1. EUSUSTEL WP3 Report on the Hydrogen Economy

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1.1 Introduction

Although hydrogen (H_2) has attracted considerable attention as an energy carrier of the future, it is rarely used as such, at present. It is produced and used worldwide in the petrochemical industry for petroleum refining and also produced as a by-product in some chemical industries.

The primary focus of a possible shift towards H_2 thus far has been on its applications in the automotive sector. In that sector, it is one of the few solutions for shifting away from fossil fuels, which is desirable both for environmental and security of supply reasons. However, H_2 can also be used for direct heating and for power production, although whether this latter use is an energy efficient solution depends on the situation.

This report discusses the situations in which H_2 might be used for power generation, possible sources of the H_2 and technologies for power production from H_2: fuel cells, gas turbines and internal combustion engines.

1.2 General issues concerning hydrogen technologies

The use of H_2 for power generation is not likely to be a major option for the short to medium-term, for reasons both of costs and the overall efficiency of primary energy resource use.

Like electricity, H_2 is an energy carrier that is clean at the point of use but that must be generated from primary energy resources. Due to the capital costs and energy losses associated with the conversion, both electricity and H_2 are inherently more expensive (per kWh) than the primary resource from which they were produced.

However, there are a number of specific situations in which H_2 might be a viable option for power generation; these are described in the section 1.2.1. As an energy carrier, rather than a source, the environmental credentials of H_2 are entirely dependent on the way in which it is produced transported and utilised; this is discussed in section 1.2.2.

1.2.1 Peculiarities

As H_2 is, in general, more expensive than primary energy resources, there are few situations in which its use for stationary power generation[1] would be economic in comparison to direct generation of electricity from the primary resource.

Some situations have been identified in which H_2 might potentially be used for power generation, described below.

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[1] The use of hydrogen in fuel cells for vehicle propulsion produces electricity to drive the electric power train, but that is outside the scope of this report.

Primary resource is remotely located

In a situation in which the primary energy resource is located where there is no existing electricity transmission infrastructure (or insufficient transmission capacity) or where there are surplus renewable energy resources, the resource could be used to produce H_2 rather than electricity. The H_2 could then be transported to a population centre and used either as a transportation fuel or for stationary power generation, ideally in a Combined Heat and Power (CHP) system, thereby maximising energy utilisation.

One example of such a situation could be offshore wind resources, such as those off the coast of Scotland. Areas where the wind resource is large tend to be sparsely populated, precisely because of the local climate. On the island of Unst, in the Shetland Islands off the coast of mainland Scotland, a pilot wind-H_2 scheme was established (described in [1]), which could be scaled up to serve all of the inhabitants' energy needs as well as potentially exporting H_2 to mainland Scotland.

Iceland is keen to develop a H_2 economy, due to its large renewable energy resource (geothermal and hydro) and the expense of importing oil to its remote location. The Euro-Hyport study is investigating the feasibility for the export of H_2 from Iceland to the European continent.

Similarly, one possible source of large-scale H_2 production is from solar energy in deserts. For example, the Sahara desert could potentially provide huge quantities of renewable H_2, shipped to Europe in liquid form at a cost of US$7-9/GJ [2].

Carbon capture and storage

In order to capture and store CO_2 most cheaply, this should be done on as large a scale as practicable, using technologies that allow a large proportion of the CO_2 to be captured and transporting the CO_2 as short a distance as possible [3]. In practice, this may mean a few large plants that produce energy from fossil fuels or biomass, located near to sites for CO_2 storage.

However, such a large-scale approach may conflict with other aims of energy policy that encourage smaller-scale power generation near to the point of consumption to minimise transmission losses and utilise the heat in a CHP system. One way to meet both objectives might be to produce H_2, or syngas[2], on a large scale near to sequestration sites and then transport this via pipeline to areas of heat and power demand for use in CHP on a smaller scale.

As part of the UK's Carbon Abatement Strategy [4], £25m (€35m) was allocated in June 2005 for fossil technologies associated with carbon capture and storage. This may

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[2] Synthesis gas, known as syngas, is the product of processes such as gasification and is generally a mixture of H_2, CO_2, carbon monoxide (CO), water and sometimes methane. Depending on the proportions of H_2 and CO, syngas can be quite energy-dense. If necessary, the CO can be converted to H_2 using the water gas shift process, which requires the addition of water vapour: $CO + H_2O \Rightarrow CO_2 + H_2$

involve a coal gasification project with sequestration of the CO_2 and production of H_2 which would be used for power generation of up to 800 MW [5].

Availability and demand for energy resources do not coincide

While conventional thermal power generation is schedulable to coincide with demand for electricity, many sources of energy cannot be scheduled to produce energy only when required. These energy sources are generally renewable and fall into two categories: predictable sources, such as tidal and – in some climates – solar, and unpredictable sources, such as wind and wave.

This situation offers an opportunity for the use of H_2 for electricity storage, which is discussed in detail in a separate report. While with current technology conversion to H_2 and back to electricity does not provide a particularly good round-trip efficiency[3] compared to some other electricity storage options, H_2 does provide greater flexibility as it can be used for transport or in a CHP system. Research efforts also proceed to increase conversion efficiency.

Using H_2 in this way may particularly apply to island systems that are predominantly reliant on intermittent renewable resources. The Hydrogen Stand Alone Power Systems (H-SAPS[4]) project under the EU Altener program examined many of the issues for such systems. The recommendations of this study [6] included:

- undertaking targeted analysis of potential markets, focusing on portable applications, H-SAPS, grid islanding, large wind/H_2 systems and residential units;
- setting cost targets for each component of the stand-alone system;
- review existing regulations that discourage ‘islands’ within a grid system; and
- focused research on areas where there are critical barriers.

The study identified a number of critical barriers, presented in prioritised order:

- High costs of both electrolyser and fuel cell solutions
- Low energy efficiency of the hydrogen energy system - especially critical for small systems
- Development of easy-to-use and energy efficient gas and electricity control systems
- Short lifetime warranties and little lifetime experience for PEM electrolysers and PEM fuel cells.

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[3] Round-trip efficiency is defined as the proportion of the electricity supply entering the storage system that is available upon exit. In the case of H_2 as an electricity store, the round-trip efficiency would be in the region of 40-50%, only around half that from the most efficient technologies.

[4] http://www.hsaps.ife.no

Back-up / off-grid power

Essentially replacing diesel generators, this application would see H_2 used as back-up for essential services, e.g. in hospitals, and also for off-grid applications. In addition to the potential to decarbonise such forms of power generation, there may be other important benefits, such as the reduction in local pollution and noise.

While H_2 fuel cells could be used for portable applications such as consumer electronics, the focus in this area is currently on the development of direct methanol fuel cells (DMFCs).

Availability of surplus energy

H_2 is currently produced as a by-product in a number of industrial processes, mainly the production of ethylene, chlorine and acetylene via electrolysis. At present, this is generally mixed with natural gas and used for thermal processes

In future, where H_2 is being produced for the transport sector in a plant with a large capacity, it is likely that there will initially be insufficient demand from transport to fully utilise the plant's production capacity. In some situations, such as where H_2 is being produced from waste, there is good reason - and likely fiscal incentive - to operate the plant at full capacity, which may lead to surplus H_2 being available for power generation, until displaced by transport demand. This linkage between stationary and transport sectors could help break the typical problem of low initial demand threatening the viability of production and infrastructure investments, accelerating the move to H_2 in both sectors.

1.2.2 Environmental aspects

In addition to being generally more expensive than direct production from primary resources, power generation from H_2 can result in higher CO_2 emissions from the complete energy chain. The additional conversion step required for production of H_2 and then electricity reduces the overall efficiency of the energy chain, resulting in higher CO_2 emissions when using non-renewable resources. Even when renewable resources are used, the lower efficiency of the energy chain means that a greater quantity of renewable resource is required per kWh generated than for direct renewable electricity use. As renewable energy resources are at a premium in most countries that are trying to mitigate climate change, this is likely to lead to higher overall CO_2 emissions.

The CO_2 emissions relating to the use of H_2 are entirely dependent on the method of production and distribution. H_2 can be produced from a wide variety of energy sources, at a range of scales and distributed in different ways, and one cannot attribute a single emissions factor to it, or even a narrow range.

Much of the work on CO_2 emissions from H_2 energy chains has focused on its use in the transport sector. Such studies generally take a 'well-to-wheels' approach, comprising two parts: a 'well-to-tank' analysis to calculate the carbon-intensity of the H_2 used, and a 'tank-to-wheels' analysis that focuses on the efficiency with which the H_2 is used. The well-to-tank component of such analyses identifies the CO_2 emissions from each part of the energy chain, from extraction and distribution of the original feedstock, through H_2 production and compression/liquefaction. This ‘well-to-tank’ component therefore provides a good representation of the range of CO_2 emissions that are ‘embodied’ in a megajoule of H_2, though the ‘tank-to-wheels’ component of such analyses are not directly relevant for power generation from H_2.

The most comprehensive well-to-wheels study to date was undertaken in 2003 by CONCAWE, EUCAR and the Joint Research Centre of the EU Commission (JRC). This report evaluates “the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options” [7]. This includes a number of automotive fuels, including H_2; Figure 1 illustrates the chains for compressed H_2 considered in the study.

Figure 1 Representation of hydrogen energy chains (from Concawe et al, 2004)

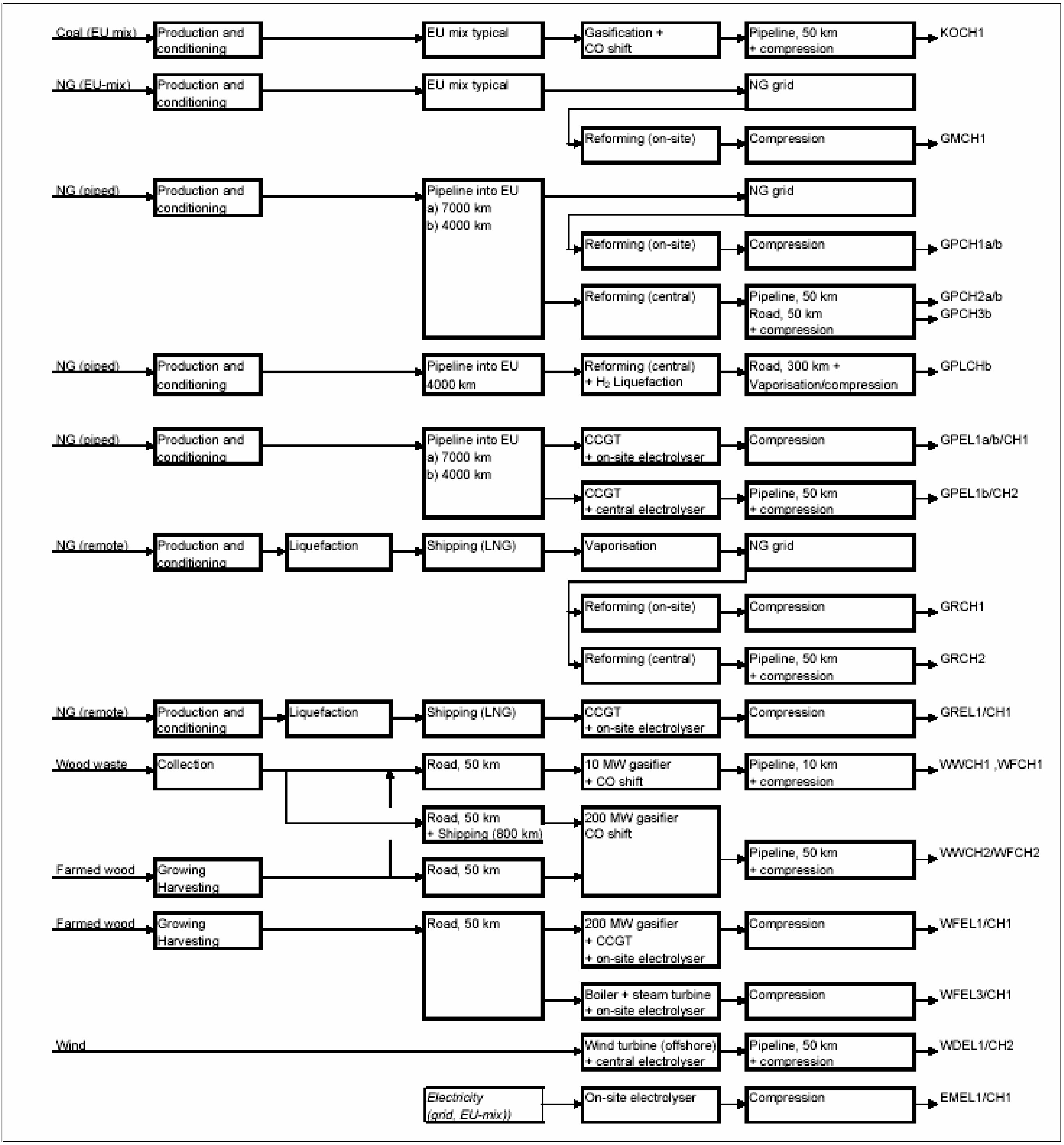


Figure 2 Well-to-tank CO_2 emissions for electricity to H_2 chains

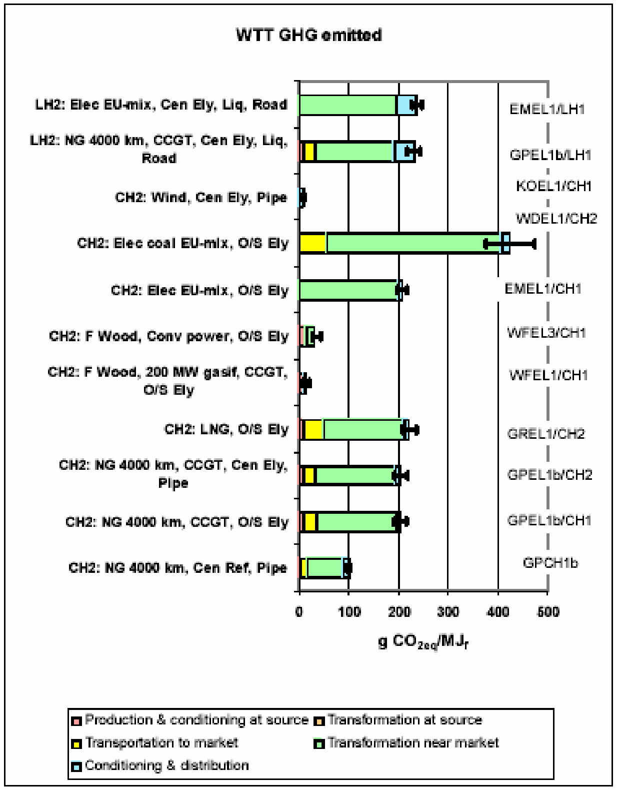


Figure 3 Well-to-tank CO_2 emissions for natural gas to H_2 chains

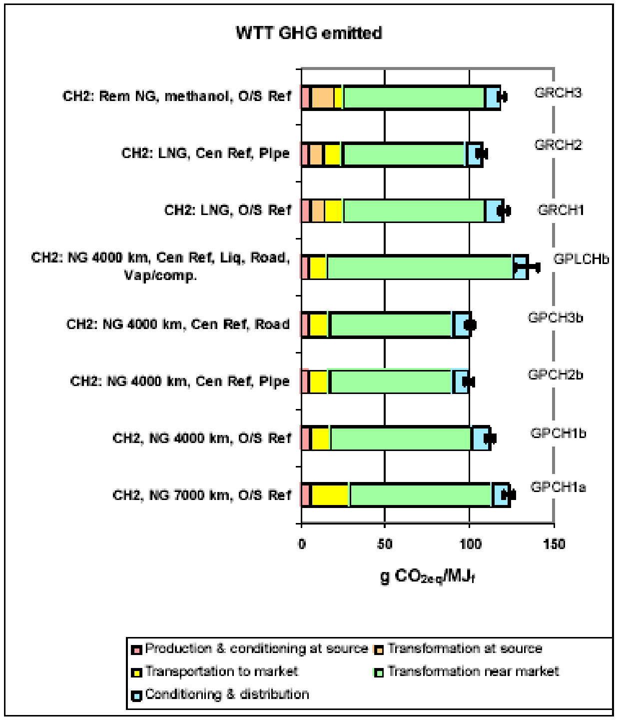
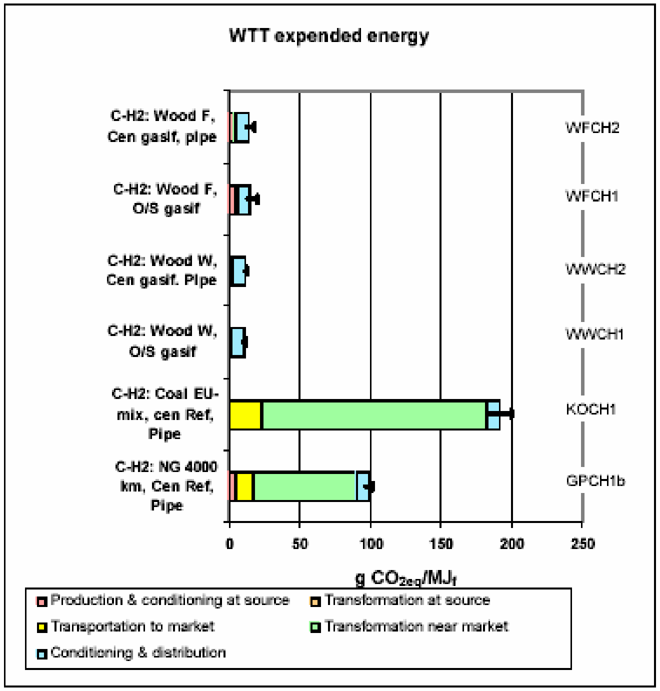


Figure 4 Well-to-tank CO_2 emissions for wood and coal to H_2 chains



All Figures above are taken from Concawe et al (2004)

The results of the well-to-tank component of this study are presented in Figures 2-4, showing the chains for H_2 from electricity, natural gas, wood and coal. The range of results for the carbon-intensity of the H_2 chains is very wide, especially for the electrolysis routes. The lowest well-to-tank emissions are less than 20g CO_2 equivalent per MJ, from a centralised wind-H_2 route using pipelines for H_2 distribution. The highest CO_2 is a factor of more than 20 greater at over 400g CO_2 equivalent per MJ, with the H_2 coming from electrolysis using electricity from existing coal-fired power stations.

The analysis presented above covers many of the ways in which H_2 might be produced and distributed primarily for use in the transport sector; if an infrastructure for the transport sector is developed, this is also likely to be the main source of H_2 for the power sector. However, as described in section 1.2.1, H_2 is sometimes produced as a by-product of industrial processes. Studies that have considered this as a source of H_2 for the transport sector have tended to assume that the H_2 would otherwise be mixed with natural gas and used in thermal processes. They have therefore treated the CO_2 emissions for this H_2 as those that would otherwise result from combustion of the natural gas displaced in such processes [8].

1.3 Description of hydrogen technologies

As the H_2 economy is still in the early stages of development, few technologies that have been designed or optimised specifically to run on H_2 could be described as mature. The H_2 economy is usually discussed in conjunction with fuel cells, whether for transport or stationary applications. However, H_2 can also be used in conventional combustion technologies such as gas turbines and internal combustion engines (ICEs), though some modifications are required.

Presently, there are no commercially available gas turbines designed to run on pure H_2, which has a higher temperature of combustion than that of natural gas. Such turbines are likely to be of significant scale and require specialist materials, and as such may only be considered for larger scale power generation [9]. H_2 can be mixed with natural gas for use in conventional gas turbines. Such mixtures can improve the performance characteristics of the turbine, for example the wide flammability limit of hydrogen allows the turbine to be operated at lower loads than otherwise possible [10].

As electrolysers would play an important role in the interaction between a H_2 economy and electricity system, these are also considered a key technology and are discussed in detail below.

1.3.1 Hydrogen Fuel Cells

As electrochemical devices, fuel cells are inherently more electrically efficient than combustion technologies. Various types are commercially available or in development, although some of these, such as direct methanol, molten carbonate and solid oxide fuel cells are designed for direct use of hydrocarbons. The two main types designed to run on pure H_2 are proton exchange membrane (PEM) and alkaline fuel cells.

Fuel cells are particularly flexible because they are inherently modular and could potentially be assembled economically in units of varying sizes – from a few watts to at least 10MW. Fuel cells can therefore cover virtually any size of end use requirement, from small appliances to individual homes, large office buildings and on to industrial facilities and merchant power.

Alkaline fuel cells require oxygen, rather than air as the oxidant, as the cell degrades when operated in the presence of CO_2. As such, they are likely only to fill small niches and therefore not benefit from the large scale investment and deployment to reduce costs and benefit from technical development. Such niches may include the use of regenerative systems for storage of electricity, e.g. in stand-alone power systems, where oxygen can be produced, stored and used in parallel with hydrogen. However, costs would have to reduce substantially in order to compete with other electricity storage options, many of which have significantly superior round-trip efficiencies.

In contrast, the development of PEM fuel cells, the main candidate for automotive applications, is being driven by the transport sector. This may result in more extensive technical development and cost reductions than might otherwise occur and as such, PEM is likely to be the long-term choice for power generation from sources of pure H_2. PEM fuel cells are therefore the main fuel cell technology considered here for power generation from H_2.

PEM fuel cells run on H_2 and air, operating at a temperature of approximately 80 °C, allowing a short start-up time, which is useful for vehicles. This low operating temperature limits the applicability of PEM fuel cells for CHP, although they have a high electrical efficiency.

PEM fuel cells are sensitive to contamination of the H_2 stream with carbon monoxide (CO), which permanently damages the membrane and leads to a loss of performance. It is therefore imperative that supplies of H_2 for these fuel cells are pure. This will be the case for H_2 produced for the automotive sector, as these will also use PEMs, and also for H_2 produced via electrolysis, e.g. in a stand-alone power system based on renewable electricity [9].

1.3.2 Hydrogen Internal Combustion Engines (H_2ICEs)

In 2005, Ford Power Products introduced an H_2ICE for stationary power generation, paralleling Ford's introduction of H_2ICE vehicles. Ford currently has two different hydrogen engines prototyped in the industrial marketplace: a 4.2-litre V-6 engine and turbocharged 6.8-liter V-10 engine, rated at 60 and 140 kW respectively [11]. H_2ICEs are also being introduced by other automotive manufacturers such as BMW, although they are not making this engine available for stationary power generation.

The wide flammability range of H_2 means that an ICE can operate using a lean mixture, i.e. with a lower ratio of fuel to air. This generally yields a higher efficiency and also a lower final combustion temperature, reducing emissions of pollutants, such as nitrogen oxides. However, there is a limit to how lean the engine can be run, as lean operation can significantly reduce the power output due to a reduction in the volumetric heating value of the air/fuel mixture. H_2ICEs can run on A/F ratios of anywhere from 34:1 to 180:1 by mass, compared to a ratio of 14.7:1 for gasoline ICEs [12].

The power output of an H_2ICE depends on the method used to mix the H_2 with air prior to injection into the combustion chamber. Direction injection yields a maximum output 15% higher than an equivalent gasoline engine, while carburetted and port injection methods yield a power output 15% lower than a gasoline engine. However, these power outputs are only available at the stoichiometric air/fuel ratio (34:1), at which H_2 engines produce a large amount of NOx. At double this air/fuel ratio, NOx formation is reduced to nearly zero, but the power output of the engine is reduced to around half the maximum power, due to reduction in the heating value of the air/fuel mixture.

The NOx produced by gasoline engines can also be reduced by increasing the air/fuel ratio; however, this also has the effect of increasing emissions of carbon monoxide and hydrocarbons. Consequently, H_2 engines are typically designed for a higher air/fuel ratio than a gasoline engine and therefore tend to be larger in order to achieve the same power output.

Mixtures of natural gas and H_2 can be used in ICEs, with the degree of modification required depending on the proportion of H_2. At mixtures up to 20% H_2, a natural gas engine can run unmodified; a mixture of 80% natural gas and 20% H_2 is known as Hythane[5] and results in a disproportionate reduction in local emissions (i.e. greater than 20%).

1.3.3 Electrolysers

Given the potential for H_2 to be used as an energy store, for regeneration of power at a later time, technologies for producing the H_2 from electricity are important. There are 3 types of electrolyser that may play a role in H_2 production:

- PEM electrolysers
- alkaline electrolysers
- high temperature electrolysers

The largest electrolyser units currently available for H_2 production are of the alkaline type and produce slightly more than 1 tonne H_2 per day, consuming 2.3 MW. PEM electrolysers have significantly higher unit costs than alkaline and are therefore only available in small sizes [13]. Demonstration projects thus far have generally used alkaline electrolysers.

Alkaline electrolysers use potassium hydroxide (KOH) in an aqueous solution as its electrolyte. They are generally operated at load factors of between 80-100% and switched off while not in use. Units should not be operated below 25% load for safety reasons, as the KOH electrolyte contains small quantities of dissolved H_2 and O_2, which can find

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[5] *Hythane* is a registered trademark of Brehon Energy PLC

their way into the wrong output stream. At lower loads, less ‘fresh’ gas is produced to dilute these impurities leading to higher levels of impurity in both the H_2 and O_2 streams. Thus, while the electrolysis unit itself actually performs more efficiently at low loads, more gas cleaning is required, resulting in a higher overall energy consumption per unit of H_2 produced [14].

Despite assurances to the contrary from manufacturers, experience at the HARI demonstration project in the UK suggests that the current generation of alkaline electrolysers does not work well when directly connected to an intermittent electricity supply [15]. While the unit performs acceptably when the power input is within the range of 25-100% of the electrolyser’s rated capacity, below 25% the unit must be switched off. Switching the unit off leads to some of the surface of the bipolar plates, including the catalyst, being stripped off; as a consequence the performance and lifetime of the unit are significantly reduced. The HARI project is therefore buffering the electricity input using ZEBRA batteries, in order to minimise the number of occasions on which the electrolyser is shut down.

Alkaline electrolysers could be deployed in conjunction with alkaline fuel cells in a regenerative system for electricity storage; the production of oxygen in the electrolysis process could be used in the fuel cell, removing problem of carbon dioxide reactions with the alkaline electrolyte. Experience at HARI and previously wind-electrolysis experiments [16] suggest that the current overall efficiency of electricity to H_2 conversion using intermittent sources is in the range 4.8-5.4 kWh / Nm^3. This compares to performance in steady-state conditions of 4-4.5 kWh / Nm^3.

Proton Exchange Membrane (PEM) electrolysers use the same materials as PEM fuel cells and operate at similar temperatures. PEM electrolysers produce relatively pure hydrogen and can therefore be used in conjunction with a PEM fuel cell for regeneration of electricity. Indeed, it is possible for a PEM system to be designed to operate both as a fuel cell and in reverse mode as an electrolyser. Such systems are, however, not at a very advanced stage of development.

PEM electrolysers are currently only available from one manufacturer: Proton Energy Systems, whose currently available products are in the range 0.5-6 Nm^3 per hour or 1.1-13 kg per day. The efficiency of these units is significantly inferior to that of alkaline electrolysers, at 6.7-7.3 kWh/Nm^3 [17]. It is likely that their costs and performance will be strongly linked to that of PEM fuel cells and may therefore overtake alkaline electrolysers on a cost basis if PEM fuel cells become widespread in the automotive sector.

High temperature electrolysers (HTEs) are only at the research and lab-scale demonstration stage. HTEs are suitable for situations in which a large heat source is available for which there is no other load, e.g. a nuclear power station. The energy input provided by the heat reduces the electricity demand per unit of hydrogen output. However, one issue in their development thus far has been to find materials that can cope with their high operating temperature (800-1000°C). HTEs can actually use heat sources from 150°C, though the thermodynamic advantage is greater for higher temperatures [18].

Given their requirement for a substantial heat input, the prospects of HTEs would appear to depend on political decisions regarding the future of nuclear power. While there may be a few other isolated heat sources that provide a potential niche, it is likely that the necessary technological development would only occur if driven by significant new nuclear build.

1.3.4 Future Hydrogen Technologies

Significant development in technologies is not only expected, it is vital to the emergence of H_2 as an energy vector. The necessary developments are both technical and economic; the US Department of Energy (DOE) has set targets for both of these aspects of technology development [19]. The technical targets cover the entire sector, from H_2 production, through delivery and storage to final use in fuel cells / ICEs. The targets for fuel cells are as follows:

- By 2010, develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW; by 2015, a cost of $30/kW.
- By 2010, develop a distributed generation PEM fuel cell system operating on natural gas or LPG that achieves 40% electrical efficiency and 40,000 hours durability at $400-$750/kW.
- By 2010, develop a fuel cell system for consumer electronics with (<50 W) an energy density of 1,000 Wh/L.
- By 2010, develop a fuel cell system for auxiliary power units (3-30 kW) with a specific power of 100 W/kg and a power density of 100 W/L.

Tables 1-3 present the more detailed targets for fuel cells, for consumer electronics, transportation and auxiliary power units (APUs). The two main focuses for these applications are generally on cost reductions and substantial (fivefold plus) improvements in durability, both of which are also important for stationary power applications.

Table 1 Technical Targets: Fuel Cells for Consumer Electronics (sub-Watt to 50-Watt)

Characteristic	Units	2004 Status	2006	2010
Specific Power	W/kg	10–20	30	100
Power Density	W/L	10–15	30	100
Energy Density	W–h/L	50–200	500	1,000
Cost	$/W	40[a]	5	3
Lifetime	hours	<1,000	1,000	5,000

Source: US DOE [19]

Table 2 Technical Targets: 80-kWe (net) Transportation Fuel Cell Stacks Operating on Direct H_2

Characteristic	Units	2004 Status	2005	2010	2015
Stack power density[b]	W/L	1330[c]	1500	2000	2000
Stack specific power	W/kg	1260[c]	1500	2000	2000
Stack efficiency[d] @ 25% of rated power	%	65	65	65	65
Stack efficiency[d] @ rated power	%	55	55	55	55
Precious metal loading[e]	g/kW	1.3	2.7	0.3	0.2
Cost[f]	$\$/kW_e$	75[g]	65	30	20
Durability with cycling	hours	–1000[h]	2000	5000[i]	5000[i]
Transient response (time for 10% to 90% of rated power)	sec	1	2	1	1
Cold startup time to 90% of rated power					
@ –20°C ambient temperature	sec	120	60	30	30
@ +20°C ambient temperature	sec	<60	30	15	15
Survivability[j]	°C	–40	–30	–40	–40

Source: US DOE [19]

Table 3 Technical Targets: Auxiliary Power Units (3–5 kW rated, 5–10 kW peak) and Truck Refrigeration Units (10–30kW rated)

Characteristic	Units	2004[a] Status	2006	2010	2015
Specific Power	W/kg	35[b]	70	100	100
Power Density	W/L	35[b]	70	100	100
Efficiency @ Rated Power[c]	%LHV	15	25	35	40
Cost[d]	$\$/kW_e$	>2,000	<800	400	400
Cycle Capability (from cold start) over operating lifetime	number of cycles	5	40	150	250
Durability	hours	100	2,000	20,000	35,000
Start□up Time	min	60–90	30–45	15–30	15–30

Source: US DOE [19]

Many of the other economic targets focus on the development of H_2 vehicles rather than supply and are therefore less relevant here. Relevant cost reduction targets include:

- 60% peak energy-efficient, durable fuel cell power system (including hydrogen storage) that achieves a 325 watts per kilogram (W/kg) power density and 220 watts per litre (W/L) operating on hydrogen. Cost targets are at $45/kW by 2010 ($30/kW by 2015)

- internal combustion engine powertrain systems operating on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, having a peak brake engine efficiency of 45%, and that meet or exceed emissions standards

In July 2005, the DOE published a revised H_2 cost goal of $2.00-3.00 per gallon of gasoline equivalent (delivered, untaxed, 2005$, by 2015), independent of the pathway used to produce and deliver H_2 [20]. Technical targets for H_2 production, delivery and storage have also been set as part of the US Hydrogen, Fuel Cells & Infrastructure Technologies Program [19], but are not presented here.

1.4 Present Hydrogen Market

The market for H_2 as an energy vector is presently very small, although expected to become significant in the period to 2030. Substantial quantities are produced and used in industry, most commonly in refineries for the production of low-sulphur fuels. By far the most common technology for H_2 production within industry is reforming of natural gas, with a market share of around 95% [21], although electrolysis is sometimes used where natural gas is unavailable or there is surplus electricity available[6].

In most industrial applications, H_2 is either produced at the site or transported relatively short distances by pipeline. Pipelines are generally the most efficient method of transporting H_2, although the economics strongly favour large flow rates and short distances.

Transportation of H_2 by road is less common and usually requires liquefaction of the H_2 in order to transport sufficient quantities, due to the low volumetric storage density of compressed H_2. However, the liquefaction process is highly energy-intensive, requiring energy equivalent to 30-40% of that contained in the H_2 [7] and is therefore generally avoided where possible, on economic and environmental grounds.

1.5 Future Development

Future developments in H_2 markets are somewhat difficult to predict, as it is a sector in the early stages of development and there are many options to choose from. However, an EU-funded roadmapping exercise called HyWays[7] is currently being undertaken by a collaboration of industry and academia. This project aims to answer many of the questions regarding the future development of H_2 within the EU. Similar studies have been, or are being, undertaken elsewhere in the world (e.g. US, Canada, Japan).

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[6] An example of surplus electricity being available is hydro generation in Canada, which has large amounts of rainfall at certain times of year and can therefore produce more electricity than required to meet demand.

[7] www.hyways.de

The work under the HyWays project is currently ongoing and therefore final results are unavailable. However, it is clear that the European Union is likely to pursue a route to H_2 that focuses on renewable pathways, contrasting with the US approach which favours fossil fuels, predominantly coal. The pathways that are likely to predominate within Europe are biomass gasification, off-peak (renewable or nuclear) electrolysis and possibly coal gasification with sequestration, where suitable sinks are available.

In Europe, the High Level Group on Hydrogen and Fuel Cells Technologies [22] has presented levels of potential penetration of vehicles running on zero-CO_2 H_2:

- **by 2020:** 5% of new cars and 2% of fleet
- **by 2030:** 25% of new cars and 15% of fleet

However, these levels of penetration are only indicative at this stage and are for transport rather than stationary applications. However, the expected technological improvements within the timeframe above are relevant to both automotive and stationary power applications. Combined with the flexibility of H_2 as an energy vector this suggests that the use of H_2 for power generation could be significant for some applications in some parts of the EU by 2030.

References

1. J N Baker and S Carter, *Evaluation Of Hydrogen Demonstration Systems (Task 18 Of IEA Implementing Agreement On Hydrogen)*. 2005, UK Department of Trade and Industry (DTI).
2. Ogden, J.M. and J. Nitsch, *Solar Hydrogen*, in *Renewable Energy*, Johannsen T.B. et el, Editor. 1995, Island Press.
3. IEA, *Transmission of CO_2 and Energy*. 2002: Paris.
4. UK Department of Trade & Industry, *A Strategy For Developing Carbon Abatement Technologies For Fossil Fuel Use*. 2005: London. http://www.dti.gov.uk/energy/coal/cfft/cct/pub/catreportlinked.pdf
5. BBC News, *'Green power plant' plan unveiled*. 6th June 2005. http://news.bbc.co.uk/1/hi/england/tees/4615469.stm
6. H-SAPS, *Market Potential Analysis for Introduction of Hydrogen Energy Technology in Stand-Alone Power Systems - Final Report*. 2004, EC ALTENER Programme. http://www.hsaps.ife.no/Reports/HSAPS%20Final%20report.pdf
7. CONCAWE, EUCAR, and EC Joint Research Centre, *Well-To-Wheels Analysis Of Future Automotive Fuels And Powertrains In The European Context (version 1b)*. 2004. http://ies.jrc.cec.eu.int/Download/eh/31
8. Institute for Prospective Technological Studies, *Potential for Hydrogen as a Fuel for Transport in the Long Term (2020 - 2030) - Full Background Report*. 2004, EC Joint Research Centre. http://www.lbst.de/ipts2004/LBST-study-IPTS_2004_eur21090en.pdf
9. H-SAPS, *Market Potential Analysis for Introduction of Hydrogen Energy Technology in Stand-Alone Power Systems - Technology Report*. 2004, EC ALTENER Programme. http://www.hsaps.ife.no/Reports/HSAPS%20Technology%20Report.pdf
10. Hayes, G., P.G. Andrews, and D.M. MKPadi. *Hydrogen as a Pilot and Main Fuel In Gas Turbines for Stationary and Transport including Aero Applications*. in *1st World Congress of Scientists on Hydrogen Energy Systems*. 2004. Italy.
11. Ford Power Products, *Ford Power Products Introduces Hydrogen Internal Combustion Engines To Industrial Marketplace*. 2005. http://media.ford.com/article_display.cfm?article_id=20332
12. College of the Desert and Sunline Transit, *Hydrogen Use in Internal Combustion Engines*, in *Hydrogen Fuel Cell Engines and Related Technologies Course Manual*. 2001, U.S. Federal Transit Administration.
13. Ivy, J., *Summary of Electrolytic Hydrogen Production - Milestone Completion Report*. 2004, National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy04osti/36734.pdf

14. Joffe, D., D. Hart, and A. Bauen, *Modelling of hydrogen infrastructure for vehicle refuelling in London.* Journal of Power Sources, 2004. **131**(1-2): p. 13-22. http://dx.doi.org/10.1016/j.jpowsour.2003.11.076

15. CREST, *The Hydrogen Economy comes to the UK*. January 2005. http://www.lboro.ac.uk/departments/el/research/crest/news/2005-hydrogeneconomy.pdf

16. Dutton A.G., et al., *Experience in the design, sizing, economics, and implementation of autonomous wind-powered hydrogen production systems.* International Journal of Hydrogen Energy, 2000. **25**: p. 705-722.

17. Proton Energy Systems, *HOGEN Hydrogen Generation Systems - Technical Specifications*. Accessed November 2005. http://www.protonenergy.com/data/Unsorted/hogen-specs-16982.pdf

18. Udagawa, J., *Potential for High Temperature Electrolysis in Hydrogen Infrastructure*, in *Centre for Energy Policy & Technology (ICEPT)*. 2005, Imperial College London.

19. US Department of Energy, *Hydrogen, Fuel Cells & Infrastructure Technologies Program - Multi-Year Research, Development and Demonstration Plan: Planned program activities for 2003-2010*. 2003. http://www.eere.energy.gov/hydrogenandfuelcells/mypp/

20. US Department of Energy, *DOE Announces New Hydrogen Cost Goal*. 14th July 2005. http://www.eere.energy.gov/hydrogenandfuelcells/news_cost_goal.html

21. US Department of Energy, *Hydrogen Production & Delivery*. Accessed November 2005. http://www.eere.energy.gov/hydrogenandfuelcells/production/basics.html

22. High Level Group on Hydrogen and Fuel Cells Technologies, *Hydrogen Energy and Fuel Cells - A vision of our future*. 2003, EC Directorates-General for Research & Energy and Transport: Brussels. https://www.hfpeurope.org/uploads/678/688/hydrogen-vision-report_HLG_2003_en.pdf