Introduction to hydrogen energy projects

Information Resource for Highlands & Islands Enterprise

About this document

- In 2006 the HIE Renewable Energy team commissioned a consulting team to assist with the identification and assessment of hydrogen energy opportunities across the region. As part of this work the project team conducted a workshop in each LEC area to introduce the hydrogen energy opportunity and identify potential project ideas. Over 80 individual ideas surfaced, at varying levels of ambition, detail and feasibility.
- The project team worked with HIE to identify several recurrent themes among the ideas:
  - What are all the issues that need to be considered when setting up a hydrogen project?
  - What different stationary and portable hydrogen applications are there?
  - How can hydrogen be used in road vehicles?
  - How can hydrogen be stored and what refuelling facilities would be required for hydrogen vehicles?
  - What are the prospects for hydrogen use in maritime applications or cooking? Could bottled hydrogen and oxygen be produced and sold?
  - How can developers undertake technical and economic evaluation of their ideas?
- HIE judged that the best way to provide value to the LECs would be through a suite of information resources and tools based on these themes, to enable ideas to be developed and assessed further. These tools fit together as shown overleaf.

Document Map

This document

Introduction to hydrogen energy projects
Read this first to gain an overview of hydrogen energy and some key issues to consider when setting up a project

Stationary and portable fuel cells information resource
Read this to learn about the types, availability and project-related considerations for stationary and portable fuel cells

Hydrogen vehicles
Read this for background technical information on hydrogen vehicles, their current availability and the key operational issues.

Hydrogen refuelling and storage infrastructure
Read this to learn about the options for refuelling hydrogen vehicles and for storing hydrogen at a range of scales.

Novel hydrogen applications – review of status and prospects
Read this to learn about the status and prospects for raw gas production using electrolysis and hydrogen use in cooking and maritime applications

Project evaluation tool manual | **Project evaluation tool**
Use these if you would like to undertake a techno-economic evaluation of a project. Read the manual before using the tool.

Each box represents one document

About the authors

Element Energy

- **Element Energy is an engineering consultancy specialising in the low carbon energy sector. It formed in 2003 as a spin off from larger engineering practice Whitbybird.**
- **Services:**
  - Engineering services for low carbon energy projects
  - Innovation in new energy technologies and storage solutions
  - Strategic advice and consultancy
  - Project management and funding assistance
  - Specialist knowledge in hydrogen and fuel cell projects

E4tech

- **E4tech is a sustainable energy business consultancy, based in the UK and in Switzerland (established 1997)**
- **Services:**
  - Business strategy
  - Organisational support and interim management
  - Technology and market review to assist financing
  - Policy input for local and national government
  - Support to technology startups
  - Focus on hydrogen energy, bioenergy and sustainable buildings

PURE Energy Centre

- **The Pure Energy Centre has one aim: to give you access to the most effective energy storage techniques in the world to grow your business/community and increase your energy independence**
- **Services/products:**
  - Renewable hydrogen training courses
  - Consultancy for energy and storage technologies
  - Sales of hydrogen production units
  - R&D contract work for third parties

Commonly used acronyms

AFC Alkaline Fuel Cell

C H2 Compressed Hydrogen

CHP Combined Heat and Power

CNG Compressed Natural Gas

CRES Centre for Renewable Energy Studies (Greece)

DoE United States Department of Energy

EC CUTE European Commission Clean Urban Transport for Europe

EC HyCom EC Hydrogen Communities

FC Fuel Cell

FP6&7 Framework Programmes 6&7 (EU instrument for funding research)

H&I Highlands and Islands

H2ICE Hydrogen Internal Combustion Engine

HAZOP Hazard and Safety Operational Studies

HHV High Heating Value

HIE Highlands and Islands Enterprise

HSE Health and Safety Executive

ICE Internal Combustion Engine

LCIP Low Carbon Innovation Programme (Carbon Trust)

LEC Local Enterprise Company

LHV Low Heating Value

LNG Liquid Natural Gas

LPG Liquid Petroleum Gas

MCFC Molten Carbonate Fuel Cell

MCPs Manifold Cylinder Packs

MEA Membrane Electrode Assembly

NOx Nitrous oxides (pollutants)

O&M Operation and Maintenance

OEM Original Equipment Manufacturer

PAFC Phosphoric Acid Fuel Cell

PE Primary Energy

PEM Primary Exchange Membrane/Polymer ion Exchange Membrane

PSA Pressure Swing Absorption

R&D Research and Development

ROCs Renewable Obligation Certificates (see Defra website)

SME Small to Medium Enterprises

SOFC Solid Oxide Fuel Cell

UPS Uninterruptible Power Supply

VSA Vacuum Swing Absorption

ZEMSHIPS Zero Emission Ships

Contents

How to use this report

There is increasing interest in the use of hydrogen as a means for delivering lower carbon energy systems, including stationary power, transport, portable power and off-grid applications. The intention of this document is to provide background information and preliminary guidance to those considering developing hydrogen energy projects.

Guidance is given on: the components of hydrogen energy systems, outline technical advice, technoeconomics, safety, and funding. A spreadsheet based electronic tool has also been developed to facilitate initial economic assessments of a range of hydrogen energy projects.

This is one of a number of fuel cell and hydrogen reports produced for H&I enterprise. These information resources should be read in concert with this document to aid understanding.

Caveat

Hydrogen energy systems are novel and are relatively complex. The information contained in this document, and the electronic toolkit, can be used to provide initial guidance, but should not be used to design complete systems.

Limitations on the appropriate use of the electronic toolkit are described, and guidance is given as to appropriate next steps after the toolkit is used.

Contents

Introduction to renewable hydrogen systems

What is a hydrogen energy system?

Many existing energy systems are based on fossil fuels (hydrocarbons), particularly crude oil. These hydrocarbons are made of atoms of hydrogen and carbon. Remove all carbon from the energy cycle and what is left is a hydrogen energy system.

Hydrogen does not occur naturally in any significant quantities, it is almost always combined with other atoms, such as in water molecules or hydrocarbons. As a result hydrogen has to be manufactured, a process which requires energy. This energy can be recovered thermally, by combustion, or electrochemically, in a fuel cell. Hydrogen is therefore a means of storing energy and is often referred to as an ‘energy carrier’ or ‘energy vector’.

Hydrogen is not naturally occurring, it must be manufactured.

It can be made from fossil fuels (a process which results in the emission of CO_2), from biomass, or it can be produced by the electrolysis of water (which consumes electrical energy). Most hydrogen in use today is produced from methane, and used as a feedstock in industrial processes. However, there is considerable interest in the use of hydrogen as part of clean, renewable energy systems. A renewable hydrogen energy system would generate hydrogen from renewable energy, for example via electrolysis, or by the chemical reformation of biomass. Further discussion of these methods of generating hydrogen is given in the ‘Components of Hydrogen Energy Systems’ section of this report (page 17) and in the ‘Hydrogen Refuelling and Storage Infrastructure’ resource.

Hydrogen as an energy carrier

Hydrogen can be used to provide a range of energy services, for example:

- Electricity (in a fuel cell or in a hydrogen gas turbine).
- Transport (in a modified internal combustion engine or in a fuel cell powered electric vehicle).
- Heat (by direct combustion, or as a co-product with electricity in combined heat and power systems).

Introduction to renewable hydrogen systems

Why is there so much interest in hydrogen and fuel cells?

Recent advances in fuel cell technology – a significant amount of private investment in fuel cells has brought down costs and increased performance of fuel cells. In certain markets they are near commercial.

Potential for clean and quiet energy generation – Fuel cells run on hydrogen generate electricity, heat and water. This has led to their application in the automotive sector.

Unlocking renewables – many areas with significant renewable energy resources are relatively remote, with weak electricity infrastructures. Hydrogen could offer an alternative method to use or export energy.

Carbon dioxide abatement – If generated from a renewable source (i.e. biomass or using renewable electricity in an electrolyser) then it can play a significant role in de-carbonising energy systems. This can be by unlocking renewable resources and as a means of integrating a renewable fuel into the transport system.

Increasing demands for portable power – A key early market for some fuel cells is in the portable electronics (consumer and military) sector where battery technology can no longer deliver the required performance improvements. Methanol powered fuel cells are thought to be near commercial application.

Energy diversity and security of supply – Hydrogen can be generated from a variety of primary energy sources, and so can act as an integrated energy vector, carrying “energy” from point of generation to point of use.

Increased efficiency – The automotive sector is investing billions of dollars in fuel cell development as peak fuel cell efficiencies can be significantly higher than the combustion engine.

Job creation – the novel hydrogen and fuel cells sector is seen as having potential for skills development and job creation.

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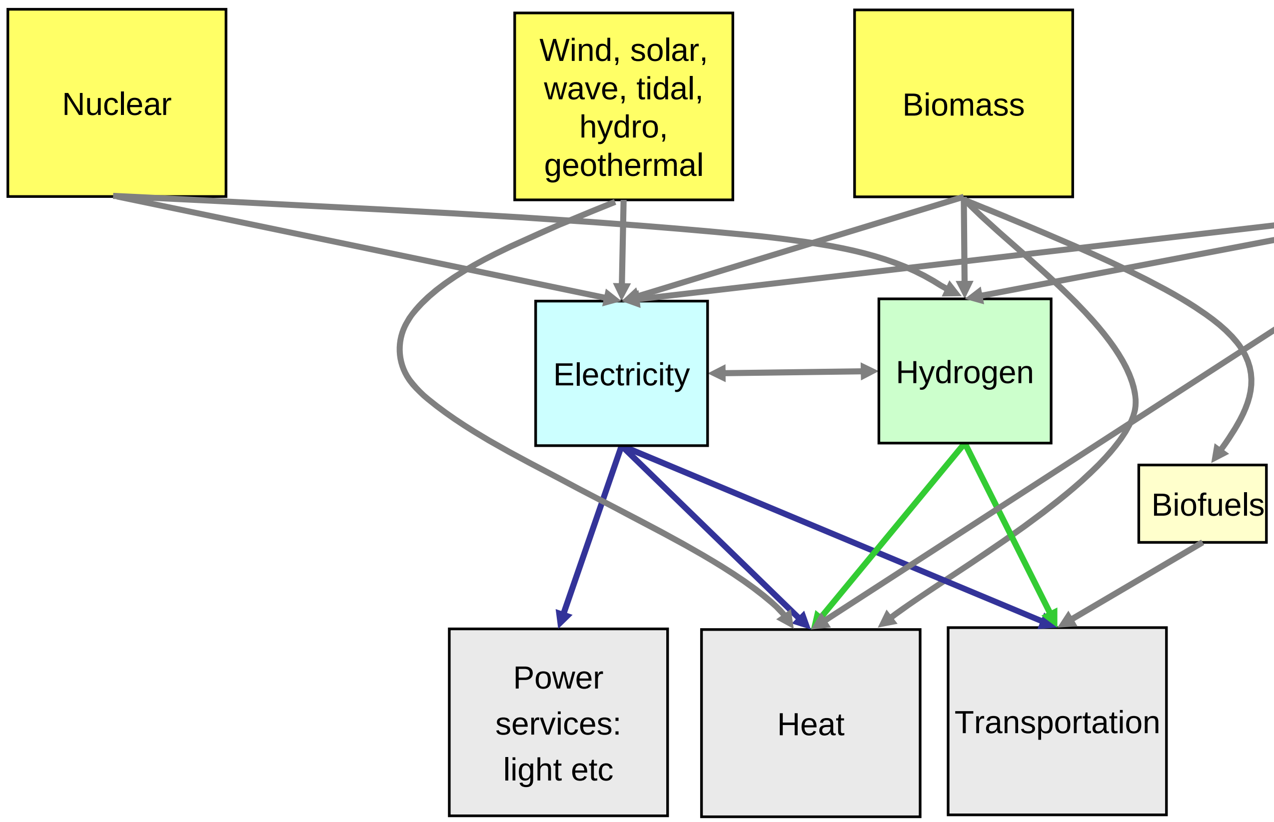
Hydrogen energy chains

The diagram below illustrates the potential role of hydrogen in a variety or energy systems. The diagram highlights two important facts about hydrogen:

• It can be generated from diverse sources, either directly or by first generating electricity which is then used for electrolysis

• It can be integrated into a wide variety of end-uses, either by combustion or by generation of electricity in a fuel cell



Following the arrows from energy source to end-use in this diagram defines an ‘energy chain’.

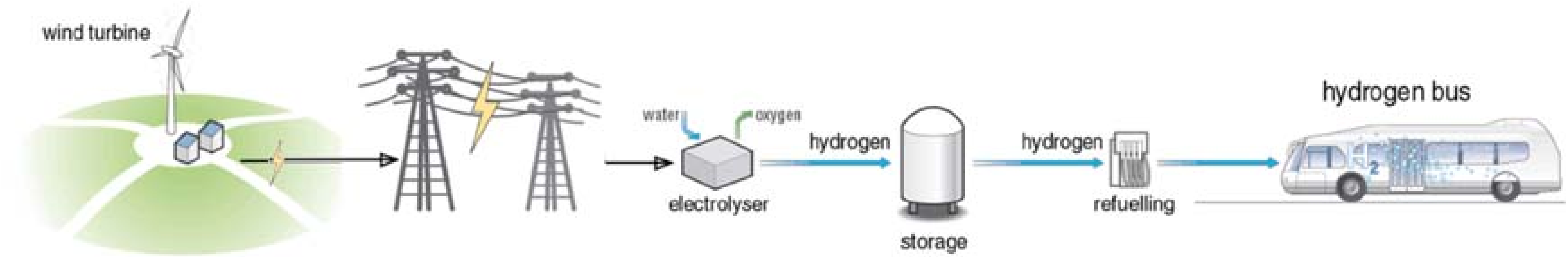
In the following slides, hydrogen energy chains are considered in more detail.

Hydrogen energy chains

Components of a hydrogen energy chain

Primary Energy Source → Primary Energy Transmission → Hydrogen Generation → Hydrogen Infrastructure → End Use → Potential Market Applications

Example of a wind – hydrogen – transport chain

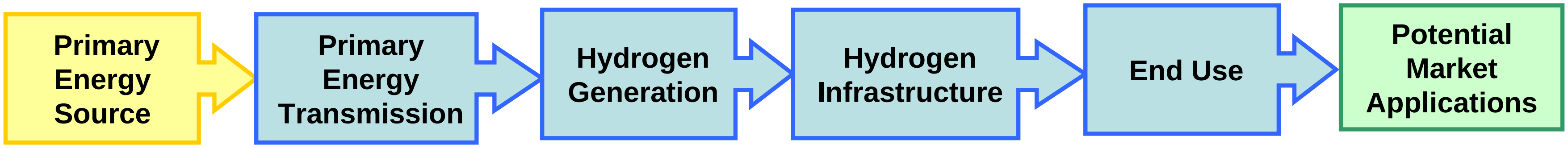


The image above is a simplified example of a renewable hydrogen project. A primary energy source (in this case, electricity from a wind turbine) is fed into an electrolyser, which is a device for generating hydrogen. The hydrogen is then compressed and stored before being sent to a refuelling dispenser. In the example above, a hydrogen powered bus defines the end of the chain. In general, however, the hydrogen may be also used to generate electricity, or heat.

Taken together, the individual components and stages form a complete energy chain. Generally, all stages in the chain exist to some extent. For example, an off-grid example of the above project would not transmit the wind energy over the grid, however the “primary energy transmission” stage would be represented as the short section of DC or AC cabling that joins the wind turbine and the electrolyser.

When considering hydrogen energy systems it is vital to consider what the primary energy source is and what the end use will be.

Hydrogen energy chains



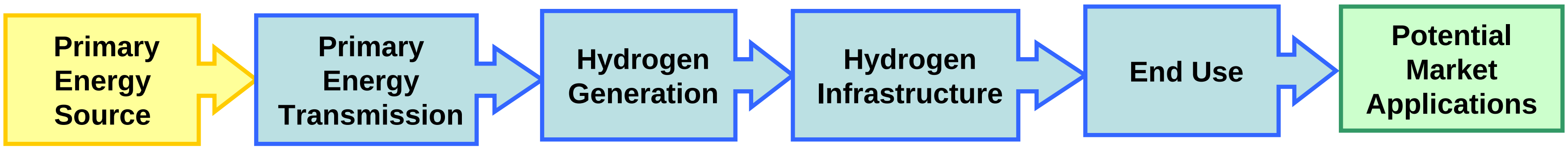
Efficient energy chains

If a fuel cell is used, this can make the end of the chain very efficient. However, inefficiencies are incurred at each step in the chain, and it is important to recognise these so that the overall efficiency of the chain can be calculated. For example a fuel cell bus may be twice as efficient as a combustion engine, however, some energy is lost in the electrolyser (e.g. 75% efficient) and some energy is lost in the hydrogen compressor (15%). These energy losses work against the energy improvements in the fuel cell, and must be borne in mind.

Also each stage in the energy chain is associated with a particular piece of equipment that must be bought and maintained, and these add costs to the project.

In general, simple projects with short chains are beneficial, not only because of reduced energy losses, but also through lower capital and running costs. We can take an example of renewably generated hydrogen, which can be sold for a high price to a distant end use (requiring a significant hydrogen infrastructure), or it may be sold locally, but at a lower price. The increased cost and lower efficiency inherent in the more complex hydrogen distribution infrastructure may imply that a more local project is preferred, even though the revenue from the local sale of hydrogen, is lower.

Hydrogen energy chains



CO_2 impact of the energy chain

To understand the carbon dioxide impact of delivering a particular energy service, for example hydrogen transport, it is necessary to consider the complete energy chain, as CO_2 could be produced at each stage.

If the primary energy source is renewable, the overall CO_2 impact is likely to be low, but it is not necessarily zero. For example consider a biomass to hydrogen chain where the biomass feedstock is transported by road from the source to the point where hydrogen is generated. CO_2 emissions will result from the road transport of the primary resource. Another example is a chain in which once the hydrogen has been generated, it is compressed and then transported by truck to the end-use location. In this case CO_2 could be attributed to the electricity consumption of the compressor and to the road transport of the compressed gas.

To fully account for the CO_2 impact of a particular energy chain can be complicated, requiring an assessment of all the inputs and outputs at every stage of the chain. An analysis of the CO_2 impact of a variety of hydrogen energy chains (compared to chains not including hydrogen) can be found in the following document:

'*A strategic framework for hydrogen energy in the UK*', E4Tech, Element Energy & Eoin Lees Energy, December 2004

(http://www.dti.gov.uk/files/file26737.pdf)

Hydrogen energy chains

The preceding pages have introduced the concept of an energy chain as a sequence of processes from the primary energy source to the end-use requirement for energy. There are a wide variety of potential energy chains, beginning with different energy sources and involving a range of hydrogen generation and end-use technologies to satisfy particular energy needs.

The table below highlights some of the key technologies that could be involved at each stage of hydrogen energy chains (this table is not exhaustive).

<table>
<tr><th>Primary energy source</th><th>Primary energy transmission</th><th>Hydrogen generation</th><th>Hydrogen storage</th><th>Hydrogen distribution</th><th>End-use</th><th>Potential market application</th></tr>
<tr><td>Natural gas, coal, oil fired power plant</td><td rowspan="3">Electricity transmission</td><td rowspan="3">Electrolyser</td><td rowspan="6">Compressed gas

Liquefaction and liquid storage

Solid state storage</td><td rowspan="6">Delivery by truck (gas & solid state)

Hydrogen pipeline (gas)

Tanker truck (Liq.)

Barge (Liq.)</td><td rowspan="6">Fuel cell

Combustion engine

Hydrogen turbine

Boiler

Catalytic converter</td><td rowspan="6">Transport

Stationary power

Portable power

Heating demands

Cooking / niche applications</td></tr>
<tr><td>Nuclear power</td></tr>
<tr><td>Renewable electricity</td></tr>
<tr><td>Natural gas, biogas</td><td>Gas grid, pipeline</td><td>Steam reformation</td></tr>
<tr><td>coal</td><td>Delivery truck</td><td>Gasification</td></tr>
<tr><td>Biomass</td><td>Delivery truck</td><td>Gasification</td></tr>
</table>

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Components of renewable hydrogen energy systems

In the following slides some of the key components of hydrogen energy chains are considered in more detail. The components discussed are fuel cells, electrolysers and hydrogen storage technologies.

The focus of the discussion is on hydrogen generated by electrolysis, as this is thought likely to be most relevant to the Highlands & Islands, given the plentiful renewable resources that could be exploited by electricity generating technologies, such as wind turbines and marine devices. The section concludes with a brief discussion of the options for generating hydrogen from biomass.

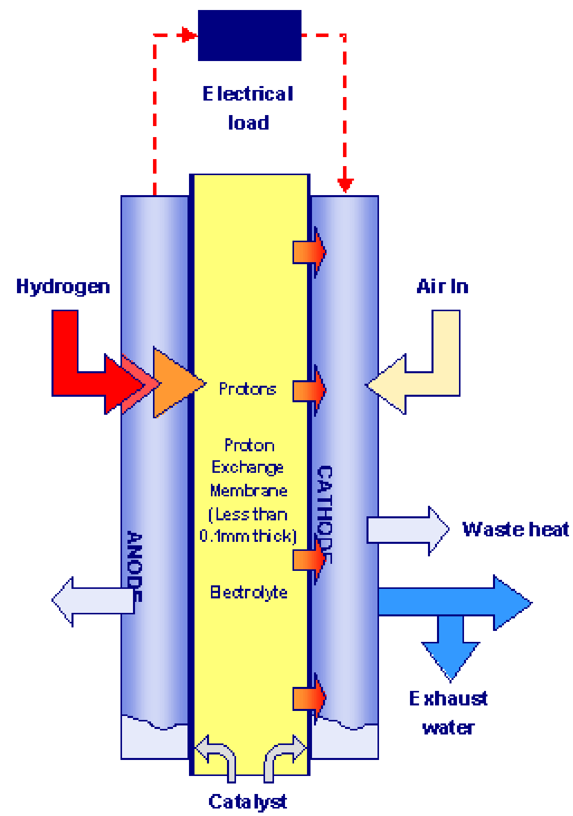
Further details on the technologies can discussed here can be found in other documents in this series of information resources:

- **Fuel cells** – Refer to the *Stationary and Portable Fuel Cell Applications* resource and, for discussion of the potential use of hydrogen in road vehicles, the *Hydrogen Vehicles* resource
- **Electrolysers** – Electrolysis is discussed in the *Hydrogen Refuelling and Storage Infrastructure* resource as a potential option for generation of hydrogen at a refuelling station.
- **Storage technologies** – Refer to the *Hydrogen Refuelling and Storage Infrastructure* resource.
- **Hydrogen from biomass** – Reformation of hydrocarbons is the principle route for generation of hydrogen today. Gasification and steam reformation technologies are being developed on smaller scales more appropriate to non-industrial hydrogen demands and are key technologies for generation of hydrogen from biomass. Steam reformation is discussed in more detail in the *Hydrogen Refuelling and Storage Infrastructure* resource.

Components of renewable hydrogen energy systems

Fuel Cells

Fuel cells are devices that consume a fuel (e.g. hydrogen) and oxygen in an electrochemical reaction, producing electricity, heat and reaction products such as water. In contrast to most incumbent technologies (which first generate heat through combustion, before electricity is generated from product heat) fuel cells avoid this intermediate process, and thereby hold the potential for more efficient electricity production.



Cross section through a typical fuel cell

The fuel for fuel cells

A range of fuel cell technologies are under development. For simplicity they may be divided into higher and lower temperature fuel cells. Generally, low temperature fuel cells can only accept a single, specific fuel e.g. PEM (Proton Exchange Membrane) cells require hydrogen, while methanol cells require methanol. Higher temperature fuel cells can accept hydrogen, but can also accept other fuels such as methane.

It is important to note that if the fuel cell uses a hydrocarbon, such as methane, then CO_2 is also emitted as a byproduct. Fuel cells have the potential to be a clean energy technology (i.e. very low pollutants at the point of use), but are not necessarily sustainable (CO_2 may have been generated elsewhere in the energy chain).

Components of renewable hydrogen energy systems

Electrolysers

Electrolysis is the process of splitting Water (H_2O) into hydrogen and oxygen by an electric current. Electrolysis can be used to convert an electrical source of energy into hydrogen. Mainly, electrolyser development has been for the industrial gases industry to satisfy small-scale hydrogen demands. Increasingly, however, smaller scale electrolysers are being developed due to the interest in hydrogen energy.

Some sources quote a hydrogen production efficiency of up to 85% although currently 65-75% is more typical (where efficiency is defined as the energy content of the hydrogen generated as a percentage of the electrical energy consumed). Due to small volume production, electrolysers are a major cost component for most - wind-derived hydrogen. Cost is very sensitive to size, particularly up to 20kW. Very large systems are £500 - 750/kW, but lower capacity systems have a much higher specific cost. Industry cost targets are £200-350/kW.

Electrolyser technology is advancing, particularly at small-scale. Newer technologies (such as PEM electrolysers) offer the potential for cost reductions and efficiency improvements. However, to-date, these newer technologies have not demonstrated the reliability of more conventional, alkaline electrolysers.

A commercial alkaline hydrogen generator
Source: Hydrogen Systems (now Hydrogenics)

Components of renewable hydrogen energy systems

Hydrogen storage type

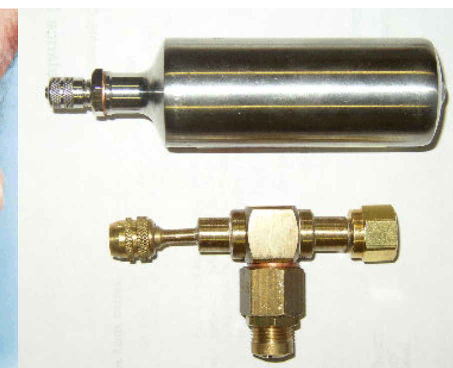
The most common method for storing hydrogen is as a compressed gas, in cylinders. These are widely available from hydrogen merchants, although the cost can be very high if the cylinders have to be moved any distance from the point where they are filled. The industry standard pressure for these cylinders is 220bar, and many standardised fixtures and fittings are available. Also, the safety procedures for this gas pressure are well known.

Unfortunately, the energy density (kWh/kg) of this storage media is quite low, and this had led to the use of much higher storage pressures for e.g. transport applications. Storage at 350 bar has been standard in most hydrogen vehicles and some prototype fuel cell passenger cars are trialling hydrogen cylinders at 700 bar, in order to achieve the range of a modern petrol or diesel car. Clearly, at these high pressures, higher costs combine with increased safety concerns.

There are a number of alternatives to compressed storage. For example, “solid” hydrogen storage may be more suitable to a stationary end use, due to the much lower pressures involved (a few bar) and where weight is less of an issue).

In general, the nature of the hydrogen end use technology may dictate the type of hydrogen storage used.

Please refer to the ‘Hydrogen Refuelling and Storage Infrastructure’ resource for further details on hydrogen storage options.

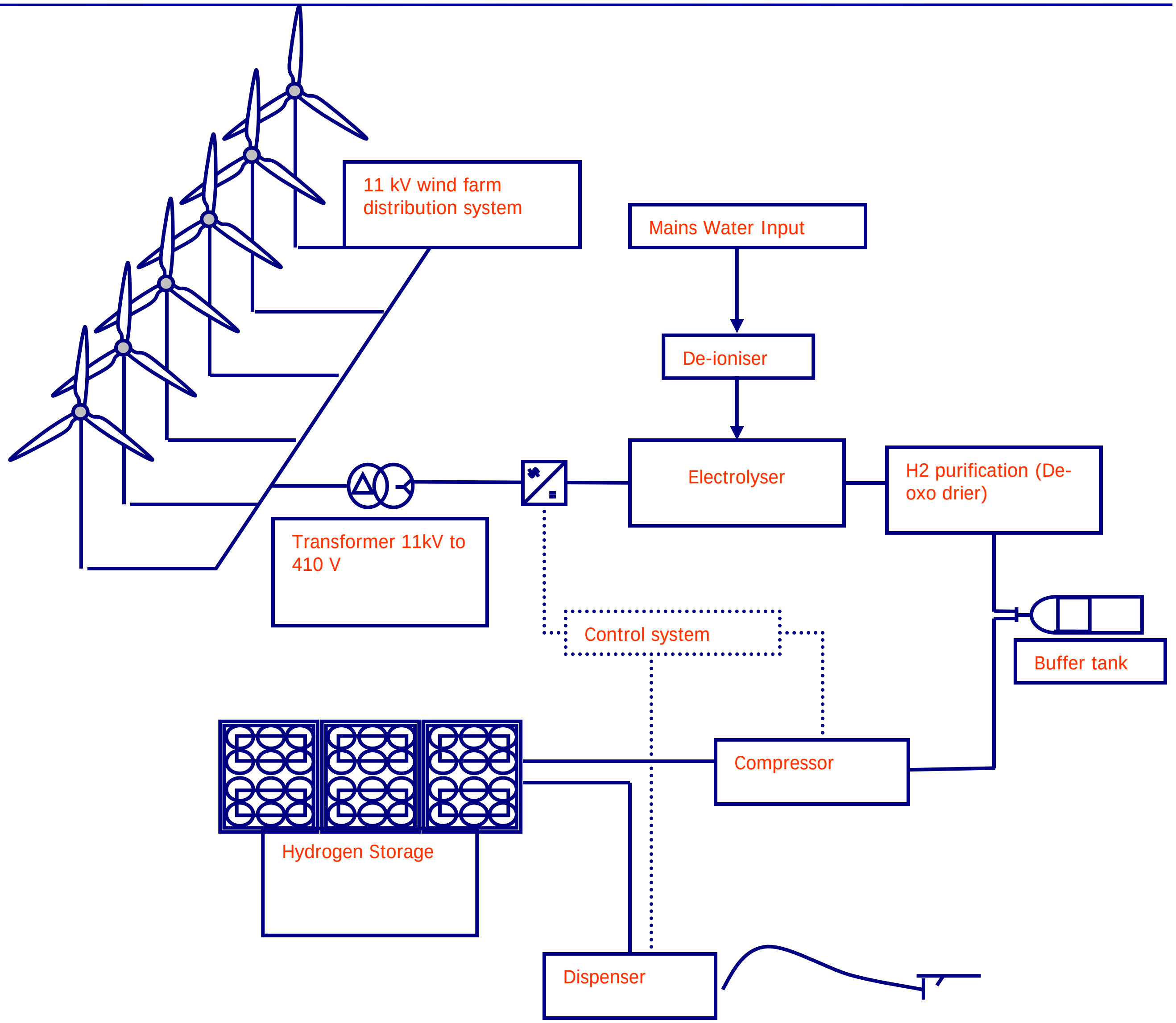


Top: Industrial scale pressurised hydrogen storage (Messer). Bottom: Solid Hydrogen storage (metal hydride).

Components of renewable hydrogen energy systems

This example is a schematic for a relatively large wind to hydrogen system, where the end use is in a transport application. In this example, the wind farm is rated at 5MW, and the electrolyser rated at 200kW. The electrolyser requires conditioned DC, and deionised water as an input. The generated hydrogen is dried and compressed to the required storage pressure.

For smaller applications, solid hydrogen storage, or a standard storage pressure of 220 bar may be appropriate. For larger vehicles, higher storage pressures may be required. Also, to ensure refilling can occur within acceptable times, the dispenser unit may also require a high pressure, fast refill compressor.

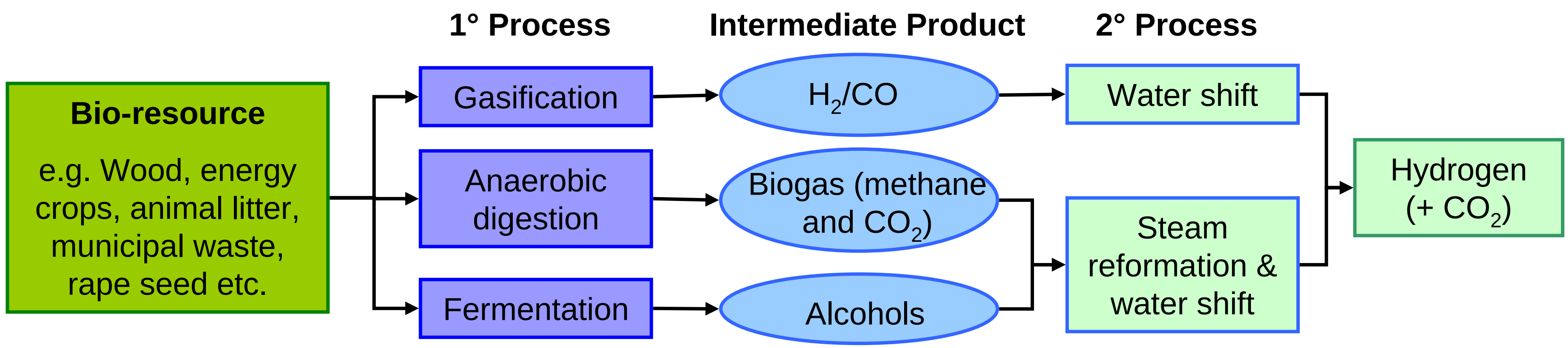


Components of renewable hydrogen energy systems

Hydrogen from biomass

There are a variety of routes for the generation of hydrogen from biomass, including thermochemical process, such as gasification and pyrolysis and biological processes such as anaerobic digestion and fermentation.

The diagram below is a simplified illustration of some of the potential routes from biomass to hydrogen



Gasification is a relatively well-known technology for the generation of hydrogen from heavy hydrocarbons at a large-scale and is being developed as an option for the treatment of municipal solid waste (MSW). However small-scale biomass gasifiers are rare and the technology is still undergoing substantial R&D. The hydrogen produced by small-gasifiers usually requires extensive clean-up before it can be used in a fuel cell, or even gas engine.

Steam reformation and the water-shift reaction are also key processes for production of hydrogen from biomass. Again this technology is common at a large scale, for the production of hydrogen from natural gas, but is less common at smaller-scales. However, recently small-scale reformers have been developed, particularly targeted at generation of hydrogen from natural gas at hydrogen filling stations. For a discussion of this technology, please refer to the '*Hydrogen Refuelling and Storage Infrastructure*' information resource.

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Preliminary Design Issues

Is the project demand led or supply led?

With demand led projects, the main concern is the component at the end of the energy chain. An example might be the requirement for a clean bus service, or an existing local industry that consumes hydrogen. The requirements of the end use (e.g. kg of hydrogen per day) can be used to size/define the remainder of the hydrogen energy system.

A supply led project is one where the primary energy source is well defined. For example, there may be excess wind energy which, because of grid capacity constraints, cannot be exported to the grid. Generation of hydrogen could, in this case, offer an alternative revenue stream for the wind developers. In this scenario, the challenge is to find an appropriate end use for the hydrogen.

Is there is a strong motive for a hydrogen system?

With few exceptions, hydrogen energy systems are novel, technically complex, and relatively expensive. It is important to find clear justification for the development of a hydrogen project. Is the project helping to solve a grid capacity problem, thereby unlocking the significant deployment of wind energy? Is the project contributing to local skills development and retention? Will the project help to demonstrate a technology that is poised to enter commerical markets? The answers to questions like these could help to support the project.

Can an existing technology do just as well as hydrogen?

Part of building a case for the hydrogen project is to analyse whether existing alternative technologies can provide the same service. For example, wind energy could be used to charge a battery for a clean electric vehicle. This system could be very efficient and be cheaper than the hydrogen alternative. On the other hand, battery technology has a number of limitations (recharging time, range). If these are considered serious enough, this could support the case for hydrogen.

Preliminary Design Issues
Linking the primary energy source to the electrolyser

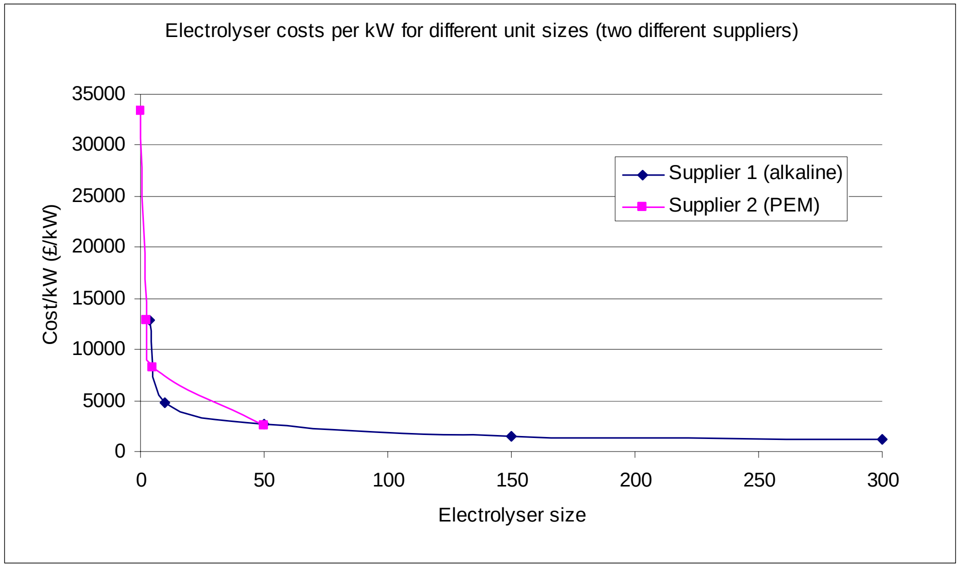
Capacity factors/load factors.

A piece of equipment with a high load factor is in frequent use. In contrast, a piece of equipment with a low load factor is used only rarely, or when it is used, it is operated at part load. For a fixed equipment size (capacity), generally the economics improve with higher load factors. For example, to produce 24kWh of hydrogen per day, generally it would be preferable to use a 1kW electrolyser and run it for 24 hours, rather than use a 24kW electrolyser and run it for only one hour.

However, hydrogen systems have many components with complex and often contradictory requirements. For example, it may be the case that the nature of the primary energy supply precludes the load factor on the electrolyser being as high as one would like. Nevertheless, exploring how to design systems to increase load factors is a useful exercise and helps insure that the resulting system is optimised.

Specific cost and economies of scale

In general, while larger systems have a higher capital cost, the specific capital cost (i.e. $/kW) tends to be lower. Above 50kW, electrolysers have many industrial applications, and the specific cost is relatively constant. However, smaller systems are built in lower volumes and at present, the specific costs ($/kW) are much higher. This issue affects many hydrogen system components and should be borne in mind when the system is being developed.



Preliminary Design Issues
Electrolyser sizing

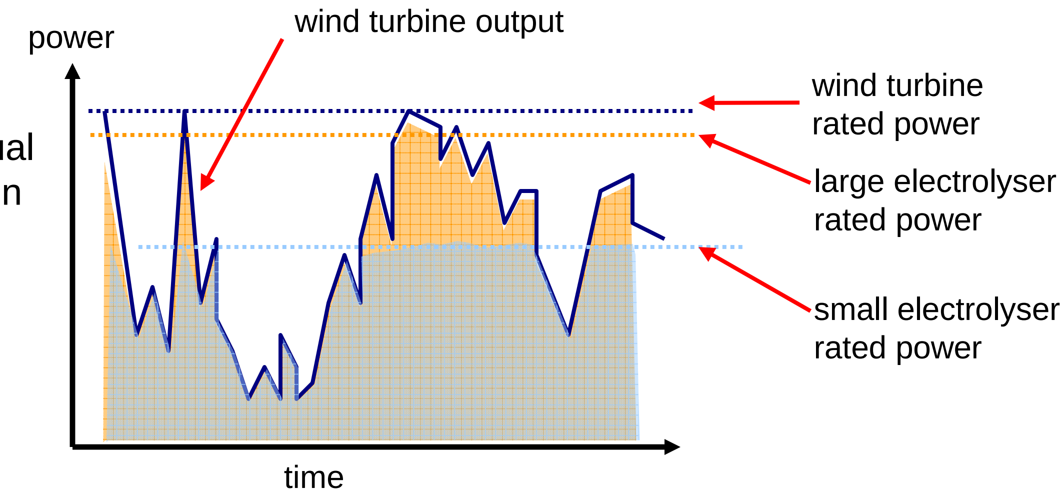
In the example here, the power output from a wind turbine is compared with two sizes of electrolyser.

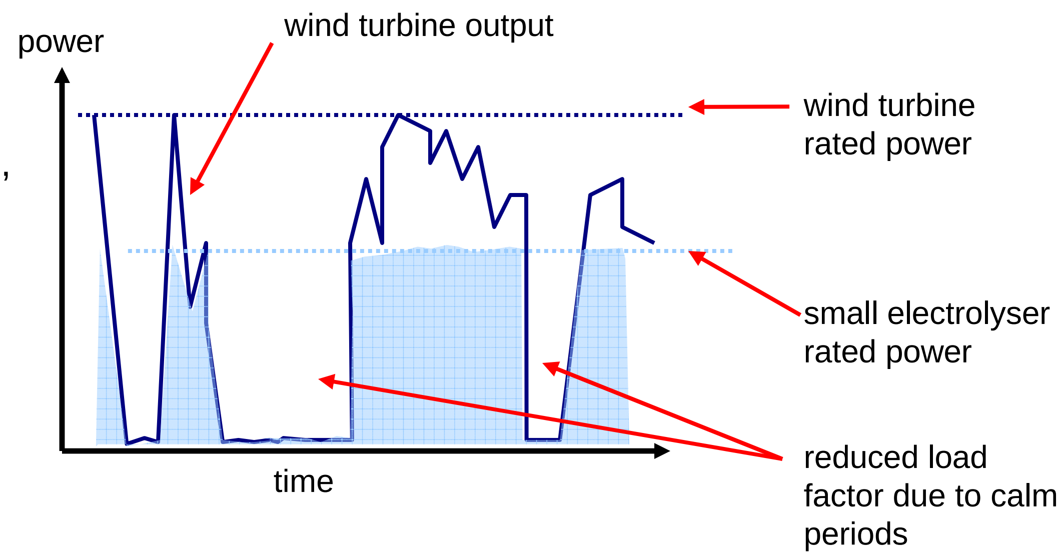
The larger electrolyser has a rated capacity almost equal to that of the wind turbine. As a result, the load factor on this electrolyser (orange shaded area), and that of the turbine, are almost equal (most wind load factors are between 30% and 50%). This is a relatively poor utilisation for the electrolyser.

In contrast, the smaller electrolyser has a better utilisation rate (blue shaded area), and this represents better use of the electrolyser. In this example, the utilisation of the electrolyser gets better as its capacity gets smaller.

When the rated capacity of the electrolyser is less than that of the turbine, the turbine must either be shut down, or power routed to an alternative use. For larger applications this might be export to the grid, for smaller turbines a resistive heating load could be used.

Note that if the turbine frequently produces no output, this will also reduce the load factor on the electrolyser, even if the electrolyser is small.





Preliminary Design Issues
Electrolyser sizing

The electrolyser is a key system component. Electrolysers can be a substantial cost element in the overall project, so correct sizing is important. The electrolyser needs to be sized so as to produce the required amount of hydrogen, however this could be achieved with a large electrolyser operating at a low load factor, or a smaller electrolyser operating at a high load factor. Optimal system designs can result in substantial cost savings.

Grid connected electrolysers

If the electrolyser is grid connected (and assuming the grid is relatively reliable), the electrolyser can be operated nearly 24 hours per day in order to provide the required hydrogen. While the system would need to be oversized somewhat to account for maintenance requirements, ultimately a relatively small, cost effective electrolyser could be used. As a result, the capacity factor on the electrolyser can be high*.

Renewably generated hydrogen

Most renewable energy sources are intermittent. For example the load factor on a wind turbine may be between 30%(in less windy areas) to 50%(in areas where the wind is more constant). If the electrolyser capacity is the same as that of the turbine, then the load factor on the electrolyser cannot be higher than the load factor on the turbine.** This low load factor on the electrolyser can result in high system cost.

It may be more cost effective to increase the capacity of the renewable primary energy resource, relative to that of the electrolyser. Then, the load factor on the electrolyser may be increased. Even so, there will still be times when little or no energy is generated, and so the load factor on the electrolyser may not be very high***.

*Although use of grid electricity to generate hydrogen is not preferable from a CO_2 perspective, allowing some use of grid electricity for electrolysis can limit the need for over-sizing of renewable generators and electrolyser plant, with significant benefit for the system economics

**An exception is a hybrid system where grid energy is supplied to the electrolyser during lulls in the wind.

*** These effects can only be quantified by (at least) hourly or sub hourly simulations of the complete system throughout the year.

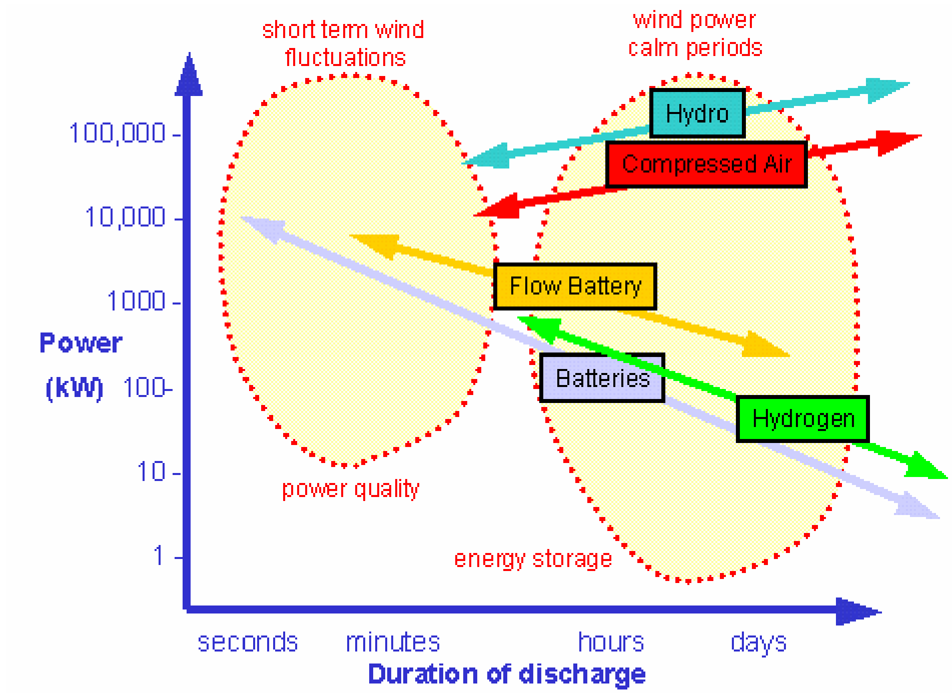
Preliminary Design Issues
Hydrogen Storage

Storage capacity requirements

The overall project requirements will help define the amount of hydrogen to be stored. For example, the aim of a project may be to demonstrate the use of hydrogen as a means for buffering or smoothing out wind energy. This could be on a second-by-second scale (smoothing out voltage fluctuations), or it could be used to supply power though long lulls in the wind (over a period of a few weeks, for example).

Economics of energy storage

While energy storage projects can be very valuable, it is important to keep note of the economics. No storage system is 100% efficient – there is always some energetic loss, and also there are capital and running costs to consider. A small storage system that is filled and emptied very often, would add a small premium onto the cost of energy. In contrast, a larger storage system (a seasonal energy store, for example) would be used much less frequently and, because of its size, come at a higher cost. This system would add a larger premium onto every unit of energy (and hydrogen) that passes through it. To remain economic, the energy produced by the store must have a higher value than the energy consumed by the store.



The selection of the most appropriate type of energy storage will depend on the power that the storage system needs to supply and the duration of time over which that power is to be supplied. The plot above suggests that when high levels of power is required in short bursts, battery technologies may be more appropriate than hydrogen storage. Hydrogen is more appropriate when the duration of discharge is longer, e.g. in a wind power system, hydrogen storage might be used to provide power when there is a lull in wind speed that lasts several hours or days but would be less appropriate for smoothing out the short term fluctuations in wind power.

Preliminary Design Issues
Hydrogen Safety

All hydrogen energy systems must be designed to be safe. The excellent safety record that industrial hydrogen systems enjoy demonstrates that systems can be engineered to be very safe indeed.

Safety issues should be considered from the outset of a project. While individual components should not inherently be dangerous, the integration of these components into complete systems is where safety should be designed in.

During early feasibility, it is recommended to discuss the project with an experienced Hazop (Hazard and safety operational studies) expert. Industrial gas merchants undertake such analyses routinely; also the Health and Safety Executive can provide useful references for outline design guidance. However, during detailed design, a full Hazop analysis should be conducted.

Well engineered systems can reduce risk of accidents to near negligible levels. However, it should always be borne in mind:

- Hydrogen has very broad flammability limits

-Equipment containing gas pressures of 220 bar and above can be dangerous if used incorrectly.

Further discussion of hydrogen safety issues and the regulations, codes and standards being developed to control hydrogen use in energy applications is given in the Hydrogen Vehicles and Hydrogen Refuelling and Storage Infrastructure resources.

Tests by the University of Miami show H_2 on the left and gasoline on the right. Major studies by automobile manufacturers show that H_2 can be as safe, or safer, than existing fuels, but they must be engineered to achieve these safety levels. *(Tests performed by Dr Michael Swain, University of Miami, 2001)*

Preliminary Design Issues
Hydrogen end use

A hydrogen project is not complete without an appropriate end use. This is a relatively novel issue for energy systems, as the end uses tend to already be in place.

Matching supply and demand of hydrogen can be technically challenging, however another important dimension is the level of buy-in to the project that the end-user has. For the end user, the use of hydrogen can entail higher costs, extra training requirements, lower reliability and unusually high maintenance requirements etc. If the end user is very cost focused (a commercial bus operator for example) then these issues could be a significant barrier to their involvement in the project. Despite this, early on in project development it is important to highlight both the benefits and drawbacks of the use of hydrogen, to ensure commitment from all parties. There are many examples of worthy hydrogen generation projects that failed to find an end use.

For this reason, it may be useful to consider small scale demonstrator projects where the project initiators have control over the production and end use of the hydrogen. Further discussion of a variety of potential end-uses for hydrogen can be found in the *Portable and Stationary Fuel Cell Applications*, *Hydrogen Vehicles* and *Novel Hydrogen Applications* resources.

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Hydrogen Energy Project Funding

The use of hydrogen as an energy vector is still relatively novel. While this provides an opportunity for innovation, it also means that most hydrogen energy projects require significant levels of grant funding in order to be viable.

EC FP7 funding – The EC is developing its HYCOM (Hydrogen Communities) initiative for Framework 7 round of funding. HYCOM is meant to support large scale integrated projects, with many partners across Europe. Previous discussions with EC commissioners has highlighted the potential for regions in Scotland (where there is a wind resource, but insufficient grid capacity), to introduce hydrogen as an energy vector. Preparing integrated projects (as the coordinator) requires circa 3-4 man months of work, and it may be preferable to keep a watching brief on relevant proposals in order to become a partner. The FP6 funded Roads2Hycom and HYlights projects are helping in the development of FP7 and should be referred to at regular intervals.

Carbon Trust - The Carbon Trust has funding under the Low Carbon Innovation Program (LCIP) to support development and demonstration of innovative technology. Hydrogen and fuel cells are priority areas for the Trust.

DTI - new hydrogen funding - The DTI has received a hydrogen strategy report, which recommended a long term strategic framework for hydrogen development. A demonstration fund of £15M has been announced. However the fund has to clear EC competition law and it is unlikely that the fund will be opened until early 2007.

DTI - New technologies fund - the DTI will support R&D into fuel cells under the New technology program. This support is focused on R&D, but may support demonstration if sufficient innovation is realised.

Energy Savings Trust - have a number of programs which could support various components of a hydrogen project.

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Hydrogen Initiatives

The most notable projects in the H&I are the Pure project on Shetland which is a wind hydrogen initiative, and the hydrogen lab in the Lews Castle College of UHI.

PURE (Promoting Unst Renewable Energy) (http://www.pure.shetland.co.uk)

The PURE Project has delivered a zero emissions, off-grid renewable hydrogen hybrid power supply to an industrial estate on Unst, the most northerly island in the UK. The project incorporates high and low cost stored energy (hydrogen and thermal) as well as a fuel supply for the UK's only road licensed renewable H_2 fuel cell car. The system consists of two 15 kW wind turbines and an innovative load management system that controls supply of renewable electricity to the electrolyser, for hydrogen generation, and to thermal storage units. Building on the success of the project, the PURE Energy Centre has recently been established on Unst to investigate and commercialise the many R&D opportunities arising out of the PURE project. The core products of the PURE Energy Centre are training, consultancy, a "pay-as-you-go R&D facility" and the supply of PURE Energy Systems.

Western Isles Hydrogen Lab

The Hydrogen Lab has been established at Lews Castle College in Stornoway by the University of the Highlands and Islands. The lab contains a variety of small-scale hydrogen generation, storage and fuel cell technologies for educational and research purposes. The establishment of the lab is a step forwards in the Western Isles plans to develop an energy innovation zone on the islands. A central plank of these plans is the council's vision for a 'Hebridean Hydrogen Park', where it is intended that a hydrogen production facility will be established using electricity from wind turbines and generated from the biogas produced by an anaerobic digestion waste treatment plant. The hydrogen produced will be used in the hydrogen lab, to power hydrogen vehicles and a variety of other potential end-use applications.

Hydrogen Initiatives

As the interest in hydrogen energy grows, an increasing number of projects are being established around the world at a variety of scales. Some examples of the types of initiatives underway internationally are given below:

Crest, Loughborough University (www.lboro.ac.uk/departments/el/research/crest/index.html)

The CREST project is based around a renewable energy system aiming to give self sufficiency to a farm and residential dwelling. A combination of wind turbines and photovoltaics are used to power the system which includes a variety of energy storage systems. These include batteries and an electrolyser-fuel cell system. The hydrogen system is based around a 10 Nm^3 IMET electrolyser from Hydrogen Systems. The hydrogen produced is compressed and stored and used to power a stationary PEM fuel cell. The electrolyser was supplied and commissioned in autumn 2003.

Achill Island, Republic of Ireland (http://www.managenergy.net/products/R220.htm)

Achill Island, with approx 1300 inhabitants, took part in a recent Altener project aimed at 100% renewable Islands. The lack of suitable renewable fuel for transport was seen as the major barrier to a true 100% self sufficient renewable Island. A study by Keogh[1] investigated the options for generation of H2 from renewables on the island and use of this in grid balancing and the transport sector. No further reports of progress were obtained.

Iceland (www.newenergy.is/newenergy/en/)

Various large industrial players including Shell and Daimler Chrysler have joined forces with local players to create Iceland New Energy and a vision for an entirely sustainable Iceland by 2040. The aim is to use Iceland's abundant geo-thermal and hydro-electric resources to create a society free from fossil fuels. The initiative has begun with the delivery of a hydrogen filling station and three Daimler Chrysler Citarro fuel cell buses. The island is also planning a major conversion of the fishing boat fleet to hydrogen powered fuel cells.

[1] 100% sustainable generation on Achill Island, Sustainable Energy Research Group, University College Cork, Department of Civil and Environmental Engineering.

Hydrogen Initiatives

Utsira Island, Norway (www.hydro.com/en/our_business/oil_energy/new_energy/hydrogen/winds_change.html)

Utsira municipality, Norsk Hydro Energy and Haugaland Kraft have developed a project investigating the technical and economic possibilities for a wind–hydrogen system at Utsira. In periods of little wind, the hydrogen can be used for power and heat production via fuel cells. Electrical power produced in a wind turbine is used for hydrogen production in an electrolyser process. The hydrogen is compressed and stored in pressurised tanks. The hydrogen can in turn be used for power and heat production using fuel cells in times of little wind. The hydrogen system (60kW – 216 Megajoules) is dimensioned to cover the energy demand of Utsira Havstuer. The wind turbine (600 kW – 2160 Megajoule) is dimensioned on the basis of covering parts of the municipality's demand for electrical power.

Prince Edward Island Hydrogen Village, Canada (www.gov.pe.ca/envengfor/index.php3?number=1007450&lang=E)

Prince Edward Island is a focus for renewable energy and energy innovation efforts in Canada. The Island hosted a conference in summer 1993 investigating opportunities for the development of the countries nascent H2+FC industries, focused on developments on the Islands[1]. Canada is unusual in its surfeit of H2+FC industries, including Ballard (PEM fuel cells), Dynetek (storage), Stuart Energy (electrolysers). The PEI energy corporation has published its intentions to include H2 demonstrations as an integral part of their energy plan[2].

The PEI Hydrogen Village is a $10M initiative. The region announced in 2005 the acquisition of $5.1M from the federal Canadian government. $2.5M funding comes from regional development, and the remaining $2.5M comes from the revenue from a local wind farm owned by the local authority. A significant industrial partner is Hydrogenics, which makes electrolysers and fuel cells.

[1] The PEI Wind Hydrogen Symposium, Charlottesville, Prince Edward Island, Canada, June 2003.

[2] Prince Edward Island Renewable Energy Strategy, PEI energy corporation, June 2003