Hydrogen's Role in Scotland's Climate Journey

Commissioned by Friends of the Earth Scotland
June 2022

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Special thanks to **Dom Eagleton** at Global Witness for helpful comments and review.

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Executive summary and policy recommendations

Hydrogen is being posited as a low-carbon solution to decarbonising Scotland's economy. Proponents argue that the gas, which can be extracted from fossil fuels or renewables, could help cut greenhouse gases in sectors currently reliant on oil and gas, including transport, heating and industry.

However, the evidence suggests this is far from certain. A number of challenges arise from producing and using hydrogen that fundamentally call into question its role in the just transition.

High carbon emissions

Far from being low-carbon, today's hydrogen production is responsible for huge greenhouse gas emissions – around 830 million tonnes of CO_2 a year. Blue hydrogen – where emissions are captured and stored – is in its commercial infancy in the UK. Research highlights that carbon capture rates at actually operating hydrogen facilities only capture around 60% of emissions – well below industry targets. Even if high capture rates were to be achieved, it is unlikely that blue hydrogen plants would meet UK carbon reduction targets in the next decade.

Huge levels of renewable energy

Though lower carbon than grey (where no emissions are captured) or blue hydrogen, green hydrogen nevertheless has drawbacks. The most significant of these is the vast levels of renewable energy required to create green hydrogen. For example:

- 5 GW of green hydrogen would require 80% of current renewable energy generation in Scotland – solely to meet green hydrogen energy demands
- Using green hydrogen to meet Scotland's heating demand would require 180% more renewable energy than Scotland produces currently
- Adopting green hydrogen in industry would require nearly twice as much new renewable energy capacity compared to electrification technologies.

Low efficiencies

Though its potential end uses are numerous, hydrogen is a fairly inefficient energy vector, with lots of energy lost along the hydrogen conversion chain. This means that electrification technologies – including cars, heat pumps, batteries etc – are often more efficient in terms of energy, generally cost less, and are more advanced commercially.
For example:

- Electric heat pumps may be 168–342% more efficient than hydrogen boilers
- Hydrogen boilers may be 53–68% more expensive than electric heat pumps
- Electric vehicles are more than twice as energy efficient than hydrogen fuel cell vehicles

Hard to decarbonise sectors

There are, however, some sectors where hydrogen may have a role to play in decarbonisation strategies. For example, heavy transport like ships and aeroplanes cannot easily be electrified, and so hydrogen could be used as a combustion fuel or in a fuel cell. Even so, challenges remain in terms of storing hydrogen in a cost competitive way.

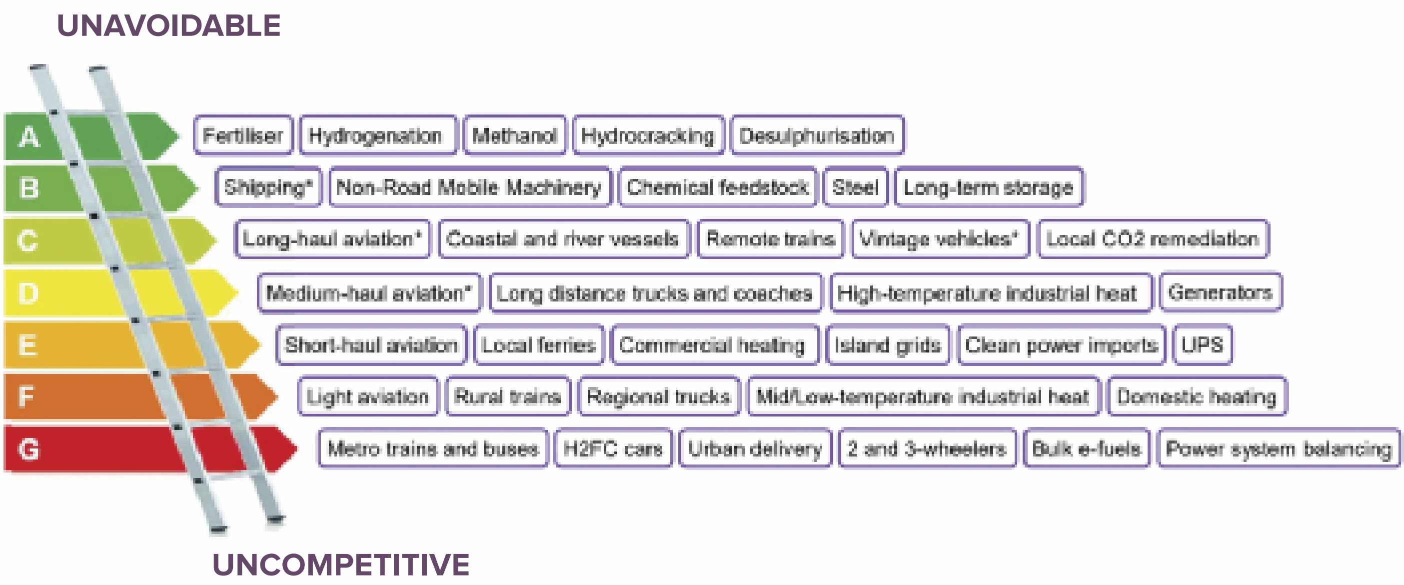
Industrial applications – for example high temperature heating and as industrial feedstocks to make petrochemical products – could be sectors where hydrogen plays a decisive role alongside other electrification technologies in Scotland. More research is needed to understand how hydrogen and electrification technologies can be used in this way. There is also a need for clear analysis into how the oil, gas and petrochemical industries will transform away from fossil fuels, therefore requiring less hydrogen for refining, as Scotland transitions to a low-carbon economy over the next twenty five years.

A targeted role for hydrogen in Scotland

Given that low carbon blue hydrogen production is far from certain, that unsustainable levels of renewable energy are needed for green hydrogen production, and that electrification technologies are more competitive than hydrogen technologies in heating and transport, we call for a limited, targeted application of hydrogen in Scotland that prioritises green hydrogen production only to be used in sectors where direct electrification is not possible.

This approach is best illustrated in the Clean Hydrogen Ladder (below), which lists hydrogen uses in order of priority. The top of the ladder refers to hydrogen use that is unavoidable because no other alternative exists (primarily industrial applications), and the bottom of the ladder lists hydrogen uses that should not be prioritised (light vehicles, domestic heating) because more efficient alternatives exist (battery electric cars, heat pumps etc).

Figure 1: Clean Hydrogen Ladder[1]



** Most likely via ammonia or e-fuel rather than H2 gas or loquid*

Prioritising hydrogen in this way would lessen the risk of locking Scotland into using an inefficient energy resource for decades to come. It would also ensure that renewable energy is not entirely diverted to green hydrogen production and is able to continue decarbonising all sectors of the economy – crucial if Scotland is to meet its legally binding carbon reduction targets.

Recommendations

- The Scottish Government must not support the development of hydrogen derived from fossil fuels (blue or grey), in line with the urgent need for a phase out of fossil fuels to stay within the 1.5°C temperature limit set by the Paris Agreement.

- Any funding for blue or grey hydrogen and associated carbon capture and storage (CCS) should instead be redirected to renewables and energy efficiency, as part of a just transition of the energy system.

- Recognising the greater efficiency, lower costs and lower emissions of electrification when compared to hydrogen, the Scottish Government must prioritise electrification over hydrogen, particularly in heating and transport, and support the use of green hydrogen only in sectors where direct electrification is not possible.

- Any renewable energy intended for green hydrogen production must be sourced from additional or surplus renewable energy capacity. This will ensure renewables are not diverted from decarbonising the electricity grid and prevent the need for fossil fuels to fill the gap.

CHAPTER 1:

What is hydrogen?

Chapter key points

- Hydrogen can be created from fossil fuels (blue and grey hydrogen) or from electricity and water (green hydrogen)
- 98% of global hydrogen production today is unabated grey hydrogen, primarily made from gas, and used in the oil, gas and chemical industries
- It emits around 830 million tonnes of CO_2 a year, more than 1.5 times the annual emissions of the UK
- As an energy vector, hydrogen is generally inefficient and costly to produce, store and transport
- It could potentially be used in transport and industry, but these uses are in their commercial infancy in the UK and Europe.

What is hydrogen?

Hydrogen is a gas that can be used as an **energy vector**. If combusted, it produces heat energy, meaning it can be used in a similar way to fossil fuels like gas and oil to power turbines for electricity, or in engines for transport. It can also be used in a fuel cell for power generation.

Hydrogen production

Although hydrogen is one of the most common elements in the universe, it does not exist naturally in a pure form that can be readily used. It must be extracted – from fossil fuels, biomass or water.

Around 98% of hydrogen production is made from fossil fuels – 76% from gas, and nearly all the rest from coal.[2] This is **grey hydrogen**, created through reforming gas where the resulting carbon emissions are not captured. Currently, this grey hydrogen is used in the petrochemical and oil refining industries.

Hydrogen can also be created by splitting water with electricity through a process called **water electrolysis**. This is **green hydrogen** and is potentially low carbon because its primary inputs are electricity from renewable energy and water.[3] Globally, electrolysis accounts for just 2% of hydrogen production. The water electrolysis process is used primarily in markets that require high purity hydrogen (for example, electronics and steel making).[4]

Grey, blue and green hydrogen definitions

Hydrogen is often referred to by different colours – primarily grey, blue or green. These colours correspond to different production methods, and not the colour of the actual hydrogen gas (which has no colour, odour or taste).

Grey hydrogen refers to hydrogen made from fossil fuels – gas, coal or oil – and the carbon dioxide emissions are not captured during the production process. Other terms include 'unabated hydrogen' and 'fossil hydrogen without CCS.'

Blue hydrogen refers to hydrogen made in the same way as grey hydrogen, but where carbon dioxide emissions are captured, transported and stored (CCS). Other terms include 'hydrogen + CCS' and 'fossil hydrogen with CCS.'

Green hydrogen refers to hydrogen made from splitting water and electricity (electrolysis). Other terms include 'renewable hydrogen' and 'electrolytic hydrogen'.

Production costs

The cost of producing blue hydrogen is dependent on how much it costs to build a hydrogen facility and the price of gas. In 2021, prices for grey hydrogen were between £0.70 – £1.67 per kilogram ($0.70 – $2.20/kg),[5] with analysis by Energy Transitions Commission calculating blue hydrogen at around £0.99 – £2.20/kg ($1.3 – $2.9/kg).[6]

Green hydrogen production has historically been a lot more expensive than blue hydrogen production. Costs are dependent on prices for electrolysers and electricity, as well as conversion efficiencies and annual operating hours. BloombergNEF calculates that green hydrogen costs around £3.67–£5.06 ($4.84 – $6.68/kg) in Europe, the Middle East and Africa.[7]

UK CCC modelling highlights that costs are likely to decrease over time as both technologies develop and scale up. However, blue hydrogen plants will face energy penalty costs for CCS technology (see Chapter 3), and will also be impacted by fluctuating gas prices. At time of writing, the outbreak of war in Ukraine in spring 2022 has dramatically pushed up gas prices, impacting on the competitiveness of blue hydrogen technologies. Analysis by Rystad suggests that blue hydrogen now costs between £9.10 – £10.62/kg ($12–$14/kg).[8] This means that for the first time, green hydrogen production is now cheaper than blue hydrogen. BloombergNEF had already forecast green hydrogen production becoming cost competitive with blue hydrogen by 2030 because of falling electricity prices.[9]

Current and potential uses of hydrogen

Hydrogen is currently used in the oil, gas and petrochemical sectors for a variety of different processes and applications. Global hydrogen demand in 2019 was around 70 million tonnes (Mt), with the top four applications being oil refining (33%), ammonia production (27%), methanol production (11%) and steel production (3%).[10] The remaining 26% of hydrogen is used in electronics, the food industry and other industrial sectors.[11]

As an energy vector, hydrogen is very flexible, and can theoretically be used in a wide variety of applications beyond its current industrial uses, including:

- In **domestic heating**, if burnt as a combustible fuel or possibly used in a fuel cell
- In **industrial heat** for processes like steel production, if burnt as a fuel
- For **power**, if burnt as a fuel to create electricity
- For **power storage** and power system balancing, if created using a surplus of renewable power (for example on windy days when wind turbines would otherwise be curtailed) and then burnt later at a time when renewable production is low but demand high (for example on cold winter days)
- For **aviation or shipping**, if burnt as a combustible fuel or converted into ammonia
- For **land transport**, either as a hydrogen fuel cell or combustible fuel for cars or heavy duty transportation vehicles like buses, lorries or trains
- As a **chemical feedstock** for the production of fertilisers or methanol in the chemicals sector, or desulphurisation in the oil and gas sectors.

Growing interest in hydrogen for decarbonisation

Because hydrogen can be produced using electricity, and that electricity can be generated using renewable energy, there is growing interest in the potential for green hydrogen to decarbonise the world's energy system. Proponents of hydrogen highlight that as well as being able to be used in the many different sectors listed above, it could have a particularly useful role in decarbonising areas of the energy system where low carbon alternatives to fossil fuels are challenging, for example as a chemical feedstock for fertiliser production, or as a fuel for heavy transport vehicles like cargo ships and aeroplanes.

In Europe, hydrogen forms a key part in the European Union's 2020 European Green Deal, with *'A hydrogen strategy for a climate-neutral Europe'* arguing that hydrogen is a key priority for Europe's clean energy transition.[12] Their hydrogen roadmap aims for 6 gigawatts (GW) of hydrogen electrolysers powered by renewable energy to be installed by 2024, increasing to 40 GW by 2030. By 2050, they estimate that a quarter of renewable electricity will be used for green hydrogen production.[13] The hydrogen will be used to initially decarbonise the oil, gas and chemical industries, and then applied to wider uses including steel making, transportation (trucks, trains and ships) and balancing the electricity grid through storage.

The UK sees a similar role for hydrogen in meeting its legally-binding emission reduction targets. Its most recent Energy Strategy, released in April 2022, commits to rapidly scaling up hydrogen production from 1 GW in 2025 (either in operation or construction) to 10 GW by 2030. The UK Government commits to 'at least half' being green hydrogen.[14]

The Scottish Government also has an ambition to scale up hydrogen production from virtually zero today, to 5 GW in 2032, to 25 GW in 2045 – the year it aims to be net zero. It plans a mixture of blue and green production but does not commit to set percentages of either.

Figure 2:
Hydrogen targets in EU, UK and Scotland

	2025	2030	2045	Blue or green?
EU	6 GW	40 GW		Existing grey hydrogen plants to be blue. 40 GW of green hydrogen electrolysers by 2030
UK	1 GW	10 GW		At least 50% green
Scotland		5 GW (by 2032)	25 GW (*net zero*)	Both, but no explicit percentage of either

Challenges of using hydrogen

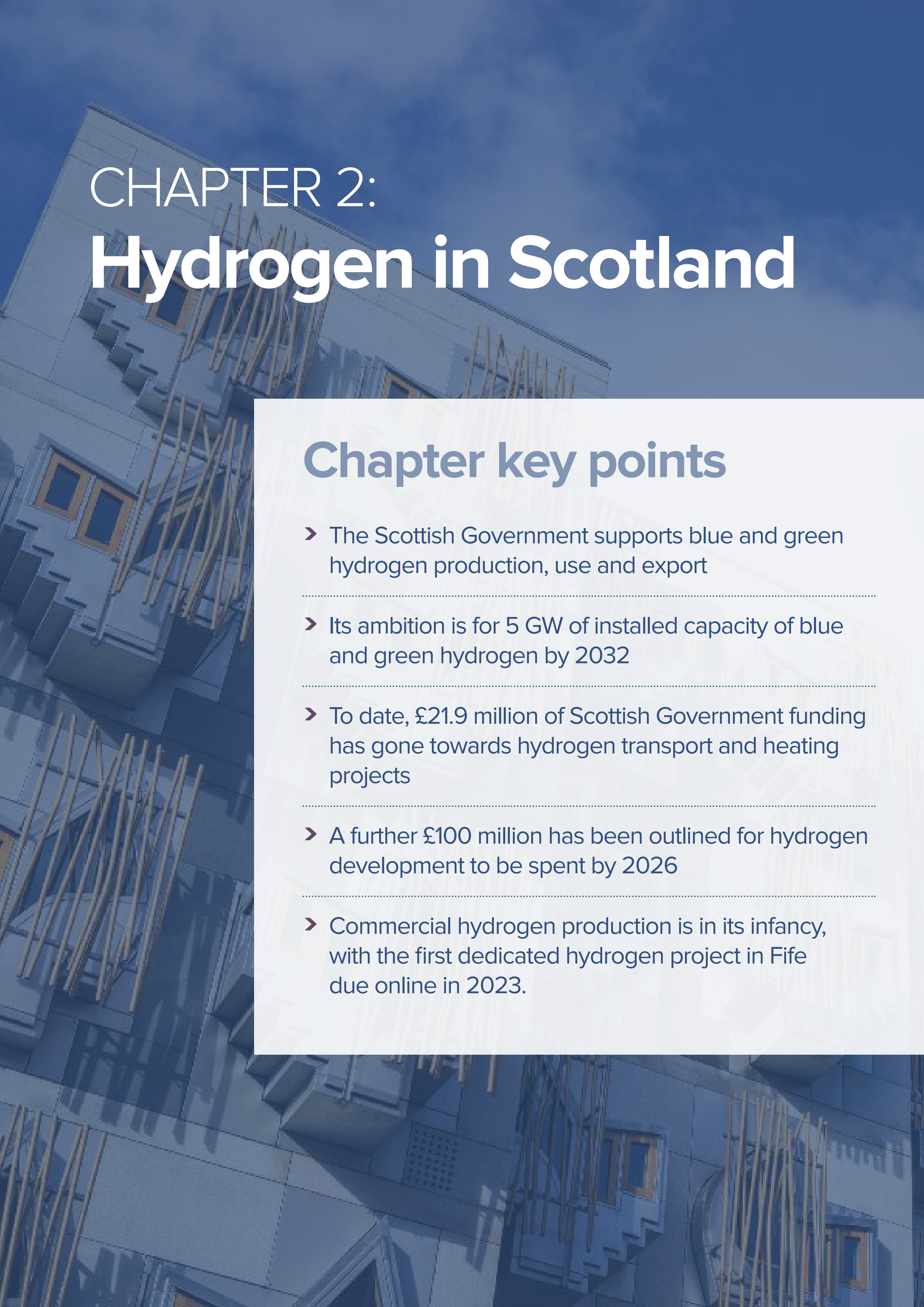
Efficiency. When taking into consideration the whole energy supply chain, hydrogen is likely to have relatively low efficiency compared with alternative technologies like electrification. Each step along the hydrogen supply chain – production, storage, transmission, combustion or use in a fuel cell – creates energy losses. For example, using electric heat pumps to heat homes is over four times more efficient than using green hydrogen in boilers.[16]

Molecular size. Hydrogen is a smaller molecule than methane, meaning it may leak much more easily than gas. This may pose challenges for long-term storage for power balancing. Hydrogen released into the atmosphere can react with methane and ozone forming a short-lived, indirect but potent greenhouse gas. Scientists recently warned that hydrogen can be two hundred times more potent than carbon dioxide when released kilogram for kilogram.[17]

Storage volume. Hydrogen as a gas takes up huge amounts of storage space. It takes up less space as a liquid, but this requires energy to lower its temperature to around -235°C, meaning costly storage equipment that also takes up space. This is a particular challenge if it's being used for freight transport like shipping where space is a key constraint.[18]

Technological maturity. The technology for producing green hydrogen is in its infancy in the UK. Similarly, using hydrogen for heating, transport and power storage is not widespread in Europe. This is compared with electrification technologies (like heat pumps and electric cars) that are much more widespread and increasing year on year.[19, 20] This raises significant questions as to whether hydrogen can scale up at the speed required to meet climate targets.

Costs. As well as overall efficiency, costs are incurred from all the extra conversion steps associated with electrolysis, reforming and gasifying, as well as the potential costs of storage. Upgrading key infrastructure like the National Grid so that hydrogen can be used will also incur costs. Analysis suggests that using hydrogen for heating could be over 50% more expensive than electric alternatives.[21]



CHAPTER 2:

Hydrogen in Scotland

Chapter key points

- The Scottish Government supports blue and green hydrogen production, use and export
- Its ambition is for 5 GW of installed capacity of blue and green hydrogen by 2032
- To date, £21.9 million of Scottish Government funding has gone towards hydrogen transport and heating projects
- A further £100 million has been outlined for hydrogen development to be spent by 2026
- Commercial hydrogen production is in its infancy, with the first dedicated hydrogen project in Fife due online in 2023.

Scottish context

Hydrogen is a fledgling industry in Scotland. The main demand for hydrogen comes from the country's petrochemical industry at Grangemouth, which uses grey hydrogen for refining and producing petrochemicals. However, the Scottish Government has made a series of commitments to support the scaling up of both supply and demand of hydrogen over the next two decades across the whole of Scotland.

Scottish Government policy and support

The Scottish Government has positioned itself over the last few years as a keen supporter of hydrogen, seeing Scotland as a potential place for hydrogen to be produced, used and even exported to the rest of the UK and to Europe. The Climate Change Plan update sees hydrogen playing a key role in achieving net zero carbon emissions by 2045 by helping to decarbonise various sectors of the energy system including heating, transport, industry and power.[22]

Between 2020 and 2021, the Scottish Government unveiled a series of documents and statements in support of creating a 'hydrogen economy'. These include:

- **The Scottish Hydrogen Assessment**, assessing the potential role of hydrogen in Scotland's economy. Using submissions from experts, industry and policy groups, it discusses three potential scenarios for Scotland in terms of hydrogen: Focused Hydrogen (limited and targeted production and use of hydrogen); Green Export (producing enough hydrogen to export into Europe) and Hydrogen Economy (transforming gas networks, industry and transportation to be reliant on hydrogen).

  The report assesses hydrogen applications in domestic and industrial heating, industry, and transport. On blue hydrogen, the industry stakeholders were evenly split on whether it would have a significant role to play or not.

- **Hydrogen Policy Statement**, that confirms the Scottish Government's support for blue and green hydrogen production and development in Scotland and highlights what it sees as the 'economic opportunity' of hydrogen in Scotland, aiming to produce the lowest cost hydrogen in Europe.

- **The Hydrogen action plan** (draft), that sets out a potential route map to developing hydrogen into 2030 and 2045, as well as the series of actions the Government will take to make this happen. Significantly, the draft hydrogen action plan sees a role for both blue and green hydrogen in achieving 5GW of installed electrolyser capacity by 2032, but does not set a target for a certain amount or percentage of either.

The Scottish Government has already provided a suite of investment for different aspects of hydrogen development. Around £15 million has already been invested in hydrogen bus fleets and infrastructure in Aberdeen, and £6.9 million has gone towards the H100 Fife project (see below). A further £100 million has been outlined for hydrogen under the Emerging Energy Technologies Fund launched alongside the Hydrogen action plan (draft) to be spent between 2021–2026.

The following table provides an overview of the 'low-carbon funding landscape' set out by the Scottish Government where support for hydrogen projects may be available, totalling around £1.25 billion.

Figure 3:
Scottish Government Hydrogen Funding Landscape[23]

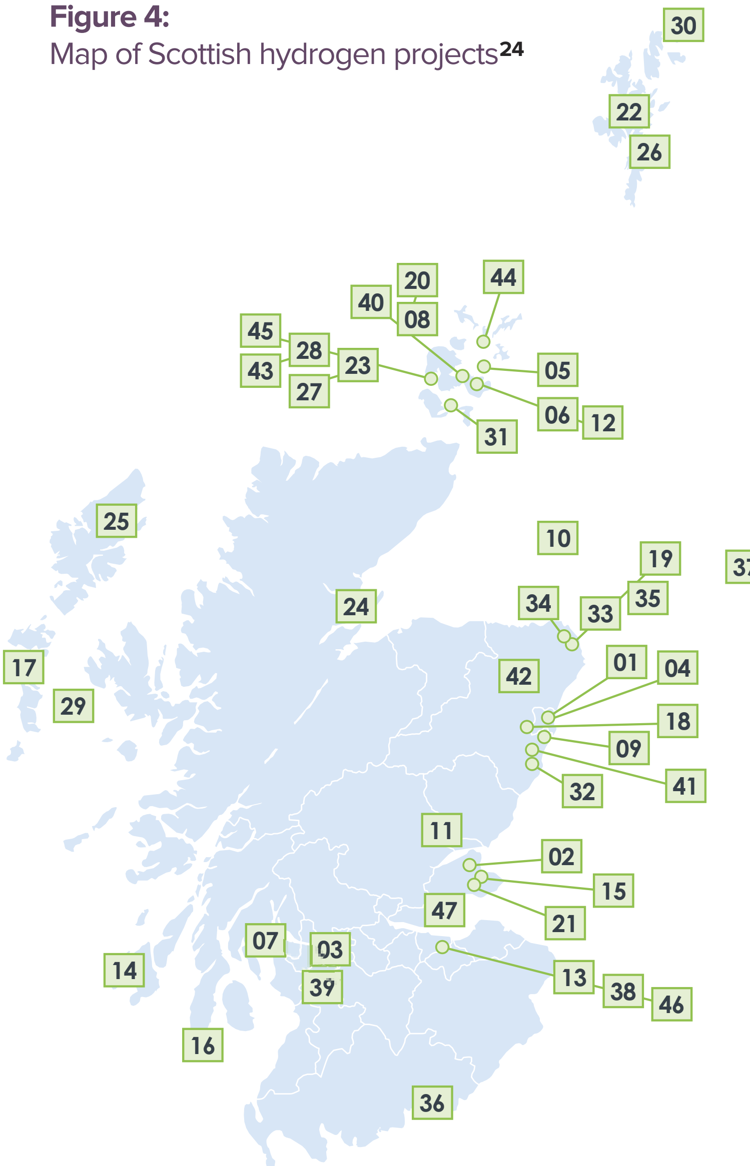
Funds	Dates	Target group	£ million
Emerging Energy Technologies Fund	2021 – 26	Business/Industry	180 (100 for hydrogen, 80 for CCS/NETS)
Energy Transition Fund	2020 – 25	Business	62
Energy Investment Fund		Third Sector	60
Community & Renewable Energy Scheme (CARES)	2021 – 22	Community Third Sector	8.25
Successor to the Low-Carbon Infrastructure Transition Programme (LCITP)	2021 – 26	Public and Private Sector	400
Low-Carbon Manufacturing Challenge Fund		Business	50
Scottish Industrial Energy Transition Fund (SIETF)	2021 – 26	Business/Industry	34
Green Supply Chain Development Fund		Business	50
Green Jobs Fund	2021 – 26	Enterprise Agencies	100
Green Business Support Fund		Business	50
Green Growth Accelerator Programme		Local Authorities	200 +
Switched-On Fleets		Public Sector	12
Scottish Zero Emissions Bus Challenge Fund		Public and Private Sector	50
TOTAL			**1,256.25**

Current projects

In their 2021 Draft Hydrogen Action Plan, the Scottish Government lists 47 hydrogen projects currently located across Scotland. The majority of these are research and test projects linked to educational institutions, though some are commercial projects in different stages of early development and construction.
Out of the 47 projects listed:

- 17 are for the end user (for example, hydrogen buses, hydrogen fuel cells)
- 14 are multi-vector (for example, looking at both storage and transmission)
- 2 are focused on hydrogen production
- 3 are for storage
- 1 is for transmission and distribution

Figure 4:
Map of Scottish hydrogen projects[24]



End User
01 Cloverhill's Aberdeen Hydrogen First
02 Eden Mill distillery
03 Glasgow Hydrogen Gritters
04 HECTOR project
05 HyDIME
06 HyFlyer
07 HySeas III
08 HySpirits
09 Hytransit Project - Aberdeen Hydrogen Busses
10 Hytrec
11 JIVE 2 - Dundee Hydrogen Transport
12 Kirkwall Airport Decarbonisation
13 Liquid Organic Hydrogen Carriers (LOHC) for the transportation of hydrogen
14 Project HyLaddie
15 Scottish Hydrogen Train project
16 TimberLINK
17 Uist Distilling Company

Multi-vector
18 Aberdeen Hydrogen Hub
19 Aberdeen Vision
20 BIG HIT
21 East Neuk Power to Hydrogen
22 GENCOMM - AD
23 ITEG - Integrating Tidal Energy into the European Grid
24 North of Scotland Hydrogen Programme
25 OHLEH - Outer Hebrides Local Energy Hub
26 Orion Project
27 PITCHES
28 ReFLEX (Responsive Flexibility) Project
29 SWIFTH2
30 PURE Energy Centre
31 Flotta Hydrogen Hub

Production
32 Aberdeen Hydrogen Centre (ACHES)
33 Acorn CCS
34 Acorn Hydrogen
35 Caledonia Clean Energy Project
36 Chapelcross Initiative
37 Dolphyn Project
38 Edinburgh International Festival decarbonisation project
39 Green Hydrogen for Glasgow
40 Hammars Hill Green Ammonia project
41 Kittybrewster Refuelling Station
42 Skelmonae Green Hydrogen
43 'Surf 'n' Turf'

Storage
44 Eday Flow Cell Battery Project
45 HyAl
46 HyStorPor Project

Transmission/distribution
47 H100 Fife project

Acorn Hydrogen and CCS

Acorn Hydrogen and CCS is a large-scale blue hydrogen project aiming to produce hydrogen from gas and then store the resulting CO_2 using CCS. The project is located at the St Fergus gas terminal near Aberdeen to specifically take advantage of existing oil and gas infrastructure – pipes, terminals, supply chains etc. – linked to the offshore North Sea oil and gas industry in order to minimise costs. The project is being led by Pale Blue Dot Energy Limited. Its parent company is Storegga Limited, a UK-based company specialising in CCS technologies. Oil and gas industry partners include Shell, Harbour Energy and North Sea Midstream Partners.

The size of the project would be an initial 200 MW plant, producing the equivalent of around 1.6 TWh annually. The proposal is to blend the hydrogen into the national gas network (a blend of up to 2% hydrogen) for the purposes of heating homes. According to the project website, the 'first Acorn Hydrogen plant can be online in 2025.'[26] Proponents highlight that the project can scale up to meet the theoretical growing demand for hydrogen in the future decades.

Acorn Hydrogen is running in parallel with the Acorn CCS project. The first phase of Acorn CCS – 'delivered by the mid 2020s'[27] – aims to create the infrastructure to capture, transport and store around 300,000 tonnes per year of CO_2 from the gas processing units at St Fergus. Later, when it comes online, the aim is to also capture CO_2 at the Acorn Hydrogen production site. The plan is to store the captured CO_2 under the sea bed of the North Sea in old oil and gas wells.

The Acorn Project as a whole has received backing and support from the UK Government as part of the UK Hydrogen Strategy,[28] including £30 million of UK Government funding under the Industrial Strategy Challenge Fund in 2021. In late 2021, however, Acorn CCS did not receive Track 1 funding from the UK Government's CCS competition funding.[29] The Scottish Government has supported the Acorn Project since 2017, providing funding and policy support through its feasibility and development phases.[30] Most recently, it promised £80 million to the CCS project, providing that the UK Government upgrades it to Track 1 status to give it financial backing.[31] The CCS project was also listed as a Project of Common Interest at the EU level. This means that it could have benefited from accelerated planning and permit granting support.[32]

H100 Fife

H100 Fife is a project located in Levenmouth, Fife, aiming to create green hydrogen and supply it through a dedicated gas network to heat homes.[33]

The project is being led by SGN in collaboration with Cadent, Northern Gas Networks, Wales and West Utilities, Ofgem and the Scottish Government. Ofgem have awarded up to £18 million for the project through its Network Innovation Competition, and the Scottish Government have invested another £6.9 million.[34] Cadent, Northern Gas Networks and Wales and West Utilities have contributed a further £2 million.[35]

A 5 MW alkaline electrolyser will create around 2,000 kg of green hydrogen per day (around 730 tonnes a year), powered by renewable energy from a nearby offshore wind turbine. The hydrogen will then be piped to the homes of customers who opt-in to the scheme. The project is expected to provide up to 300 homes with hydrogen for heating and cooking, and come online from 2023.[36] The project is expected to run for 5 years.

CHAPTER 3:

Environmental impacts of hydrogen

Chapter key points

- Every tonne of grey hydrogen produced emits 9 tonnes of CO_2. Current production is responsible for around 830 million tonnes of CO_2 a year
- Blue hydrogen is dependent on CCS technology that is in its infancy in Europe and has repeatedly failed to get off the ground in the UK
- Data from existing blue hydrogen plants suggests only 60% of CO_2 is captured
- Even if CCS became viable, blue hydrogen is unlikely to meet 2030 and 2035 carbon reduction targets
- Green hydrogen needs vast amounts of renewable energy. To achieve 5 GW of green hydrogen, Scotland would need an additional 80% of current renewable energy
- Hydrogen itself is a greenhouse gas 11 times more powerful than CO_2, and is likely to have leakage rates of 6–13% during production, transportation and storage.

Context

Though promoted as low carbon by proponents, hydrogen has a variety of environmental impacts that take place during production, transportation, storage and combustion. Hydrogen made from fossil fuels emits methane and carbon dioxide. Though green hydrogen emits less CO_2 than grey or blue hydrogen, there are still environmental issues associated with its production and use. Moreover, hydrogen in general (blue and green) is associated with fugitive emissions of the hydrogen gas itself, as well as nitrogen oxide when combusted.

Blue hydrogen

Greenhouse gas emissions

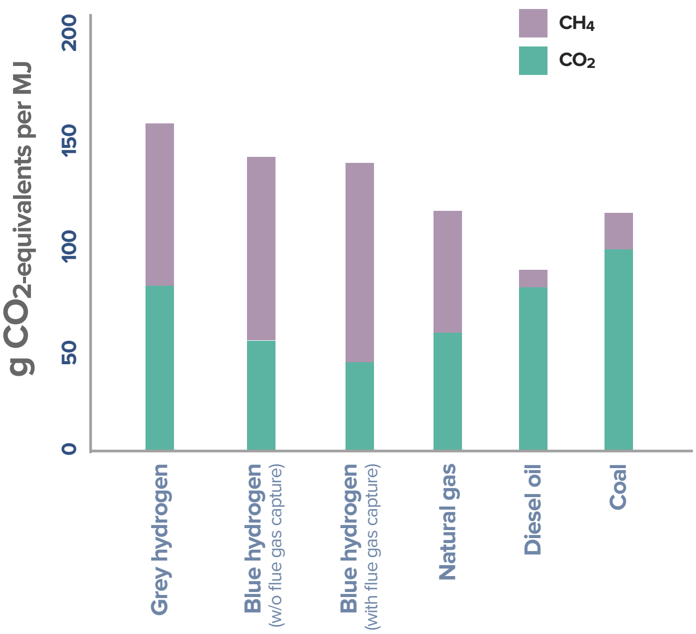
Blue hydrogen is created using gas (primarily methane) and high temperature steam. At each stage of production, greenhouse gases are emitted – primarily methane and carbon dioxide. While grey hydrogen captures none of these emissions, blue hydrogen aims to capture CO_2 at the site of production.

Methane emissions

Fugitive methane emissions are releases of gas into the atmosphere at various different sites of extraction, transportation, storage and production of gas. It is not possible to use and process gas without some methane emissions, both from accidental releases from leaky infrastructure as well as the need to purposefully vent methane during extraction and processing.[37, 38] Methane is a greenhouse gas that is 86 times more powerful than carbon dioxide in a twenty year time frame.[39]

Methane emission rates vary across production sites. Research into North Sea oil and gas sites indicates that, on average, 0.23% of methane is lost as fugitive emissions – though there are often large discrepancies between sites, and data depends on the time of day and whether oil platforms are actively flaring and venting.[40, 41] Research from the US, however, highlights much higher rates; Haworth and Jacobson (2021) estimate that 3.5% of gas is lost as fugitive methane emissions.[42] This data led them to conclude that in the US, blue hydrogen production has a higher greenhouse gas footprint than gas, diesel and coal per unit of heat energy.

Figure 5:
Greenhouse gas footprint per unit of energy: US comparisons between between grey hydrogen, blue hydrogen, gas, diesel and coal [43]



Carbon dioxide emissions

Every tonne of hydrogen produces 9 tonnes of CO_2,[44] emitted at three stages of production:

- From the chemical reaction between the gas and high temperature steam required to make the hydrogen (process emissions)
- From the burning of gas to heat the steam (combustion emissions)
- From the burning of gas to provide the power to run the CCS unit (energy penalty), unless the power is sourced from grid electricity.

Understanding how much carbon dioxide is emitted depends on the type of technology and whether this is done in conjunction with CCS.

Carbon capture and storage

The UK Committee on Climate Change (UKCCC) highlights that blue hydrogen production must be coupled with Carbon Capture and Storage (CCS) technology in order to be truly low carbon. Both the UK and Scottish Government hydrogen plans assume that hydrogen can be coupled with CCS, and that these plants will be both commercially viable and able to rapidly scale up in time to meet their 2030 targets.

However, there are serious challenges with CCS technology. There are currently no operational plants in the EU or the UK. Globally, it has yet to be proven at scale to be commercially viable.[45] Recent research has highlighted that the majority of operating CCS plants actually produce more carbon than they capture.[46]

What is CCS?

Carbon Capture and Storage (CCS) is used to capture carbon dioxide from large industrial processing sites like gas-fired power plants, steel and cement production, and oil refining.

During processing, carbon dioxide is separated from other gases, compressed and transported (either in pipes, trucks or ships) and then injected underground (at more than 1km deep), into either depleted fossil fuel reservoirs or saline aquifers. The well is then plugged with cement and other materials at pressure to keep the CO_2 from escaping back into the atmosphere. CCS technology can potentially be added on to existing fossil fuel-fired power plants, or new plants can be built with integrated CCS technology.

Globally, there are only 27 large-scale CCS facilities currently operating, with a further 108 plants at different stages of development or construction (including 2 that are suspended).[47] The 27 operational plants have a combined capture capacity of 36.6 million tonnes of CO_2 per year[48] – around 0.1% of total global emissions. Five projects are tied to geological storage sites, and the remaining 22 facilities use the captured CO_2 for Enhanced Oil Recovery, where CO_2 is injected into fossil fuel wells to recover more oil and gas.[49] In Europe, there are only two plants currently operating, and these are both in Norway operated by Northern Lights Consortium that captures and stores 1.7 $MtCO_2$/year from the gas processing industry. As of 2021, a further 35 projects are in the pipeline in Europe.[50]

CCS in the UK

The past 15 years has seen CCS repeatedly fail to get off the ground in the UK. Previous Governments have attempted to commercialise CCS through a suite of private investment and funding competitions, first in 2007 that eventually resulted in the winner, Scottish Power, abandoning their project when a financing deal could not be reached with the government. The second attempt was in 2012, and again ended in the competition winner, Drax, pulling out of its £1bn project citing commercial challenges.

The last two years has seen the UK Government attempt to kick-start CCS technology for a third time, launching a £1bn Infrastructure Fund together with a target to establish two CCS 'clusters' by the mid 2020s, and four by 2030 with a capture capacity of 10Mt/year.[51] In late 2021, the Government shortlisted two projects for funding, both of which are in England. The first of these is the East Coast Cluster – led by BP in collaboration with Shell, TotalEnergies, Eni, Equinor and the National Grid – that aims to transport and store CO_2 emissions from two industrial zones in Humber and Teesside. The second project, led by Italy's Eni in collaboration with a consortium of energy and petrochemical companies including Essar and Inovyn, aims to produce hydrogen and store the resultant CO_2 emissions in depleted oil and gas fields in Liverpool Bay.[52] A third project – the Acorn Cluster led by Storegga, Shell, Harbour and National Grid in Aberdeenshire, Scotland – was listed as a reserve should the first two projects not proceed.

Blue hydrogen capture rates

There are only two commercial hydrogen plants that use CCS technology operating today. These are Shell's Quest Plant in Alberta, Canada, that uses hydrogen to convert tar sands bitumen into synthetic crude oil; and the Air Products' facility at the Valero Port Arthur Refinery in Texas, US, that refines crude oil into gasoline, diesel, aviation fuel and other oils.

Steam methane reforming (SMR) technology is the most widespread in blue hydrogen production, and both projects use this process coupled with CCS. Theoretically, SMR+CCS can capture up to 90% of CO_2 emissions. However, according to the UKCCC, the two facilities operating in Canada and the US only capture around 60% of their CO_2 emissions – well below industry targets.[53] Moreover, research analysing life cycle emissions suggests that the Shell plant in Canada captures less than 40% of greenhouse gases.[54]

Autothermal reforming technology (ATR) coupled with CCS can theoretically capture higher rates of CO_2 than SMR, though actual data is hard to quantify because there are much fewer ATR plants in operation (though an increasing number are in the pipeline in Europe). Recent research highlights that even with very high capture rates of 98%, coupled with a low methane leakage rate of 0.2%, ATR hydrogen would still struggle to meet the EU's emissions standard for hydrogen (under 3 tonnes of CO_2e per 1 tonne of hydrogen produced).

According to data from the UKCCC, with high capture rates of 90% and 95%, SMR and ATR with CCS could emit fairly low levels of CO_2 – and could potentially meet the UKCCC target of below 0 grams of CO_2 per kWh (gCO_2/kWh) by 2030. However, this is in the very best scenario, and average grid intensities could actually be much higher. Indeed, neither technology would meet the 2035 target of below $10gCO_2/kWh$.

Figure 6:
Carbon intensities of SMR and ATR + CCS hydrogen[57]

Technology type and target	gCO_2/kWh (range)
SMR+CCS	45 – 120
ATR+CCS	29 – 99
UK 2030 target	0 – 50
UK 2035 target	0 – 10

Energy penalty and efficiency losses from CCS

A further challenge with blue hydrogen is understanding what impact the CCS technology itself has on the hydrogen production plant. The technology to capture carbon and pump it underground requires energy to run, and therefore requires more inputs either in gas (to create the electricity) or electricity from renewables. This is called **the energy penalty**.

The energy penalty is often calculated at around 25% additional electricity to enable the CCS process to run. However, there is a lack of consistent, reliable data from actually operating plants with CCS from around the world.[58] If this additional gas is combusted without CCS, CO_2 emissions will increase further and any additional gas used will create additional fugitive methane emissions from extraction, transportation, storage and processing.

The energy penalty can also be expressed in terms of additional costs for a plant to run for the same output, or in terms of decreased efficiency. The UKCCC estimates that overall efficiency of hydrogen production could reduce by 5% if CCS was added to an SMR facility, increasing costs by £2–5 per megawatt hour (MWh). Additional capital costs could be incurred at £3/MWh for CO_2 capture, as well as a further £3/MWh for CO_2 transport and storage infrastructure (if CO_2 was priced at £15 a tonne).[59] According to the IEA, capital expenditure increases by around 85% for hydrogen gas reformers operating with CCS compared to non-CCS facilities, and the efficiency drops by 7%.[60]

Green hydrogen

Electrolysis – creating hydrogen from electricity and water – currently accounts for around 2% of global hydrogen production. Its main inputs are electricity and water.

Renewable energy demand

A huge amount of electricity is needed for electrolysis, requiring vast amounts of renewable energy.

Globally, around 70 Mt of hydrogen is produced today and 98% of this is grey – produced from fossil fuels with no CCS. It emits around 830 Mt of CO_2.[61] Producing the same amount of hydrogen using electrolysis (green hydrogen) would need an annual electricity demand of 3,600 TWh.[62] To put this in perspective, this is 70% more than the entire global electricity generation from solar and wind combined.[63]

In 2020, Scotland produced 31.8 TWh from renewable energy.[64] If Scotland were to meet its ambition of 5 GW of hydrogen by 2030 using only green hydrogen, it would need 25.5 TWh of renewable electricity capacity solely for hydrogen production. This is the equivalent of the electricity needs for over 6.3 million homes. Or, in other words, Scotland would use 80% of what it currently produces in renewable energy just for green hydrogen production.[65]

Additionality

An issue that has recently come to light around hydrogen production is the need to ensure that the renewable electricity used to make green hydrogen is *additional* to already existing renewable energy. In other words, the electricity that powers electrolysis must come from renewable energy installations – solar panels or wind turbines – that have been built *specifically* for hydrogen production, in addition to existing renewable energy sites. Or, if existing renewable energy is used, it must only be sourced at times when the electricity is surplus to requirements and otherwise would have been wasted, for example on sunny days in summer when solar panels are already creating enough energy to meet the relatively low electricity demand.

This principle of creating hydrogen only from additional or surplus renewable energy is important for two reasons. First, it means that hydrogen production does not divert renewable energy from existing wind and solar installations that are helping to decarbonise the energy grid.

Second, without an additionality requirement, renewable electricity that does get diverted from existing sources may be replaced by electricity created from fossil fuels. Gas-fired power plants may be fired up to fill the energy gap that hydrogen production could create, meaning increased greenhouse gas emissions. This is a particularly big issue given the huge levels of renewable energy required for green hydrogen if Scotland were to meet its ambition of 5 GW by 2030.

Recent research has highlighted that large fossil fuel companies pushing hydrogen have lobbied against additionality requirements at the EU level.[66] The UK Government is not currently considering additionality requirements for green hydrogen production.[67]

Blue and green hydrogen

Hydrogen emissions

A recent study commissioned by the UK Department of Business, Energy and Industrial Strategy highlights that hydrogen itself acts as a greenhouse gas when released into the atmosphere. According to the research, hydrogen is 11 times more powerful a greenhouse gas than carbon dioxide over 100 years, and over a shorter time span of twenty years, it is 33 times more powerful. These figures are far higher than previous estimates.[68]

According to a second study also commissioned by the UK Government, hydrogen production may be a key area responsible for hydrogen emissions. Around 9.20% of hydrogen may be lost through the electrolysis production process (though this may drop to 0.52% if technology is added to the process that repurposes purged and vented hydrogen).[69] Blue hydrogen with CCS may emit around 0.52% fugitive hydrogen emissions.

Transportation and storage are other key areas where hydrogen emissions may be considerable. Hydrogen is most likely to leak during road transportation (when cooled to a liquid) with emissions of around 13.20%. Above ground storage tanks (where hydrogen is stored as a gas) may emit around 6.52% of the stored hydrogen.

Nitrogen oxide emissions

Combusting hydrogen can form air pollutants called nitrogen oxides (NOx). They can react with oxygen to produce smog and acid rain, contributing to a variety of respiratory health problems. Transport is a major source of NOx emissions, but NOx can also occur from the combustion of hydrogen in for example hydrogen boilers in homes. A 2022 study found that using hydrogen boilers to heat homes in Europe would result in more than double the amount of NOx compared to using electric heat pumps.[70]

CHAPTER 4:

Hydrogen for heating

Chapter key points

- Hydrogen is being proposed as a solution to decarbonising Scotland's heating emissions, through blending hydrogen into the grid and using it as a fuel in boilers
- However, electric heat pumps are around 168–342% more efficient than hydrogen boilers
- Hydrogen boilers may also be 53–68% more expensive than heat pumps, and be exposed to fluctuating gas prices that are currently at an historic high
- Meeting Scotland's heating demand using green hydrogen would require a 180% increase in renewable energy generation.

Greenhouse gas emissions from heating

Today, Scotland's 2.5 million occupied dwellings account for around 13% of total greenhouse gas emissions,[71] and around 30% of Scotland's total energy consumption (44 TWh).[72] A further 220,000 buildings are used for non-domestic purposes (retail, offices, schools, industrial buildings[73]). These account for 7% of Scotland's total GHG emissions, and around 12% of Scotland's final energy consumption (17 TWh).[74]

The Scottish Government's 2020 Climate Change Plan update states that to meet Scotland's legally-binding climate targets, emissions from homes and non-domestic buildings will have to fall by 68% by 2030 as compared with 2020. Scotland's Heat in Buildings Strategy sets out a range of measures to try and achieve this, including scaling up energy efficiency standards in new builds, retrofitting existing buildings, and changing the fuel source from gas to low carbon alternatives. The Scottish Government has also made it illegal to fit gas heating in housing developments consented after 2024 and pledged that fossil fuel boilers will be phased out of all homes by 2030. Heat pumps – both ground source and air source – are the main alternative to achieving decarbonisation. Hydrogen is also mentioned as a second option, though the extent of its role in the Strategy is uncertain and unspecified.

Hydrogen for heating

The main way that hydrogen could play a role in decarbonising Scotland's heat in buildings is by being used like gas – through combustion in boilers to heat water for domestic heating systems. This could be done in two ways: either by blending a proportion of the gas with hydrogen (up to 20%), or using 100% hydrogen in certain parts, or all, of the gas network.

Challenges of hydrogen in domestic heating

There are several challenges to using hydrogen for heating buildings, relating primarily to hydrogen's inefficiency as an energy vector compared to low carbon alternatives.

Blending hydrogen into the grid only saves a small percentage of GHG emissions

Blending 20% of hydrogen into the grid would not actually save 20% greenhouse gas emissions as would be expected – it would only save around 6–7%. This is because hydrogen is a less efficient energy vector than gas. This means that to generate the same amount of energy as using just gas would require a larger volume of any blended mix of hydrogen and natural gas. For a blend of 20% hydrogen, a household would have to burn 13% more of the blended mix to create the same amount of energy as they would for pure natural gas.[75]

Blending hydrogen is not a long term solution to emissions reductions

In the UK, the Gas Safety (Management) Regulations prohibit the blending of hydrogen above 0.1% by volume – though it is widely expected this will be increased to 20% by volume as part of the UK Government's hydrogen strategy.[76] Beyond 20%, however, evidence suggests that the existing transmission, compression and storage infrastructure will need to be upgraded. This is because hydrogen can accelerate the degradation of steel pipelines (embrittlement of steel), requiring pipelines to be coated with an inner layer, or changed to fibre-reinforced polymer pipelines that come in smaller diameters.[77]

If hydrogen blending is limited up to 20% volume without major infrastructure (and regulatory) changes, and 20% blending only achieves carbon reductions of 6–7%, hydrogen blending is unlikely to be an effective long-term strategy to reduce residential heating emissions by 68% by 2030. As the UKCCC highlights, hydrogen blending:

"is not a key stepping stone on the way to full conversion to hydrogen, as it fails to tackle key challenges associated with higher proportions of hydrogen supply (i.e. costs and disruption of conversion at the household level, public acceptability of hydrogen as a fuel). Blending of hydrogen with natural gas and repurposing the gas grid to 100% hydrogen are quite separate things."[78]

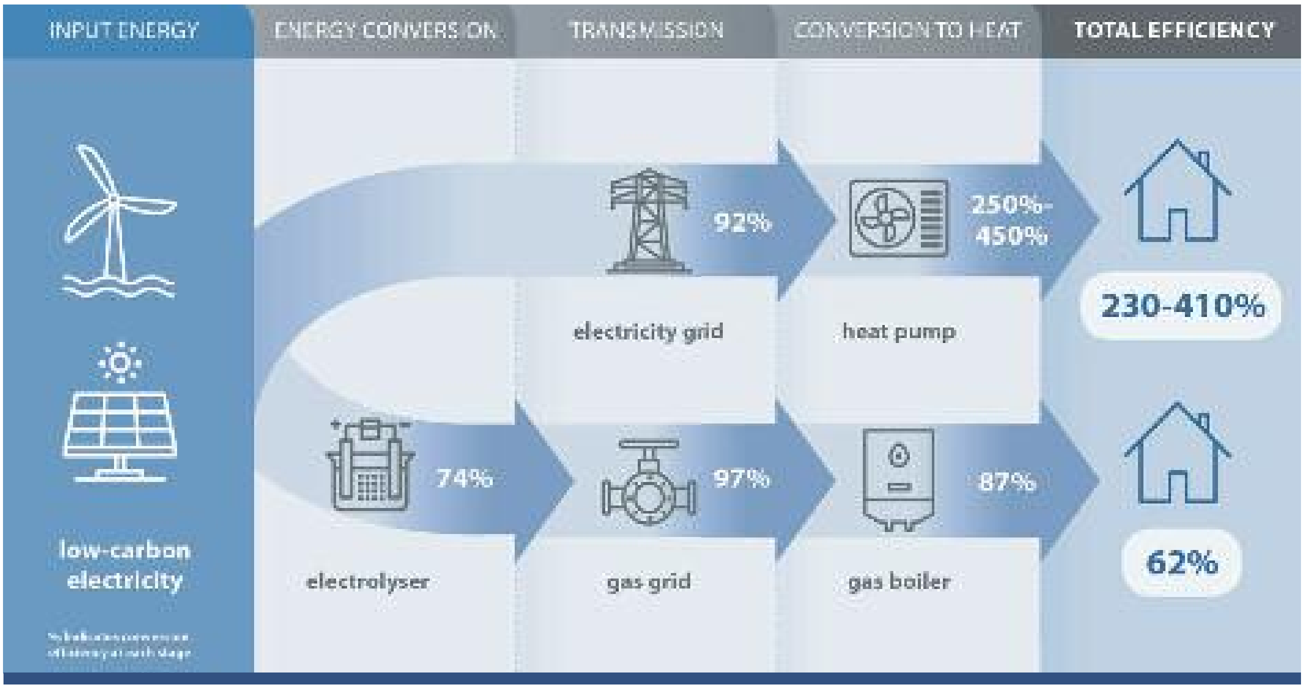
The UK's natural gas transmission network extends over 280,000km so repurposing the entire grid to instead carry hydrogen would require an enormous amount of resources in terms of time, money and labour.[79]

Hydrogen boilers are less efficient than electric heat pumps

Electric heat pumps work by using electricity to extract heat from the air, ground or water. They are extremely efficient, producing several units of heat for each unit of electricity that is put in. There are very few stages from creation to use for the energy to be lost along the way.

Green hydrogen is by comparison much less efficient, with lots of energy being lost between energy creation, electrolysis, storage, transmission through the gas network, and final combustion in a gas boiler. Analysis by the UKCCC highlights that while electric heat pumps have around 230–410% total efficiency, hydrogen has a total efficiency rate of just 62%.[80] In other words, electric heat pumps are around 168–342% more efficient than hydrogen boilers.

Figure 7:
Relative efficiency of heating: electricity in heat pumps vs. electrolytic hydrogen in boilers[81]



Source: CCC analysis.

Notes: The diagram shows the indicative efficiency of using a given amount of zero-carbon electricity in delivering heat for buildings. Whilst in practice each of the efficiency numbers could vary, this would not be sufficient to change the conclusion that heat pumps provide a much more efficient solution for providing heat from zero-carbon electricity than use of electrolytic hydrogen in a boiler.

Hydrogen is more expensive for consumers than electric heat pumps

A 2021 study by the European Consumer Organisation compared the consumer costs between electric heat pumps, hydrogen boilers, and hybrid heat pump hydrogen systems. In each country electric heat pumps came out as significantly cheaper. For both the Czech Republic and Poland – countries that are significantly colder in the winter than Scotland – hydrogen boilers would be 56–68% and 53–61% more expensive than heat pumps over their lifetime.[82] In a similar study comparing the three types of heating appliance, research commissioned by the UKCCC found that costs for energy are higher in the hydrogen scenario.[83] Indeed, one significant consideration is that hydrogen boilers installed in the short term would still be reliant on fluctuating gas prices – currently at historic highs for energy consumers in the UK.[84]

Challenges of decarbonising heat

Scotland's Heat in Buildings Strategy highlights a key role for energy efficiency to play in decreasing carbon emissions. Energy efficiency can be achieved through retrofitting homes through for example installing cavity wall and loft insulation, sealing gaps in the building's fabric, and replacing windows to double glazing. Indeed, much of the modelling comparing electric heat pumps and hydrogen assumes that there will be deep retrofits to residential buildings to make them much more energy efficient in both scenarios. Heat pumps work best in homes that are well insulated, while combusting any fuel for heating (whether hydrogen or gas) will be cheaper if the home is well insulated.

However, a key challenge is that Scotland's building stock is old, meaning that in many cases retrofitting buildings to increase the energy efficiency will be technically challenging and thus incur significant costs. The Scottish Government estimates that the average cost of energy efficiency measures is around £2,000, with heat pumps currently around £10,000. The total capital costs of converting all of Scotland's homes to zero emissions by 2045 is in the region of £33 billion.[85]

Scotland's tenement buildings, which make up around 24% of Scotland's housing stock, are a particular challenge to both insulate and heat with a low carbon system. Tenements are draughty, with high ceilings and chimneys that decrease heating efficiency. The viability of installing heat pumps is also unclear, and will likely be dependent on the specific circumstances and fabric of each building. However, the following may provide insight into how to overcome the challenge of decarbonising heating for tenements:

- The recent UK-wide Electrification of Heat Demonstration project, funded by the Department for Business, Energy and Industrial Strategy, installed around 750 heat pumps in a variety of buildings (by type and age) across England, including flats. A key conclusion was that the project did not "identify any particular type or age or property that cannot have a successful heap pump installation. The suggestion that there are particular home archetypes in Great Britain that are "unsuitable" for heat pumps is not supported by the project data." [86]
- A retrofit of eight tenement buildings in Glasgow is currently taking place, including deep renovation of its ventilation systems, insulation of its external walls and roofs, and the installation of ground and air source heat pumps in four of the flats.[87] This will provide key evidence on how tenements can be retrofitted across Scotland.
- One solution to heating Scotland's tenement buildings is through district heat networks supplied by heat pumps that heat water at a large facility and then pipe it into individual homes. The Scottish Government has committed to scaling up heat networks, from today's level of 1.18 TWh to 6 TWh by 2030 (around 8% of heat demand).[88] Modelling by the UK Government suggests that heat networks could potentially supply around 28% of heat demand in Scotland.[89]

Hydrogen would require more renewable energy than is produced in the UK

Because of the inefficiencies of hydrogen, replacing gas with green hydrogen in all boilers would require a vast amount of renewable energy generation. The UKCCC highlights that this demand at the UK level would go well beyond what can be produced in the UK from electrolysis.[90] According to its chief executive, Chris Stark, the UK would need around 30 times more renewable energy capacity than it currently produces to meet this demand.[91] This would be on top of the increasing demand for renewable energy required to decarbonise other parts of the energy system, namely electricity.

In Scotland, energy consumption for domestic and non-domestic heating totals 61 TWh.[92] If Scotland were to meet this demand using green hydrogen, it would need 88.9 TWh of renewable energy generation.[93] This is 180% more renewable energy than what it currently produces – and would be solely for green hydrogen production.[94]

Using hydrogen at this scale, therefore, would entail either importing green hydrogen from elsewhere (adding further inefficiencies to the hydrogen supply chain) or producing blue hydrogen – with all the additional greenhouse gas emissions that would entail. Even if blue hydrogen with CCS was proven to be commercially viable in Scotland, it is unlikely to be deployed at scale until well into the mid 2030s. This leaves a huge gap in terms of sourcing the high levels of renewable energy for green hydrogen production before then.

CHAPTER 5:

Hydrogen for transport

Chapter key points

- Hydrogen is being considered as a potential way to decarbonise Scotland's transport
- However, for journeys that need to be made by car, direct electrification is already much more efficient, cheaper, and more advanced commercially than hydrogen
- Buses and trains in Scotland are already facing large-scale electrification
- There is also scope for directly electrifying industrial machinery
- Hydrogen may have a role to play in shipping and aviation where electrification is not as possible – but there are still big challenges to making this commercially viable.

Greenhouse gas emissions from transport

Transport in Scotland is the largest contributor of greenhouse gases, accounting for 14.8 $MtCO_2e$, around 35.6% of all emissions.[95] Emissions are further split into transport modes:

- Road transport (cars, vans, lorries, buses etc) account for 10 $MtCO_2e$ (68% of transport emissions)
- Shipping accounts for 2.3 $MtCO_2e$ (15.5%)
- Aviation accounts for 2.23 $MtCO_2e$ (15.1%)
- Rail emissions account for 0.16 $MtCO_2e$ (1.1%).

Hydrogen in transport

Hydrogen can potentially be used in a variety of transport applications – from cars, lorries, ferries to even aeroplanes. It can be used in transport in two ways – either as a fuel like petroleum that is combusted to power an engine, or in a fuel cell that uses hydrogen to produce electricity.

If hydrogen can be used like petroleum – i.e. vehicles can continue to be filled up at petrol stations – additional charging infrastructure may not be needed, and therefore the driver's experience could remain quite similar to how it is currently.

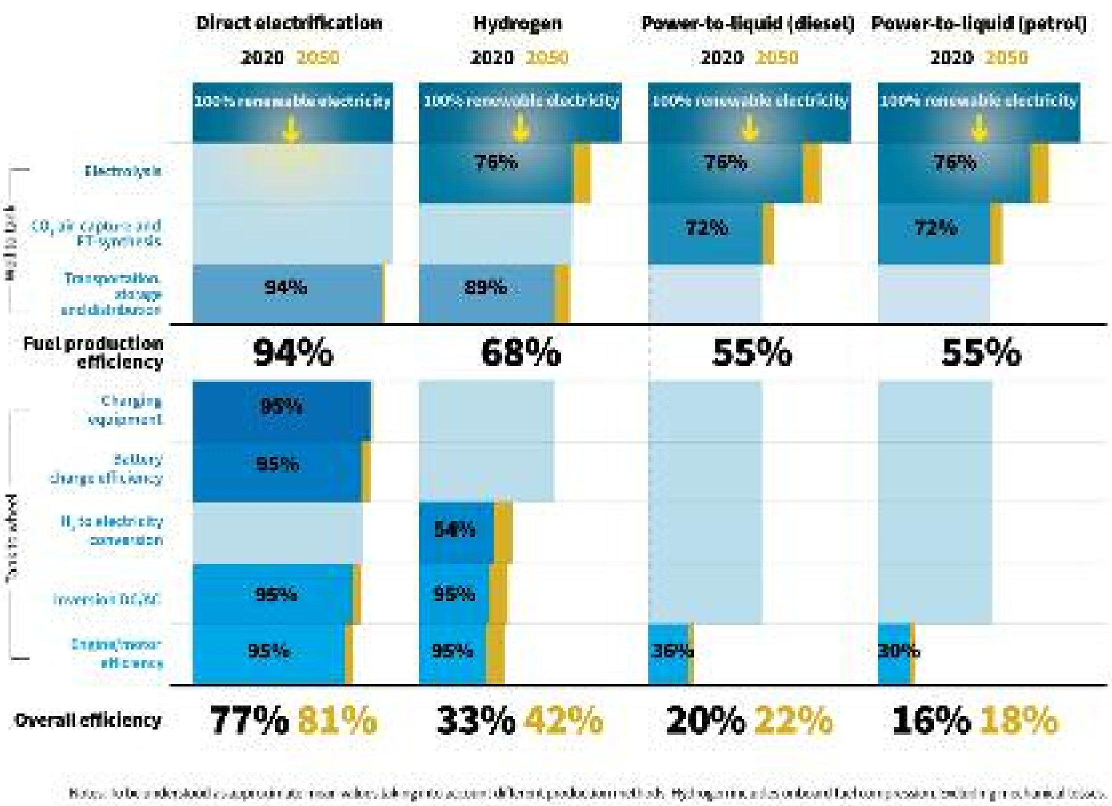
Challenges of hydrogen in light transport

There are, however, significant challenges in using hydrogen for transportation – particularly for land transport vehicles like cars, lorries, buses and trains.

Hydrogen road vehicles are less efficient than electric road vehicles

For journeys where no alternative to a car is possible, electric cars are generally more efficient than hydrogen. Compared to electric vehicles, a lot of energy is lost converting electricity into the green hydrogen needed (either as a fuel cell or fuel) to power a road vehicle. For cars, this means that battery electricity has an overall efficiency of 77% compared to just 33% efficiency of a hydrogen fuel cell car.[96] Even for heavier vehicles like lorries, estimates suggest that electric vehicles have an efficiency of 69% compared with just 23% for hydrogen.[97]

Figure 8:
Efficiency comparisons of electric, hydrogen, diesel and petrol vehicles[98]



Hydrogen vehicles cost more than electric

Not only do hydrogen cars tend to be bulkier, heavier, and less efficient,[99] they also cost more. According to BloombergNEF forecasts for 2030, battery electric vehicles may cost around £0.31 ($0.41) per mile, while hydrogen fuel cell vehicles are between £0.43 – £0.51 ($0.56 – $0.67) per mile. Significantly, hydrogen cars in this scenario would not even compete with conventional internal combustion engines using petrol, which come out at £0.41 ($0.53) per mile.[100] For electric lorries running long distances in the EU, analysis by Transport and Environment estimate that the total cost of ownership over the first five years is around £327,065 (€393,000) for electric compared to £381,992 (€459,000) for hydrogen powered.[101]

Electric infrastructure is more advanced than hydrogen

One significant challenge that hydrogen faces in scaling up is that the infrastructure for electric charging vehicles is already much more advanced and therefore much more competitive. For example, there are only 12 places across the whole of the UK where you can refuel a hydrogen car – with only 3 refuelling points in Scotland (one in Edinburgh, two in Aberdeen). This compares with around 30,000 electric charging points across the UK.[102] In terms of options for buyers, there are only two hydrogen car models to choose from in Europe: the Toyota Mirai and the Hyundai Nexo. Global sales of these two vehicles combined in 2021 were still only at 15,538 vehicles. This compares to 4.6 million global sales of battery electric vehicles, and 1.9 million plug-in hybrids in 2021.[103] In the UK, there are around 840,000 electric vehicles (460,000 battery electric, and 380,000 plug-in hybrid),[104] compared to only 300 hydrogen vehicles (mostly passenger cars and buses).[105] And according to recent research, the hydrogen fuelled trucking sector is also less advanced than battery electric technology, with over 150 battery electric truck models already being developed.[106]

One important caveat highlighted by the Scottish Government concerning car use is that if Scotland is to substantially reduce carbon emissions, it will not be enough to simply replace all conventional cars with electric vehicles. Car miles must be reduced overall, alongside a modal shift to public and active transport options.[107] For journeys where alternatives to private cars are not possible, however, electrification technologies are already much more advanced than hydrogen technology options. In fact, it is difficult to see how hydrogen alternatives could be scaled up at the speed required to hit decarbonisation targets in the UK and Scotland.

Hydrogen for heavier transport

Similar to cars, there has already been a lot of progress to date in electrifying buses, trams and trains. However, for heavier vehicles like industrial machinery, ships and planes, the weight and efficiency requirements mean electrification is more difficult. This gives hydrogen a potential role to play – though still with significant challenges to overcome.

Buses, trams and trains

Though hydrogen is often highlighted as an option for low carbon public transport, in Scotland, there has already been significant work in electrification of these modes. In the Scottish Government's most recent funding support for operators, 276 electric buses were purchased.[108] To date, only Aberdeen has used hydrogen as part of its fleet, with 15 buses launched by First in 2021. However, all 15 buses were taken off the road in February 2022 due to a mechanical issue.[109] Currently, Scotland's only trams are in Edinburgh and are fully electric.

Scotland's train network is currently undergoing a process of electrification. Around 29% of the total track length of Scotland's railways is electrified, though this constitutes around 76% of all passenger journeys in terms of proportion of total vehicle kilometres under electric traction.[110] By 2045, Transport Scotland aims to have the majority of the rail network fully electric.

However, there are some lines where this will be difficult because of geography, including: the lines from Glasgow to Fort William, Oban and Mallaig; parts of the line from Inverness to Kyle of Lochalsh, Wick and Thurso; and a small stretch between Ayr and Stranraer. For these sections, an 'alternative traction' solution will likely be required – including battery electric bi-modes (trains that have batteries that charge where they are connected to the electric cables and then use this power on sections without cables), or hydrogen fuel cell trains. Transport Scotland notes that hydrogen trains require large fuel storage volume for longer ranged trains, and that they are expected to have both higher capital and operating costs compared to diesel trains.[111] It also notes that battery electric bi-modes can be brought into service relatively soon.[112]

Industrial heavy goods vehicles and machinery

Both electrification and hydrogen options are being considered to decarbonise heavy industry vehicles, though there has been fairly limited progress in either to date. On the one hand, analysis by McKinsey suggests that, although take-up has been slow, there are growing options for battery electric vehicles in some segments of industry and that total cost of ownership could be 20% lower than conventional internal combustion engine vehicles.[113]

On the other hand, proponents of hydrogen highlight that electrification is not suitable for some vehicles that are constantly in use and work in remote locations far away from charging infrastructure. The company JCB is actively developing hydrogen technology, and launched the world's first hydrogen powered excavator in 2020.[114]

Shipping and aviation

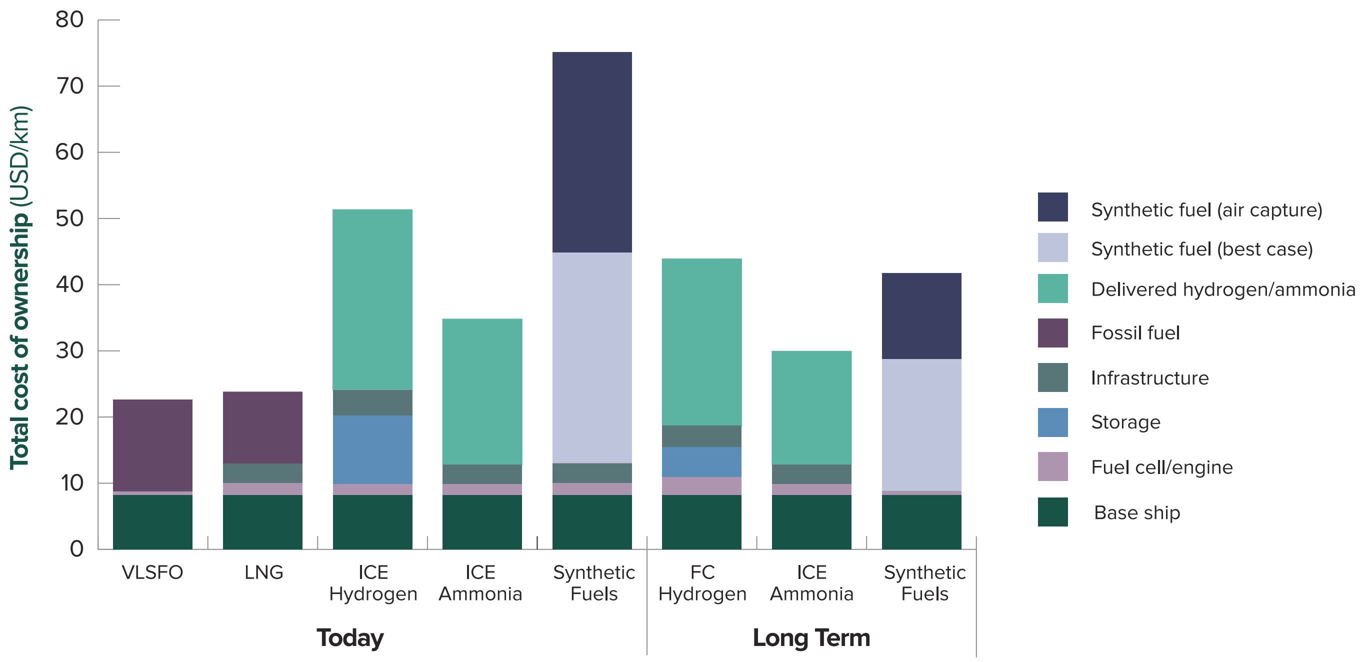
Shipping and aviation are two sectors where decarbonisation options like electrification remain a real challenge. However, switching to hydrogen is also not without difficulties.

There are a small number of electric ships now in operation,[115, 116] primarily passenger ferries in Scandinavia that sail distances comparable to some of Scotland's island ferry routes.

However, for heavier ships including freight, alternatives are more limited. Most ships use Heavy Fuel Oil – a tar-like substance that is heavy in sulphur and emits black carbon – in order to create enough energy to power their weight and size. There are fairly limited alternative fuel options that offer the same power without major drawbacks (including electrification). Hydrogen could theoretically be used either as a fuel cell, fuel cell hybrid, or as a combustion fuel – but one big limitation is the space dimensions needed to store the hydrogen onboard the ship. Hydrogen as a gas takes up huge amounts of storage space. It takes up less space as a liquid, but this requires lowering its temperature to around -235°C, meaning costly storage equipment that also takes up space onboard.[117]

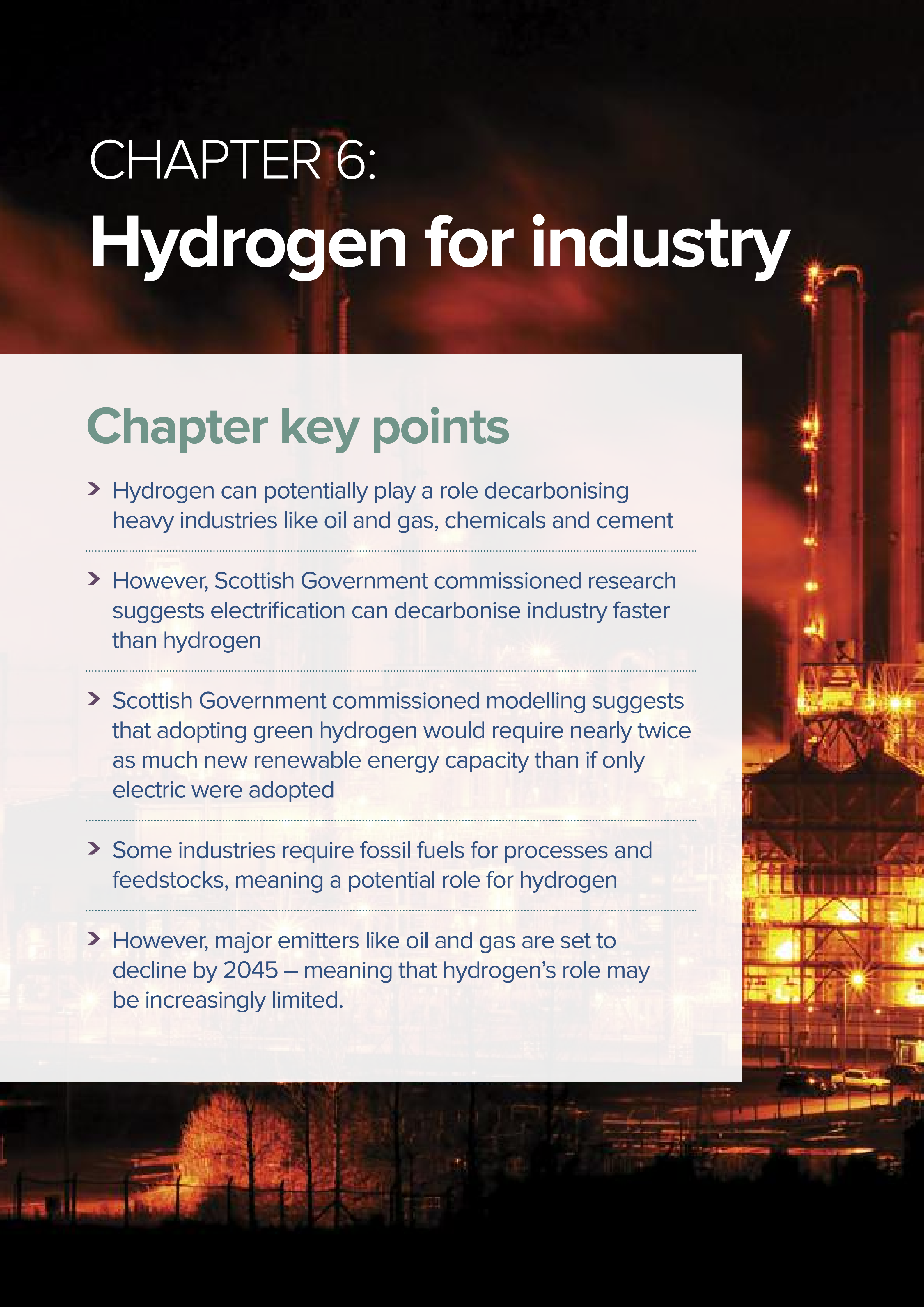
Another alternative talked about in the shipping industry is using hydrogen in the form of ammonia. Ammonia can be used as a combustion fuel,[118] and is easier to store than hydrogen as a liquid as its boiling point is only -33°C meaning less expensive storage equipment. Ammonia is made by reacting hydrogen and atmospheric nitrogen under pressure (called the Haber-Bosch process), and is primarily used as a fertiliser for agriculture. Currently, it is predominantly derived from blue hydrogen but could theoretically be derived from green hydrogen to lower carbon emissions. As with green hydrogen production generally, there are serious questions about how much renewable energy would be required to produce ammonia at scale for shipping fuel, on top of current ammonia production for fertiliser. There are also significant questions about cost and scalability.[119]

Figure 9:
Current and future total cost of ownership of fuel/powertrain alternatives in a bulk carrier ship[120]



For aviation, hydrogen could also have a potential role to play, but there are similar challenges. Hydrogen technology in aviation is still very much in the research and development phase, with only a handful of small prototype planes in existence. Similar to shipping, hydrogen takes up a lot of space – with estimates suggesting this could be up to four times the space required for kerosene.[121] There will also be substantial costs involved in upgrading infrastructure so that refuelling of hydrogen (or other fuels like ammonia) can take place globally.

Finally, one significant drawback of using hydrogen for aviation is that planes would produce water vapour which, at high altitudes, acts as a greenhouse gas. This fact led the UKCCC to conclude that there 'does not therefore appear to be a role for hydrogen in decarbonising aviation.'[122]



CHAPTER 6:

Hydrogen for industry

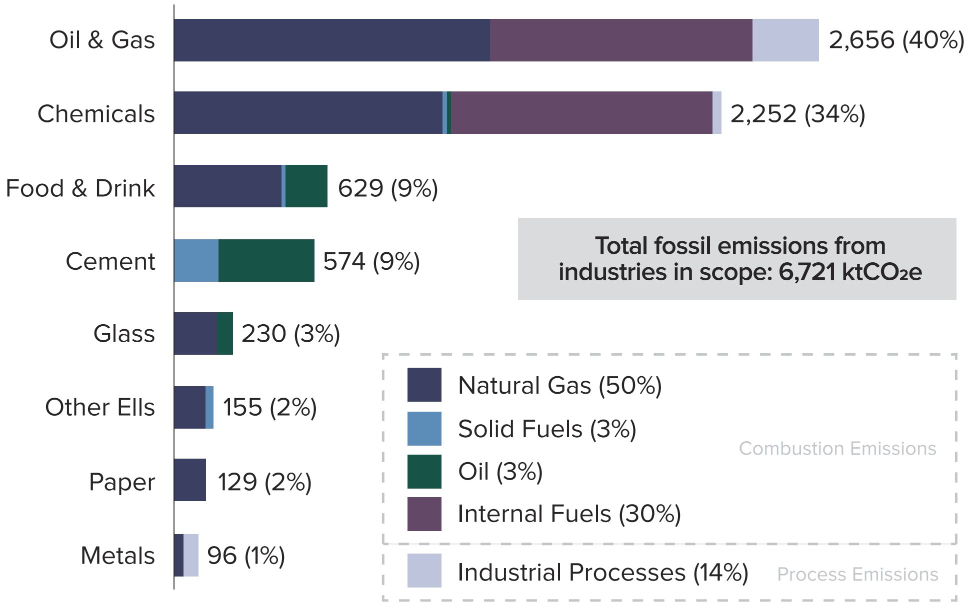
Chapter key points

- Hydrogen can potentially play a role decarbonising heavy industries like oil and gas, chemicals and cement
- However, Scottish Government commissioned research suggests electrification can decarbonise industry faster than hydrogen
- Scottish Government commissioned modelling suggests that adopting green hydrogen would require nearly twice as much new renewable energy capacity than if only electric were adopted
- Some industries require fossil fuels for processes and feedstocks, meaning a potential role for hydrogen
- However, major emitters like oil and gas are set to decline by 2045 – meaning that hydrogen's role may be increasingly limited.

Greenhouse gas emissions from industry

In 2018, emissions from all Scottish industries combined accounted for 28% of Scotland's emissions – 11.5 million tonnes of CO_2 equivalent ($MtCO_2e$).[123] This sector covers Scotland's core manufacturing base, and includes industries and businesses that consume high levels of energy and emit high levels of GHGs. These energy intensive industries include oil and gas refining; chemicals; food and drink; cement; glass; paper; and metals.

Figure 10:
Total emissions by Scottish industry sector, kilotonnes of CO_2 equivalent[124]



Percentages correspond to the proportion of all fossil emissions from industries in scope and may not add up to 100% due to rounding.

Challenges of hydrogen in industry

Hydrogen is discussed as a possible option for decarbonising Scotland's industries, primarily through fuel switching. Industries that combust high levels of fossil fuels for their industrial processes could instead switch to burning hydrogen that emits no CO_2 when combusted.

Compared to other sectors like heating and transport, there has been fairly limited analysis into how industries can decarbonise using hydrogen versus alternative technologies like electrification. Both options are in their commercial infancy in Scottish industry, with few real world examples of industries trialling either decarbonisation method.

Nevertheless, what little modelling has been done suggests that large-scale take up of electrification may have the edge over hydrogen in terms of decarbonising Scottish industries.

Electric industrial heating technology is advancing

Nearly three quarters of greenhouse gas emissions from Scotland's industries are from fuel combustion to create heat for various industrial processes.[125] Thus, decarbonising industrial heating is an important priority.

Recent analysis by McKinsey highlights that of all the fuel that the global industrial sector combusts for heating, almost 50% could be replaced with electricity using technologies available today.[126] It points out that many of the technologies used for lower grade heating, up to 450°C, are already commercially available and widespread. Separate analysis looking at European industry highlights that 78% of energy used for heating (excluding feedstocks) can be potentially electrified with technology currently available and in use.[127] It suggests that further advances in electrification technologies over the coming decades could increase this to 99% of industrial heat energy (though this is the best case scenario based on future technology that is very uncertain, and also excludes feedstocks).

Electric heating technology can decarbonise industry faster than hydrogen

According to the Scottish Government commissioned report *Deep Decarbonisation Pathways for Scottish Industries*,[128] decarbonisation can be achieved slightly faster through electrification technologies than hydrogen. The study modelled two alternative pathways where there is large-scale take-up of electrification in one scenario, and hydrogen in another. It found that the electrification pathway reduced emissions on 1990 levels by 52–57% by 2030, whereas the hydrogen pathway reduced emissions only by 49–52%. This was primarily due to some electrification technologies already being available today for roll-out, whereas hydrogen is only expected to come online by 2028 at the earliest. By 2050, the full electrification scenario reduces emissions by 72–90%, slightly deeper than the hydrogen scenario reductions of 71–90%.

Figure 11:
Residual emissions and estimated abatement from all Scottish industries comparing electrification and hydrogen pathways[129]

	2030		2040		2045	
	Residual emissions ($MtCO_2e$)	Reduction from 1990 levels (%)	Residual emissions ($MtCO_2e$)	Reduction from 1990 levels (%)	Residual emissions ($MtCO_2e$)	Reduction from 1990 levels (%)
Electrification	9.1–10.1	52–57%	2.9–6.5	69–86%	2.0–6.0	72–90%
Hydrogen	10.1–10.7	49–52%	3.2–6.7	68–85%	2.2–6.1	71–90%

Hydrogen requires much more energy than electrification

The same report highlights that switching fully to hydrogen would require a lot more energy than if industries switched fully to electric. By 2045, the end use demand for hydrogen is 26.7 TWh, whereas it is much lower for electrification at 23.9 TWh. In terms of primary energy demand, the hydrogen scenario requires 5.9 more terawatt hours than electrification. Finally, if all the hydrogen in the hydrogen scenario was renewable, nearly twice as much new renewable energy capacity would be required (9 GW) compared to the electrification scenario (5.3 GW).[130]

Fossil fuel refining is set to decline under 2045 net zero targets

A crucial bit of context to any future industrial decarbonisation strategy – whether through electrification or hydrogen – is that the sector responsible for most emissions is oil and gas refining which accounts for approximately 40% of industrial emissions.

Given the Scottish Government's commitment to achieving net zero by 2045, it is very unlikely that the oil and gas sector will be operating at the same level of output over the next twenty five years.[131] For example, the Scottish Government's Climate Change Plan update has a target of reducing car kilometres by 20% by 2030 which will have a significant impact on petroleum consumption. UK wide, the Sixth Carbon Budget estimates that decarbonisation of the transport sector will decrease CO_2 emissions by around 9.5 million tonnes in 2050. As the Carbon Budget highlights, this would lead to "large reductions in demand for oil refineries,"[132] significantly impacting operations like Grangemouth in Scotland.

Declining demand for oil and gas refining is likely to lessen the need to find large-scale decarbonisation technologies through hydrogen or electrification. However, this may be offset to an extent through the implementation of just transition and circular economy measures such as recycling and processing Scottish scrap steel domestically.

The limits of electrification

Though the above evidence suggests that electrification technologies may be more effective at decarbonising Scottish industries than hydrogen, there are nevertheless limits to electrification.

Sectors like oil and gas refining and chemical processing require high temperature heat (upwards of 850°C and, in the case of cement kilns, 2000°C). As discussed above, technologies exist to create these temperatures through electrification – for example electric arc furnaces – but these are not yet established in Scotland.

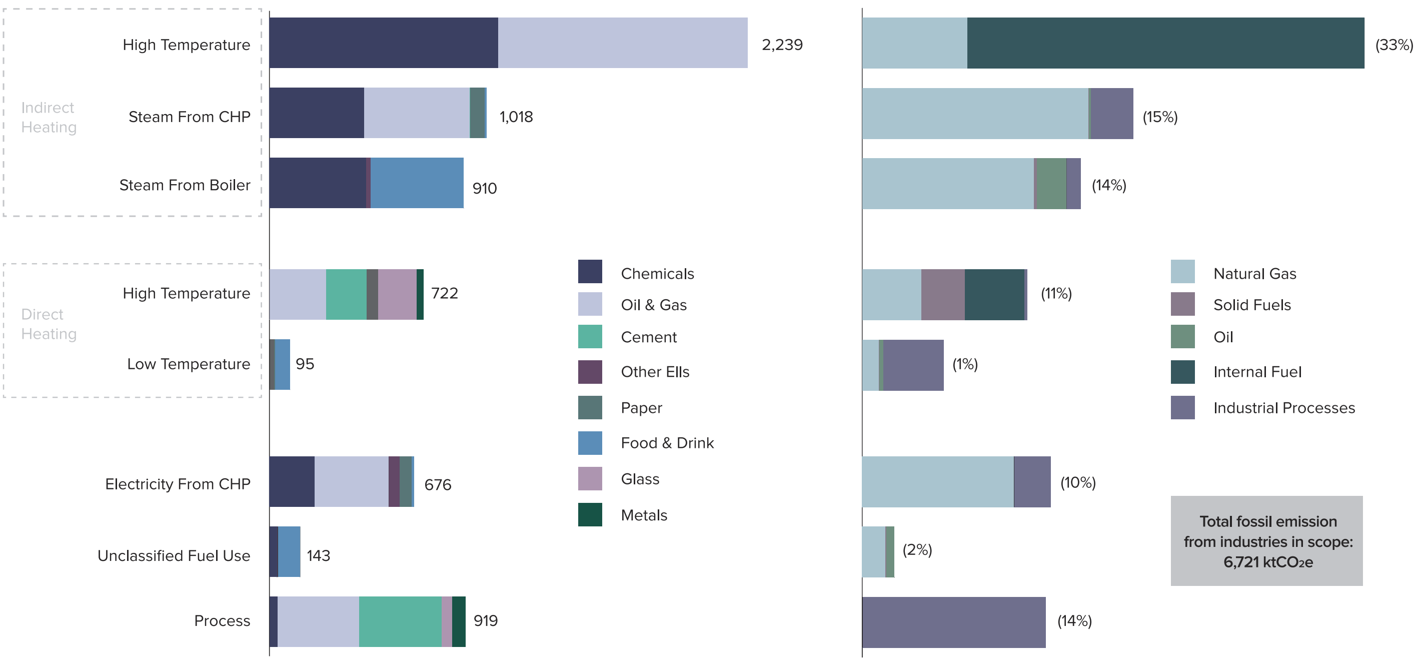
A bigger challenge lies in low carbon options for industries that require the combustion of fossil fuels to create a chemical reaction to make their industrial product. In Scotland, this includes the sectors refining oil and gas and producing chemicals, cement, glass and steel.[133]

Greenhouse gases that arise from reactions within these sectors are called process emissions, and account for around 14% of industrial emissions – around 919 kilotonnes of CO_2 equivalent a year ($ktCO_2e$/year).[134] Process emissions cannot be straightforwardly decarbonised without major changes to the way these industries operate, or by switching to an alternative fuel like hydrogen. In fact, one of the main sources of process emissions in Scotland is the SMR blue hydrogen plant at Grangemouth, that creates the hydrogen required for its fossil fuel and chemical refining operations.

Many of these industrial processes create further emissions from combusting industrial byproducts – referred to as internal fuel emissions – that also cannot easily be decarbonised through electrification. By-products include fuel off-gases from ethylene production at Grangemouth and Mossmorran chemical plants, and petroleum coke created at the Grangemouth oil refinery. These byproducts cannot be used or sold, and so are burnt – emitting around 2,016 $ktCO_2e$ a year, or 30% of total industrial emissions.[135]

As highlighted above, however, the biggest sector of process emissions in Scotland comes from oil and gas refining – an industry that is set to decline significantly under the 2045 target of net zero. It therefore remains hugely unclear how much a role hydrogen will play in an industry set to completely transform over the next three decades.

Figure 12:
Total emissions by cross-sectoral process ($ktCO_2e$) [136]



Percentages correspond to the proportion of all fossil emissions from industries in scope and may not add up to 100% due to rounding.

Hydrogen for storage and power system balancing

As the energy grid transitions away from fossil fuels, there will be significant challenges in making sure energy supply meets energy demand. This is because renewable energy like wind and solar only generate energy at particular times. Solar panels only work when the sun is shining, and don't generate anything at night even though there might be demand for electricity. This gap in supply and demand is particularly marked between seasons; on a cold, cloudy winter's day, solar will produce little – just at the time when people need high levels of energy to heat their homes. Currently, this gap is plugged by fossil fuel power stations.

A way to help overcome this challenge is to store surplus energy and use it to balance out the grid on days when renewables aren't producing much. Hydrogen is one such potential storage technology. On days where there is surplus solar or wind power, this energy could be used to create hydrogen. It could be stored and used at times when the sun isn't shining or the wind isn't blowing.

Though this sounds simple in principle, the practicality of hydrogen storage faces challenges. As discussed throughout this report, transformations within the hydrogen supply chain are generally inefficient. A lot of energy is lost turning electricity into hydrogen, storing it, transporting it and then turning it back into electricity. These inefficiencies mean that hydrogen storage may simply be too expensive. Balancing power on a day-to-day level may be more economically viable through other technologies like electric batteries, as well as shifting energy demand through smart demand response technologies.[137]

Storing hydrogen for longer periods of time to balance seasonal gaps or for deep resilience may be more economical, but there are still challenges. In particular, it requires suitable storage locations – including large salt caverns (as is being trialled in Germany), saline aquifers, or depleted oil and gas wells – close enough to where the hydrogen is produced and used so as to decrease efficiency losses from transportation.

Overall, using hydrogen for storing energy and balancing the energy system may make more sense than in other applications like heating and transport – though there are still challenges to using it in this way.

Key points & recommendations

What is hydrogen?

- Hydrogen can be created from fossil fuels (blue and grey hydrogen) or from electricity and water (green hydrogen)
- 98% of global hydrogen production today is unabated grey hydrogen, primarily made from gas, and used in the oil, gas and chemical industries
- It emits around 830 million tonnes of CO_2 a year, more than 1.5 times the annual emissions of the UK
- As an energy vector, hydrogen is generally inefficient and costly to produce, store and transport
- It could potentially be used in transport and industry, but these uses are in their commercial infancy in the UK and Europe.

Hydrogen in Scotland

- The Scottish Government supports blue and green hydrogen production, use and export
- Its ambition is for 5 GW of installed capacity of blue and green hydrogen by 2032
- To date, £21.9 million of Scottish Government funding has gone towards hydrogen transport and heating projects
- A further £100 million has been outlined for hydrogen development to be spent by 2026
- Commercial hydrogen production is in its infancy, with the first dedicated hydrogen project in Fife due online in 2023.

Environmental impacts of hydrogen

- Every tonne of grey hydrogen produced emits 9 tonnes of CO_2. Current production is responsible for around 830 million tonnes of CO_2 a year
- Blue hydrogen is dependent on CCS technology that is in its infancy in Europe and has repeatedly failed to get off the ground in the UK
- Data from existing blue hydrogen plants suggests only 60% of CO_2 is captured
- Even if CCS became viable, blue hydrogen is unlikely to meet 2030 and 2035 carbon reduction targets
- Green hydrogen needs vast amounts of renewable energy. To achieve 5 GW of green hydrogen, Scotland would need an additional 80% of current renewable energy
- Hydrogen itself is a greenhouse gas 11 times more powerful than CO_2, and is likely to have leakage rates of 6–13% during production, transportation and storage.

Hydrogen for heating

- Hydrogen is being proposed as a solution to decarbonising Scotland's heating emissions, through blending hydrogen into the grid and using it as a fuel in boilers
- However, electric heat pumps are around 168–342% more efficient than hydrogen boilers
- Hydrogen boilers may also be 53–68% more expensive than heat pumps, and be exposed to fluctuating gas prices that are currently at an historic high
- Meeting Scotland's heating demand using green hydrogen would require a 180% increase in renewable energy generation.

Hydrogen for transport

- Hydrogen is being considered as a potential way to decarbonise Scotland's transport
- However, for journeys that need to be made by car, direct electrification is already much more efficient, cheaper, and more advanced commercially than hydrogen
- Buses and trains in Scotland are already facing large-scale electrification
- There is also scope for directly electrifying industrial machinery
- Hydrogen may have a role to play in shipping and aviation where electrification is not as possible – but there are still big challenges to making this commercially viable.

Hydrogen for industry

- Hydrogen can potentially play a role decarbonising heavy industries like oil and gas, chemicals and cement
- However, Scottish Government commissioned research suggests electrification can decarbonise industry faster than hydrogen
- Scottish Government-commissioned modelling suggests that adopting green hydrogen would require nearly twice as much new renewable energy capacity than if only electric were adopted
- Some industries require fossil fuels for processes and feedstocks, meaning a potential role for hydrogen
- However, major emitters like oil and gas are set to decline by 2045 – meaning that hydrogen's role may be increasingly limited.

Recommendations

- The Scottish Government must not support the development of hydrogen derived from fossil fuels (blue or grey), in line with the urgent need for a phase out of fossil fuels to stay within the 1.5°C temperature limit set by the Paris Agreement.

- Any funding for blue or grey hydrogen and associated carbon capture and storage (CCS) should instead be redirected to renewables and energy efficiency, as part of a just transition of the energy system.

- Recognising the greater efficiency, lower costs and lower emissions of electrification when compared to hydrogen, the Scottish Government must prioritise electrification over hydrogen, particularly in heating and transport, and support the use of green hydrogen only in sectors where direct electrification is not possible.

- Any renewable energy intended for green hydrogen production must be sourced from additional or surplus renewable energy capacity. This will ensure renewables are not diverted from decarbonising the electricity grid and prevent the need for fossil fuels to fill the gap.

Technical appendix

Hydrogen definition

Hydrogen is a chemical – the first on the periodic table. It is symbolised by an H and has an atomic number of 1. As a gas it is usually found as a molecule comprised of two hydrogen atoms, with the chemical symbol $\mathbf{H_2}$. It is abundant in the world around us, being a key component of water (H_2O) and found in all organic life.

Production

98% of hydrogen is created through reforming gas. There are two main types of technologies:[138]

- **Steam methane reforming** (SMR), where water is used as both an oxidant (an oxidizing agent, or a substance that accepts electrons from another substance) and a source of hydrogen. This process is mainly used to extract hydrogen from gas and less frequently from liquified petroleum gas and naphtha (a substance used for chemical solvents). SMR is the most widely used technology today.
- **Autothermal reforming** (ATR), where the required heat is produced inside the reformer itself. It is less widespread than SMR and is currently more costly.

Aside from reforming, hydrogen can also be produced from coal and biomass (organic material like wood, wood residues or crops) through **gasification**. In this case, the fuel is gasified into synthesis gas (a mixture of hydrogen, carbon monoxide, carbon dioxide and methane) and is then converted into pure hydrogen and carbon dioxide.

2% of hydrogen is made from electrolysis, by passing electricity through water. There are three primary types of electrolyser technologies used today. These are:

- **Alkaline electrolysis**, characterised by two electrodes operating in a liquid alkaline electrolyte solution. It is a mature and commercial technology that has been in operation since the 1920s, and capital costs are generally low.
- **Proton exchange membrane** (PEM) electrolysers, that contain a cell equipped with a solid polymer electrolyte responsible for the conduction of protons, the separation of product gases, and electrical insulation of the electrodes. These are less widely deployed and have higher costs than alkaline electrolysers.
- **Solid oxide electrolysis cells** (SOECs), that transfers oxygen ions through a solid ionic conductive membrane that recombine with electrons to form oxygen molecules. It is the least developed technology and not yet commercialised.

Calculations

Calculations for renewable energy demand are based on the following assumptions by the Scottish Government[139] for 1 GW required input-output energy:

- A 1 GW blue hydrogen production facility, operating with a capacity factor of 86% and a conversion efficiency of 80%, would produce around 7.5 TWh, or 225,000 tonnes, of blue hydrogen in a year. This requires around 9.75 TWh of gas.
- A 1 GW offshore windfarm, operating at a 58% capacity factor connected to a 1 GW electrolyser with an electrolyser conversion efficiency of 69%, would produce 3.5 TWh, or 92,000 tonnes, of green hydrogen in a year. This requires around 5.1 TWh of input electrical energy.

Renewable energy demand for 5 GW green hydrogen:

- 1 GW of green hydrogen requires 5.1 TWh of input electrical energy
- 5 GW of green hydrogen requires 5.1 x 5 = 25.5 TWh
- Current Scottish renewable energy generation = 31.8 TWh
- 25.5 = 80% of 31.8. Or, renewable energy would need to increase by 25%

Renewable energy demand for green hydrogen to meet Scotland's heating demand:

- Scotland heating demand = 61 TWh.
- 5.1 TWh of input electrical energy creates 3.5 TWh of hydrogen
- 61 / 3.5 = 17.42
- 5.1 x 17.42 = 88.88
- So 88.9 TWh of input electrical energy would be needed to create 61 TWh of hydrogen
- Current Scottish renewable energy generation = 31.8 TWh
- Scotland's average energy use per household is 4001 KWh.[140] 25.5TWh / 4001KWh = 6,375,000 households

Acronyms

ATR	Autothermal reforming	Mt	million tonnes
CCS	Carbon capture and storage	MW	Megawatt
CH_4	Methane	MWh	Megawatt hour
CO_2	Carbon dioxide	NETs	Negative Emission Technologies
CO_2e	Carbon dioxide equivalent	NO_x	Nitrogen Oxide
GHG	Greenhouse gas	SMR	Steam methane reforming
GW	Gigawatt	TW	Terawatt
GWh	Gigawatt hour	TWh	Terawatt hour
H_2	Hydrogen	UKCCC	UK Climate Change Committee
ICE	Internal Combustion Engine	VLSFO	Very Low Sulphur Fuel Oil
Kt	kilotonnes	Wh	Watt hour
m^3	cubic metres		

End Notes

1 Michael Leibreich, Clean Hydrogen Ladder version 4.1a, 9 September 2021, https://drive.google.com/file/d/1X-oH04NH1477eig_BmYjtD9mHyTcoiVc/view

2 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, pp.37–38

3 Note: Green hydrogen refers to hydrogen created from electrolysis powered by renewable energy. However, green hydrogen is only as 'low carbon' as the electricity it uses. If electrolysis is powered by electricity from the grid, the process is only as 'low carbon' as the grid itself. The breakdown of energy for the UK's National Grid for 2021 (year average) was around 40.4% fossil fuels, 25.5% renewable energy, and 25.2% for other (primarily nuclear and biomass). Figures from https://grid.iamkate.com/ (last accessed 23/03/22)

4 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, p.42

5 Recharge News, 'Green hydrogen will be cost competitive with grey H_2 by 2030 – without a carbon price', 27 April 2021, https://www.rechargenews.com/energy-transition/green-hydrogen-will-be-cost-competitive-with-grey-h2-by-2030-without-a-carbon-price/2-1-1001867

6 Energy Transitions Commission, Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy, April 2021, https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Executive-Summary-Short.pdf, p.8

7 Recharge News, Ukraine War: Green hydrogen 'now cheaper than grey in Europe, Middles East and China': BNEF, 7 March 2022, https://www.rechargenews.com/energy-transition/ukraine-war-green-hydrogen-now-cheaper-than-grey-in-europe-middle-east-and-china-bnef/2-1-1180320

8 Recharge News, Russia's war pushes blue and grey hydrogen costs way above those of green H_2: Rystad, 22 March, 2022 https://www.rechargenews.com/energy-transition/russias-war-pushes-blue-and-grey-hydrogen-costs-way-above-those-of-green-h2-rystad/2-1-1189003

9 BloombergNEF, 'Green' Hydrogen to Outcompete 'Blue' Everywhere by 2030, 5 May 2021, https://about.bnef.com/blog/green-hydrogen-to-outcompete-blue-everywhere-by-2030/

10 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, p.89

11 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.19

12 European Commission, A hydrogen strategy for a climate-neutral Europe, 8 July 2020, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

13 European Commission, A hydrogen strategy for a climate-neutral Europe, 8 July 2020, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf, pp.5-7

14 UK Government, British Energy Security Strategy, 7 April 2022, https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

15 Scottish Government, Hydrogen action plan: draft, 10 November 2021, https://www.gov.scot/publications/draft-hydrogen-action-plan/documents/ p.13

16 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.26

17 Euractiv, Scientists warn against global warming effect of hydrogen leaks, 14 October 2021, https://www.euractiv.com/section/energy/news/scientists-warn-against-global-warming-effect-of-hydrogen-leaks/

18 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.61

19 The Guardian, Britons buy more electric cars in March than in whole of 2019, 5 April 2022, https://www.theguardian.com/business/2022/apr/05/uk-car-sales-chip-shortages-electric-cars-petrol-diesel-prices

20 Statista, Annual amount of heat pumps in operation in the United Kingdom (UK) from 2013 to 2019, https://www.statista.com/statistics/740491/heat-pumps-in-operation-uk/

21 The European Consumer Organisation, Goodbye gas: why your next boiler should be a heat pump: Executive summary and key findings, November 2021, https://www.beuc.eu/publications/beuc-x-2021-112_goodbye_gas_why_your_next_boiler_should_be_a_heat_pump.pdf

22 Scottish Government, Update to the Climate Change Plan 2018 - 2032, 16 December 2020, https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/documents/, p.61–62

23 Data from Scottish Government, Hydrogen action plan: draft, 10 November 2021, https://www.gov.scot/publications/draft-hydrogen-action-plan/, p49

24 Scottish Government, Draft Hydrogen Action Plan, 10 November 2021, https://www.gov.scot/publications/draft-hydrogen-action-plan/documents/, p.17

25 Element Energy, Hydrogen in Scotland, July 2020, https://theacornproject.uk/wp-content/uploads/2020/09/Hydrogen-in-Scotland-The-role-of-Acorn-Hydrogen-in-Enabling-UK-Net-Zero.pdf, pp.12–13

26 The Acorn Project, About Acorn, https://theacornproject.uk/about/

27 The Acorn Project, About Acorn, https://theacornproject.uk/about/

28 UK Government, UK government launches plan for a world-leading hydrogen economy, August 2021, https://www.gov.uk/government/news/uk-government-launches-plan-for-a-world-leading-hydrogen-economy

29 Energy Voice, 'Extremely disappointing': Scottish Cluster misses out on first round of UK Government's £1bn CCUS competition, 19 October 2021, https://www.energyvoice.com/renewables-energy-transition/ccs/357231/scottish-cluster-misses-out-on-track-1-ccs-support-from-uk-gov/

30 Scottish Government, Carbon capture, utilisation and storage (CCUS) Scotland Act 1998 subsection: FOI release, 5 January 2022, https://www.gov.scot/publications/foi-202100253888/

31 Press and Journal, Scottish Government puts £80 million on table for north east Acorn project, 14 January 2022, https://www.pressandjournal.co.uk/fp/business/3846546/scottish-government-80million-for-north-east-acorn/

32 European Commission, Key cross border infrastructure projects, https://energy.ec.europa.eu/topics/infrastructure/projects-common-interest/key-cross-border-infrastructure-projects_en

33 BBC News, The neighbourhood leading a green energy revolution, 16 March 2022, https://www.bbc.co.uk/news/business-60241966

34 SGN, We've received the go-ahead to build our world-first hydrogen heating network, 30 November 2020, https://sgn.co.uk/news/h100-fife-ofgem-approved-world-first-hydrogen-heating-network

35 Ofgem / H100 Fife Project, Network Innovation Competition Screening Submission Pro forma, https://www.ofgem.gov.uk/sites/default/files/docs/2020/05/sgn_h100_fife_nic_isp_final_06.04.20.pdf, p.7

36 Scottish Construction Now, SGN purchases hydrogen electrolyser for 'world-first' project in Fife, 27 September 2021, https://www.scottishconstructionnow.com/articles/sgn-purchases-hydrogen-electrolyser-for-world-first-project-in-fife

37 Howarth, R.W., Santoro, R. and Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic change, 106(4), pp.679-690, https://doi.org/10.1007/s10584-011-0061-5

38 Alvarez, R.A., Zavala-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J., Herndon, S.C., Jacob, D.J., Karion, A. and Kort, E.A., 2018. Assessment of methane emissions from the US oil and gas supply chain. Science, 361(6398), pp.186-188, https://doi.org/10.1126/science.aar7204

39 IPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013, https://www.ipcc.ch/report/ar5/wg1/

40 Riddick, S.N., Mauzerall, D.L., Celia, M., Harris, N.R., Allen, G., Pitt, J., Staunton-Sykes, J., Forster, G.L., Kang, M., Lowry, D. and Nisbet, E.G., 2019. Methane emissions from oil and gas platforms in the North Sea. Atmospheric Chemistry and Physics, 19(15), pp.9787–9796, https://acp.copernicus.org/articles/19/9787/2019/

41 Oil and Gas Climate Initiative, OGCI reports significant progress on aggregate upstream methane and carbon intensity targets, 19 October 2020, https://www.ogci.com/ogci-reports-significant-progress-on-aggregate-upstream-methane-and-carbon-intensity-targets/

42 Howarth, R.W. and Jacobson, M.Z., 2021. How green is blue hydrogen?. Energy Science & Engineering, 9(10), pp.1676–1687, https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/ese3.956

43 Howarth, R.W. and Jacobson, M.Z., 2021. How green is blue hydrogen?. Energy Science & Engineering, 9(10), pp.1676–1687, https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/ese3.956. Note that these figures are from the US where there are particularly high levels of fugitive methane emissions. Comparable emissions from the North Sea are lower, at around 0.2%.

44 IEA, Data and Assumptions - the Future of Hydrogen, December 2020, https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions, p.3

45 Tyndall Manchester, A Review of the Role of Fossil Fuel-Based Carbon Capture and Storage in the Energy System, December 2020, https://foe.scot/wp-content/uploads/2021/01/CCS_REPORT_FINAL.pdf

46 de Kleijne, K., Hanssen, S.V., van Dinteren, L., Huijbregts, M.A., van Zelm, R. and de Coninck, H., 2022. Limits to Paris compatibility of CO_2 capture and utilization. One Earth, 5(2), pp.168-185. DOI: 10.1016/j.oneear.2022.01.006

47 Global CCS Institute, Global Status of CCS 2021, November 2021, https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf

48 Global CCS Institute, Global Status of CCS 2021, November 2021, https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf

49 Tyndall Manchester, A Review of the Role of Fossil Fuel-Based Carbon Capture and Storage in the Energy System, December 2020, https://foe.scot/wp-content/uploads/2021/01/CCS_REPORT_FINAL.pdf, p.12

50 Global CCS Institute, Global Status of CCS 2021, November 2021, https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf, p.38

51 Global CCS Institute, Global Status of CCS 2021, November 2021, https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf, p.39

52 S&P Global, UK flags two CCS projects for funding, but Scottish venture 'disappointed', 19 October 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/101921-uk-flags-two-ccs-projects-for-funding-but-scottish-venture-disappointed

53 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.67

54 Global Witness, Hydrogen's Hidden Emissions, January 2022, https://www.globalwitness.org/en/campaigns/fossil-gas/shell-hydrogen-true-emissions, p.5

55 Global Witness, Hydrogen's Hidden Emissions, January 2022, https://www.globalwitness.org/en/campaigns/fossil-gas/shell-hydrogen-true-emissions, p.10

56 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.66

57 Data from UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.66

58 Howarth, R.W. and Jacobson, M.Z., 2021. How green is blue hydrogen? Energy Science & Engineering, 9(10), pp.1676–1687, https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/ese3.956

59 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.69

60 IEA, G20 Hydrogen report: Assumptions, December 2020, https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf, p.3

61 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, pp.37–38

62 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, p.37

63 Global solar and wind combined in 2019 was 2,108 TWh. Data from IEA Data and Statistics, Renewable electricity generation by source (non-combustible), World 1990-2019, accessed 14 April 2022, https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Electricity%20and%20heat&indicator=RenewGenBySource

64 Scottish Government, Scotland Energy Statistics Q4 2020, March 2021, https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2018/10/quarterly-energy-statistics-bulletins/documents/energy-statistics-summary---march-2021/energy-statistics-summary---march-2021/govscot:document/Scotland+Energy+Statistics+Q4+2020.pdf, p2

65 Calculations are based on Scottish Government assumptions for 1 GW of green and blue hydrogen production. See technical appendix and Scottish Government, Scottish Hydrogen Assessment Report, December 2020, https://www.gov.scot/publications/scottish-hydrogen-assessment-report/, p.42

66 Global Witness, Greenwashed Hydrogen, June 2021, https://www.globalwitness.org/en/campaigns/fossil-gas/greenwashed-hydrogen/, pp.3–4

67 UK Government, the UK Low Carbon Hydrogen Standard, Government response to consultation, April 2022, https://www.gov.uk/government/consultations/designing-a-uk-low-carbon-hydrogen-standard

68 Nicola Warwick, Paul Griffiths, James Keeble, Alexander Archibald, John Pyle, University of Cambridge and NCAS and Keith Shine, University of Reading, Atmospheric Implications of increase Hydrogen use, April 2022, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067144/atmospheric-implications-of-in creased-hydrogen-use.pdf, p.54

69 Frazer-Nash Consultancy, Fugitive Hydrogen Emissions in a Future Hydrogen Economy, March 2022, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067137/fugitive-hydrogen-emissions-future-hydrogen-economy.pdf, p.6

70 European Climate Foundation, Building Europe's Net-Zero Future, March 2022, https://europeanclimate.org/wp-content/uploads/2022/03/ecf-building-emmissions-problem-march2022.pdf, p.12

71 Scotland's 'Residential' sector is defined as 'Emissions from fuel combustion for heating/cooling and garden machinery and fluorinated gases released from aerosols/metered dose' in Scottish Greenhouse Gas Statistics 2019. It accounts for 6.2 million tonnes of CO_2e, around 13% of total CO_2e. The majority of this is from heating. See https://www.gov.scot/publications/scottish-greenhouse-gas-statistics-1990-2019/

72 Scottish Government, Heat in Buildings Strategy, 7 October 2021 https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings, p.12

73 The Scottish Government lists non-domestic purposes as: retail and financial; offices and workshops; public assembly; restaurants, cafes and takeaways; industrial, hotels, education; storage and distribution; healthcare; and other. See Scotland's non-domestic energy efficiency baseline: report, 13 December 2018, https://www.gov.scot/publications/scotlands-non-domestic-energy-efficiency-baseline/pages/2/

74 Scottish Government, Heat in Buildings Strategy, 7 October 2021 https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings, p.13

75 Fraunhofer IIE, The limitations of blending in the European gas grid, January 2022, https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FINAL_FraunhoferIEE_ShortStudy_H2_Blending_EU_ECF_Jan22.pdf, p.33

76 This would build on the trial project at Keele University where 20% hydrogen by volume was blended into the network. See HyDeploy: Demonstrating non-disruptive carbon savings through hydrogen blending, August 2021. https://hydeploy.co.uk/app/uploads/2018/02/21063_HyDeploy_Carbon_Savings_Report1_DIGITAL.pdf

77 ACER, Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure, 16 July 2021, https://extranet.acer.europa.eu/official_documents/acts_of_the_agency/publication/transporting%20pure%20hydrogen%20by%20repurposing%20existing%20gas%20infrastructure_overview%20of%20studies.pdf, p.7

78 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.45

79 SGN 'Gas Goes Green' initiative https://sgn.co.uk/about-us/future-of-gas/gas-goes-green

80 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.26

81 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.26

82 The European Consumer Organisation, Goodbye gas: why your next boiler should be a heat pump: Executive summary and key findings, November 2021, https://www.beuc.eu/publications/beuc-x-2021-112_goodbye_gas_why_your_next_boiler_should_be_a_heat_pump.pdf

83 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.32

84 BBC News, Gas prices hit new record sparking fears over bill rises, 4 March 2022, https://www.bbc.co.uk/news/business-60613855

85 Scottish Government, Heat in Buildings Strategy, 7 October 2021, https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings, p.80

86 BEIS / Energy Systems Catapult, Electrification of Heat Demonstration Project Heat Pump Installation Statistics, December 2021, https://es.catapult.org.uk/report/electrification-of-heat-installation-statistics, p.4

87 Passivhaus Trust, A retrofit template for hard-to-heat tenement homes, https://passivhaustrust.org.uk/news/detail/?nId=1020

88 Scottish Government, Heat networks delivery plan - draft: consultation, 15 November 2021, https://www.gov.scot/publications/draft-heat-networks-delivery-plan, p.4

89 BEIS, Opportunity areas for district heating networks in the UK, September 2021 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1015585/opps_for_dhnnca_hc.pdf, p.8

90 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.27

91 The Times, Switching all boilers to hydrogen 'is impractical', 7 December 2020, https://www.thetimes.co.uk/article/switching-all-boilers-to-hydrogen-is-impractical-zw00f3v9l

92 Scottish Government, Heat in Buildings Strategy, 7 October 2021 https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings, pp.12–13

93 Calculations based on Scottish Government assumptions that 3.5 TWh of green hydrogen output requires 5.1 TWh of renewable electrical energy input. See Technical Appendix as well as Scottish Government, Scottish Hydrogen Assessment Report, December 2020, https://www.gov.scot/publications/scottish-hydrogen-assessment-report/, p.42

94 2020 renewable generation was 31.8 TWh. Scottish Government, Scotland Energy Statistics Q4 2020, March 2021, https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2018/10/quarterly-energy-statistics-bulletins/documents/energy-statistics-summary---march-2021/energy-statistics-summary---march-2021/govscot:document/Scotland+Energy+Statistics+Q4+2020.pdf, p2

95 Transport Scotland, Carbon Account for Transport No. 12: 2020 Edition, September 2020, https://www.transport.gov.scot/media/48199/sct07209535161.pdf, p.7

96 Transport and Environment, Electrofuels? Yes, we can… if we're efficient: Decarbonising the EU's transport sector with renewable electricity and electrofuels, December 2020, https://www.transportenvironment.org/wp-content/uploads/2020/12/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf, p.29

97 The Centre for Sustainable Road Freight, Long-haul lorries powered by hydrogen or electricity? 9 February 2020, https://www.csrf.ac.uk/blog/long-haul-lorries-powered-by-hydrogen-or-electricity/

98 Transport and Environment, Electrofuels? Yes, we can… if we're efficient: Decarbonising the EU's transport sector with renewable electricity and electrofuels, December 2020, https://www.transportenvironment.org/wp-content/uploads/2020/12/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf, p.29

99 Recharge News, Liebreich: 'Oil sector is lobbying for inefficient hydrogen cars because it wants to delay electrification', 20 June 2021, https://www.rechargenews.com/energy-transition/liebreich-oil-sector-is-lobbying-for-inefficient-hydrogen-cars-because-it-wants-to-delay-electrification-/2-1-1033226

100 BloombergNEF, Hydrogen Economy Outlook Key Messages, 30 March 2020, https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf, p.7

101 Transport and Environment, Comparing hydrogen and battery electric trucks, 2 July 2020, https://www.transportenvironment.org/discover/comparing-hydrogen-and-battery-electric-trucks/

102 Zap Map, EV Charging Stats 2022, accessed March 2022, https://www.zap-map.com/statistics/

103 Recharge News, 'Hydrogen car sales almost doubled last year – after drivers were offered 50-65% discounts', 14 February 2022, https://www.rechargenews.com/energy-transition/hydrogen-car-sales-almost-doubled-last-year-after-drivers-were-offered-50-65-discounts/2-1-1168221

104 Zap Map, Electric vehicle market statistics 2022, https://www.zap-map.com/ev-market-statistics/#:~:text=With%20increasing%20consumer%20demand%2C%20greater,further%20380%2C000%20plug%2Din%20hybrids.

105 UK Government, UK Hydrogen Strategy, August 2021, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf, p.64

106 Recharge News, 'Hydrogen unlikely to play major role in road transport, even for heavy trucks': Fraunhofer, 2 February 2022, https://www.rechargenews.com/energy-transition/-hydrogen-unlikely-to-play-major-role-in-road-transport-even-for-heavy-trucks-fraunhofer/2-1-1162055

107 Transport Scotland, A route map to achieve a 20 per cent reduction in car kilometres by 2030, 13 Jan 2022, https://www.transport.gov.scot/media/50872/a-route-map-to-achieve-a-20-per-cent-reduction-in-car-kms-by-2030.pdf, p.21

108 Transport Scotland, Scottish Zero Emission Bus challenge fund, https://www.transport.gov.scot/public-transport/buses/scottish-zero-emission-bus-challenge-fund/

109 BBC News, Aberdeen's hydrogen buses taken off the road due to technical issue, 4 February 2022, https://www.bbc.co.uk/news/uk-scotland-north-east-orkney-shetland-60266199

110 Transport Scotland, Rail Services Decarbonisation Action Plan, https://www.transport.gov.scot/media/47906/rail-services-decarbonisation-action-plan.pdf, p.14

111 Transport Scotland, Rail Services Decarbonisation Action Plan, https://www.transport.gov.scot/media/47906/rail-services-decarbonisation-action-plan.pdf, p.18

112 Transport Scotland, Rail Services Decarbonisation Action Plan, https://www.transport.gov.scot/media/47906/rail-services-decarbonisation-action-plan.pdf, p.18

113 McKinsey, Harnessing momentum for electrification in heavy machinery and equipment, 9 April 2019, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/harnessing-momentum-for-electrification-in-heavy-machinery-and-equipment

114 JCB, JCB leads the way with first hydrogen fuelled excavator, 1 July 2020, https://www.jcb.com/en-gb/news/2020/07/jcb-leads-the-way-with-first-hydrogen-fuelled-excavator

115 Electrive, World's largest electric ferry launches in Norway, 2 March 2021, https://www.electrive.com/2021/03/02/worlds-largest-electric-ferry-yet-goes-into-service-in-norway/

116 Stockholm's 30mph electric ferry "a whole new take on public transport", 26 March 2021, https://www.intelligenttransport.com/transport-news/120053/electric-ferry/

117 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.61

118 Shell, Decarbonising shipping: all hands on deck, 2020, https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf

119 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.61 and Shell, Decarbonising shipping: all hands on deck, 2020, https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf

120 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, p.141

121 McKinsey, How airlines can chart a path to zero-carbon flying, 13 May 2020, https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/how-airlines-can-chart-a-path-to-zero-carbon-flying

122 UK Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf, p.61

123 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/

124 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/ p.24.
Note the graph refers to industries in scope of report analysis, not total emissions from all industries.

125 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/, p.3

126 McKinsey, Plugging in: What electrification can do for industry, 28 May 2020, https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry#:~:text=It%20is%20technologically%20possible%20to,149%20million%20terajoules%20in%202017.

127 Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K.A., Krüger, C. and Luderer, G., 2020. The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). Environmental Research Letters, 15(12), https://iopscience.iop.org/article/10.1088/1748-9326/abbd02/pdf

128 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/

129 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/, p62. Ranges refer to uncertainties over the decarbonisation pathways for the rest of Scotland's industries.

130 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/, pp.74–77

131 Note, the Deep Decarbonisation Pathways for Scottish Industries report assumes the same level of operations until 2045. See p.95 of https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/,

132 UK Committee on Climate Change, The Sixth Carbon Budget: Fuel Supply, 9 December 2020, https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Fuel-supply.pdf, p.15

133 Process emissions differ between industries. Cement making requires fossil fuels to create the required chemical reaction, while steel making requires fossil fuels as a primary input or feedstock.

134 Note this figure refers to industries in scope of Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/

135 Note this figure refers to industries in scope of Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/, pp.24–25

136 Element Energy, Deep Decarbonisation Pathways for Scottish Industries, December 2020, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/, p.28

137 Michael Liebreich, The Clean Hydrogen Ladder V4.1, 15 August 2021, https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

138 IEA, The Future of Hydrogen, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, pp.37–38

139 Scottish Government, Scottish Hydrogen Assessment Report, December 2020, https://www.gov.scot/publications/scottish-hydrogen-assessment-report/, p.42

140 Scottish Energy Statistics Hub https://scotland.shinyapps.io/sg-energy/

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June 2022