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Hydrogen with CCS for decarbonised heat in the Scottish context

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ClimateXChange commissioned this short review[1] as a summary of current knowledge about the potential for deploying hydrogen as a heat vector through repurposing of the natural gas grid. This report reviews recent literature and summarises what we know from existing and planned hydrogen-for-heat projects with relevance to the Scottish context.

Introduction

Heating for commercial and residential buildings represents 53% of Scotland's total energy demand. The draft Scottish Energy Strategy [1] identified heat decarbonisation as a key challenge.

Natural gas currently provides most of Scotland's heat: 79% of homes used gas as their primary heating fuel in 2015 [1]. Gas is supplied through an extensive and well-established distribution network and trunk transport infrastructure. However, due to the carbon dioxide (CO_2) released when it is burnt, long-term use of natural gas for space and water heating at this level is incompatible with Scotland's commitments to climate action.

The UK gas distribution network is currently being upgraded. This 30-year project, the Iron Mains Replacement Programme [2], will replace most intermediate and low pressure distribution pipes with polyethylene for safety reasons, reducing risks of leakage and pipe failure. If mains gas heating is phased out by 2050 this infrastructure will face early decommissioning.

Hydrogen can be used as an alternative to natural gas for space and water heating and can potentially be delivered through the existing gas distribution network following upgrade. Switching from natural gas to hydrogen has been identified as the principal option to enable the gas networks to continue supplying energy for space and water heating in line with climate targets [3].

Hydrogen is a particularly versatile energy vector. It can store energy and provide fuel for heating buildings, industrial processes, transport or conversion to electricity. Hydrogen can be distributed through pipelines or by road using tube-trailers and has no harmful emissions at the point of use. Hydrogen therefore offers a range of options for a cross-sectorial transition to a low carbon economy.

The greenhouse gas emissions impact of hydrogen depends on its means of production. The emissions associated with hydrogen produced by electrolysis of water will depend on the carbon intensity of the electricity supply. Production of hydrogen from carbon-containing feedstocks (e.g. natural gas, coal or biomass) can also be low carbon provided it is integrated with capture and permanent sequestration of CO_2, that is, carbon capture and storage (CCS) technology.

Hydrogen production by electrolysis is currently capital intensive but is already finding application at small scale for storage of excess electricity from variable renewable sources where output would otherwise be curtailed. While hydrogen supply from electrolysis is likely to have valuable niche and local applications, national-scale provision of hydrogen for heat through electrolysis would be challenging - it would require a several-fold increase in electricity

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supply beyond current projections [4]. In contrast, hydrogen production from natural gas by the steam methane reforming (SMR) process is a well-established, large-scale industrial process, which, if integrated with CCS to avoid CO_2 emissions, could provide a low-carbon supply of hydrogen at regional or national-scale.

Conversion of the gas distribution network to carry hydrogen represents a significant heat decarbonisation opportunity for Scotland. A recent study on gas network conversion to hydrogen in the city of Leeds estimated up to 87% reduction in CO_2 emissions compared to current levels [5]. Scotland has the assets required for this development, including vast CO_2 storage capacity in the North Sea, gas transport infrastructure and local industry expertise. This option is proposed, alongside heat pumps and district heating, in the draft Scottish Energy Strategy [1] and the draft Climate Change Plan 2017 – 2032 [6].

This report summarises current literature and knowledge from existing and planned projects for the use of hydrogen for heating. The report is structured as follows: the first section presents a high-level overview of bulk-scale production and distribution methods for hydrogen; the second part reviews current pilot projects to pull out lessons relevant to Scotland and propose areas where further research or piloting would be valuable.

Hydrogen production and distribution

Hydrogen production with carbon capture and storage

Steam methane reforming is currently the most common method for producing hydrogen in large quantities, although other hydrocarbons can also be reformed. The process produces a gas mixture which when separated gives the desired hydrogen product and CO_2 as a by-product[2].

There are currently around 12 hydrogen SMR plants producing hydrogen for sale as an industrial gas in the UK [7] and a number of other SMRs integrated directly into refineries and chemical sites. The CO_2 by-product can be compressed or liquefied for use as an industrial or food-grade gas - this is the main source of such supply. Alternatively the captured CO_2 can be injected deep underground for permanent storage in geological formations; in this way the hydrogen produced is low-carbon. The technologies of capturing, transporting and permanently storing CO_2 are collectively termed carbon capture and storage. Both these alternatives are established at industrial scale, however, currently much CO_2 from hydrogen production is vented to the atmosphere.

Hydrogen safety

Hydrogen is the lightest element and its buoyancy causes it to rise and disperse rapidly. Its high diffusivity relative to natural gas makes it more susceptible to leakage and to permeating through materials, although recent studies estimate a hydrogen leakage rate of 0.1% of total volume during pipeline transport, which is considered negligible [8]. Hydrogen is odourless, tasteless and has no colour, so it is not detectable by human senses. It is essentially non-toxic although can cause asphyxia through displacement of oxygen. Its main hazard is its flammability and ability to form explosive mixtures over a wide range of concentrations. Hydrogen combustion produces no smoke and only a faint blue light. These hydrogen properties present specific safety issues which may be overcome by odourisation, installation of hydrogen detectors [9], ceiling venting designs [10] and other good practices. Globally, approximately 45 million tonnes of hydrogen are produced every year for use in oil refining and chemical industries, with production rates expecting to increase in the future [4]. Production and hazard mitigation strategies used in these sectors can be adapted to hydrogen use as an energy vector.

Energy capacity and storage

The energy content of hydrogen is 2.5–3 times higher by weight than liquid fossil fuels or natural gas, giving it the highest energy content per unit mass of any fuel [4]. However, as it is very light, its energy density by volume is

[2] Hydrogen can also be made by gasification or partial oxidation of carbon-based materials such as coal or biomass, and separation from the resulting gas mixture. Alongside SMR, these methods all produce a mixture, known as syngas, containing carbon monoxide and hydrogen. Further hydrogen can be produced from the carbon monoxide by the water-gas shift reaction using more steam. Further details can be found in Annex I.

about one third that of natural gas[3]. For transport, the differing properties of hydrogen and natural gas roughly balance out and flow in a pipeline is similar [11]. However for storage, three times the volume or three times the pressure would be required to store the same amount of energy in hydrogen compared to natural gas. The volume of gas present in a pipeline network during normal operation (termed linepack) is currently used as a short-term energy store to meet peak demand. Relative properties of the gases mean the energy available from hydrogen as linepack storage may only be a quarter of that for natural gas [11,12] and other short-term hydrogen storage may be needed.

Gas blending

Use of hydrogen in the UK energy system is not new. Town gas, produced by gasification of coal or oil, consisted of 40 to 60% hydrogen by volume. It was piped to residential and industry users until it was finally phased out in 1988 [9]. Discovery of natural gas in the North Sea in the 1960s led to conversion of systems from town gas to natural gas in the 1970s. Currently the permitted hydrogen concentration in the gas network is 0.1%, set on the basis of North Sea gas composition, as reintroduction of hydrogen has not been considered until recently. Industry experience in hydrogen use for heating as well as the conversion period will be valuable in the development of any future conversion programme.

Natural gas blending with hydrogen has been proposed as an intermediate measure to decarbonise heat, lowering overall emissions while scaling up the hydrogen production industry. If implemented at low concentration, this strategy of storing and delivering blended gas could operate without the need to convert household appliances. However, the appropriate blend concentrations vary significantly depending on the pipeline network system and natural gas compositions [13].

Power-to-gas

Power-to-Gas technology is an approach to providing energy storage, particularly for variable renewable electricity systems. It utilises excess electricity generated by renewable energy sources and converts this to hydrogen by electrolysis of water. Hydrogen gas can then be injected into the gas distribution network to be delivered to consumers as a methane/hydrogen blend, or it may be stored for future use [14]. One major driver for power-to-gas technology is to give value to currently-curtailed renewable electricity. The hydrogen produced may be used directly for local heating, distributed through the gas network for heating, used to supply hydrogen-fuelled vehicles, or it may be reconverted to electricity through fuel cells.

Pipeline systems

Natural gas is transported by interconnected pipeline networks. A national transmission system, owned and operated by National Grid, supplies high-pressure gas to a number of distribution networks, owned and operated by separate companies. Gas pressure is sequentially lowered in each level of network with low-pressure gas delivered to end-point users. National transmission and high-pressure distribution pipelines were installed pre-1970s and are made of high-strength steel. Intermediate pressure pipes were made of steel, while medium to low pressure pipes were cast iron. Pipes within individual buildings are generally copper [12]. The Iron Mains Replacement Programme [2] is converting some intermediate and most low-pressure pipes to medium-density polyethylene, which is compatible with hydrogen transport. Under this programme, all pipes will be upgraded to polyethylene by the mid-2030s.

Current high-pressure steel pipes are incompatible with hydrogen transport mainly due to hydrogen diffusivity and embrittlement effects on high strength steel. Higher pressures increase the likelihood of embrittlement, so the current high-pressure transmission pipeline is not suitable for hydrogen transport. However, the current intermediate pressure steel pipes are compatible with hydrogen transport [12]. Ultimately, depending on supply logistics, the high-pressure transmission system pipelines may require upgrading if the whole network switches to hydrogen. However, smaller scale pilot projects can utilise the existing medium to low pressure pipes which will be largely hydrogen-compatible after the completion of the Iron Mains Replacement Programme in the 2030s [4].

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[3] This means that when a given volume of gas at the same temperature and pressure is burned, hydrogen releases about one third of the energy that would be released by natural gas.

CO_2 storage

The production of hydrogen by SMR generates CO_2 as a by-product. Without CO_2 storage therefore, large-scale hydrogen production by SMR cannot be considered low carbon. For Scotland, developing CO_2 storage in the North Sea is key to the feasibility of gas network conversion for heat decarbonisation using hydrogen.

A full-scale hydrogen SMR+CCS chain would consist of the following elements: natural gas supply to the production site; SMR process plant, gas separation, purification and compression for both hydrogen product and CO_2 by-product; pipeline distribution network for hydrogen and transport infrastructure for CO_2 to the storage site; and an injection well into a carefully selected geological storage site.

CCS is an established technology with 17 large-scale projects currently operating worldwide [15]. The Sleipner CO_2 storage project has been successfully operating for over 20 years in the Norwegian North Sea.

A vast capacity of suitable CO_2 storage sites exists in the North Sea. These are generally depleted hydrocarbon fields or natural saline aquifers, which are capable of holding CO_2 securely over geological timescales [16].

Hydrogen storage in geological formations

Storage of hydrogen is likely to be required for short and mid-term timescales to allow balancing of supply to variable heat demand.

Salt caverns are artificially created cavities excavated in natural salt deposits. They are suitable for the storage of gases under high pressure and large quantities of gas can be safely stored. Hydrogen has already been successfully stored in salt caverns in the UK, Europe and the US for long periods of time [17]. However, the availability of suitable salt deposits is limited to certain areas; in the UK such deposits occur mostly in Cheshire and North and East Yorkshire.

Alternatively, hydrogen could be stored in depleted gas reservoirs or in aquifers, in a similar way to CO_2 and to existing storage of natural gas. Deep sandstone aquifers and depleted gas fields are much more common than salt deposits and would offer a higher diversity in potential storage locations. This is especially significant for Scotland, as there are no salt deposits in Scotland. There is a wealth of industry and academic expertise in gas storage, although more hydrogen-specific feasibility studies will be required to account for the different chemical and physical properties of hydrogen relative to CO_2 or methane. Recent desk-based studies found that hydrogen is expected to be chemically stable with minerals commonly found in natural sandstones, while its higher diffusivity would not lead to significant risk of leakage from the reservoir [8]. However, more studies are required to assess the effect of hydrogen-consuming microorganisms found in sandstone reservoirs, which convert hydrogen to methane. Another important area of future research is the performance of porous reservoirs in terms of how quickly hydrogen can be moved between the gas network and an inter-day storage site. The deliverability of hydrogen from a porous rock storage site is lower than that from salt caverns and research will be required to assess site-specific hydrogen injection and production rates, which greatly depend on whether the storage site is a depleted gas field or an aquifer, the amount of gas currently in the system and the porosity of the rock.

End-user appliances

Switching from natural gas to hydrogen would require changes to the gas network and end-user appliances, because the physical properties of hydrogen differ from those of natural gas. A recent white paper commissioned by H2FC SUPERGEN concluded that most heating technologies that use natural gas can be adapted to use pure hydrogen and will provide identical or similar service [18]. Natural gas and hydrogen blends of up to 20% were found to be applicable for use with common unmodified domestic appliances without increased safety hazards [19].

Towards full chain hydrogen for heat: current projects

Using hydrogen to supply heat on a large scale will require integration of several elements of a value chain, including: hydrogen production by SMR, hydrogen transmission pipelines, hydrogen storage, an upgraded gas distribution network with suitable pipelines, adaption of end-user appliances and a full chain of CO_2 capture, transport and storage. Most parts of the hydrogen value chain are already established industry technologies at some level, although they may not currently be in widespread usage. However, some parts of the chain, and particularly the way parts interact, may need to be proven in smaller-scale pilot projects to promote understanding of technical feasibility and the implications for scaling up. Pilot projects will provide evidence for further expansion and increase stakeholder confidence in future investments.

The progress in research and development has already been significant, with operational pilot projects in the UK across the whole value chain. Additionally, there are a number of active international projects that could be approached for international collaboration or knowledge sharing in the period of research and development of Scotland's transition to a hydrogen-based heating network.

The following sections summarise the status of value chain elements and progress in these pilot projects. Areas that could benefit from more research and development are identified.

Hydrogen transmission pipeline

Two SMR plants with integrated CO_2 capture currently operate at Teesside industrial estate. Hydrogen distribution pipelines at the Teesside site connect different chemical processing plants. There are at present no hydrogen pipelines in the UK running across the country, but current UK pipeline safety regulations already encompass hydrogen use and provide guidance on pipeline design [20].

Hydrogen transmission pipe networks are established overseas, with a total length of 1600km identified in Europe, mostly in Germany, France, Italy, Sweden, Belgium and the Netherlands, and with another 800km in the USA [21].

Hydrogen distribution network – 100% hydrogen and mixed concentration blends

A feasibility study by **SGN** is investigating site-specific evidence to support future physical demonstration of a 100% hydrogen network [19]. The project will evaluate three possible tests sites in Scotland, engage with customers and stakeholders and develop full technical network designs. The subsequent demonstration project will involve a first-of-its-kind network including gas supply chain, transport, storage, injection, distribution and utilisation of hydrogen. On-site testing will include pipeline and infrastructure materials, pressure reduction and compression and safety testing.

The **HyDeploy project at Keele University** is currently exploring hydrogen blending with natural gas. The project aims to test the effects of blending on the UK pipe system. It will use Keele University's private distribution network for a pilot study to build a framework for a further UK-wide assessment. Hydrogen blends will vary from 0.1 to 10% and potentially up to 20% of the total volume, which is potentially within the capability of the current UK pipeline network [22]. Areas of research will include assessing pipeline and jointing materials, leak detection, network maintenance and metering procedure development. The results of this demonstration project will be particularly useful for any future power to gas projects, which produce hydrogen from excess renewable energy and inject it into the gas grid [23].

Similar studies have been undertaken internationally. A four year pilot project in the Netherlands tested the gas network of an apartment building with hydrogen mixes of between 5 and 20% using standard Dutch gas appliances and found them largely applicable to gas mixing [24]. In Germany, a blend of up to 10% hydrogen in natural gas is permitted, and a few projects have undertaken hydrogen injection. Other blending tests, including a 15% blend Danish study and the 20% blend NaturalHy project in the Netherlands, found that hydrogen mixtures had no negative affect on pipeline integrity [19].

Appliances at end-use points

While both SGN and HyDeploy projects incorporate appliance testing in their studies, the **HyHouse project by Kiwa Ltd** focused entirely on safety issues related to domestic leaks. The project tested low- and high-rate gas leaks in a household with three levels of simulated air tightness. The gas compositions leaked included 100% natural gas, 100% hydrogen, natural gas with 3% and 10% hydrogen mixed in and a Town gas mixture (50% hydrogen, 25% CO_2, 25% natural gas). The study concluded that the risk of fire associated with a hydrogen leak was not significantly higher than for natural gas as, despite being more flammable, hydrogen is also more buoyant and more diffusive, so it disperses faster in air. Further work to follow up on this study would be needed to investigate the damage capacity of explosions from similar gas mixtures and assess compounds suitable for hydrogen odourisation [10].

Hydrogen storage in geological formations

There are over 30 large salt caverns presently in use in the UK storing natural gas for the power and heating market. Many could be re-used for hydrogen storage or new caverns could be constructed in salt deposits available in some parts of the UK. New cavern development and re-use of existing ones is currently planned by the Leeds H21 project [5]. Another ongoing project is currently identifying salt deposits in Cheshire, Teesside and East Yorkshire that could be used for salt cavern storage of hydrogen [25]. Desk based studies exist on hydrogen storage in depleted gas fields and saline aquifers [6, 16] but there are no ongoing demonstration projects. Given the lack of salt deposits in Scotland, the exploration and testing of alternative storage sites would seem an important research priority.

Power-to-Gas

ITM Power is a UK-based company currently operating two power-to-gas projects in Germany. One is RWE's power-to-gas project in North Rhine-Westphalia, which uses waste heat recovery during hydrogen production from electrolysis to achieve an overall efficiency of 86% [27]. ITM Power is also part of a consortium operating Thüga power-to-gas plant in Frankfurt [28]. Hydrogen generated in both of these plants is injected into the German gas grid.

The Surf'n'Turf project [29] and the related BIG HIT project [30] based on Eday and Shapisay in the Orkney archipelago have been awarded Scottish Government and EU funding to produce hydrogen from excess wind power using a 0.5 MW and a 1 MW electrolyser respectively. Between them the projects aim to use hydrogen as energy storage to re-generate electricity using a fuel cell, and to construct hydrogen refuelling stations, acquire 10 hydrogen fuel cell vans and demonstrate two hydrogen-powered boilers.

Power-to-gas research and development projects have lately received significant attention in Europe through efforts to increase renewable energy integration and efficiency. In 2016 there were 49 projects in Europe; Germany has 17 pilot projects and there are significant developments underway in France, Denmark and Belgium [31].

Hydrogen production with integrated CCS

The technologies for hydrogen production by SMR or gasification and for CO_2 capture, transport and geological storage are all established at large scale, as outlined in Section 2 above. Facilities that integrate hydrogen production with CCS are more limited, however, they are also established at industrial-scale; known examples are outlined in Annex 1. These include manufacture of hydrogen by both SMR and gasification, for ammonia synthesis and for petroleum refining, with capture of by-product CO_2. Most examples are in North America and much of the captured CO_2 is used for enhanced oil recovery, however, in two recent examples the captured CO_2 is stored in saline aquifers. These are the Quest project at a bitumen refinery in Alberta, Canada [32] and the Tomakomai CCS Demonstration Project on Hokkaido, Japan [33].

In the UK, two large SMR facilities in Teesside, where CO_2 is separated but currently vented, have been evaluated as potential capture sites by the Teesside Collective project [34]. CO_2 from these plants would be transported for storage in depleted gas fields or saline aquifers under the North Sea. On CO_2 storage, much work has been done through the UK Government CCS Commercialisation Competitions [35] and other projects, to bring several well-characterised storage sites to a position where they are ready for commercial development [16]. Moving forward, a feasibility study is underway for a project to capture emissions from the St Fergus gas processing plant and store these under the North Sea; the project will largely re-use existing plant and pipeline infrastructure to minimise initial capital costs [36].

Large scale feasibility studies

H21 Leeds City Gate

The H21 Leeds City Gate project is currently by far the most comprehensive feasibility study concerning hydrogen for decarbonised heat globally. Its aim is to determine the technical and economic feasibility of converting the gas network in the city of Leeds to 100% hydrogen. The study proposes hydrogen production by SMR and CO_2 transport infrastructure in Teesside, with CO_2 storage offshore. Four SMR units with total capacity of 1025 MW and two scales of hydrogen storage are proposed to match the inter-day and inter-seasonal heat load demand variation. For inter-day variation, hydrogen would be stored in salt caverns at Teesside, some of which may be repurposed from existing caverns. A new inter-seasonal storage salt cavern would be needed, to be located on the East Humber coast. High pressure hydrogen transmission pipelines would be installed to carry hydrogen from SMR sites to the city network and to storage sites. In addition to the current programme of polyethylene pipe conversion, further conversion of the existing gas network would be required, to be undertaken incrementally through the summer months over a three-year period [5].

The project is led by Northern Gas Networks. Ongoing work includes a £15 million industry bid to provide safety evidence for gas network conversion, considering alternative methods for hydrogen production and storage, and examining the feasibility of conversion to hydrogen in other major cities in the UK [37].

Energy H2@SCALE

The United States Department of Energy (National Renewable Energy Lab) has presented plans for a potential pathway towards decarbonisation through hydrogen usage. The plans focus on electrolyser-generated hydrogen, rather than SMR of natural gas. Currently feasibility studies are underway on a range of production methods, applications, storage techniques and distribution networks for hydrogen. The project is examining grid-scale hydrogen storage technologies, material compatibility for pipelines and compressors and efficient conversion methods [38].

Summary: ongoing projects across the value chain

Many key parts of the hydrogen for heat value chain are already mature and established technologies. Other elements are currently being piloted in the UK and globally. UK projects show a good spread across the different elements of the hydrogen for heat chain (Figure 1).

Summary of current progress:

Mature technology:

- Hydrogen production from SMR with CO_2 capture is a well-established process, utilised in industry globally. Many SMRs with CO_2 separation already operate in the UK.
- Scotland has significant expertise in CO_2 capture and storage technology and valuable gas transport and offshore CO_2 storage resources. Feasibility studies into CCS at the St Fergus site can lead to an operational full-chain system by 2022, with CO_2 storage in the North Sea.
- Hydrogen storage in salt caverns is a mature technology.

Advanced R&D:

- Leeds H21 City Gate provides a comprehensive full chain feasibility study that can be adapted by other areas.
- Hydrogen pipelines exist in Teesside and are more widespread in Europe. There is good level of knowledge of pipeline requirements for hydrogen.
- Two projects are currently studying hydrogen injection in low to medium pressure pipelines:
    - SGN will demonstrate 100% hydrogen network
    - HyDeploy in Keele University are testing 0.1 – 20% hydrogen blends
- Gas blending has been tested in the UK and in many places globally, including Power-to-Gas projects, with positive results.
- The HyHouse project tested appliance and hydrogen leak safety in a domestic setting, and indicated no significant safety issues.

Early R&D:

- There are currently no demonstration projects for hydrogen storage in porous rocks as would likely be required in Scotland.
- No studies have been done on the feasibility of hydrogen storage, other than in geological formations, specifically for the purpose of balancing heat demand.
- Further studies are needed to investigate the damage capacity of hydrogen explosions in a domestic setting.

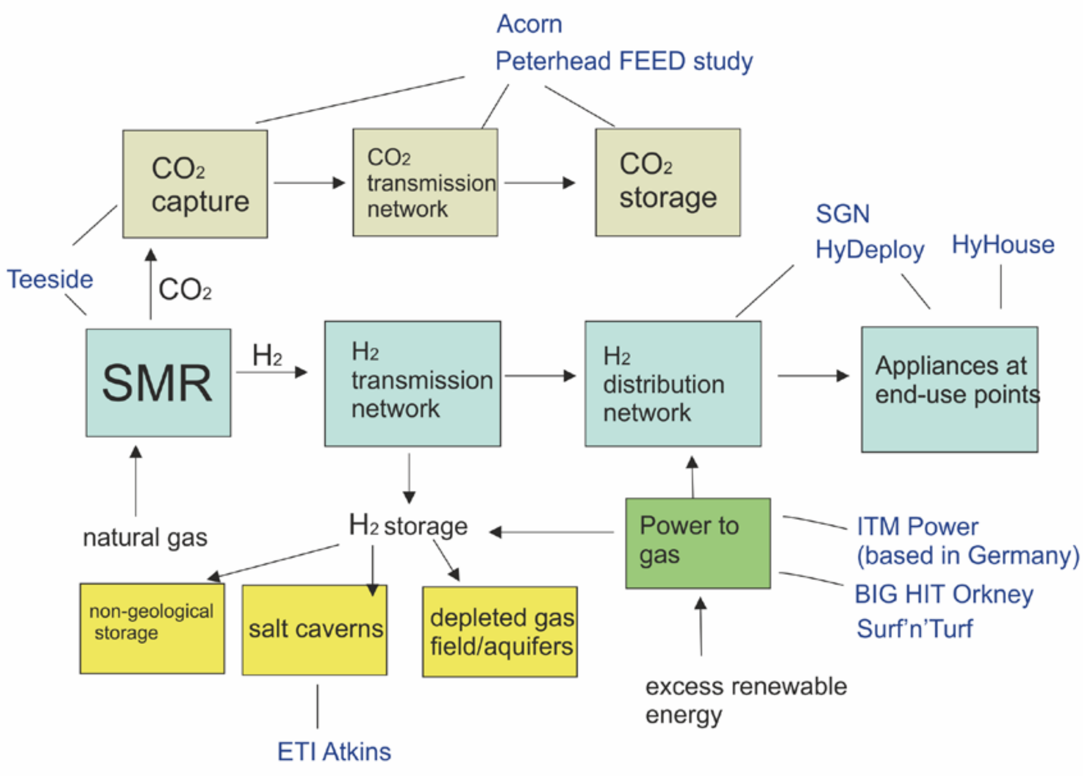

Figure 1. The Hydrogen for Heat chain. Projects currently active in the UK marked in blue, indicating their focus.

Annex I

Interchange of fuel gases

The ability to interchange fuel gases can be assessed by comparing the Wobbe Index (WI) of gases, which is derived from the gross calorific value and the density of a gas. Currently the WI of natural gas supplied to appliances in the UK is in the range 47.20 – 51.41 MJ/Nm^3. The WI of hydrogen is close to this, about 46 MJ/Nm^3, meaning that hydrogen can be burnt in most appliances without modification, although some adjustments may be required for safety reasons due to a higher flame speed [9].

Hydrogen Production with CCS

Some technical notes:

Most hydrogen is made by Steam Methane Reforming (SMR), although can be from reforming other hydrocarbons. It can also be made from gasification or partial oxidation of fossil or biological 'hydrocarbons' and separation from resulting syngas. These methods all produce a mixture of (at least) CO and H_2; further H_2 can be produced by the water-gas shift reaction, using more steam.

SMR reaction: $CH_4 + H_2O \rightarrow CO + 3\ H_2$

Shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$

SMR is used to produce hydrogen in several applications, or market niches:

- Industrial gas supplies – pure H_2 and CO_2 for sales.
- Refinery – H_2 from SMR used for hydrotreatment (deslphurisation, denitrogenation) and hydrocracking ('upgrading' heavy fractions), CO_2 usually vented.
- Fertilisers – H_2 from SMR used with N_2 to make ammonia, CO_2 often captured, sometimes used for urea manufacture, sometimes vented.

There are several techniques for separating the H_2 and CO_2 following SMR: pressure swing (and related) absorption (PSA), amine absorption, membranes, cryogenic. Most common is probably PSA. Often the lean H_2 stream following PSA, containing most CO_2, is used as a combustion fuel for the process (and/or other processes) so the CO_2 is diluted with nitrogen from combustion air before being vented, making it less efficient to capture CO_2 from the emission. However, by adding additional process step(s) it is possible to separate the lean H_2 stream giving pure CO2 and a more concentrated H_2 recovery stream. See article outlining a proprietary system: https://union.dk/reference-cases/industrial-gases/co2-capture-from-hydrogen-production/

Some producers use amine absorption to separate the CO_2, similar to typical post-combustion processes but starting from higher partial pressure of CO_2 so more efficient. The CO_2 stream produced is generally pretty pure, but will be wet and require dehydration before downstream use or transport.

Known hydrogen projects with CO_2 capture where there is an interest in storage, including CO_2-EOR, are summarised in the Table 1 overleaf.

Beyond these there are several IGCC plants operational or proposed with pre-combustion capture of CO_2. While these will probably usually be optimised to give a H_2-rich syngas, the H_2 is not separated as a product. Synfuels plants based on coal gasification, similarly, produce a hydrogen-containing syngas, but this is processed further to methane (as synthetic natural gas) methanol, or other liquid fuel products. Hence these uses are not detailed here.

Project	Status	Sector	H2 Process	Description	Feedstock	CO2 fate	Scale Mt/yr
Air Products Port Arthur (Texas, USA)	Operating	Refinery	SMR	CO_2 capture retrofitted to Air Product's two steam methane reformers located within the Valero Port Arthur refinery	Natural gas	CO_2 transported by pipeline for EOR in West Hastings oilfield	1.0
Quest (Alberta, Canada)	Operating	Refinery	SMR	CO_2 capture using amine solvent from 3 steam methane reformers at Scotford oil sands upgrader facility.	Natural gas	CO_2 piped for storage in saline formation in Alberta	1.0
North West Redwater (Alberta, Canada)	In build	Refinery	Gasification	New build bitumen refinery with integrated gasification of waste products to produce hydrogen for upgrading while capturing a high concentration CO_2 stream	Refinery waste	CO_2 for EOR via Enhance Energy's Alberta Carbon Trunk Line	1.2
Tomakomai CCS Demonstration (Hokkaido, Japan)	Operating	Refinery	SMR (uncertain, possibly gasification)	Project to build new compression and injection facilities adjacent to Hokkaido refinery to capture CO_2 produced at existing hydrogen plant.	Natural gas (possibly refinery byproducts)	CO_2 for storage in offshore saline aquifers.	0.1
Coffeyville Gasification Plant (Kansas, USA)	Operating	Refinery/ Fertilisers	Gasification	Gasification of petcoke from adjacent refinery gives hydrogen rich syngas; this is separated to give	Petcoke (refinery residues)	CO_2 sold to Chaparral Energy for use in North	0.85

				hydrogen for ammonia manufacture and CO_2 for EOR		Burbank oil unit, Oklahoma	
Enid Fertilizer CO_2-EOR Project (Oklahoma, USA)	Operating	Fertilisers	SMR	CO_2 capture from ammonia manufacture. CO_2 excess to requirement for urea manufacture sold for EOR	Natural gas	Piped for EOR in Oklahoma	0.7
PCS Nitrogen (Louisiana, USA)	Operating	Fertilisers	SMR	CO_2 by-product from ammonia plant, some for urea production, some for EOR	Natural gas	CO_2 sold to Denbury for EOR in Texas	0.4
Agrium Fertiliser Plant, Redwater (Alberta, Canada)	In build	Fertilisers	SMR	New compression facilities from capture at existing ammonia plant	Natural gas	Enhance Energy piping for EOR in Alberta	0.58
Agrium Fertiliser Plant (Texas, USA)	Operating	Fertilisers	SMR	Pilot scale capture from existing ammonia plant	Natural gas	EOR in Anadarko basin	0.1
CF Fertilisers (Billingham, UK, previously GrowHow)	Speculative	Fertilisers	SMR	One of proposed capture sites of Teesside Collective, CO_2 already captured but vented	Natural gas	Proposal to pipe to storage in North Sea	0.375
BOC (Billingham, UK)	Speculative	Industrial gases	SMR	One of proposed capture sites of Teesside Collective, CO_2 currently vented as combustion flue gas	Natural gas	Proposal to pipe to storage in North Sea	0.3

Table 1. Known hydrogen projects with CO_2 capture where there is an interest in storage. Source SCCS Global Map: http://www.sccs.org.uk/map

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