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Critical Literature Review

(ANTA602)

Do the benefits of using fuel cells as a power source in Antarctica, justify overcoming the challenges that remain in constructing and operating them there?

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Abstract:

Fuel cells are being developed in a number of countries as it is thought that they can provide an environmentally friendly alternative to fossil fuel burning combustion engines such as those in vehicles and some stationary power sources.

This paper reviews the existing literature on the use of fuel cells as power sources in Antarctica. It also examines literature regarding the use of fuel cells in similar environments and highlights other relevant research which could impact on their use in Antarctica.
The paper then summarises the benefits offered by fuel cells in Antarctica, and identifies the challenges which are still to be overcome.

The paper concludes that there is enough evidence to suggest fuel cells can provide significant benefits over diesel generators (including emission reduction and likely cost savings), and offer benefits over other renewable energy sources (such as the ability to produce energy when there is no wind or sunlight), so overcoming the remaining challenges is justified.

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The general benefits and disadvantages of fuel cells

Unlike combustion engines, which convert chemical energy into electric energy via heat then mechanical energy, fuel cells convert chemical energy directly into electrical power, so are often more efficient. An introduction to fuel cells is given in appendix 1. Fuel cells have no moving parts, so are very quiet and require less maintenance than combustion engines. Fuel cells produce power as long as fuel is supplied, unlike batteries which have finite life, or need to be recharged. Fuel cells produce very few harmful emissions.

The main issues at present include their cost, operating life, power density and the production and storage of their fuel. The most common fuel is hydrogen (see appendix 2 for more information about its production and storage).

The development of fuel cells

The main fuel cells under development today are the proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC) and phosphoric acid fuel cell (PAFC). Work first started on these cells in the 1960's which is also when AFCs and PEMFCs were used successfully in spacecraft. The challenges identified during this time (e.g. scaling up cells to produce more power, materials optimisation to improve power density and durability, and reducing costs by increasing the effectiveness of catalysts), have determined the focus of subsequent research.[1] Extra challenges faced now include establishing manufacturing processes for fuel cells and developing improved materials for hydrogen storage.
Significant investment by the transport industry, which hopes to use fuel cell technology commercially in vehicles, has seen a lot of recent developments.

Studies into the main issues of fuel cell degradation have outlined the durability of fuel cells as a major factor in making them cost effective and improving performance.[2 3] They list the issues associated with flooding, membrane dehydration, electrode/electro catalyst degradation and mechanical/thermal membrane degradation. Performance degradation by absorption of carbon monoxide and ammonia onto the catalyst surface from impure hydrogen fuel and the loss of catalyst surface area by the catalyst particle growth have been studied.[4 5]
As fuel cell vehicles are intended for wide use in a range of climates, studies have looked at the impacts of cold temperatures on PEMFCs.[6-11] More work is required to better understand the freezing mechanisms. A study into a PEMFC bus operating at high altitude in Mexico City, concluded a performance drop was due to the air compressor rather than fundamental problems with the PEMFC.[12] Such studies are of interest to those looking to use fuel cells in the cold temperatures of Antarctica, where altitude is also a factor in some locations.

An indication on the emergence of fuel cells is shown by the fact that in the year proceeding November 2011, 34 North American companies bought or deployed a total of 250 fuel cells for stationary power, 240 fuel cells for telecommunication sites, and more than 1,030 fuel cell powered forklifts.[13]

Theoretical studies of remote power solutions involving hydrogen generation and fuel cells

An analytical optimization of a power system for a hypothetical remote Alaskan village of 150 people with the solar isolation, wind and temperature resources of the coastal Alaskan town Kotzbue (so probably not dissimilar to some Antarctic bases) showed that by adding wind turbines to diesel generators, about 50% of fuel and 30% of costs can be saved (compared with purely using diesel).[14] Adding a phosphoric acid fuel cell to the system (coupled with a turbine powered electrolyser, which breaks water into hydrogen and oxygen) showed no additional financial benefit (the extra environmental benefits were not examined). Alternatively a Zinc-air fuel cell (zinc pellets are used to store energy rather than hydrogen) reduces diesel use by 30%.

A similar study on the integration of wind and hydrogen technologies on the Corvo Island, Azores (380 inhabitants) used software to model a diesel generator based system and compare it with a proposed system (of wind turbines, electrolyser, hydrogen storage, a 50kW PEM fuel cell and diesel generators).[15] The proposed system reduced the power generation costs by 43%, with 80% of the electricity generated by renewable energy. A cost-benefit analysis included current subsidies, job creation and estimated financial savings from reduced emissions (using EcoSenceLE). It showed the system would be quite a profitable investment for both an investor and society.

Both of these studies are theoretical and assume that the technology is ready for use.

The use of fuel cells in Antarctica

A paper presented at the Sixth Symposium on Antarctic Logistics and Operations in Rome in 1994 outlined several alternative power sources, including fuel cells.[16] It states using electrolysers to produce hydrogen for fuel cells with an AC output, would have an efficiency of around 30%, which could approach 60% if excess heat from the fuel cell was used for heating purposes. It also stated that for storing large amounts of excess renewable energy, hydrogen storage was better than batteries. This was a theoretical study, so didn't involve any experimentation. This was a French-Australian piece of work to prepare the move 'Towards new Energy Systems for Antarctic Stations'. The authors hoped more Antarctic nations would work together on this in the future.

The economics of operating Methanol powered fuel cells in six Argentinian bases has been examined theoretically.[17] Calculations based on assuming methanol fuel cells were 40% efficient (compared with 20% for diesel generators) showed 58% less methanol was needed than diesel (despite diesel having the greater energy density), reducing the purchase and transportation costs (it was assumed that the freed up space on ships could be hired out). Transferring the fuel from ship to shore via helicopter is cheaper and savings made on generator maintenance costs. After 3 years, methanol fuel cells become more economical than diesel generators (after 12 years, the savings reach US $1.76 million). Other benefits, which weren't included for calculation purposes are a reduction in environmental impacts, improved comfort of personnel, and the easier delivery/storage due to methanol's lower freezing temperature. If it had been possible to associate costs with these benefits, it would have increased the savings.

A 500W PEMFC was tested at the Indian Maitri station between 1997-99, for the reason being that although diesel generators are highly reliable and simple to operate, their disadvantages are fuel transport costs and pollution potential, degradation of performance in sub-zero temperatures, noise pollution, solidification of lubricants and mechanical wear and tear.[18] A PEMFC was chosen for high power density and an ability to start in low temperatures. The report highlights the availability of fossil fuels which will be a future issue, and says fuel cells and wind power are the preferred choices for clean energy as solar produces limited power and the waste from nuclear power is dangerous.

The problems experienced related to cooling of the stack and external humidification system for the electrolyte (which are necessary for performance). Water cooling was unsuccessful as it froze; natural cooling or use of a coolant was suggested for future designs. Internal humidification was tried and suggested for the future, as was a pump to compress and re-circulate the gases to improve efficiency. The fuel cell gave an output of 15.6v which could re-charge a battery in 3.5 hours, or run a light bulb if an AC invertor was used. Problems were experienced with the gas cylinder regulator diaphragms in the outside temperatures. A metal hydride unit was used to store the hydrogen and found to be quick to charge in the cold (charging is exothermic, taking longer in warmer climates). The report suggests future electrical power generation may be a hybrid of conventional/non-conventional resources.

The potential use of fuel cells at the German Neumayer III station was presented at the 2004 Council of Managers of National Antarctic Programmes (COMNAP) symposium.[19] This considered different types of fuel cell and fuel and ruled out Arctic diesel (no reformer was available) and methanol (due to high logistic costs and the need for two fuel infrastructures). When powered by wind produced hydrogen, PEMFCs are emission free, but as no reliable system had been proven it was concluded that a combination of wind power and diesel generators was best.

The German PerenniAL Acoustic Observatory in the Antarctic Ocean (PALAOAO) is self-sufficient, running on solar cells and wind turbines for 90% of the time and a methanol powered fuel cell in the winter when it is not windy.[20] Involved since 2005, 'SFC Energy' reported issues with the cell stack and exhaust hose freezing, which have been overcome by improving insulation and positioning of affected components.[21] Remote access and control allows it to operate as an unattended site. The power of the cell is not documented, but is likely to be 25W, 65W or 90W as these models are available from SFC.

A PEM Fuel cell was installed at Mawson station for use during the 2007 Antarctic winter and worked from February, supporting a hyrdophonics study.[22] A satellite link was used to monitor and fine tune the cell from Sweden. Extreme cold caused problems with start up on one cell, but this was overcome. No details were given. The vent lines were positioned to give a downward flow of condensate, to stop the low temperatures causing a blockage. The fuel cell was shut down in low winds when there was no excess wind power for hydrogen production. A wider hydrogen demonstration project was undertaken during the 2005-06 season at Mawson but no results have been published.

Hydrogen production and use at the Argentinian Hope Bay station in Antarctica was studied for 2 years, due to Argentina's desire to reduce fossil fuel consumption in Antarctica by 50% in 15 years, reduce CO_2 emissions by 50%, generate a minimum of 150kW using clean energy and reduce the helicopter hours used for fuel re-supply to minimize the risk of spills of pollutants.[23] A 4.5kW wind turbine was installed in 2007, and one of 5kW added in 2009. Hydrogen produced by an electrolyser (powered by wind turbine charged batteries) was used for a hydrogen fuelled engine, fuel cells for a television, computers, ovens burning hydrogen and also for an oxy-hydrogen cutting/welding device. Proper ventilation, leak detection and monitoring of oxygen and hydrogen composition were necessary safety features. Tests for suitable water (with a conductivity of less than 10 micro S/cm) to electrolyse, showed shoreline ice bergs were satisfactory in summer, otherwise snow was used. Direct use of sea water would have required changes in the electrolyser design. Failure of a hydrogen sensor and several blades and the guidance system of one wind turbine were reported. The electrolyser worked well for more than 18 months before gas purity issues led to it being shut down, and said staff and visitors (having a respect for the Antarctic environment) quickly accepted the hydrogen powered devices. The report did not specify the total hydrogen or electricity produced during the study.

The benefits of using fuel cells in Antarctica

- Theoretical studies show fuel cells linked to wind turbines and electrolysers in certain environments can save money and have environmental benefits.
- Calculations suggest methanol fuel cells can save money over diesel generators in Antarctica, even if environmental factors are not taken into account. Tests have demonstrated that wind turbine / electrolyser / fuel cells systems can provide power on a small scale (such as to power a portable TV, computers, lights).
- Cost savings from a reduction in diesel purchases, will be a big benefit at the Political and National Programme level if renewal hydrogen is used, as savings would be available for the science programme.
- The reduction of emissions will benefit the Antarctic environment (humans and wildlife) directly by reducing their exposure to it. The coastal stations, which tend to have better wind speeds (for hydrogen production), are mostly located on ice free areas which are sometimes also used by animals.
- A 1996 study concluded that there was considerable potential to use wind power at Antarctic station sites, but highlighted past problems due to severe conditions.[24] Wind generating technology has developed further since then.
- Fuel cells will allow national programmes, to fulfil their commitment to reducing the environmental impact of their operations as outlined in Article 3 of the Madrid Protocol.[25]
- People working in Antarctica, who understand their environmental impact, may feel increased motivation when using fuel cells, so productivity could rise. Using fuel cells in the challenging environment would be a success story.
- Power generation is centrally important to the safety/efficiency of all operations in Antarctica. With very few moving parts, a reduction in mechanical breakdowns would be beneficial to the bases and also field teams currently reliant on small generators would benefit, with less time spent resolving mechanical issues.

- The reduced noise of fuel cells will benefit those working/living near them (along with any animals nearby), with fuel cells less likely to disturb sleep and concentration. This allows fuel cells to be located near to where any heat they produce can be used.
- Existing renewable energy sources (wind turbines and solar panels) can be used to produce hydrogen if electrolysers are used (for example at night when electrical demands are less). Energy can be stored (as hydrogen) for non-windy days. Stations already using wind generators for electrical power (such as Scott Base) could add in electrolysers to produce hydrogen for fuel cells.
- Methanol fuel cells provide an alternative to hydrogen. These would be useful where portability was required, or in regions with insufficient wind to generate hydrogen (such as on the polar plateau).
- Commercially available Methanol powered forklift trucks could be used at larger bases where forklifts are already used.
- The Antarctic programmes can benefit from the privately funded research into fuel cells conducted due to their potential to power vehicles in future.
- Further testing in Antarctica will be of benefit to those trying to use them in similar climates.
- Although the tests so far in Antarctica involved lower PEMFCs, more powerful versions are in use elsewhere. The world's largest PEMFC (1.1MW) was installed in October 2012 at the U.S. Toyota headquarters.[26]

<u>The challenges that remain in operating and constructing fuel cells in Antarctica</u>

The challenges which remain include those which are technological and political.
For fuel cells to be used in Antarctica, their cost effectiveness and reliability needs to be beyond doubt. Some assurance will come from the general worldwide fuel cell research, but the climatic conditions in Antarctica mean more testing has to be done in Antarctica.

I think it is only a matter of time before fuel cells generally become a fairly common source of power in at least some aspects of everyday life (such as in vehicles), although it is not clear how long this will take. The challenges are centred on reducing the cost of fuel cells by studying and improving the lifetime of fuel cells (e.g. studying fuel cell degradation), developing mass production techniques and making hydrogen fuel available.

Another major challenge relates to the scale of the power system required. The trials in Antarctica so far have shown that hydrogen can be generated for use in small systems by wind generation at coastal systems, or by using methanol. The question of whether these systems can be scaled up to provide the larger power supplies needs to be answered. It may be that in Antarctica, fuel cells are limited to coastal environments (where incidentally a lot of stations are) or other locations where the wind is enough to generate hydrogen (unless methanol fuel cells are used more widely). The energy required in a station is a complex mix of routine demands such as for lighting, heat, water production, cooking etc to more challenging requirements such as the latest experimental apparatus.

The production of hydrogen needs to be safe and robust. As production relies on wind turbines, electrolysers and storage solutions, each of these components is a source of weakness. Spares for all the parts would need to be available.
Studies are needed to see if enough hydrogen could be produced using wind power (in terms of winds speeds, couple with efficiency of electrolysers) to generate the larger quantities of electrical power needed (assumed larger fuel cells were used).

There needs to be interest in fuel cells at a political and national programme level as it will focus effort, and provide the additional investment needed to achieve the benefits of using fuel cells. The benefits most attractive at this level is likely to be cost savings and a reduction in emissions, so demonstrating these through more studies needs to be a priority.
Detailed fuel cell performance data is missing from some of the literature I have examined, this need to be available for the political/programme decision makers.
It will be necessary to overcome any reluctance to move away from seeing diesel generators as the only source of electricity. They are tried and tested, and people have relied on diesel generators for a long period. Funding would be needed to train staff on the operation of fuel cells.
People may advocate waiting until fuel cell technology is more developed world wide, before looking at their potential in Antarctica.

Whilst work on fuel cells in Antarctica is mostly taking place by countries individually, Argentina shared their Hope Bay experience at the 2010 COMNAP symposium.[27] Future focus for this team will be on developing a 100W fuel stack, and then 1kW stack to increase the power output.
If all Antarctic programmes were to agree through COMNAP that fuel cells were worth investigation, a COMNAP funded project could be instigated to advance knowledge. If this proved fuel cells could save programmes money, help meet the protocol requirements and not negatively impact the science programmes, it may be that the project could be endorsed by the CEP and IATCM. This would raise the profile of fuel cell research within the IATCM countries.
The Argentinian energy targets already detailed are the reason for their hydrogen fuel cell research. At present there are no Antarctic Treaty wide targets for emissions. Perhaps some could be agreed amongst the treaty members, which could drive forward the development of fuel cells for use in Antarctica.

Conclusion

Some fuel cells are now commercially available (e.g. methanol cells being sold by SFC), with others still in development. Fuel cells are not yet commonly used in everyday life, and questions remain regarding their reliability and cost.

If these issues can be resolved the identified benefits of using fuel cells, in a range of worldwide applications are clear. These benefits make them particularly attractive for use in Antarctica, although supplying the required fuel needs to be carefully considered. If renewable resources (most likely wind turbines) can reliably generate hydrogen fuel in sufficient volume, the electrical energy produced would be emission free and has the potential to be cost effective (money related to fuel transportation would be reduced). These benefits would be a huge value to national programmes.

The national programmes of Argentina, Australia and India have trialled the use of PEMFCs in Antarctica, coupled with hydrogen generation by renewable resources. Published reports from the Argentinian and Indian studies state the tests were largely successful, but did report some problems. The German programme has used a methanol powered fuel cell at an Antarctic observatory.

The fact that countries have invested in trialling fuel cells in Antarctica may be interpreted as a positive indication of their future potential.

There is enough evidence to suggest fuel cells can provide significant benefits over diesel generators in Antarctica (including emission reduction and likely cost savings), and offer benefits over other renewable energy sources (such as the ability to produce energy when there is no wind or sunlight), so overcoming the remaining challenges is justified.

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Appendix 1 - Introduction to fuel cells

A fuel cell is a device which generates an electrical current directly from the oxidation of a fuel. Fuel cells consist of an anode and cathode separated by an electrolyte. Fuel is oxidised at the anode producing negatively charged electrons which travel by an external circuit to the cathode, where the oxidant is reduced. The electrolyte allows the transfer of charged atoms between the anode and cathode (and not electrons) to complete the chemical reaction.

Sir William Grove is credited with the invention of the fuel cell in 1839 when he combined oxygen and hydrogen at different electrodes in a cell, connected four of these cells together in series and produced an electric current. This reaction is a reversal of the electrolysis of water (when an electric current is used to split water into its components of hydrogen and oxygen).

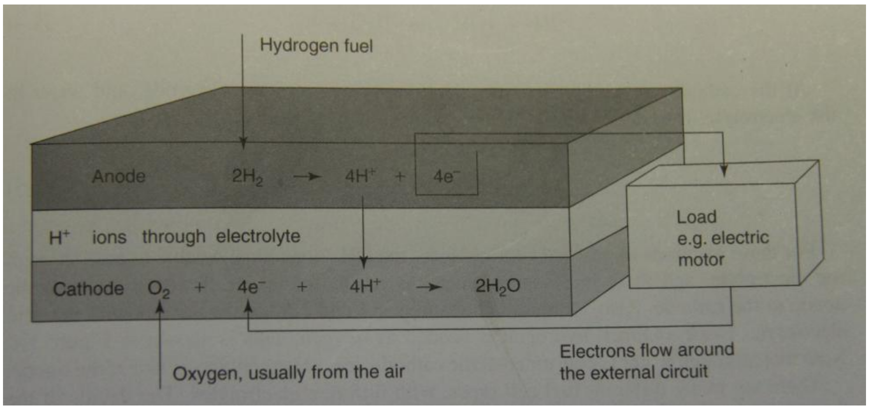

Figure 1. The electrode reactions and charge flow for an acid electrolyte fuel cell.[28]

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Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Figure 2. A comparison of the main types of fuel cells.[29]

The types of fuel cell are named after the electrolyte they contain, as this defines the chemistry taking place, a comparison is given below.

All of the fuel cells listed in figure 2, above, use hydrogen fuel, with PEM fuel cells also capable of running on methanol, MCFC's and SOFC's on methane and SOFC's running on carbon monoxide.

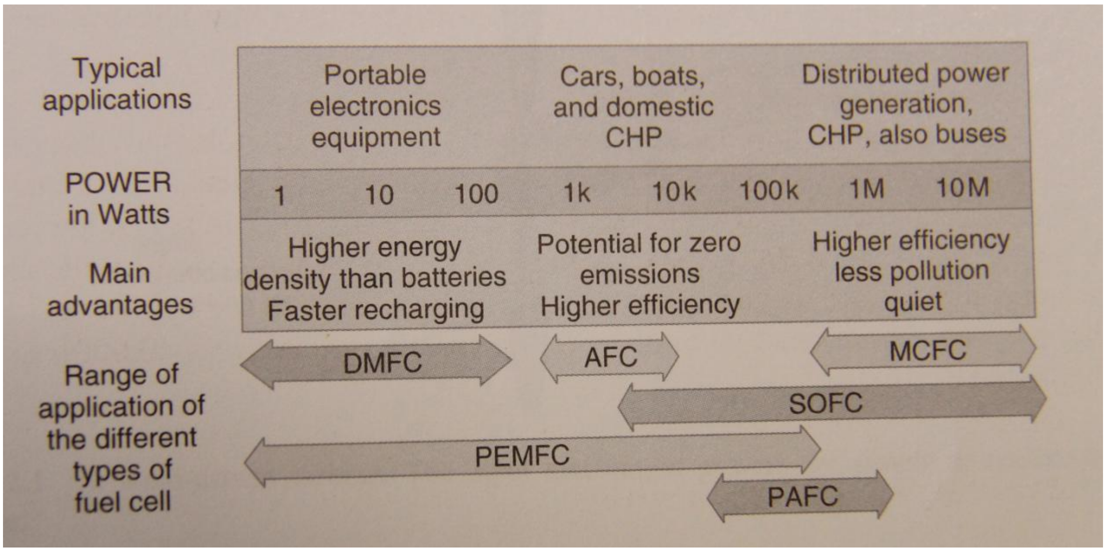

Figure 3. Summary of applications and main advantages of fuel cells of different types and in different applications. DMFC is a Direct Methanol Fuel Cell.[30]

Appendix 2 - Hydrogen generation and storage for use in fuel cells

While hydrogen is an abundant element, its molecular state is rare as a natural resource, so it needs to be generated for fuel cell use.
Generating hydrogen from fossil fuels is possible but it is harmful to the environment.
Environmentally clean hydrogen can be produced using wind turbines to power electrolysers which split water into hydrogen and oxygen.
Home based, solar powered electrolysers have been demonstrated for powering fuel cells in vehicles as has a transportable design for remote areas.[31 32]
Replacing fossil fuel powered cars in the US with ones powered by hydrogen fuel cells, will improve air quality, health and climate whether the hydrogen was produced by wind electrolysis, steam reforming of natural gas or coal gasification, but wind electrolysis achieves the biggest improvement.[33] This is based on a reduction in urban pollution.
It has been estimated the world could generate the hydrogen needed to satisfy the global electricity requirement by global wind power.[34]

Failure mechanisms in PEM electrolysers have been examined and recommendations to improve their durability have been suggested.[35]
Research into high pressure PEM electrolysis producing high pressure hydrogen for direct storage in pressurized vessels, showed it is expensive but the advent of mass produced PEMFC's could reduce the costs as many of the components shared.[36]

Hydrogen storage is necessary if it is used for portable devices or when hydrogen is being generated by a renewable source such as wind. Alternatively a DMFC can run from methanol.
The main ways of storing hydrogen are outlined in the table below, including storage as a gas or as other chemicals.

Method	Gravimetric storage efficiency, % mass H_2	Volumetric mass (in kg) of H_2 per litre	Comments
High pressure in cylinders	0.7–3.0	0.015	'Cheap and cheerful' widely used
Metal hydride	0.65	0.028	Suitable for small systems
Cryogenic liquid	14.2	0.040	Widely used for bulk storage.
Methanol	6.9	0.055	Low-cost chemical. Potentially useful in a wide range of systems
Sodium hydride pellets	2.2	0.02	Problem of disposing of spent solution.
$NaBH_4$ solution in water	3.35	0.036	Very expensive to run.

Figure 4. Data for comparing methods for storing hydrogen. The figures contain the associated equipment, for example tanks for liquid hydrogen, or reformers for methanol.[37]

"It is worth noting that the method with the worst figures (storage in high-pressure cylinders) is actually the most widely used. This is because it is so simple and straightforward".[37]

The first hydrogen demonstrative project in Latin America, at Pico Truncado in Patagonia, was designed to address hydrogen safety concerns and demonstrate safe generation using wind powered electrolysers, storage and use in devices such as fuel cells.[38] The design addressed the hazards e.g. combustibility, pressure, low temperature, hydrogen embrittlement.