IPHE Renewable Hydrogen Report

March 2011

International Partnership for Hydrogen and Fuel Cells in the Economy

IPHE Renewable Hydrogen Report

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) has developed this report in order to highlight the potential of renewably produced hydrogen, while drawing attention to many of the projects that have been successfully implemented in recent years to demonstrate and develop renewable hydrogen.

The report consists of two parts: 1) an introduction summarizing the various methods of producing hydrogen from renewable resources and 2) a collection of project overviews outlining past and current demonstrations, including R&D projects involving hydrogen that is produced from renewable sources. IPHE hopes that sharing this information among researchers will facilitate future international networking and collaboration and serve as a valuable resource to policy makers, researchers, and the general public.

INTRODUCTION

As the world faces unprecedented energy challenges, many countries are looking to include hydrogen and fuel cell technologies as part of a clean, sustainable portfolio of solutions. A key advantage of hydrogen is that it can be produced from a variety of sources, including fossil fuels, nuclear power, biomass, and renewable energy. On a lifecycle basis, hydrogen fuel cells can potentially result in reduced greenhouse gas (GHG) emissions in several application areas, namely transportation and stationary power generation.[1] Hydrogen produced from renewable sources offers the best opportunity for reducing GHG emissions and dependence on petroleum fuels.

Fuel cell vehicles that run on hydrogen are projected to produce less GHG

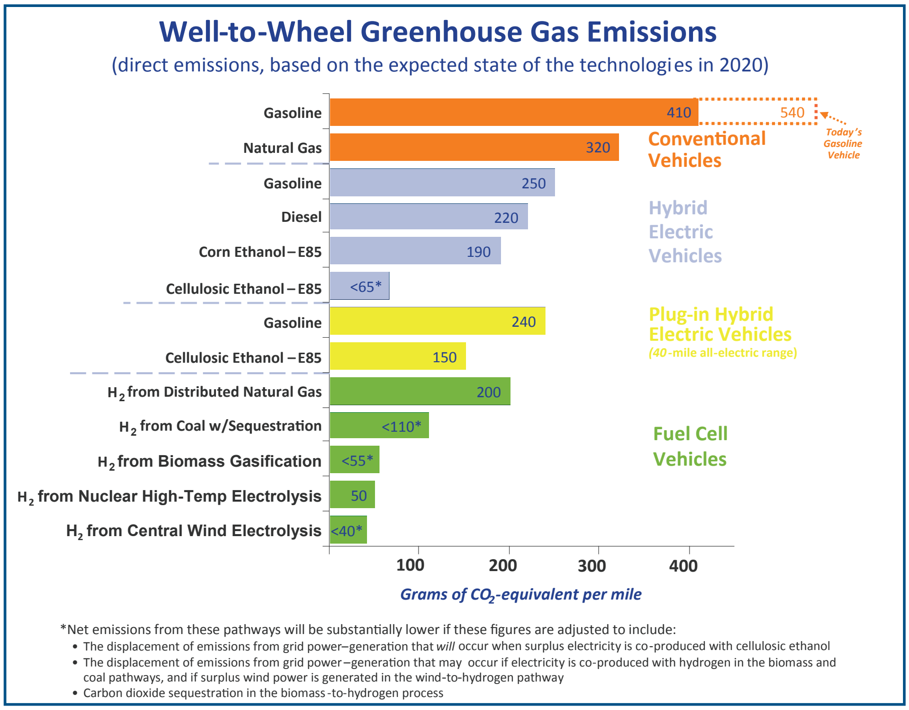

Figure 1. Projections of fuel cell and conventional vehicle well-to-wheels greenhouse gas emissions (U.S.)[2]

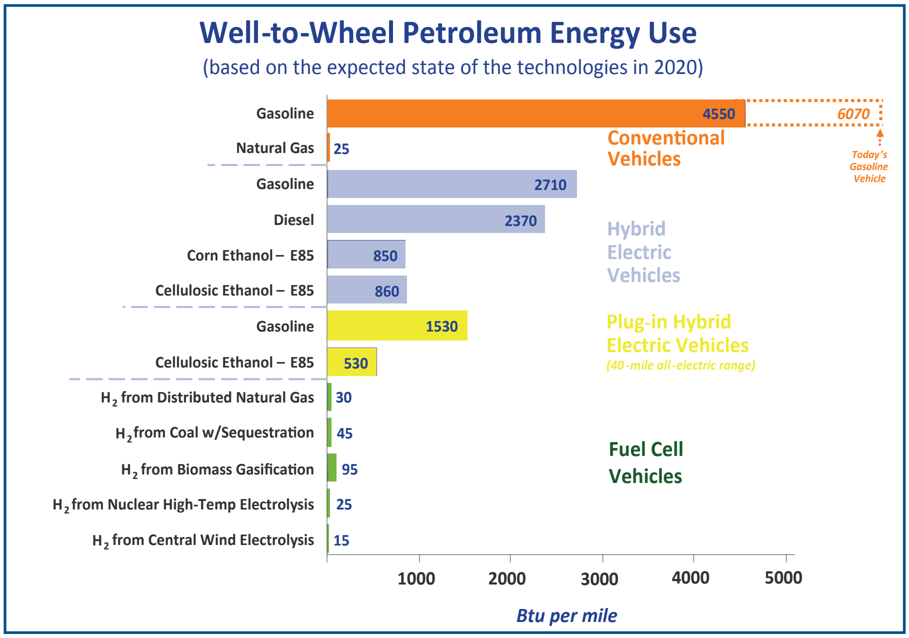

Figure 2. Projections of fuel cell and conventional vehicle well-to-wheels petroleum energy use (U.S.)[2]

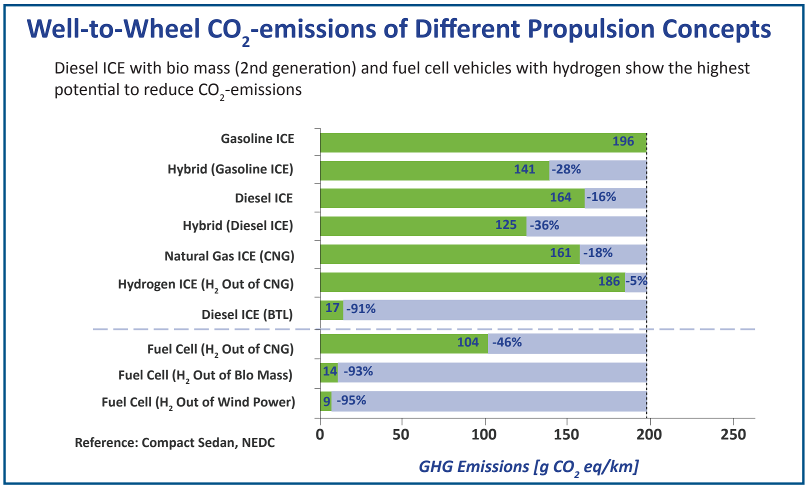

Figure 3. Projections of fuel cell and conventional vehicle well-to-wheels CO_2 emissions (Germany)[3]

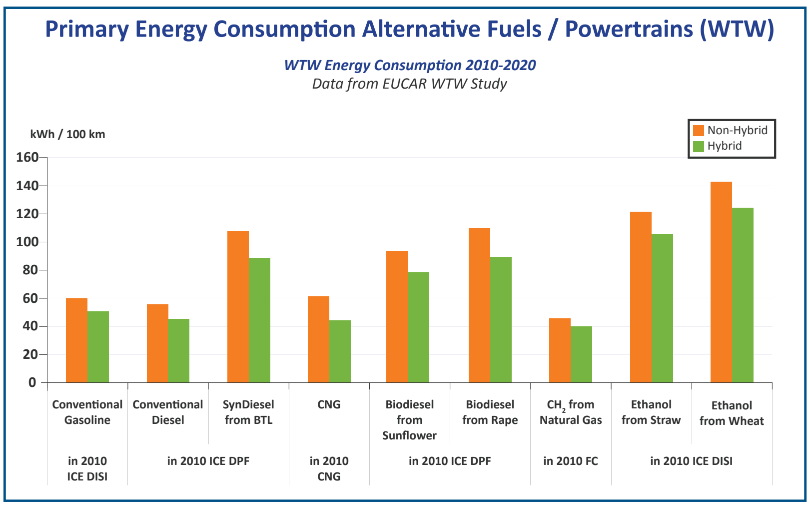

Figure 4. Projections of fuel cell and conventional vehicle well-to-wheels energy consumption (Germany)[3]

on a well-to-wheels basis than cars running on traditional technologies, and using renewable hydrogen increases this advantage significantly. The figures presented in this introduction show the drastic reductions in emissions and petroleum use that is possible with hydrogen fuel cell vehicles when compared to other vehicle technology and fuel pathway options. Figures 1 and 2 highlight data from well-to-wheels studies conducted in the United States, figures 3 and 4 display results from similar studies conducted in Germany, and figures 5 and 6 show study findings from Japan. The results from all three countries indicate that switching to hydrogen fuel cell vehicles is expected to reduce both well-to-wheels GHG emissions and energy use. In comparing the expected capabilities of various advanced vehicle technologies in the year 2020, U.S. analysis predicts GHG emissions reductions ranging from just over 50% for fuel cell vehicles running on hydrogen from distributed natural gas to over 90% for hydrogen produced from central wind electrolysis. Similarly, Germany's analysis projects reductions of approximately 46% for fuel cell vehicles using hydrogen from natural gas, and up to 95% with hydrogen from wind power. Japan's analysis suggests emissions reductions up to 70%.

Today, about 45 billion kilograms of hydrogen are produced annually, but most of it is used for industrial purposes. The majority of today's hydrogen is generated using fossil fuels (largely natural gas) because these technologies are currently the most mature and cost-effective (see Figure 7).

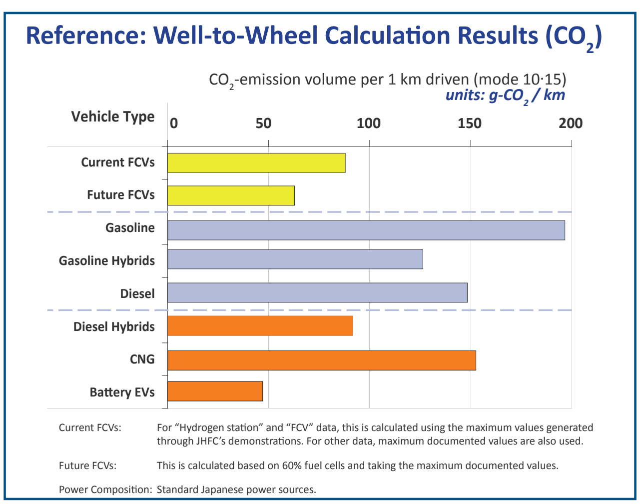

Figure 5. Projected CO_2 emissions for various drivetrains (Japan)[4]

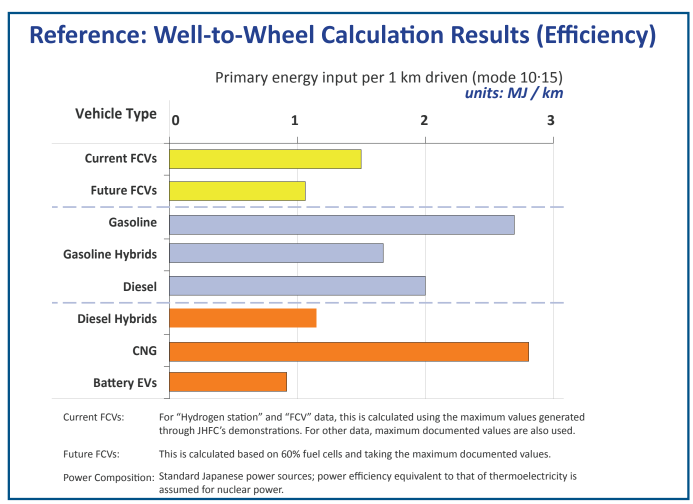

Figure 6. Projected efficiencies for various drivetrains (Japan)[4]

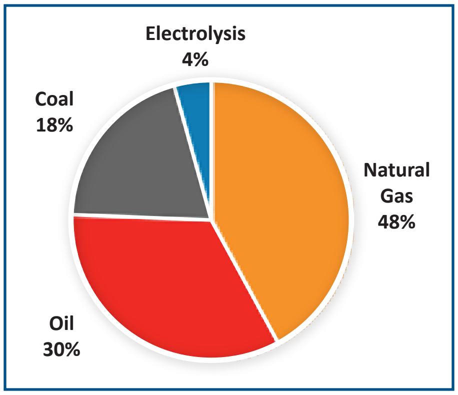

Figure 7. Sources of current worldwide hydrogen production[5]

In hydrogen fuel cell vehicles, hydrogen produced from natural gas still offers significantly less GHG emissions and reductions in petroleum energy use reductions over traditional fuels (see above), but this advantage can be greatly increased using renewable hydrogen. To further enable emissions and energy use reductions, researchers worldwide are working to develop and refine technologies that produce hydrogen in more economical ways from renewable resources. The following section describes several of these processes.

RENEWABLE HYDROGEN PRODUCTION TECHNOLOGIES

While some hydrogen production technologies are already being used—such as natural gas reforming, coal gasification, and electrolysis from both renewable and non-renewable energy sources—others like the photolytic processes are still a long way from commercial use. The greatest technical challenge to the various renewable hydrogen production methods is cost reduction. Current research seeks ways to reduce the cost of capital equipment, operations, and maintenance costs, while improving hydrogen production efficiency. Figure 9 shows data from the United States' Fuel Cell Technologies Program on projected high volume costs for several production methods. This section summarizes various renewable hydrogen production methods and provides a status for each. Figure 8 shows current and future methods for hydrogen production.

Renewable Electrolysis

Electrolysis, in which water is separated into hydrogen and oxygen using electricity, is a common method of hydrogen production. The electricity used can come from any source, including nuclear power, grid power, or renewables.

Renewable electrolysis refers to the process of producing hydrogen from electrolysis using electricity from renewable resources such as wind, solar, hydroelectric, or geothermal power. This is a promising option for future hydrogen production and is currently used in many locations around the world.

Currently, cost is the biggest obstacle to this production method—reduced capital cost for electrolysers as well as reduced cost of renewable electricity are needed to make it cost effective. Increasing electrolyser efficiency can also make electrolysis more economical by lowering the impact of the cost of electricity.[8]

Thermal Processes

Thermal processes use the energy in resources including natural gas, coal, or biomass to produce hydrogen. Three renewable-based thermal processes are described below.

Biomass Gasification

Biomass gasification, similar to coal gasification, converts an organic material (such as wood, switchgrass, or sugarcane) into a gaseous mixture of hydrogen, carbon monoxide, carbon dioxide, and other compounds at elevated temperatures in the presence of steam

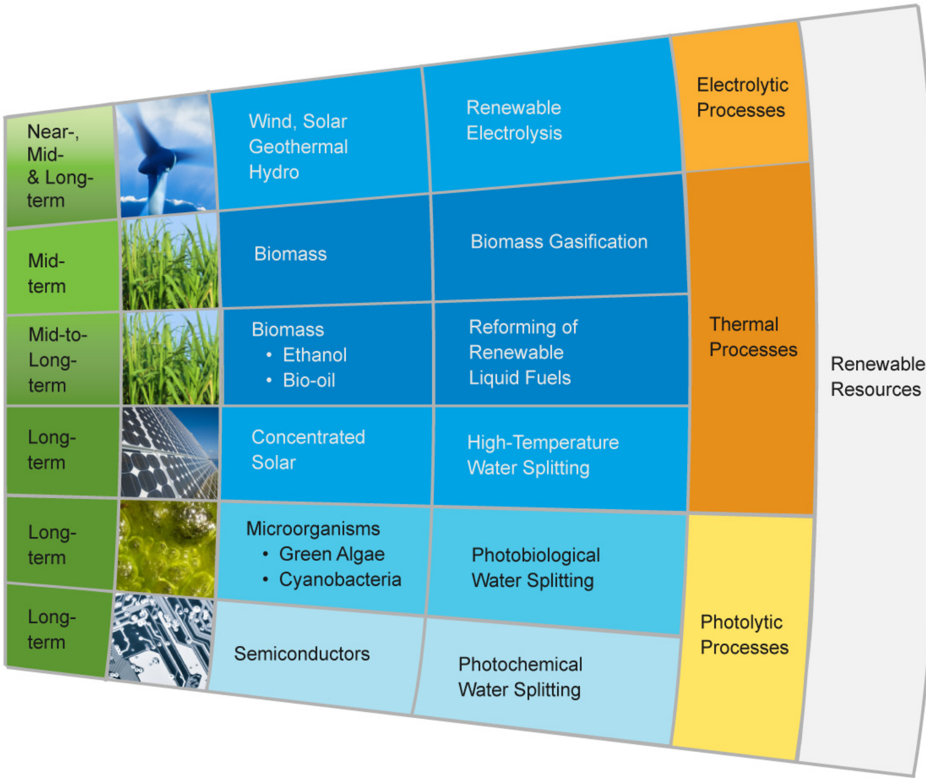

Figure 8. Hydrogen production technologies and methods

and a controlled amount of air or oxygen. This process is anticipated as a mid-term hydrogen production technology and can utilize feedstocks including agriculture crop and forest residues, crops grown specifically for renewable energy use like switchgrass and willow trees, organic municipal solid waste, and animal wastes. This method results in near-zero net GHG emissions and, when carbon capture and sequestration is incorporated, can result in negative emissions.

Renewable Liquid Fuel Reforming

Biomass can also be used to produce hydrogen by first converting it to liquid fuels such as ethanol or bio-oil. These liquid fuels can be transported at a relatively low cost to an end-use location, such as a refueling station, where it can be reformed to produce hydrogen. Reforming renewable liquid fuels, similar to reforming natural gas, involves reacting the biomass-derived fuel with steam at elevated temperatures to produce hydrogen. This is considered a mid- to long-term hydrogen production method.

High-Temperature Water Splitting

High-temperature water splitting is a method of producing hydrogen in which very high temperatures (up to 2,000°C) drive chemical reactions that produce hydrogen. These high temperatures can be provided by nuclear power or using concentrated solar power. During the reactions, all reactants except for hydrogen, oxygen and water are reused, creating a closed process that produces hydrogen and oxygen from water. Researchers have identified many possible chemical cycles and are currently working to identify and improve the most promising possibilities. Other research challenges with this method include finding appropriate high-temperature construction materials, reducing the cost of solar concentrators, and developing heat-transfer mediums.[9]

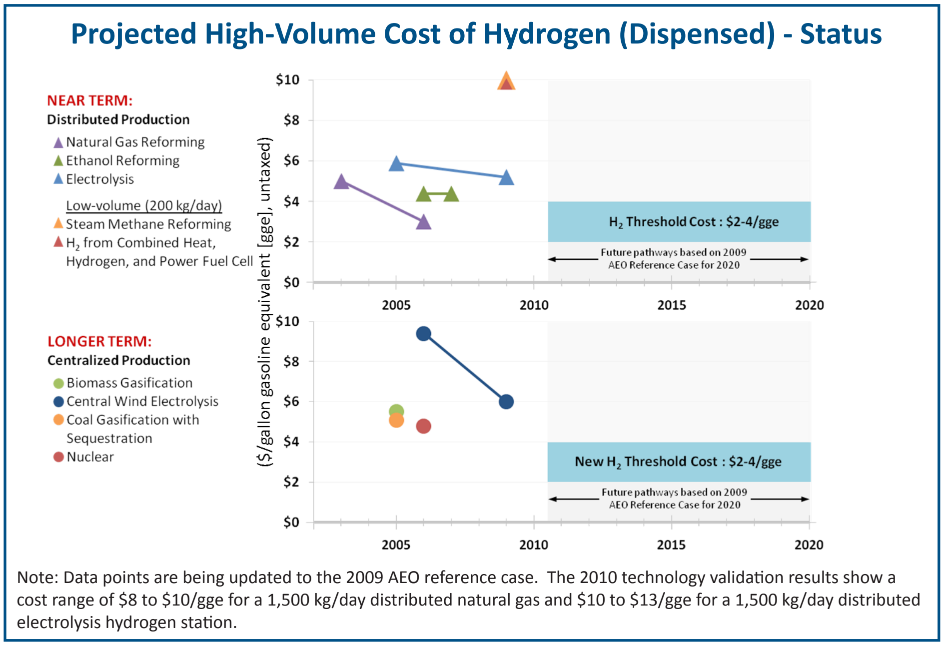

Figure 9. Data from the U.S. Fuel Cell Technologies Program on projected high volume costs of various hydrogen production methods[7]

These processes produce near-zero emissions but are seen as long-term hydrogen production options since they are currently only in early development stages. The feasibility of this method has been successfully demonstrated in the laboratory, but further significant research and development will be required for it to be a practical large-scale option.

Photolytic Processes

Photolytic processes use light energy to split water into hydrogen and oxygen. These processes offer the potential for sustainable hydrogen production with low environmental impact but are still in the very early stages of research.

Photobiological Water Splitting

In this process, hydrogen is produced from water using sunlight and micro-organisms such as green algae and cyanobacteria. Hydrogen is a byproduct of these microorganisms' natural metabolic processes, which require sunlight and consume only water. This technology faces a challenge in that the microorganisms produce hydrogen much too slowly for commercial hydrogen production. Scientists are exploring ways to speed up the process in these microbes, as well as searching for other microbes that may produce hydrogen at higher rates.

Photoelectrochemical Water Splitting

The primary difference between photoelectrochemical and photobiological water splitting is that photoeletrochemical water splitting utilizes semiconductor materials to split water into hydrogen and oxygen. The semiconductor materials used are similar to those used in photovoltaics, and research is currently underway to identify improved materials that will have both increased efficiencies and improved durability.

By-product Hydrogen

Stranded Hydrogen

The term "stranded hydrogen" refers to hydrogen that is produced as a byproduct of industrial processes and is not re-sold or used within the plant where it is produced. In these cases, the hydrogen is essentially a waste product that is commonly vented into the atmosphere. While not a long-term source of hydrogen because there are limited volumes available, stranded hydrogen offers a temporary, near-term source of hydrogen while larger infrastructures are being built.

Excess hydrogen production occurs in industries including chlorine production and other chemical plants, as well as refineries and coking plants in steel mills. Depending on the industrial process that is being used, the excess hydrogen may come from either renewable or non-renewable sources. However, because it is being produced regardless of its end use (the CO_2 emitted in its production is essentially a sunk cost), the non-renewably produced hydrogen can be considered carbon-neutral.

Analyses have been done in several IPHE countries to estimate the amount of stranded hydrogen that could be made available for use as fuel for transport or stationary applications. In Germany, a study conducted in the state of North Rhine-Westphalia (NRW), estimated that there is approximately 35,000 tons of stranded hydrogen available in NRW per year. That is enough to support 6,000 buses or 300,000 fuel cell cars.[10] Further, it is estimated that twice this amount is available in Germany as a whole. In Japan, extra hydrogen production capacity from municipal gas companies and oil refineries is estimated at 4.7 billion normal cubic meters (Nm^3), enough to fuel 5 million fuel cell vehicles.[11] In the U.S., a 2007 Department of Energy/Argonne National Laboratory study found that hydrogen separated from coke oven gas in the U.S. could produce about 370,000 metric tons of hydrogen, enough to fuel 1.7 million vehicles.[12]

RENEWABLE HYDROGEN PRODUCTION PROJECT EXAMPLES

The following section provides overviews of several current and past demonstration projects that involve hydrogen produced from renewable sources, as well as projects demonstrating recent R&D progress for longer-term production methods. The projects presented showcase a wide variety of renewable production methods, including near-, mid-, and long-term processes, and represent regions from around the world.

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12 Joseck, Wang, and Ye "Potential Energy and Greenhouse Gas Emission Effects of Hydrogen Production from Coke Oven Gas in U.S. Steel Mills," http://www.transportation.anl.gov/pdfs/AF/528.pdf

CT-TRANSIT Hybrid Electric Fuel Cell Transit Bus Demonstration

Hartford, Connecticut, USA

Designed by UTC Power, with a fuel cell system using the Pure Motion® Model 120 fuel cell power system, New England's first hybrid electric fuel cell transit bus debuted in Hartford, CT, on April 10, 2007. A year prior, the Greater Hartford Transit District had contracted with UTC Power to make the demonstration project possible: CT-TRANSIT would operate the fuel cell bus, and UTC Power would provide two years of support that included the use of UTC Power's hydrogen refueling stations at its headquarters in South Windsor, CT. The hydrogen supplied here is renewably produced.

Objectives

Through this demonstration project, CT-TRANSIT and UTC Power aimed to gain experience and lessons learned regarding emerging fuel cell technology. Operational data would be obtained from the fuel cell bus and compared to three diesel buses.

In addition, increased public awareness has been a significant goal of the project. CT-TRANSIT has received requests throughout the project to demonstrate the fuel cell bus at various community and local events; and it fulfills as many requests as possible. Between January 2008 and February 2009, CT-TRANSIT showcased the fuel cell bus at a total of 22 events.

Approach

This particular fuel cell bus is considered a prototype technology that is in the process of being commercialized. From January 2008 through February 2009, it comprised part of a study that collected operating data on four buses: the fuel cell bus and three diesel buses—all operating in the Hartford, CT, area. The results of this study, published by the National Renewable Energy Laboratory (NREL) in May 2009, are meant to serve as lessons learned in operating fuel cell buses. The results are intended to help in evaluating hydrogen and fuel cell systems and infrastructure in transit applications, as well as to assess progress toward technology readiness.

In order to assess the project goal to increase public awareness, CT-TRANSIT conducted two surveys in the fall of 2008. One survey was targeted at passengers, while the other was targeted at bus operators.

Project Overview

What

CT-TRANSIT Hybrid Electric Fuel Cell Transit Bus Demonstration

Who

CT-TRANSIT
UTC Power

When

Bus Debuted: Apr. 2007
Evaluation Started: Jan. 2008
Evaluation Completed: Feb. 2009

Participants

United States

Renewable Technology

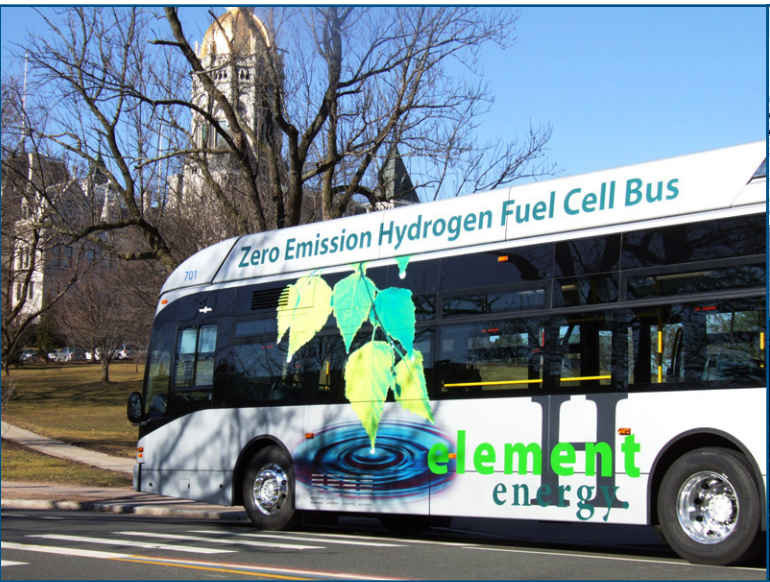
This project uses hydrogen refined from chemical company by-products.

Application

Buses

Website

http://www.cttransit.com
http://www.utcpower.com



Accomplishments

UTC Power's PureMotion Model 120 system is the result of more than six years of R&D and partnership among UTC Power, the Department of Defense through the U.S. Army Tank-Automotive and Armaments Command, and the Department of Transportation through the Northeast Advanced Vehicle Consortium (NAVC). This system is based on Proton Exchange Membrane (PEM) technology and maximizes the benefits of fuel cells by employing a compact, ambient pressure, hydrogen fuel cell system. The ambient pressure technology allows the system to deliver the highest level of efficiency, no emissions, and quiet operation.

Overall, the benefits of the fuel cell-powered hybrid bus include high efficiency and reliability, energy cost savings, zero emissions, and low noise. Its clean operation has had an immediate positive impact on street-level emissions.

The fuel cell bus has accumulated 12,115 miles and the fuel cell system clocked 2,049 hours. According to the evaluation results, the fuel cell bus had a 46% overall higher fuel economy over the diesel buses studied.

CT-TRANSIT has reported high community and regional interest since the start of the fuel cell bus demonstration. Two surveys were conducted during this demonstration to measure public awareness and perception of the fuel cell technology. Of the passengers who were surveyed, 82% were first-time fuel cell bus riders. More than 60% were aware that they had boarded a fuel cell bus. More than 60% were unaware that the hybrid fuel cell bus produced zero emissions and that it charged its batteries with energy converted from braking. The majority of passengers surveyed felt that the fuel cell bus noise, acceleration, braking, and vibration were all improved over a standard bus. Finally, 81% of respondents said that riding the fuel cell bus had improved their opinion of the technology, and 84% even preferred the fuel cell bus to a standard bus.

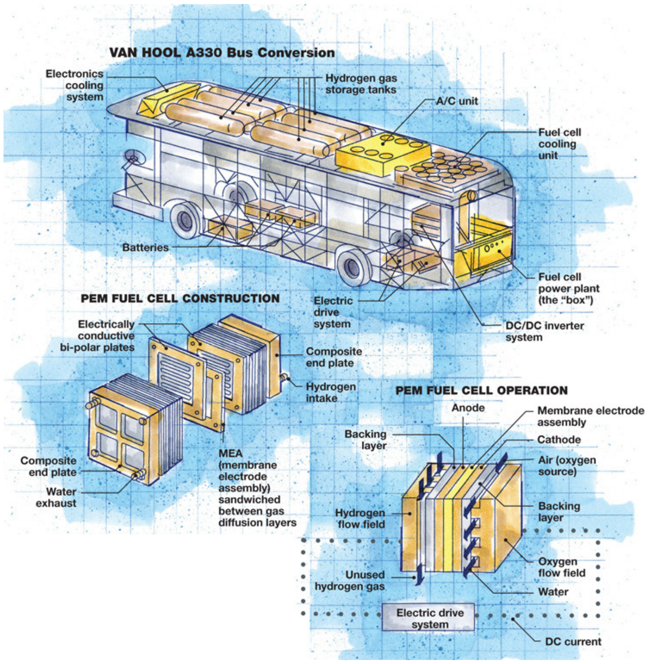
Renewable Hydrogen Production

CT-TRANSIT used hydrogen from UTC Power headquarters to power the fuel cell bus. Praxair supplied this hydrogen, producing it renewably by refining by-product hydrogen from chemical companies in the Niagara Falls area.

Future Plans

Future plans for the fuel cell bus include reduced operation to limit operating costs and extend the life of the bus to an additional two to two-and-a-half years. CT-TRANSIT plans to receive up to four new fuel cell buses from Van Hool and UTC Power as part of the Federal Transit Agency's National Fuel Cell Bus Program through the NAVC and UTC Power. In addition, CT-TRANSIT plans to purchase a fifth new fuel cell bus under a state grant.

Left to Right: Pure Motion 120 fuel cell system; hybrid fuel cell bus on the streets of Hartford, CT; and illustration of the hybrid fuel cell bus



International Partnership for Hydrogen and Fuel Cells in the Economy

ECTOS Bus Demonstration

Reykjavik, Iceland

The ECTOS project, led by Icelandic New Energy (INE), introduced the first pre-commercial hydrogen refueling station in the world. Located in Reykjavik, Iceland, the station provided hydrogen produced with renewable energy to three fuel cell buses serving the city.

The ECTOS Bus Demo began in March 2001. The European Commission 5th Framework Programme sponsored the project and brought together a team of partners spanning Iceland, Germany, The Netherlands, Norway, and Sweden. The team spent two years conducting preliminary studies on potential social, economic, and environmental impacts.

Reykjavik was chosen to be this project's location because of its metropolitan characteristics–it is the capital of Iceland with a population of approximately 200,000. It comprises a highly educated population with a generally high level of acceptance for a hydrogen infrastructure.

In April 2003, the ECTOS project marked the beginning of the hydrogen production phase with the opening of the hydrogen refueling station. This phase included installing a hydrogen compression, storage, and dispensing system. By October 2003, the three fuel cell buses had arrived and began servicing Reykjavik.

Objectives

The ECTOS project supported the Icelandic government's goal for its country to become the world's first hydrogen-based modern society. The project's primary objective was to find a safe, logical, and clean way to integrate hydrogen into the current energy system.

Approach

Icelandic New Energy took a learning-by-doing approach with the ECTOS project. Through operation of the hydrogen fueling station, INE was able to gain real world experience in using the station to refuel three hydrogen fuel cell buses daily.

Accomplishments

Throughout the ECTOS project, the hydrogen refueling station provided the fuel cell buses with over 17,000 kilograms of hydrogen–the energy equivalent to nearly 17,000 gallons of diesel fuel.

Producing hydrogen and running the fuel cell buses added no greenhouse gases to the environment. The hydrogen used was produced at the refueling station by electrolysis using grid electricity that was generated by geothermal and hydropower.

In addition, since the completion of the ECTOS project, the team has compiled

Project Overview

What

ECTOS Bus Demonstration

Who

Icelandic New Energy Ltd.

When

Started: March 2001
Completed: August 2005

Participants

Lead Country
Iceland

Partner Countries
Germany, The Netherlands, Norway, Sweden

Renewable Technology

This project produced hydrogen using electrolysis from renewable grid energy (geothermal and hydropower).

Application

Buses

Website

www.newenergy.is

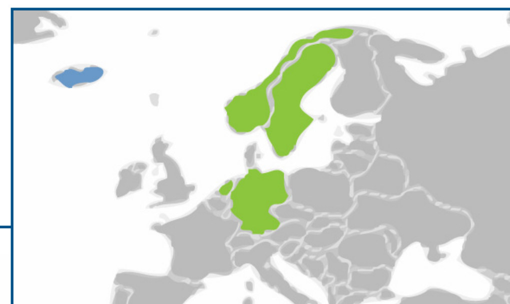
lessons learned on hydrogen-based transportation infrastructure that resulted in development of a crisis management plan, an emergency response procedure plan, and an incident reporting system.

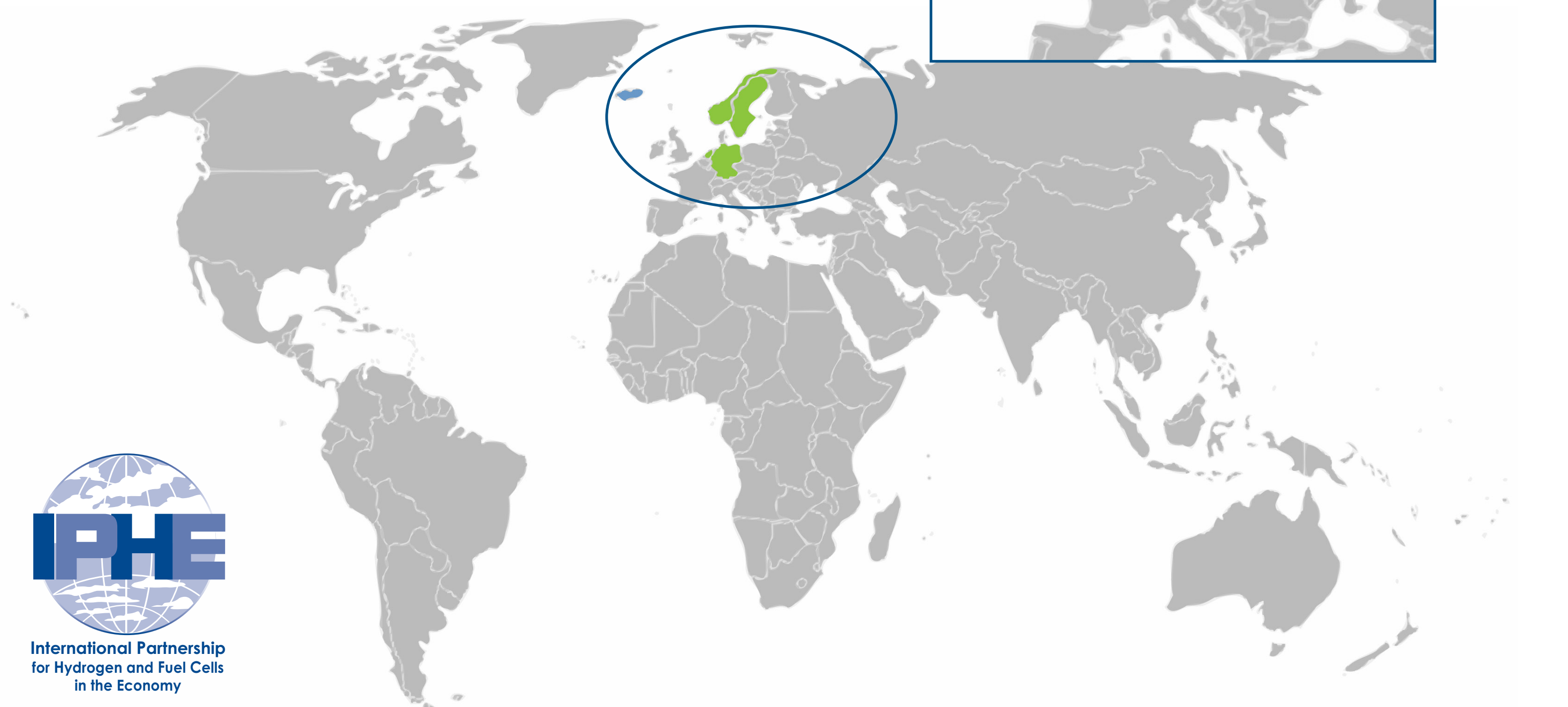
Renewable Hydrogen Production

The electricity used to power the electrolyser in order to produce hydrogen at the station came from geothermal and hydropower. Approximately 80% of Iceland's electricity is produced through hydropower with the remaining from geothermal power.

Follow-up Work

The hydrogen refueling station remained in operation after the completion of the ECTOS project, and the buses took part in the HyFLEET:CUTE project, which involved 47 fuel cell buses in 10 cities across three continents. The station was also upgraded to service passenger vehicles as well as buses and now serves 22 hydrogen-powered vehicles in Iceland.





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HYDROSOL-II

Thessaloniki, Greece

The HYDROSOL-II project has developed a thermochemical technology that produces hydrogen solely from solar energy and water, up to the pilot plant scale. This project and its predecessor, HYDROSOL, were both co-funded by the European Commission within Framework Programmes 6 and 5, respectively. Both projects demonstrate production of solar hydrogen via a two-step water splitting process. These are performed on monolithic honeycomb reactors, capable of developing high temperatures under concentrated solar irradiation and coated with active redox materials that are capable of water-splitting and regeneration.

In the HYDROSOL project, the technology was developed at the laboratory scale. The proof-of-concept and the capabilities of the technology were demonstrated, establishing HYDROSOL as the world's first, closed solar-only, thermochemical cycle in operation capable of continuous hydrogen production.

HYDROSOL-II aims to scale-up the technology on a dual reactor with a power level of 100kW/reactor, coupled on the solar tower facility of Plataforma Solar de Almeria, Spain. This demonstrates continuous solar hydrogen production within an optimized pilot plant.

Objectives

HYDROSOL-II's demonstration of a successful and efficient scale-up of a carbon-dioxide, emissions-free solar hydrogen production process demonstrates the potential for mass production of solar hydrogen. A successful demonstration will narrow the gap between research and market implementation and show that using concentrated solar power facilities coupled with high temperature processes can be a viable way to produce large amounts of emission-free hydrogen at a reasonable cost.

Approach

An international consortium of experts in various areas has been involved in this project including Aerosol & Particle Technology Laboratory (APTL, Greece), DLR (Germany, concentrating solar technologies), Johnson Matthey (U.K., automotive catalysis), Stobbe Tech Ceramics (Denmark, ceramic manufacturing), and the Centro de Investigationes Energéticas, Medioambientales y Tecnológicas (CIEMAT, Spain, solar tower facilities).

The feasibility and scalability of solar hydrogen production by the HYDROSOL process and the stability of the redox/support assemblies was initially demonstrated by several solar test campaigns at the solar furnace facilities in Cologne, Germany. This is where multi-cyclic solar thermochemical splitting of water was successfully achieved on the dual chamber, or Conti, reactor, producing hydrogen by cyclic operation with a pair of coated monoliths exclusively at the expense of solar energy for up to 54 cycles in a row with the same redox coating. In addition,

Project Overview

What

HYDROSOL-II: Solar Hydrogen via Water-Splitting in Advanced Monolithic Reactors for Future Solar Power Plants

Who

A European consortium coordinated by APTL-Aerosol and Particle Technology Laboratory, CPERI/CERTH, Greece

When

Started: November 1, 2005
Completed: October 31, 2009

Participants

Lead Country
Greece

Partner Countries
Germany, Spain, Denmark, U.K.

Renewable Technology

Concentrated solar

Application

None - production demonstration only

Website

http://www.hydrosol-project.org

Contacts

Dr. Athanasios G. Konstandopoulos
Coordinator
Tel. +30 2310 498192, 498112
Fax: + 30 2310 498190
agk@cperi.certh.gr

The thermochemical solar hydrogen plant at Plataforma Solar de Almeria, Spain, with the solar tower where the scaled-up HYDROSOL-II reactor is installed

the first successful cyclic solar hydrogen production tests with the 100-kW scale reactor were carried out in September 2008 at PSA, Spain. In comparison, further parametric studies currently in progress are showing that hydrogen production is possible on a solar tower under realistic conditions.

Within HYDROSOL-II, the Conti reactor was chosen as a starting point for the design of the pilot-scale reactor that consists of two adjacent, but separated, reaction chambers that represent a minimum array of modules suitable for the continuous production of hydrogen. Scale-up to 100 kW_{th} was implemented mainly by increasing the absorber surface. HYDROSOL-II is the largest pilot-scale project of its kind, the production target of the HYDROSOL-II reactor being around three kilograms of hydrogen per hour.

Accomplishments

The technology has currently reached the status of a pilot plant demonstration on a 100 kW scale, with the pilot solar hydrogen production reactor having been designed, built, installed, and operated on the SSPS-CRS solar tower facility of the Plataforma Solar de Almeria, Spain. The first hydrogen cyclic production tests were successfully carried out in September 2008, after exhaustive thermal qualification tests and implementation of a practicable operational control strategy for the coupling of the solar field to the thermal requirements of the reactor for the two process steps. Further tests and parametric studies are currently in progress showing that hydrogen production is possible on a solar tower under realistic conditions and demonstrating the high potential of this particular thermochemical cycle technology for further scale-up. The achievements and the potential impact of the HYDROSOL project have been acknowledged by the global community with three major international awards "...in recognition of the outstanding scientific and technological achievements...":

- The Global 100 Eco-Tech Award at the Expo 2005, Aichi, Japan.
- The inaugural Technical Achievement Award of the International Partnership for the Hydrogen Economy in 2006.
- The European Descartes Research Prize 2006 for Excellence in Scientific Collaborative Research.

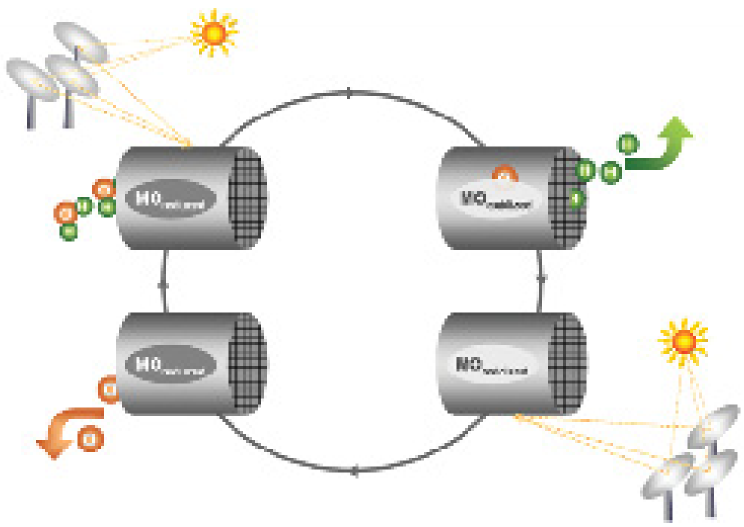
Lessons Learned

For effective commercialization of solar hydrogen production via thermochemical cycles, reactor concepts like the ones proposed and advanced within HYDROSOL-II seem to be the most promising. An example of this is reactors that do not involve moving high-temperature reactor parts or circulation of hot solid particles. However, elaborate and robust control strategies compatible with industrial standards need to be further developed in order to effectively couple the operation of a solar field with both the heat requirements and the time scales of the HYDROSOL-II reactor operation steps. In addition, improvements on the reactor design, supported by detailed modeling and operation simulations, are needed to maximize the reactor's chemical and thermal efficiency and hydrogen yield per reactor volume.

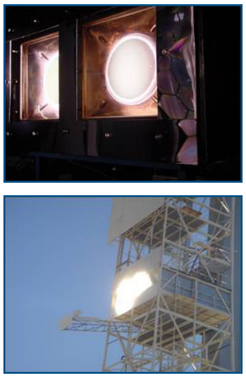
Future Plans

Future plans include designing and building a HYDROSOL-technology-based, 1 MW solar demonstration plant, with the goal of producing renewable hydrogen that is cost-competitive with non-renewable methods. Activities will include the complete design of the whole plant--the solar hydrogen reactor and all necessary upstream and downstream units needed to feed in the reactants and separate the products--and the calculation of the necessary plant and hydrogen supply costs.

Right: Schematic of the two-stage, water-splitting/ hydrogen production (top) and regeneration/ oxygen release (bottom) HYDROSOL process



Below: Dual-chamber HYDROSOL-I (Conti) (top) and HYDROSOL-II reactors (bottom) operating under concentrated solar irradiation



HYLINK: Distributed Hydrogen Energy System for Remote Areas

Wairarapa, New Zealand

The HyLink project, run by Industrial Research Limited (IRL), demonstrates a remote area hydrogen energy application well suited to rugged terrain and a plentiful supply of distributed energy resources, both of which are found in New Zealand. In this project, hydrogen was produced by wind electrolysis at an exposed hilltop and piped 2 kilometers (km) to a farming community where it was used to provide power and hot water. The project has shown that its concept is feasible using existing technologies and that there is a possibility for commercial opportunities through further technology development and cost reductions.

Objectives

The New Zealand Government is the sole shareholder in IRL, which seeks to discover whether community micro-generation could significantly improve options for providing energy services in remote areas—benefiting both utility companies and their rural customers—by providing a less costly alternative to running power lines.

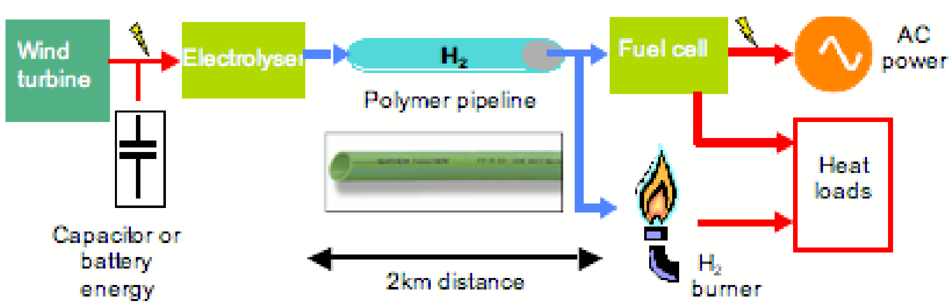
In remote communities, delivery of local renewable energy is often not economical due to the cost of running overhead power lines for long distances over rough terrain and dealing with intermittency of the power delivered. These issues led IRL to investigate the potential for hydrogen to contribute to the delivery of remote renewable energy. The project aimed to demonstrate that hydrogen conveyed in a pipeline can be used to both transmit and store intermittently produced energy at high power. Another objective was to reduce the cost of the hydrogen technologies used in the project, while maintaining safety and reliability.

Approach

This project was conducted in the small, remote farming community of Totara Valley, Wairarapa, where the load consisted of three farmhouses and a collection of farm buildings. The community was grid-connected throughout the project but had a strong desire to use as much local renewable energy as possible.

The proof-of-concept HyLink system consists of an 18-millimeter polymer hydrogen pipeline connected at the supply end to a 400-watt proton exchange membrane (PEM) electrolyser, and at the demand end to a one-kilowatt PEM fuel cell and a one-kilowatt hydrogen combustor located in a woolshed.

Power to the electrolyser is provided by a 300-watt wind turbine. Hydrogen produced via electrolysis directly pressurizes the pipeline, which both stores the hydrogen and conveys it at high efficiency (greater than 99%) over relatively long distances. The pipeline provides a storage volume of 400 liters, equivalent to about 5 kWh of energy at 4 bar pressure.



Schematic of the HyLink system

Project Overview

What

HYLINK

Who

Industrial Research Limited

When

Started: March 2001
Completed: August 2005

Participants

New Zealand

Renewable Technology

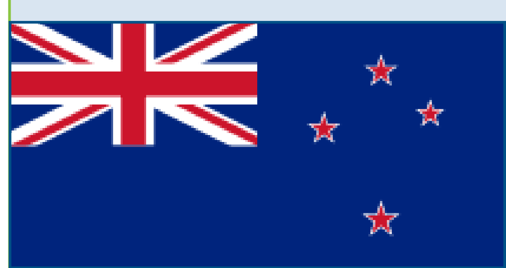
Wind power

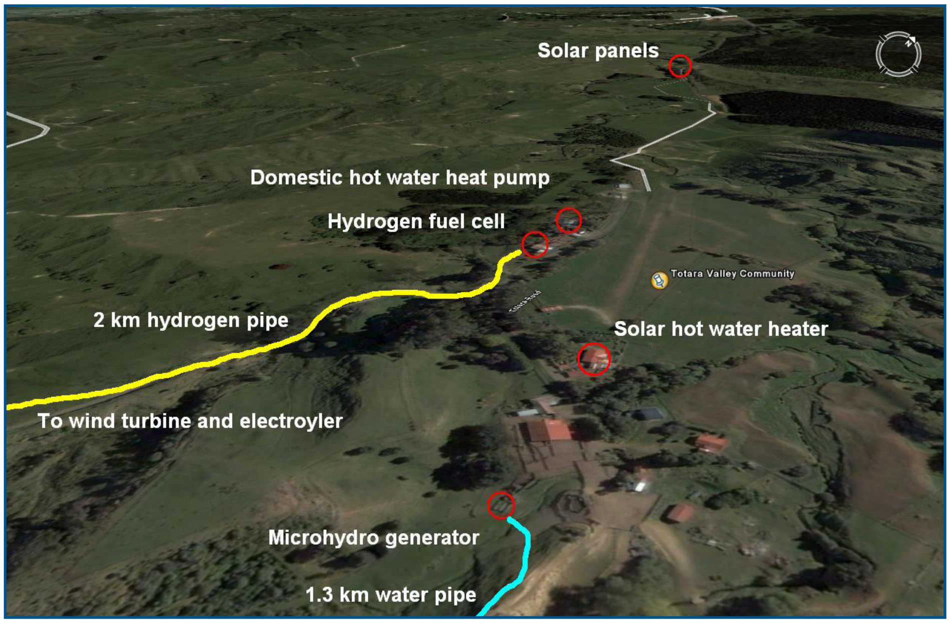
Application

Remote community power

Website

http://www.irl.cri.nz





Geographical layout of the HyLink system including other renewable technologies at the site.

The control systems at each end operate independently. The hilltop controller runs the electrolyser whenever the battery is fully charged and the pipeline pressure is below 4 barg (gauge pressure). The woolshed controller starts the fuel cell when the pipeline pressure reaches a high set point and delivers power to the electrical network (which is "net-billed" by the energy retailer) until the pipeline pressure drops to a lower set point. The fuel cell then goes back into standby mode until the upper threshold is again reached.

Monitoring systems at both the hilltop site and at the woolshed log and report basic system operating parameters, such as wind speed, power flows, battery status, hydrogen production, and pressure, electrolyser temperatures, water level, etc. The data is telemetered from the hilltop via the cellular General Packet Radio Service network and automatically sent to an Internet mailbox.

Accomplishments and Lessons Learned

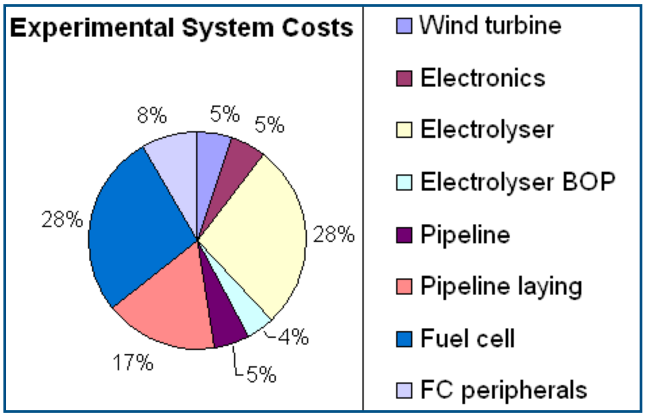
The project successfully demonstrated the feasibility of producing and using hydrogen from wind remotely using existing technology. It is anticipated that as hydrogen conversion technologies mature and become proven, larger community scale hydrogen network systems that take advantage of the economies of scale for wind turbines will be the most cost effective.

The system performed well, although less wind energy was collected than anticipated due to the small size of the 300W wind turbine and the turbulent and gusty wind conditions. At high wind and turbulent sites, wind turbine generators with power-limiting settings should be used under high wind conditions rather than going to power-shutdown mode.

Hydrogen storage within a low pressure pipeline is useful as a low cost, supply-demand power matching buffer that becomes more substantial the further away the wind generator is located. The storage capacity is easily increased by using a larger pipe. At practical power flow rates, pipeline hydrogen diffusion losses are negligible.

Cost analysis of the project showed that the fuel cell and the electrolyser represent significant portions of the cost and are good opportunities for cost reduction (see below). Pipeline laying represented a significant cost to the project, because regulations required the pipeline to be buried. However, this was much lower than the cost of a medium voltage electrical circuit, which in New Zealand in this terrain costs about $30,000/km.

Demonstration system hardware cost breakdown



Future Plans

Having successfully developed the concepts, IRL's objective is to reduce the cost of the hydrogen technologies at each end, while maintaining the safety and the inherent reliability. In particular, the electrolyser and gas management have been identified as areas for further development.

IRL is planning to use the HyLink technology demonstrated in this project on Matiu/Somes Island in Wellington Harbour as part of a project to use renewable energy to replace diesel generation, and are also investigating the possibility of using such systems to power remote villages in India.

International Partnership for Hydrogen and Fuel Cells in the Economy

RES2H2 Project

Keratea, Greece & Pozo Izquierdo, Spain

The Cluster Pilot Project for the Integration of Renewable Energy Sources into European Energy Sectors Using Hydrogen, known as RES2H2, involves the integration of wind energy with hydrogen technologies—electrolyser, storage, and fuel cells—and water desalination by reverse osmosis. The project, financed by the Fifth Framework Programme of the European Commission, has installed two demonstration prototypes at test sites in Greece and Spain. The prototypes are self-sufficient energy systems driven by wind energy, capable of producing “green” hydrogen for energy storage and for supplying electricity and fresh water.

Objectives

The RES2H2 project is focused on the following goals:

- Increasing the penetration of wind energy in weak electricity grids.
- Optimizing integrated systems of wind energy and hydrogen.
- Advancing the technical and economic feasibility of the production of hydrogen from wind energy on a commercial scale.

Approach

Greek Test Site

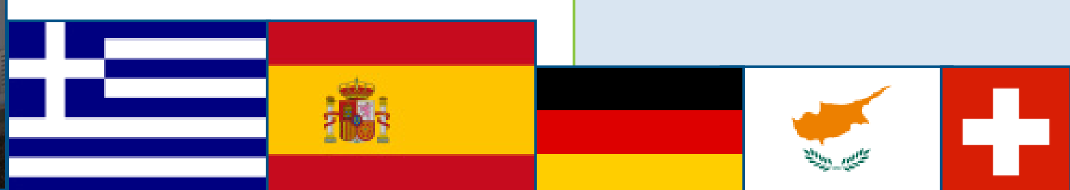
At the Greek test site, the plant was designed to study hydrogen production and storage integrated with wind energy. The prototype system is composed of a 25 kW water electrolyser, six metal hydride tanks filled with a $LaNi_5$-type alloy with a 3.6 kg hydrogen capacity, and a hydrogen compressor for filling hydrogen cylinders, all powered by a 500 kW synchronous wind turbine. The advanced alkaline electrolyser produces a maximum of 0.45 kg of hydrogen per hour directly at 20 bar pressure, which is compressed up to 220 bar in a single stage with an additional 10% energy loss. A 7.5 kW proton exchange membrane (PEM) fuel cell was recently integrated. The hydrogen was initially used only to supply experimental hydrogen vehicles but was later also used to fuel the PEM fuel cell in periods of low wind. Activities at the Greek test site are supported by a national project called Excellency and are also integrated with the national Renewable Energy Park project, which includes educational displays of different renewable energy technologies.

Spanish Test Site

The prototype installed in Spain was designed to satisfy the electricity and water needs of a theoretical isolated village. During the initial testing phase, the system was connected to the grid. The performance data collected during this phase defined the appropriate wind turbine system capable of satisfying the demands of the project in stand-alone mode operation.

The grid-connected system has been in operation since 2007 at the Instituto Tecnológico de Canarias, S.A. (ITC) facilities in Pozo Izquierdo, Gran Canaria, Spain. This location is exposed to the trade winds and creates an excellent testing environment. When electricity supply exceeds the theoretical demand, an alkaline electrolyser uses excess electricity to produce 0.99 kg of hydrogen per hour at 25 bar (5,500 Nm^3, or normal cubic meters, of storage) and the reverse osmosis plant also uses this excess electricity to produce a maximum of 110 m^3 per day of desalinated water. When power from the wind turbine does not cover demand from the electrical loads connected

Test site in Pozo Izquierdo, Spain



Project Overview

What

RES2H2 Project: Cluster Pilot Project for the Integration of Renewable Energy Sources into European Energy Sectors Using Hydrogen

Who

Instituto Tecnológico de Canarias, S.A., Spain

When

Started: February 2002
Completed: October 2007

Participants

Lead Countries
Greece, Spain

Partner Countries
Cyprus, Germany, Switzerland

Renewable Technology

This project demonstrates hydrogen produced from wind electrolysis.

Application

Vehicles and renewable energy storage

Website

http://www.res2h2.com

Contacts

Salvador Suárez García
Head of Renewable Energies Department
Instituto Tecnológico de Canarias, S.A.
Tel. +34 928 727574
ssuarez@itccanarias.org

Elli Varkaraki
Project Manager
Centre for Renewable Energy Sources
Tel. +30 2106603397
evarkara@cres.gr

to the system, the stored hydrogen is used in six 5 kW PEM fuel cells to produce electricity.

Accomplishments

Greek Test Site

The performance of the electrolyser, compressor, and metal hydride tanks was assessed under different operating strategies, and the optimum conditions of integrated operation were determined. The power supply to the electrolyser varies in a range of 20 to 100% of its nominal power, but the compressor operates only in an on-off mode. By filling in cascade the modular high pressure section, the energy loss for compression is drastically decreased. Electrolytic hydrogen without purification is stored in three of the six metal hydride tanks, in order to avoid a 5 to 8% hydrogen loss in the purification section and to study the effect of oxygen and humidity impurities on the cycling capability. The results show that the efficiency of the system, from wind power to the high heating value of hydrogen stored, varies from 50 to 70%.

Spanish Test Site

At the Spanish test site, dynamic and stationary testing of all components has been performed to obtain the efficiency, range of operation, power consumption, transient response, and the operation curve of the fuel cells and electrolyser. The response of the components to typical wind power variations and their interactions with the rest of the system have been analyzed. A plan for converting from the current grid-connected system to a stand-alone system has been developed, and an initial topology of the stand alone system has been designed.

Lessons Learned

The main conclusion regarding both sites is that the potential for optimization of the electrical interfaces among the individual components is very important. More R&D is necessary in the field of power electronics for the integration of the wind turbine and the hydrogen system (i.e., electrolyser, fuel cells). This would address, in particular, the harmonics distortion generation that creates electrical instabilities and malfunction in the electrical system of the stand-alone solution. Also, in remote locations, the plant should not only be protected against a direct lightning surge, but also from secondary lightning currents. (The computer in the control room of the Greek site was destroyed by such a current). Concerning specifications for fuel cells, the impurities present in electrolytic hydrogen should also be addressed: a small amount of oxygen and humidity content should be tolerated to avoid the cost and losses of a purification section.

At the Spanish site, it was concluded that careful integration of the SCADA system with the main control system is important to synchronize each component's control strategies with an intermittent wind energy source.

At the Greek site, metal hydride tanks presented some benefits: during intermittent operation, they may be charged almost completely without external cooling with a concomitant savings in cooling energy. Also, they can be charged with electrolytic hydrogen that by-passes the purification section, which represents some 30% of the total cost for alkaline electrolysers and a 5 to 8% hydrogen loss for all electrolysers. The effect of the oxygen and humidity content of the hydrogen on the cycling capability of the metal hydride tanks is still under investigation, but the eventual regeneration of the tanks toward their end-of-life may be a more cost-effective solution than the installation of a deoxidizer and drier. However, the inertia of the system, that is, the time and energy required to heat up the whole mass of the tank, makes them difficult to incorporate in a fully automatic system. This is because the response of the system largely depends on the state-of-charge and the ambient temperature for external storage.

Future Plans

At the Greek site, the cogeneration capability of the fuel cell will be used to supply heat to the metal hydride tanks in order to avoid the use of an electrical boiler and further increase the efficiency of the integrated system. Other plans include the modification of a gasoline vehicle to run on hydrogen, the revamping of the electrolyser by installing a more potent power supply, and the upgrade of the compressor to 350 bar or higher.

International Partnership for Hydrogen and Fuel Cells in the Economy

Test site in Keratea, Greece

Test site in Pozo Izquierdo, Spain

Sahara Wind-Hydrogen Development Project

Morocco and Mauritania

The trade winds that blow along the Atlantic coast from Morocco to Senegal represent one of the largest, most productive wind potentials available on Earth. The same region currently suffers from a limited, decentralized grid infrastructure in need of stabilization. The Sahara Trade Winds to Hydrogen Project aims to utilize these Saharan winds to produce hydrogen in order to enhance the access and integration of wind electricity in Morocco and Mauritania. The project uses a phased approach, beginning with demonstrations in academic settings to build capacity and knowledge and later moving on to larger projects in industrial settings.

Coordinated by Morocco's Sahara Wind Inc., this project began in the second half of 2007 and is expected to last four to five years. Its team is composed of 10 partners from Morocco, eight from Mauritania, and four co-directors from the United States, Germany, Turkey, and France.

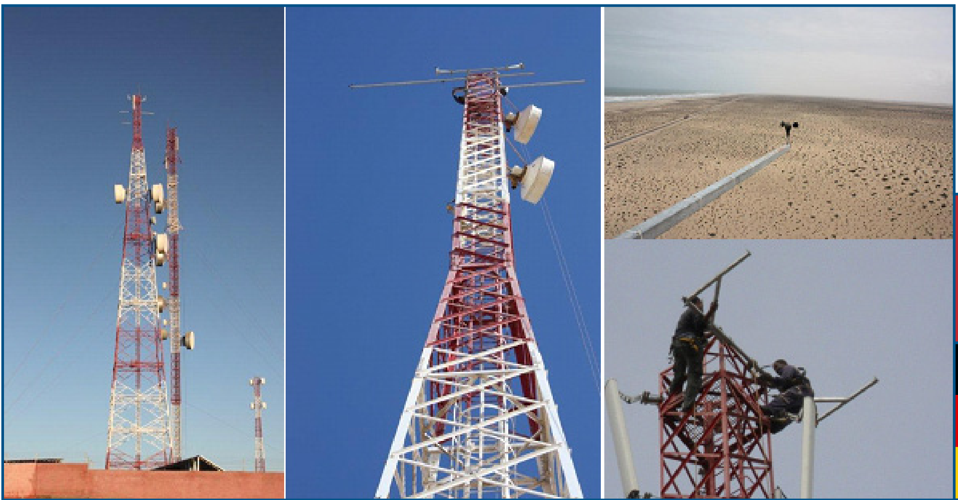
Objectives

The erratic nature of the trade winds resource means that wind energy cannot provide a sustainable source to the region's weak infrastructure, prohibiting any conventional approach of a continuous feed into smaller local electricity markets. The size of Morocco's grid is also relatively small (approximately 5,000 MW) and cannot handle large amounts of wind-generated electricity before encountering grid stability problems, such as generation intermittency and power margins. These problems escalate further south in Mauritania where the grid capacity is less than 120 MW.

Therefore, the project team believes that the most beneficial approach is to use wind electrolysis as a means of grid stabilization within integrated applications utilizing electrolysis by-products such as hydrogen for power storage restitution/backup, or as a fuel or feedstock for specific uses in remote locations.

The Sahara Wind-Hydrogen Project has led to a NATO Science for Peace and Security (SfP-982620) contract aiming to accomplish the following goals:

- Use electrolysers as a stabilizer in weak electricity grids.
- Co-develop wind-electrolyser systems for local conditions.
- Map regional wind resource potential.
- Build "Green Campus Concepts" with hydrogen storage.
- Develop integrated wind electrolysis applications within the region's industries and load centers.



Trade wind resource assessment using telecom tower infrastructures

Project Overview

What

Sahara Wind-Hydrogen Project

Who

Sahara Wind Inc.

When

Started: 2007
Duration: 4-5 years

Participants

Lead Country
Morocco

Partner Countries
Mauritania, U.S., Germany, Turkey and France

Renewable Technology

This project will demonstrate hydrogen production from wind electricity along with hydrogen storage used as a feedstock for specific industries and hydrogen shipping via pipeline.

Application

Renewable energy storage

Website

www.saharawind.com

Contact

Project Director:
Mr. Khalid Benhamou
Sahara Wind Inc.
kb@saharawind.com

Approach

The initial phase of the project is being carried out through applied research programs in academic settings to develop local expertise in the technologies. This is being done through the deployment of wind electrolysis systems within "Green Campus Concepts" programs at several universities in Morocco and Mauritania for demonstration and training purposes. The systems use a series of small, 5 kW wind turbines that simultaneously provide power to the grid and to a 30 kW pressurized alkaline electrolyser. The electrolyser produces hydrogen that is then stored in cylinders at a pressure of 12 bar and used in a 1.2 kW fuel cell to produce electricity and stabilize the grid at times of low wind speed.

After being initiated at the universities, the technology will gradually be extended to the region's industries. Current plans are to install demonstration systems followed by larger pilot projects at Morocco's water and electric utility's corporate headquarters and main water treatment plant, as well as at the Tarfaya desalination plant. These systems will consist of small wind turbines powering hypochlorite (membrane) electrolysers. The hydrogen is stored and used in a fuel cell and internal combustion engine generator for back-up power, as well as being used as fuel for electro-mobility applications. A similar project using alkaline electrolysers and wind turbines will be put in place at Mauritania's iron ore company in the city of Nouadhibou.

Accomplishments

Small wind turbine industrial engineering programs have been established at several universities, enabling development of the technological expertise that will be needed to support the planned and future demonstration projects.

The project has also allowed for a wind monitoring infrastructure to be deployed in both Morocco and Mauritania with the help of the project's industrial partners. Both of the telecom operators in Morocco and Mauritania have made their telecommunication mast tower infrastructures available for this project, enabling the establishment of a regional wind mapping network. Atmospheric parameters such as pressure, temperature, and humidity are being recorded in addition to wind direction and speed on International Measuring Network of Wind Energy Institutes (MEASNET)-calibrated instruments at several tower heights. The wind mapping network is expected to facilitate future utilization of the area's trade wind resources by providing specific information about the quality of the resource over large geographical areas. This means projects involving utilization of hydrogen can be deployed as part of a large-scale, integrated system using high voltage direct current (HVDC), local use of hydrogen, and hydrogen pipelines for export.

The wind and electrolyser equipment for training and applied research purposes was put into operation in early November 2010 at the Al Akhawayn University of Morocco and the University of Nouakchott in Mauritania.

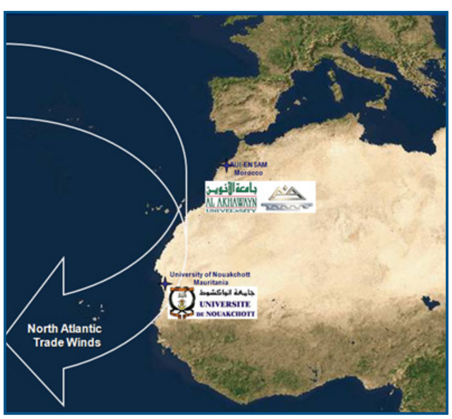
These systems will be gradually updated to increase their wind generation capacities with a goal of providing system stabilization of up to 30% of the base load.

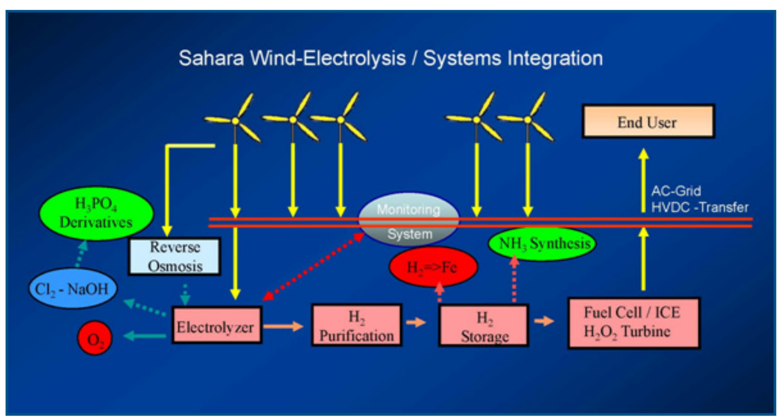
Other small, wind-turbine test benches were delivered to the Ecole Nationale Supérieure d'Arts et Métiers (ENSAM) School of Engineering in Meknes, Morocco, and were installed in late 2010. The technical economic analysis for end-user pilot project applications has already been completed, including technical equipment configurations.

Future Plans

In the future, the project team plans to partner with the region's industries representing the main local energy loads to build an integrated energy system complementary to Sahara Wind's High Voltage DC Transmission project. This system will use hydrogen storage and hydrogen shipping via a pipeline. By enhancing the local ownership of wind resources on a regional basis and supporting industrial use of local mining resources using cleaner and more sustainable processes, such a system could potentially serve as a secondary power source to both North Africa and Europe.

Ultimately, project participants would like to see enhancements to the integration of an end-user-driven, comprehensive, sustainable, applied research program. This is likely to lead to the adoption of a holistic, integrated approach to renewable energy technologies in North Africa.





Map showing the locations of two of the university projects (left). Schematic of Sahara Wind wind-hydrogen system (right).

International Partnership for Hydrogen and Fuel Cells in the Economy

Utsira Wind Power and Hydrogen Plant

Utsira Island, Norway

In 2004, the small windswept island of Utsira, Norway, became home to the world's first, full-scale combined wind power and hydrogen plant.

In this pilot project, 10 households were supplied exclusively by the energy generated from wind turbines. In windy weather, the turbine powers the houses directly. When the wind power production exceeds the households' demand, the excess power is used to produce hydrogen in an electrolyser. The hydrogen is compressed and stored, and when the winds are either too mild or too strong to generate enough energy from the turbine, a hydrogen engine and a fuel cell uses stored hydrogen to produce the necessary electricity. This system ensures a continuous and reliable energy supply to the homes for up to three days when wind power is not available.

Objectives

By developing and testing a full-scale, wind-hydrogen energy system, this project aimed to demonstrate how renewable energy can provide a safe, continuous, and efficient energy supply to remote areas.

With this project, owned by Statoil ASA and operated in collaboration with German wind turbine manufacturer Enercon, the two firms want to ensure that the installed components in the system worked together—to deliver power to the customers with the expected quality; to reduce costs and optimize the technical solutions of the project; and to commercialize and market the production method.

Approach

The frequent wind at Utsira made the island an ideal location for wind power production. Two Enercon E40 wind turbines were installed at Utsira, each with a capacity of 600 kW. One turbine produces electricity for the external grid only, while the other is connected to the stand-alone system and is pitched down to approximately 150 kW to better match demand. To stabilize the intermittent renewable energy, a flywheel with a 5 kWh capacity and a 100 kVA master synchronous machine are installed to balance and control voltage and frequency. In order to store the surplus energy, a 10 Nm^3/h Hydrogen Technologies electrolyser with a peak load of 48 kW, a 5 kW Hofer compressor and a 2,400 Nm^3, 200 bar hydrogen storage pressure vessel are installed. To generate power when there is no wind, or too much wind, a 55 kW MAN hydrogen internal combustion engine and a 10 kW IRD fuel cell were installed.

Project leader Torgeir Nakken, from Statoil's R&D center in Porsgrunn

Project Overview

What

Utsira Wind Power & Hydrogen Plant

Who

Statoil ASA & Enercon GmbH

When

2004-2008

Participants

Norway, Germany

Renewable Technology

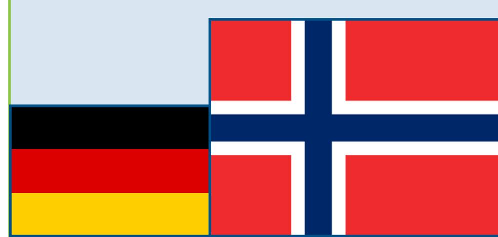
This project demonstrates hydrogen production through wind electrolysis.

Application

Renewable energy storage

Website

http://www.statoil.com/en/NewsAndMedia/Multimedia/features/Pages/HydrogenSociety.aspx



Accomplishments

Utsira is practically offshore—one hour with the local ferry from the nearest town running three times a day – and weather conditions are often severe. This has required solid engineering and meticulous project execution. The wind turbines had to be installed before the autumn storms, and roads and a small port were constructed for equipment transportation. After start-up, the facility was remotely operated from an inland power plant control center.

The project was operated continuously for four years, with more than 50% of the time in stand-alone mode. The power quality was very good, and, with no complaints reported, the customers seemed to be satisfied. The project also had a public education aspect including involvement in local activities, good media coverage, articles in several publications, and a number of presentations at conferences and at industry fairs. In 2004, the Utsira project won the prestigious Platts award for "Renewables Project of the Year" in New York City.

Lessons Learned

Despite the successful demonstration and operation of the system, several challenges were identified. In this project, the wind energy utilization was only 20%, revealing a need for the development of more efficient electrolysers, as well as improved hydrogen-electricity conversion efficiency. The fuel cell experienced some technical problems that did not allow it to be fully integrated into the system, including leaking of the coolant fluid, damage to the voltage monitoring system during assembly, and frequent false grid failure alarms. In addition, the fuel cell experienced very rapid degradation even when idle and was operated for less than 100 hours over the duration of the project. These issues, combined with the low efficiency of the hydrogen engine and increased electricity use by customers over time, heightened the probability that hydrogen would run out during windless periods. The contingency plan was to connect the customers back to the grid if this happened so that they would not be without power.

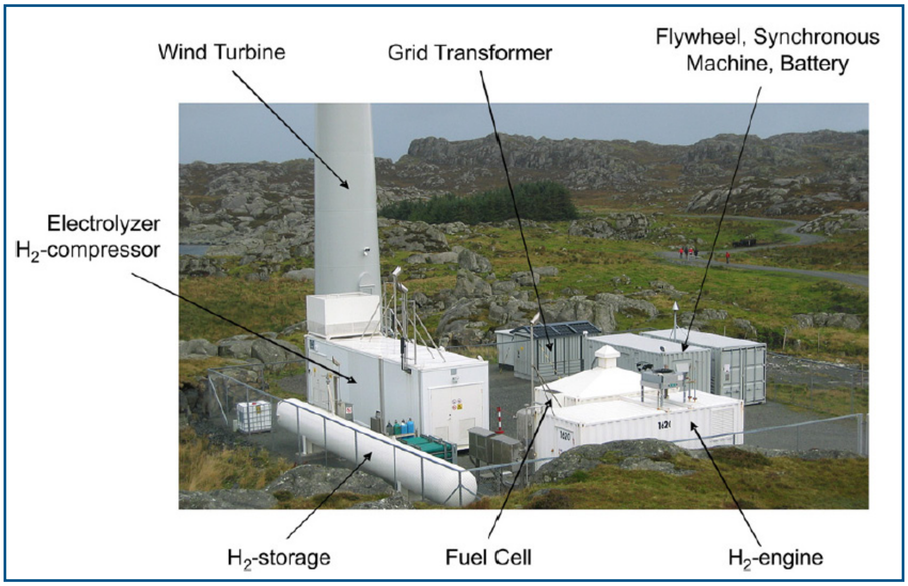
The hydrogen engine provided more than three years of reliable service but eventually experienced some technical problems and had to be replaced. Although the engine was seen as a good, near-term solution, project leaders concluded that the cost and durability of the fuel cell would have to be improved to make this type of project commercially viable. They also recommended that future projects include more than one renewable energy source (i.e., wind, solar, and/or bioenergy).

The following points were identified as the most important considerations in planning, building, and operating such a project:

- Having a well-defined design basis and operational philosophy focusing on climatic conditions, signal quality, communication (control and regulation), and key component interfaces.
- Keeping safety, health, and environment in mind—it is important to use equipment with a high degree of fail-safe and remote operation capability.
- Selecting an appropriate location with good wind conditions but that is not too remote; a small but representative load; a back-up system in place; a supportive community, and access to service personnel.

Future Plans

The success of the Utsira project in demonstrating the feasibility of combining renewable energy and hydrogen in remote locations opens new opportunities for the application of electrolysers in future energy systems. One goal of the Utsira project was to see if the wind-hydrogen concept could be made commercially feasible. Though much tweaking will have to be done to achieve this goal, the time frame to be competitive with conventional remote-site power supplies—diesel or combined wind and diesel generators—has been estimated to be about five to 10 years.



Utsira wind/hydrogen demonstration plant

International Partnership for Hydrogen and Fuel Cells in the Economy

Wind-to-Hydrogen (Wind2H2) Project

Boulder, Colorado, USA

The U.S. National Renewable Energy Laboratory (NREL) and Xcel Energy launched a demonstration wind-to-hydrogen (Wind2H2) project that uses electricity from wind turbines and photovoltaic (PV) panels to produce and store hydrogen. Located at NREL's National Wind Technology Center, the new facility closely links wind turbine and PV electricity to electrolyser stacks using NREL-designed, built, and tested power electronic converters. The power converters track the maximum power point of the wind turbine and PV sources in order to extract the maximum amount of energy and then pass the electricity through water to split the liquid into hydrogen and oxygen. The hydrogen is compressed, stored, and used later to generate electricity from an internal combustion engine (ICE) generator or fuel cell, or further compressed to refuel a fuel cell vehicle.

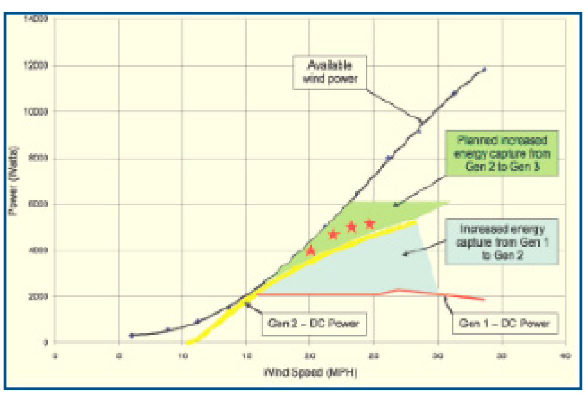
Objectives

NREL's Wind2H2 Project aims to improve the system efficiency and reduce the capital costs of producing hydrogen from the renewable resources of wind and solar in quantities large enough and at costs low enough to compete with traditional energy sources such as coal, oil, and natural gas. Their further goals include:

- Exploring system-level integration and optimization opportunities for renewable energy-based electrolysis production facilities.
- Quantifying system-level efficiency improvements and cost reductions achieved by designing and building integrated power electronics to closely couple wind turbines and PV arrays to the electrolyser stacks.
- Gaining operational experience of a hydrogen production facility, evaluating appropriate safety systems and system controls for safe operation, and identifying areas for cost and efficiency improvements.
- Evaluating the ability to integrate renewable energy from variable-output wind turbines and PV arrays and exploring the potential of using hydrogen as an energy storage mechanism.
- Determining the system impacts, efficiency, and ability of each electrolyser technology to accommodate the varying energy input from wind turbines and photovoltaics.
- Producing fuel cell-grade hydrogen while minimizing the production of greenhouse gases or other harmful by-products.
- Compressing and storing hydrogen for use during peak demand.

Approach

NREL is examining the issues related to the integration of these technologies as well as the operation and response of commercially available electrolysers being supplied varying stack current from the NREL-designed power converters. Two 7-kW HOGEN 40RE proton exchange membrane (PEM) electrolysers (2.25 kilograms per day) from Proton Energy Systems, and one Teledyne HMXT-100 alkaline electrolyser (12 kg/day)



Energy transfer improvements from the 10-kW wind turbine tested by NREL; the graph shows continued improvement, including the latest preliminary third generation improvement in the green-shaded area

Project Overview

What

Wind2H2 Project

Who

U.S. National Renewable Energy Laboratory (NREL) & Xcel Energy

When

Started: 2007
Completed: 2010

Participants

United States

Renewable Technology

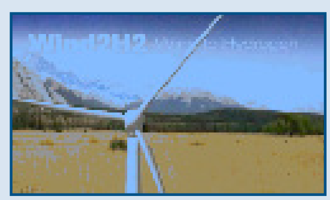
This project demonstrates hydrogen production from wind and solar-generated electricity.

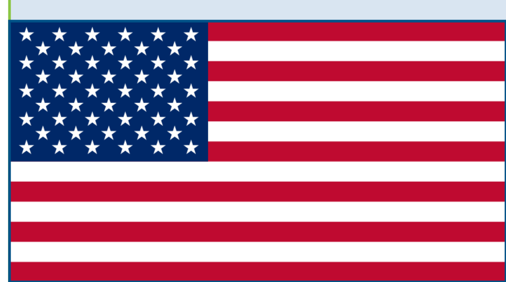
Application

Renewable energy storage and vehicles

Website

http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html





produce hydrogen and oxygen from water at pressures from 150 to 200 psi (10 to 13 bar). Once produced, compressed, and stored, the hydrogen gas can be converted to electricity and fed back to the grid using the 60 kW ICE generator from the Hydrogen Engine Center. The electricity will be routed into the utility grid during peak demand hours. The Wind2H2 system also includes a second compressor, higher pressure storage tanks, and a hydrogen dispenser to allow fueling of hydrogen fuel cell or ICE vehicles.

The Wind2H2 project uses two wind turbine technologies: a Northern Power Systems 100-kW wind turbine and a Bergey 10-kW wind turbine. Both have variable speed options; the blade speed varies with wind speed, producing alternating current (AC) that varies in magnitude and frequency (known as wild AC) as the wind speed changes. The energy from the 10-kW wind turbine is converted from its wild AC form to direct current (DC) and is then used by the electrolyser stack to produce hydrogen from water. The 10-kW PV array is configurable to produce DC voltage between 60 and 240 V. Since this voltage is too high for the electrolyser stacks, NREL has designed, built, and tested maximum power point tracking (MPPT) power electronics to make the DC-DC conversion. Currently, the AC power output signal from the 100-kW wind turbine is monitored at the Wind2H2 Control Building and conditioned to directly drive the stack current of the 33-kW alkaline electrolyser stack.

Accomplishments

Energy transfer optimization:

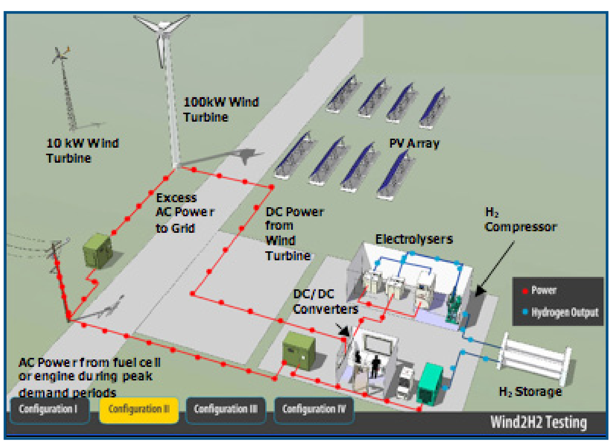
- NREL engineers are investigating how to maximize renewable energy use and optimize energy transfer within the Wind2H2 system by designing and incorporating dedicated power electronics packages.
- NREL also investigated energy transfer from the 10-kW solar PV array, comparing a direct-connect from the PV array to the electrolyser stack with a connection through an MPPT power electronics package designed and built at NREL. The measurements showed that, in all cases, the system employing MPPT electronics captured 10 to 20% more energy than the direct-connect configuration.
- To improve energy transfer within wind-turbine-based renewable energy systems, NREL has designed and continues to test improved AC-DC power electronics systems for a 10-kW wind turbine connected to a PEM electrolyser stack. The test results, shown in the graph on the previous page, indicates continued improvement from the Gen1 to the Gen3 design (based on Gen 3 preliminary data).

Reduced Cost:

- Based on investigations, NREL engineers estimated that optimizing power electronics in large-scale, wind-based renewable electrolysis systems could reduce the cost of wind-to-hydrogen production by 7%, from \$6.25/kg to \$5.83/kg. System-level integration of renewable energy sources and electrolyser stacks can improve energy transfer within the system, increasing system efficiency and lowering overall cost of production.

Efficiency Measurements:

- The Wind2H2 Project found PEM electrolysers to be more efficient than alkaline electrolysers, contrary to expectations. At full stack current, the PEM electrolyser had a system efficiency of 57% HHV. At the rated stack current, the alkaline system had a system efficiency of 41% HHV. Worthy of note, the measured hydrogen flow from the alkaline electrolyser was 20% lower than the manufacturer's specifications. If the full hydrogen flow was measured, the alkaline system efficiency would have reached 50% HHV (HHV = 39.4 kWh/kg).



Schematic showing operation of the Wind2H2 system when powered by the 100 kW wind turbine

Lessons Learned

- ***System Integration:*** More research and engineering design related to renewable electrolysis system integration would improve energy transfer and overall system efficiency and would reduce system complexity and capital costs. The development of optimized power electronics packages is a promising area for system-level improvements.
- ***System Communication:*** Creating renewable electrolysis systems requires that equipment from a wide range of manufacturers work together as a single system. Future renewable electrolysis systems would benefit from an open-architecture approach to component development, including the development of consistent communications protocols.
- ***Codes and Standards:*** Developing clear and consistent codes and standards will expedite implementation and reduce the cost of renewable electrolysis projects.

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