NIST/TIP White Paper Topic
"Renewably Generated Hydrogen for Commercial PEM Fuel Cell Systems"

Hydrogen is an energy carrier that can be produced from domestic resources that are clean, diverse, and abundant. Fuel cells provide a technology to use this energy in a highly efficient way, in numerous applications, with only water and heat as byproducts. Together, hydrogen and fuel cells represent a radically different approach to energy conversion that could replace conventional power generators like internal combustion engines, turbines, and batteries. Hydrogen can become a valuable green energy carrier, complementing green electricity. Producing hydrogen offers an important way to store electric energy generated from intermittent renewable sources such as solar and wind, so the energy can be used later in a variety of applications. It is an enabling technology for renewable energy. We can domestically produce all the hydrogen we need in a number of ways. Hydrogen can be produced from natural gas, from biomass, from coal with sequestration, and by electrolysis of water with electricity generated from nuclear and renewables. DOE and industry agree hydrogen can be produced and delivered today by distributed natural gas reforming at a cost of $3.00/gallon of gasoline equivalent. Given the high efficiency of fuel cells, that translates to a cost of $1.50/gallon of gasoline on a per mile driven basis for the consumer (see the recent National Academy report[1] for details).

> "Of all the challenges we face as a nation and as a planet, none is as pressing as the three-pronged challenge of climate change, sustainable development and the need to foster new and cleaner sources of energy. The Obama administration and the Office of Science and Technology Policy are committed to addressing this looming issue aggressively, intelligently and in a way that will not only minimize the negative impacts of past policy failings but also strengthen our economy and enhance our national security. That is why we have set a goal of reducing our greenhouse gas emissions 80 percent below 1990 levels by 2050. It takes harnessing the best science and technology and ensuring evidence-based policy decisions." White House Office of Science and Technology Policy

An Area Of Critical National Need:

The proposed topic "Renewably Generated Hydrogen for Commercial PEM Fuel Cell Systems" addresses a critical national need in attaining sustainable energy independence under any future , global greenhouse gas mitigation program. This includes technologies needed for zero emission, hydrogen-fuel-cell-powered vehicular and stationary power systems. With PEM fuel cells advancing rapidly toward commercialization, commercially viable, renewably generated hydrogen fuel is the remaining "silver bullet" impeding the development and implementation of these sustainable zero emission systems. Research and development are needed to address two areas of water-electrolysis-based hydrogen generation. The focus of one area will be to increase the efficiency of high capacity commercial electrolyzers to improve their cost effectiveness. The second area in which research is needed is in the development of low cost power electronics interface to provide the option to efficiently power an electrolyzer directly from renewable generation systems. While electrolysis-based, renewable hydrogen fueling systems can be constructed with existing commercial components, they are not commercially viable for lack of R&D in these two critical areas. High capacity, hydrogen fueling systems are now coming to the commercial market but a non-carbon water based electrolysis hydrogen system is critical for the next generation of hydrogen PEM fuel cell applications. A unique opportunity exists to focus U.S. Government-supported enabling R&D on the two identified research areas and advance the respective technologies to a high state of commercial readiness. Success in these areas will afford U.S. industry the opportunity to establish itself as the leader in the extensive commercialization of renewable hydrogen fueling and storage. The need for renewable hydrogen fuel for fleet operations of fuel cell vehicles in the near term is apparent now and establishing the threshold for widespread applications for automotive fueling in the long term will open vast new commercial opportunities for U.S. companies.

Input regarding potential challenges was obtained from government agencies (such as NASA, Department of Energy, Department of Transportation and The National Science Foundation), industry (fuel cells, wind and solar generation), companies, universities, industry organizations (Energy Storage Council, National Hydrogen Association, The Partnership for Advancing the Transition to Hydrogen and national labs (NREL).

Magnitude of the Problem:

A significant investment has been made by both U.S. manufacturers and the Department of Energy in the development of hydrogen-fuel-cell-powered vehicles. These investments have resulted in fleet vehicles such as buses and lift trucks ready for commercial adoption both in the U.S. and overseas markets and automobiles at the commercial prototype stage. In parallel with the fuel cell vehicle development, The U.S. DOE had been providing some support for the technology development of hydrogen systems and hydrogen infrastructure in conjunction with their automotive fuel cell program. It was widely accepted that the technology and infrastructure advancements resulting from these efforts would be directly adaptable to other developing applications (i.e. fuel cell bus and fuel cell lift truck fleets) that would precede the wide scale introduction of fuel cell powered automobiles.

However, any DOE support for improving electrolysis systems efficiencies and developing the interface systems for large scale renewable hydrogen generation systems was essentially eliminated when DOE's hydrogen and automotive fuel cell program was zeroed. While hydrogen fuel cell powered vehicles are ready for commercial adoption both in the U.S. and worldwide, without a hydrogen infrastructure, this new market for U.S. made vehicles cannot be realized. The elimination of DOE funding for the development of hydrogen generation and distribution systems has left a void in this area of development, which, if not addressed, will most certainly eliminate U.S. industry from the competition to develop and sell renewable hydrogen generation systems for both domestic and world markets. Within the next three years, in an effort to develop their hydrogen infrastructure, 1000 hydrogen stations in Europe and 500 in Japan will be built.

The magnitude of the task to develop renewable hydrogen system technologies is significant and will require an investment that no U.S. corporation or venture capital firm could currently justify for two basic reasons:

1. A gap exists in the technology needed for the construction of a commercial, high capacity renewable hydrogen generation system.
2. The size of the near term market for these systems is not sufficient to justify the investment.

With a high capacity, reasonably-priced electrolyzer becoming available, a commercial grid-powered system could be designed and built***. However, the highly desirable aspect of providing the capability of also being powered from renewable generation cannot be achieved without the development of a viable high capacity electronics interface for power from grid, wind or solar generation***. Secondly, hydrogen fuel cell powered cars, buses and lift trucks have been introduced into the commercial market, however, their numbers are limited and will likely not increase until a viable hydrogen infrastructure is introduced into the market place in more than a demonstration size. While this market will increase as the infrastructure is put into place, in the near term it will not provide the return on investment fast enough to justify commercial investment in the design and technology development of a hydrogen generating and dispensing system. However, the Government's investment in these technologies would afford the opportunity to advance the commercialization process in three ways.

1. Providing the enabling technology for a commercial renewable hydrogen prototype.
2. Lowering the equipment capital cost.
3. Reducing the cost of the hydrogen generated by improving the electrolyzer efficiency.

The availability of a commercial prototype would allow the initial early adapter market to be addressed and the lower capital cost and lower cost hydrogen would create a "market pull" that would advance the market from the early adapter, demonstration phase to the initial stage of commercialization. This would have the desirable effect of providing U.S. manufacturers and electronics companies the opportunity to service a developing domestic market as well as the rapidly developing markets in Europe and Japan.

Maps To Administration Guidance:

America's future well-being is linked to the availability of clean, secure, sustainable energy. To reduce or eliminate our dependence on imported oil, and to ensure that the nation has access to domestic, clean energy supplies, the United States is actively engaged in research and development (R&D) of materials and enabling technologies for producing, delivering, storing, and using hydrogen as an energy carrier. Many scientific, technical, and institutional challenges must be overcome to realize the vision of the hydrogen energy economy.[2] This Roadmap focuses on one major challenge—developing low cost, high-volume manufacturing of hydrogen technologies—which has been identified by U.S. industry as a potential showstopper to a future hydrogen economy.

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) was created by Congress in the Energy Policy Act of 2005. The Committee has adopted a Vision Statement that may help guide decision makers as they consider the options for the

nation’s energy future:
Our vision of the future is that hydrogen will become a universal and economically competitive energy carrier, progressively substituting for carbon-based fuels over time, to meet the needs of the planet. Hydrogen will be produced from a number of sources, increasingly with the lowest possible carbon impact. To realize this vision, the nation must aggressively bring to the market the hydrogen-based technologies that are available now and those that will be developed in the future. HTAC’s role is to aid the nation in developing a policy framework that takes into account the technical, political, social, cultural, environmental and commercial requirements for the hydrogen transition.

To expand the use of clean and renewable energy sources and reduce America's dependence on foreign oil, Energy Secretary Steven Chu announced $41.9 million in American Recovery and Reinvestment Act funding for fuel cell technology. April 15, 2009. These efforts will accelerate the commercialization and deployment of fuel cells and will create jobs in fuel cell manufacturing, installation, maintenance, and support services. The new funding will improve the potential of fuel cells to provide power in stationary, portable, and specialty vehicle applications, while cutting carbon emissions and broadening our nation's clean energy technology portfolio.

"The investments we're making today will help us build a robust fuel cell manufacturing industry in the United States," said Secretary Chu. "Developing and deploying the next generation of fuel cells will not only create jobs—it will help our businesses become more energy efficient and productive. We are laying the foundation for a green energy economy."

The $41.9 million will support immediate deployment of nearly 1,000 fuel cell systems for emergency backup power and material handling applications (e.g., forklifts) that have emerged as key early markets in which fuel cells can compete with conventional power technologies. Additional systems will be used to accelerate the demonstration of stationary fuel cells for combined heat and power in the larger residential and commercial markets yet there is a missing link in the development of hydrogen as the ultimate fuel of the future. That link is the development of the technologies that will assure the commercial viability of renewable hydrogen generation.

The Hydrogen Posture Plan was prepared by the U.S. Department of Energy (DOE) Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Science; Nuclear Energy, Science and Technology; and the U.S. Department of Transportation (DOT) to outline the activities, milestones, and deliverables that the Federal government plans to pursue to support the development of hydrogen-based energy systems. The Hydrogen Posture Plan integrates the planning and budgeting for program activities that will aid in this development. More specifically, this Plan outlines the DOE role in hydrogen energy research and development, in accordance with the National Hydrogen Energy Vision and Roadmap.2, 3 The Plan lays the foundation for a coordinated response, including collaboration with the DOT, to the President’s plan for accelerating implementation of hydrogen infrastructure and fuel cell technologies. Hydrogen and fuel cell technologies must meet market-based requirements for cost, operability, safety, maintenance, and overall performance. Given the uncertainty of overcoming all the technical hurdles, this plan assumes that the major policy (at this time) is to conduct the research, development, and validation necessary to address key technical and cost targets. The goal is “technology readiness” of hydrogen production, delivery, storage, and fuel cell technologies, to enable the automobile and energy companies to opt for commercial availability of fuel cell vehicles and hydrogen fuel infrastructure by 2020. Technology that meets consumer requirements is necessary, but not sufficient, for industry to move forward with commercialization. Portable and stationary power systems, which generally have less stringent cost targets, will likely be commercialized sooner than vehicles.

America's economy and lifestyles have been shaped by the low prices and availability of energy. In the last decade, however, the prices of oil, natural gas, and coal have increased dramatically, leaving consumers and the industrial and service sectors looking for ways to reduce energy use. To achieve greater energy efficiency, we need technology, more informed consumers and producers, and investments in more energy-efficient industrial processes, businesses, residences, and transportation. As part of the America's Energy Future project, *Realistic Prospects for Energy Efficiency in the United States* examines the potential for reducing energy demand through improving efficiency by using existing technologies, technologies developed but not yet utilized widely, and prospective technologies.

Installation of renewable power sources to produce renewably-generated-hydrogen expands the renewable power infrastructure, including for utility power generation. Hydrogen fueling infrastructure provides a means of storing excess renewable power at wind farms, for smart grids, and at photovoltaic installation thus promoting expansion of distributed and national renewable power infrastructure. This supports U.S. goals of ensuring 25% of our electricity comes from renewable sources by 2025, and also ensures that the U.S. maintains a technological lead in developing and deploying advanced energy. Expanding the clean hydrogen infrastructure (with hydrogen and fuel cells being the ultimate passenger transportation end-game), which is growing quickly outside of the U.S., lays the foundation for a secure renewable energy source today. This advanced R&D for unique renewable power connection (along with more efficient electrolyzers) enhances the United States capability for secure energy sources.

The California 2050 goal is to reduce Greenhouse Gas's by 80% below 1990 levels. This calls for a profound change in energy supply and other parts of the economy. It will require technological innovation; the process of inventing new products and approaches, bringing them to market and enabling them to become widely used. Fuel cell vehicles and hydrogen fuel are well on the way to providing that innovation. Fuel cell vehicles using hydrogen produced from natural gas reduce greenhouse gas emissions by roughly 50%. When hydrogen comes from clean energy, like solar electrolysis or biomass, the GHGs are zero. The life-cycle costs of hydrogen produced with electricity, splitting water in an electrolyzer, are enumerated in the graphic below. Although $4.25/kg (which is roughly comparable to a gallon of gas in terms of volume) seems high, when hydrogen is used as fuel in a fuel cell, it is 2-3 times as efficient as burning gas in an internal combustion engine, so a price of $1.417 would be a fair comparison of an equivalent miles-per-gallon of gas. Also, these are monetary costs only, and do not include the health, environmental, and other hidden costs associated with hydrogen production from natural gas reformation. The graphic below is showing the life-cycle costs when hydrogen is produced from water using standard grid power. When produced using renewable energy, once the costs of the renewable power are depreciated, and under a net-metering system with the electric utility, the hydrogen production costs could be greatly reduced. That is, unused renewable power or low value renewable power could be used to generate low-cost hydrogen.

Justifies Government Attention:

A sound understanding of projected costs for manufacturing hydrogen components and systems will be a key factor in industry's commercialization decision on hydrogen fuel cell vehicles and fueling systems. The Congress, in passing the Energy Policy Act of 2005 (Public Law 109-58), authorized R&D on the manufacturability of hydrogen systems under Title VIII – Hydrogen, Section 805.5 Manufacturing R&D.

For each kilogram of hydrogen (from water) used, about one gallon of diesel is offset. That comparison does not take into account the greenhouse gases produced from petroleum extraction, refining, and delivery, along with cleanup for spills, equipment maintenance along the way, etc.

For each kilogram of hydrogen produced from water, if the hydrogen is used for electricity production, some amount of coal power is reduced, as well as the extraction, cleaning, delivery, and other greenhouse gas and toxic releases associated with the equipment maintenance, accidents, water and spoil pit contaminations, etc., not to mention mercury in our systems, including fish, acid rain, and more.

The water use and emissions are both local or regional, for the most part, and both clean. Water diverted is put back, cleanly, into the same system, with no losses or permanent diversions from our freshwater systems.

The higher capital cost of a renewably-generated-hydrogen station versus a natural-gas-based system can be offset by lowering overhead and profit margins slightly, by mass production of electrolyzers, and by an increase in renewable power sources. Financial assistance for collaborated efforts to implement hydrogen infrastructure and its related green manufacturing supply chain would greatly reduce any other variance in installation/implementation prices, possibly to the point that overhead and profit margins may remain competitive to attract, re-train, and hire more employees. Any financial assistance to expand renewable power sources would promote hydrogen economy efforts, and "lift all ships" related to clean energy infrastructure.

Federal and/or state Renewable Portfolio Standards, either implemented or proposed greatly increase expansion of clean energy infrastructure and support all projects. 80% of the renewable power manufacturing in the U.S. is done in states that have implemented a RPS.

A bus requires around 15 kg for a fill-up, and can travel 150 miles (10 mi/ kg). A fuel cell automobile, if running solely on hydrogen, can run about 300 miles on a fill-up (about 4 kg).

All use of hydrogen as fuel, or for power, both maximizes displacement of petroleum and use of the best of alternative fuels (zero-emission, start to finish). In a system in which renewable energy is used to generate hydrogen to be used in a fuel cell bus, there are no petroleum products used anywhere in the process. The entire system is a total displacement of petroleum-based fuels, from the generation of fuel to the consumption/use, including operation of the station itself. This petroleum reduction both reduces U.S. dependence on foreign oil and reduces greenhouse gas emissions. The use of renewable power to run the electroloyzer to generate the hydrogen also reduces greenhouse gas emissions from coal-powered utility plants. As an example, use of one fuel cell transit bus (versus a standard diesel transit bus) reduces petroleum-based fuels by 19,060 gallons per year (of diesel), and maximizes use of alternative fuels by replacing that petroleum (diesel) fuel with zero-emission hydrogen fuel.

Fueling stations which produce hydrogen from reformed fossil fuels (natural gas) have been in place for years. The demand for even these non-sustainable systems is great due to the increasing desire for zero-emission vehicles. So the demand for zero-emission fuels along with zero-emission fuel generation is more compelling. It will match the cost of the non-sustainable systems, even at this early-market entry phase, when utilizing life-cycle costing and/or life-cycle assessment.

There is much interest in the use of hydrogen fuel, especially when generated renewably. In a natural-gas-reforming station process, natural gas is purchased from a supplier, and then put through a reformer. The reformer burns natural gas to run the process. The rest is waste – mostly CO_2. Then it is liquefied, which purifies the gas. When hydrogen is utilized in liquid form, it is then allowed to vaporize, then captured and compressed. If boil-off rate doesn't match the use rate, any excess hydrogen is wasted. A natural gas turnkey system does not meet sustainability goals. There is no capability to use renewables to power the system. **And this assessment of natural gas systems versus water-electrolyzer systems does not include the numerous environmental and biodiversity (and resultant economic) impacts related to extraction and distribution of natural gas versus the simple acquisition of local freshwater (similar to those stated above for petroleum).**

Initial costs of the natural gas system and the electrolyzer system are similar considering overhead, profit margin, and labor costs. But that comparison is before considering mass production. Even if 10 or fewer renewable hydrogen stations are built, their cost would still be comparable to a turnkey natural gas station's cost. As more renewably-generated-hydrogen stations are built, the cost will gradually decrease. Even if powered by the standard grid the hydrogen costs are comparable to current gasoline prices ($2.50 - $3.00 per gallon). When using renewable power for the electrolyzer the cost comparison is ~$1.50 per gallon of gasoline.

Carbon Dioxide Emissions for Various Hydrogen Production Methods

Production Method	kg CO_2/kg H_2
Coal Gasification	19
Natural Gas Reformation	17.6
Electrolysis – Non-Renewable Power Source	12
Electrolysis – Renewable Power Source	0

Why TIP Funding Is Needed:

Renewably generated hydrogen is a critical element in our nations drive towards sustainable energy independence and will be a valuable commodity in any future, global greenhouse gas mitigation program. While the basic technologies to generate hydrogen renewably are in hand, the technologies that would render renewable hydrogen commercially viable are not and the small early adapter market for renewable hydrogen is not sufficient for the commercial community to invest in the advancement of these technologies. Thus,TIP funding is needed to fill this funding gap and thereby enable the development of the two technologies critical to the commercialization of renewable hydrogen systems; improved electrolysis stack efficiency and viable power management interface systems between the electrolyzer and the renewable generation systems.

Development of the systems cited above will accelerate the installation of renewable power sources to produce renewably-generated-hydrogen in hydrogen fueling stations thereby expanding the renewable power infrastructure. This hydrogen station infrastructure will also provide a means of storing excess renewable power at wind farms, for smart grids, and at other locations – thus promoting even more expansion of distributed and national renewable power infrastructure. This supports U.S. goals of ensuring 25% of our electricity comes from renewable sources by 2025, and also ensures that the U.S. maintains a technological lead in developing and deploying advanced energy.

The Department of Energy's Hydrogen, Fuel Cell, and Infrastructure Technologies (HFCIT) Program review states: Transforming the PEM fuel cell market requires transitioning from a prototype to a design-stable, application-ready PEM power system. Manufacturing processes will need to be developed and qualified for high-rate production of durable and reliable PEM fuel cell systems for commercial, real-life backup power, and materials handling applications. A successful market transformation investment will need to minimize the risks inherent in the development of new manufacturing processes for emerging technology.

"Investment risk of developing manufacturing capability for hydrogen and fuel cell technologies is high." *-U.S. Department of Energy HFCIT MYPP*

In response to the HFCIT Program's assessment, the National Renewable Energy Laboratory (NREL) has initiated an activity to address the need to understand the current status and associated risk levels of the PEM fuel cell industry. As Greene succinctly concludes, "the non-automotive fuel cell industry in North America appears to be at a critical point" where industry can begin commercialization of PEM fuel cells for backup power applications and materials handling equipment. The applications identified by Greene reference the HFCIT-sponsored market analyses of Mahadevan et al. of Battelle. Mahadevan concludes that a federal requirement for PEM use in backup power and materials handling equipment (MHE) can lead the market transformation for PEM fuel cell systems. Such federal government requirements would increase production from the current industry-wide production of hundreds of PEM systems per year to several thousands of PEM systems per year. Greene and Mahadevan et al acknowledge that manufacturing processes will need to be developed and qualified to provide reliable PEM fuel cell systems in the backup power and MHE applications at production rates of several thousands of PEM systems per year.

Success with the R&D proposed herein would enable the renewable and grid-powered hydrogen systems being proposed to be brought into the commercial market as an on-site hydrogen supply option to purchased hydrogen. The market approach being taken is to first address premium niche applications then broaden the applicability. The goal is to lower the critical component costs (electrolyzer, power electronics), and hence the system capital cost, by moving down the manufacturing learning curve as the number of installations increases. The impact would be significant both in emission reductions and significant job creation in a "totally U.S." scenario. Regarding emission reductions, one could envision a "totally green", scenario in which an on-site electrolysis system is powered either by "green" electrons off the grid or by on-site renewable generation. This "green" hydrogen would then be used to power fuel cell systems, totally eliminating greenhouse gas emissions from the cycle. An example of one of the early entry niche markets is fuel cell powered lift trucks. 720,000 lift trucks (battery-powered) in operation in US warehouses today. The opportunity exists to replace all of them eventually with FC powered systems. The advantages of fuel cells replacing batteries in the 720,000 lift trucks in use in the U.S. is well documented and as a result the numbers being manufactured and put into service are increasing rapidly. A cost effective hydrogen supply is a recognized problem. Fuel cell grade hydrogen (from reformed natural gas) delivered as high pressure gas is extremely expensive and delivered liquid hydrogen is impractical. It is impractical because lift truck fleet hydrogen demand is highly cyclic and, since there are typically long periods with no demand, the liquid "boil off" loss from a liquid hydrogen supply can prohibitively increase the effective cost of the hydrogen fuel. On-site hydrogen produced by reforming natural gas suffers from the same problem in that steam reformers are made to operate constantly, not for cyclic operation. On-site generation with the systems under development has the potential to provide the best solution both from an emissions standpoint as well as cost.

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[2] In July 2008, the U.S. Department of Energy published a report titled *The Effects of a Transition to a Hydrogen Economy on Employment in the United States*. The study estimated that up to 675,000 new jobs could be generated by 2050. The report is available at http:// www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf.

[3] The **Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)** was created by Congress in the Energy Policy Act of 2005. The Committee has adopted a **Vision Statement** that may help guide decision makers as they consider the options for the nation's energy future: "Our vision of the future is that hydrogen will become a universal and economically competitive energy carrier, progressively substituting for carbon-based fuels over time, to meet the needs of the planet. Hydrogen will be produced from a number of sources, increasingly with the lowest possible carbon impact. To realize this vision, the nation must aggressively bring to the market the hydrogen-based technologies that are available now and those that will be developed in the future. HTAC's role is to aid the nation in developing a policy framework that takes into account the technical, political, social, cultural, environmental and commercial requirements for the hydrogen transition."