International Energy Agency Activities

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Abstract

Hydrogen systems can provide viable, sustainable options for meeting the world's energy requirements. Hydrogen is relevant to all of the energy sectors – transportation, buildings, utilities and industry. It can provide storage options for baseload (geothermal), seasonal (hydroelectric) and intermittent (PV and wind) renewable resources, and, when combined with emerging decarbonization technologies, can reduce the climate impacts of continued fossil fuel utilization. However, hydrogen energy systems still face a number of technical and economical barriers that must first be overcome for hydrogen to become a competitive energy carrier. Advances must be made in hydrogen production, storage, transport and utilization technologies and in the integration of these components into complete energy systems.

To expedite the advancement of hydrogen technologies and realize a hydrogen future, nations have come together under the auspices of the International Energy Agency's (IEA) Hydrogen Program to collaborate and address the important barriers that impede hydrogen's worldwide acceptance. Through well-structured, collaborative projects, experts from around the world address many of the technical challenges and long-term research needs that face the hydrogen community. These collaborations have already led to significant advances in renewable hydrogen production and solid storage materials and to the development of tools to evaluate and optimize integrated hydrogen energy systems.

Introduction

The members of the IEA Hydrogen Agreement recognize that a long-term research and development effort is required to realize the significant technological potential of hydrogen energy. This effort can help create competitive hydrogen energy production and end-use technologies, and supports development of the infrastructure required for its use. The following have been established as the guiding principles on which the IEA Hydrogen Program is based:

- Hydrogen—now mainly used as a chemical for up-grading fossil-based energy carriers—will in the future increasingly become an energy carrier itself. It is necessary to carry out the analysis, studies, research, development and dissemination that will facilitate a significant role for hydrogen in the future.
- Significant use of hydrogen will contribute to the reduction of energy-linked environmental impacts, including global warming due to anthropogenic carbon emissions, mobile source emissions such as CO, NOx, SOx, and NMHC (non-methane hydrocarbons), and particulates.
- Hydrogen is currently used to up-grade lower-quality, solid and liquid fossil fuels, such as coal and heavy oils. The use of hydrogen in such applications reduces harmful emissions through more efficient end-use conversion processes and extends the range of applicability. Ultimately, with the addition of hydrogen, carbon dioxide emissions can be used to produce useful chemicals and fuels.

- Hydrogen has the potential for short-, medium- and long-term applications and the steps to realize the potential for applications in appropriate time frames must be understood and implemented.
- All sustainable energy sources require conversion from their original form. Conversion to electricity and/or hydrogen will constitute two prominent, complementary options in the future.
- Hydrogen can assist in the development of renewable and sustainable energy sources by providing an effective means of storage, distribution and conversion; moreover, hydrogen can broaden the role of renewables in the supply of clean fuels for transportation and heating.
- Hydrogen can be produced as a storable, clean fuel from the world's sustainable non-fossil primary energy sources – solar energy, wind energy, hydropower, biomass, geothermal, nuclear, or tidal. Hydrogen also has the unique feature that it can upgrade biomass to common liquid and gaseous hydrocarbons, thus providing a flexible, sustainable fuel.
- Hydrogen can be used as a fuel for a wide variety of end-use applications including important uses in the transportation and utility sectors.
- All countries possess some form of sustainable primary energy sources; hence, hydrogen energy technologies offer an important potential alternative to fossil fuel energy supply (in many instances to imported fuels). Utilization of hydrogen technologies can contribute to energy security, diversity and flexibility.
- Barriers, both technical and non-technical, to the introduction of hydrogen are being reduced through advances in renewable energy technologies and hydrogen systems including progress in addressing hydrogen storage and safety concerns.
- Hydrogen energy systems have potential value for locations where a conventional energy supply infrastructure does not exist. The development of hydrogen technologies in niche applications will result in improvements and cost reductions that will lead to broader application in the future.

If the technological potential of hydrogen is realized, it will contribute to the sustainable growth of the world economy by facilitating a stable supply of energy and by helping to reduce future emissions of carbon dioxide. Cooperative efforts among nations can help speed effective progress towards these goals. Inasmuch as hydrogen is in a pre-commercial phase, it is particularly suited to collaboration as there are fewer proprietary issues than in many energy technologies.

Research and Development Activities

The use of hydrogen as an energy carrier is considered a mid- to long-term goal. Hydrogen production from renewables will likely not be cost-competitive with fossil-based production, at least in the near-term. Likewise, infrastructure barriers, particularly in the storage area, hinder near-term application of hydrogen for transportation applications. Additionally, safety issues, both real and perceived, are concerns for acceptance of hydrogen by the general population.

- Production
  Today, large, centralized steam methane reformers (SMR) are the primary source of hydrogen and will be the likely choice for meeting increasing demand in the near term. The incorporation of CO_2 sequestration technologies can significantly reduce the emissions from fossil resources. Smaller, distributed SMR could provide efficient resources and reduce transportation requirements for hydrogen. Other novel reformer technologies could improve

efficiency, cost and/or purity of hydrogen production. Coal systems that incorporate sequestration can further add to the portfolio of fossil-based hydrogen production technologies.

Electrolyzers are the source of today's high purity hydrogen. The power source is the electricity grid, supplied primarily by coal- and natural gas-fired power plants, hydroelectric and nuclear. Material and efficiency improvements, size reduction and use of renewable power resources are all research opportunities. Other electrolytic processes - chemical cycles, direct water splitting with semiconductor technology, etc. - could supply high-purity hydrogen. Water-splitting microorganisms are another potential source for unlimited quantities of hydrogen.

Biomass may provide an economical, carbon-neutral (or negative with the addition of carbon sequestration) alternative to fossil-based production. Thermal technologies like gasification and steam reforming of bio-oils show great promise as viable production options. In the longer-term, fermentation may also yield carbon-neutral renewable hydrogen.

- Storage

  Today, hydrogen is stored and transported as a compressed gas or cryogenic liquid. For hydrogen to be a competitive fuel for vehicles, the hydrogen vehicle must be able to travel a comparable distance to conventional hydrocarbon-fueled vehicles. Meeting these distance requirements with current compressed gas technology would require a fuel tank substantially larger and heavier than today's convention due to the low energy density of gaseous hydrogen.

  In its liquid state, hydrogen's energy density is substantially improved. However, hydrogen losses become a concern and will need to be addressed by improved tank insulation. Also, hydrogen liquefaction is an energy-intensive process, requiring nearly a third of the energy the hydrogen will deliver as a fuel to liquefy the hydrogen. Advances in liquefaction efficiencies will reduce this net-energy penalty.

  Energy density can also be improved by going to higher gas pressure. This will require material and design improvements in order to ensure tank integrity and advances in compression technology to improve efficiencies. Advanced composite materials can yield three-fold increases in storage pressure capability and improved conformable tanks may facilitate lower pressure storage, as well as reducing energy compression requirements.

  Solid materials, like metal hydrides and carbon nanotubes, have the ability to ab/adsorb high volumes of hydrogen and to release that hydrogen on demand by small changes in temperature and/or pressure. These materials, along with chemical storage, may provide safe high-density storage options for both stationary and mobile applications.

- Utilization

  Today, hydrogen is primarily used as a chemical to produce industrial commodities, such as reformulated gasoline, ammonia for fertilizer and food products. Hydrogen has also long been used in the space program as a propellant for the space shuttle and for the on-board fuel cells that provide the shuttle's electric power.

  Combustion engines (CE) can be used for both mobile and stationary applications. Conventional CE can be modified to run efficiently on hydrogen or hydrogen/natural gas mixtures. Microturbines can provide high-efficiency reliable power. Hydrogen will continue to be a key component in space propulsion.

Fuel cells can be used to power a wide variety of applications, both mobile and stationary, small- and large-scale. Fuel cell type will be selected based on input stream and application. Size, weight and cost reduction are needed to make fuel cell systems economically competitive. If the fuel cell were reversible, meaning it could produce and use its own hydrogen, then it could prove ideal for many remote and military applications.

- Infrastructure
  Liquid tankers, compressed gas tube trailers and pipeline make up today's hydrogen delivery infrastructure. Improved tank materials and design, compression technology, and pipeline materials and metering could reduce the cost for hydrogen delivery. Solid and chemical storage media may require additional infrastructure, including material recycling/regeneration. On-site production using centralized or home refuelers can reduce or eliminate transportation costs and requirements. Standardizing the fueling interface, robotics and education will facilitate widespread hydrogen utilization, as well as reduce the risk to the consumer.

  Safety is primary to realization of the hydrogen economy. Uniform codes and standards must be developed and universally adapted. Leak detection will need to be incorporated into all applications. Materials resistant to embrittlement will be used and material compatibility emphasized. Testing and certification standards will need to be established for emerging technologies and markets. The existing hydrogen safety experience needs to be captured and translated to training personnel and emergency teams for tomorrow's hydrogen energy applications.

The Hydrogen Agreement is pursuing many of the above-discussed technologies in order to overcome some of the infrastructure barriers and/or reduce the cost of hydrogen systems, included the design, optimization and evaluation of integrated hydrogen energy systems, which will be discussed here in detail. Other activities include photobiological and photoelectrolytic hydrogen production, hydrogen from carbon-containing materials (both fossil and biomass) and liquid and solid-state materials for hydrogen storage.

IEA Integrated Systems Activities

Through the IEA's Integrated Systems activities, twenty-seven component models have been developed to model hydrogen production, storage, distribution and utilization [1]. Guidelines for a standardized modeling platform have been defined to ensure that the component models can be linked to simulate fully integrated systems [2]. Using the component models and guidelines, a number of integrated hydrogen energy systems have been designed and evaluated, including the two conceptual systems that will be discussed here in detail.

Life cycle assessments were performed on these two systems through a joint effort between the U.S., Norway, and the Netherlands. Each system was examined in a cradle-to-grave manner and therefore includes all process steps necessary for operation such as construction of the wind turbine, natural gas production and distribution, and transportation of the hydrogen.

Case Study for a Remote Application

In Norway, more than 99% of the electricity demand is supplied by hydropower. During the last 10 years, however, public resistance, based on environmental issues, has virtually brought the development of the remainder of these resources to a standstill. Because of the increase in power demand and good wind resources along a sparsely populated coastline (a potential of around 10 TWh/year is recognized), the focus on wind energy plants has grown over the last years. As such, a wind-hydrogen system for a remote location is being studied to determine the feasibility of producing hydrogen for transportation applications (Figure 1). Two comparative systems were examined: (1) hydrogen is produced from wind/electrolysis and excess electricity is sent to the grid providing some power on the island, and (2) hydrogen is produced via a central steam methane reforming (SMR) plant then a portion of the hydrogen is shipped to the remote island.

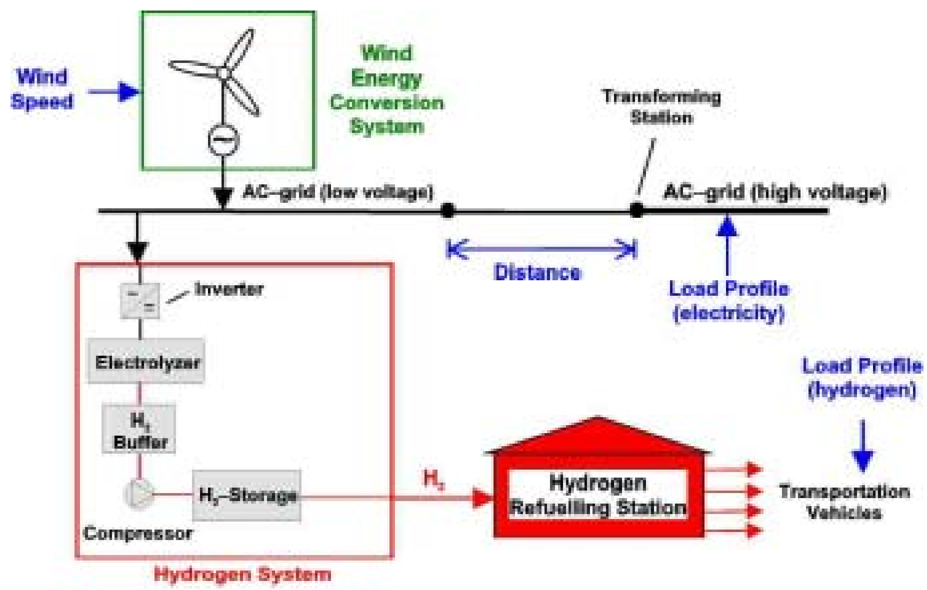

Figure 1 – Schematic of the Remote Communities System.

For this application, hydrogen production and storage are required in order to fuel three PEMFC buses. The resulting hydrogen requirement based on the fuel consumption and driving range is 32 kg/day of hydrogen. The modeling work was done by the Institute for Energy Technology (IFE Norway) and examined several wind/electrolysis operating cases [3]. For all of the cases examined, the size of the wind turbine was kept constant at 2 MW. In one case, the electrolyzer is operated at constant power to minimize the size of the electrolyzer. This means that at times power must be supplied from the grid when the wind resources are poor and some hydrogen storage is required. Two stand-alone scenarios were also examined where the electrolyzer only operates when there are adequate wind resources. In one stand-alone case, referred to as the direct-connect scenario, the electrolyzer operates any time that the wind resources are adequate and the hydrogen storage is sized accordingly. The size of the electrolyzer and storage unit were determined by optimization calculations to achieve a design where the hydrogen storage is never entirely depleted but there is adequate storage for periods of peak hydrogen production. For this case, the electrolyzer is operated at 80-100% of its maximum power 75% of the time and is idling 10% of the time. This resulted in an electrolyzer that is 48% greater and hydrogen storage that is 29 times larger than the constant power case. In the second stand-alone case, referred to as the top-charging scenario, the hydrogen storage is minimized and the operation of the electrolyzer is guided by the amount of hydrogen in the storage vessel. The electrolyzer is set to operate when the hydrogen storage reaches the lower dead-band limit and begins idling when the upper dead-band limit is reached. For this case, the electrolyzer operates near full power 30% of the time and is idling 60% of the time. The electrolyzer is not always operating when the wind resources are adequate, thus the electrolyzer must be larger than that for the direct-connect stand-alone scenario. For the top-charging stand-alone scenario, the electrolyzer is 248% greater and the hydrogen storage is 4 times larger than the constant power case. This means that the electrolyzer is 135% greater and the hydrogen storage is 85% less than the direct-connect stand-alone scenario. Considering both the economics (higher costs for the larger electrolyzers and storage units for the two stand alone cases) and the best operating practice, the most logical wind/electrolysis scenario for this situation is the constant power operation case, therefore, a life cycle assessment was done for this case only.

Because the wind turbine produces more electricity than is required for hydrogen production, the excess electricity is sent to the grid. At those times when the wind resources are poor, electricity is required from another source. Although the majority of Norway's electricity comes from hydro, new capacity is being generated from natural gas. Therefore, the electricity required during times of poor wind resources is assumed to come from a natural gas combined-cycle (NGCC) system via a sub sea cable. If the island were farther out in the ocean then the electricity would probably have come from diesel generators. Table 1 shows the electricity production and consumption of the wind/electrolysis system. The graphic in Figure 2 shows the processes that make up this system.

Table 1: Wind/electrolysis System Electricity Balance

	Electricity produced or required (GJ/yr)
Total electricity produced by the wind turbine	20,866
Electricity required for hydrogen production and compression	2,281
Electricity required during times when wind resourced are poor	308
Excess electricity from wind turbine	18,892

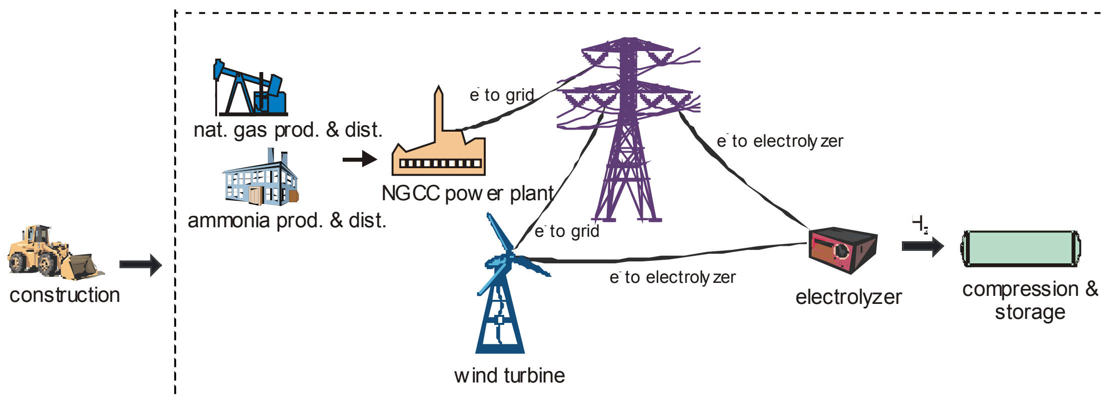

Figure 2 – Remote Wind/Electrolysis System

For comparison, a life cycle assessment was performed on a fossil-based system, steam methane reforming. Hydrogen is assumed to be produced at a large central SMR plant then a portion of the hydrogen is compressed and shipped to the island in tube trailers over a distance of 100 km. Figure 3 shows the processes involved in hydrogen delivery from the SMR system.

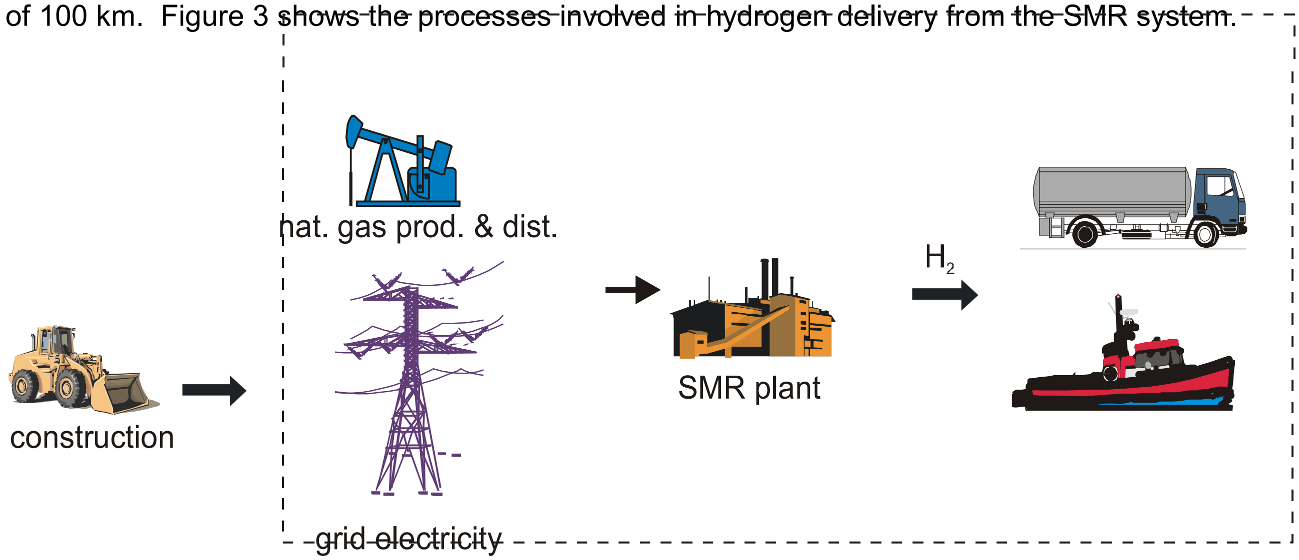

Figure 3 – Remote SMR System

LCA Results for Remote Application

Results of the remote system show that, in general, the (non-feed) resource requirement per kg of hydrogen is somewhat higher for the wind/electrolysis system than for the SMR system. This is due to the steel and concrete used in constructing the wind turbine. However, the air emissions and fossil energy consumption are lower for the wind/electrolysis system. Figure 4 compares the resource consumption of each system and Figure 5 compares the major air emissions. Note that because of its magnitude, CO_2 is shown on a different scale. Table 2, which follows the graphs, gives the resource consumption, air emissions, global warming potential (GWP), solid waste generated, and energy consumption for both the wind/electrolysis system and the SMR system.

As expected, the natural gas consumption per kg of hydrogen for the SMR system is considerably higher than that for the wind/electrolysis system. The air emissions show that the wind/electrolysis system has a considerable reduction in CO_2 and CH_4. Particulate emissions are higher for the wind/electrolysis system due to the concrete requirement. They come primarily from quarrying the sand and limestone needed for concrete production. The GWP is greatly affected by the use of natural gas, mostly because of the CO_2 emissions released during combustion and partly because of the CH_4 that is emitted to the atmosphere during natural gas production and distribution. The energy balance shows that the wind/electrolysis system produces 22 MJ of H_2 are for every MJ of fossil energy consumed while the SMR system produces only 0.7 MJ of H_2 for every MJ of fossil energy consumed. The upstream energy consumption for the SMR system is high because when the natural gas feedstock energy is excluded, the external energy ratio is still low. Also, note that the energy ratio for the SMR system is lower than the wind/electrolysis system even after subtracting out the energy content of the natural gas, 5 versus 22.

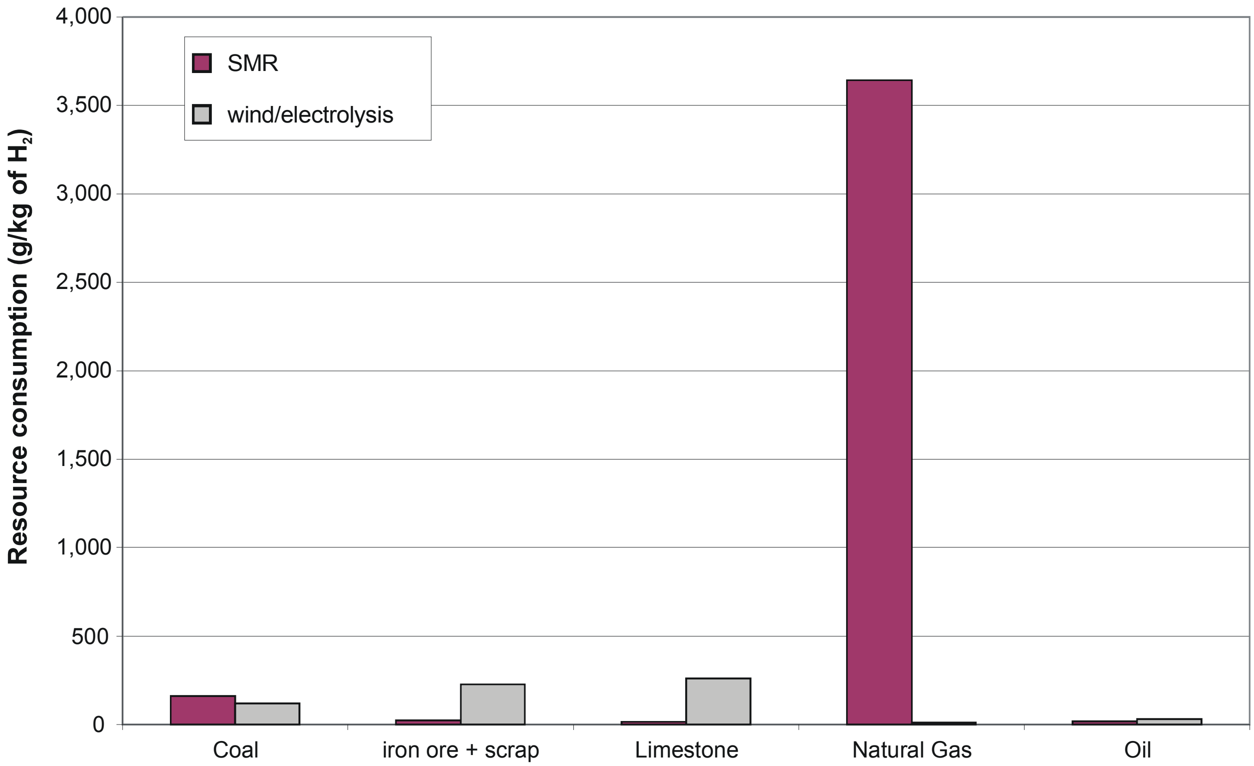

Figure 4 – Remote Application: Comparison of Resource Requirements

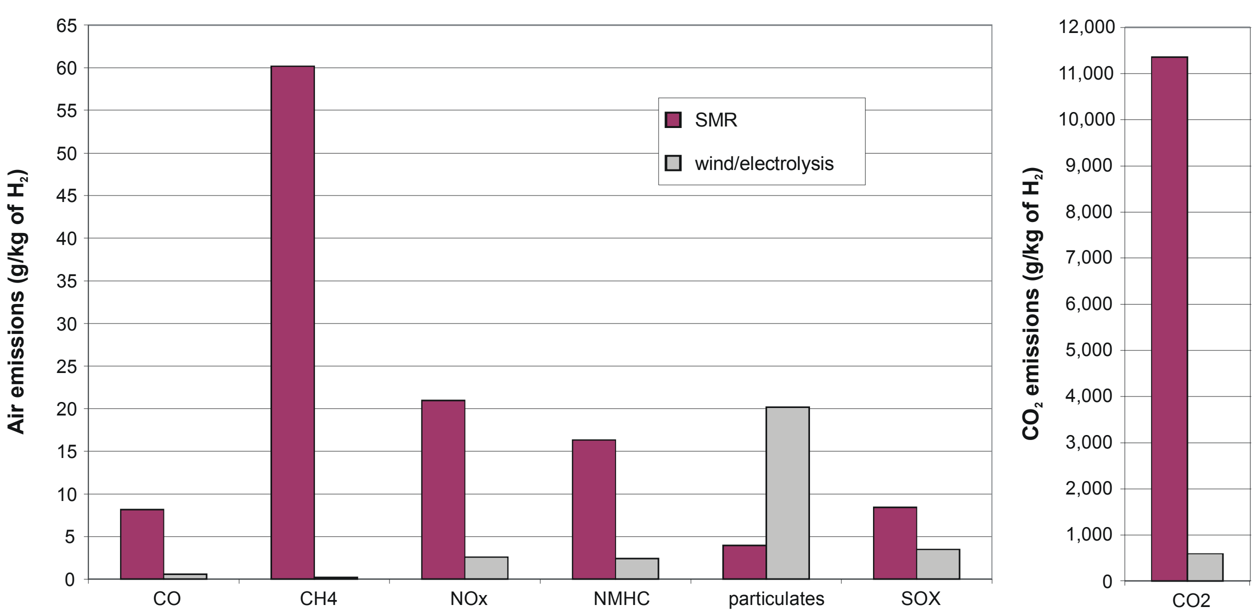

Figure 5 – Remote Application: Comparison of Major Air Emissions

Table 2: Comparison of LCA Results for Remote Application

	SMR	**Wind/Electrolysis**
Resource consumption	(g/kg of H_2)	(g/kg of H_2)
coal	159	119
iron (ore + scrap)	21	227
limestone	16	261
natural gas	3,642	10
oil	16	31
	(liters/kg of H_2)	(liters/kg of H_2)
Water consumption	33	21
Air Emissions	(g/kg of H_2)	(g/kg of H_2)
CO_2	11,357	590
CO	8	0.6
CH_4	60	0.2
NOx	21	3
N_2O	0.1	0.02
NMHC	16	2
particulates	4	20
SOx	8	3
	(g of CO_2-equivalent/kg of H_2)	(g of CO_2-equivalent/kg of H_2)
GWP (a)	12,665	602
% contribution from CO_2	89.7%	98.0%
% contribution from CH_4	10.0%	0.7%
% contribution from N_2O	0.4%	1.3%

	SMR	**Wind/Electrolysis**
Solid Waste	(g/kg of H_2)	(g/kg of H_2)
waste generated	224	140
Energy balance	(MJ/kg of H_2)	(MJ/kg of H_2)
total energy consumed	195	5
net energy ratio (E_{H2}/E_{ff}) (b), (c)	0.7	22
external energy ratio $(E_{H2})/(E_{ff} - E_{ngfeed})$ (c), (d)	5	N/A

(a) The GWP is considered to be a combination of CO_2, CH_4, and N_2O emissions. The capacity of CH_4 and N_2O to contribute to the warming of the atmosphere is 21 and 310 times higher than CO_2, respectively, for a 100 year time frame according to the Intergovernmental Panel on Climate Change (IPCC). Thus, the GWP of a system can be normalized to CO_2-equivalence to describe its overall contribution to global climate change.
(b) This term illustrates how much hydrogen energy is produced for each unit of fossil fuel energy consumed.
(c) E_{H2} = the energy in the hydrogen produced; E_{ff} = the total fossil energy consumed by the system
(d) E_{ngfeed} = the natural gas feedstock to the SMR plant; This term excludes the natural gas to the hydrogen plant indicating the fossil energy consumption from upstream processes.

Case Study for a Residential Application

The development of “greenfield” communities is an important opportunity for hydrogen energy systems. In the Netherlands, new residential districts are being developed, with housing additions of 60,000 (1-2% of the total housing market of 6 million). There is an ambitious national plan to require the power generation mix to include 3% renewables (green energy) by 2010 and 10% renewables by 2020. The Dutch national energy policy includes price supports via an eco-tax of up to 30% on non-green energy. Given the requirement to integrate renewables in the national power mix, continued deregulation of utilities, and the desires by many communities to include “green” homes, hydrogen systems offer interesting opportunities for residential developments.

An integrated systems approach was used to perform a preliminary design and assessment of energy systems for a residential district containing 1,300 houses and requiring heating and electricity of 6,880 MWh/yr and 4,380 MWh/yr, respectively. The Energy Research Centre of the Netherlands (ECN) performed the modeling work. Four configurations were modeled and are shown in Figure 6. The conventional system uses a natural gas distribution system where heat is provided to each home by burning natural gas in a boiler and the electricity comes from a central natural gas combined-cycle plant. The Sankey diagram showing the district energy flow for this conventional system is shown in Figure 7. A life cycle assessment of this system was performed.

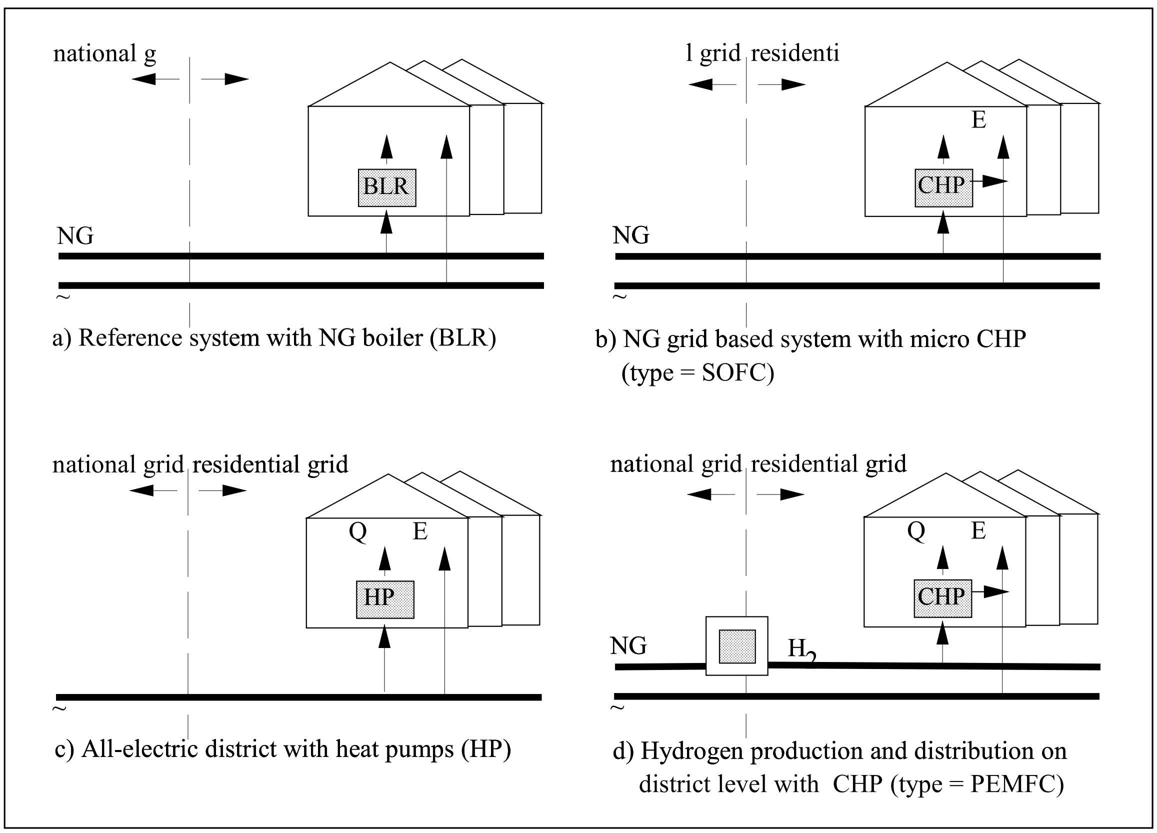

Figure 6 - Schematics of the four main configurations examined

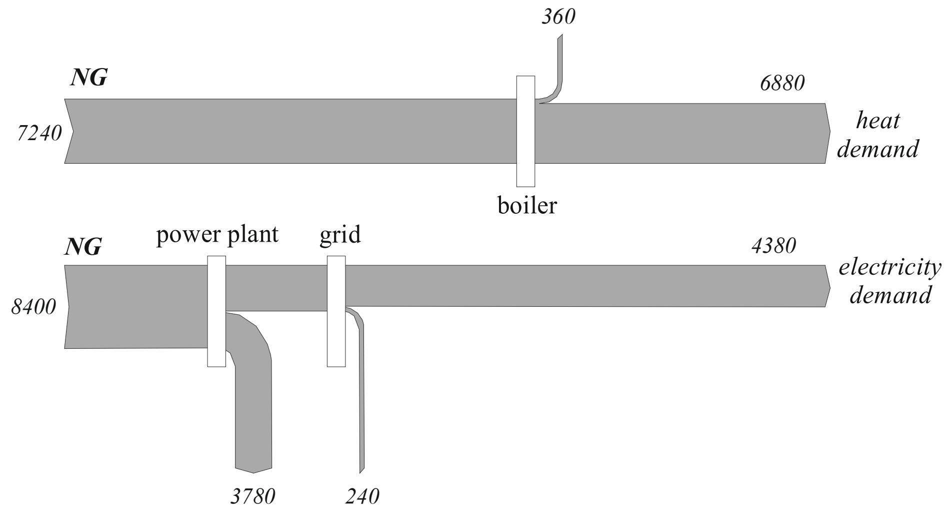

Figure 7 - Sankey Diagram for Conventional Natural Gas System (Energy Flow in MWh/yr)

The hydrogen distribution systems that ECN examined integrated a combination of PEM fuel cells, solid oxide fuel cells, heat pumps, natural gas burners, hydrogen burners, heat storage, and hydrogen storage. The hydrogen system chosen for the life cycle assessment work uses a 0.38 kW PEM fuel cell integrated with a heat pump and hydrogen storage, along with make-up electricity from the grid. The Sankey diagram showing the district energy flow for this hydrogen network system is shown in Figure 8.

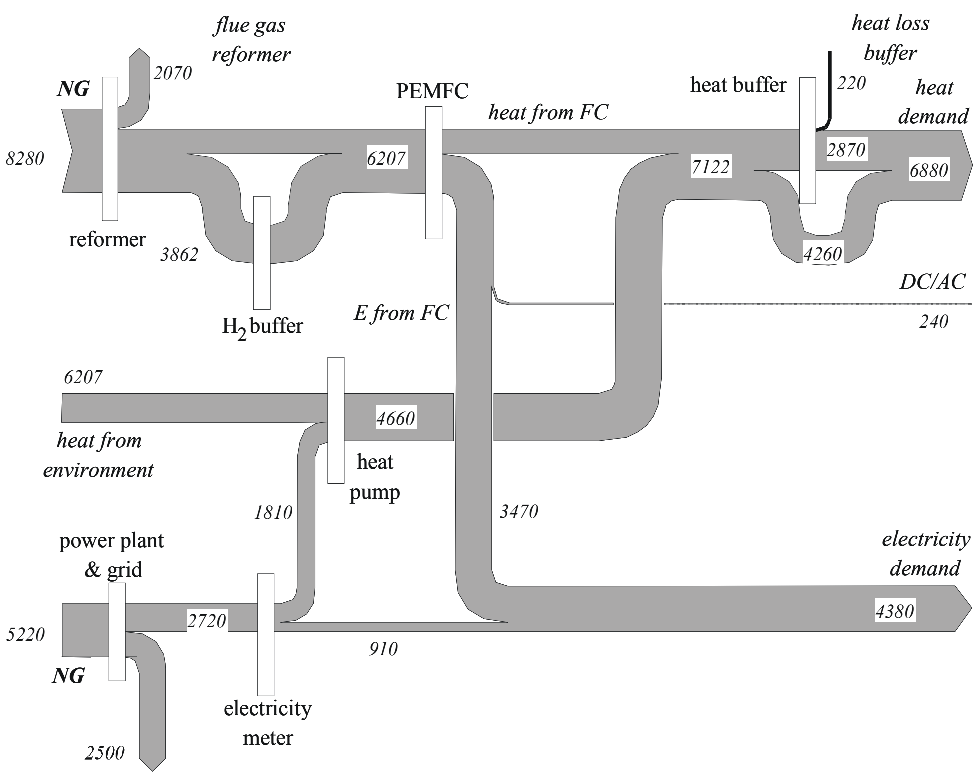

Figure 8 - Sankey Diagram for Hydrogen System (Energy Flow in MWh/yr)

LCA Results for Residential Application

Figure 9 is a comparison of the resource consumption and Figure 10 is a comparison of the major air emissions for the conventional and hydrogen systems examined. Again, because of its magnitude, CO_2 is shown on a different scale. Except for natural gas, the hydrogen system consumes slightly more resources than the conventional system per kWh of heat and electricity supplied to the district. Because of the design and efficiency of the district heating and electricity production, the amount of natural gas required by the hydrogen system is less than that for the conventional system. The hydrogen system also produces less air emissions per kWh of heat and electricity supplied to the district.

The resource consumption, air emissions, GWP, solid waste generated, and energy balance for the each system are given in Table 3. The GWP of the hydrogen system is 16% less than that for the conventional system. The CH_4 emissions, primarily from natural gas production and distribution, contribute about 12% to the each system's GWP. The energy consumption of the conventional system is higher than the hydrogen system, 6.3 MJ/kWh of heat plus electricity compared to 4.9 MJ/kWh of heat plus electricity. The difference between the net energy ratio and external energy ratio indicates that the conventional system consumes considerably more upstream energy than the hydrogen system for every kWh of heat and electricity supplied to the district. There is also slightly less solid waste produced from the hydrogen system.

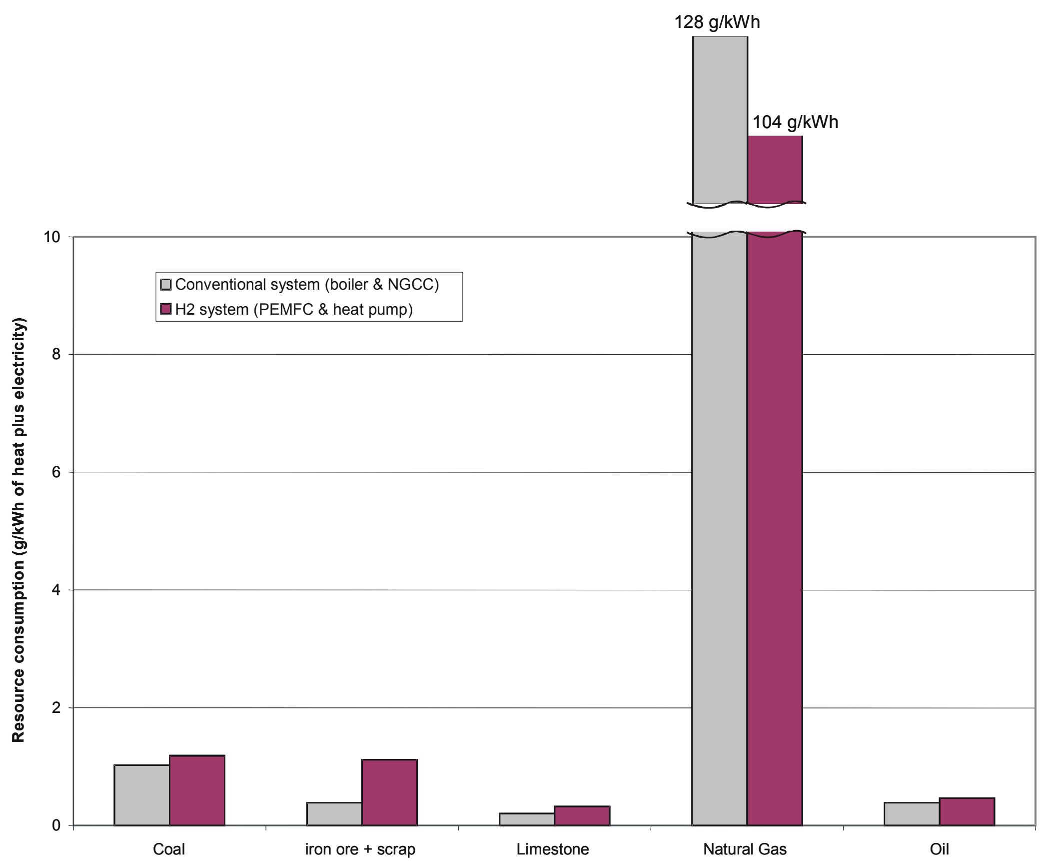

Figure 9 - Residential Application: Comparison of Resource Requirements

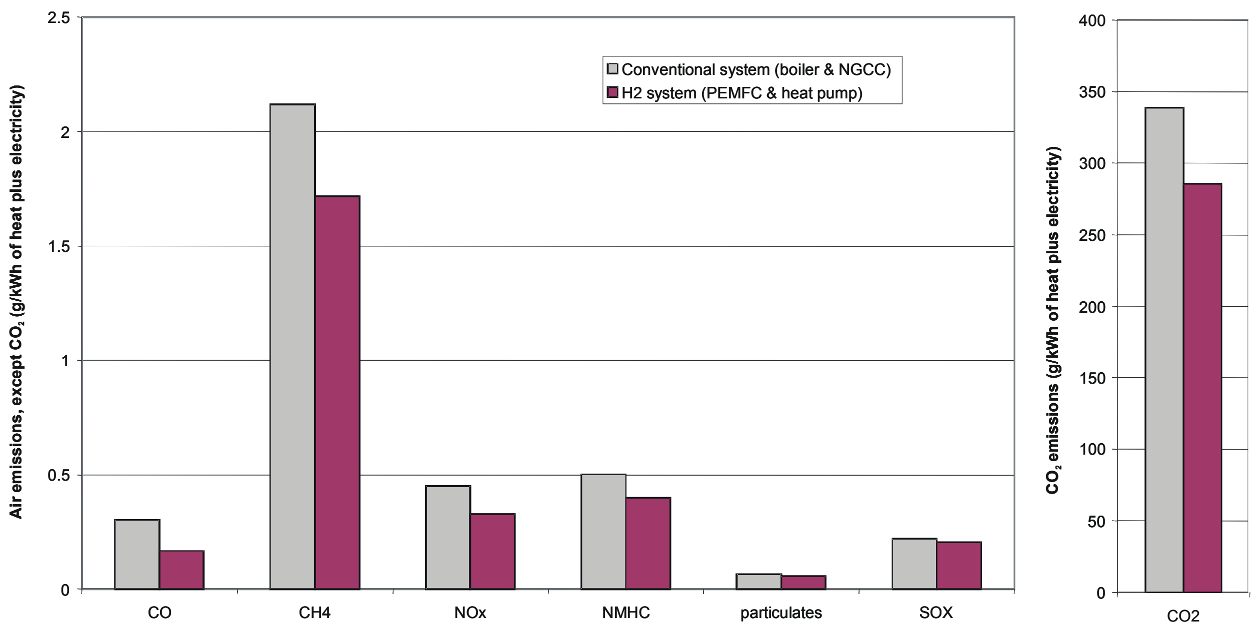

Figure 10 - Residential Application: Comparison of Major Air Emissions

LCA Summary and Recommendations

For the remote application, in general, the renewable hydrogen system consumes more resources than the SMR system with the exception of the large amount of natural gas consumed by the SMR system. Apart from that, there is a considerable reduction in the air emissions, solid waste generated, and energy consumption by using wind/electrolysis. For the residential application, the resource consumption is higher for the hydrogen system compared to the conventional system. However, the air emissions, energy consumption, and solid waste generated are somewhat less for the hydrogen system. The hydrogen system in the residential application is fossil-based, but if this system were to use hydrogen produced from a renewable source, then the air emissions, especially CO_2 and CH_4, and the energy consumption will be even lower. The economics of these systems are being examined by Norway and the Netherlands. Putting this information together with the LCA results will give the cost of avoided emissions, waste, and energy consumption for the novel versus conventional system. It is recommended that this be done in the future. This is especially important for the residential application to determine if the small savings in emissions, waste, and energy consumption merit the anticipated higher cost of the hydrogen system. Additionally, in terms of the residential application, if the central SMR plant were located close to the district and some of the steam from this hydrogen production facility were available, it would be interesting to examine a scenario where steam is used instead of additional heat from a heat pump.

Table 3: Comparison of LCA Results for Residential Application

	Conventional System (Boiler & NGCC)	Hydrogen System
Resource consumption	(g/kWh of heat plus electricity)	(g/kWh of heat plus electricity)
coal	1.0	1.2
iron (ore + scrap)	0.4	1.1
limestone	0.2	0.3
Natural gas	127.5	103.8
oil	0.4	0.5
	(liters/kWh of heat plus electricity)	(liters/kWh of heat plus electricity)
Water consumption	0.02	0.4
Air Emissions	(g/kWh of heat plus electricity)	(g/kWh of heat plus electricity)
CO_2	338.5	285.4
CO	0.3	0.2
CH_4	2.1	1.7
NOx	0.4	0.3
N_2O	0.0012	0.0006
NMHC	0.5	0.4
particulates	0.065	0.057
SOx	0.22	0.20
	(g of CO_2-equivalent/kWh of heat plus electricity)	(g of CO_2-equivalent/kWh of heat plus electricity)
GWP (a)	383	322
% contribution from CO_2	88.3%	88.7%
% contribution from CH_4	11.6%	11.2%
% contribution from N_2O	0.1%	0.1%
Solid Waste	(g/kWh of heat plus electricity)	(g/kWh of heat plus electricity)
waste generated	4.7	4.0
Energy balance	(MJ/kWh of heat plus electricity)	(MJ/kWh of heat plus electricity)
total energy consumed	6.3	4.9
life cycle efficiency $(E_{dist}-E_u - E_{ng})/(E_{ng})$ (b), (c)	-53.8%	-29.6%
external energy efficiency $(E_{dist} - E_u)/(E_{ng})$ (c), (d)	46.2%	70.4%
net energy ratio $(E_{dist})/(E_{ff})$ (c), (e)	0.6	0.7
external energy ratio $(E_{dist})/(E_{ff} - E_{ng})$ (c), (d)	2.8	6.9

(a) The GWP system is considered to be a combination of CO_2, CH_4, and N_2O emissions. The capacity of CH_4 and N_2O to contribute to the warming of the atmosphere is 21 and 310 times higher than CO_2, respectively, for a 100 year time frame according to the Intergovernmental Panel on Climate Change (IPCC). Thus, the GWP of a system can be normalized to CO_2-equivalence to describe its overall contribution to global climate change.

(b) This efficiency includes the fossil energy consumption of all process steps in the system.

(c) E_{dist} = electric and heat energy delivered to the district; E_u = energy consumed by the upstream processes; E_{ng} = energy contained in the natural gas to produce heat and power; E_{ff} = total fossil energy consumed within the system (i.e, $E_{ff} = E_u + E_{ng}$)

(d) Excludes the natural gas to the hydrogen plant indicating the energy consumption from upstream processes.

(e) This term illustrates how much electric and heat energy is delivered to the district for each unit of fossil fuel energy consumed.

Case Studies of Integrated Hydrogen Energy Systems

In addition to the design and evaluation of conceptual systems, a number of international hydrogen-based energy system demonstrations have also been critically evaluated and compared, with system performance measurement as the central focus [5]. Of consideration were the project goals, the main components, experimental results and lessons learned. The following criteria were used for project selection:

- The projects were required to be integrated systems, with two or more of subsystems (production, storage, transport/distribution and end use) included in a relevant connection.
- The selection was primarily restricted to projects located in one of the countries participating in the IEA Hydrogen Implementing Agreement (to ensure access to data and other relevant information).
- Active cooperation of the project leaders was required.

A comparative overview of the selected integrated systems indicated that the sun is a primary source of energy for many of the hydrogen demonstration projects.

Accordingly, the operation of electrolyzers with intermittent sources of power (solar and wind) and the possibilities for matching photovoltaic current with the characteristics of the electrolyser was one of the recurrent design issues in all such projects. Most of the electrolysers were of the alkaline type and operated at low pressure. Two projects used solid polymer electrolysers, and three projects operated the electrolyzer at higher pressures. While the storage technologies were restricted to the use of compressed gas and metal hydrides, a great variety of utilisation technologies and applications were included. In most of the projects, hydrogen is used in a fuel cell, with a wide variety of fuel cell types included. Transportation applications included two projects in which vehicles were fitted with polymer exchange fuel cells, and one in which trucks were fuelled with compressed hydrogen generated from a PV-electrolysis system, fed to a modified internal combustion engines.

To date, ten projects have been analysed and evaluated in detail (Table 4). Another ten projects are currently being evaluated (Table 5).

Hydrogen energy system demonstrations continue to be undertaken throughout the world. The experiences gained from these projects need to be compiled and made available to future demonstrators. Public response must be captured and considered when planning any hydrogen demonstration. System efficiency and cost optimization will also remain paramount issues for developing competitive hydrogen-based systems. Thus, utilizing all available information and international expertise and continually refining and expanding modeling tools will be imperative.

Summary

Concerns about global climate change and energy security create the forum for mainstream market penetration of hydrogen. Ultimately, hydrogen and electricity, our two major energy carriers, will come from sustainable energy sources, although, fossil fuel will likely remain a significant and transitional resource for many decades. The IEA Hydrogen Program has a vision for a hydrogen future that is one of clean sustainable energy supply of global proportions that plays a key role in all sectors of the economy. This vision will be implemented through advanced technologies including direct solar production systems and low-temperature metal hydrides and room-temperature carbon nanostructures for storage. Hydrogen in the new millennium is synonymous with energy supply and security, climate stewardship, and sustainability.

Table 4: Demonstration Project Reports Completed

Project Title	Project Description
Solar Hydrogen Demonstration Project at Solar-Wasserstoff Bayern (Germany)	PV, Solid Polymer Electrolysis, Alkaline Electrolysis, MH, compressed gas, Heat, PAFC, PEM (mobile)
Solar Hydrogen Plant on the M. Friedli Residential House (Switzerland)	PV, electrolysis (pressurized), compressed, PEM (stationary)
A.T. Stuart Renewable Energy Test Site (Canada)	PV-Electrolysis, Stove
PHOEBUS Jülich Demonstration Plant (Germany)	PV, SP electrolysis, compressed, alkaline FC (stationary)
Schatz Solar Hydrogen Project (USA)	PV, electrolysis, compressed, PEM (stationary)
INTA Solar Hydrogen Facility (Spain)	PV, electrolysis, MH, compressed, PAFC (stationary)
Clean Air Now (USA)	PV, electrolysis, compressed, ICE (mobile)
SAPHYS: Stand-Alone Small Size Photovoltaic Hydrogen Energy System (Italy)	PV, electrolysis (pressurized), compressed, MH, PEM (stationary)
Hydrogen Generation from Stand-Alone Wind-Powered Electrolysis Systems (Italy)	Wind, electrolysis
Palm Desert Renewable Hydrogen Transportation Project (USA)	PV, electrolysis, MH, compressed, PEM (mobile)

Table 5: Demonstration Project Reports Under Development

Project	Description
SunLine Transit – Hydrogen Commercialization for the 21st Century	Hythane® Buses, Hydrogen Fuel Cell Bus, Hydrogen ICE vehicles, PV-electrolysis, grid-electrolysis, natural gas reforming
Zero-Emission Buses in Real-World Use (Vancouver and Chicago projects)	Filling station and 3 fuel cell buses
Bavarian Fuel Cell Bus	Fuel Cell Bus in city operation
WEIT – Hydrogen-powered delivery vans	Filling station and 6 ICE vehicles
Munich Airport Demonstration	Electrolysis, filling station, hydrogen vehicles
Ford Filling Station (Dearborn, MI)	Filling station
Nevada Refueling Station	Power cogeneration system
Hamburg Hydrogen Fuel Cell System	Stationary 200 kW PAFC plant
Grimstad Renewable Hydrogen System	Energy Park with PV, electrolysis, storage, alkaline fuel cell
Hydrogen from Windpower (Stralsund)	PV, Wind, electrolysis, storage

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