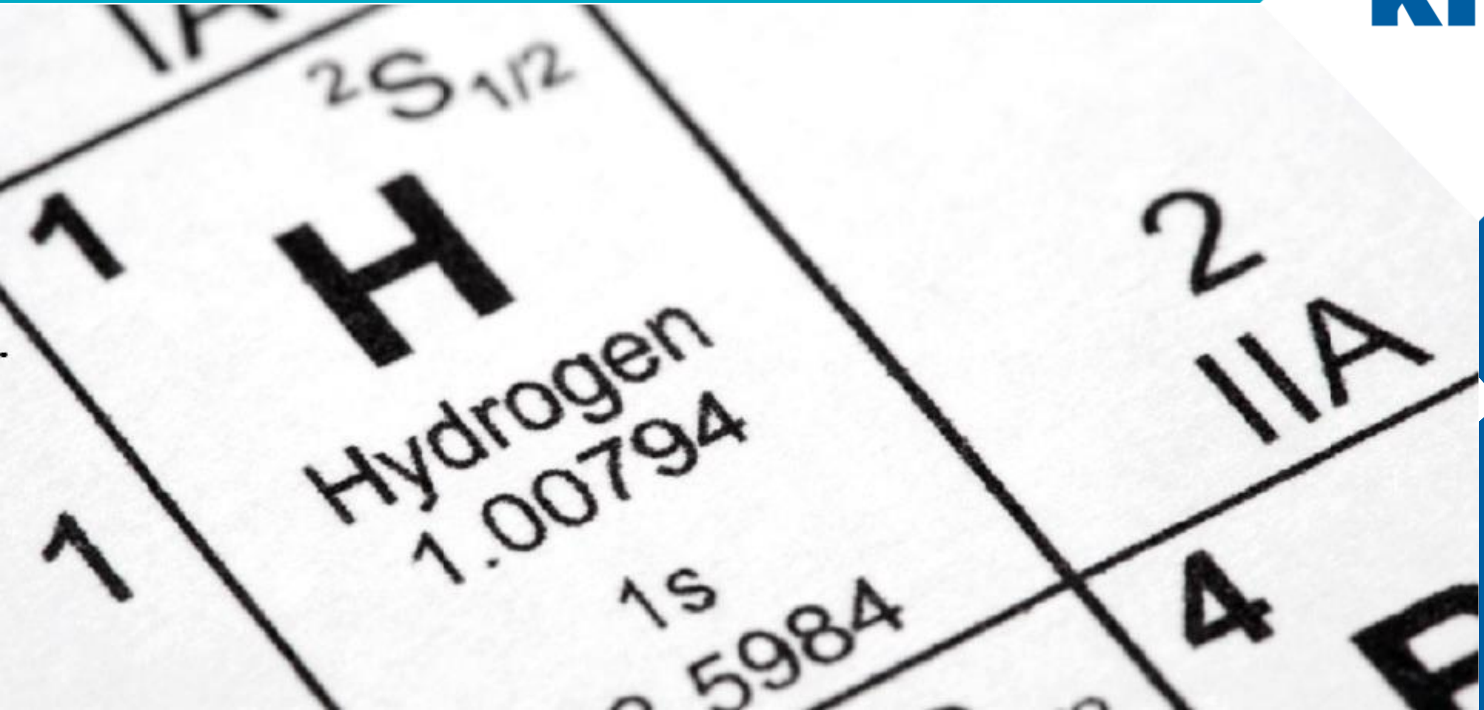
The role of hydrogen in a net zero future

Mark Crowther



Kiwa Gastec

Trust
Quality
Progress

The David Gunn Lecture

The role of hydrogen in a net zero future

The solution for a real problem

Mark Crowther
Technical Director – Kiwa Ltd

Assertions

- The world is not short of renewable energy

  6,200 km2 of Sahara desert would produce all UK final energy needs (1/2 of an Australia sheep farm!)

- The world does require an energy vector

  Reliable, modestly priced to move this energy from point of production/capture and transfer to consumer when required

- Historically, storage has enabled transparent markets

  The separation of production from use improves the efficiency of both

- Ideally the vector should not be poisonous, or of short life

- Ideally no greenhouse gas emissions at point of use

Sahara

Red square shows land area for UK energy supply at 300 kWh/m²/y

Options for energy vectors include:

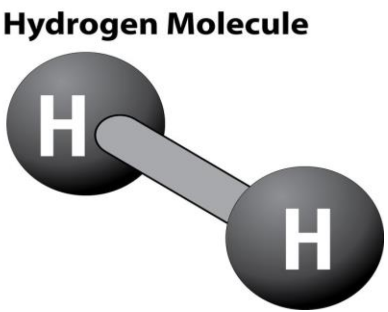
- Electricity
- Hot water / Steam
- Methane with a biologically derived carbon atom
- Ammonia etc
- Hydrogen-liquid & gas

Today I will major on gaseous Hydrogen-mostly at low pressure

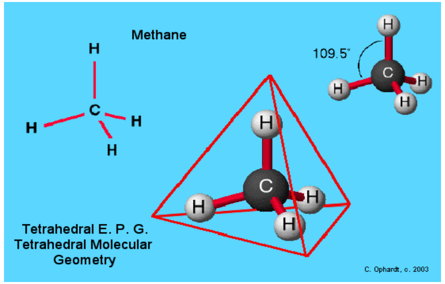
The origins of this paper lie in a presentation by myself to DECC 29th Feb 2012.

Until this date it had been presumed de-carbonisation required an All Electric World.

Hydrogen: its properties



H_2 about 80% of the diameter of methane molecule



	MW	CV MJ/kg	Density @ 288K	Wobbe Index (15/15)
Hydrogen	2.016	141.8	0.0852	45.8
Methane	16.04	55.5	0.678	50.6
Propane	44.1	50.35	1.86	76
CO	28.1	10	1.18	12.1
Air	28.9		1.22	0

- Flammable, colorless, biologically inert gas burns to water
- Very light gas, density ~0.08kg/m^3 (about 1/8 methane, ~0.67 kg/m^3)
- Low calorific value of about 11,930kJ/m^3 (about 1/3 methane, ~37,600kJ/m^3)
- Stoichiometric mixture 29% (Methane 10%)
- Flammable limits 4-74% (Methane 4-15%)

Other issues

Town's Gas was about 50%v/vH_2

- Still used in parts of the world; Town's Gas also contains high concentrations of carbon monoxide, a poisonous gas
- CO is also produced from poor natural gas combustion.
- Town's Gas had a good safety record with regards to fire & explosion

Hydrogen is buoyant in air

- Hydrogen flames ascend rapidly and cause less radiation damage than hydrocarbon fires

Objections due to experience of the old airships

- Cause of the Hindenburg disaster unclear, probably an atmospheric-related static spark. 2/3 of the passengers and crew survived. Many deaths were the result of falls or burning diesel fuel. It was an aviation accident

Other issues

The UK gas industry is very safe; about 13 injuries in 2018 compared to 18 from dishwashers alone.

A high percentage of these injuries are from 3rd party and DIY damage

No reason why hydrogen should not be equally safe.

Distributed hydrogen will be odorised with the same odorant and at the same concentration as Natural Gas. The HSE will insist upon this.

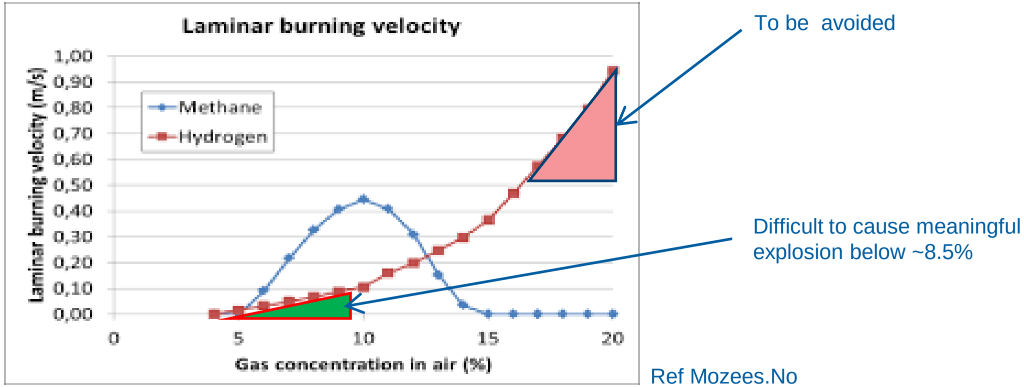
Hydrogen is essentially an energy vector (similar to electricity or steam)

Rather than a source, it has to be created (often from water) using another form of energy.

Hydrogen: safety

Stoichiometric hydrogen (~29%v/v) and methane (~10%v/v) burn to create similar temperatures (~2100°C) and pressures (~8bara)

But the burning velocity is different, hydrogen (at high concentrations) burns much faster; levels above ~18%v/v should be avoided



Ref Mozees.No

In practice this means that for small and medium leaks hydrogen is safer/comparable to methane.

Large leaks could be more dangerous but this can be solved with excess flow valves that interrupt the flow of hydrogen entirely in the event of a punctured/ruptured pipe

Hydrogen appliances will have to be rigorously tested (BSI PAS4444).

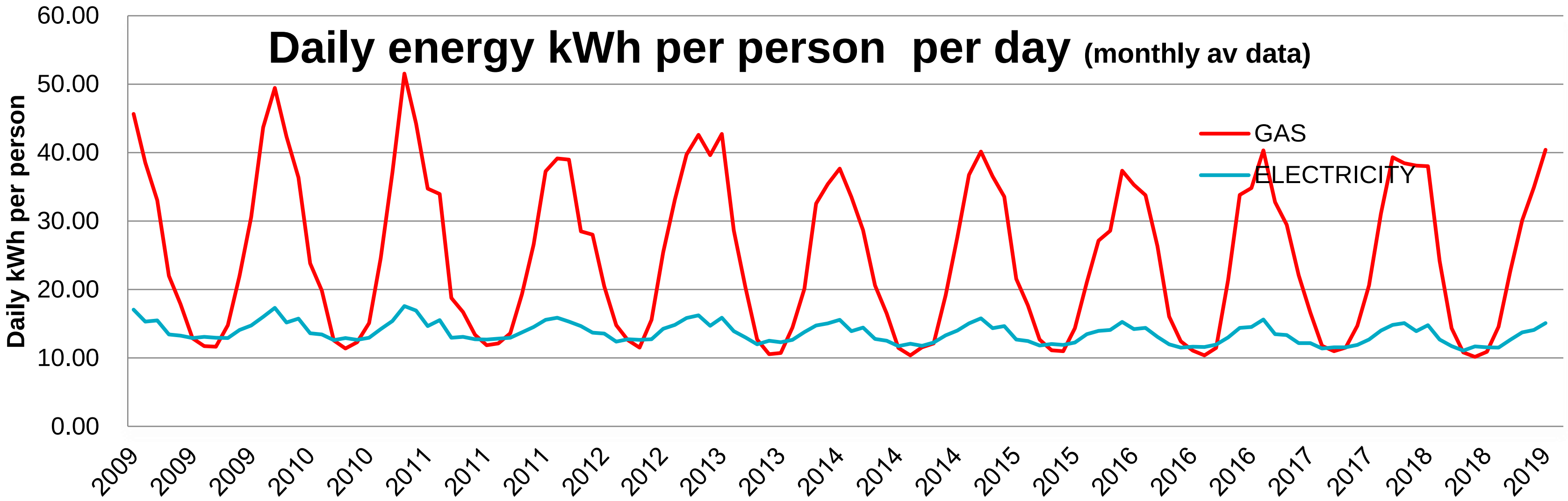
Hydrogen

Hydrogen is not a solution looking for a problem, BUT a solution to very real and complex issues, the principal one being:

UK inter-seasonal variation in energy demand

UK inter-seasonal variation in energy demand

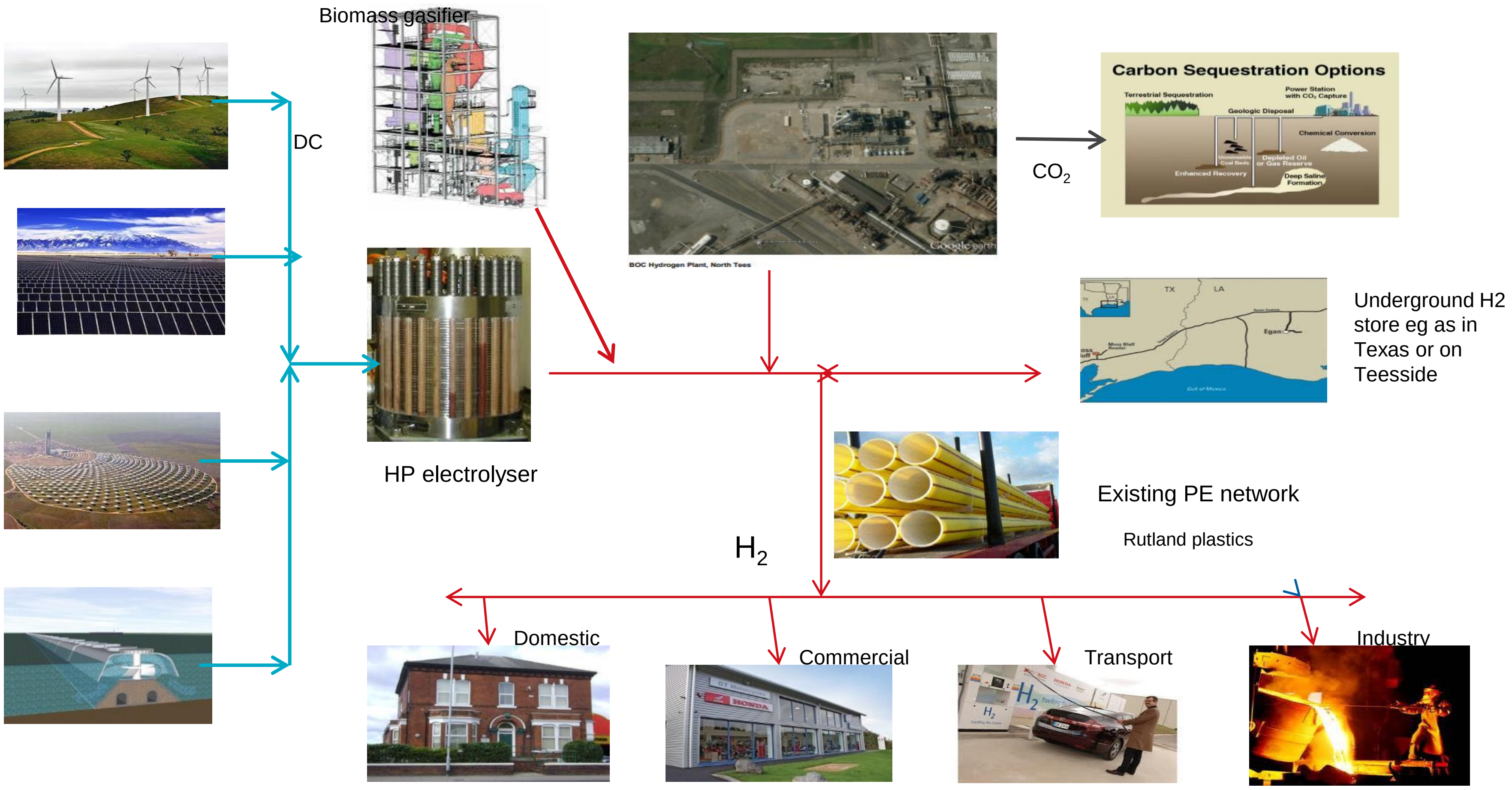
10 years energy demand:



Hypothesis of this presentation

- **Hydrogen to replace natural gas in the existing plastic low pressure distribution systems (some ~2barg, but principally 25-70millibarg)**

  As required, these would be inter-connected with a new high pressure national/international hydrogen transmission system at 85bar


Biomass gasifier
DC
HP electrolyser
BOC Hydrogen Plant, North Tees
CO_2
Carbon Sequestration Options
Terrestrial Sequestration
Power Station with CO_2 Capture
Geologic Disposal
Chemical Conversion
Depleted Oil or Gas Reserve
Enhanced Recovery
Deep Saline Formation
TX
LA
Egan
Underground H2 store eg as in Texas or on Teesside
Existing PE network
Rutland plastics
H_2
Domestic
Commercial
Transport
Industry

Overview of concept

The plan offered here is to convert local gas networks to hydrogen on a piecemeal basis in order to provide zero carbon energy supplies for:

- Current users of natural gas including industry, commerce and the domestic sectors
- Transport, via the installation of hydrogen dispensing pumps at filling station forecourts within the zone

These could be based around any of the following recent studies:

- Leeds H21 The first GDNO city wide scheme by NGN. Main contractor Kiwa Gastec
- North of England. Teesside, Leeds, Manchester and Liverpool (the most recent)
- HyNet around Merseyside by Cadent
- Project Cavendish. London. Hydrogen south of the Thames

Advantages 1

- Conceptually simple. Permitted by 1986 Gas Act, where hydrogen is a specifically identified gas
- No substantial change to the infrastructure is required either in the street, or in the home, although appliances will need to be converted/replaced
- Transition can be locally based and locally decided
- Meets localism criteria
- No impact on international carriage of natural gas through the UK
- No impact on power generation or other very large gas users
- Gas infrastructure is inherently low cost and hydrogen is a well proven and low cost technology

Advantages 2 – low hassle factor for users

Conversion to H_2 should take <36hrs ie less than 2 working days, be free at time of conversion (ref Gas '86) and should be managed by the GDNO.

In contrast:

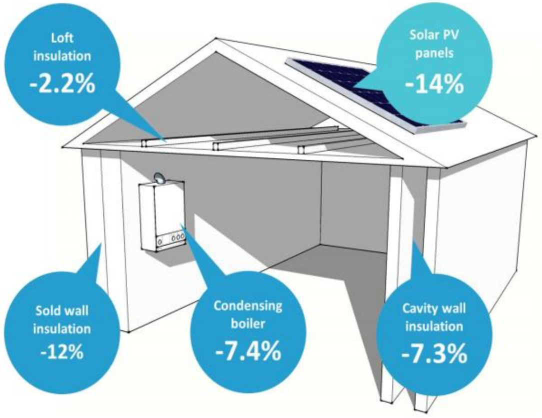
External/internal insulation

- Redecoration & aesthetic changes
- Large capital expenditure (£10k)

Air Source Heat Pump

- Giving up combi boiler
- Installing large DHW tank
- Loss of space in garden
- Large capital expenditure (£10k)
- Good chance of higher fuel bills
- No option of morning or evening heating
- Larger radiators
- Complex discussions with tradesmen

Figure 1.1: Typical savings from energy efficiency measures installed between October 2014 and September 2015



Why Hydrogen?

Low cost to:

- Produce
- Transport
- Store
- Distribute
- Use

Range of reforming options

Manufactures hydrogen by taking the carbon atom out of methane. $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$

Steam methane reforming (SMR) plus CCS

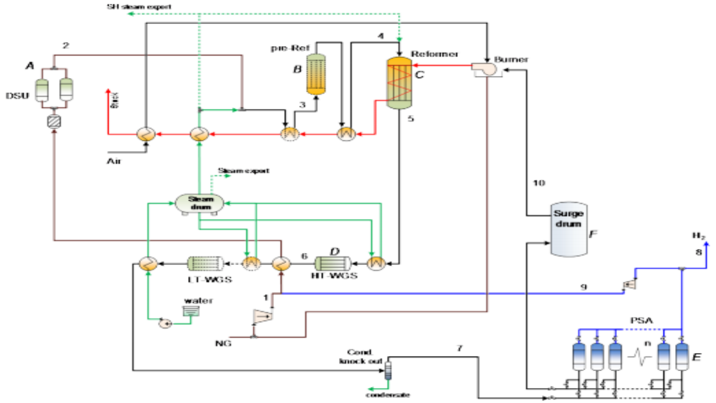


***Figure 2.** Example of plant configuration as considered in the benchmark report (case C1 in Fig.1).*

Development of H_2 Safety Expert Groups and due diligence tools for public awareness and trust in hydrogen technologies and applications

H2TRUST

Project No: 325357

BOC Hydrogen Plant, North Tees

Certainly lowest cost Hydrogen but absolutely requires CCS at a large scale

By electrolysis

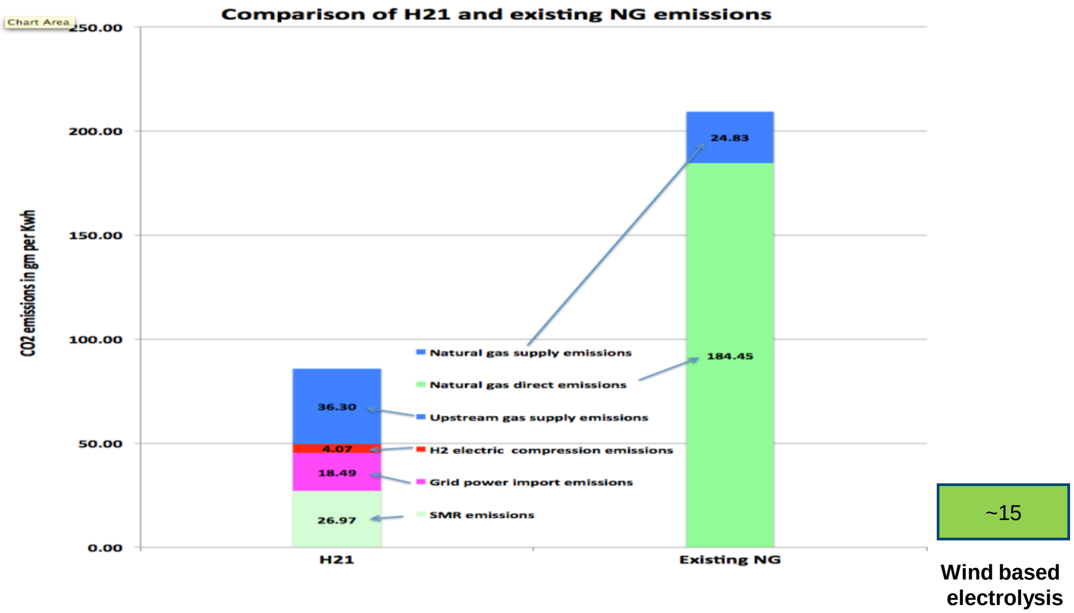
By electrolysis from renewable sources – eg this electrolyser operates at an efficiency of around 80% (including ancillary power consumption)

Inherently produces low carbon electricity but only when the wind blows or sun shines

There is unlikely to be sufficient genuinely ‘surplus’ renewable energy to be viable in the foreseeable future. Dedicated wind/solar farms will be necessary

Carbon Emissions - the rationale behind the conversion

Components of Scope 3 carbon footprint of natural gas, SMR hydrogen and wind turbine hydrogen



Current range of bulk hydrogen costs (ex works)

		Reformer ATR	SMR	Electrolysis
Feedstock	£/kW	£0.02	£0.02	£0.04
Efficiency		79.90%	79.50%	70.90%
Capital	£/kW	£631	£721	£906
Life	Years	25	25	25
%ROI		6%	6%	6%
Annual Production		8500	8500	4029
Cost of OPEX	£/kWh	£0.00	£0.00	£0.01
Cost of CAPEX	£/kWh	£0.01	£0.01	£0.02
Cost of fuel	£/kWh	£0.02	£0.02	£0.05
Cost of CO2 disposal	£/tonne	20	20	0
Cost of CO2 disposal	£/kWh	£0.00	£0.00	
Total	**£/kWh**	**£0.04**	**£0.04**	**£0.08**

Bid price Oct '19

Atmospheric electrolyser $£kW_{H2}$ Summer '19

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Hydrogen transport

- *Low pressure H_2 - broadly similar transport properties to natural gas*
- At $85bar_g$ it has a lower compressibility factor and is more difficult to compress so a new hydrogen transmission system will need slightly larger pipes and more complex compressor stations, but the cost is still very low
- Natural gas can be brought to UK for <~1p/kWh

	MW	**Dist km**	**Project cost**	**£/MW km**	**Ref GaC from public data**	**Ratio to av: gas**
Brit Ned	1000	240	£540m	£2250	Sub-sea HVDC	1:23
Scotland wind	2700	220	£350m	£589	Beauly-Denny, Scotland	1:6
S Wales NTS	24000	316	£700m	£92	Milford Haven to Stroud	
Nord Stream	68000	1222	£8800m	£106	Vyborg , Greifswold	
Carlisle to Sellafield to Heysham HV	3400	190	£2800m	£4325	Planning application through National Park	1:47
Spittal to Blackhillock	190	320	£970m	£2526	As built – mixed line	1:26

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Hydrogen storage

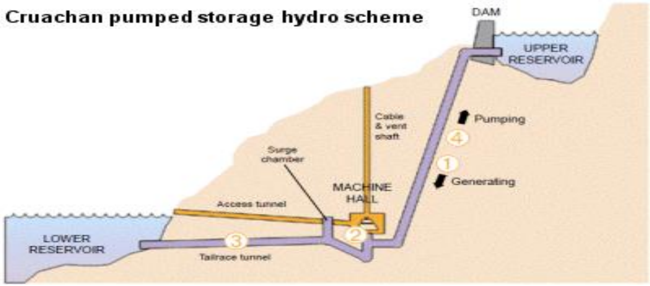
Compressed underground hydrogen storage is entirely proven and new sites are under-construction today eg PRAXAIR in Texas

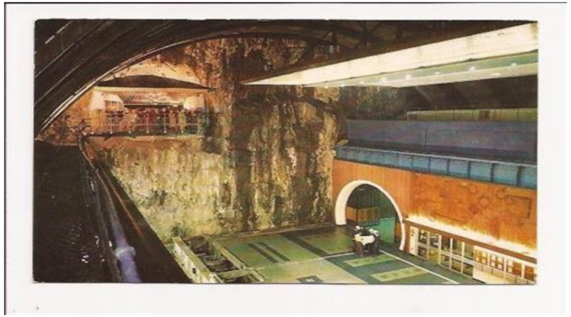
- Hydrogen caverns are operated in
- Teesside, UK by Sabic Petrochemicals (3 X 70,000 m^3)
- Clemens Dome, Lake Jackson, Texas, USA by ConocoPhillips (580,000 m^3)
- Moss Bluff salt dome, Liberty County, Texas, USA by Praxair (566,000 m^3 – maximum permitted capacity)

This last facility has the capacity of about 4mboe or 2.5% of UK annual energy demand or 50 Cruachan pumped storage stations

Hydrogen storage

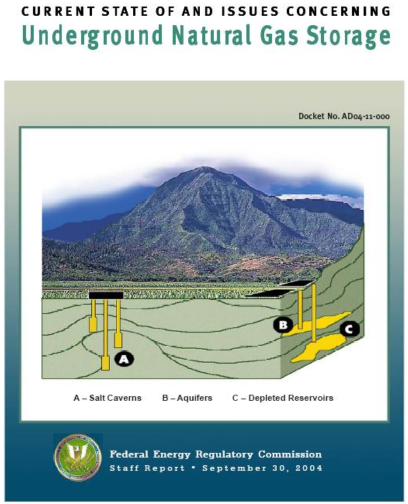
Hydrogen storage cavern for Air Liquide at the Spindletop Dome nr Beaumont in SE Texas





Indicative costs of storage

The surest route to reducing energy production cost is to increase operating hours of the producer and/or not restrict output, hence the value of storage ie to disconnect (in time) production from use.



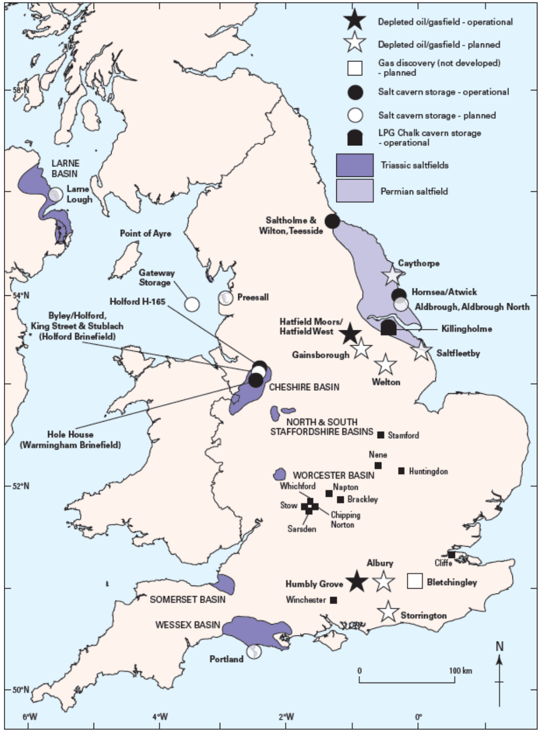
Storage capacity	GWh	8052
CAPEX		£1,991,000,000
Depreciation	years	40
ROI	%	6
Annual charge		£169,235,000
OPEX		£63,000,000
Total costs		£232,235,000
Cost storage /kWh		£0.029

By uncoupling supply and demand a free market can exist in both

UK Annual energy (final)	159,000,000	toe
kWh/toe	11,630	
UK annual TWh	1,849	
91days average use kWh (Renewable)	461	
GCV Hydrogen	3.36	kWh/m³
Equivalent volume of H2 at STP	1.37E+11	m³
At 85barg	1,614,489,578	m³
Edge of cube	1,164.87	m

HyStorPor - Hydrogen Storage in Porous Media
Lead Research Organisation: University of Edinburgh
(School of Geosciences)

Looking for suitable porous media in the Scottish central belt and elsewhere



Why Hydrogen?

Low cost to:

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- Distribute
- Use

Gas distribution

- Most of the UK low pressure distribution system is now polyethylene and operates at 25 to 75 mbar

TEST SETUP

Figure 1: The photo shows laying of the test pipes. The two black pipes to the left are 19 bar steel distribution pipes. The other pipes are new and second-hand pipes from the Danish and Swedish gas grid.

In summary, according to the tests performed in this study, we have found strong indications that polyethylene gas pipes PE80 and PE100 can be used for transportation of hydrogen without any adverse long-term effects on antioxidants, polymer structure or the mechanical performance of the polymer pipes. The same indications have been found for both new and old pipes that has been used in the Danish natural gas distribution network for more than than 20 years.

Ref Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010

Town’s Gas to Natural Gas conversion programme

- 1967 to 1977
- 13m homes & 40m appliances
- Cost then £563m (£42/customer)
- Now equivalent to £6b (based on RPI) or £14b (based upon % UK GDP) or £70b based upon on-going conversion of the Isle of Man to Natural Gas from Towns Gas (above costs exclude hydrogen production)
- Very competitive against the all electric world

(ref Leicester Gas Museum)

Why Hydrogen?

Low cost to:

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Hydrogen Appliances

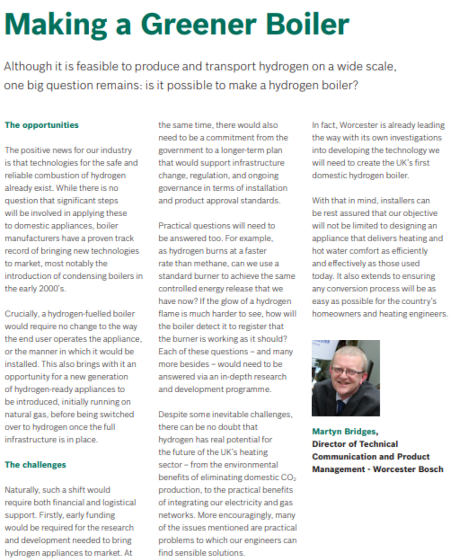
- By not taking carbon into the community we can immediately have total confidence in the true extent of carbon saving
- Hydrogen versions of some appliances already exist or are relatively simple to design
- Hy4Heat has placed development contracts with the following companies

Hy4Heat tenders are currently being assessed for catering equipment and commercial boilers

There must be opportunities for local power generation from low temperature fuel cells

Specific examples

Boilers, cookers and gas fires are all under development



Making a Greener Boiler

Although it is feasible to produce and transport hydrogen on a wide scale, one big question remains: is it possible to make a hydrogen boiler?

The opportunities

The positive news for our industry is that technologies for the safe and reliable combustion of hydrogen already exist. While there is no question that significant steps will be involved in applying these to domestic appliances, boiler manufacturers have a proven track record of bringing new technologies to market, most notably the introduction of condensing boilers in the early 2000's.

Crucially, a hydrogen-fuelled boiler would require no change to the way the end user operates the appliance, or the manner in which it would be installed. This also brings with it an opportunity for a new generation of hydrogen-ready appliances to be introduced, initially running on natural gas, before being switched over to hydrogen once the full infrastructure is in place.

The challenges

Naturally, such a shift would require both financial and logistical support. Firstly, early funding would be required for the research and development needed to bring hydrogen appliances to market. At the same time, there would also need to be a commitment from the government to a longer-term plan that would support infrastructure change, regulation, and ongoing governance in terms of installation and product approval standards.

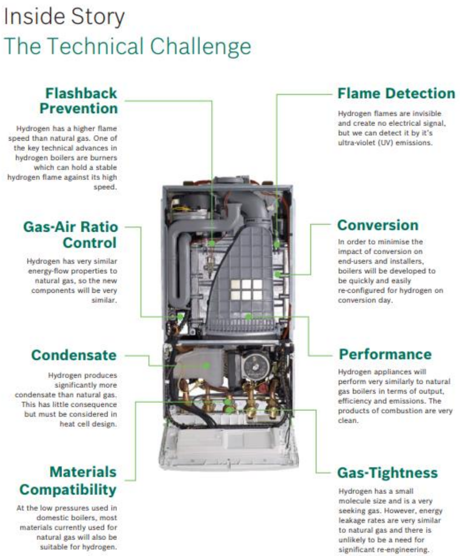
Practical questions will need to be answered too. For example, as hydrogen burns at a faster rate than methane, can we use a standard burner to achieve the same controlled energy release that we have now? If the glow of a hydrogen flame is much harder to see, how will the boiler detect it to register that the burner is working as it should? Each of these questions – and many more besides – would need to be answered via an in-depth research and development programme.

Despite some inevitable challenges, there can be no doubt that hydrogen has real potential for the future of the UK's heating sector – from the environmental benefits of eliminating domestic CO_2 production, to the practical benefits of integrating our electricity and gas networks. More encouragingly, many of the issues mentioned are practical problems to which our engineers can find sensible solutions.

In fact, Worcester is already leading the way with its own investigations into developing the technology we will need to create the UK's first domestic hydrogen boiler.

With that in mind, installers can be rest assured that our objective will not be limited to designing an appliance that delivers heating and hot water comfort as efficiently and effectively as those used today. It also extends to ensuring any conversion process will be as easy as possible for the country's homeowners and heating engineers.

Martyn Bridges, Director of Technical Communication and Product Management - Worcester Bosch



Empa - Self - Hydrogen cooker
empa.ch

Why Hydrogen?

Low cost to:

- Produce
- Transport
- Store
- Distribute
- Use – Transport sector

Use in Transport

- 28m vehicles on UK roads
- About 9000 filling stations in the UK
- Would equate to £9bn at £1m/station (ref California today about £1.6m/fill point including generation)
- Compares with £30bn for HS2 rail-line
- Hydrogen vehicles are available now with similar performance to existing gasoline/diesel stock
- Several high volume manufacturers eg Toyota believe hydrogen will be the preferred fuel for the future of the world automotive industry
- Connecting these filling stations up to the existing LDZ would be relatively easy
- This would ensure the UK stayed in the world league in this important manufacturing sector

Current state of play

Transport

- New zero-emission hydrogen buses are being deployed in Aberdeen, Dundee, Cologne, Wuppertal, and elsewhere.

Alexander Dennis has added a hydrogen double-deck model to its range of low emission vehicles (Picture: Andrew Macintosh)

The hydrogen-powered Enviro400 has an electric driveline with axle-mounted motors. An on-board battery is charged by feeding hydrogen from secure tanks to a fuel cell system where it is converted to electricity.

Aberdeen H_2 Buses

Current state of play

Mirai helps Met Police clean up London

The first of 11 cars have been delivered to the Met with support from the FCHJU* grants programme and are equipped to work as both marked and unmarked vehicles.

Alstom and Eversholt Rail have unveiled the design of a new hydrogen train for the UK market. The train, codenamed 'Breeze', will be a conversion of existing Class 321 trains, reengineering some of the UK's most reliable rolling stock, to create a clean train for the modern age.

Why Hydrogen?

Low cost to:

- Produce
- Transport
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- Distribute
- Use – Industry

Industrial uses of Hydrogen

- For many years UK manufacturing has been moving towards higher added value products. A generous supply of low cost hydrogen would greatly assist this
- The existing petrochemical use of hydrogen is widespread. The addition of low carbon hydrogen as a chemical feedstock will expand the commercial possibilities, across a wide range of ‘low carbon’ goods eg low carbon copper, steel or other metals
- The market for low carbon manufactured goods will grow
- Those companies who wished to remain on Natural Gas could be assisted to run dedicated medium pressure lines to the existing (and remaining) National Grid
- SABIC Wilton have carried out a major conversion to hydrogen as have other sites on Merseyside.
- Fusina Hydrogen Power Station (~12MW) , Veneto, has operated since 2010

Indicative costs of retail hydrogen

A few memorable numbers :
Hydrogen (SMR) is more expensive than Natural Gas but much cheaper than electricity

Price, p/kWh	H2	Nat Gas	Electricity
Retail	7.6	~4.8	15.8
Including conversion	9.3	NA	NA

Cost of Leeds H21	
£	£ 2,054,000,000
Houses	266,000
Cost/house	£ 7,721.80
Roughly	
Appliance change over	£1bn
Hydrogen supply	£1bn
Compared to	
Hinckley C	£18-24bn
Sellafield wires ONLY	£2.8bn

- Complies with Stern valuation of global warming. 1.5% of GDP.

Ann Gas	kWh/y	£ 6,000,000,000
H2 Leeds H21	£/kWh	£ 0.093
Current cost NG	£/kWh	£ 0.047
Marginal cost	£/kWh	£ 0.046
Total marginal	£/yr	£ 276,000,000
GVA Leeds	£/yr	£ 18,800,000,000
Leeds H21 as % GVA		1.47%

How costs are allocated between taxation, domestic and commercial/industrial users must be essentially political

The beginnings of a greater role out.

H21 North of England potential Hydrogen scheme- a serious examination of a Norwegian link

Conversion of 3.7 million meter points equivalent to 85 TWh of annual demand (14% of all UK heat) and circa 17% of total UK domestic meter connections

A 12.15 GW natural gas-based hydrogen production facility (this is 1,215 times larger than 10 MW, i.e. 12,150 MW), delivering low carbon heat for Tyneside (Newcastle, Gateshead), Teesside, York, Hull, West Yorkshire (Leeds, Bradford, Halifax, Huddersfield, Wakefield), Manchester and Liverpool

8 TWh of inter-seasonal hydrogen storage, equivalent to 62,000 Australian mega batteries

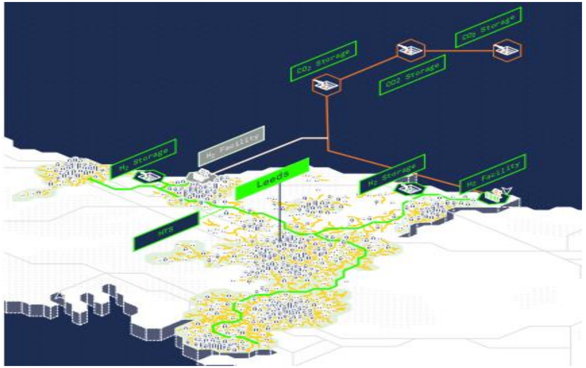
→ A 125 GW capacity hydrogen transmission system

→ CO_2 transport and storage infrastructure with the capacity to sequester up to 20 Mtpa of CO_2 by 2035

The scheme is summarised in Figure ES.2 which is an isometric map of the North of England.

ITEM	CAPEX (£M)	OPEX (£MPA) POST 2035 (ONCE CONVERSION AND COMMISSIONING IS COMPLETE)
Natural gas connection	0 (included in HPF)	0
Hydrogen Production Facility (HPF)	8,520	285
Inter-seasonal hydrogen storage	1,991	63
CO_2 transport and storage	1,340	24
Hydrogen transportation system	3,427	3
Appliance conversion	7,500	0
SUB TOTAL	22,778	375
Additional energy cost for Hydrogen Production Facility	N/A	580 (total annual gas cost is £2,292m based on gas price of £23/MWh)
TOTAL	22,778	955

Table ES.3: H21 NoE project costs table



Exploring the potential for London

National Grid/SGN/Cadent potential hydrogen schemes

Project Cavendish Hydrogen for South London

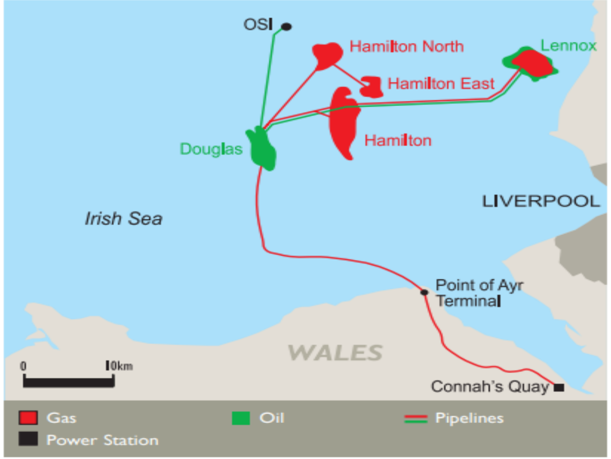
Another study in the NW

Cadent potential hydrogen schemes

Figure 2.2: Conceptual Pipeline Routes and Configurations

Source: Map data ©2017 Google

Figure 1.5: The Liverpool Bay Complex of Oil and Gas Fields



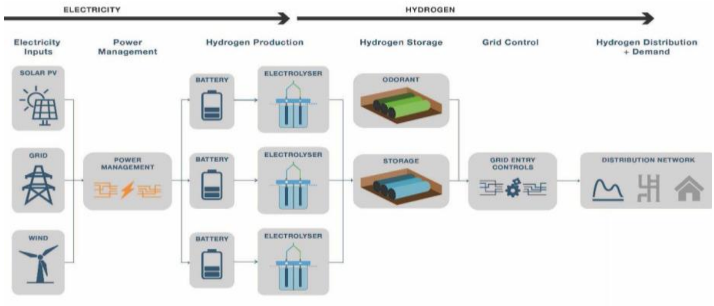
Source: BHP Billiton Petroleum Operational and Financial Review 2006

As well as a real scheme for approaching 1000 houses

SGN potential Hydrogen scheme-grant application now with BEIS

Levenmouth Innovation Zone

Project Methilltoune



7MW turbine

300 to 500 domestic connections, maybe up to 1000.
Uniquely parallel pipes will be used to investigate social aspects of conversion

To return and validate my original hypotheses

Hydrogen has a future because it is low cost to:

Transport - Because it is a gas of reasonable Wobbe No.

Store - Because it a compressible flammable gas of reasonable CV.

Distribute - Because it is compatible with current PE pipe and was ~50% of Town's Gas.

Use - It has excellent and proven potential in all three sectors (space heating, transport and industry) either directly or via fuel cells.

Produce - As production is never demand constrained, reducing the risk premium compared to that associated with future electric plant

And it compliments electricity as an energy vector and addresses the inevitable intermittency issues for electricity generation (especially renewable)

Discussion

Mark Crowther

Kiwa Ltd

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