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Abstract: **Residential and small stationary hydrogen energy systems: risks and opportunities**

The almost universally recognised need to curb greenhouse gas emissions and at the same time secure a cheap and environmentally friendly supply of energy is a major economic and social driver for many countries. Many see fuel cells using hydrogen or other fuels such as natural gas, as the key technologies for the residential and small stationary market, and for the development of sustainable decentralised power generation.

A small number of installations are already in place utilizing Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cell (SOFC) technologies to provide back up power, renewable energy storage systems, and Combined Heat and Power (CHP) units.
This paper will review the full range of safety issues relating to such systems, including in particular, those connected with the fuel supply/storage and the positioning, installation, operation and maintenance of the fuel cell system. The availability of best practice and codes, and standards will also be examined.

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1. Introduction

It is clear Hydrogen and Fuel Cell Technologies will form an essential part of any future fuel strategy. In such a strategy, hydrogen will be used as an energy carrier (in addition to other fuels) to provide a clean and simple energy cycle to power a range of applications, while producing zero emissions of CO_2 at the point of use as illustrated in Figure 1.

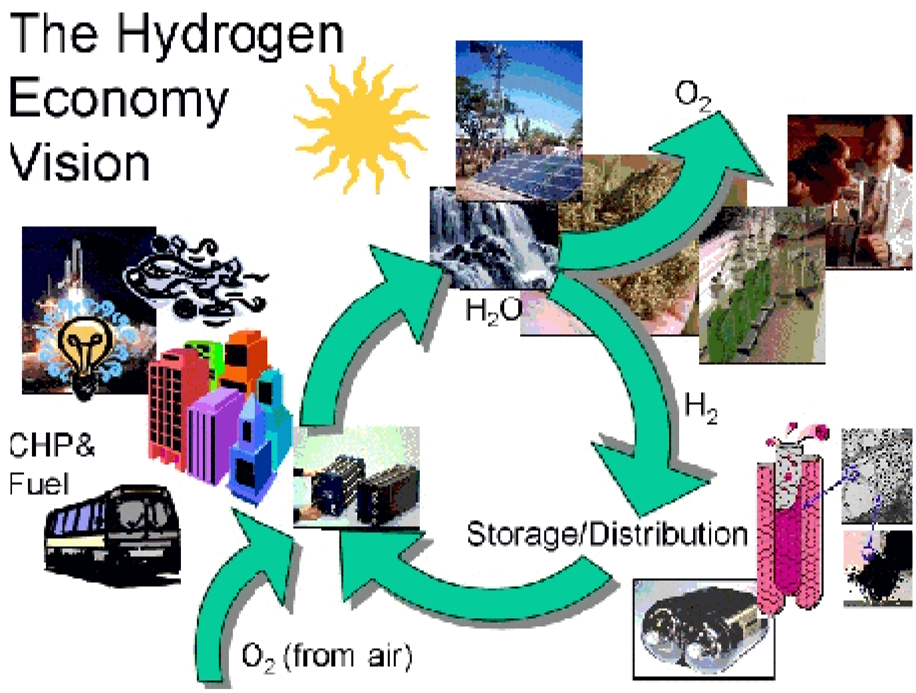

Figure 1. The Hydrogen economy - *U.S. Climate Change Technology Program – Technology Options for the Near and Long Term, November 2003 - Page 71.*

Hydrogen energy systems could play a major role in addressing energy demand increases, mounting pressure on conventional petroleum based fossil fuels, climate change challenges and national security issues. Clearly, worldwide demand for energy is growing, figures from the European “World Energy Technology and Climate Policy Outlook” (WETO) (1) predict an average annual growth rate, for primary energy worldwide, of 1.8% per annum for the period to 2030. This is being met largely by finite reserves of fossil fuels, which are becoming more expensive and have a direct effect on the environment through emissions of CO_2.

At the same time, fuel cells using hydrogen and other fuels will provide an efficient means of generating power and heat as part of distributed, stand alone power networks and power smoothing systems while producing limited or zero pollution.

At present, applications of hydrogen and fuel cell technologies are developing in a number of areas including vehicles, stationary applications and some portable applications. This paper is concerned with stationary applications of a smaller type, which may use hydrogen or other more traditional fuels in a fuel cell system. In particular, it is concerned with safety issues associated with the use of hydrogen and or fuel cells in such systems. This work is related to a new EU funded project known by the acronym “HyPer”, which has a full title of “Installation Permitting Guidance for Hydrogen and Fuel Cell Stationary Applications”. This project brings together a diverse range of partners to produce the guidance, gather and produce prenormative data and best practice for such systems, and is described in more detail in section 6.

2. Hydrogen as energy carrier of the future.

The significant advantage of Hydrogen as a fuel/energy carrier is that its reaction with oxygen (either through a conventional combustion system or a fuel cell) produces water vapour with few other contaminants (limited amounts of NOX depending on the application). Hydrogen gas, however, does not occur naturally on earth and so has to be separated from compounds such as methane or water. At the present time hydrogen is most commonly produced from steam reforming of natural gas, or on a smaller scale by the electrolysis of water.

At present nine millions tons, 90 billion cubic meters, of hydrogen is produced annually (almost all from steam reforming of natural gas (3) – black hydrogen) in the US, which is enough to power over 8 million homes. Most of this hydrogen is used by industry in petroleum refining, methanol synthesis, hydrogenation and ammonia manufacturing. While this production is almost all on an industrial scale, other production methods are being used and developed. Many of these new techniques are sustainable and use, for example solar energy (indirect i.e. combined with electrolysis and direct) or wind power to produce green hydrogen for direct consumption, or for storage and use in vehicles or other applications such as the PURE project on the Shetland Islands (4).

In addition to production, storage of molecular hydrogen is also an energy intensive technical challenge. At atmospheric pressure 4kg occupies 44m^3. At present the two prevalent techniques are compression (to 350 bar or even 700 bar in vehicle applications) and cryogenic storage, which gives a roughly equivalent fuel density to 700 bar hydrogen. In addition, the storage of hydrogen in metal hydrides and alloys etc, is an area of intense research and already commercially available in certain applications.

In terms of both its combustion properties and its methods of storage, in certain situations hydrogen potentially presents more demanding levels of hazard than those found with hydrocarbon fuels commonly in use today. However, these challenges are manageable and there is currently considerable activity in understanding and addressing them in order to facilitate current installations and enable future developments.

3. Hydrogen systems

As already discussed, hydrogen and fuel cell based technologies are finding applications in transport, stationary (small and industrial scale) and portable applications. The technologies in these areas are at different stages of development and some examples of this are discussed below.

3.1 Fuel cells

A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, heat, and water (see Figure 2). Depending on the type of fuel cell, the hydrogen may be supplied in a pure form (e.g. PEMFC) from local storage or generated on site by reforming or electrolysis. It may be also fed into the system directly (case of SOFC fuel cell) as a hydrocarbon fuel such as natural gas, gasoline, diesel, or methanol. Oxygen is supplied from the surrounding air around the fuel cell.

Fuel cells typically operate at high efficiencies (30 to 60% depending on type) and can be used as part of a CHP unit such that the excess heat produced can be used to increase the efficiency still further. The fuel cell itself has no moving parts, making it a quiet and reliable source of electricity, heat, and water.

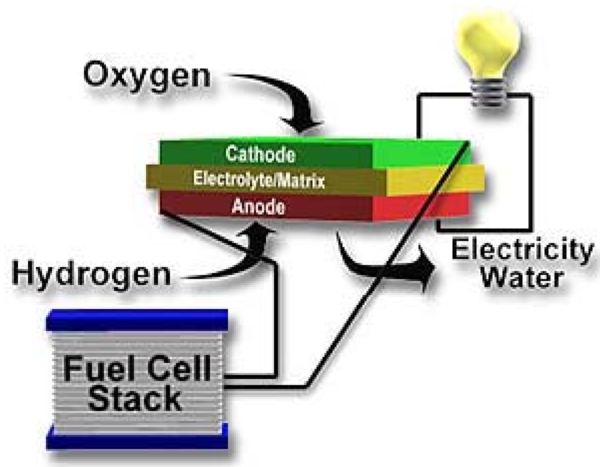

Figure 2 Fuel Cell Configuration US Department of energy, Permitting Stationary fuel Cell Installation, PNNL-14518, 1/12/2004

A typical fuel cell comprises individual fuel cells “stacked” to make a fuel cell stack that is the heart of the fuel cell equipment or power plant. In addition, there may be fuel-processing equipment (e.g. reformer or electrolyser) that may be remote from the fuel cell or form part of the installation. Fuel cells produce a steady Direct Current output (DC) and where Alternating Current (AC) power is needed, there will be a power conditioning/inverter to produce this. The electrical output of the fuel cell may then be used for a stand-alone electrical system or grid, or linked into a larger distributed power network.

The key element of a fuel is the electrolyte matrix where the chemical reaction between hydrogen and oxygen takes place. There are a number of different types of fuel cell which use different electrolytes, these can be loosely grouped into; those with acidic electrolytes, those where the electrolyte is alkaline and those that operate at very high temperatures. Successful examples of acidic electrolyte fuel cells are the proton exchange membranes or polymer electrolyte membrane (PEM) and the Phosphoric Acid Fuel Cell (PAFC). Both devices can generate high levels of power, and PEMFCs have found wide application in vehicle applications. PAFC fuel cells have found greater use in stationary applications providing powers of the order of 100 kW for distributed power and back up power systems.

Alkaline electrolyte fuel cells (AFCs) need very high purity hydrogen feed and use an aqueous solution of potassium hydroxide as the electrolyte and operate at quite high temperature (100 to 250 ^{o}C).

High temperature fuel cells, including Solid Oxide Fuel Cells (SOFCs), are currently being developed as stationary sources to run, in particular, on natural gas. These units operate at around 650^{o}C and use molten metal carbonate suspended in a porous ceramic matrix as the electrolyte. These cells do not require a separate reformer and suitable hydrocarbon fuels can be fed directly into the cell where reforming to hydrogen takes place (internal reforming). SOFCs use a hard, non-porous ceramic material as the electrolyte and are currently most suitable for stationary applications. These fuel cells are a promising technology for use as a source of heat and electricity in buildings.

The percentage of fuel cell units manufactured and sold by technology type has remained fairly steady in recent years. Overall, however, the market continues to be dominated by PEMFC, the most flexible and market-adaptable fuel cell technology. However, other types of fuel cells are slowly gaining acceptance, creating a more dynamic and robust industry. At the larger end of the fuel cell scale, Molten Carbonate Fuel Cells (MCFC) dominate, with Fuel Cell Energy leading in this area. Solid oxide cells are still struggling to make the jump from the research laboratory to the market and to find practical applications.

Phosphoric Acid Fuel Cell (PAFC) unit numbers remained practically unchanged in 2005, and thus the cumulative market share went down, but this trend is expected to change within two years when UTC Power releases a new enhanced PAFC with a lifespan of 80,000 operating hours, the highest in the market.

For stationary applications the main technology is currently proton exchange membrane, and a majority of units sold through 2005 were PEMFC. SOFC has a small but significant market share in this sector, and there has been talk of early commercialization by several SOFC companies.

3.2 Hydrogen storage

A key safety issue in relation to many hydrogen or fuel cell systems is the storage of hydrogen or fuel on site. The two most common modes of storage for hydrogen are as a compressed gas (potentially at pressures up to 700 bar), absorption on metal hydrides etc and cryogenic storage at a temperature of –253^{o}C, although this is not expected to be widely used in small stationary systems.

While compressed and liquid storage are widely used in industry, both need further investigation to develop suitable safety codes for small installations that might be used in domestic or small commercial premises. Issues concerning high-pressure systems include the behaviour of jets (ignited and un-ignited), spontaneous ignition of releases and the potential for the production of high overpressures during deflagration/detonation. Leaks from liquid storage also need to be better understood in terms of their dispersion behaviour (the cold gas initially sinks, before warming and becoming buoyant).

Cryogenic storage of hydrogen presents unusual hazards, for example, careful design is necessary to prevent the condensation of oxygen-rich liquid air on un-insulated surfaces exposed to cryogenic temperatures. Consequently, it is important not to have potentially flammable materials beneath pipe-work where a risk from the condensation of oxygen-enriched air exists. Even materials such as tarmac (bitumen) should be considered combustible if exposed to liquid oxygen condensate.

There are two main types of hydride storage systems:

- Traditional hydrides, which involve the reversible absorption of hydrogen into the molecular lattice of transition metals or alloys. These materials, which are frequently flammable and in some cases pyrophoric, are solids and are encased in a pressure vessel,
- Complex hydrides using sodium aluminium hydride and similar flammable materials, these substances usually react vigorously with water to produce hydrogen.

4. Applications

Most of the effort to-date has focused on mobile (road) vehicles both in the Europe and the USA (Cute, California Hydrogen Partnership etc.). While portable and stationary applications have received less attention, applications have been developed and implemented, and are likely to increase considerably in the near future. For example, the Strategic Research Agenda (SRA), developed by the European Hydrogen and Fuel Cell Technology Platform, envisages that fuel cells using hydrogen or other fuels such as natural gas will be the key technologies for stationary and decentralised power generation within a comparable timeframe. It also emphasises the importance of safety issues and the importance of a suitable regulatory framework to success in this area.

Figure 3. Use of PlugPower GenCore © Fuel System to provide remote power for a telecommunication mast in Scotland (© BBC)

In terms of practical applications, these include back-up, remote power and residential power. PlugPower have installed a number of remote power applications such as that shown in Figure 3 (4). The fuel cell is a GenCore©PEMFC based type. This unit is designed for back-up applications and will replace the standard valve-regulated lead batteries that are in use today. The system runs on 99.5% pure H_2 and is usually set up with up to six bottles of hydrogen.

Portable power units are replacing battery Uninterruptible Power Supply (UPS) applications to provide longer operating times and reliability. Off grid units for isolated and remote sites (e.g. powering remote communication stations etc) provide similar advantages. Micro CHP units and decentralized production employing high power cogeneration (natural gas, biomass, biogas) are also now finding wider application. Manufacturers such as Vaillant, Arcotronics, Baxi and Sulzer Hexis have already trialed installations of PEFC and SOFC systems in CHP home applications. These provide a complementary base-load power for renewable energy sources. Use of hydrogen produced by some industries is also a viable option that has already been demonstrated by projects such as the Tees valley hydrogen project (8&9).

It is expected that the future development and commercialisation of hydrogen and fuel cell systems for stationary power applications will lead to a wide range of uses, many of which will be situated in urban environments, servicing industry, SME's and domestic premises.

Figure 4 below illustrates the different potential elements of a small hydrogen fuel cell stationary system and details the key technological, safety and permitting drivers (ventilation, sensing, connection to services, protection devices, positioning).

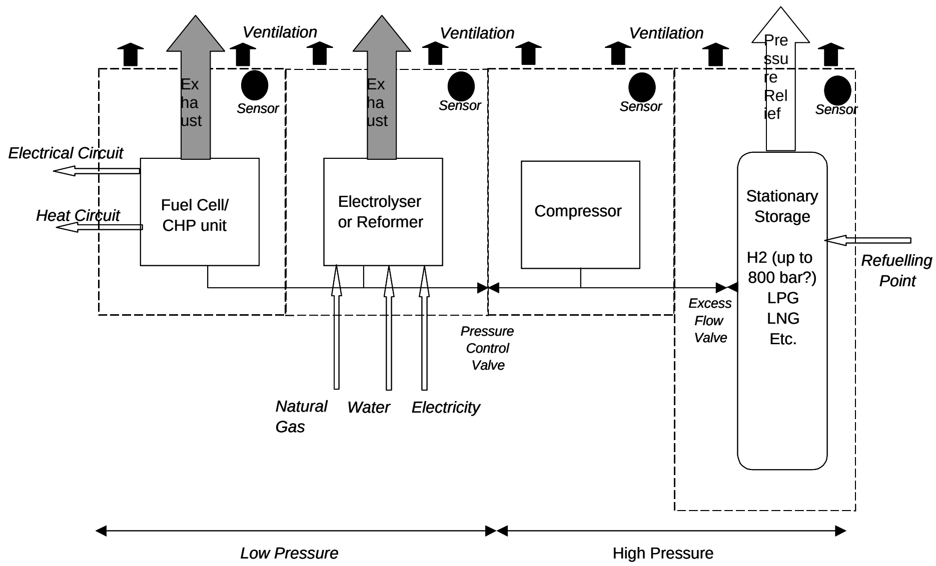

Figure 4 Schematic showing potential elements of stationary fuel cell/hydrogen system. (Note that connections are simply schematic).

5. Hazards associated with stationary hydrogen and fuel cell systems

An appropriate working hypothesis is that the public's expectation will be that hydrogen systems should provide a level of safety and reliability equivalent to that of conventional liquid and gaseous fuels currently in use. In the case of stationary and domestic applications this means principally natural gas, fuel oil and diesel. Hydrogen clearly presents different hazards and challenges to safe operation, it is increasingly recognized that these differences are not insurmountable but do require modification of current techniques and philosophies to recognise and respect the differences. There is currently considerable effort going into achieving this for vehicle and stationary applications. There are a number of reviews and studies available on the relative safety of hydrogen compared to other fuels, which have concentrated on the safety of hydrogen as a vehicle (automotive) fuel compared to gasoline.
Comparison with methane (CH_4) is shown in Table 1.

Property	Dry natural gas (methane)	Hydrogen
Density (Kg/m^3) *	0.65	0.084
Diffusion coefficient in air (cm^2/s) *	0.16	0.61
Viscosity (g/cm-s x 10^{-5}) *	0.651	0.083
Ignition energy in air (mJ)	0.29	0.02
Ignition limits in air (vol %)	5.3 – 15.0	4.0 – 75.0
Auto ignition temperature (C)	540	585
Specific heat at constant pressure (J/g)	2.22	14.89
Flame temperature in air (C)	1875	2045
Quenching gap (mm) *	2	0.6
Thermal energy radiated from flame to surroundings (%)	10-33	5-10
Detonability limits (vol % in air)	6.3-13.5	11-59
Maximum burning velocity (m/s)	0.43	3.49

* at normal temperature and pressure – 1 atmosphere and 20^oC. Data from reference 11

Table 1 Safety characteristics of Hydrogen and Dry Natural Gas

As Table 1 shows, hydrogen is gaseous under atmospheric conditions and is in fact the lightest of all the elements. Hydrogen gas has the smallest molecular size and has a greater propensity to escape than methane and propane. For high-pressure storage systems hydrogen would leak nearly three times faster than natural gas and over five times faster than propane. However the low energy density of hydrogen means that it produces substantially lower energy leakage rates.

As hydrogen diffuses more rapidly through air and through solid materials compared to other fuel gases such as methane or propane, it will usually disperse more rapidly if released. Although buoyancy effects are less significant for a high momentum releases from a high-pressure hydrogen systems. When harnessed through intelligent equipment design and layout, this buoyancy and hydrogen's rapid dispersion rate can become a significant safety asset.

The buoyancy of hydrogen can also be used to manage the risk from fire and explosion by segregating the hydrogen from foreseeable sources of ignition using internal partitions and bulkheads and differential pressurization. Also by locating all potential sources of ignition well below the level of the equipment from which hydrogen may leak and accumulate, and ensuring adequate ventilation and safe discharge of the exhaust. Hydrogen leakage through welds, flanges, seals, gaskets, etc. is an important consideration and an important design and operational issue for hydrogen systems.

There is, therefore, a need for good equipment design and fabrication to limit/eliminate the likelihood of leaks occurring. Best practice needs to be developed which can be practically applied to a wide range of equipment e.g. reducing the number of connections, reducing inventories and regular maintenance.

When released, hydrogen is a colorless, odorless gas that burns with a barely visible flame. The use of odorants to detect leaks (12) is being investigated, however, all the odorant chemicals so far considered have been rejected due to concerns regarding their potential to ‘poison’ the fuel cell membrane catalysts. Furthermore, they may have limited effectiveness for small leaks, as the odorant molecules will inevitably be much larger than the hydrogen molecules.

Hydrogen readily forms an explosive mixture with air. The range of air/hydrogen concentrations that will explode is extremely wide requiring as little as 4% v/v hydrogen. For the bulk of its flammable range (18 to 69% v/v) there is a significant risk that a hydrogen/air mixture in a confined and congested space may detonate thereby causing much more damage than a deflagration.

The wide range of flammability of hydrogen-air mixtures compared to propane and methane-air mixtures is, in principle, a disadvantage. There are, however, only minor differences between the Lower Flammability Limit (LFL) of hydrogen and that of methane or propane. The Lower Explosive Limit (LEL) of hydrogen is considered by many experts to have a greater significance in hazard ranking than the width of the fuel’s flammable range. Furthermore, in the case of low momentum releases the dispersion characteristics of hydrogen will make it less likely that a flammable mixture will form.

The apparently low emissivity (10 & 13) of hydrogen flames (total flux of heat radiated) potentially reduces the heat transfer by radiation to objects near the flame, thus reducing the risks of secondary ignition and burns. However, such effects have not been fully quantified and work is needed to address these issues.

With respect to explosion the maximum burning velocity of hydrogen-air mixture is about eight times greater than those for natural gas and propane air mixtures. The high burning velocity of hydrogen makes it difficult to confine or arrest hydrogen flames and explosions, in particular in closed environments.

Experiments with large-scale hydrogen clouds and elevated initial temperature and pressure conditions have shown that the deflagration-detonation transition (DDT) is a possibility even at concentrations as low as 11% volume over a large detonable range, when confined. In the open, detonation of a flammable hydrogen-air mixture is much more difficult and a high-energy ignition source is usually required.

In summary, in the event of a leak there is the potential for hydrogen to form a flammable mixture more readily than methane and propane due to its higher buoyancy, rapid mixing in air, its slightly lower flammable limit and larger flammable range.

Leaks of hydrogen within enclosed areas containing potential sources of ignition such as electrical equipment may produce a serious risk of fire and explosion, which for stationary hydrogen systems should be capable of management to levels comparable to those currently presented by natural gas systems.

Safety regulations require that adequate ventilation be provided to ensure that releases of dangerous substances do not accumulate to dangerous levels. Appropriate sensor and shutdown systems are usually also installed to support effective ventilation. Other requirements would include ensuring that all equipment complies with the requirements and protective systems for use in potentially explosive atmospheres (ATEX), and preventing the build up of static electricity.

The use of suitable separation zones around equipment handling or storing hydrogen is a fundamental requirement for a safe installation. The recommended separation distance is the minimum distance that will mitigate the effects of a likely foreseeable event and prevent a minor incident escalating into a major one. The separation zone is intended to give people and equipment some suitable degree of protection from an event such as a hydrogen leak and subsequent fire and to protect the installation from off-site events such as mechanical impact, release of flammable materials, uncontrolled ignition, radiation from off-site fires, etc. Separation distance is not intended to provide protection against catastrophic events or major releases, which should be addressed through engineering and procedural design.

In relation to systems that will use on-site hydrogen storage, a key issue will be to establish the best practices in respect of safety distances and hazardous area definitions. There is a body of expert opinion that considers the safety distances for hydrogen powered systems should be less than those currently used for hydrocarbon storage, but despite modeling and other studies, there is no definitive experimental data to demonstrate this. This is an important deficiency that must be addressed to allow full utilisation of stationary hydrogen storage in situations where safety distance considerations prohibit the use of LPG/LNG on site storage. The difficulty at present is that the separation distances given within existing guidance and proposed for the systems of interest are based entirely upon what has been developed for large industrial systems. Consequently they are impractical in the vast majority of instances and will exclude many potential small-scale uses within urban environments.

6 Summary - Permitting guidance, HyPer.

At present there is limited relevant guidance available to assist installers of fuel cell and hydrogen stationary systems. The establishment of consistent universal safety codes and standards for hydrogen fuel is essential to securing public and institutional acceptance of hydrogen.

The Installation Permitting Guidance (IPG) for Hydrogen and Fuel Cell Stationary Applications (HyPer) project is aimed at developing for small stationary hydrogen and fuel cell systems to fast track approval of safety and procedural issues, by providing a comprehensive agreed installation permitting process for developers, design engineers, manufacturers, installers and authorities. The project brings together a group of 27 organisations, made up of 15 partners and 12 members of a supporting Monitoring and Implementation Group. The partners include hydrogen system and fuel-cell manufacturers, installers and operators, regulators, research laboratories and universities. The group has a complementary make up and includes industrial associations, hydrogen distributors and an aerospace company.

To produce IPG, the project will carry out an experimental program to gather data to develop safety distances, establish ventilation requirements for enclosures and the application of sensors within a fuel cell system and work may also be coordinated with the work of The Department Of Energy (DOE) in the USA. The project will look at a number of case studies of operational hydrogen and fuel cell systems to gather and compare best practice.

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