in geothermal energy, it is important that the state obtain a more valid assessment of the potential use of the geothermal power in Minnesota.
- RESEARCH: Minnesota has more than 100 open mineral exploration drill holes and deep wells that may be used to collect heat flow and thermal conductivity data. Selected bore holes and wells should provide data detailing rock type, location, vertical depth interval used for heat flow determination, average thermal conductivity, average temperature gradient over the depth interval, mean heat flow, standard deviation, correction for postglacial warming, and adjusted heat flow.
- MILESTONE: In-field sampling provides accurate data used to develop a Minnesota-specific heat flow map that shows temperature depth profile and heat flow determinations for the state. The data and map provide for comprehensive renewable energy resource planning and decision-making in the state.
- TIMELINE: Less than 5 years

Cross-Cutting Issues

In order to maximize overall benefits, research that is focused in a specific high-level category—such as energy efficiency and bioenergy—should complement research in other categories. The question, "How might this research project complement or be dependent upon other research?" should preface the state's approach to projects. In some cases, however, research may be centered on an issue that applies to many other categories of research. "Cross-cutting issues" are those that transcend the high-level categories listed in the roadmap. Three key cross-cutting issues are itemized below:

(1) Smart Grid; (2) bio-feedstocks and conversion; and (3) financing.

Smart Grid

Research focused on renewable electricity should consider interaction with the regional transmission and local distribution systems, including increasing generation from the state's distributed residential and commercial-scale solar PV, wind and biogas-to-electricity installations. As previously noted in this roadmap, energy storage technologies represent a particularly strong opportunity for the state. However, research should also leverage recently accelerated federal and utility investment for a wide variety of Smart Grid implementation strategies.

- Smart transmission system products are increasingly available for digital, real-time coordination of information from both generating plants and demand-side resources, and for automatic re-routing of power to areas of need.
- Smart distribution systems are incorporating technologies such as intelligent universal transformers, multifunction solid-state switchgear systems, sensors for real-time distribution system monitoring, and advanced end-user metering.

While developments of Smart Grid technologies are driven by the need to increase efficiency and effectiveness of the system as a whole, they can also leverage more rapid incorporation of cost-effective, multiple, and diverse distributed renewable power technologies and facilitate the interconnection of new generating sources to the grid. The state should identify and coordinate with Smart Grid efforts as a means to enhance the ability to maximize local, renewable energy-related projects and value.

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.

Scale of facility and feedstock throughput 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.

Financing

Research and commercialization cannot proceed without financing. In regard to Roadmap scope, there are three cross-cutting financing-related focus areas: (A) interagency collaboration; (B) federal grant programs; and (C) state grant programs.

Interagency collaboration

It is fairly common practice for companies seeking funding for their renewable energy technology to request meetings with individual state agencies. An informal clean/renewable energy network is in place to ensure that agencies involved with clean/renewable energy projects share input and coordinate funding and other assistance where possible. The agencies that are part of this network include the Minnesota Office of Energy Security, Departments of Agriculture, Natural Resources, Employment and Economic Development, Pollution Control Agency and the Iron Range Resources. To best utilize personnel and expertise and leverage resources, agencies should formalize this network such that support for consistent communication and collaboration continues to occur. A simple questionnaire or form could be used by interested clean/renewable energy companies to provide key business and stage-gate[4] information needed by state agencies to determine how best to assist these companies. In addition, input and issues identified by developers could be more consistently communicated among the agencies, allowing each to work from the same basic pool of information and knowledge. At no additional cost to state agencies, implementation of a formal, yet flexible, communication approach would help ensure that clean/renewable energy business ventures receive the assistance needed to best achieve commercial success.

Federal grant programs

Federal grant programs offer an extremely important avenue for obtaining the financing required to move from prototype to commercial-scale operations, as well as achieving technology transfer. Applications and procedures for comparatively small federal grant programs can be very complex. Programs offering large awards are both complex and lengthy. Although the state provides assistance to educate and assist Minnesota companies regarding business plan requirements, grant opportunities, procedures, and applications, Minnesota would be well served if the level of this assistance could be increased in order to attract a greater number of federal awards to the state. Receipt of such awards increases ability of the company to attract the venture capital typically needed before institutional financing is available.

Due to the interdependent factors and long project development timelines, this assistance is particularly important for competitive development of the state's renewable energy industry. States such as Ohio, Michigan, Kentucky,

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Virginia and Florida reportedly receive a larger percentage of federal awards as compared to other states, due in part to a more comprehensive partnership-building, financial, regulatory, and siting assistance program effort.

Minnesota is recognized as a hub of excellence in many energy-related areas; however, due to the relationships and partnerships established in construction of early commercial demonstration projects, manufacturing centers frequently flow to states that have sited such projects. Integrated assistance has been shown to increase the number of commercial-scale projects sited in a state. Providing more comprehensive assistance is important for creation of long-term, high-paying jobs in Minnesota, particularly in regard to obtaining competitive funding from a wide variety of sources for the state's renewable energy industry.

State grant funding

Research and development is inherently risky and only a small percentage of new ideas will find commercial use. For all federal, state, or private-sector financing, it is the responsibility of the applicant to provide facts on technology readiness and other factors so that an accurate assessment of product development can be made to ensure that the project is ready to progress into the next stage.

Despite these needs, it is costly for a developer to obtain the independent measurement, verification and evaluation (MV&E) required to satisfy a funder's need to understand the technical, economic and market potential for the technology. The quality metering and measurement needed to determine metrics such as the materials and energy balance, emissions, system performance and scale-up design costs of a given technology vary. MV&E for a bench-scale system may cost only a few thousand dollars, whereas studies for a $10 million dollar project can cost hundreds of thousands of dollars, and studies for a $250 million facility can easily exceed one million dollars. Developers are often financially unprepared to acquire this kind of independent evaluation needed to secure federal, venture capital or institutional funding. Many good inventions fail not because they are poor ideas, but because of the inventor's inability to finance independent evaluations for their process.

Without the ability to fund quality verification and feasibility studies, innovative research cannot proceed to commercialization. A competitive state grant program could fill this void by providing funds for the demonstration and independent evaluation of clean energy technologies. Armed with quality performance verification data, Minnesota innovators would be much better positioned to obtain the funding required for successful commercialization.

Summary

Coupled with increased multi-agency collaboration, multi-program federal grant application assistance, and a developer's system performance verification data; the research priorities identified in this Roadmap could be implemented at relatively low cost to the state, especially when compared to the benefits received from statewide development of Minnesota's clean/renewable energy industry.

Appendix A

Minnesota Energy-Related Mandates and Statutes

STATE GREENHOUSE GAS REDUCTION GOAL

2007 Minn. Stat. 216H.02 requires that the state reduce greenhouse gas 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.

Status

Various studies are in progress to determine most feasible use of such tools as cap and trade, low carbon fuel standards, and emissions baselines and profiles.

- 2007 Minn. Stat. 216H.02 (https://webrh12.revisor.leg.state.mn.us/statutes/?id=216H.02) and
- Subd. 2. Definition; statewide power sector carbon dioxide emissions (https://webrh12.revisor.leg.state.mn.us/statutes/?id=216H.03&year=2008)

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

Status

All electric utilities are on track to meet 2012 goals. (https://www.revisor.leg.state.mn.us/statutes/?id=216B.1691)

ENERGY POLICY GOALS

2007 Minn. Statute 216C.05 Subd. 2, states it is the energy policy of the state of Minnesota that:

- (1) 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
- (2) 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)

ENERGY SAVINGS

2007 Minn. Stat. 216B.241 changed minimum spending requirement to energy savings requirement for Minnesota electric and natural gas utilities. Utilities are to reduce retail energy sales by 1.5% based on a three year average through Conservation Improvement Program investments.

Status

Electric utilities

- 1.5% of electricity sales amount to about 1 billion kWh/yr
- Electric utilities are currently conserving around 500,000 kWh/yr, or 50% of target.

Natural gas utilities

- 1.5% of natural gas sales amount to about 4.9 billion cubic feet of natural gas
- Natural gas utilities are currently conserving around 1.9 billion cubic feet, or about 40% of target.

(https://www.revisor.leg.state.mn.us/statutes/?id=216B.241)

BIODIESEL CONTENT MANDATE

2009 Minnesota Statute, 239.77 Biodiesel Content Mandate requires that all biodiesel fuel sold or offered for sale in MN for use in internal combustion engines contain the following percentage of biodiesel fuel oil by volume:

May 1, 2009	5 percent
May 1, 2012	10 percent
May 1, 2015	20 percent

"Biodiesel fuel" means a renewable, biodegradable, mono alkyl ester combustible liquid fuel that is derived from agricultural and other plant oils (excluding palm oil) or animal fats.
(https://www.revisor.leg.state.mn.us/statutes/?id=239.77)

Status

The state currently has achieved its 5% requirement. The 10% (2012) and 20% (2015) requirements will require a considerable amount of industry interaction to achieve. Cold weather properties and other issues of these higher blends are being reviewed by the Biodiesel Task Force
(http://www.mda.state.mn.us/renewable/biodiesel/biodieselforce.htm)

OXYGENATED GASOLINE

2005 Regular Session Minn. Statute 239.791 Subd. 1a. requires that by August 30, 2013 all gasoline sold or offered for sale in Minnesota must contain at least 20 percent denatured ethanol by volume. "Agricultural alcohol gasoline" means a gasoline-ethanol blend with ethanol derived from agricultural products, such as potatoes, cereal, grains, cheese whey, sugar beets, forest products or other renewable resources. (Requirement is subject to EPA approving a 211(f)(4) waiver to the clean air act certifying E20 as "gasoline" by December 31, 2010.)

Status

Approximately 2.8 billion gallons of gasoline were sold in the state last year, of which about 285 million gallons, or 10%, was ethanol. (Of this amount of fuel-blended ethanol sold, approximately 15 millions gallons was E85.) To achieve the 20% fuel-blended ethanol sales by 2013, an additional ten percent must be blended within five years.
(https://www.revisor.leg.state.mn.us/statutes/?id=239.791)

HYDROGEN ENERGY ECONOMY GOAL

2003 1st Special Session, Minn. Statute 216B.8109 sets a goal that Minnesota move to hydrogen as an increasing source of energy for its electrical power, heating, and transportation needs.
(https://www.revisor.leg.state.mn.us/statutes/?id=216B.8109)

Status

Biennial Reports http://www.energy.mn.gov "Hydrogen Projects Report"

MERCURY EMISSIONS REDUCTION GOAL

1999 Regular Session Minn. Stat. 116.915 sets a goal that the state reduce mercury contamination by reducing the release of mercury into the air and water of the state by 60 percent from 1990 levels by December 31, 2000, and by 70 percent from 1990 levels by December 31, 2005. The goal applies to the statewide total of releases from existing and new sources of mercury.
(https://www.revisor.leg.state.mn.us/statutes/?id=116.915)

Status

The Mercury TMDL Implementation Plan June 2008
(http://www.pca.state.mn.us/publications/wq-iw1-20.pdf)

Appendix B

Stage-Gate Management

Research & development (R&D) is inherently risky and only a small percentage of new ideas will find commercial use. Stage-Gate[5] provides for methodical decision-making in the R&D process. It provides for fact-based funding decisions based on a set of criteria used to determine whether a technology is ready to pass into next stage.

Research to show the technical and economic potential for a technology in successive project stages provides important information for making judgments about the project and for committing funding in the long-term. The expectation is that projects with serious technical or other issues will be identified and resolved early-on, enabling greater investment in the projects with the greatest probability for success in later stages.

Gates

Gates are decision points for initiating funding or moving forward with a project. A major reason for R&D failing to produce a market impact is the neglect of market, business and financial factors early in the R&D process.[6]

It is the responsibility of the interested party to provide facts so that an accurate assessment of the current stage of development is known, and determine if a technology is ready to pass onto the next stage of development.

Common Stages of Product Development

1. Idea – the thought: "I wonder if…"
2. Preliminary Investigation – Idea exploration: Back-of-the-envelope technical and market assessment. "Has anyone else done this?" Initial literature and patent review. No laboratory work.
3. Initial Laboratory Investigation – Basic observation and application: Studies related to the technology's basic properties are reviewed. Basic assumptions and principles are observed and evaluated in a laboratory setting. Practical application of the technology is formulated but yet not proved. Individual components are researched and tested but are not yet integrated. Experiments may demonstrate technical viability, or raise new and important scientific questions.
4. Detailed Laboratory Investigation – Proof of concept: Work identifies unproven steps in laboratory setting, and documents the known/unknown capabilities of the technology. Thorough literature review and patent search occurs. Performance of components are individually verified. Data is used to model integrated system performance and simulate how components would work together. Proof of concept is validated.
5. Laboratory scale-up – Proof of application: Research is narrowed down to most feasible line of investigation. Technical capabilities, energy balance and environmental considerations are verified. Laboratory performance of integrated components validate proof of application . Issues that must be solved to achieve technical and economic viability are clearly determined. Data provides inputs for modeling simulation to determine most realistic system design and

5 *Stage-Gate is a registered trademark of R.G. Cooper & Associates, a methodology which has been successfully applied throughout industry and government to increase rate of success bringing new energy technologies to market.*

6 *U.S. Department of Energy, "Stage Gate Innovation Management Guidelines; Industrial Technologies Program," V 1.3, February 2007.*

technical performance at prototype-scale and throughput.

6. Prototype Project – Validation in relevant environment: Demonstrates scale-up prototype performance of integrated components in a market-niche's simulated or actual operational environment. Develops convincing data that the technical and economic issues previously identified are, or can be, resolved. Verified data provides inputs for modeling results of commercial-scale operations and system design, develops engineering scale-up data, and clearly documents potential to achieve economic viability for the selected application of the technology.
7. Commercial-scale demonstration project – Validation in actual environment: Demonstration project provides for actual operating conditions, testing and evaluation at commercial-scale operation. Accuracy (level of error) of the projections made through use of the results obtained from the prototype project is determined. Technology has is proven to work in its final form, operating scale and conditions. The information created from the construction, use and evaluation of a commercial-scale project, commonly undertaken with an industrial partner, must be sufficient to support decision for investment in commercial production of the technology.
8. Commercial production – Final design: Information obtained from commercial-scale demonstration project provides for final design, detailed engineering, production data, manufacturing processes, performance and market metrics needed to acquire financing and to justify commercial production.
9. Market entry – Initial sales: Leading-edge customers determine that it is good practice to purchase the technology and implement change. Explicit technical and economic performance is established.
10. Market penetration and diversification – Market success: Proven results create additional sales. Market penetration increases. As the technology matures, options to expand the number of applications for the technology are identified.

Economic investigation

Economic investigations include an assessment of market and customers, competing research, technology, and patents, identification of problems and risks that must be solved to achieve economic viability in the world market place. The economic investigation—the business case for the technology—is updated throughout all ten stages of product development.

Business plan

Results of each product development stage and the evolving economic investigation provide information for a dynamic business plan that illustrates the route, challenges and solutions needed to achieve commercialization. The business plan includes a detailed description of progress to date, documents if the appropriate "gate" has been passed, describes the next project development stage, its budget and metrics to be used to evaluate progress.

Impact

All successful products begin with an idea. However, it is the technologies that achieve commercial viability and market acceptance, i.e. products that are sold—that ultimately provide the profits needed to fund development of more ideas. Stage-gate management does not curtail development of innovation, but does provide for methodical decision-making as a means to increase the percentage of new ideas that achieve commercial success and impact.

Appendix C

Primary References

Published research and industry roadmaps identified and circulated by members as a means to provide for informed discussion and consideration of the wide spectrum of research areas available.

Energy Efficiency

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