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HYDROGEN DEMAND IN SCOTLAND: A MAPPING OF INDUSTRIAL APPLICATIONS

A report for

Scottish Enterprise

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Element Energy (an ERM Group Company)

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Executive Summary

Introduction

The Climate Change Act, approved by Scottish Government (SG) in 2019, set an economy wide net zero greenhouse gas emissions target for 2045. Interim targets for 2030 and 2040 with emissions reductions of 75% and 90%, respectively against a baseline year of 1990 were also included in the Act. To achieve these targets, decarbonisation of energy-intensive and difficult-to-decarbonise industries will be important.

One of the key uncertainties is over which technologies will be best placed to provide a cost-effective and technically feasible decarbonisation pathway for Scottish industry. Hydrogen is widely regarded as holding strong potential to replace fossil fuels in industrial processes, whilst also offering an opportunity to store and transport low carbon energy. It has similarities to natural gas and could be blended into existing gas distribution and storage infrastructure, with some modifications. Scottish Government have highlighted that hydrogen is likely to play an important part in its energy system (alongside alternatives like electrification), especially in sectors such as heavy-duty transport, shipping, aviation, and industrial high temperature heat[1].

To support the development of the hydrogen economy in Scotland, Scottish Enterprise commissioned Element Energy (an ERM Group Company) to produce an updated mapping of potential hydrogen usage in Scotland for industrial processes and non-domestic heating (the Sectors of Interest). The sectors within this study are glass, cement, paper and pulp, fertilisers, distilleries, food and drink, power generation, oil and gas refining and chemicals and pharmaceuticals. The aim of this report is to support prospective hydrogen producers to identify viable offtakers by mapping and describing potential hydrogen users in each of the Sectors of Interest.

This study applied thresholds to focus on larger industrial and non-domestic building sites. For the industry scope, industrial NAEI 2019 CO_2 emissions data was filtered to filter sites with annual emissions >10,000 tCO_2. However, all Scotch Whisky distilleries were included, as most emit less CO_2 than the threshold. The calculations for the industry sectors reflect theoretical potential hydrogen use based on current energy requirements, adjusted downwards where assumptions could be made that certain offtake will not switch to hydrogen, or based on other studies' findings. For the non-domestic buildings sector, a threshold of 2,000,000 kWh/year of energy (combined heating and electricity) was used. Please see the Appendix for more detail.

Key Barriers and Opportunities for Hydrogen

There are several common technoeconomic barriers and opportunities for fuel switching to hydrogen, in addition to more specific one within each subsector (examined in Chapter 3). Key barriers include uncertainty around future hydrogen costs, the availability of future hydrogen distribution and storage infrastructure, and the relative current technical immaturity of dedicated hydrogen-fired appliances. Industrial processes are typically run continuously, so there are risks over the security of hydrogen supply in the early stages of the market. Major policy decisions that will affect the role and viability of hydrogen in the UK may also influence deployment of hydrogen-fired appliances.

However, if these barriers can be addressed there are significant opportunities in relation to hydrogen fuel switching. Hydrogen as a gaseous fuel can potentially offer a lower cost decarbonisation pathway for certain processes, relative to alternative decarbonisation pathways (which also have their merits).

Potential uses of hydrogen in Sectors of Interest

Hydrogen is regarded as a potential decarbonisation pathway for most of the Sectors of Interest due to its versatility; it can be combusted in a similar way to natural gas to provide high temperature direct heat or to raise steam for use in indirect heating. It is also used as a feedstock for industrial processes in several subsectors (e.g. chemicals and pharmaceuticals, agricultural feedstocks). The main types of end-use cases are presented in Table 0.1, with a commentary on alternative decarbonisation technologies and factors which may affect the competitiveness of hydrogen for fuel switching in each sector.

[1] Scottish Government, 2022, *Hydrogen Action Plan*, https://www.gov.scot/publications/hydrogen-action-plan/pages/2/

Table 0.1: Summary of hydrogen end use cases by Sector of Interest

Sector	Type of use case(s)	Alternative technologies	Notes on hydrogen usage potential and likelihood
Chemicals & pharmaceuticals	Indirect heating processes, Chemical feedstock	Electrification, CCUS	Industrial heating requirements could be met both by electrification or hydrogen, though some processes also require hydrogen as a feedstock
Oil and gas refining	Indirect heating processes	CCUS, electrification	Refineries use hydrogen and have many energy uses, showing a strong potential for hydrogen use
Cement	Direct heating processes	Biomass, CCUS	Due to the process emissions, CCUS is more likely to be used as a decarbonisation pathway
Fertilisers	Indirect heating processes, Chemical feedstock	Electrification, alternative fuels	Hydrogen may be produced on site before conversion into ammonia, so this may not be a source of additional hydrogen usage
Glass	Direct heating processes	Electric furnaces	High temperatures mean that hydrogen may be better suited than electrification, though issues remain over flame characteristics
Paper and pulp	Indirect heating processes, Direct heating processes	Biomass, Waste-derived fuels	Many sites have moved to alternative fuels e.g., biomass to partially decarbonise their operations, so there is less 'push' to switch to hydrogen
Distilleries	Indirect heating processes	Electrification, Biomass	The Scottish Whisky Association found that hydrogen will have a significant role to play in all net zero sectoral pathways
Food and drink	Indirect heating processes, Direct heating processes	Electrification	Unique subsector processes and equipment may impair the potential for hydrogen to replace some existing natural gas fired appliances
Power Generation	Indirect heating processes	CCUS, Renewables	The only CCGT power plant in Scotland (Peterhead) has chosen to pursue CCUS and so is unlikely to be a source of hydrogen usage
Non-residential heating	Indirect heating processes	Electrification	SG policy does not prioritise hydrogen for heating in buildings, but there may be edge-cases
Large Events and Construction	Indirect heating processes	Electrification, Biofuels	Currently met through diesel powered generators, with hydrogen being seen as a viable alternative. Batteries and biofuels are potential alternatives.

Indirect heating processes **Direct heating processes** **Chemical feedstock**

Distribution of potential hydrogen uptake in Scotland

Considering all the Sectors of Interest in scope, **the potential use for hydrogen is assessed at 13.5 TWh/year (405,000 tH_2/year)[2].** The largest potential demand for hydrogen is in the Oil and Gas Refining and Chemicals and Pharmaceuticals sectors, with the two totalling around 60% of the assessed potential. Some of the more prominent sites within these sectors are in the Central Belt of Scotland, e.g., Falkirk and Fife. The next two sectors with the largest potential are Distilleries, which may require different fuel supply models depending on size, and the Events and Construction sector requiring mobile hydrogen-fuelled equipment such as generators. The lowest demand potential overall corresponded to the Food & Drink, Metals and Non-Domestic Heating sectors due to the number of sites in Scotland or the nature of their energy requirements. .

[2] For reference, the Scottish Government's Hydrogen Action Plan states that 5GW installed renewable and low-carbon hydrogen production capacity is translated to more than 17.5 TWh/year and over 450,000 tH_2/year.

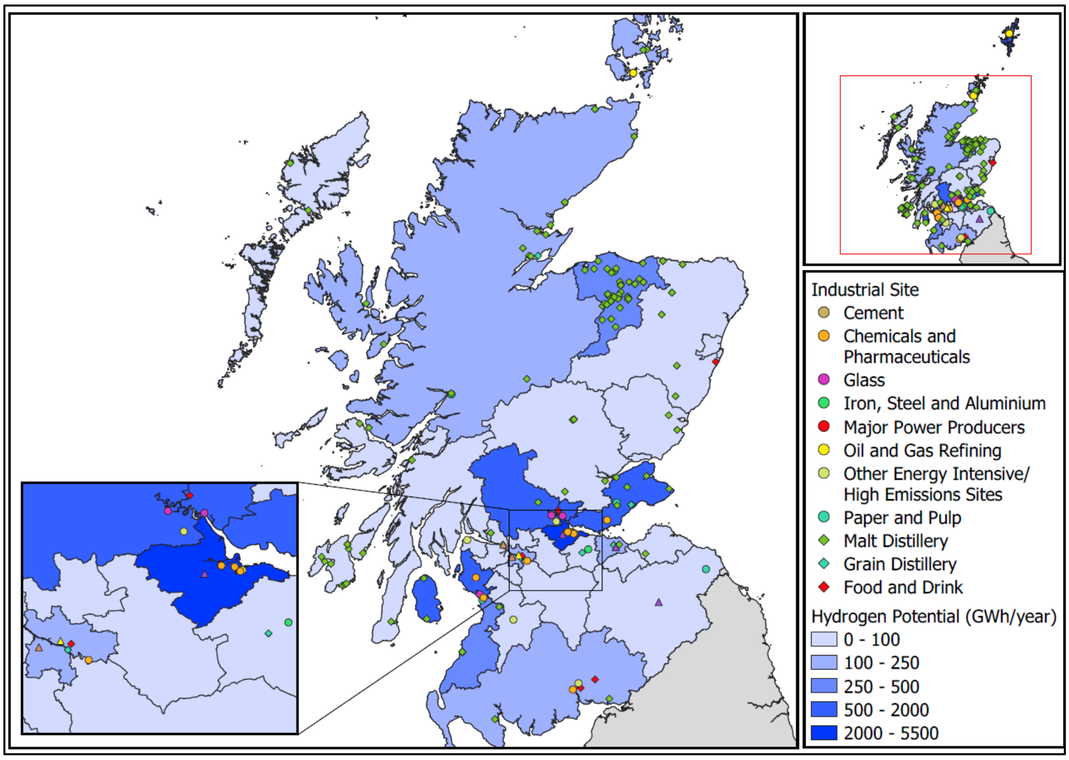

Figure 1: Heat map showing the GWh/year potential for industrial end use of hydrogen in different Scottish Local Authorities

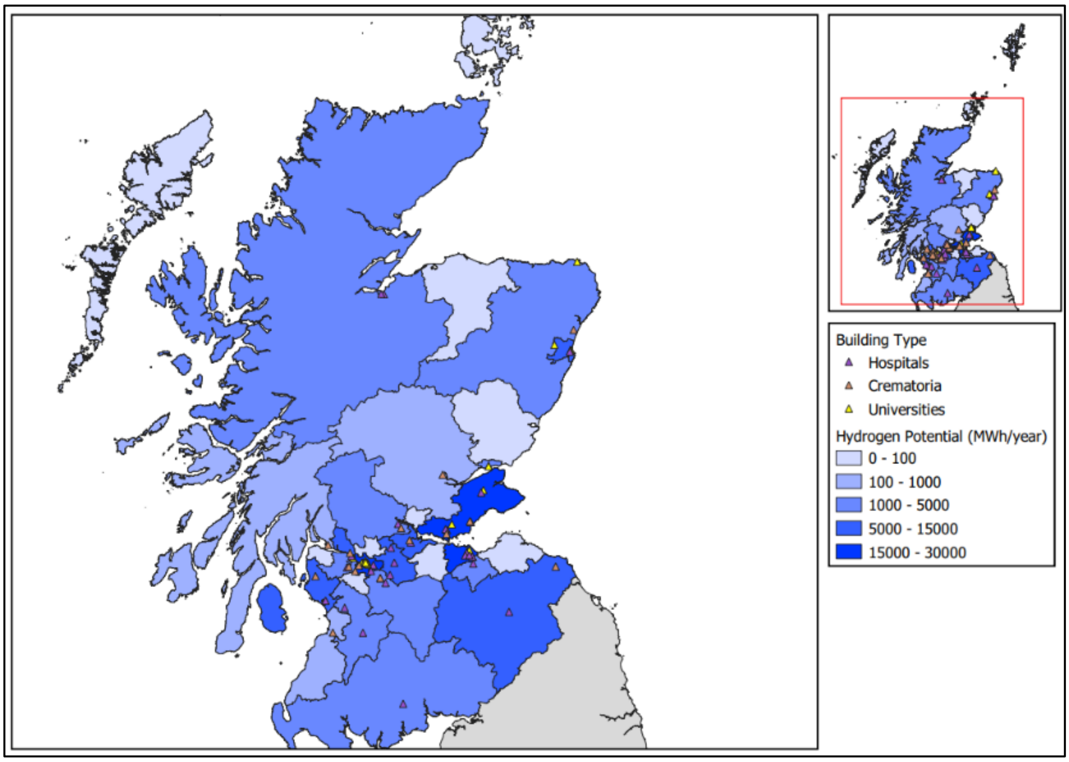

Figure 2: Heat map showing the MWh/year potential for end use of hydrogen in non-residential buildings in different Scottish Local Authorities

Regional Hydrogen Energy Hubs

Regional Hydrogen Energy Hubs describe areas where a local hydrogen value chain can be developed, from production to end-use, including distribution and storage. Several Regional Hydrogen Hubs have already begun to be formed in Scotland to create and support demand for hydrogen.

Figure 3: Map of potential regional hydrogen hub locations

As seen in Figure 3, the 13 hubs identified in the Scottish Government's Hydrogen Action Plan (2020) are: 1) Aberdeen, 2) Argyll and Islands, 3) Ayrshire, 4) Cromarty, 5) Dumfries and Galloway, 6) Dundee, 7) Fife, 8) Glasgow, 9) Grangemouth, 10) Orkney, 11) Scottish Borders, 12) Shetland and 13) Western Isles.

Section 4 provides a deep dive into the potential offtakers in scope within the Regional Hydrogen Energy Hubs.

Drivers for short- and long-term opportunities

There are a variety of drivers that will determine the attractiveness and viability of low-carbon hydrogen as a decarbonisation pathway in Scottish industry and non-domestic buildings.

In the short term, the Regional Hydrogen Energy Hubs approach will drive opportunities for hydrogen demand development by coupling production with multiple local end-uses to build up scale. Locations with onshore wind curtailment or substations for offshore wind will prove promising for green hydrogen production. Early uptake may be focused in sectors which already have equipment and skills compatible with the use of hydrogen or natural gas blends, and where hydrogen-fired appliances are becoming more mature.

Long term opportunities around hydrogen fuel switching in the Sectors of Interest will be driven by the increasing market-readiness of hydrogen equipment and availability of hydrogen, with interconnectivity between future hydrogen supply and demand points likely to play a critical role in defining and enabling longer-term opportunities beyond 2030. The development of hydrogen distribution infrastructure will enable the deployment of hydrogen spur pipelines to potential demand points outside of the Regional Hydrogen Energy Hubs, enabling further uptake. Gradual expansion of the initial hydrogen pipeline network could enable the use of hydrogen in non-domestic buildings and smaller industrial sectors, though this is partially dependent on UK-level policy decisions on the role of hydrogen for heating in the public gas network, unless private hydrogen pipelines were developed. The scale of hydrogen production is also planned to increase, with larger projects becoming operational around 2030. This will be partly enabled by the development of substantial offshore wind projects like ScotWind which will provide a source of renewable electricity at proportions which are likely to reduce the cost of hydrogen to more competitive levels.

Authors

This report has been prepared by Element Energy, an ERM Group company.

Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 100 specialists provides consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport. Element Energy provides insights on both technical and strategic issues, believing that the technical and engineering understanding of the real-world challenges support the strategic work. In June 2021, Element Energy joined the ERM Group, the largest independent sustainability consultancy, with a global footprint and over 7,000 employees worldwide.

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Disclaimer

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Note on terminology

Whilst Carbon Capture, Utilisation, and Storage (CCUS) and Carbon Capture and Storage (CCS) are used almost interchangeably in the literature, for consistency purposes, this report only uses CCUS, with an exception when CCS is used directly in the cited sources.

Acronyms

CCS	Carbon, Capture and Storage	Mt	Mega tonne
CCUS	Carbon Capture, Utilisation, and Storage	NAEI	National Atmospheric Emissions Inventory
CHP	Combined Heat and Power	NG	National Grid
CO_2	Carbon Dioxide	NOx	Nitrous Oxide
EPC	Energy Performance Certificate	R&D	Research and Development
ESO	Energy System Operator	SG	Scottish Government
F&D	Food and Drink	SMR	Steam Methane Reforming
GW	Gigawatt	SWA	Scotch Whisky Association
GWh	Gigawatt Hour	TRL	Technology Readiness Level
LPA	Litres of Pure Alcohol	TWh	Terawatt Hour
MW	Megawatt	UK	United Kingdom
MWh	Megawatt Hour	UV	Ultraviolet

Contents

1 Introduction

Scotland has committed to an economy wide net zero greenhouse gas emissions target by 2045, which is set out in the Climate Change (Scotland) Act of 2019. This includes interim targets for 2030 and 2040 of emissions reductions of 75% and 90%, respectively, against a baseline year of 1990. Decarbonising energy-intensive industries will be key to achieving net zero emissions, but heavy industries are regarded as amongst some of the most difficult to decarbonise[3], with significant uncertainty over the technologies that will be most well-suited to their decarbonisation. Scotland's Climate Change Plan has targets for energy intensive industries, with industrial and commercial emissions intensity falling at least 30% by 2032[4].

Hydrogen has been described by some as a decarbonisation 'Swiss army knife'[5], which could be used to replace fossil fuels in industrial processes whilst also offering an opportunity to store and transport renewable energy. It has many similarities to natural gas and could be blended into existing gas transport and storage infrastructure with some modifications. The Scottish Government have highlighted that hydrogen is likely to play an important part in its energy system (alongside electrification), especially in sectors such as heavy-duty transport, shipping, aviation, and industrial high temperature heat [6]. Scotland also has ambitious plans for the development of offshore wind, which enables the opportunity for Scotland to become a producer and exporter of renewable hydrogen.

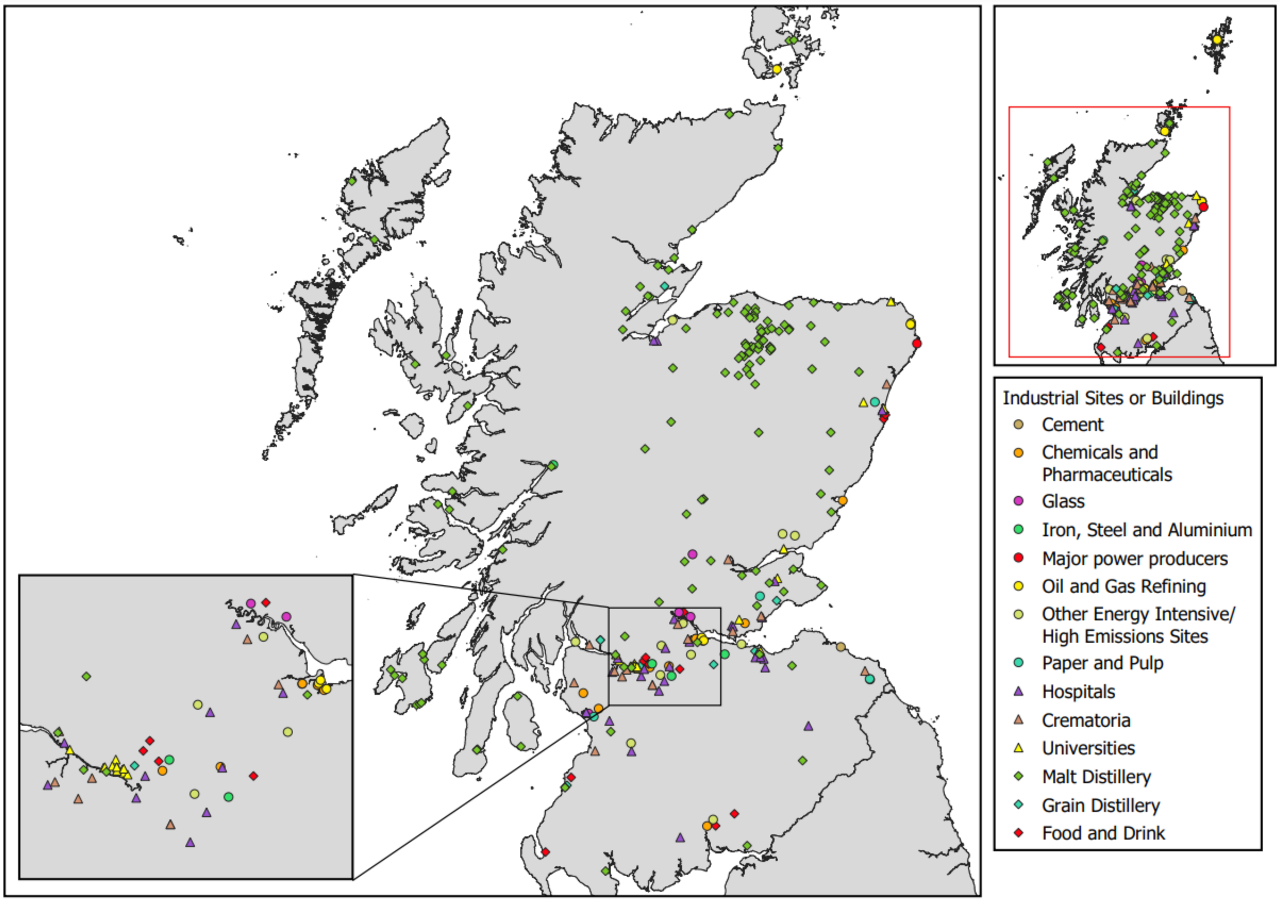


Figure 4: Map of Scotland showing the sites within the Sectors of Interest included in the assessment

Within this context, Scottish Enterprise commissioned Element Energy to produce an updated mapping of potential hydrogen usage in Scotland for the Sectors of Interest (non-domestic heating and industrial

[3] Brookings, 2021, [The challenge of decarbonizing heavy industry](#)
[4] Scottish Government, 2018, [Update to the Climate Change Plan](#)
[5] Bill Gates, To cut emissions, use this Swiss Army Knife, *https://www.gatesnotes.com/Clean-Hydrogen*
[6] Scottish Government, 2022, *Hydrogen Action Plan*, https://www.gov.scot/publications/hydrogen-action-plan/pages/2/

processes), which are shown in Figure 4. The industrial subsectors of interest in this study are the glass, cement, paper and pulp, distilleries, food and drink, power generation, oil and gas refining and chemicals and pharmaceuticals subsectors.

This study applied thresholds to focus on larger industrial and non-domestic building sites. For the industry scope, industrial NAEI 2019 CO_2 emissions data was filtered to filter sites with annual emissions >10,000 tCO_2. However, all Scotch Whisky distilleries were included, as most emit less CO_2 than the threshold. The calculations for the industry sectors reflect theoretical potential hydrogen use based on current energy requirements, adjusted downwards where assumptions could be made that certain offtake will not switch to hydrogen, or based on other studies' findings. For the non-domestic buildings sector, a threshold of 2,000,000 kWh/year of energy (combined heating and electricity) was used. Please see the Appendix for more detail.

The mapping of hydrogen potential and description of potential hydrogen uses can be subsequently used by prospective hydrogen producers to identify viable offtakers. The results are presented in this work alongside a collation of findings from a range of past studies, and a discussion of the short and long-term opportunities for hydrogen producers in Scotland is also included.

In parallel, Scottish Enterprise commissioned Ricardo to conduct a study into the potential hydrogen usage for mobility applications in Scotland, and a technical study into the use of hydrogen in Scottish distilleries.

2 Overview of the Scottish Industrial Hydrogen Potential

2.1 Location of Scottish Industry

Scotland has a strong industrial heritage, with one of the six industrial clusters in the UK and a main entry point of natural gas at St Fergus.

Across Scotland, over 6MtCO_2 were emitted from the industrial sector in 2019[7]. Industrial sites in Scotland are distributed mainly in the central Belt of Scotland, including the Grangemouth, Fife and Lower Forth regions. St Fergus in the Northeast of Scotland also has significant amounts of industry, due to the St Fergus Gas terminals, power station and related infrastructure located there.

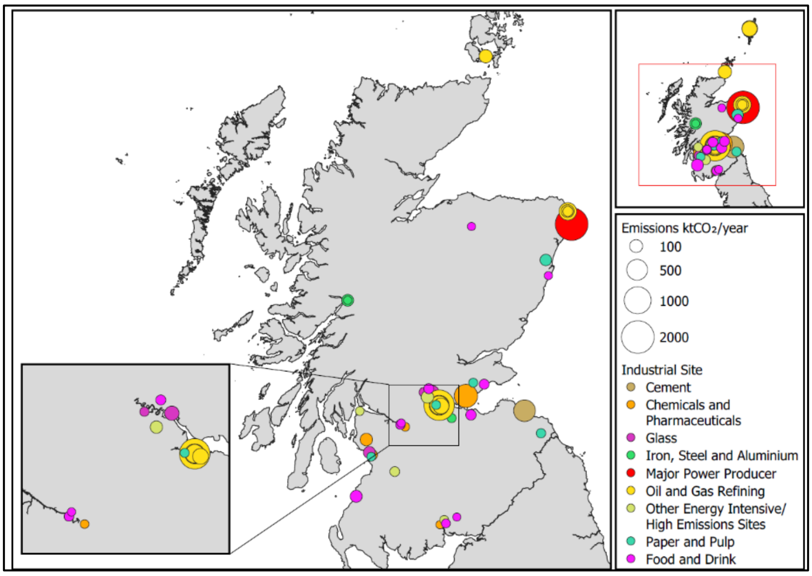


Figure 5: Annual emissions per industrial site, based on 2019 NAEI data[7]

Oil and gas refining represents the largest emitting Scottish industrial subsector, accounting for ~42% of point source emissions in 2019. Other industrial subsectors with significant emissions include cement, food and drink and chemicals and pharmaceuticals, making up a total of over 49% of industrial emissions in 2019.

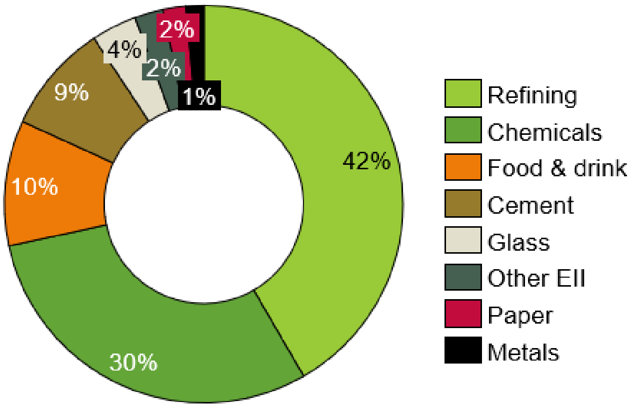


Figure 6: Breakdown of Industrial Emissions in 2019 by sector[7]

The use of hydrogen in industry is regarded as particularly promising due to its ability to provide high temperature heat for energy-intensive processes, which is currently met by natural gas and other fossil fuels. High temperature industrial heat was identified on the Hydrogen Hierarchy set out in the Scottish Hydrogen

[7] National Atmospheric Emissions Inventory, 2019, *NAEI Dataset*, filtered to sites with annual emissions above 10,000 tCO2

Action Plan as having significant market opportunity[8], alongside use as a chemical feedstock, in refineries and in distilleries. In Scotland, several studies have examined the potential for hydrogen to meet these industrial process requirements and quantified the total hydrogen usage through the modelling of different scenarios. A total of fifteen studies were reviewed and categorised by this work. Five particularly relevant studies to this work were identified:

- The Committee on Climate Change, *Sixth Carbon Budget (2021)*[9]
- ClimateXChange & Energy Systems Catapult, *Scottish Whole Energy Scenarios (2022)*[10]
- Element Energy, *Hydrogen in Scotland* (2020)[11]
- SGN & Wood, *North East Network and Industrial Cluster Development* (2021)[12]
- Element Energy, *Deep Decarbonisation Pathways for Scottish Industries* (2020)[13]

The annual hydrogen usage in 2045 in Scottish industrial sectors was found to range between 0 – 21.3 TWh depending on the scenarios examined by each study. Other studies examined in the literature included Phase 1 Reports from the Green Distilleries Competition, Future Energy Scenarios from the National Grid, the UK's Hydrogen Strategy, and the Scotch Whisky Association's Pathway to Net Zero. Whilst these did not provide quantitative estimates of future hydrogen usage in industry, these studies were important in understanding how hydrogen could be used in the industrial sector and specific barriers and opportunities to its use in the UK and Scotland.

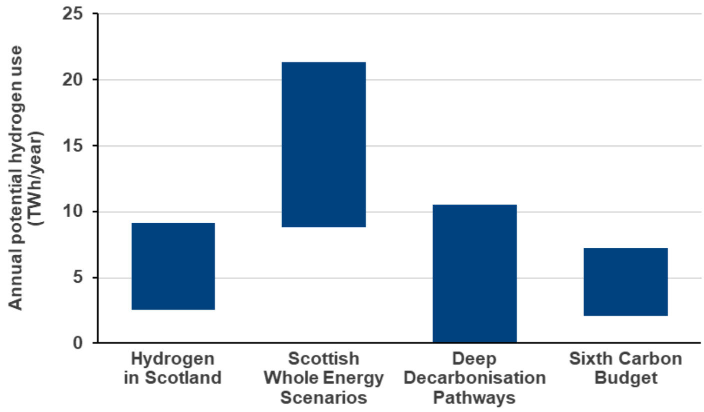


Figure 7: Range of annual hydrogen usage in Scottish industry in 2045 identified across the literature. The SGN study is not presented as it only examined the North East Network region of Scotland

2.2 Technoeconomic barriers and opportunities for hydrogen

Across all industrial subsectors examined in this work, there are several common technoeconomic barriers and opportunities for fuel switching to hydrogen, in addition to more subsector-specific barriers and opportunities, which are examined in Section 3. Previous studies on hydrogen use in Scotland discussed some of these common barriers and opportunities for hydrogen.

Key Barriers

1. **Infrastructure Requirements**: Fuel switching to hydrogen for industrial and non-domestic heating will rely on the national availability of future distribution and storage infrastructure for hydrogen, which was

[8] Scottish Government, 2022, Hydrogen Action Plan,
[9] Committee on Climate Change, 2021, Sixth Carbon Budget, https://www.theccc.org.uk/publication/sixth-carbon-budget/
[10] ClimateXChange & Energy Systems Catapult, 2022, Scottish Whole Energy Scenarios, https://www.climatexchange.org.uk/media/5419/cxc-scottish-whole-energy-system-scenarios-may-2022.pdf
[11] Element Energy, 2020, *Hydrogen in Scotland*
[12] SGN & Wood, 2021, North East Network and Industrial Cluster Development, *https://sgn.co.uk/about-us/future-of-gas/ne-network-industrial-cluster*
[13] Element Energy, 2020, *Deep Decarbonisation Pathways for Scottish Industries*, https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/

identified in many studies as currently being unclear. Where on-site storage is required, there may be additional space and pressure considerations.

2. **Technological Maturity and Requirements**: Hydrogen end use appliances are not yet widely available at scale, with various technologies in the technology push phase. Further, the requirements for equipment modification also pose a barrier to hydrogen fuel switching, especially in cases where the investment cycles for industrial equipment are not aligned with decarbonisation objectives. The potential for appliances to operate with small blends of hydrogen into natural gas may mitigate early barriers to switching to hydrogen.

3. **Policy decisions in relation to hydrogen:** It was noted that current limits to business model support delays deployment of key anchor projects, which should benefit from these schemes, as part of the wider decarbonisation needs of Scottish industry. Equally, UK-level policy decisions which are due in 2026 on the role of hydrogen for heating and its use in gas distribution networks, can also impact hydrogen uptake.

4. **Security of Supply**: Industrial processes are often run continuously, meaning that uninterrupted supply of fuel and feedstocks is essential to cost effective operation. Security of supply was highlighted as a barrier for hydrogen fuel switching, though stakeholders noted that long-term plans for supply and demand interconnectivity currently being pursued could increase confidence in security of supply.

5. **Economic Uncertainty**: Many studies highlighted the high uncertainty of future hydrogen costs as a key barrier to its uptake and recognised that low-carbon hydrogen would lead to higher costs in the short-to-medium term compared to traditional fuels. The UK Government launched a revenue support mechanism (Hydrogen Business Model) to offset this disparity within eligible projects.

6. **Health and Safety**: The risk relates to ensuring safe industrial operations involving hydrogen, due to its high flammability and explosivity, as well as possible leakage risks. An important aspect of this is perceived risks, and how they compare to actual risks.

Other barriers identified in stakeholder engagement activities included i) lack of sufficient information for industrial sites to make informed decisions on their most favourable decarbonisation pathway, as well as ii) a hydrogen-production focused view of research conducted to date, with less attention on downstream hydrogen uses.

Key Opportunities

1. **High applicability to industrial sectors:** Hydrogen has a high potential to provide process heat or steam across multiple industrial subsectors, potentially in a more cost-effective manner than other low carbon options. As a gaseous fuel, it can be more familiar than electrification for those industrial users who are used to running their operations on fuels like natural gas. Lastly, hydrogen is versatile and can also be converted to electricity if run through a fuel cell.

2. **Possibility of repurposing infrastructure**: Gas infrastructure and some existing fossil-fuel appliances in industrial processes could be retrofitted for hydrogen use, offering less disruption than other low-carbon pathways.

3. **Wider economic benefits**: Developing a hydrogen economy in Scotland will create and safeguard jobs and investment opportunities, whilst also offering an opportunity for export of domestically produced hydrogen[14]. Some industrial hydrogen users who will also be producers may choose to enter this market.

4. **Limitations around electrical grid connections:** A barrier to alternative electrified technologies that hydrogen fuel switching would mitigate (when produced centrally and distributed) is the limitation of electrical grid connections in specific locations, which would affect the ability of industrial sites to electrify, due to costs.

[14] In the stakeholder engagement activities, it was highlighted that not all the economic benefits of hydrogen use will remain in Scotland, as core hydrogen equipment can also be manufactured outside of Scotland and the UK.

5. **Potential for blending into the gas grid:** IA small blend of hydrogen (under 20%) could be blended into the transmission network without retrofit requirements for the vast majority of appliances. Enabling blending into the grid would make 'first moving' to hydrogen easier. However, some industrial users' equipment may be sensitive to the composition of delivered gas and need de-blending.

2.3 Hydrogen-fired industrial appliances

Fossil fuel sources such as coal, petroleum and natural gas are currently used to meet industrial heat requirements, with natural gas as the dominant fuel used in the UK industrial sector by final energy consumption[15]. Switching away from the consumption of fossil fuels will be essential to meet industrial net zero targets, with hydrogen having been proposed as one of the available decarbonisation options (with alternative options including biomass and electrification).

Process energy demands in industry can be categorised according to the heat requirements[16], which may affect the suitability of decarbonisation technologies to meet these demands. A key difference is whether processes are heated through direct contact between the combustion flame and air (direct heating) or whether heat is transferred through a heat exchanger from an enclosed flame (indirect heating):

1. **Indirect heating processes**, which can be further categorised[17] into:

   1. Steam
   2. High temperature indirect heating
   3. Low temperature indirect heating

2. **Direct heating processes**

   1. Reduction processes
   2. High temperature direct heating
   3. Low temperature direct heating

Hydrogen is regarded as being feasible for most heating applications in industry, either used directly as a 100% fuel for combustion or in combination with gas or other fuels[18]. Similarly to natural gas, it can be combusted to produce a direct flame, which could either be used in direct heating applications or could be used to generate steam or another heating medium for use in indirect heating. Some natural gas-fired appliances can be used with a limited blend of hydrogen fuel. However, there are several key differences that currently pose a barrier to complete fuel switching, which are explored as follows:

Key differences between hydrogen and natural gas

1. Flame speed (the speed at which the flame front in combustion expands): hydrogen has a much higher flame speed than natural gas, posing risks of the flame moving upstream from the desired combustion location.

2. Adiabatic flame temperature: the flame temperature of hydrogen is approximately 245C higher than natural gas, which means equipment may not be suitable and NOx gases may be produced during combustion.

3. Flame emissivity: hydrogen flames radiate less infrared light and more UV radiation than natural gas, which means that the flame is significantly more difficult to see with the naked eye.

[15] 40% of final energy consumption in 2021, taken from Energy consumption in the UK 2022
[16] Industrial fuel switching market engagement study (publishing.service.gov.uk)
[17] **"Low temperature"** corresponds to processes requiring temperatures of 30-80°C for indirect heating, and 80-240°C for direct heating**. High temperature** corresponds to processes requiring temperatures of up to 600°C for indirect heating, and up to 2,000°C for direct heating. Steam at different pressures can meet indirect heating requirements in the 80-240°C range
[18] Based on interviews and workshops conducted with industrial stakeholders and technology suppliers in Element Energy & Jacobs, 2018, *Industrial fuel switching market engagement study*

Key differences between hydrogen and natural gas (cont.)

4. Safety considerations: hydrogen has a larger flammability limit, and due to its smaller molecular size, it is also more prone to leakage. Hydrogen flames also have a low radiant heat, making it difficult to sense their presence.

Typically, fuel switching for direct heating will be more challenging than for indirect heating, due to the varying characteristics of hydrogen combustion detailed above. Combustion characteristics in direct heating applications are also more likely to affect industrial product quality.

Due to these different characteristics of hydrogen combustion, existing natural gas appliances will need to be modified or redesigned to solely operate on hydrogen without adversely affecting production rates and product quality, or switched entirely with a new hydrogen-ready appliance. The Hy4Heat 2019 study[19] characterised industrial subsectors by the hydrogen equipment which would be required at sites, with a summary of the relevant subsectors to this work presented in Table 2.1.

Table 2.1: Sector-specific equipment requirements, evaluated from the Hy4Heat Industrial Hydrogen Equipment study[20]

Subsector	Boiler/ Indirect dryer	Direct dryer/ ovens	Kiln	Conventional furnace	Proprietary equipment	Glass furnace	Gas Turbine	Gas engine
Cement			✓					
Refining		✓		✓			✓	
Chemicals	✓	✓		✓			✓	
Glass			✓		✓	✓		
Paper and pulp	✓							
Distilleries	✓							
Food and drink	✓	✓			✓		✓	
Dispatchable Power Generation							✓	
Non-residential heating	✓							
Large events and construction								✓

2.4 Theoretical potential for use of hydrogen in the Sectors of Interest

Following the methodology set out in the Appendix, this study calculated estimates for the *theoretical potential* use of hydrogen for the Sectors of Interest, with the results presented in Figure 8. This study uses the term theoretical potential as the assessment investigated what would be the total hydrogen use if the industrial processes in scope that can fuel switch to hydrogen (from a technical feasibility perspective) did convert to hydrogen use. Nonetheless, this study describes the specific cases when hydrogen is excluded from the assessment (whether it is because certain sites are proposing non-hydrogen decarbonisation projects or because CCS is likely to be deployed on a site and used to abate process or internal fuel emissions). This analysis is based on 2019 site-level emissions of fossil CO_2 for the sites within the industrial Sectors of Interest, obtained from the National Atmospheric Emissions Inventory (NAEI).

The Appendix also describes the methodology employed to assess the theoretical potential use of hydrogen in distilleries, non-residential buildings and in large events and construction sites.

[19] Element Energy, 2020, *Hy4Heat: Conversion of Industrial Heating Equipment to Hydrogen*
[20] Element Energy, 2020, Hy4Heat Industrial Hydrogen Equipment

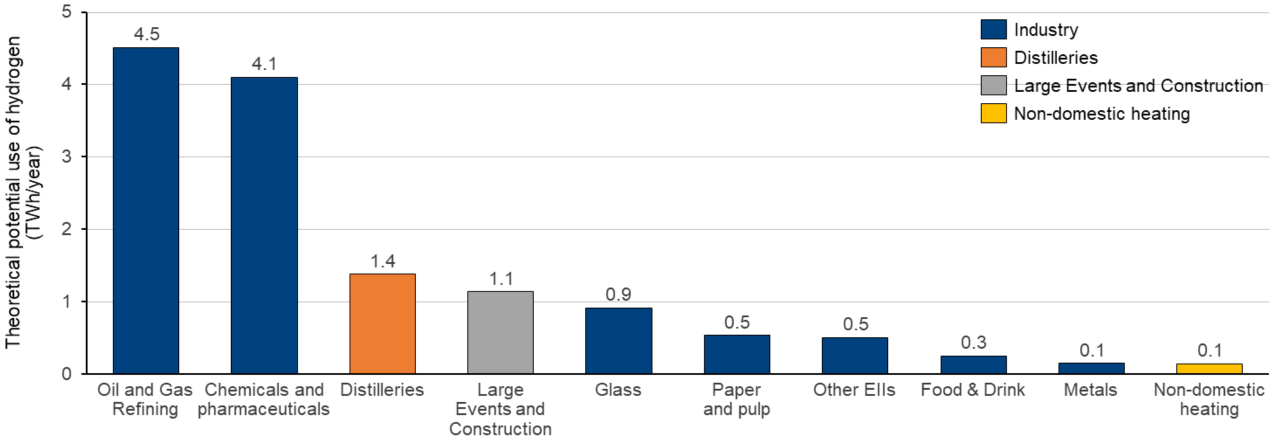


Figure 8: Assessed theoretical potential use of hydrogen (TWh/year) by each of the Sectors of Interest. Other EIIs include iron, steel and aluminium, other non-metallic mineral products, print products, rubber, and veneer sheets and wood-based products

We note that there are alternative decarbonisation pathways other than hydrogen, such as CCUS, electrification, and biomass fuel switching. Chapter 2 qualitatively discusses how well positioned hydrogen fuel switching is in each sector, relative to other options. Equally, industrial use of hydrogen will also depend on availability of infrastructure to ensure security of supply of hydrogen. To delve into these and other factors in detail, Chapter 0 discusses how these drivers can be used to identify higher-likelihood end-uses of hydrogen.

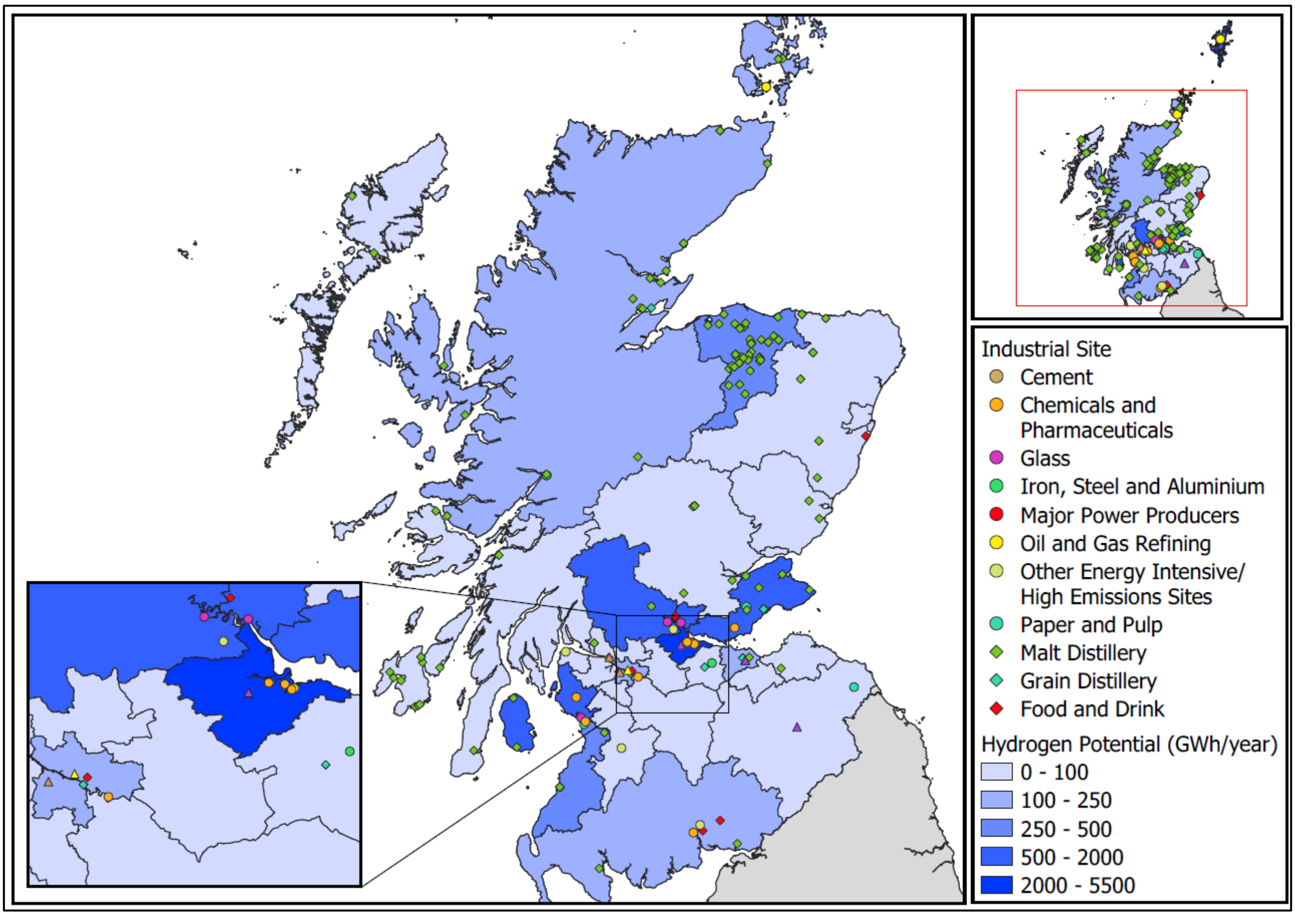


Figure 9: Heat map showing the GWh/year potential for industrial end use of hydrogen in different Scottish Local Authorities

Given the premise of theoretical potential, Figure 8 shows the TWh/year of possible hydrogen use in the different Sectors of Interest, with a hydrogen usage in industry (including distilleries) of 12.3 TWh/year (370,000tH_2/year), and a total for all the Sectors of Interest of 13.5 TWh/year (405,000tH_2/year). Referring to Figure 7, one can see that the calculated figure is within the upper range of the assessments' hydrogen demand conducted to date. This is likely to be the case due to the large geographic scope covered by this study, and the assumption that hydrogen is assumed to be used to fuel switch the majority of the industrial subprocesses (see introduction of this section for the methodology used), where technically viable.

Figure 9 shows the location of the sites within each of the Sectors of Interest in Scotland. The specific end uses of hydrogen within each of these sectors are described in Chapter 3, whilst Chapter 4 provides a deeper regional dive into specific areas of Scotland.

From the sectoral analysis presented, it becomes apparent that the largest potential demand in terms of volumes is in Scotland's Oil and Gas Refining as well Chemicals and Pharmaceuticals sectors. These organisations are likely to have plans in place to link with national infrastructure improvements and CCUS-enabled hydrogen projects. When comparing regional distribution of hydrogen end use potential, the heat map presented suggests there is a cluster of industrial sites that could be decarbonised with hydrogen in the Central Belt of Scotland, in Local Authorities such as Falkirk and Fife.

Smaller decentralised sites can still represent opportunities for offtake. Some like the distilleries on Islay may currently be off-grid and reliant on deliveries of fuel oil or LPG, which could switch to deliveries of hydrogen via tube trailers.

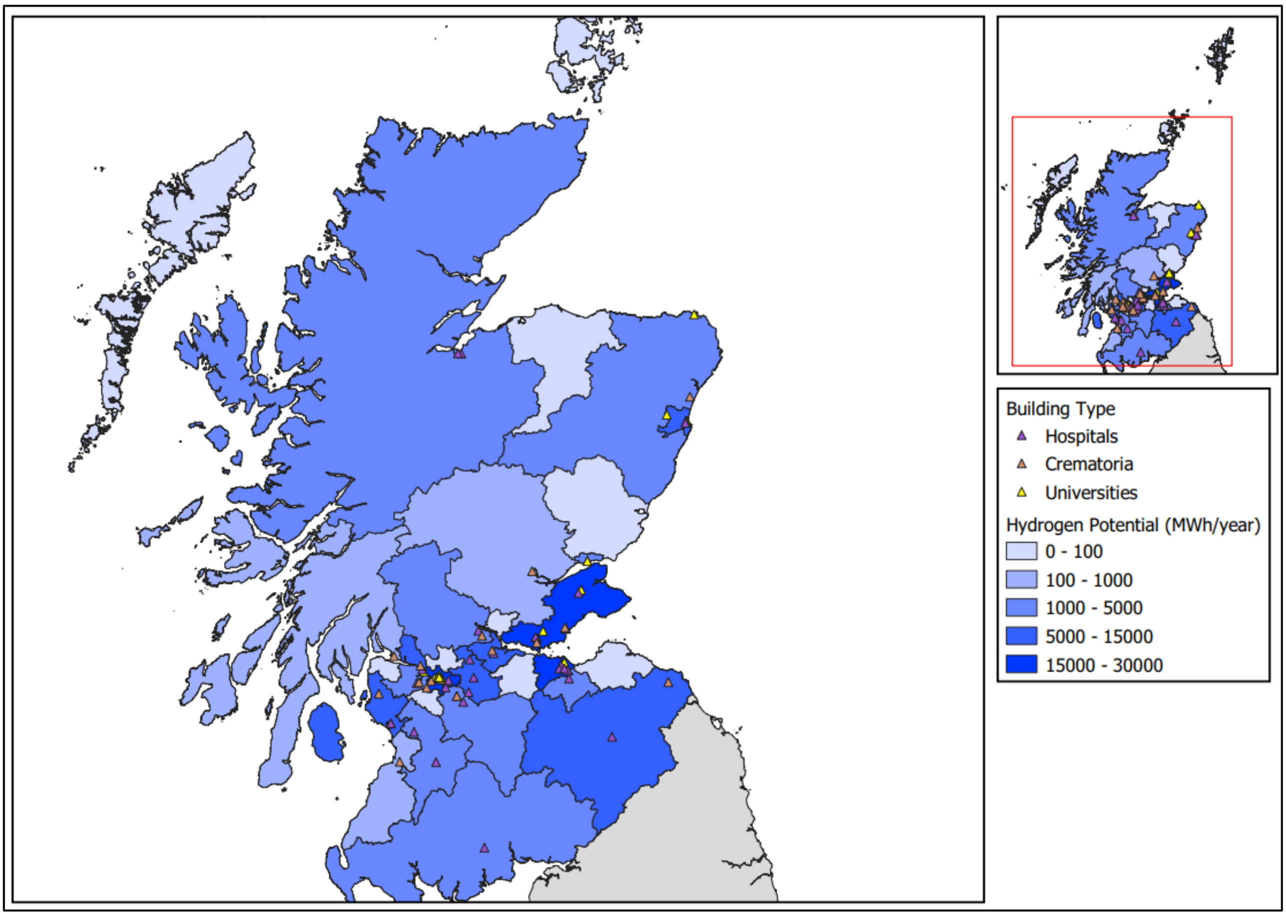


Figure 10: Heat map showing the MWh/year potential for end use of hydrogen in non-residential buildings in different Scottish Local Authorities

The map suggests that largest potential demand from these types of buildings would come from urban areas, such as Glasgow City, urban areas in the Fife Local Authority, and the City of Edinburgh.

The table below indicates the number of sites by the scale of their potential hydrogen demand. Of the total of 167 sites, all except 32 sites are distilleries. Overall, there are 100 Very Small and Small sites which would each use less than 150 tH2/year, potentially representing an opportunity for decentralised deliveries or smaller production projects to be developed. Conversely, the 44 Large and Extra Large energy users may require bespoke, co-located large production.

Table 2.2: Distribution of Scottish industrial sites (including distilleries) by ranges of potential hydrogen use (GWh/year)

Size of potential hydrogen use (GWh/year)	Number of sites	Corresponding range of potential hydrogen use (tH_2/year)
Very small (<1 GWh/year)	40	<30
Small (1 - 5 GWh/year)	60	30-150
Medium (5 - 15 GWh/year)	23	150-450
Large (15 - 300 GWh/year)	33	450 – 9,010
Extra Large (>300 GWh/year)	11	>9,010

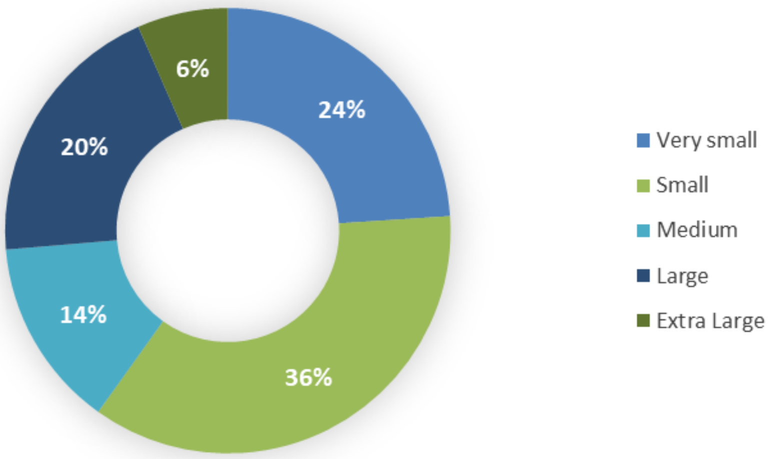


Figure 11: Breakdown of industrial end-users by the scale of potential hydrogen usage

3 Factors driving hydrogen usage across sectors

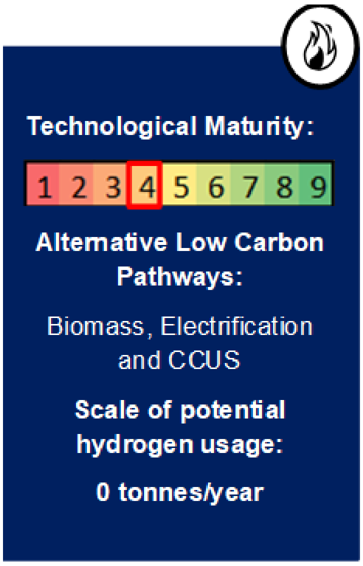
As discussed earlier, estimates for hydrogen use in industry can vary significantly due to different assumptions when modelling industrial decarbonisation. Within each subsector of industry, there are several factors that could reduce actual hydrogen demand relative to its theoretical potential. As highlighted in Section 2.3, industrial demand for heat could also be met with fuel switching to biomass or through electrification, or by retrofitting CCS on processes using fossil-fuels. Whilst all these technologies could be used to achieve the required heating profiles for industrial processes, some technologies are regarded as more suitable than others for particular heating requirements.

Biomass is less well suited to replacing natural gas for direct high-temperature heating[21] as the products of combustion have a less desirable composition than those from natural gas[22], though it is already used to produce indirect heat in industry. Both hydrogen and biomass are regarded as feasible for most heating profile applications[23], though hydrogen is regarded as more competitive for high temperature heating requirements, as biomass can become comparatively expensive when required in large volumes and is currently only used for relatively low temperature heating[24]. Electrification is a suitable option for low temperature heating, especially when heat pumps are able to be deployed because of their higher efficiencies than alternatives such as hydrogen, but electrification requires the replacement of existing equipment, whilst hydrogen and biomass can be utilised with only partial changes to equipment (as discussed in Section 2.3).

The suitability of hydrogen against alternative low-carbon pathways within each subsector can be estimated by examining sector-specific hydrogen barriers, identifying announced projects for non-hydrogen pathways in Scotland and through findings from previous engagement with industrial site operators in Scotland. This subsection conducts a brief discussion of each industrial subsector, highlighting key points that may affect the estimates of usage presented in Section 2.4 and announcements made at large scale sites that may affect the likelihood of specific sites in Scotland to fuel switch to hydrogen. Technology Readiness Levels (TRLs) for each sector were taken from the International Energy Agency's Clean Technology Guide[25], the Hy4Heat study19[19] and independent research conducted into pilot projects for hydrogen in each subsector.

[21] High temperature is taken in this work to refer to processes requiring temperatures of up to 600C for indirect heating, and up to 240 - 2,000C for direct heating.
[22] Committee on Climate Change, 2020, *The Sixth Carbon Budget Methodology Report*
[23] Based on interviews and workshops conducted with industrial stakeholders and technology suppliers in Element Energy & Jacobs, 2018, *Industrial fuel switching market engagement study*
[24] International Energy Agency Bioenergy, 2-22, *Role of Biomass in Industrial Heat*
[25] International Energy Agency, ETP Clean Energy Technology Guide, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

3.1 Cement



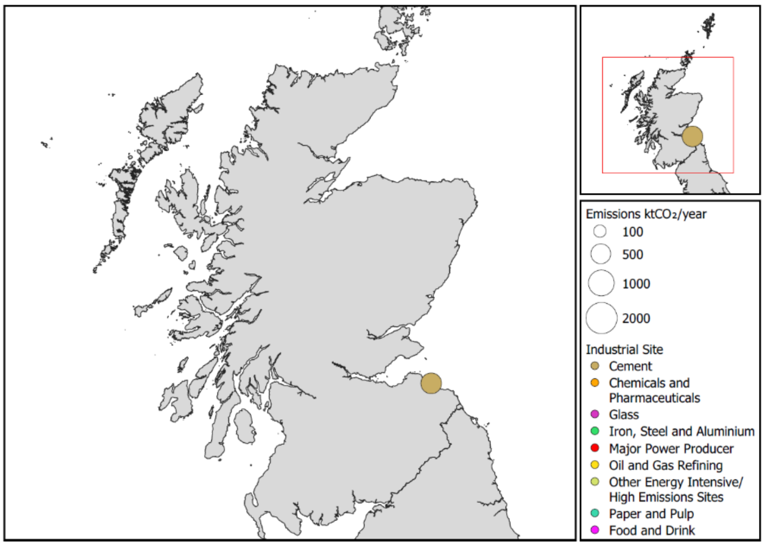


Figure 12: Map showing the cement site in Scotland

There is only one Scottish cement site; the Dunbar Works, located in the South-East of Scotland. Cement is produced through the heating of raw materials (mainly limestone and clay), which are crushed and then fed into a cement kiln, which heats the mixture to 1,300 – 1,500C to produce clinker. The cement kiln's direct heating requirements are typically met through fossil fuels such as coal, heavy fuel oil and natural gas, though biomass and solid waste materials are also used. As per BEIS' *Energy Consumption in the UK (ECUK): End Use Tables – Table 4*, in 2019 the cement sector's energy usage was 20% solid fuels, 2% oil, 57% natural gas and 21% electricity[26].

The heating profile required in cement production is dominated by high temperature direct heating, qualifying hydrogen as a suitable decarbonisation technology. Co-firing of hydrogen with current fuels has been explored in industry, with up to 50% blends by volume of hydrogen having been used so far in pilot projects and modelling[27], though co-firing of hydrogen with other fuels does require modifications to cement kiln burners. Further R&D needs to take place before kilns can be solely fired with hydrogen [28], as new designs will be required to account for hydrogen's higher temperature and flame speed, and lower flame radiant emissivity [29] when compared to fuels such as natural gas.

There are several alternative low-carbon pathways to hydrogen use in cement production, including biomass, electrification and CCUS, and many cement kilns have been converted to run with a mixture of biomass and solid waste fuels. Dunbar Works has begun using non-hazardous waste materials that cannot be recycled, due to its aim to replace up to 45% of its traditional fossil-based fuels with low carbon alternatives[30]. Electric kilns are also being explored in pilot projects. However, CCUS can be considered a more appealing option than fuel-switching (either to hydrogen, biomass or electrification) due to its ability to abate both process- and heating-related emissions. Fuel switching alone can only abate up to 30% of emissions[28], while 70% of CO_2 emissions are associated with the chemical process within cement production. **As a result of the Dunbar Works decarbonisation decision, it is assumed that the cement sector in Scotland sees no use of hydrogen.**

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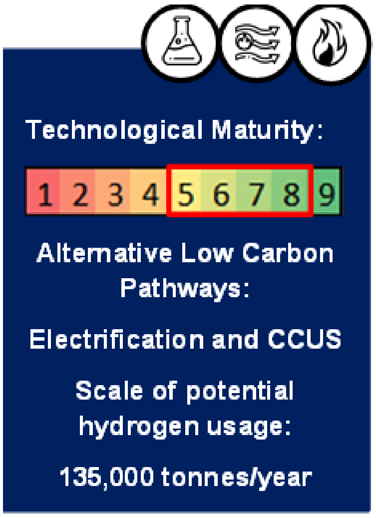
[26] Energy Consumption in the UK (ECUK): End Use Tables (BEIS). Source. The figures provided here actually refer to the 2 digit SIC *Code 23 - Manufacture of other non-metallic mineral products*, which includes other industrial sectors, such as glass.
[27] Mineral Productions Association, VDZ gGmbH, Cinar Ltd, Hanson, Tarmac, 2022, *State of the art fuel mix for UK Cement production*
[28] Mineral Products Association, Cinar Ltd, VDZ gGmbH, 2019, *Options for switching UK cement production sites to near zero CO2 emissions*
[29] A measure of how well a flame emits thermal radiation
[30] "Solid Recovered Fuel" is supplied by Hamilton Waste and Recycling to Dunbar Works, with no residual waste produced on consumption – Tarmac, 2019, *Tarmac Sustainability Report*

3.2 Oil and Gas Refining



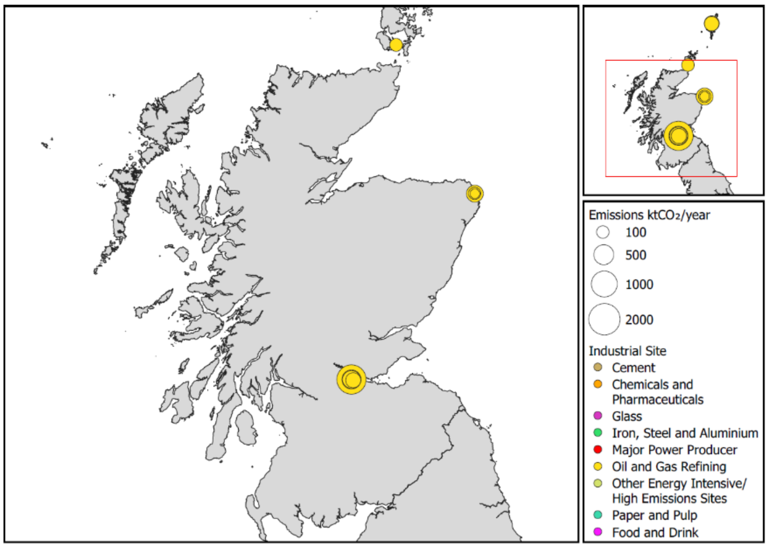


Figure 13: Map showing oil and gas refining sites in Scotland

Refining processes are one of the most significant contributors to Scottish industrial emissions. The sector's emissions are mainly from the Petroineos refinery in Grangemouth, but also from upstream oil and gas terminals such as Kinneil at Grangemouth and Sullom Voe in the Shetlands. In these terminals, there are a variety of processes requiring power and heat, such as fractionation and heating of crude hydrocarbons[31].

Fossil fuels such as oil and natural gas are used both as a feedstock and an energy source in refineries. A range of processing steps take place, including distillation, cracking, reforming, and treating, most of which have high process heating and steam energy requirements. High temperature indirect heat, produced by natural gas fired furnaces, accounts for approximately 45% of the energy requirements in this sector. A combined heat and power (CHP) plant is also used to produce steam and electricity for consumption in the Grangemouth cluster, whilst upstream of the refining plant gas turbines are used to power pumping stations at the Kinneil Terminal to transport crude oil to the complex.

Hydrogen is already used in vast quantities in refineries. Typically, hydrogen is produced on site through steam methane reformation (SMR) from natural gas. This grey hydrogen production can be abated using CCUS (becoming blue hydrogen), or it can also be displaced using green hydrogen, though this will depend on the flexibility of operational processes in the refinery and security of supply of green hydrogen[32]. Equally, refineries usually have some process emissions, the abatement of which would require adoption of CCUS.

As a result, the extent to which hydrogen is employed to meet energy uses can depend on refinery-level decisions to also use other decarbonisation pathways, e.g., CCUS. Nonetheless, there is an opportunity to fuel-switch high temperature process heating requirements in a refinery which are met with fossil fuels, including use in heaters, boilers and CHPs providing power and indirect steam. Electrification is also an alternative for some of these processes. It is worth noting that fuel switching to hydrogen to meet energy needs would require a significant review of incumbent equipment, such as integrated CHP plants.

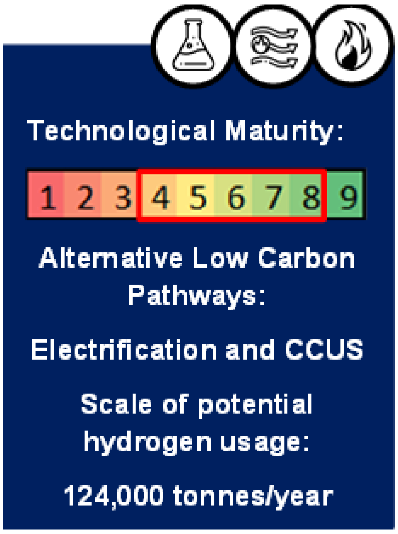
Blending hydrogen with the hydrocarbon fuels currently used for heating could minimise the need to replace equipment (such as natural gas fired furnaces) in the short term, though there is a limit to how much blending is possible without replacement. Use of hydrogen as a feedstock and in refining processes is already mature,

[31] In this study, we have assumed that heaters and boilers used in the St Fergus gas terminals are not fuel switched to hydrogen, due to their proximity to Acorn CCS, and potential role to act as one of the anchor emitters for the CO_2 T&S project. Source. Accessed in March 2023.

[32] In this study, we omit displacement of the refinery's SMR grey hydrogen production feedstock from the assessment, as this process represents existing hydrogen demand. It is assumed that grey hydrogen production (whether existing or new reformer) is abated via CCS, where this decarbonisation pathway is also be used to abate emissions from internal fuel combustion in the refinery's furnaces.

with hydrogen currently produced from natural gas, **so hydrogen was assessed as having a high likelihood of uptake in this sector.**

3.3 Chemicals and Pharmaceuticals



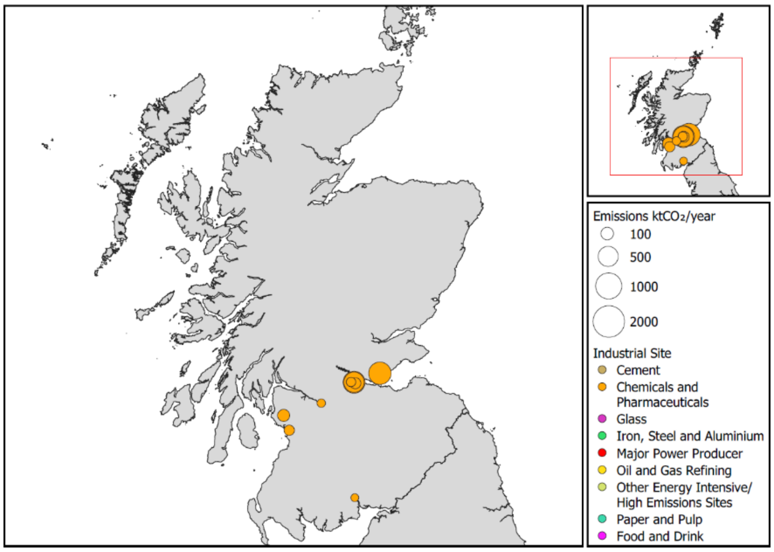


Figure 14: Map showing chemicals and pharmaceutical sites in Scotland

Chemicals (including petrochemicals) and pharmaceuticals are the second largest contributor to industrial emissions in Scotland. These industrial sites are mainly located in or close to the Grangemouth Industrial Cluster, centred around INEOS' olefins plant. ExxonMobil also operates an Ethylene plant in Fife, Eastern Scotland, whilst there are several sites located on the West Coast. The largest of these is GlaxoSmithKline's antibiotic plant in Irvine[33].

Energy usage in the chemicals and pharmaceuticals sector is dominated by use of natural gas in boilers and CHPs to provide heat and raise steam (80% of natural gas consumption[19]). Furnaces and direct fired equipment such as dryers are also important, with some processes requiring direct high temperature heat.

As per BEIS' *Energy Consumption in the UK (ECUK): End Use Tables – Table 4*, in 2019 the chemicals and pharmaceuticals sector's energy usage was 1% solid fuels, 4% oil, 55% natural gas and 40% electricity[34].

Hydrogen could be used to substitute the use of natural gas to raise steam and power in boilers and CHPs, and is also well suited to providing high temperature heat when compared to alternative low carbon pathways such as electrification. There are some hydrogen boilers operating in the sector[19], though 100% hydrogen boilers need further cross-sector demonstration and pilot projects for direct dryers and hydrogen furnaces would need to be taken forward before hydrogen fuel switching could take place. There is currently uncertainty over the use of hydrogen in furnaces for the chemicals sector.

Due to the variety of energy uses in this sector, there are several alternative low-carbon pathways, including CCUS and especially electrification to supply high temperature indirect heating. **Due to the requirements for high temperatures, the chemicals sector was assessed as having a high likelihood for fuel switching to hydrogen[35].**

[33] A site within the chemicals and pharmaceuticals sector excluded (but just below the 10,000t$CO2_e$/year threshold) include Glaxo Operations UK Limited site in Montrose.

[34] Energy Consumption in the UK (ECUK): End Use Tables (BEIS). Source. The figures provided here actually combine those of the 2 digit SIC *Code 20 - Manufacture of chemicals and chemical products* and the 2 digit SIC *Code 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations*.

[35] In this study, we assume use of hydrogen for CHP processes, as well as indirect steam from boilers. It is worth noting that hydrogen could also be used in the furnaces of the chemical and petrochemical sectors, however CCS is also a viable decarbonisation pathway for this specific subprocess.

3.4 Fertilisers

Technological Maturity:

1 2 3 4 5 6 **7 8 9**

Alternative Low Carbon Pathways:

Biomass, Electrification and CCUS

Scale of potential hydrogen usage:

Not incorporated into demand estimates

Nitrogenous fertiliser usage in Scotland was estimated at 131,000 tonnes in 2020 on a tonnes of nitrogen basis, which would correspond to a potential scale of hydrogen usage of 728,000 tonnes per year*. All fertilisers are currently imported into Scotland, with distribution and storage sites located in Scotland such as the YARA-owned liquid fertiliser storage site in Perth[36]. Imports are from domestic production in the UK from plants owned by CF Fertilisers and YARA, whilst a high proportion is also imported through UK ports from the EU, Baltic States and Russia (pre-2022).

Ammonia - a key intermediate chemical for fertiliser production – is produced by reacting hydrogen with nitrogen through the well-established Haber-Bosch process, typically carried out at 400 – 650 C. The hydrogen is currently mainly produced from natural gas through the SMR process, which also releases CO_2.

Low-carbon hydrogen produced in Scotland could be used directly as a feedstock for the Haber-Bosch process, reducing the need for on-site SMR processes and enabling the production of low-carbon fertiliser in Scotland (though this would likely have a significant price premium relative to fertiliser produced from fossil fuels that is available on the global market). It could also be used to supply process heat requirements on site, for example to achieve the high temperatures required for the Haber-Bosch process.

Few modifications would be required for externally produced hydrogen to be used as a feedstock in ammonia or other fertiliser production processes, though using hydrogen to provide process heat in agricultural product synthesis would require retrofitting or replacement of existing natural gas-based boilers. However, due to the relative ease of transporting ammonia, locating ammonia/other fertiliser plants at sites of hydrogen production could be appealing.

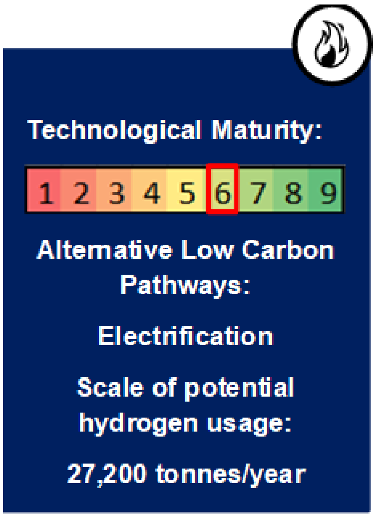
While there is potential for fertilisers to be produced in Scotland in future to meet domestic demand and for export, the current lack of domestic fertiliser production means that the hydrogen usage potential for this sector is not included in Figure 8.

Section 3.12 “Emerging uses of hydrogen” provides more details on ammonia production.

[36] YARA, https://www.yara.co.uk/about-yara/about-yara-uk/where-yara-operate-in-the-uk/

* Assuming nitrogenous fertiliser is anhydrous ammonia (which has a hydrogen content of 18%); in reality, as other compounds used for nitrogenous fertiliser will also be imported, the hydrogen usage will differ.

3.5 Glass



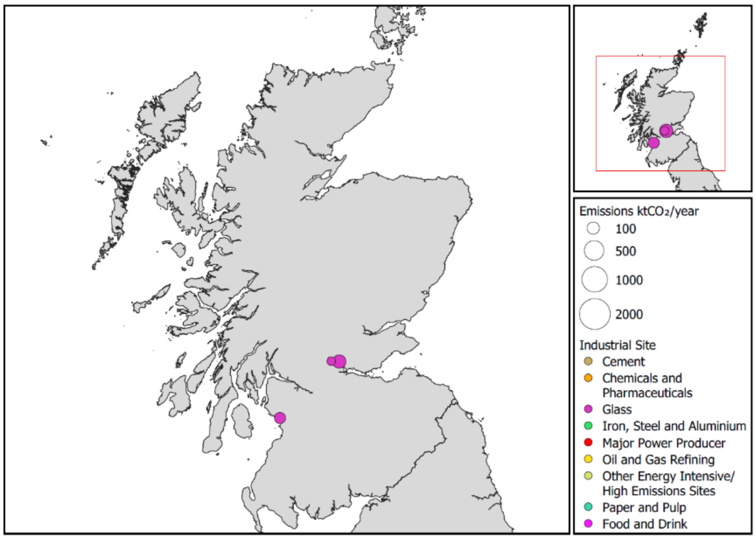


Figure 15: Map showing glass sites in Scotland

The Scottish glass industry has three large-scale sites, located at Alloa, Irvine and Stirling, with the largest plant at Alloa. These sites produce a variety of glass end products. In the glass production process, the raw materials (sand, recycled glass, soda ash and limestone) are melted in a furnace at temperatures of up to 1,600C. Raising the furnace to this temperature is the dominant requirement for heat use in the glass production process (90%). Heat is typically supplied through combustion of natural gas, though ~10% of heat is often supplied at by electricity through an 'electric boost[19] . Hydrogen could be combusted instead of natural gas to supply the high temperature heat required in the furnace. In addition to the furnace, smaller appliances used for further processing of the product (e.g., annealing lehrs and forehearths) also consume natural gas and could be replaced with hydrogen-fired appliances.

As per BEIS' *Energy Consumption in the UK (ECUK): End Use Tables – Table 4*, in 2019 the glass sector's energy usage was 20% solid fuels, 2% oil, 57% natural gas and 21% electricity[37].

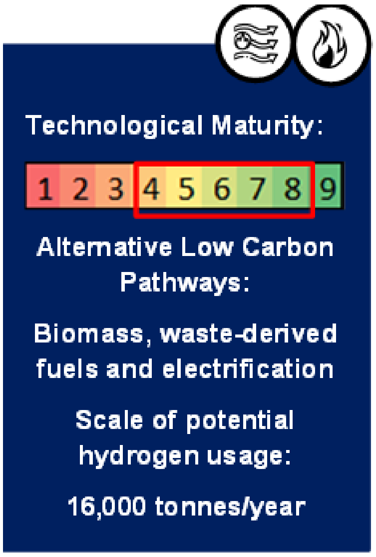
However, flame emissivity and the balance between radiative and convective heat transfer is very important in glass furnaces, so existing natural gas-based furnaces may need to be rebuilt or retrofitted. Higher flame temperatures from hydrogen may mean that different refractory materials in the furnace may be needed. However, despite these challenges a pilot project was successfully completed in the UK in 2021 at Pilkington.

Electrification is the main alternative low-carbon technology pathway, with many glass production sites worldwide using 'electric boosting'[38] to provide between 5-20% of the heat required. However, due to the high temperatures required, hydrogen is regarded as more suitable than electric heating as existing natural gas-fired equipment could be retrofitted to run on hydrogen.

Carbon capture would enable the capture of process emissions from the carbonisation reaction and well as those associated with combustion. Further, carbon capture also avoids the short-term barrier for low carbon hydrogen which is that there is insufficient supply to meet the large-scale heating needs of glass sites. However, due to the presence of high levels of impurities in the flue gas from the glassmaking process, carbon capture is particularly challenging. Hybrid furnaces can run on multiple fuels, e.g., natural gas and electricity, with future opportunities to combust hydrogen[39]. **However, due to the high temperatures required for glass making, the likelihood of switching to hydrogen was assessed as high.**

[37] Energy Consumption in the UK (ECUK): End Use Tables (BEIS). Source. The figures provided here actually refer to the 2 digit SIC Code *23 - Manufacture of other non-metallic mineral products*, which includes other industrial sectors, such as cement.
[38] Applying electric energy to a furnace through methods such as thyristors or controlled transformers
[39] British Glass, Glass sector Net zero strategy 2050

3.6 Paper and pulp



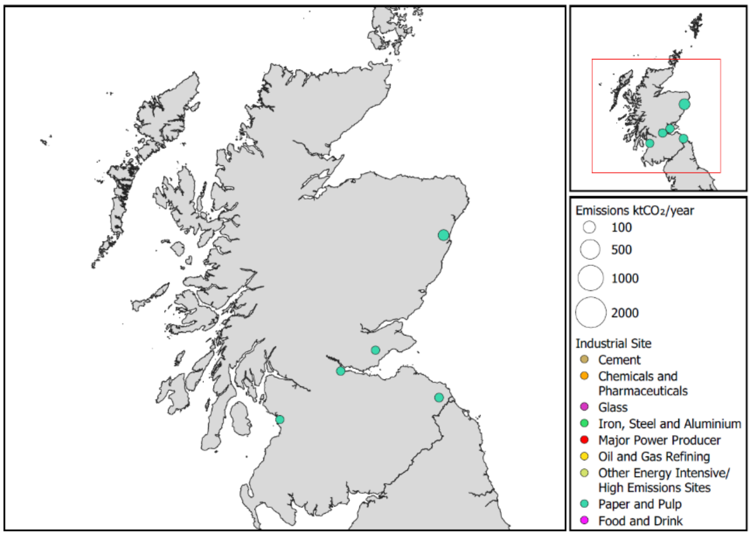


Figure 16: Map showing paper and pulp sites in Scotland

There are five paper and pulp sites in Scotland in the scope of this work, though the future of Arjo Wiggins Stoneywood paper mill is currently unclear. Other companies include UPM-Kymmene, located in North Ayrshire, and Fourstones Paper Mill in Fife. The paper industry's energy needs are mainly met through CHP plants, due to the requirements of both heat and electricity in the paper-making process. The steam and hot water generated by CHPs is used for pulping, drying, refining and finishing.

Hydrogen could be used to replace the natural gas-fired boilers and CHP units, which account for 87% of the consumption on site[40]. The remaining 13% of the total natural gas consumption in the paper production process is in direct fired dryers, which could also be replaced by hydrogen-fired dryers.

As per BEIS' *Energy Consumption in the UK (ECUK): End Use Tables – Table 4*, in 2019 the paper and pulp sector's energy usage was 6% solid fuels, 3% oil, 34% natural gas and 58% electricity[41].

However, equipment in the paper sector is unlikely to be ATEX[42] compliant and so will require additional retrofitting before it can be run on hydrogen. Paper production processes are typically run continuously at close to full capacity, which would make fuel switching more difficult and disruptive, whilst there are also technical challenges around hydrogen's flammability, energy density, and its propensity to leak.

Using hydrogen to provide both heat and power poses issues around energy losses and costs when compared to alternative low-carbon pathways, such as biomass, biogas, and electrification. Biomass is a proven source of energy for the paper sector, with many sites having moved to biomass and waste-derived fuels to reduce emissions. However, there are issues around supplies of sustainable biomass in the UK, and the UK Government has announced that they will be prioritised for sectors that do not have other viable fuel sources.

Biogas can be produced on site using site process waste, though the relative sizes mean that anaerobic digestion could only provide less than 10% of mill energy needs[43], so biogas is not likely to play a significant role in decarbonising paper and pulp production. Electrification is regarded as well suited for supplying heat for paper production, though there are issues around cost and the requirement to scale up the electrical connections at paper mills for widespread electrification. **Despite this, because of the requirements of both heat and electricity on site, the sector is considered less likely to fuel switch to hydrogen.**

[40] Element Energy, 2020, *Hy4Heat: Conversion of Industrial Heating Equipment to Hydrogen*
[41] Energy Consumption in the UK (ECUK): End Use Tables (BEIS). Source. The figures provided here refer to the 2 digit SIC Code *17 - Manufacture of paper and paper products*.
[42] European Directives for controlling (Atmosphères Explosives in French),https://www.hse.gov.uk/fireandexplosion/atex.htm
[43] UK Paper Sector Decarbonisation Roadmap – Technical Update, 2022, https://thecpi.org.uk/library/PDF/Public/Publications/Position%20Papers/PP_2050RoadmapFeb22.pdf

3.7 Distilleries

Technological Maturity:

1 2 3 4 5 6 **7** 8 9

Alternative Low Carbon Pathways:

Anaerobic digestion, biomass and electrification

Scale of potential hydrogen usage:

42,000 tonnes/year

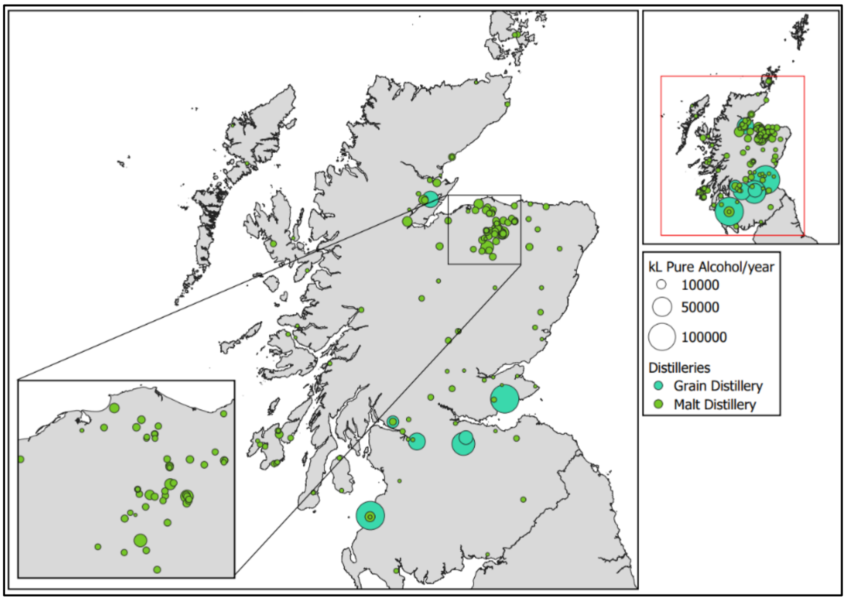


Figure 17: Map showing malt and grain distilleries in Scotland, grouped by litres of pure alcohol (LPA) production capacity.

Scotland is home to over 140 malt and grain distilleries[44] of varying output, distributed widely across both rural and urban areas[45]. Generating heat for distillation is a key emissions source in the whisky subsector, with the energy demand normally met through fossil fuels, e.g., fuel oils in the case of remote or island sites or natural gas for those connected to the network[48]. Heat is typically low-grade steam, which is produced using steam boilers and used for distillation; direct firing is not as common anymore.

As per BEIS' *Energy Consumption in the UK (ECUK): End Use Tables – Table 4*, in 2019 the distilleries' energy usage was 1% solid fuels, 4% oil, 61% natural gas and 34% electricity[46].

Because of the large number of distilleries, they are grouped based on their litres of pure alcohol (LPA) production capacity. There are 26 large sized (above 5m LPA) distilleries, 72 medium sized (between 1-5m LPA) and 40 small sized distilleries[47].

Hydrogen could be used to provide the heating requirements for distillation within the whisky production process, using hydrogen boilers. Net zero pathways modelled by the Scottish Whisky Association found that hydrogen would have a central role to play among other decarbonisation alternatives, meeting approximately 19% of emission reductions in their balanced pathway[48]. The report also emphasises that energy efficiency measures are to be prioritised first, as per the energy measure hierarchy.

Retrofitting burners in boilers would require the swapping out of an existing burner appliance with a hydrogen burner and other associated infrastructure, rather than needing a completely new heating system. This technology is already commonplace in the industry, to enable switching between different hydrocarbon fuels[49]. Further, like hydrocarbons, hydrogen is a combustible fuel, and this similarity may be perceived as being less disruptive, though engagement in Scottish Enterprise's study on Hydrogen in Scottish Distilleries report [50] found

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[44] Scotch Whisky Association, Distillery Map, *https://www.scotch-whisky.org.uk/discover/distillery-map*
[45] Unlike for other sector maps, the distilleries maps does not show size of emissions per site as the dataset used does not include this information (i.e., website referencing the Scotch Whisky Industry Review 2021 includes litres of pure alcohol production, LPA).
[46] Energy Consumption in the UK (ECUK): End Use Tables (BEIS). Source. The figures provided here actually refer to the 2 digit SIC *Code 11 - Manufacture of beverages*.
[47] Information from Whisky Invest Direct: Malt Whisky Distilleries in Scotland and Grain Whisky Distilleries in Scotland. Both sources accessed in March 2023.
[48] Scotch Whisky Association, 2020, Net Zero Report, *https://www.scotch-whisky.org.uk/media/1731/swa-net-zero-report-2020-exec-summary.pdf*
[49] HySpirits 2, 2021, *Green Distilleries Competition Public Report*

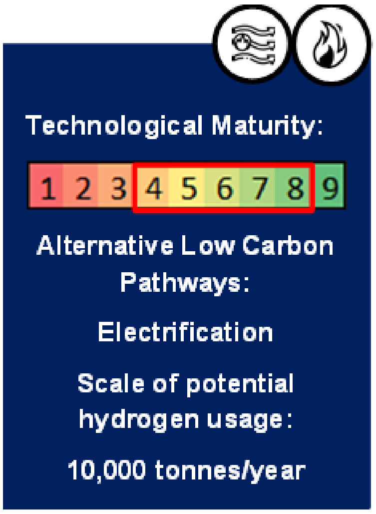
that purchasing a new boiler is sometimes more cost effective than retrofitting for distillery operators (this can depend on the age of the existing asset).

However, hydrogen distribution has been flagged as a key barrier to deployment of hydrogen technologies in the whisky sector, due to the remote nature of many distilleries. Hydrogen-based technologies in the whisky industry are also relatively immature, but the Green Distilleries Competition has funded the testing of hydrogen burner prototypes in operational environments and innovative on-site hydrogen production technologies.

Alternative low carbon technologies include anaerobic digestion, biomass, and high temperature heat pumps. Anaerobic digestion could be used to produce biogas from co-products from the whisky process, which could then be converted to generate heat and/or power. Anaerobic digestion plants already exist in the sector, including both smaller systems serving a single distillery and larger operations processing by-products from multiple sites[48]; however anaerobic digestion systems need to be very precisely designed due to sensitive to the feedstock used. Biomass is similarly widely adopted across the sector, though heat supplied cannot be ramped up and down as quickly as a gas heating system, implying that biomass is better suited to distilleries with a constant demand. Electrification technologies such as heat pumps could also be used to raise steam, though commercial scale demonstrator projects have not yet been implemented in the sector. Electrification of heating for distilling may be favourable in areas where distilleries are connected to a grid that can absorb the additional needs. Overall, however, the Scottish Whisky Association has concluded that **hydrogen will have a key role to play in the decarbonisation of the sector so it is highly likely that at least 20% of the assessed potential will be met through hydrogen (see Appendix - Methodology).**

A deeper techno-economic analysis is available in Scottish Enterprise's Hydrogen in Scottish Distilleries report[50].

3.8 Food and drink (exc. Distilleries)



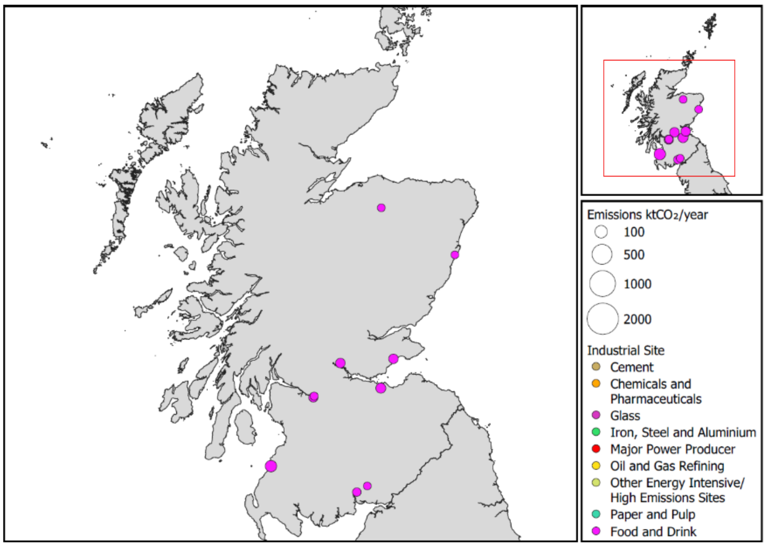


Figure 18: Map showing F&D in Scotland

Within the food and drink (F&D) industry, there are wide range of processes with different heating requirements, with hot water and steam production among some of the most important sources of heat. Large sites in this sector include Dundas Chemical Company in Dumfries, which produces salmon oil and hydrolysate from salmon, and the Arla Foods creamery in Lockerbie, which produces cheese and dairy products[51]. Energy demand in the food and drink sector is typically met through natural gas-based boilers and CHPs (~70% of gas consumption), although a significant proportion of electricity is also consumed in the sector [52]. Steam was modelled as accounting for 71% of the total energy requirements in the food and drink sector. Indirect heating

[50] Scottish Enterprise & Ricardo, 2023, *Hydrogen in Scottish Distilleries*
[51] Some sites within the food and drink sector excluded (but just below the 10,000tCO_{2e}/year threshold) include The Caledonian Cheese Company Limited site in Stranraer, and Dundas Chemical Company (Mosspark) Limited's site in Motherwell and Nestle's site in Girvan.
[52] Element Energy, 2020, *Hy4Heat: Conversion of Industrial Heating Equipment to Hydrogen*

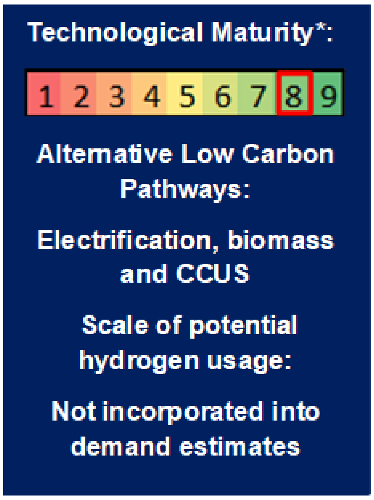
requirements in the F&D sector (e.g., producing steam in boilers) could be met by hydrogen-fired appliances, though the applicability of this to different processes and appliances will likely vary significantly. Direct heating needs in the sector (e.g., ovens, dryers) could also be met through hydrogen-fired appliances and are currently being explored in projects funded through the Industrial Fuel Switching Programme[53].

As per BEIS' *Energy Consumption in the UK (ECUK): End Use Tables – Table 4*, in 2019 the food and drink's energy usage was 1% solid fuels, 4% oil, 61% natural gas and 34% electricity[54].

However, equipment is very specific in the F&D industry, due to the large range of bespoke products and production processes, which may limit the potential for hydrogen fuel switching. There are also strict quality standards so testing may be required on a product-specific basis for direct hydrogen-fired equipment. Legacy equipment in the sector is likely to have fuel switched multiple times across its lifetime, so converting these pieces of equipment may be technically or economically prohibitive[19]. Due to the large number of small sites and appliances across the sector, deploying hydrogen across the whole sector could also be more expensive than alternatives due to the cost of transportation and supply infrastructure[52].

Alternative low-carbon technologies are mainly electric-powered appliances, such as inductive heating, advanced ovens, and e-boilers, though alternative fuels and renewable heat could also be used to provide low-carbon heat in the sector. Electrification of heat has been highlighted as one of the most important options available for the F&D sector to decarbonise its provision of low-grade heat, whilst biomass was also cited as having significant potential, especially as feedstock availability for biomass is considered less of a barrier than in other sectors[55]. The main barriers to electrification and biomass are the reliability of new appliances and their potential impacts on product quality (for direct heating applications)[56]. **Due to the opportunities for electrification and the large number of bespoke products and production processes in the sector, food and drink was assessed as less likely to rely on hydrogen as its main decarbonisation pathway.**

3.9 Power Generation



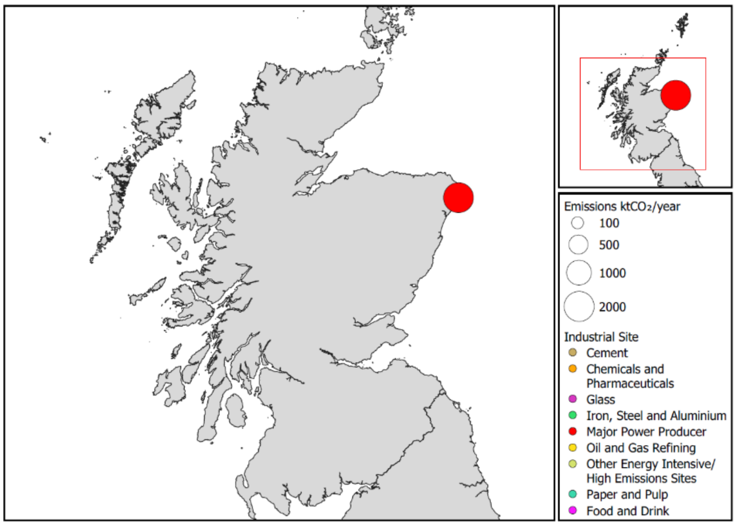


Figure 19: Map showing the Power Generation sites in Scotland

[53] BEIS, 2022, *Industrial Fuel Switching Programme, Phase 1 summaries of successful projects*
[54] Energy Consumption in the UK (ECUK): End Use Tables (BEIS). Source. The figures provided here actually combine those of the 2 digit SIC *Code 11 - Manufacture of beverages* and the 2 digit SIC *Code 10 - Manufacture of food products*.
[55] Department of Energy and Climate Change, 2015, Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Food and Drink
[56] Food and Drink Europe, 2021, Decarbonising the European Food and Drink Manufacturing sector
* TRL 8 applies to turbines using hydrogen blends, but large-scale application of pure hydrogen is at a lower TRL. As highlighted in Hy4Heat, there is existing evidence of the use of hydrogen in gas turbines, with Siemens and BHGE having supplied hydrogen-fired turbines.

Fossil fuel power stations play a role in providing dispatchable electricity. Scotland has one large gas-fired power station, located at Peterhead[57].

Hydrogen could be used to fuel turbine(s) in power stations to generate electricity at times of grid stress. As hydrogen is well placed for long-duration energy storage compared to other forms of energy storage (e.g., batteries), hydrogen power plants could play an important role alongside variable renewable energy, producing electricity as a flexible power generator. An important barrier to use of hydrogen in power generation is the need to access large-scale hydrogen storage (e.g., geological storage in salt caverns, which is limited in Scotland), as power plants can operate in an intermittent manner not necessarily in sync with the hydrogen production facility.

Some existing gas turbines can operate with hydrogen blends and could be converted to run solely on or with high blends of hydrogen with some modifications. There is existing evidence of the use of hydrogen in gas turbines, with Siemens and BHGE having supplied hydrogen-fired turbines.

Alternative low-carbon power sources include biomass, renewables and natural gas with CCUS. Renewables cannot provide a 'peaking plant' capacity, but when combined with energy storage they could provide dispatchable power. If Peterhead Power Station was switched to run on hydrogen this would require 8,500 GWh of hydrogen per year[58]. However, CCUS is currently being explored to decarbonise its operations[59], so **it is unlikely that power generation will be a source of large-scale hydrogen demand unless marked changes in strategy occur**. This potential has therefore been excluded from the aggregated demand figures.

3.10 Non-residential heating

Technological Maturity:

1 2 3 4 5 6 **7** 8 **9**

Alternative Low Carbon Pathways:

Electrification

Scale of potential hydrogen usage:

3,000 tonnes/year

Non-residential buildings comprise the office, retail, industrial, health and hospital subsectors; in this study crematoria, universities and hospitals were selected as the Sectors of Interest. It is estimated that natural gas makes up ~50% of all non-residential heating fuel supply in Scotland[60], with heat supply presenting the largest opportunity for hydrogen use. Large-scale deployment of hydrogen for heating in buildings would see hydrogen boilers displacing natural gas boiler technology, though domestic and commercial heating is identified as a low priority use in the Hydrogen Hierarchy[8].

There is also potential for hydrogen to be used either as the primary source or as a back-up / top-up source of heat for district heating networks (again, displacing natural gas in larger-scale boilers). However, district heating is a relatively small share total heat supply in Scotland.

As per the Draft Energy Strategy and Just Transition Plan[61], currently under consultation, the Scottish Government does not consider that hydrogen will play a central role in the overall decarbonisation of residential heat, favouring instead alternative low-carbon heating technologies that are more readily available in the

[57] Lerwick Power Station, owned by SSE Thermal, in its current state, is nearing the end of its operational life as a full duty power station, so it was assumed to be out of scope for this analysis. Source. Accessed in March 2023.
[58] SGN and Wood, 2021, *North East Network and Industrial Cluster Development Summary Report November 2021*
[59] SSE Thermal, 2022, *Powering the Next Generation*
[60] Scottish Government (2022): Non-domestic buildings - heating systems: research report
[61] Scottish Government (2023): Draft Energy Strategy and Just Transition Plan

immediate term. Whilst the Plan specifically references residential (rather than non-residential) heat in relation to the use of hydrogen for heating, the non-conversion of the low pressure (LP) natural gas distribution network would mean non-residential buildings would also not be able to rely on hydrogen supply from the grid.

The decision on hydrogen playing a role in heating is reserved to the UK Government and a decision may be delivered in 2026. However, the Scottish Draft Strategy and Plan also adds that there is potential, pending these decisions, for specific areas of the gas grid to be converted to 100% in the 2030s and beyond, such as such as rural island areas and Statutory Independent Undertakings (SIUs). Nearly all natural gas boilers available on the market today are "hydrogen blend ready", in that they can accept up to 20% hydrogen in fuel supply. Boilers that burn 100% hydrogen are still at safety trial stages. Network operators such as SGN are developing multiple studies on how to convert the gas distribution network of specific regions to use hydrogen, e.g., the Aberdeen Vision project.

Hydrogen fuel cells are unlikely to be practical or cost-effective in most building applications but are already being demonstrated as a solution for electricity supply to construction sites and one-off events, in place of diesel generation (discussed in Section 3.11). Heat pumps are the most likely alternative low carbon technology that could displace natural gas heating systems in non-domestic buildings.

Demand profiles

The demand profiles for non-residential buildings differ significantly between the selected site types (hospitals, universities and crematoria). The demand profiles for each are presented below[62].

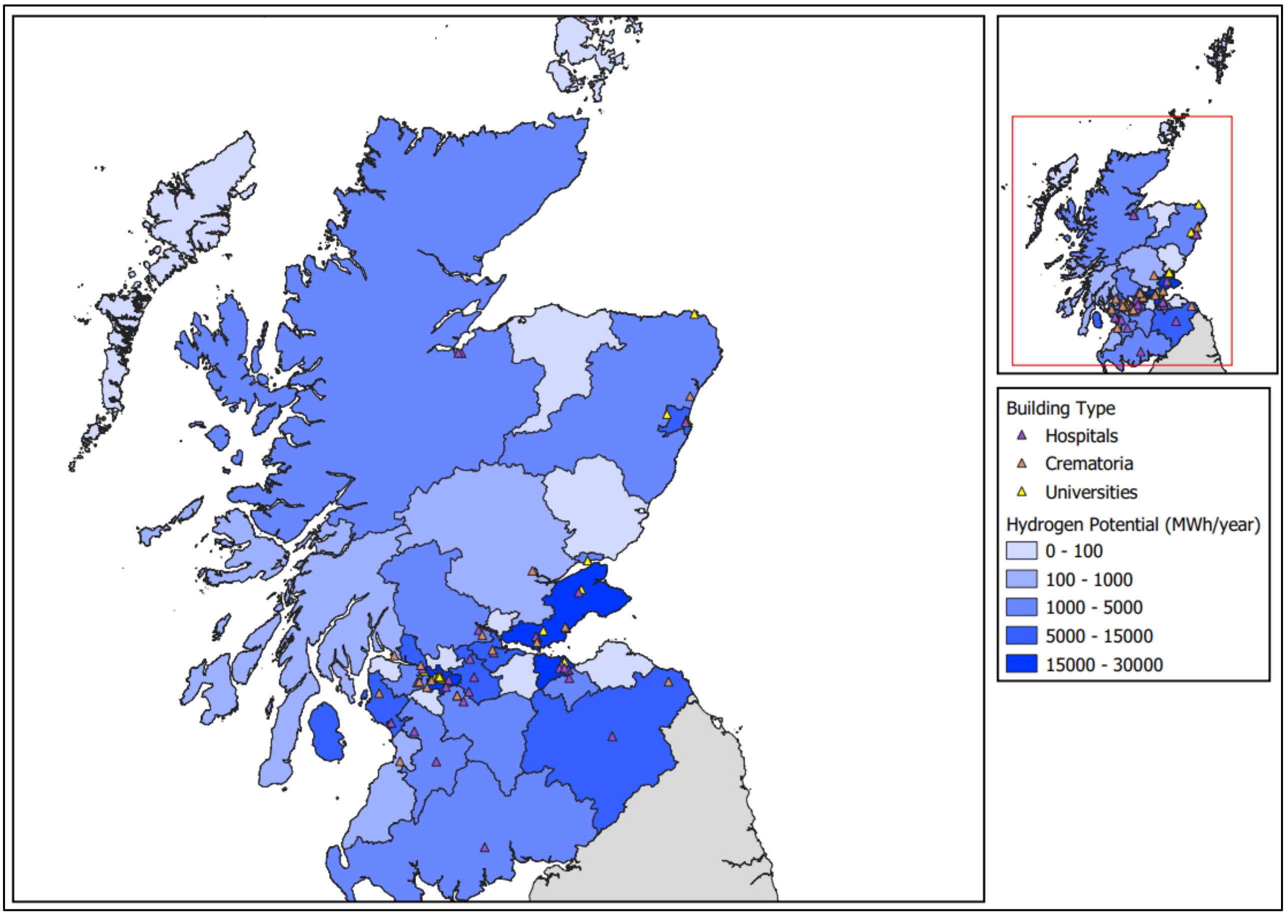


Figure 10 Heat map showing the MWh/year potential for end use of hydrogen in non-residential buildings in different Scottish Local Authorities

[62] Based on half-hourly gas consumption data for a London-based university, modified for average UK weather trends

Hospitals

In this report, the term “hospitals” is an umbrella term that captures conventional larger hospital buildings, alongside care homes and health centres. Twenty-nine hospital buildings were within the scope of this study, with a theoretical potential hydrogen usage of 97,600 MWh (2,930 tonne) per year. The distribution is presented in Figure 10.

Hospitals have typically large heat demands throughout the year and throughout the day, due to high hot water demands for sanitary purposes and the need for well-conditioned buildings in the winter (leading to high space heating consumption in these periods). Where many non-domestic buildings would have low heat demands in the summer, hospital hot water loads lead to high heat loads in this period of the year. Hospitals are therefore often seen as “baseload” type heat demands. This is generally true across conventional large hospitals, care homes and health centres.

Heat demands tend to be of a similar scale on weekdays and weekends due to the type of use these buildings receive, i.e., highly occupied throughout the week. Depending on the type of hospital, demand drops off toward the end of the day as the building becomes less occupied, however the demand for heat is spread more widely across a typical day than for other non-domestic building types, due to the large hot water load and longer occupancy hours than other non-domestic buildings.

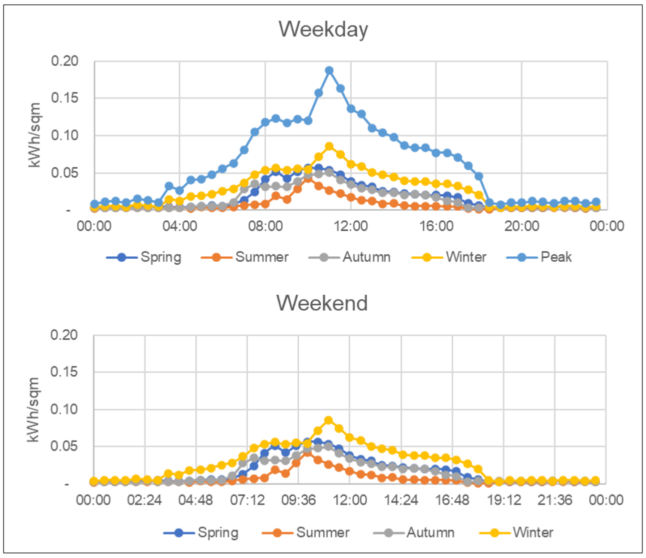


Figure 20: Weekday and weekend demand profiles for heat supply to hospitals using a hydrogen boiler

Medium and large hospitals are typically supplied with heat via natural gas-fired combined heat and power (CHP) engines, supported by natural gas-fired boilers. CHP engines can simultaneously produce a large fraction of the heat required by the hospital, supplemented by the boilers, whilst the electricity they generate can offset the need for grid imports. This is from one fuel input source (natural gas). Care homes and health centres may also be supplied heat via CHP engines supported by natural gas-fired boilers, however smaller buildings will likely only use natural gas-fired boilers due to the economies of scale available with CHP engines.

Historically, when the difference in cost between natural gas and electricity tariffs (known as the “spark gap”) has been high, and emissions associated with the UK’s electricity grid were high (due to high levels of coal-fired power supply), gas CHP engines provided a significant cost- and carbon-benefit. However, as the UK grid has continued to decarbonise, gas CHP is becoming increasingly obsolete as a carbon-saving solution to heat provision. The cost-saving aspect remains a reality, as the spark gap is still high and is likely to be so for the foreseeable future whilst natural gas is an available fuel source.

CHP is cost-effective for the generation of electricity. Thus, for an alternative combustible fuel such as low- or zero-carbon hydrogen to displace natural gas, it would need to be competitive, which is unlikely given hydrogen's high-cost production, storage and distribution methods. In addition, hydrogen-fuelled CHP engines are at a very early stage of development. However, there is ongoing R&D in this space which may coincide with the wider availability of hydrogen as a fuel in the late-2030s / mid-2040s.

Another alternative is to replace CHP engines with CHP fuel cells. These are typically marginally less efficient than CHP engines and higher in upfront cost, but can deliver a heat supply system that is most like those found in larger hospitals today. Larger hospitals are likely to be more cash-constrained and therefore more likely to invest in hydrogen boiler technology rather than fuel cell CHP, should the option of heat from hydrogen be available. For mid-to-small size hospitals, we expect hydrogen boilers to be employed as the heating technology where electrification of heat or other renewable sources were not in place.

Hospitals will come under increasing pressure to significantly reduce or eliminate direct and indirect emissions associated with energy supply over the next 10 years, with most Scottish councils having announced climate emergencies and NHS Scotland stating an aim to become net zero by 2040[63]. In choosing the heat decarbonisation measures which are most cost-effective to their site, hospitals will have to consider their electric grid connectivity against the availability of hydrogen supply. **It is expected that hospitals in locations with grid constraints which make electrification challenging, particularly the islands, could implement hydrogen solutions.**

Universities

Twenty-eight university buildings in Scotland were within the scope of this work, with a total theoretical potential hydrogen usage of 43,600 MWh (1,310 tonnes) per year. Their distribution across Scotland is presented in

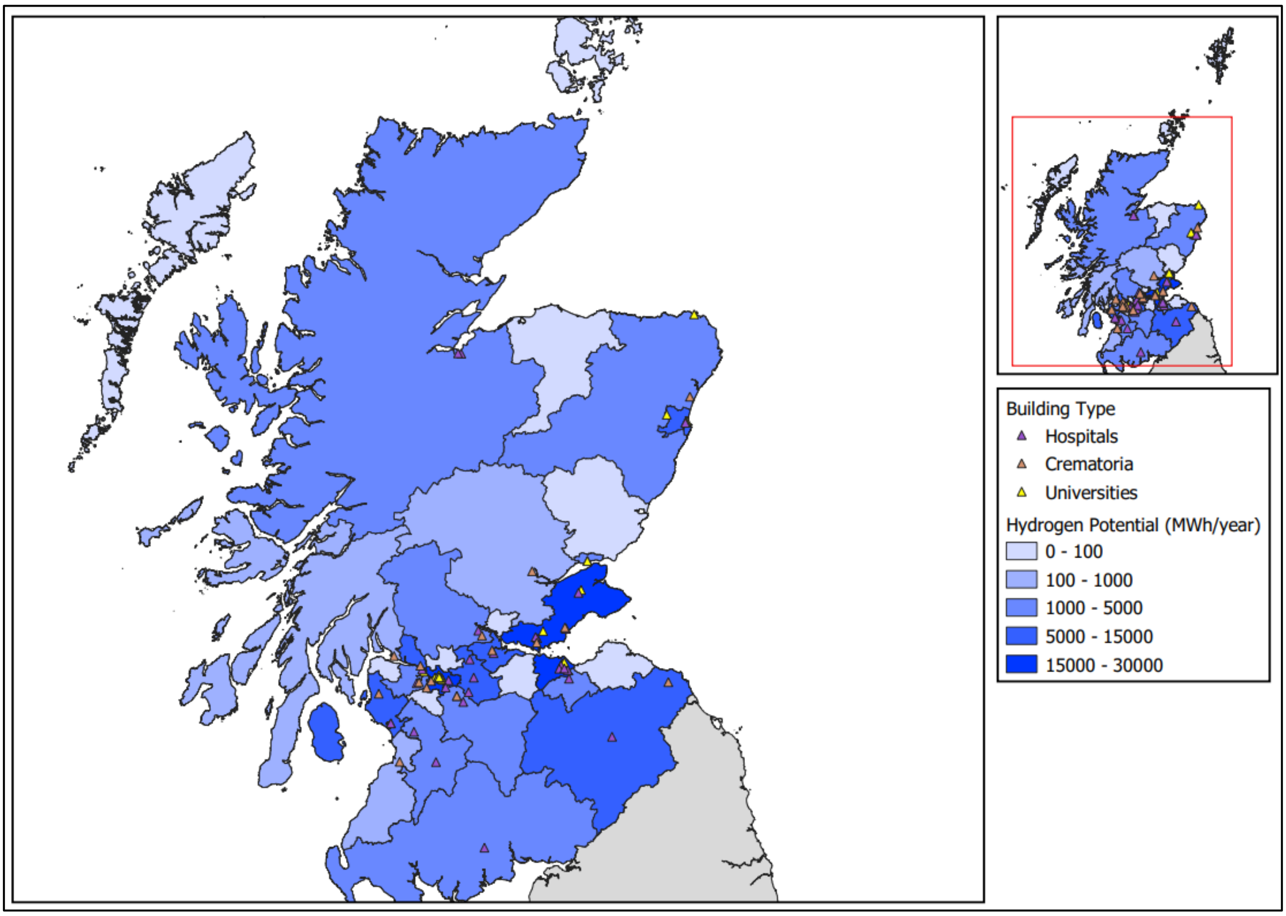


Figure 10, with the largest demand coming from university buildings in Glasgow. University heat demand is highly seasonal, due to the winter and summer holidays for students, as well as shorter breaks throughout the rest of the year. Weekends typically have significantly lower heating demands as buildings are far less occupied than on weekdays. A typical weekday heat demand profile shows a large spike when heating systems

[63] NHS Scotland (2022): NHS Scotland climate emergency and sustainability strategy: 2022-2026

are switched on at around 6-7am, after which they are continuously operating throughout the day to service the various university buildings on a given campus, switching off around 6-7pm as students leave the buildings.

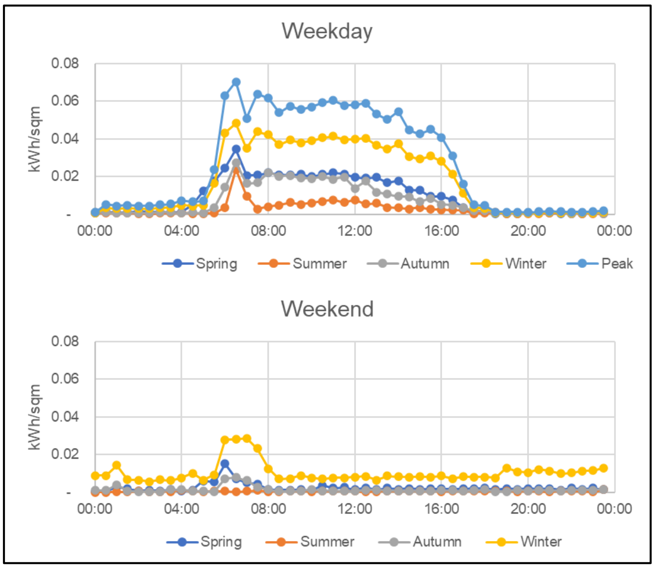


Figure 21: Weekday and weekend demand profiles for heat supply to universities using a hydrogen boiler

This type of demand profile is typical of non-domestic buildings, such as offices (which many buildings on a university campus will likely be), as well as e.g., teaching spaces, libraries, IT suites, and laboratories (which add significantly to the "top-hat" shape profile as well-conditioned spaces are required all day).

Similarly to hospitals, larger universities will typically employ natural gas-fired CHP engines as the primary heat source. The same challenges apply to universities as to hospitals, in that the revenue stream from CHP engine electricity generation is possible to replace with hydrogen fuel cell CHP, but this requires high investment and an amenable hydrogen fuel price to make the use of CHP cost-effective.

A case could be made that hydrogen boilers would be more attractive in universities than in hospitals, purely because of the heat demand profile which does not have a significant "base load". Hospitals tend to have a high base load which in theory are more suitable to CHPs. Smaller university buildings are likely to choose hydrogen boilers, should hydrogen be the preferred heat supply fuel.

In most cases however, it is expected that universities will seek alternative heat decarbonisation approaches, such as heat pumps. Similarly to hospitals, the availability of heat pump technology makes it more attractive in the short- to medium-term for heat decarbonisation purposes, whereas hydrogen fuel is unlikely to support the net zero timeframes set across much of the country to date.

Crematoria

As of 2019 there were 30 operational crematoria in Scotland[64], with a total theoretical hydrogen usage of 2,266 MWh (8 tonnes) for the 16 crematoria that were above the scale used for filtering (their distribution is presented in

[64] Scottish Government (2019): Inspector of Crematoria: annual report 2018-2019

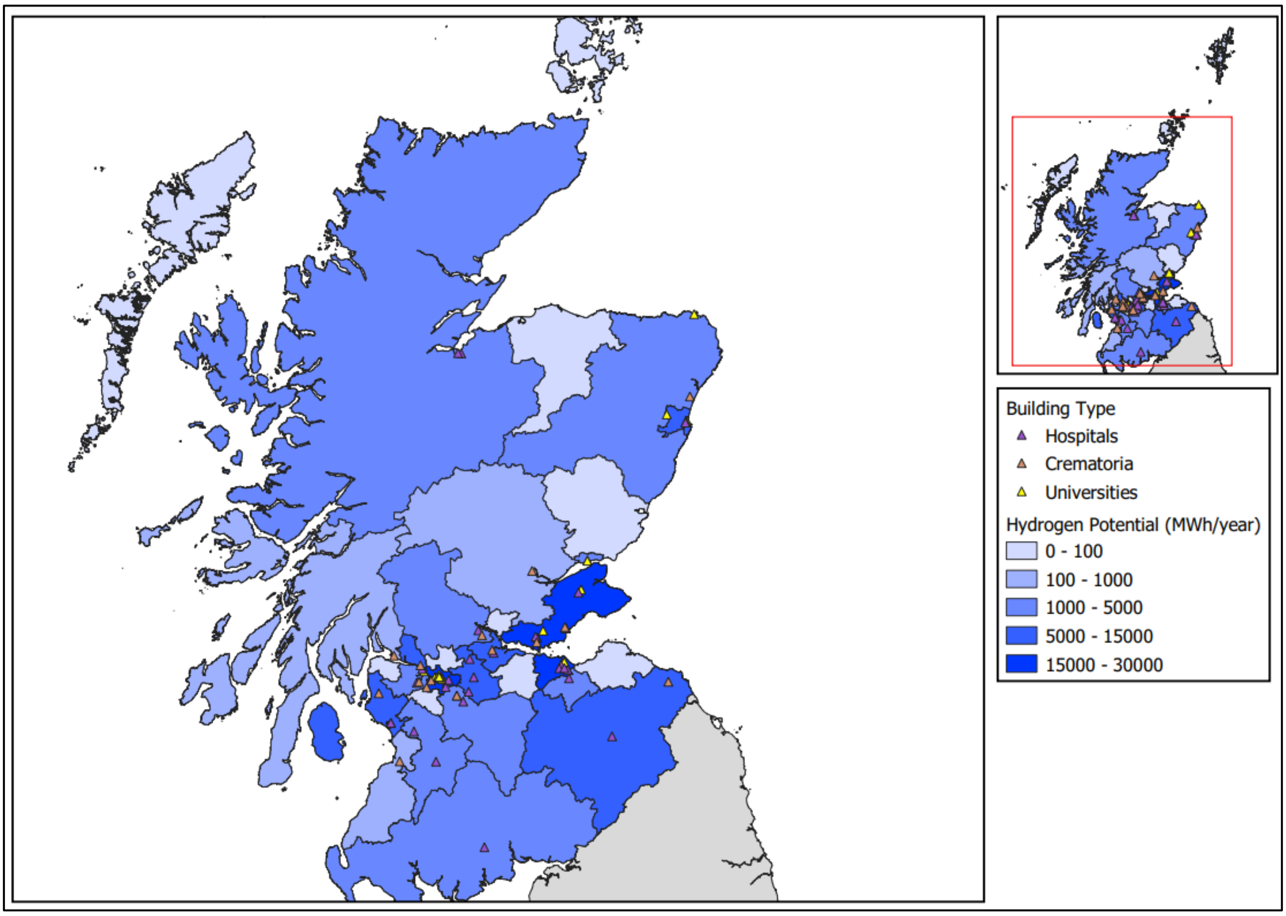


Figure 10). Although no daily demand profiles could be sourced, approximate fuel demands are available and can be used to estimate total energy consumption in Scotland. It is assumed crematoria are "on" or "off", with cremations occurring throughout the operational day.

There are two conventional methods of cremation: electric and direct fossil fuel combustion. In Scotland only one crematorium uses electricity[65]; all others use direct fossil fuel combustion, of which the majority are understood to use natural gas as the combustion fuel. It is assumed that the single crematorium using electric cremators in Scotland would not convert to hydrogen.

As with natural gas boilers, it is expected that burners and other key components of cremation equipment using natural gas would need to be replaced to allow for hydrogen combustion, however it is not clear whether a major overhaul of all-natural gas equipment would be required for conversion to hydrogen. An Australian company [66]is testing hydrogen cremators, but only blends are being investigated at the present time, with the eventual plan to investigate 100% hydrogen. This technology is not expected to be available any time soon.

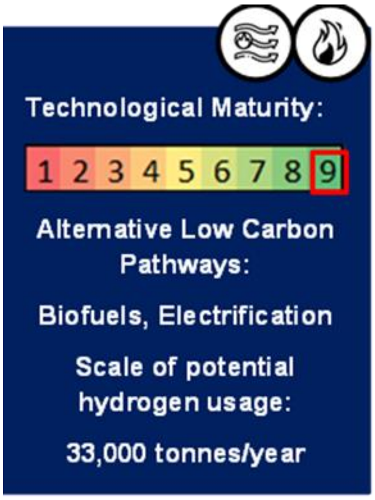
Electric cremators are an operating cost-equivalent option versus natural gas and produce at least 50% lower emissions overall per cremation[67]. As the UK grid decarbonises further, these emissions savings will become more pronounced versus natural gas. In addition, NOx emissions are significantly lower (33%) versus natural gas. With a hydrogen-fuelled cremation system, NOx emissions may remain high as fuel combustion occurs in the presence of air, therefore air quality concerns may remain with hydrogen.

Whilst on a capital cost basis electric cremators are higher cost than natural gas systems, there is currently no information on the expected cost of 100% hydrogen-fuelled systems. On an operating (fuel) cost basis, however, it could be expected that hydrogen is higher-cost due to the methods of production required for genuinely zero-carbon hydrogen. There does not appear to be specific legislation or policy for decarbonisation of crematoria, but as they are public buildings, it is assumed that they are required to meet the decarbonisation

[65] Inspector of Crematoria Scotland (2018): Parkgrove Crematorium
[66] Austeng (2022): Green hydrogen cremators
[67] Coventry University (2021): A comparison of gas and electric cremator emissions in the UK

targets set by Scottish Government for the public sector. **As a result, it is concluded that the role hydrogen could play in crematoria is limited.**

3.11 Large Events and Construction



Festivals, outdoor events, and construction sites typically use portable off-grid power generators for catering trucks, lighting towers and sound systems [68]. Currently, power generators are powered by diesel, with the UK events industry using an estimated 380m litres of diesel each year[69].

Hydrogen could be used to displace diesel generators to provide off-grid power for festivals, outdoor events, film crews and in the case of power outages in populated areas due to weather events. can also be used in non-road mobile machinery used in construction, offering quiet, uninterrupted power that only emits water. It could either be used in a fuel cell generator or directly combusted in a similar manner to diesel generators. The approach taken to estimate the scale of potential hydrogen usage from large events and construction is set out in the Appendix.

The main technical barrier facing the use of hydrogen in large events and construction is over safe and effective storage of hydrogen – to meet required energy densities, hydrogen needs to be stored at very high pressures, posing an explosive risk. However, there is regulation in place and in Scotland hydrogen generators are already being used – HebCelt's 25th anniversary festival in Stornoway used PlusZero's hydrogen generator to provide power for the Islands Stage for three days and nights. They also supplied the green hydrogen used in the fuel cell lighting towers provided by Taylor Construction Plant for the event. [68]

The main alternative technology in the events and construction sector are mobile batteries, which are charged up prior to the event through the grid or directly from renewable sources. However, these do not offer the same flexibility in power output as hydrogen generators and take a long time to recharge when compared to refuelling a hydrogen generator. Biofuels could also be used to decarbonise festivals, with traditional diesel generators able to run on biofuels with minor modifications.

There is not a clear preferred option, due to the sectors' current reliance on diesel and only small-scale adoption of alternative technologies.

[68] Hydrogen Industry Leaders, *Decarbonising the Events Sector*, https://hydrogenindustryleaders.com/decarbonising-the-events-sector-the-role-of-green-hydrogen/

[69] Hope Solutions and Zap, *A Greener Festival*, https://www.agreenerfestival.com/wp-content/uploads/UK-Events-and-Diesel-use-Factsheet.pdf

3.12 Emerging Uses of Hydrogen

Hydrogen has several new industrial applications, that are only beginning to emerge with the development of new low carbon technologies and processes. These include in the synthesis of green ammonia and synthetic hydrocarbon fuels.

Ammonia

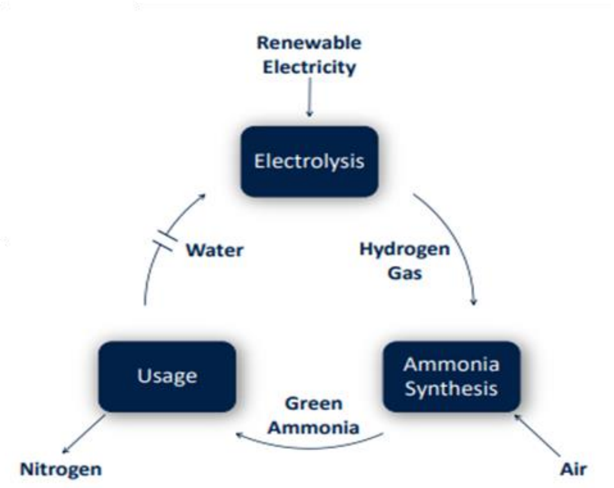


Figure 22: Simplified depiction of green ammonia production

Ammonia is currently produced from fossil fuels (e.g., steam methane reforming of natural gas), and its production from hydrogen accounts for approximately 1.8% of global carbon emissions[70], with roughly 6kg of ammonia produced per kg of hydrogen. It currently plays a key role in the production of fertilisers[70], but decarbonising fertiliser production is unlikely to lead to a substantial hydrogen demand, as ammonia is typically reacted with CO_2 sourced on site from the steam methane reforming process to form urea (a solid fertiliser).

However, ammonia is increasingly receiving interest for use as an energy storage medium, as a zero-carbon fuel and as an effective energy carrier due to its physical properties and high energy density by volume. Ammonia is easily stored in large quantities as a liquid in modest conditions (typically 10-15 bar, -33 C) compared to hydrogen, so could enable large scale energy storage and international trading of low carbon energy. It can be used in fuel cells or internal combustion engines, and so has received significant interest as a maritime fuel, although significant uncertainties remain on whether international regulation will be created to allow its use as a fuel due to its highly toxic properties.

[70] Royal Society, 2020, Green Ammonia Policy Briefing

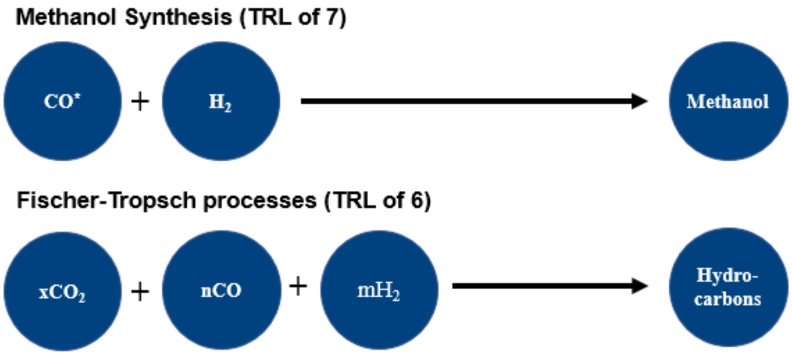


Figure 23: Chemical reactions to produce e-methanol and synthetic hydrocarbon fuels

Synthetic hydrocarbon fuels

Synthetic hydrocarbon fuels (e.g., e-methane, e-kerosene and e-methanol) have been described as critical to the decarbonisation of parts of heavy industry and long-distance transport, such as aviation[71]. Hydrogen-based fuels demand from UK domestic and international shipping has been estimated to be 75 – 95 TWh annually by 2050 (though this is principally in the form of ammonia)[72].

In Scotland, the oil and gas refining and the petrochemicals sectors currently produce and consume hydrogen on-site and emit CO_2 in large quantities. As shown in Figure 23, CO_2 and hydrogen are key feedstocks to produce synthetic hydrocarbons, highlighting the potential for these sites to become early producers of these low-carbon commodities.

Hydrogen is a key feedstock for the production of e-fuels, with a variety of synthesis pathways involving reactions with carbon dioxide and/or monoxide. Common processes[73] include a) methanol synthesis and b) Fischer-Tropsch reactions. E-fuels synthesis pathways are typically very energy intensive and so should be run using renewable energy to minimise carbon emissions. Although Fischer-Tropsch synthesis processes have been fully commercialised and used at a global scale to produce a variety of hydrocarbon products, most of these operational facilities use non-renewable feedstocks and emit CO_2. Fischer-Tropsch technologies that use renewable CO_2 routes have a lower technological maturity, so synthesis using utilisation of carbon dioxide is considered much less technologically mature.

3.13 Markets for Hydrogen Production By-Products

Different hydrogen production technologies result in the formation of by-products, which can be valorised if these by-products can be sold to offtakers.

Oxygen

Oxygen is one of the by-products of water electrolysis, and is currently the second largest used industrial gas[74] (by volume), with a variety of industrial uses:

- **Water Treatment:** Oxygen is used in industrial and municipal wastewater treatment plants, to encourage the growth of bacteria used in secondary treatment.
- **Food and drink:** Oxygen is used as an oxidizing agent for some food products and is also uses to retain freshness of vegetables by improving breathing rates.
- **Horticulture:** Oxygen can be used in greenhouse and hydroponic operations to improve dissolved oxygen content of water, which is required for plant respiration.

[71] International Energy Agency, 2022, *Low-Emission Fuel Supply*
[72] Department for Business, Energy and Industrial Strategy, 2021, Hydrogen Analytical Index
[73] Royal Society, 2019, Synthetic Fuels Briefing
[74] GZ Supplies, *Industrial Benefits of Oxygen Gas,* Industrial Benefits of Oxygen Gas - GZ Industrial Supplies (gz-supplies.com) https://www.gz-supplies.com/news/industrial-benefits-of-oxygen-gas/v

- **Aquaculture:** Oxygenation of water in aquacultures is used to increase productivity and to promote the health and stock density of fish farms[75]
- **Manufacturing Sector:** Liquid oxygen is a key material to produce steel, paper, glass, chemicals, and pharmaceuticals.
- **Space Sector:** Scotland is one of the best places in the UK for launching satellites, with five spaceports in development[76]. Oxygen is crucial to for many launch systems as it is used to oxidise the engine fuel. Many large rockets make use of hydrogen fuel, though there are not any clear plans to use hydrogen fuel in Scottish spaceports, though there are some rockets planned for deployment in Scotland[77] (the Orbex rocket and Rocket Factory Augsburg) which will use liquid oxygen and so could lead to a small demand for oxygen. Lastly**,** industrial and agriculture pollution of waterways can lead to dissolved oxygen depletion. Oxygen is essential to aquatic life, so oxygen from electrolysis could be used as natural capital in aeration systems to address water pollution[78], though this is still an emerging and uncertain application.

Whilst there are many use cases for oxygen, the ease of transporting liquid oxygen on a large scale is currently unclear and stakeholders cited issues about finding industrial uses of the scale that could be that would be co-located next to electrolytic hydrogen production. The complexity of including this in 'first of a kind' projects means that developers are focused primarily on hydrogen production, with opportunities to explore uses of oxygen in the future.

Carbon Dioxide

CCUS-enabled hydrogen production results in a pure stream of CO2 , with 8-12 kilograms produced per kilogram of hydrogen through the steam reforming of natural gas. Globally, an estimated 230 MtCO2 are used annually79, predominantly to produce urea and for enhanced oil recovery, though it has other uses in the food and drink, manufacturing, and horticulture sectors. The UK market for CO2 in 2016 was estimated between 400-500kt CO2/year80. Tata Chemical Europe's sodium bicarbonate plant at Winnington has been identified as one of the major CO2 offtakers in the UK. A range for estimated demand for CO2 in 2030 is presented in Figure 24, though stakeholder engagement suggested that the market for CO_2 will mainly be from biogenic sources rather than industrial emissions.

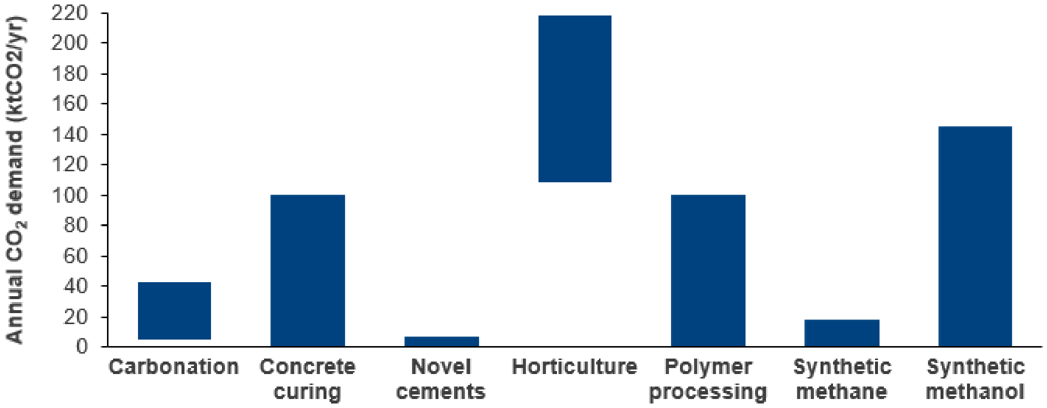


Figure 24: Range of assessed UK demand for CO_2 in 2030, by selected end uses

CO_2 utilisation differentiates between multiple grades of CO_2: industrial, and food and beverage grades. Each of these grades must conform to specific industry standards, although the exact specifications can vary between suppliers. Generally, industrial grade CO_2 has a purity of >99%, while food and beverage grade CO_2 has a purity of >99.98%. There are a range of processes in development that could use CO_2 in the future.

[75] Linde Gas, Oxygenation in Aquaculture, *https://www.linde-gas.com/en/processes/controlled_and_modified_atmospheres/oxygenation_in_aquaculture/index.html*
[76] Uk Government, Delivering for Scotland: Spaceports, https://www.deliveringforscotland.gov.uk/levelling-up/spaceports/
[77] Orbex Prime https://orbex.space/ and Rocket Factory Augsbury https://www.rfa.space/
[78] Environment Agency, 2020, https://www.gov.uk/government/news/green-energy-to-help-fish-suffering-effects-of-dry-weather
[79] International Energy Agency, 2019, *Putting CO2 to Use*
[80] Imperial College London & Ecofys, 2017, *Assessing the potential of CO2 utilisation in the UK*

Work conducted for ClimateXChange[81] examined the technological pathways for CO_2 utilisation that are ready to be deployed at demonstration scale, and evaluated technologies identified as particularly feasible in Scotland in depth. These include formic acid for agricultural applications, proteins for aquaculture and agriculture feed, ethanol as a chemical intermediate, or to be converted to kerosene; methanol for direct use as a shipping fuel or to convert to kerosene, synthetic fuels through the Fischer-Tropsch process, enhanced algae growth for biofuels or other value products; and nano-carbon materials for advanced engineering.

Carbon Black

Turquoise hydrogen uses pyrolysis to generate hydrogen from hydrocarbon feedstocks. Due to the absence of oxygen in the process, solid carbon (otherwise referred to as ‘carbon black’) is produced instead of CO_2. Solid carbon has a variety of potential and existing uses, due to its unique physical properties, and is one of the top 50 industrial chemicals manufactured worldwide[82]. Over 12 Mt of carbon black are produced annually[83], and existing uses include:

- **Coatings:** Carbon black is used for insulating wires and cables, improving UV protection for internal automotive components, and providing jetness (i.e., how deep a black coating looks).
- **Rubber and plastics:** Carbon black provides colour, UV protection and conductivity to plastics, and is also used in tyre manufacturing.
- **Batteries:** Carbon black can improve electrochemical conductivity and charging characteristics in batteries. ATME Power is planning to develop its first battery MegaFactory at Dundee, which will complement ATME’s existing facility in Caithness.[84]
- **Other process uses:** Carbon black is also used for toner and printing inks, food contact grades and in greenhouse coverings.

4 Regional Hydrogen Energy Hubs

Regional Hydrogen Energy Hubs, as defined by the Hydrogen Action Plan, are areas where a local hydrogen value chain can be developed, from production to end-use, including distribution and storage[85]. Regional Hydrogen Energy Hubs are aimed at facilitating the use of hydrogen in a variety of end-uses.

[81] ClimateXChange, 2021, *Understanding Opportunities for Developing a Scottish CO_2 utilisation economy,* *https://www.climatexchange.org.uk/media/5135/cxc-understanding-opportunities-for-developing-a-scottish-co2-utilisation-economy-february-2022.pdf*
[82] International Carbon Black Association, https://www.carbon-black.org/new-page-2
[83] Gautier et al, International Journal of Hydrogen Energy, Direct decarbonization of methane by thermal plasma for the production of hydrogen and high value-added carbon black
[84] ATME Power, 2022, ATME Power selects Dundee as preferred site for battery cell factory
[85] Hydrogen Action Plan, Scottish Government (2022)

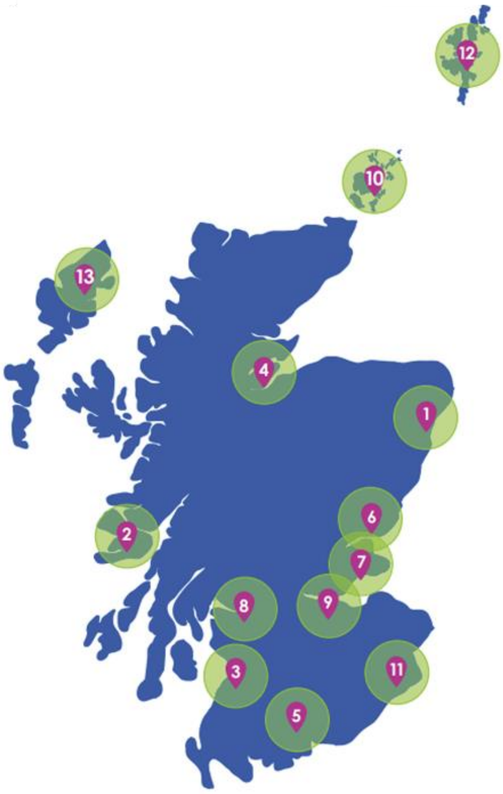


Figure 25: Map of potential regional hydrogen hub locations

The thirteen hubs are 1) Aberdeen, 2) Argyll and Islands, 3) Ayrshire, 4) Cromarty, 5) Dumfries and Galloway, 6) Dundee, 7) Fife, 8) Glasgow, 9) Grangemouth, 10) Orkney, 11) Scottish Borders, 12) Shetland and 13) Western Isles.

This chapter inspects the proposed Regional Hydrogen Energy Hubs individually and presents the sites in scope located in those developing Hubs. We also show the possible cumulative industrial and non-residential hydrogen use each Hub. Throughout this section, we extract information from Scottish Government's Hydrogen Action Plan, and use it as reference to develop the discussion.

Scottish Enterprise aims to publish the following mapping in an interactive online format alongside this report, which will also include the estimated transport demand across Scotland.

Aberdeen

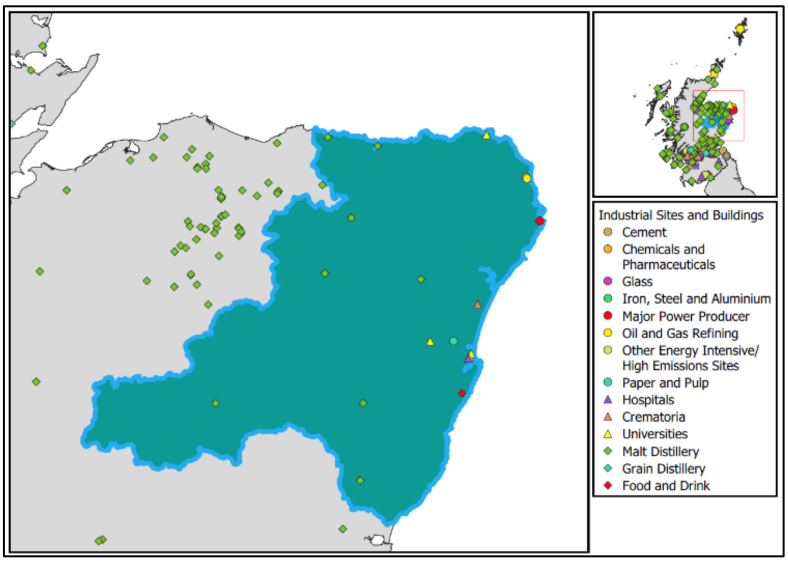


Figure 26: Map of Aberdeenshire and Aberdeen City

The Aberdeen Regional Hydrogen Energy Hub, here represented by the Aberdeen City and Aberdeenshire Local Authorities has a theoretical hydrogen energy use for industry of around 51 GWh (1,540 tonnes) per year. The Hub is home to eight malt distilleries, two food and drink sites and a pharmaceuticals site. The Hub also hosts a power plant and a paper production site. The latter, which could also use fuel switch to hydrogen, is currently in administration. The Hub is home to six university buildings, one hospital and one crematorium, totalling around 10GWh (291 tonnes) per year of possible hydrogen use. The Hub has advanced hydrogen production and use plans (both blue and green) detailed by the North East Scotland Hydrogen Ambition ($NESH_2A$) steering group[86], and enabled by energy infrastructure plans like Acorn Hydrogen and the bp Aberdeen Hydrogen Hub. It also has some of the earliest end-use examples in Scotland with functioning local authority hydrogen vehicle fleets and refuelling stations.

Argyll and Islands

Assessed industrial hydrogen use in Argyll and Bute stems mostly from use in malt distilleries. The 15 malt distilleries in the region could cumulatively amount to around 29 GWh (870 tonnes) per year of hydrogen use, and the crematorium up to 0.3 GWh (9 tonnes) per year.

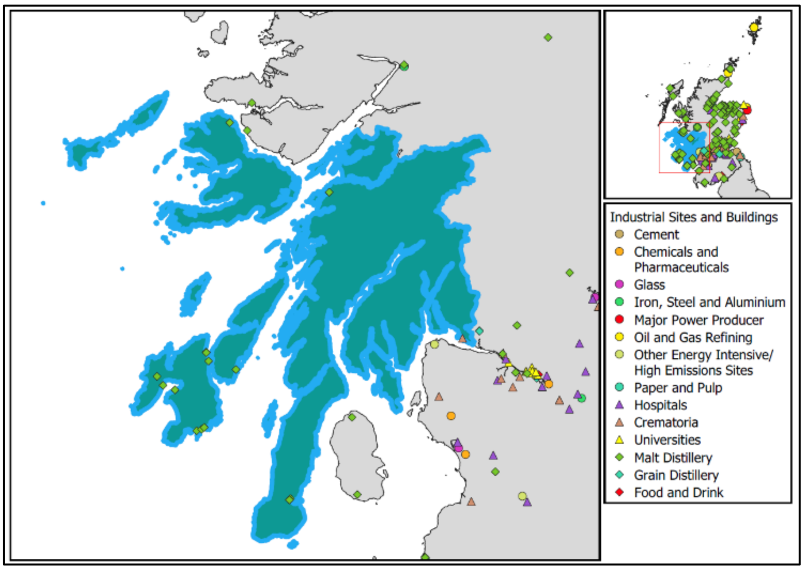


Figure 27: Map of Argyll and Bute

Distilleries in Islay face particular difficulties to decarbonise due to their island location and their lack of connection to the gas network, which requires many to receive deliveries of fuel oil by ship from the mainland. Green hydrogen production, on the island or nearby on the mainland, could provide alternatives.

Ayrshire

[86] NESHA (etzltd.com) Accessed March 2023

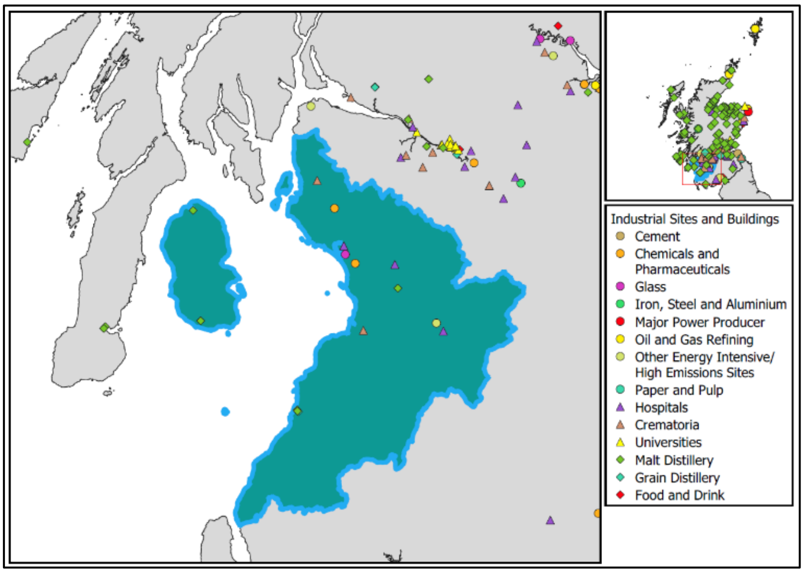


Figure 28: Map of East Ayrshire, North Ayrshire and South Ayrshire

The Ayrshire Regional Hydrogen Energy Hub is comprised of East Ayrshire, North Ayrshire and South Ayrshire for the purposes of this map. Jointly, these Local Authorities could see in the order of 1,430 GWh (42,920 tonnes) per year of potential hydrogen use in regional industries. The Hub hosts a varied range of industrial subsectors, including one grain distillery, five malt distilleries, one paper and pulp site, manufacturing of wood products, a glass site, a food and drink site and two chemicals and pharmaceutical sites. Four hospital buildings and two crematoria could use up to 13 GWh (390 tonnes) per year of hydrogen energy.

Cromarty

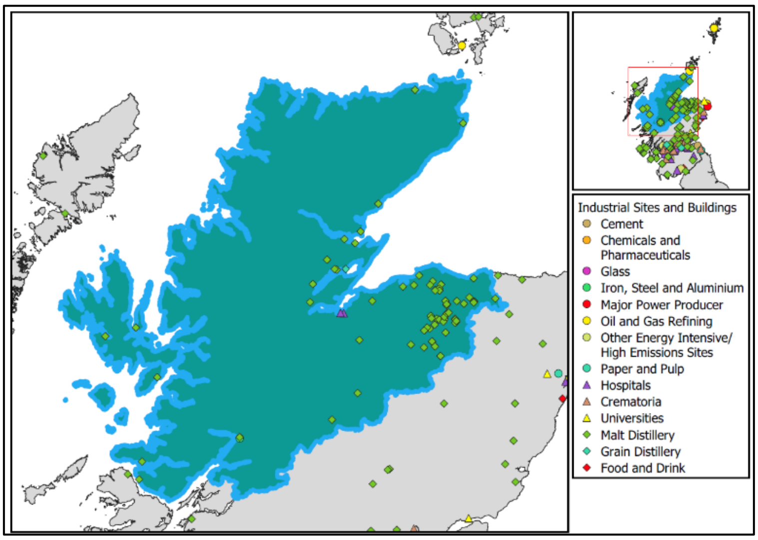


Figure 29: Map of Highlands and Moray

The Cromarty Regional Hydrogen Energy Hub is represented here by the Highlands and Moray Local Authorities to ensure full geographic coverage of Scotland. However, it is noted that Moray Council is developing separate hydrogen plans with support from Highlands & Islands Enterprise[87]. The two LAs host

[87] Moray Council (2022). Moray Council adopts hydrogen strategy

almost 80 distilleries, many clustered in the Speyside region, including a grain distillery. There is also an aluminium site and manufacture of wood products site. In total, around 500 GWh (15,010 tonnes) per year of possible hydrogen use have been assessed in industry, with an additional 3 GWh (79 tonnes) per year coming from two hospitals. The prospects to develop an Energy Hub in Cromarty are evidenced by the North of Scotland Hydrogen Programme[88] developing an end-to-end hydrogen value chain, the Inverness and Cromarty Firth Green Freeport projects and announced plans to fuel-switch local distilleries to hydrogen[89].

Dumfries & Galloway

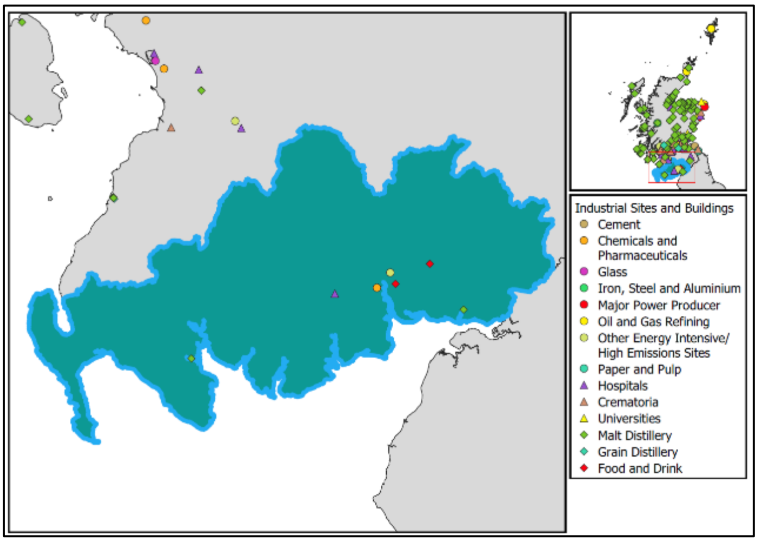
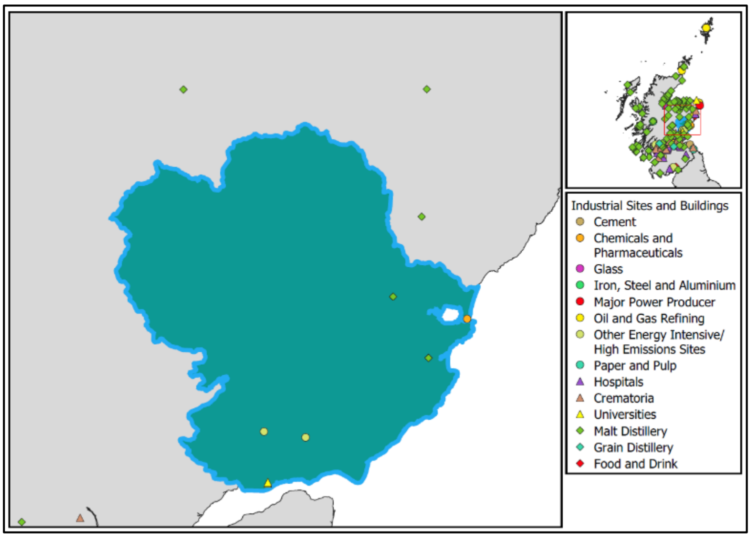


Figure 30: Map of Dumfries and Galloway

The Dumfries & Galloway Hub could potentially see 122 GWh (3,660 tonnes) per year of annual hydrogen demand within the industrial sector, coming from a variety of sites belonging to the malt distilleries and food and drink sectors, as well as two sites withing the chemicals and rubber sectors. A hospital could also use up to 4 GWh (120 tonnes) per year of hydrogen. The Hub has been characterised by its renewable energy resources and its favourable location to connect to future hydrogen distribution projects.

Dundee



[88] Green Hydrogen | Opportunity Cromarty Firth | Low Carbon. Accessed March 2023
[89] Cromarty Firth Hydrogen Plant To Boost Whisky Distillers, News Article, Accessed February 2023

Figure 31: Map of Dundee and Angus

The Dundee Regional Hydrogen Energy Hub, including Dundee City and Angus, was estimated to have a theoretical hydrogen use potential of 2 GWh (60 tonnes) per year for industry, with the potential located in the neighbouring Angus Local Authority. Most of the theoretical potential hydrogen use would be concentrated in two malt distilleries in the region, with the remaining of the potential captured by print products sites. Further, there is a potential for 3 GWh (90 tonnes) per year of use to come from a university building. Dundee has been recognised as an ideal location for hydrogen production, next to various offshore wind farms, and for its research on sustainable mobility.

Fife

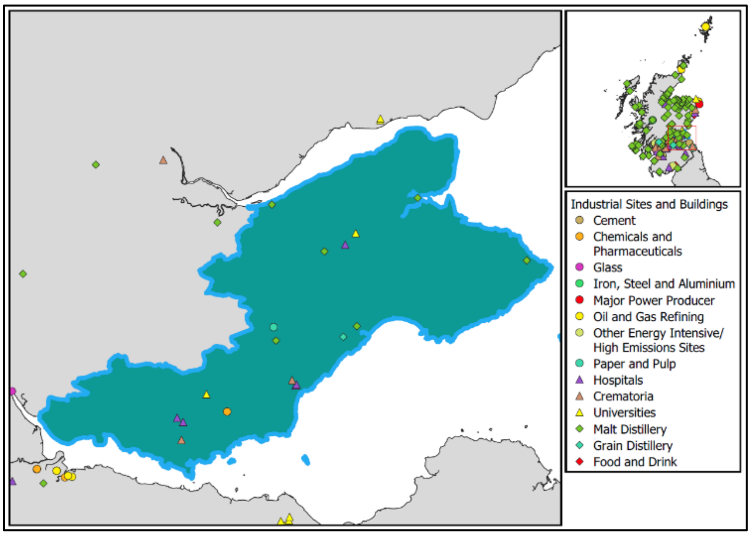


Figure 32: Map of Fife

The Fife Regional Hydrogen Energy Hub has an assessed theoretical potential hydrogen use of 1,700 GWh (51,000 tonnes) per year for the industrial sector and 24 GWh (720 tonnes) per year for the buildings sector. Within this hub, we can find a chemicals site (the Fife Ethylene Plant), the Fourstones Paper Mill, a grain distillery and six malt distilleries. There are also two university buildings, five hospitals and two crematoria. The Hub is located next to neighbouring Hubs with high potential use for hydrogen in industry, and is developing a hydrogen domestic heating trial, the H100 Fife project.

Glasgow

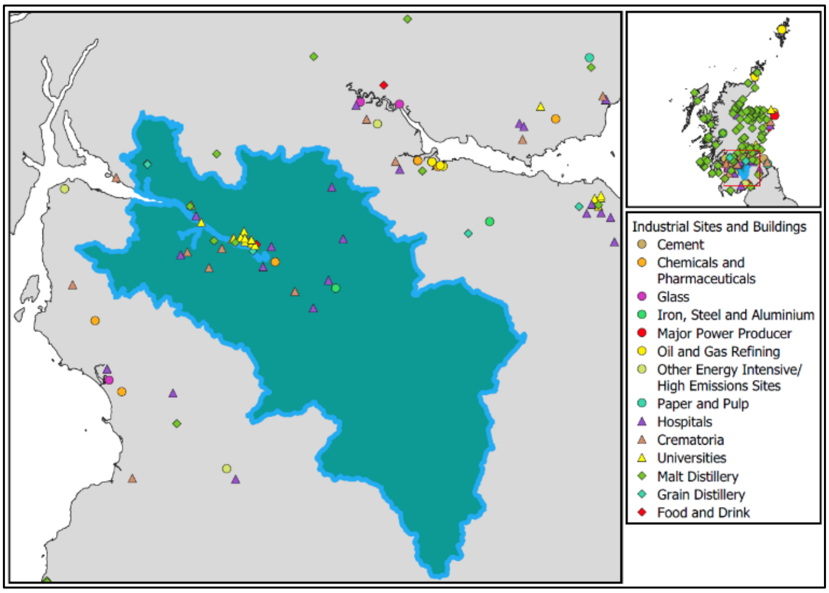


Figure 33: Map of East Dunbartonshire, East Renfrewshire, Glasgow City, North Lanarkshire, Renfrewshire, South Lanarkshire and West Dunbartonshire

The Glasgow Regional Hydrogen Energy Hub potential is shown by adding the adjacent Local Authorities of East Dunbartonshire, East Renfrewshire, Glasgow City, North Lanarkshire, Renfrewshire, South Lanarkshire and West Dunbartonshire. There are four malt distilleries, two grain distilleries, four food and drink sites, a chemical site, four sites manufacturing non-metallic mineral products and two sites manufacturing of basic metals. The total potential hydrogen use from these sites amounts to 210 GWh (6,300 tonnes) per year, whilst 50 GWh (1,540 tonnes) per year could be used by 13 university buildings, eight hospitals and six crematoria.

Grangemouth

The Grangemouth Regional Hydrogen Energy Hub, comprising the Grangemouth industrial cluster, covers the Local Authorities of Clackmannanshire, Falkirk and Stirling. It has the largest total industrial theoretical hydrogen demand, of around 6,500 GWh (195,000 tonnes) per year. There is a wide range of subsectors in the area, including a refinery, four large chemical sites, two glass sites, a food and drink site, a site manufacturing wood product, three malt distilleries and a gas terminal.

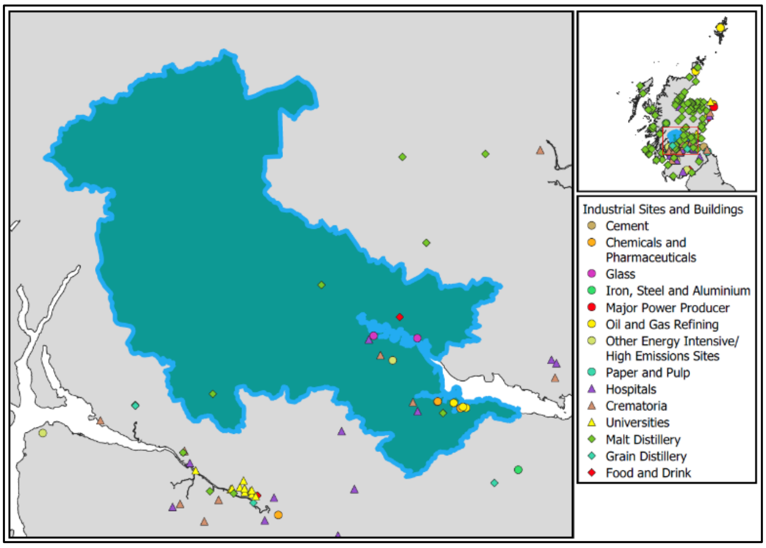


Figure 34: Map of Clackmannanshire, Falkirk and Stirling

Additionally, there are CHP sites providing steam and electricity to the refinery and some of the chemical sites. The possible hydrogen use in the buildings sector is smaller, with 8 GWh (240 tonnes) per year coming from two hospital buildings and two crematoria. INEOS has announced projects for a CCUS-enabled hydrogen facility in the region, expected to be operational by 2030[90], and will commission in a new energy plant in late 2023 that can be converted to run on hydrogen[91].

Orkney

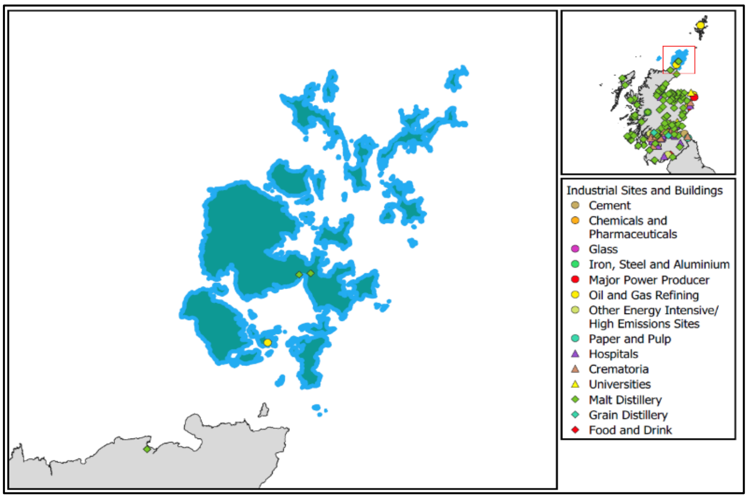


Figure 35: Map of Orkney Islands

The Orkney Regional Hydrogen Energy Hub could see a total hydrogen energy use of around 225 GWh (6,760 tonnes) per year distributed amongst an oil terminal, representing the largest potential user, and two malt distilleries. The Flotta Hydrogen Hub[92] is a proposed hydrogen production project located close to the aforementioned oil terminal. There is significant potential for green hydrogen production and export to mainland Europe, depending on infrastructure delivery, backed by prior innovative end-to-end hydrogen demonstrations[93].

[90] INEOS, 2022, *INEOS awards contract to Atkins to design its world scale low carbon hydrogen plant at Grangemouth*

[91] INEOS, 2022, INEOS at Grangemouth announces plans to construct a Low-Carbon Hydrogen Manufacturing Plant

[92] Flotta hydrogen Hub. Flotta Hydrogen Hub. Accessed March 2023

[93] Orkney.com. Hydrogen in Orkney. Accessed March 2023.

Scottish Borders

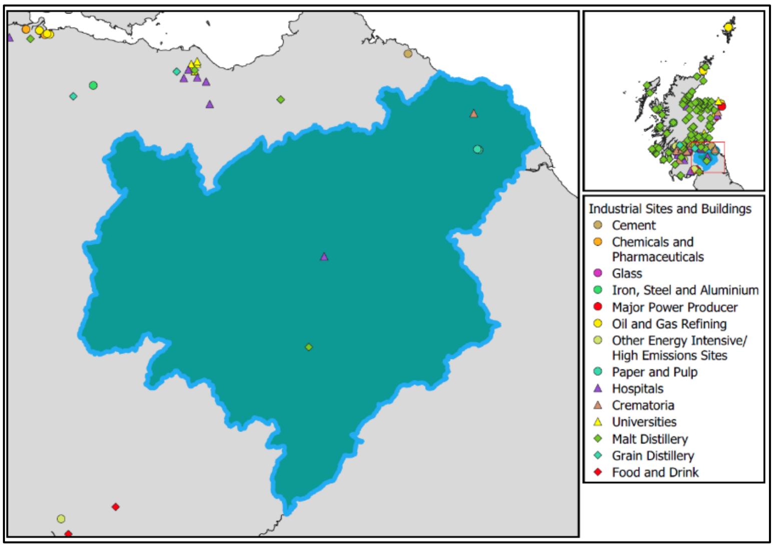


Figure 36: Map of Scottish Borders

The Scottish Borders Regional Hydrogen Energy Hub shows a relatively small industrial hydrogen use potential, with an assessed 55 GWh (1,650 tonnes) per year, distributed between a paper and pulp site and a malt distillery. Up to 9 GWh (270 tonnes) per year of hydrogen could be used by a hospital and a crematorium building. The Hub can benefit from proximity to future hydrogen distribution projects, as well as from access to nearby renewable energy production facilities.

Shetland

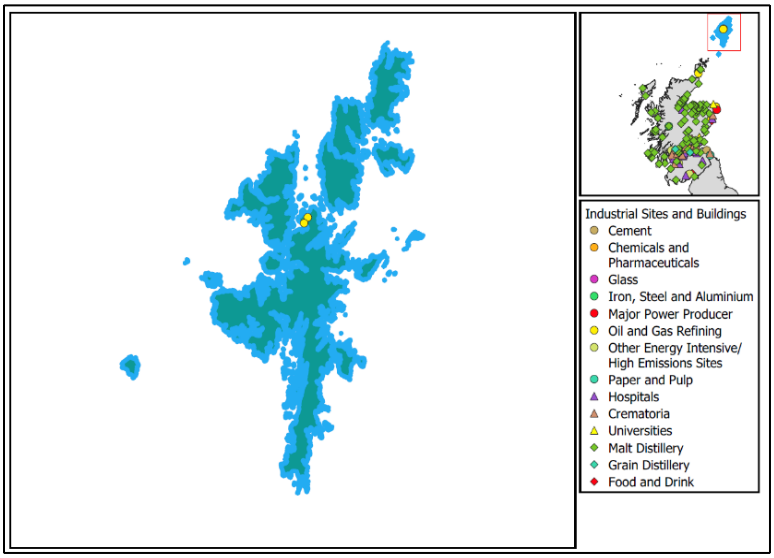


Figure 37: Map of Shetland Islands

The Shetland Regional Hydrogen Energy Hub is home to oil and gas terminals and a utilities plant. The assessed potential hydrogen use for the three sites in the complex is around 1,180 GWh (35,400 tonnes) per year. Given the industrial and logistical activity in the area, the Hub benefits from wide array of nearby renewable energy sources. There are plans to electrify some of the oil and gas installations and to produce hydrogen on site[94].

[94] News Article, Shetland News, accessed February 2023

Western Isles

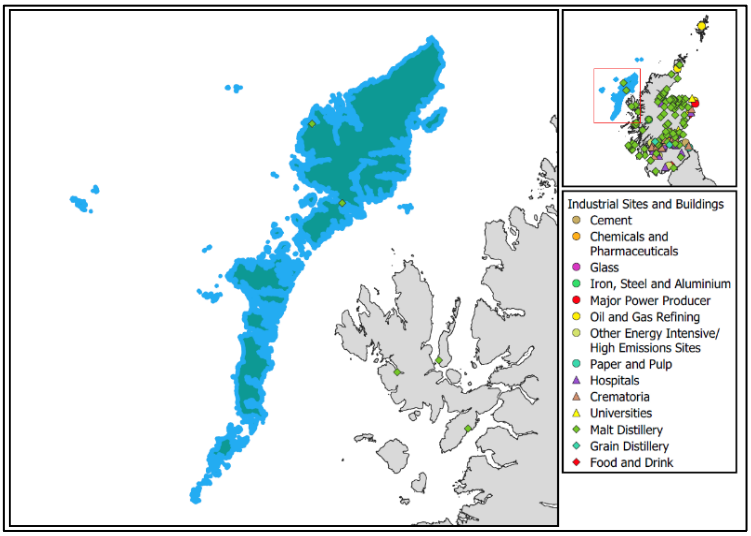


Figure 38: Map of Western Isles

The Outer Hebrides Energy Hub shows little hydrogen use potential based on existing industrial energy demand, with less than 1 GWh (15 tonnes) per year for two malt distilleries in the area. However, the Hub could become a hydrogen producer, with the benefit of plentiful wind generation resources. Western Isles Council and stakeholders like Uist Distilling Company have explored the hydrogen production required to meet energy needs on the island[95].

Table 4.1: Summary of the potential hydrogen use in industry and buildings, in the different Regional Hydrogen Energy Hubs

Regional Hydrogen Energy Hub	Industrial Potential Usage (GWh)	Industrial Potential use (tonnes)	Buildings Potential use (GWh)	Buildings Potential use (tonnes)	Total potential use (tonnes)
Aberdeen	51	1,530	10	300	1,830
Argyll & Islands	29	880	0.3	9	889
Ayrshire	1,430	42,920	13	390	43,310
Cromarty	500	15,000	3	90	15,090
Dumfries and Galloway	122	3,660	4	120	3,780
Dundee	2	60	3	90	150
Fife	1,700	51,000	24	720	51,720
Glasgow	210	6,300	50	1,500	7,800
Grangemouth	6,500	195,000	8	240	195,240
Orkney	225	6,760	0	0	6,760
Scottish Borders	55	1,650	9	270	1,920
Shetland	1,180	35,400	0	0	35,400
Western Isles	1	30	0	0	30

[95] We Love Stornoway (2022). Hydrogen hubs plan for Isles (welovestornoway.com).

5 Short and long-term opportunities for hydrogen uptake

As discussed throughout the report, there are many drivers that determine the attractiveness of low-carbon hydrogen as a decarbonisation vector in industry and non-domestic buildings. Some of these drivers include location, technical maturity of end use appliances, ability to connect hydrogen supply with demand, policy decisions, and others. The uptake of hydrogen will require a phased approach, starting with projects with more favourable characteristics. Here, we consider a variety of factors that can be useful to identify early opportunities to deploy projects supporting the hydrogen value chain, up to 2030 and beyond.

The build-up of materialised shorter-term opportunities should lead to at least 5GW installed electrolytic and CCUS-enabled hydrogen production capacity by 2030, as ambitioned by Scottish Government. This capacity figure should increase to 25 GW by 2045.

5.1 Drivers to identify shorter-term opportunities

Regional Hydrogen Energy Hubs

The Hydrogen Action Plan's approach to defining Regional Hydrogen Energy Hubs suggests that regional co-location of projects is initially needed. Thirteen potential Hydrogen Energy Hubs have been proposed thus far, with several of these being developed in the mid-2020s. To stimulate demand, Scottish Government will initially focus on supporting those Hydrogen Hubs where production can be coupled with multiple end-uses, not only limited to existing industry, e.g., transport. In the previous Chapter we showed the concentration of possible users of hydrogen in each Regional Hydrogen Energy Hubs, highlighting the scale and nature of opportunity in locations such as Fife or Grangemouth.

Locations where wind curtailment is expected

Scotland has an ambitious plan for deployment of offshore wind energy, making use of its extensive wind resources. Following the latest ScotWind leasing round, the combined wind offshore capacity in Scotland could be more than 30GW, with as much as 11GW of capacity being delivered by 2030. Such a pipeline of projects increases the risk of offshore wind power curtailment in locations where the grid network cannot absorb all wind generation[96]. Areas where this is more likely to occur include particularly in the North of Scotland and Scottish Islands, home to the proposed Argyll and Islands, Cromarty, Orkney and Shetland Regional Hydrogen Energy Hubs. Onshore wind farms currently also experience curtailment, and some wind farms have been consented but are unable to be built due to the lack of grid capacity in areas like the South of Scotland. UK-level policy rewards the use of otherwise curtailed electricity, and its use can result in lower hydrogen production costs[97]. Scottish Enterprise is publishing a study which identifies locations of curtailed energy.

Opportunities for both forms of hydrogen production

The pipeline of hydrogen production projects in Scotland and policy ambitions suggest that there will be opportunities to deploy within this decade both electrolytic and CCUS-enabled hydrogen projects. The Low Carbon Hydrogen Business Model should allow electrolytic hydrogen projects to be commissioned from mid 2020s and onwards, via the Electrolytic Allocation Round. CCUS-enabled hydrogen projects could potentially benefit from Scottish Cluster's advanced CO_2 T&S project if enabled by the UK Government, before 2030. The production capacity of each technology and the first-of-a-kind nature of these projects implies that early opportunities for electrolytic hydrogen can include meeting industrial heating demand at a smaller scale, whereas CCUS-enabled hydrogen could meet larger end-user needs.

Hydrogen use in industry enabled by maturing appliances and blending projects

Earlier opportunities for hydrogen in industry may also be enabled by end use appliances that have a higher TRL, such as hydrogen boilers. Nonetheless, it is expected that all industrial hydrogen equipment should see technical readiness by 2030, including hydrogen furnaces, turbines, dryers and ovens. Until then, shorter term

[96] Hawker, Graeme, and Gareth Oakley. The potential for hydrogen to reduce curtailment of renewable energy in Scotland. University of Strathclyde, 2023.
[97] Department for Business, Energy & Industrial Strategy: Hydrogen Production Costs 2021

opportunities may include blending hydrogen with other fuels in end use appliances in amounts that limit the need to conduct full appliance replacements and mitigate the security of hydrogen supply risk, which is inherent to the shorter-term phase.

Sectors which already have skills compatible with hydrogen use

Whilst fuel switching will be a novelty for certain industries not currently employing this commodity, some sectors already use hydrogen. This is the case for the refining sector and petrochemical sites, where hydrogen is either produced as a by-product or used to meet a variety of processing needs. Availability of existing hydrogen skills in such sectors can thus enable shorter term opportunities for hydrogen projects, whether to produce and use the hydrogen on site or as merchant projects.

5.2 Drivers to identify longer-term opportunities

Interconnectivity between Regional Hydrogen Energy Hubs

Interconnectivity between future hydrogen supply and demand points is likely to play a critical role in defining longer-term opportunities, beyond 2030. Natural gas transmission and distribution operators, such National Grid and SGN, are developing plans to increase the hydrogen transport connectivity between the proposed Regional Hydrogen Energy Hubs[98]. Plans could enable initial interconnectivity to begin in early 2030s, either via repurposed or new dedicated hydrogen pipelines. Interconnectivity between Regional Hydrogen Energy Hubs in the Central Belt of Scotland and the North East Coast would increase resilience and security of supply, a driver expected to facilitate further investments into industrial use of hydrogen

Ability to access more remote locations and grid reinforcements

The growth of a hydrogen distribution network would enable the deployment of hydrogen spur pipelines to potential centres of demand outside of the Regional Hydrogen Energy Hubs. Remote end users, away from the pipeline network, could be reached by other forms of transport such as tube trailer delivery, connecting large scale producers with small scale remote hydrogen users. If the hydrogen pipeline transport does not materialise, the role for tube trailer delivery could be larger. Equally, in the Draft Energy Strategy and Just Transition Plan Scottish Government states its intention to work with National Grid ESO and Ofgem to explore opportunities to accelerate planned electricity network investment to relieve constraints, particularly to enable the connection of the ScotWind projects towards 2030. The increased proportion (and reduced cost) of renewable energy in the system and the reduction of grid constraints could favour on-site electrolyser deployments in more locations where otherwise hydrogen would not be transported.

Large scale distribution and storage infrastructure

As hydrogen production scales up, there will be a greater need for large scale infrastructure to ensure security of supply and reduce distribution costs. As indicated previously, the UK Government has stated it will make decisions about the blending of hydrogen into the gas networks, leading in 2026 to a decision about 100% hydrogen pipelines and the use of hydrogen for residential heating. If consent is given, hydrogen could be accessed by industrial offtakers through existing pipelines. In addition, consultations are currently underway at Scottish and UK level regarding the strategic infrastructure required to store hydrogen, particularly for large users and in areas with the potential for high demand. Geological storage is available only in some locations and artificial storage is costly. Scotland in particular lacks salt caverns so studies are underway on the utilisation of depleted offshore hydrocarbon reservoirs.

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[98] SGN and Wood, North East Network & Industrial Cluster Development – Summary Report: A consolidated summary report by SGN & Wood (2021)

6 Appendix

Methodology

Theoretical potential for hydrogen use

The model used for our Deep Decarbonisation Pathways for Scottish Industry report for the Scottish Government was used in this project to calculate theoretical potential hydrogen use for Scottish industrial subsectors in scope. The methodology is detailed in **Error! Reference source not found.**. The model was u pdated with NAEI 2019 CO_2 emissions data, filtered to sites with annual emissions above 10,000 tCO_2 to capture the most energy-intensive industries. As an exception to this approach, all whisky distilleries in Scotland were included, regardless of their size, to account for the hydrogen fuel-switching projects that have begun to be developed at small scale in some distillery sites.

More recent data was not used to avoid artificial impacts of COVID-19 on industrial activity. An update check was done to ensure recent industrial events are accounted for, resulting in the removal of certain sites from the analysis, e.g., the appointment of administrators at the Arjo Wiggins Group mills in Stoneywood in 2022, the closure of McVitie's factory in Tollcross, or the "right-sizing" of PetroIneos' Grangemouth refinery in 2020.

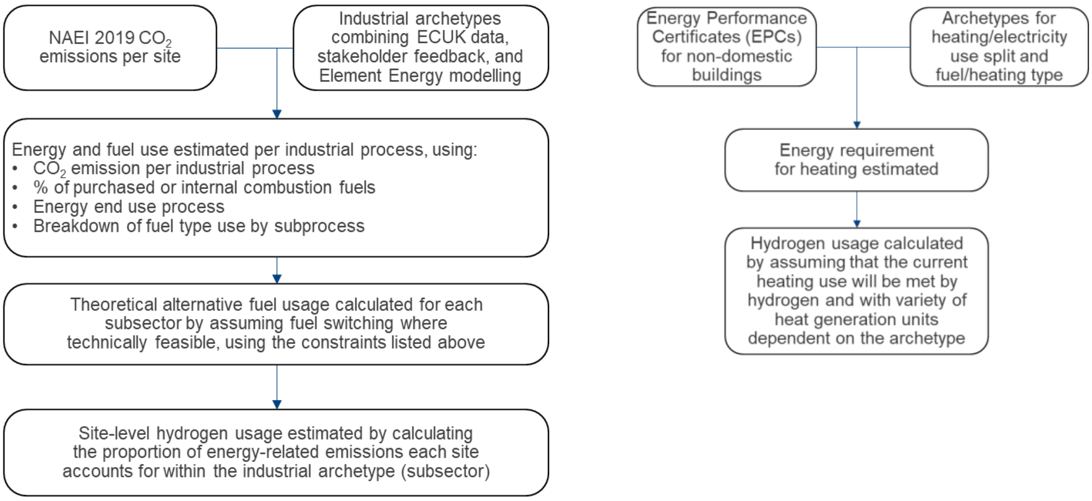

Figure 39: Methodology for industrial hydrogen usage (left) and methodology for non-residential heating hydrogen usage (right)

It is important to note that we assumed that hydrogen end use appliances will have the same efficiency than their natural gas counterparts. Limitations of the approach used here are that:

- Site level estimates are approximated from a sectoral theoretical potential hydrogen use figure; actual site level usage will differ due to site-specific processes and consumption patterns, e.g., efficiencies of end use appliances, variations in the load factors.
- Future energy efficiency improvements are excluded; baseline energy use is based on 2019 activity.

Sectors outside of the scope of this work include:

- Compression stations, e.g., Bathgate and Aberdeen natural gas compression stations. These stations are operated by gas fired compressor turbine drives, but could be fuel switched to hydrogen.[99]
- Energy from waste facilities, as abating emissions from these plants requires the use of CCS.
- Offshore emitters, such as oil and gas exploration and production sites.

[99] The SGN and Wood, North East Network & Industrial Cluster Development study assessed a potential hydrogen demand of 22MW (0.2 TWh) each, for Bathgate and Aberdeen compressor stations.

More broadly, it is also assumed that biogenic emissions arising from biomass/biogas combustion (e.g., in boilers and CHPs used in the paper and pulp, and food and drink industries) are not fuel switched to hydrogen. This is because:

- The Biomass Policy Statement considers biomass to be a low carbon energy source (due to net lifecycle emissions) and accordingly disregards the GHG effect associated with biogenic CO_2[100]. Indeed, many of the projects that replaced fossil fuels with biomass/biogas did so specifically because of the decarbonisation benefits. Relatedly, substitution of bioenergy with hydrogen would not be seen as delivering decarbonisation benefits.

Scotland has considerable ambitions for Negative Emission Technologies (NET) deployment by 2032 (as highlighted in the CCPu 2018-2032), implying that such biogenic emissions can be a valuable key contributor towards meeting Scotland's NET targets[101]. With incentives in development to account for future negative emissions (e.g., GGR business model, future adaptations of ICC), it is envisaged that biogenic emitters will be incentivised to valorise biogenic emissions as negative emissions via CCS.

Non-Residential Heating

Energy demand in non-domestic buildings such as hospitals, crematoria and universities was estimated using the Non-Domestic Energy Performance Certificates (EPCs) Dataset for Q1 2022, published by the Energy Saving Trust. EPCs the primary source of energy consumption and building floor area data but do not split out by end-uses (heating, cooling, electricity etc.).

The most applicable use of hydrogen in non-domestic buildings is to displace incumbent combustion-based heating systems, therefore, to estimate hydrogen fuel use in these contexts, heat energy consumption was extracted from the EPC total energy consumption data, with a threshold of 2,000,000 kWh/year of energy (combined heating and electricity) used to filter out smaller buildings.

Industry-standard non-heat electricity consumption benchmarks were used to get an approximate split of heat versus non-heat fuel energy use per building within each archetype. Approximate thermal efficiencies for incumbent and replacement hydrogen-based heating systems used to calculate final hydrogen fuel consumption per building. Only buildings using combustible fuels (and therefore with "wet" heating systems") are assumed to be able to switch to hydrogen. For crematoria, it is assumed only the building heating system is converted to hydrogen (cremators do not convert).

It should also be noted that the hospital buildings within the EPC register are not uniform, i.e., some are large conventional hospitals with A&E units and large long-term wards, some are care homes for elderly and infirm patients, and some are health centres for non-emergency care. The analysis ensured to assign different energy consumption benchmarks to each of the hospital buildings that reflected their use, so as to develop a more accurate reflection of heat consumption and ultimately expected hydrogen demand.

Some of the limitations of this approach are that not all buildings are in the EPC register (e.g., Glasgow's Daldowie Crematorium or the Old University Campus building), therefore the estimated hydrogen fuel use may be underestimated. However, EPCs typically tend to overestimate energy consumption, therefore the inaccuracies in EPC energy consumption estimates may balance out missed buildings in the EPC dataset. Lastly, EPC descriptions of heating systems in buildings can often be unclear, so a judgement call was taken on the heating system employed in each building based on the "main heating fuel" and any "renewable energy generation" stated in the EPC data.

Large Events and Construction

Assessment for the theoretical potential use of hydrogen to replace diesel use in generators in large events and in construction sites was made by estimates the total diesel consumption in Scotland for each sector, and then calculating the amount of hydrogen that would be required to meet the same energy demand. Adjustments

[100] Department for Business, Energy and Industrial Strategy: Biomass Policy Statement (2021)
[101] Scottish Government: Update to the Climate Change Plan 2018 – 2032, Securing a Green Recovery on a Path to Net Zero (2020)

were made to account for the relative efficiencies of hydrogen and diesel generators and scaling down factors were used when starting with data at UK-level.

Distilleries

For those distilleries not included in the NAEI 2019 CO_2 database, the potential for hydrogen use in distilleries was calculated by:

- Using data on litres of pure alcohol (LPA) production capacity taken from a website[102] referencing the Scotch Whisky Industry Review 2021
- Using energy use data, on a kWh/LPA basis, for malt and grain distilleries, plotted in SWA's Scotch Whisky Pathway to Net Zero (2020)[103]
- Assuming a representative LPA production as a percentage of the total LPA capacity stated, and finally
- Taking the balanced scenario finding from the SWA's Net Zero study stating that 20% of the baseline fossil fuel total primary energy use could be replaced by hydrogen, the figure of which was used to calculate a final TWh of energy switchable to hydrogen.

Conversion between mass and energy content

A value of 33.3 MWh/tonne of hydrogen was used to convert between hydrogen mass and energy content, which corresponds to the Lower Heating Value of hydrogen (also known as Net Calorific Value) of 119.95 MJ/kg H_2.

[102] Whisky Invest Direct: Malt Whisky Distilleries in Scotland, sourced from the Scotch Whisky Industry Review (2021)
[103] Scotch Whisky Association: Scotch whisky pathway to net zero (2020)