HYDROGEN FOR SCOTTISH DISTILLERIES

A Research Study

Final Report for Scottish Enterprise

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EXECUTIVE SUMMARY

Background

The Scottish Government has set out an ambition to produce 5GW of clean hydrogen in Scotland by 2030 and 25GW by 2040 as part of the nation's desire to reach net zero greenhouse gas emissions by 2045. Enabling hydrogen production is only part of the challenge, work is required stimulate demand as the market is established.

Hydrogen is one potential solution for industrial decarbonisation, particularly in processes that require high temperatures and are difficult and costly to electrify. Distilleries form a significant portion of Scotland's industry and face many challenges to decarbonise. Whisky alone represents more than 500,000 tonnes CO_2e/year and the Scotch Whisky Association has committed to reaching net zero emissions in its own operations by 2040.

Significant interest has already been shown by Scottish distilleries to adopt hydrogen, such as those involved in the North of Scotland Hydrogen Programme at Cromarty Firth and the Green Distilleries Competition Phase 1 and 2 funding. A 'hierarchy of use cases' for hydrogen is contained within the Scottish Hydrogen Action Plan, where distilleries rank in the second highest category.

Despite the progress to date, the use of hydrogen in Scottish distilleries is still at a nascent stage. A research study has therefore been conducted to explore this topic in depth. This included both an extensive literature review and stakeholder engagement. Guidance on the technical, economic, and regulatory aspects for Scottish distilleries considering hydrogen as a fuel to decarbonise has been provided. The study also allows hydrogen producers to better understand the market opportunity, in terms of potential demand and locations for projects.

Options to Decarbonise Distilleries

Heating is responsible for the majority of a distillery's energy demand and carbon emissions. To achieve net zero targets, a combination of energy efficiency measures and switching to sustainable fuels is required. There are a variety of fuel switching options available to distilleries each with their own set of benefits and limitations. In addition to hydrogen, these include electrification and bioenergy. Practical and economic considerations affect the feasibility of adopting a certain technology or fuel type, as does the policy landscape which may favour certain fuels above others. There is often not a 'one size fits all' approach to decarbonisation and the selection of the most appropriate fuel is site-specific.

How Hydrogen can be used to Decarbonise Distilleries

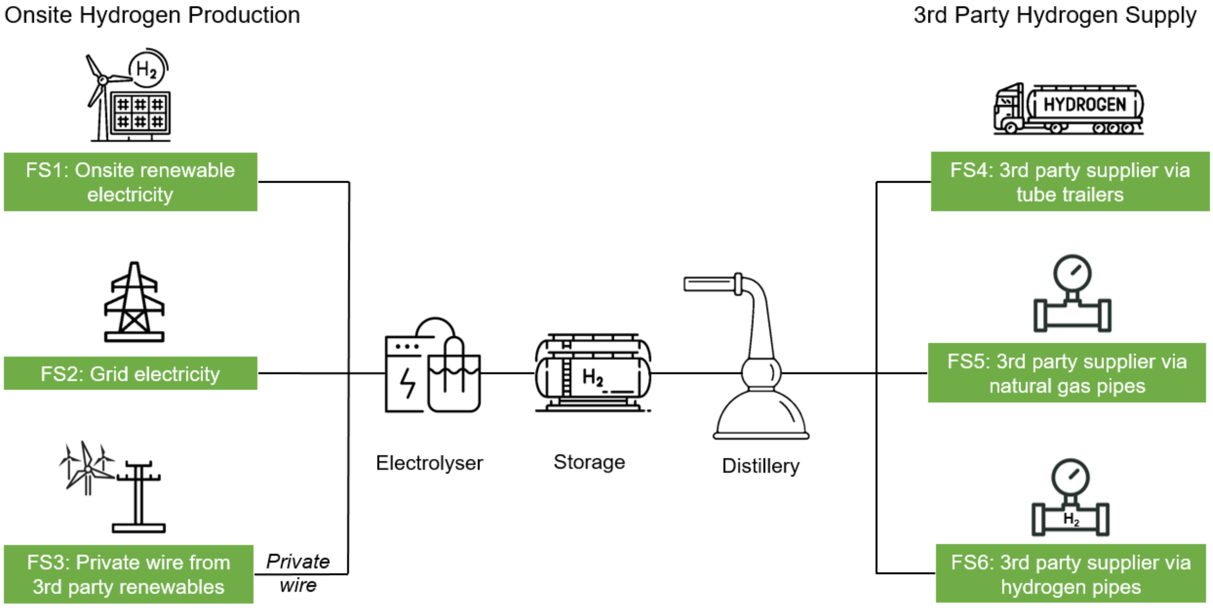
At most distilleries, the heat demand is satisfied by steam produced in boilers. Where batch distilling takes place, the demand for heat can be variable and will peak at the start of a batch. With combustion of hydrogen to raise steam in boilers, it is possible to meet sudden variations in steam demand.

Boilers providing steam can typically utilise blends of up to 20% by volume of hydrogen without any modifications being needed. Blends with greater concentrations of hydrogen, in relation to another gas, will require swapping out the existing burner with a hydrogen-compatible burner. However, due to the lower calorific value of hydrogen relative to natural gas, the same boiler will suffer a reduction in steam generating capacity, so a larger boiler will be needed to deliver the same steam output. There are a range of industrial suppliers beginning to roll out boilers and burners capable of running on blends of hydrogen up to 100%.

Hydrogen can be expected to work well as a decarbonisation option if it has been produced with zero-carbon or low-carbon methods. This presupposes that hydrogen can be obtained on a reliable basis, at reasonable cost and can be stored in sufficient quantities to ensure continuity of operations.

Fuel Supply Archetypes

The major difference between sites is how hydrogen could be supplied. Six fuel supply options have been identified as part of this study, shown below.



The most important factors influencing the appropriateness of the six fuel supply archetypes were determined through stakeholder engagement and literature review. We find these factors to be:

- Land availability: On-site hydrogen production requires land availability for electrolysis, compression, and storage. For on-site renewable power generation, additional land must be available.
- Water resource: Requirements must be considered for on-site hydrogen production
- Electricity constraints: The capacity of electrical grid connection may require upgrading should grid electricity be used to power an on-site electrolyser
- Gas grid: Any distillery connected to the national gas grid will likely receive some hydrogen in future depending on future UK Government policy to blend hydrogen in the network.

Hydrogen Requirement at Distilleries

While hydrogen is likely to be adopted at a distillery in a phased manner, the annual hydrogen demand for 100% uptake for distillery categories was estimated as follows:

Distillery category	Typical spirit production (million LPA/year)	Estimated hydrogen demand (tonne/year)
Grain	20 - 100	1,900 - 9,300
Large Malt	>5	900 - 3,500
Mid Malt	1 - 5	180 - 900
Small Malt	<1	18 - 180

A recent study was conducted by Element Energy on behalf of Scottish Enterprise titled "*Hydrogen Demand in Scotland – Industrial Applications*". The potential use of hydrogen in Scotland was estimated across a range of industrial sectors, including whisky distilleries. The annual theoretical potential hydrogen demand for all distilleries in Scotland was estimated to be 1.4 TWh. After fossil fuel refining and the chemical/pharmaceutical sector, distilleries were identified as the third largest potential demand source for hydrogen in industry.

Hydrogen Costs

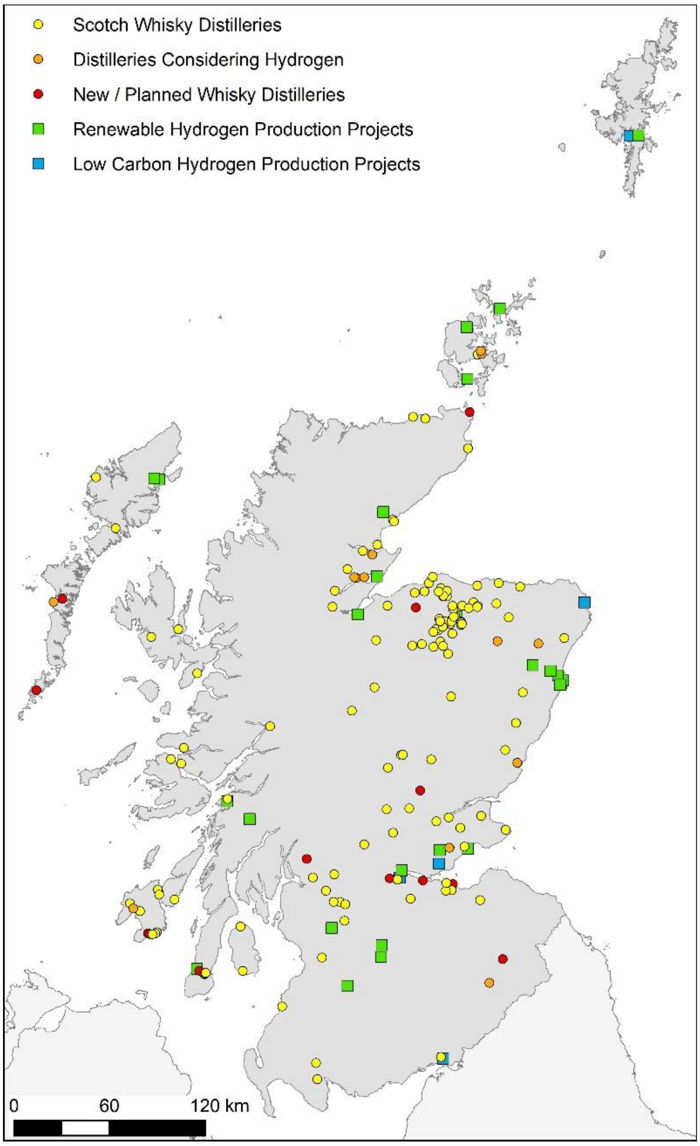
In the short-term renewable or low-carbon hydrogen will not be cost competitive with either fuel oil or natural gas. While there is a high degree of uncertainty with respect to future fuel prices and carbon prices, it has been estimated that hydrogen will be less expensive than fuel oil in 2045 with cost parity expected in the 2030-2040 decade. According to our assumptions, natural gas will remain slightly cheaper than hydrogen in 2045. Both policy decisions and market conditions will determine the relative future prices between these fuels.

Funding Mechanisms

There are a number of support mechanisms relating to hydrogen generation and consumption which distilleries may benefit from, directly or indirectly. However, many have focused on supporting innovative projects at feasibility or demonstration scale. Other financial or policy mechanisms may be required to incentivise implementation of full-scale commercial projects. This would encourage a wider rollout of integrated solutions to decarbonise distilleries in Scotland through the adoption of hydrogen. Full-scale projects, which receive financial support in the short to medium term, could accelerate the cost competitiveness of hydrogen compared to other fuels in the long term.

Map of Distilleries and Hydrogen Production

A map of distilleries and hydrogen production projects has been produced, which allows the relative positions of hydrogen production and potential demand by distilleries to be understood. This shows that locations such as Speyside or Islay could present an opportunity to develop large-scale hydrogen production projects with a cluster of distilleries serving as the main off taker, in a similar fashion to the proposed project at Cromarty Firth which has support from several distilling organisations.



ACRONYMS

Acronym	Full term
LPA	Litre of Pure Alcohol
SWA	Scotch Whisky Association
GHG	Greenhouse Gas
CCUS	Carbon Capture, Utilisation and Storage
SIETF	Scottish Industrial Energy Transformation Fund
MVR	Mechanical Vapour Recompression
TVR	Thermal Vapour Recompression
HTHP	High Temperature Heat Pump
AD	Anaerobic Digestion
GGSS	Green Gas Support Scheme
RGGO	Renewable Gas Guarantee of Origin
CHP	Combined Heat and Power
BECCS	Bioenergy with Carbon Capture and Storage
NET	Negative Emissions Technology
COP	Coefficient of Performance
PEM	Proton Exchange Membrane
SNG	Synthetic Natural Gas
COMAH	Control of Major Accident Hazards
DSEAR	Dangerous Substances & Explosive Atmospheres Regulations
PPA	Power Purchase Agreement
NZIP	Net Zero Innovation Programme
HBM	Hydrogen Business Model
NZHF	Net Zero Hydrogen Fund
LCHS	Low Carbon Hydrogen Standard
LCOH	Levelised Cost of Hydrogen

CONTENTS

1. INTRODUCTION

1.1 DISTILLING SECTOR IN SCOTLAND AND DECARBONISATION

The distilling sector in Scotland contributes significantly to the nation's economy. In terms of Scotch Whisky alone, exports to 180 markets across the world constituted an estimated £6.2 billion in 2022. This equates to 75% of all Scottish food and drink exports[1]. With regards to employment, more than 11,000 people work directly in the Scotch Whisky industry, 7,000 of whom are based in rural communities, but also indirectly through generation of tourism, agriculture, and throughout the wider supply chain. Across the UK, over 42,000 jobs are supported by the industry.

In recent years the distilling industry has rapidly expanded, and there has been a particularly burgeoning demand for Scotch Whisky. In the last six years alone 20 distilleries have opened in Scotland, and in 2021, whisky exports grew by approximately 20%[2].

The Scottish distilling industry also includes gin, vodka, and rum, although Scotch Whisky dominates both in scale and economic contribution. There are approximately 245 distilling related business in Scotland, several of which produce rum and vodka, over 90 that produce gin[3], and over 140 that produce whisky[4]. Of the whisky producing sites, less than ten are categorised as grain with the remainder being malt. Distillery production capacity is expressed in litres of pure alcohol per annum (LPA). In terms of site numbers, the currently active malt distilleries can be broken down into the following categories:

- Small malt (<1 million LPA): 31%
- Medium malt (1m-5m LPA): 55%
- Large malt (>5m LPA): 14%

The recent growth in the sector has occurred even though the UK is going through the worst cost-of-living crisis for a generation coupled with an energy crisis; factors that directly impact the distilling industry due to their energy intensive operations.

Scotland has implemented ambitious climate change legislation that sets a target date of achieving net zero emissions of all greenhouse gases by 2045, whilst the Scotch Whisky Association (SWA) has committed to reaching net zero emissions from its own operations by 2040. Diageo, who operate 28 malt distilleries and one grain distillery, accounting for more than a quarter of the industry's total capacity, have expressed their ambition to achieve net zero emissions across their direct operations (Scope 1 and 2) by 2030[5]. Distilleries are consumer facing brands and therefore face reputation pressure to reduce their emissions.

In Scotland, the distilling sector (by which we mean whisky, gin, and other spirit drinks) is faced with multiple choices as it sets a path to decarbonise its operations. However, it faces several challenges in doing so due to large energy demands, as well as the fact that many distilleries are in rural locations and consequently not connected to the gas grid. Using 2018 data as a baseline, members of the SWA represent more than 500,000 tonnes CO_{2e}/year; most of these emissions are from fossil fuels used to generate heat in the production process[6].

The 'Scotch Whisky Pathway to Net Zero' report produced by Ricardo for the SWA in 2020 modelled seven scenarios to explore the net zero gap and identify viable pathways to 2045. Three of the seven modelled pathways included the use of hydrogen. Moreover, these same pathways were the only ones of the seven that presented a route to achieving net zero, thus exemplifying the pivotal role hydrogen will play in the decarbonisation of the distilling industry. These scenarios included "Green Gas" driven by increased uptake of biogas and hydrogen, "Electrification" whereby net zero is achieved through a significant deployment of heat pumps, and finally a "Balanced" approach that applies a combination of the key heat technologies well within their maximum technical potential[7].

[1] Facts & Figures (scotch-whisky.org.uk)
[2] 'This is an exciting time!' How Scotland's whisky industry went from bust to boom | Whisky | The Guardian
[3] The Scottish Gin Society Scottish Gin Distillery Map - The Scottish Gin Society
[4] It must be noted that several distilleries produce more than one spirit product
[5] Climate crisis: Whisky distilleries to become net-zero under Diageo sustainability plans | The Independent
[6] Scotch Whisky Sustainability (scotch-whisky.org.uk)
[7] scotch-whisky-net-zero-report.pdf

Thus far, the SWA members have already reduced their emissions by 53% between 2008 and 2020, however, in order to reach their 2030 emissions target, there needs to be a further 40% reduction in GHG emissions, in comparison with their baseline year of 2018[8].

1.2 HYDROGEN LANDSCAPE IN SCOTLAND

Hydrogen is the most abundant element in the universe, being part of the chemical composition of conventional fossil fuels, and water, and has been used in industry for decades. Hydrogen production can be achieved through various methods, each of which produces hydrogen that is labelled using 'colours' based on the production process used. The three most widely used production routes are:

1. **Unabated (grey) hydrogen**: The most common method of hydrogen production, which typically involves steam methane reforming of natural gas and results in unabated high carbon emissions. For this reason, the Scottish Government does not support grey hydrogen production within its hydrogen economy ambitions.
2. **Low-carbon (blue) hydrogen:** Similar to grey hydrogen production with the exception that carbon capture, utilisation and storage (CCUS) technologies are incorporated to capture and permanently store the carbon dioxide prior to its release to the atmosphere.
3. **Renewable (green) hydrogen:** Produced using electricity from renewable sources, such as solar or wind, to power an electrolyser that separates hydrogen and oxygen from water. The green hydrogen process emits no carbon emissions and is considered the most environmentally friendly production method.

A fourth but less developed production route is biogenic hydrogen, this involves gasification of sustainable (i.e. renewable) biomass or reforming biogas obtained from anaerobic digestion[9].

The ''chicken and egg'' scenario is a common challenge faced by emerging technologies, including hydrogen. In this context, it refers to a situation where the adoption of a new technology or product is hindered by the lack of infrastructure or demand, and vice versa. For hydrogen, this is a particularly pertinent challenge, given the high investment costs required for large-scale rollout. This creates a catch-22 situation, where both demand and supply are somewhat dependent on each other, significantly slowing progress.

Scotland has ambitious plans to rollout both renewables and hydrogen. Currently, Scotland has over 13GW of renewables installed, with plans for a stretch target of an additional 12GW of onshore wind by 2030. Given that today, Scotland's annual electricity consumption matches annual renewables production, conversion of this energy to hydrogen may be beneficial to avoid curtailment. Furthermore, Scotland aims to generate 50% of its total energy consumption from renewables by 2030[10]. A significant contributor to this aim will be the latest ScotWind offshore wind leasing round. The successful projects will have a combined capacity to deliver up to 27.6GW, some of which have stated an interest in producing green hydrogen.

Many current energy consumers cannot easily be directly powered by electricity, so will need an alternative such as hydrogen if they are to decarbonise. Scotland is well placed to be a leader in the hydrogen industry for several reasons. The country has outstanding wind resources with an established wind industry, existing offshore oil and gas infrastructure with potential to be utilised for hydrogen, as well as large scale hydrogen projects both planned and underway. An example of a significant project based in Scotland is the Acorn Hydrogen project, developed by Storegga, Harbour Energy, and Shell to create hydrogen and CCUS infrastructure in Northeast Scotland[11]. The project aims to use natural gas from the North Sea and convert it into low-carbon hydrogen and store subsequent carbon dioxide in depleted offshore oil and gas reservoirs 1.5 miles under the North Sea. This project was funded by both the Scottish Government and the UK Government's Industrial Strategy Challenge Fund.

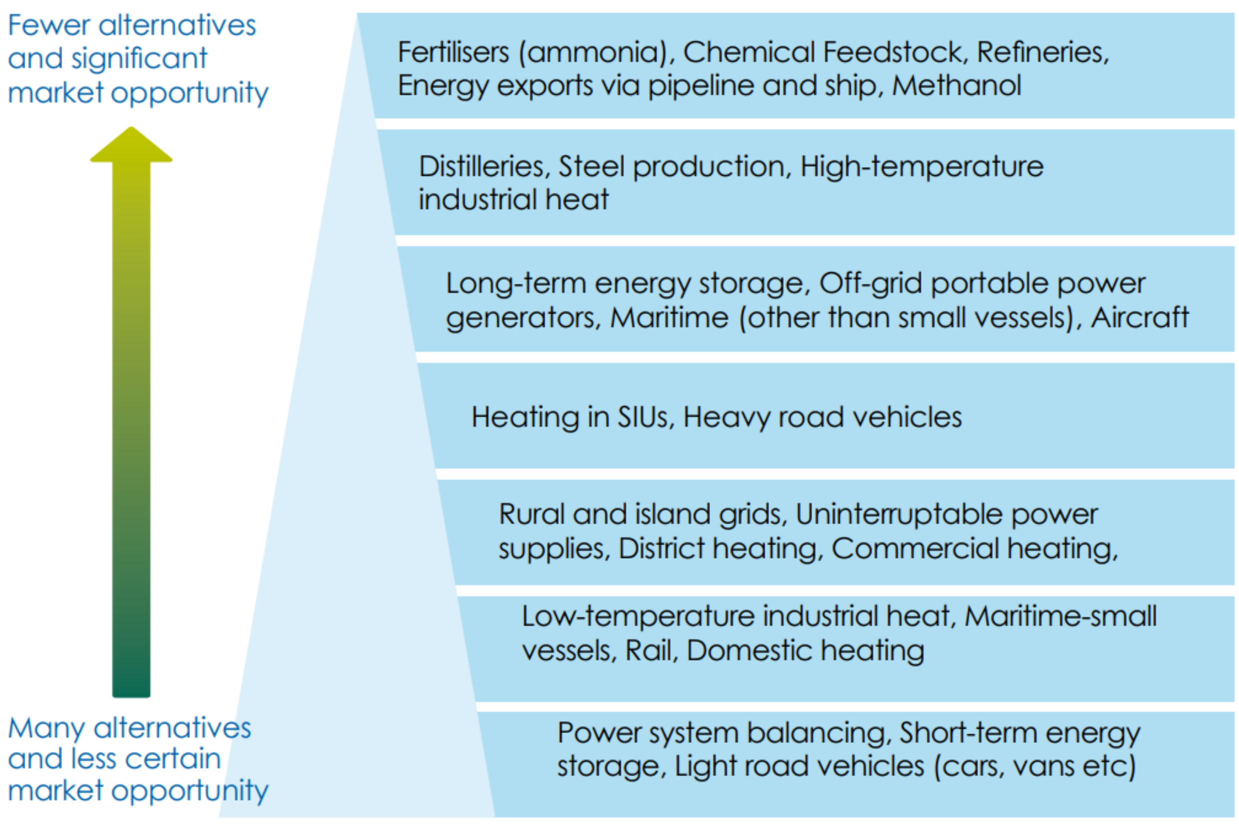
The Scottish Government recognises that hydrogen will play a role in its energy transition, evidenced by its acknowledgment within the Hydrogen Policy Statement released in 2020[12], followed by the release of the Hydrogen Action Plan in 2022. The document states the Government's target to reach 5GW installed hydrogen

[8] Scotch Whisky: Climate Change (scotch-whisky.org.uk)
[9] cepAnalyse
[10] Renewable and low carbon energy - gov.scot (www.gov.scot)
[11] Acorn Projects | Carbon Capture, Transport & Storage, Hydrogen (theacornproject.uk)
[12] Scottish Government Hydrogen Policy Statement - gov.scot (www.gov.scot)

production capacity by 2030, and 25GW by 2045, alongside a list of actions to be implemented over the next 5 years in order to achieve this[13].

Hydrogen is one potential solution for industrial decarbonisation, particularly in processes that require high temperatures and are difficult and costly to electrify. Significant interest has already been shown by major distilleries in Cromarty Firth to engage with the hydrogen hub project being developed in the area. Three hydrogen demonstration projects, one on Islay, and one in Angus, and one in Aberdeenshire, are being funded under Phase 2 of the BEIS Green Distilleries Competition. However, hydrogen is still a nascent technology, associated with higher production and distribution costs than other fuels. A 'hierarchy of use cases' for hydrogen, is contained within the Action Plan, where distilleries rank in the second highest category due to their high-grade heat applications. This hierarchy, shown in Figure 1 below, was compiled by considering the potential decarbonisation alternatives and the opportunities that hydrogen presents for each sector. Economic, technical, and logistical factors were also taken into account.

Figure 1 Hierarchy of hydrogen use cases (Scottish Government)



[13] Hydrogen action plan - gov.scot (www.gov.scot)

1.3 OBJECTIVES OF RESEARCH STUDY

The research study aims to provide practical guidance on the technical, economic, and regulatory aspects for Scottish distilleries considering the adoption of hydrogen as a fuel to decarbonise.

More explicitly, the study sets out to achieve the following tasks:

1. **Overview of Options to Decarbonise Distilleries**

There are multiple solutions to decarbonise the energy demand for distilleries, both in terms of improving energy efficiency and switching to a low carbon fuel source. An overview of these options has been compiled along with a comparison of their respective merits and limitations.

2. **Explain how hydrogen can be used to decarbonise a distillery**

The overwhelming majority of energy delivered to the spirit production process is via heat. A description of the use of hydrogen in the context of distilleries has been provided.

This task also aims to cover the production and storage of hydrogen at distilleries. Further considerations such as safety implications and the use of hydrogen to produce synthetic methane have been covered.

Hydrogen as a transportation fuel was not within the scope of the project.

3. **Explore the techno-economic implications of adopting hydrogen**

The main conclusions from the task above were used to inform the most important characteristics that determine which hydrogen supply options are applicable to distilleries. Six supply options or archetypes were identified in the study.

A literature review for the levelized cost of hydrogen was carried out with a range of LCOH applied to each fuel supply archetype.

As hydrogen becomes more cost competitive with conventional fuels, the UK and Scottish Government have announced a series of funding mechanisms to drive the hydrogen sector forward. Some of these mechanisms which may be relevant to distilleries have been outlined.

4. **Map of Distilleries and Hydrogen Production Projects**

A mapping exercise was undertaken to highlight the location of distilleries and hydrogen production projects in Scotland. Distilleries which are currently in the process of exploring hydrogen as a decarbonisation option have been highlighted.

The objectives were achieved through an extensive literature review, most notably of the BEIS Green Distilleries Phase 1 feasibility studies, as well as engagement with several stakeholders, including the three Phase 2 hydrogen projects. Overall, interviews with the Scotch Whisky Association (SWA) and Scottish Distillers Association (SDA) were conducted in addition to hydrogen project developers and six Scottish distilleries involved in the transition to hydrogen.

2. OPTIONS TO DECARBONISE DISTILLERIES

Energy use in the distilling sector is dominated by heat production. The Scotch Whisky Pathway to Net Zero report[14], published in 2020, identified that over 80% of fuel consumption, excluding fuel for transport, was attributable to heat. Several production steps in distilleries require heat, such as mashing and distillation, with distillation accounting for approximately 90% of heat-related fuel. In most cases, heat for distillation is provided indirectly by steam. In some instances, direct firing is used whereby flames heat the bottom of the stills, but this only takes place at a small number of distilleries.

Fossil fuels are the dominant energy source for the sector. In the Scotch Whisky Association (SWA) member contingent, in 2018, 75% of fuel consumption came from fossil fuels, with 17% from electricity and 8% from renewable heating fuels. Consequently, 63% of scope 1 and 2 carbon emissions arose from natural gas, 31% from fossil fuel oils and 1% from LPG or CNG

Since heating is responsible for a significant portion of a typical distillery's energy demand and carbon emissions, it is vital that heat is decarbonised if net zero targets are to be realised. A combination of energy efficiency measures and switching to sustainable fuels is therefore required. A brief description of each applicable decarbonisation measure is outlined within this section, alongside examples relevant to the distilling sector. Examples have been drawn from the Scottish Industrial Energy Transformation Fund (SIETF) and BEIS Green Distilleries Competition.

2.1 ENERGY EFFICIENCY MEASURES

Deploying energy efficiency measures reduces a distillery's heat generation requirement thereby reducing fuel usage and the costs associated with subsequent fuel switching. A range of energy efficiency options are available. One such option is vapour recompression, a waste heat recovery technology which produces upgraded heat that can be reused in the production processes. There are two varieties: mechanical vapour recompression (MVR) and thermal vapour recompression (TVR).

TVR has been installed in several distilleries successfully, such as Inchdairnie Distillery in Fife, where both the spirit and wash still contain a TVR that is capable of recovering 35% of the heat from each still. Further examples of TVR implementation include Diageo's Glen Ord and Teaninich distilleries[15]. By comparison, MVR is an emerging energy efficiency technology. It has been trialled by Chivas Brothers Ltd at Glentauchers distillery to recover energy from the spirit vapour and use it to boil the still[16]. Plans are in place to roll out MVR across all of Chivas Brother's viable distilleries by 2026.

Another heat recovery solution is discussed in a feasibility study for Edrington's Highland Park distillery. Funded by Phase 1 of the Green Distilleries Competition, the study discusses the use of a condenser hot water recovery system to recover low grade heat from stills. The project partners report there may be reduced risk to product quality in comparison to MVR/TVR. Since vapour recompression technologies need condenser modifications which can alter the contact time between spirit vapour and copper stills, which they believe can potentially impact spirit character[17].

Please see appendices for a long list of energy efficiency measures applicable to distilleries.

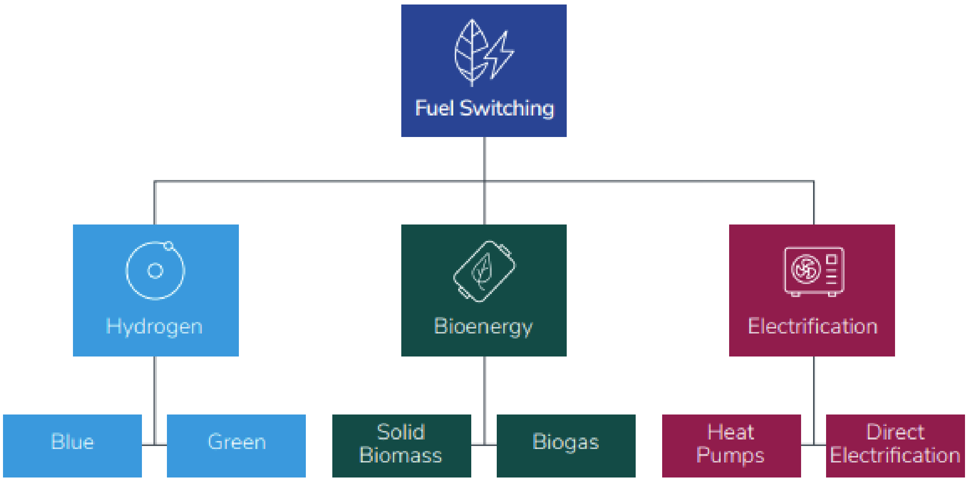
2.2 COMPETING FUEL SWITCHING OPTIONS

Fuel switching options can be split into three broad categories: hydrogen, bioenergy and electrification, as shown below[18]. The various technologies available can be complementary, meaning a distillery may choose more than one option to suit its requirements. In Ricardo's 2020 Scotch Whisky Pathway to Net Zero report, multiple decarbonisation scenarios are explored. These scenarios included "Green Gas" driven by increased uptake of biogas and hydrogen, "Electrification" whereby net zero is achieved through a significant deployment of heat pumps, and finally a "Balanced" approach that applies a combination of the key heat technologies well

[14] scotch-whisky-net-zero-report.pdf
[15] Energy Efficiency and Cost Saving Opportunities for Distilleries (ct.gov)
[16] Chivas Brothers: carbon neutral distillation by 2026 | Pernod Ricard (pernod-ricard.com)
[17] Highland Park Greenstills Demonstrator (publishing.service.gov.uk)
[18] pathways-to-industrial-heat-decarbonisation.pdf (ricardo.com)

within their maximum technical potential. The most appropriate option(s) for a specific site will depend upon the characteristics and constraints of its operations and location.

Figure 2 - Industrial fuel switching options[19]



There is often not a 'one size fits all' approach to decarbonisation, but rather the selection of the appropriate fuel is site-specific. For a distillery selecting a low carbon fuel, there are a wide number of factors to be considered, summarised in Table 1. There are a variety of competing fuel switching options, each with their own set of benefits and drawbacks. Practical and economic considerations affect the feasibility of adopting a certain technology or fuel type, as well as the policy landscape which may favour certain fuels above others. It is recommended that distilleries undertake a feasibility study to assess which low carbon fuels can fulfil their needs.

Table 1 Fuel switching considerations

Category	Considerations
Technical	Site constraints, such as: available capacity of electricity grid connection, land availability, location, proximity to gas grid, and water resource. Existing process and equipment on site Security of supply
Financial	CAPEX, OPEX, funding mechanisms available
Product	Quality, price, future proofing, brand value

2.2.1 Hydrogen

Hydrogen is one potential solution for industrial decarbonisation, particularly in processes that require high temperatures and are difficult and costly to electrify. Hydrogen is still a relatively nascent technology, and it is currently associated with higher production and distribution costs than other fuels.

There is growing interest among distilleries in exploring this option partly because, as a gaseous fuel, it resembles a familiar energy source. Of the sixteen BEIS Green Distillery Competition Phase 1 feasibility studies, published in 2021, nine proposed the innovative use of hydrogen. Four projects were granted Phase 2 funding to continue the development of their proposed fuel switching concept or solution through to demonstration, of which three focus exclusively on hydrogen and all of which are based in Scotland.

[19] Biogenic hydrogen and liquid biofuels are not shown as they are less widespread fuel switching options. Bioenergy can be equipped with CCUS to be deemed as carbon negative

Furthermore, major sprit producers are part of the North of Scotland Hydrogen Programme at Cromarty Firth, one of Scotland's 13 Regional Hydrogen Energy Hubs[20].

Published in December 2022, the Scottish Government Hydrogen Action Plan remarks that the remote nature of many distilleries across Scotland may promote hydrogen implementation. These rural sites are often hindered by grid constraints which limits the scope for both importing and exporting low carbon electricity. Hydrogen implementation using on- or near-site renewable power generation could be a favourable decarbonisation route for these distilleries.

As such, the relevance of hydrogen to the distilling sector is clear – this topic is investigated in more depth in Section 3 meanwhile further case studies are discussed in Section 4

2.2.2 Bioenergy

2.2.2.1 Biogas and Biomethane

Anaerobic digestion breaks down biodegradable materials in the absence of oxygen to produce biogas, a mixture of predominantly methane and carbon dioxide, and a resultant digestate. Biogas can be used in place of natural gas to generate heat and/or electricity. Biogas can also be purified, sometimes referred to as upgraded, to biomethane and used for transport fuel, transported to other sites or injected into the gas grid.

Some distillery co-products, such as pot-ale and draff, can be used to produce biogas. The Scotch Whisky Pathway to Net Zero report states that if all co-products from whisky making were processed in anaerobic digestion (AD) and if all of that biogas was used in the sector it would result in a 41% reduction in carbon emissions. However, there are a number of factors which govern both the viability of using the co-products for anaerobic digestion and the use of any resulting biogas. For example, AD systems take up a significant amount of space and come with significant requirements for regulatory compliance meaning they are unlikely to be suitable for all sites. Sites which are land constrained may choose to sell their co-products to a third-party AD organisation and purchase biogas back from the AD plant.

The co-products may also be used for other purposes, such as animal feeds, the extent to which waste should be apportioned to biogas production is a commercial decision and will depend upon the price received for the by-product as animal feed and the value of the fuel displaced by the biogas that AD would generate.

In 2018 Balmenach Distillery, near Grantown on-Spey, commissioned an AD system that processes pot ale and spent lees to produce biogas. Feeding a CHP engine supplying 200kW of power and 230kW of heat. The biogas, alongside a solid biomass boiler, meets over 100% of the distillery's energy requirements, with surplus electricity from the CHP engine sold to the grid[21].

The UK Government offers financial incentives to new anaerobic digestion biomethane plants to increase the proportion of 'green gas' in the UK's gas grid. Administered by Ofgem the 'Green Gas Support Scheme' (GGSS) pays participants quarterly for 15 years based on the amount of eligible biomethane they inject into the grid[22]. Adoption of the GGSS will not be viable for locations away from the gas grid. Consumers of gas from the grid who are on a 'green tariff' can be allocated a Renewable Gas Guarantee of Origin (RGGO) as evidence of their green gas consumption[23].

Biomethane production can also present an opportunity to decarbonise transport. For example, an AD plant in Speyside uses distillery co-products to fuel a fleet of bio-CNG heavy goods vehicles[24]. In the context of this study, transport decarbonisation has not been included.

Carbon dioxide from the fermentation process can be reacted with hydrogen to produce synthetic methane in a process known as methanation. This process is discussed further in Section 3.4.

Stakeholders engaged with for the purpose of this study estimated that if a typical distillery were to anaerobically digest 100% of their co-products to biogas, combustion of the fuel would meet 30-50% of the site's energy demand. Therefore, to completely decarbonise their operations the site would need to import

[20] Geographical areas that can host the entire hydrogen value chain - production, storage, and distribution to end-use

[21] Distillery installs £3M anaerobic digestion plant (foodmanufacture.co.uk)

[22] Green Gas Support Scheme and Green Gas Levy | Ofgem

[23] Certificates - Green Gas Certification Scheme

[24] Zemo Partnership, Opportunities for Biomethane as a Transport Fuel in Scotland, 2022

biogas or biomethane from elsewhere or use an alternative fuel such as hydrogen to compliment on-site biogas production.

2.2.2.2 Liquid Biofuels

Organic materials containing suitable naturally occurring oils can be used to produce liquid biofuels. One such example is biodiesel, which can be made from rapeseed oil and burned in most existing diesel engines.

Sites with a number of constraints, including space available and electricity supply can find it challenging to find a suitable location for technologies such as AD or even fuel storage of lower density fuels such as biomass. Where such constraints exist, one option would be to use liquid biofuels, particularly where fuel oils are already used.

Liquid biofuels are often used blended with conventional fossil fuel oils, such as diesel but 100% biofuel can also be used. The Oban Distillery switched to biofuel made from rapeseed oil in 2018 and has cut its carbon emissions by 98% since[25].

However, there is significant competition for liquid biofuels for other uses such as road transport vehicles and therefore a combination of cost and security of supply mean it is likely not to be suitable for every site. They may therefore play a role either for specific sites or to support a site's longer-term transition to other fuels.

Two of the Green Distilleries Competition Phase 1 feasibility studies investigated liquid biofuels. One of these proposed developing dual fuel hydrogen and bio-oil boilers[26]. The study examined the combustion of pot ale syrup from distilleries, and other bio-oils like crude glycerol and Hydrotreated Vegetable Oil (HVO). These would be burned downstream of natural gas initially, transitioning to hydrogen once it is available and affordable. The other study explored gasification of waste biomass and bio-oils in conjunction with a reactive fuel like ethanol, hydrogen, or natural gas to supply the gasifier heat requirement[27]. The organisation responsible for these studies, Colorado Construction Ltd, was awarded Phase 2 funding to further develop their novel biofuel gasification system – the only one not focusing exclusively on hydrogen.

2.2.2.3 Solid Biomass

In the context of renewable energy, biomass is organic material like wood which can be burned to generate heat, steam and electricity. Biomass systems can be for heat only, including steam, or combined heat and power (CHP). Most operational examples of biomass energy plants are in rural locations, close to commercial forestry plantations where biomass fuel is produced. In these locations sites can benefit from easier access to biomass than alternative fuels.

An example of a biomass CHP system using wood fuel to provide steam to a distillery and electricity to local homes can be found at Macallan Distillery in Craigellachie[28].

Biomass heat sources are slower to react than gas boilers and therefore take longer to ramp temperature up or down which can present operational issues to some sites, particularly smaller distilleries where there may be many separate distilling batches requiring a ramping up of heat demand. Moreover, biomass fuel takes up more space than fossil fuels and has different delivery and storage requirements, presenting a key challenge for some sites. There can also be concerns about security of biomass fuel supply for some sites, and its combustion products effect on local air quality.

The use of biomass in the UK was, until recently, driven by the Renewable Heat Incentive, however the scheme is no longer open to new applicants. As such, new biomass systems are likely to be viable in locations where the site has sufficient space for biomass fuel storage and where the site is located close to forestry plantations where biomass is produced.

2.2.2.4 Carbon Capture

One method of decarbonisation being deployed across industry is to capture carbon dioxide directly from processes or exhaust streams for storage or utilisation, which can take a number of forms.

One example is the use of biogenic fuels to produce energy with the resultant carbon emissions being captured and stored, known as 'BECCS' (Bioenergy with Carbon Capture and Storage). Since sustainable biofuels are

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[25] Greener whisky: Scottish distilleries working on reducing carbon footprint | Euronews

[26] Colorado Construction Engineering Lot 1 Phase 1: feasibility report (publishing.service.gov.uk)

[27] Batch gasification of distillery waste biomass for renewable distillery fuel (publishing.service.gov.uk)

[28] Speyside Renewable Energy Partnership CHP Power Plant

considered renewable, BECCS is thus considered a 'negative emissions technology' (NET). The UK Government is considering mechanisms to award negative emissions - options include support under the Contract for Difference (CfD) or under a UK Emissions Trading Scheme (ETS). There is an energy penalty associated with carbon capture which must be taken into consideration, but this reduces as the concentration of CO_2 in the exhaust stream increases.

For this reason, the fermentation step of alcohol production, which creates a CO_2 by-product, provides a sufficiently concentrated stream for carbon capture. This is being investigated by Herriot Watt University and the owners of Ardgowan Distillery, to realise the opportunities to capture, store and potentially use CO_2 produced by distilleries[29].

2.2.3 Electrification

2.2.3.1 Direct electrification

Carbon savings can be achieved by switching from fossil fuels to direct electric heating, even where grid electricity is used. Over the past two decades, the Scotland's electricity system has become far less carbon intensive due to the significant and growing portion of generation which is from renewable sources. Where electricity can be provided by renewable electricity from the site or through an arrangement such as a Power Purchase Agreement, the operating costs and carbon savings can be more beneficial than grid electricity alone.

One electrification solution for heat in distilleries is an electric boiler. These convert electricity to heat using a resistive heating element and can produce steam. Many sites would require an upgrade to their electricity connection capacity to move to electric heating, especially if located in rural areas, the costs will be very site specific, in some cases this could be prohibitively expensive. So practically this is likely to be an option where the grid upgrade costs are acceptable. The local Distribution Network Operator (DNO) can advise on the cost and time associated with upgrades for individual sites.

Some examples of distilleries going down the direct electrification route include[30]:

- North Point Distillery investing in a 500-litre direct electric-still (the largest commercially available) using power from Forss Wind Farm
- Beinn an Tuirc Distillers using hydro-electric power for their 220-litre copper pot still
- Sacred Spirits use of vacuum distillation running on a 100% green electricity tariff

Through literature review and stakeholder engagement it became apparent that small batch gin distillers, who import grain neutral spirit for their gin rectification process, may be suited to decarbonising via direct electric-stills.

2.2.3.2 Heat pumps

The electrification of heat via heat pumps is increasingly becoming an important part of the decarbonisation of industrial heat. The biggest advantage of heat pumps is their very high efficiency compared to combustion processes.

Heat pumps use electricity to compress a refrigerant, and upgrade heat to the temperature at which it is needed. The heat that is upgraded can be recovered from waste heat or naturally occurring heat in air or water. Heat pumps use less electricity than electric heaters, with the ratio of heat produced to electricity consumed being referred to as the 'Coefficient of Performance' (COP = thermal output power/electrical input power). The COP varies between systems and is dependent upon several factors including the temperature being supplied, the temperature of the heat source and the type of refrigerant. Depending on these factors, the COP of heat pumps can range from 2.0 – 6.0.

Heat pumps for space heating and low temperature hot water are already commercially available and in use. High temperature heat pumps (HTHPs) are now becoming available and can efficiently generate steam when there is a heat source of suitable temperature. There are commercially available heat pumps that can efficiently reach temperatures of 160°C, assuming waste heat of an appropriate grade is available on site. In the next decade, delivery temperatures could rise to 200°C through research and innovation.

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[29] Research collaboration will repurpose and reuse CO2 at new distillery - Heriot-Watt University (hw.ac.uk)
[30] How gin distilleries are harnessing renewable energy - Gin Magazine (gin-mag.com)

For distillery applications heat pumps producing the temperatures required for distillation would need to be able to recover heat from the process at adequate temperatures, which is possible on some sites but not others. The heat pumps and associated equipment, such as heat exchangers, pipework and power supplies require space which can be at a premium on some distillery sites.

They also require suitable electricity supplies and variations in the distribution network capacity mean that some sites will be more viable than others for heat pumps.

Due to the nascent stage of HTHPs, they have a high capital expenditure at present, but this is likely to reduce over time. The payback period for their installation largely depends on the relative price of gas and electricity, but recent experience of distilleries investigating this option is that the payback can be very long and reductions in plant costs would be needed for retrofit of HTHPs to compete with other means of generating steam.

For example, the feasibility study for Edrington distillery in Orkney, funded by the Green Distilleries Competition Phase 1, discusses the use of a high temperature heat pump to produce low pressure steam to displace coke used in the malting kilns[31].

A common theme from the Green Distilleries Phase 1 reports is that steam produced by HTHPs is lower in pressure than most stills are designed for. They also mention that the slower ramp rates that heat pumps achieve versus conventional heating methods necessitate additional measures like steam accumulators. Another constraint posed by heat pumps is the additional space they require over other alternatives. The 2020 Ricardo report the SWA estimates 20% of distilleries have insufficient space for heat pumps[32].

The feasibility report for Eden Mill Distillery, discussed in more detail under the 'Heat networks' section below, raises the concern that the peak heat load for their distillation required 100kW of heating at 120 °C, which could not be met by any heat pumps in the market at the time of their study[33]. However, low temperature heat pumps can be used in conjunction with other heating methods by pre-heating water before it is upgraded to the required temperature by another technology capable of doing so, such as hydrogen or bioenergy.

As part of their decarbonisation options appraisal, Inchdairnie Distillery conducted a feasibility study, in collaboration with Glasgow University, exploring the use of high temperature heat pumps to recover heat from a sprit still condenser and provide heat for mashing[34]. Modelling results for the proposed HTHP, indicated that 75% of the mashing energy requirements could be offset, equivalent to a reduction in 7.5% of the site's overall natural gas usage.

2.2.3.3 Heat storage

Technologies offering thermal storage allow a delay between heat generation and usage. This can make best use of intermittent energy sources such as wind turbines or photovoltaics (PV).

A feasibility study conducted for Highland Park Distillery in Orkney, funded by the Green Distilleries Competition, explores the use of a novel heat store technology which stores electricity and converts this to steam when required[35]. The geography of this site makes this solution economical – Orkney's remote, windy island location means that, during the windiest periods, it generates sufficient renewable electricity to meet 120% of its electricity demand. At these times, this leaves surplus renewable generation available to power the heat store which would otherwise be wasted. While this technology is predicted to be more cost effective for this site versus an electric boiler, heat pump or a hydrogen solution without thermal storage, the report explains the heat store itself is still at the early concept design stage.

Another Green Distilleries Competition Phase 1 winner, a collaboration between Heriot Watt University and Sunamp, who design thermal storage solutions, discusses a heat storage solution which uses a 'phase change material' (PCM). Again, the study concludes that the solution requires local renewable electricity generation but, in this case, this powers an electric boiler and heat pump, which feed heat to the PCM heat store to be used when required[36].

Storing heat means distilleries can reduce the capacity of the heat generation technology and store heat over time to release during times of peak heating demands. A heat source which can meet the peak demand, such

[31] Highland Park Greenstills Demonstrator (publishing.service.gov.uk)
[32] scotch-whisky-net-zero-report.pdf
[33] Eden Mill St Andrews Phase 1 Feasibility Report (publishing.service.gov.uk)
[34] Masters_Final_Publish.pdf (inchdairniedistillery.com)
[35] Orkney Highland Park Energy System: renewables heat whisky (publishing.service.gov.uk)
[36] A Large-Scale Phase Change Material Thermal Store (publishing.service.gov.uk)

as hydrogen, may still be required but only occasionally used. This combination would provide resilience while reducing the peak hydrogen demand. In a feasibility report for Uist Distilling Company[37], a 'Grid Scale High Temperature Energy Store' (GSHTES) is discussed, which takes grid electricity, generates heat using a resistive heating element, and produces steam when needed.

2.2.4 Heat networks

Heat networks feed heat from a central source to multiple end-uses, providing an efficient heating method for loads in close proximity to one another. When powered by a low carbon fuel, such as sustainably sourced biomass, the solution offers low or zero-carbon emissions heat at a lower cost than might be achieved with individual, distributed plants.

One contender in the Green Distilleries Competition selected for a feasibility study was Eden Mill distillery, who are currently relocating adjacent to an existing biomass-fired district heating network at the University of St Andrews Eden Campus. They propose joining the heat network, either on its primary side to obtain high grade heat for distillation or its secondary side to heat the mashing process, or to upgrade the secondary heat using a heat pump. The study also discusses the option of producing and burning hydrogen on-site using roof-mounted PV as the electricity source. It was concluded that the biomass heat network is the more favourable solution in this scenario due to the high carbon and cost savings for the lowest level of investment[38].

A challenge with this project came from the proposition of heating stills using hot water, which has a lower energy content than steam. To make this happen, certain modifications are required. These include the hot water having to be supplied at a higher flow rate, existing heating coils having to be replaced with a plate and frame heat exchanger and, potentially, the distillate flow rate becoming more challenging to control.

Another example can be found in Wick, which uses a combination of biomass CHP and a separate biomass boiler to feed heat and electricity to various domestic and non-domestic sites in the community, including Old Pulteney Distillery which purchases steam from the network[39].

There are relatively few heat networks in Scotland. The economic potential for future heat networks requires high levels of heat use within the area served, which distilleries can contribute significantly to.

[37] The Uist Distilleries Company Lot 1 Phase 1 Feasibility Report (publishing.service.gov.uk)
[38] Eden Mill St Andrews Phase 1 Feasibility Report (publishing.service.gov.uk)
[39] Ignis Wick Energy Centre and District Heating Scheme | FES Group Ltd (fes-group.co.uk)

2.3 BENEFITS AND LIMITATIONS OF DECARBONISATION OPTIONS

Table 2 Summary of key benefits and limitations of the main decarbonisation options

Decarbonisation option	Benefits	Limitations
Hydrogen	• Can generate very high process temperatures • Provides an opportunity to make use of renewable electricity that might otherwise be curtailed • Can provide an opportunity for distilleries to return to traditional direct firing, allowing product differentiation • Hydrogen can be used to a limited extent within existing plant without alteration. • In future, UK Government may decide to allow hydrogen to be supplied via the gas grid • Hydrogen combustion has ramp rates equivalent to conventional fossil fuel heating systems	• Least widely adopted decarbonisation option at present • Underdeveloped supply chain • Growth of hydrogen economy has been prevented by Catch 22 scenario • Cost of hydrogen is high at present but is likely to reduce • Lower volumetric energy density than natural gas • Distilleries would require adequate space for hydrogen storage • Additional safety considerations compared to conventional fossil fuels
Bioenergy	• Most common decarbonisation option for distilleries at present • AD makes use of distillery co-products (e.g. pot-ale, spent lees and draff) • When equipped with CCUS, can facilitate negative emissions, which may be rewarded in future by financial mechanisms • Biogenic carbon dioxide which arises from fermentation can be combined with hydrogen to produce synthetic methane, allowing decarbonisation with a fuel (methane) for which there is extensive experience	• RHI no longer available to new applicants • Combustion of solid biomass can negatively affect local air quality • Biomass may be difficult to access, and space is required for its storage • AD of all co-products arising at a distillery does not provide 100% of distillery heat demand • Large footprint of AD plants may be prohibitive for sites constrained by land availability • Degree of uncertainty surrounding the availability of sustainable solid biomass • Competing uses for distillery co-products (e.g. animal feed) • Solid biomass boilers have slower ramp rates than gas boilers • Running an AD plant is not within the core competencies of a distillery, so 3rd party involvement may be necessary.

Decarbonisation option	Benefits	Limitations
Electrification (Direct and Heat Pumps	• Can utilise excess power in locations with constrained renewable generation to manage price of electricity • Direct electric boilers: Similar performance and heat distribution philosophy to many conventional heating systems • Heat Pumps: Higher efficiencies than combustion processes • Heat Pumps: Facilitate pre-heating when in conjunction with higher temperature heating fuels, like hydrogen	• Large electricity demand may require costly incoming supply upgrade • For direct, this increases the likelihood that an upgrade to the electricity supply will be needed. • Heat pumps for steam not yet widely commercialised • For HTHP, steam pressure is too low for existing heat exchangers in stills, implying the need for retrofit • For HTHP, slower heating ramp rates vs. conventional heating systems which may be an issue for batch distilling • For HTHP, it requires additional space
Heat storage	• Makes use of intermittent power generation, such as wind and solar – particularly locations with constrained local renewable generation • Can allow reduced heating capacity, often in conjunction with another heat source that can meet peak heat demand (such as hydrogen) • Could facilitate economics of methanation by recovering and storing methanation waste heat for reuse in distillery.	• Some heat storage technologies are still at the design stage and not commercially available • Additional space is required
Heat network	• Efficient when multiple heat loads are close to one another • Distillery can concentrate on its core distilling activity, rather than energy supply	• Requires suitable location of heat loads to avoid excessive heat losses from distribution • Dependent on 3rd party for heat supply, so robust supply contracts have to be in place. • Where heat supplied from a network is as hot water rather than steam, upgrading the heat via heat pumps will be required and/or distillery modifications will be necessary

3. HOW HYDROGEN CAN BE USED

3.1 HEAT DEMAND AT DISTILLERIES

There are two notable demands for heat at a whisky distillery

- Mashing
- Distillation

In mashing, ground malt is dissolved in water heated to between 60-65°C. In this process the sugars are extracted from the ground barley to form a sugary liquid known as "wort". This wort is then passed on to the fermentation stage where live yeast feeds on the sugars producing alcohol (ethanol) and CO_2 and the wort is turned into a beer-like mixture known as "wash" The wash has an alcohol content of about 8% and this then passed on to the distillation step.

Distillation takes place in two steps. The first step is distillation in a wash still. Here the wash is distilled to produce a liquid distillate, called low wines, with an alcohol content of about 20%. This distillate is then passed on to a spirt still and the distillate for the spirt still has an alcohol content of 65-70%. From the spirit still, only the middle cut of the spirit is used in the final product. This middle cut is then mixed with water before being placed in oak barrels and is left to mature for a minimum of three years. The distillation step is by far the most heat intensive step and, by rule of thumb, about 85% of the heat demand at a distillery (without maltings) is consumed for distillation.

At most distilleries, the heat demand for mashing and distillation is satisfied by steam. Steam may be generated at medium pressure (5-10 bar g) in a boiler before being stepped down to 2-3 bar g, which is typical of steam conditions used at the stills. A small number of distilleries use direct flame heating of stills (e.g. Glenfiddich, Glenfarclas and Springbank) while some distilleries express a desire to go back to this traditional method of still heating, since it is known to impart deeper, richer, more characterful flavours to the distillate due to the creation of hot spots under the still. However, heat is overwhelmingly delivered to stills by steam.

An alternative indirect heat medium for distillation are thermal oils such as mineral oil. While not widely deployed across the industry, it has some perceived advantages including its low specific heat capacity, high thermal conductivity, ease of control and operability, and requires less space than equivalent steam systems. One of the Green Distilleries Phase 1 feasibility reports for the Benbecula Distillery on North Uist recommends that thermal oil is used at new build distilleries[40].

Distillation typically takes place as a batch process, but a small number of larger distilleries have continuous distillation in Coffey stills. Where batch distilling takes place, the demand for heat at the still can be quite variable and will peak at the start of a batch. This fact needs to be taken into account when considering options to decarbonise the heat for distilling. For example, steam generated in a boiler has advantages over High Temperature Heat Pumps (HTHPs) in so far as boilers can effectively respond to sudden variations in steam demand, whereas HTHPs, recovering and upgrading heat from the still condensers, are less able to do this. The response of biomass boilers to sudden changes in heat demand is typically not as good at that achieved with a fossil fuel fired boiler and that which would be achieved with a suitably sized hydrogen boiler.

Depending on the distillery, there may also be malting, whereby "green" malt (barley grains steeped in water) is cured by drying above a malting kiln. A minority of distilleries produce their own malted barley and so most of the malted barley consumed is produced by merchant malt producers. In the malting process, enzymes act on carbohydrates and convert them to sugars. About 10 distilleries in Scotland have their own malting operations.

3.2 HYDROGEN AND REUSE OF EXISTING INFRASTRUCTURE

The infrastructure to get heat to the heat-consuming processes of mashing and distillation is best considered in two parts: (1) Infrastructure to generate the heat, and (2) Infrastructure to carry heat to process. For existing distilleries, there is a natural preference to avoid changes to the heat consuming processes which might have an impact upon product characteristics. Each distiller's brand is of paramount importance, and the physical characteristics of the product is the most important part of the brand. As such, decarbonisation solutions which

[40] The Uist Distilleries Company Lot 2 Phase 1 Feasibility Report (publishing.service.gov.uk)

allow the retention of the current processes in as unaltered a state as possible are naturally preferred. For example, the implementation of TVR or MVR may require modification to the still condensers.

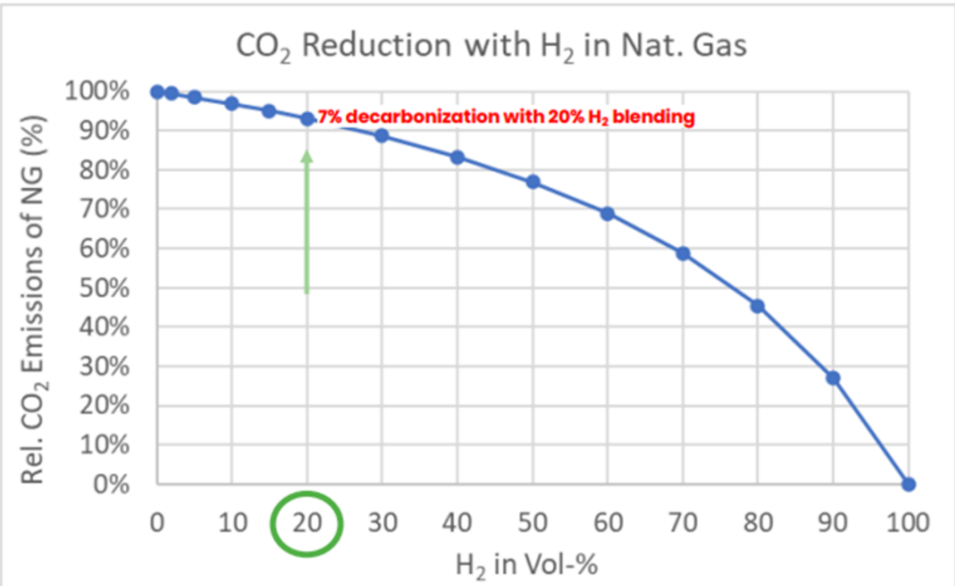
Regarding carrying heat to process, in the interests of reusing existing infrastructure to the maximum possible extent, being able to generate heat with the same grade as is currently used means that existing distribution networks and heat exchangers can be reused. In the case where steam is the heat carrying medium, this means generating steam with the same pressure. Achieving this is a particular advantage since heating the stills with lower grade steam or, indeed, medium pressure hot water would alter the rate of heat transfer into the still and require a change in flow rates that the existing heat exchangers may not be able to accommodate, necessitating heat exchanger replacement or even replacement of the still itself. This carries additional cost and the possibility of changes to product characteristics.

Regarding the reuse of existing steam generation boiler and fuelling them with hydrogen, equipment needs to be assessed on a site-by-site basis. The minimum requirement involves switching the burners with a hydrogen-compatible burner. However, experience obtained among the BEIS Green Distilleries Competition projects is that it is often necessary to change the boiler as well. A common experience is that, due to the lower calorific value of hydrogen relative to natural gas, the same boiler will suffer a reduction in steam generating capacity, so a larger boiler will be needed to deliver the same capacity. Moreover, in order to manage NO_x emissions caused by the higher flame temperatures produced by hydrogen, either lean combustion or dilution may have to be employed. In the first case excess air is used, and in the latter flue gas recycling may be employed. In both cases this leads to an increase in the size of the combustion chamber for the same output, again driving the need to replace the boiler. The experience cited by distilleries is that a 10-15% larger boiler might be needed to accommodate hydrogen.

However, boilers providing high pressure hot water or steam can typically utilise blends of up to 20% (by volume) hydrogen without any modifications being needed. Blends with greater concentrations of H_2 than this will begin to manifest the effects of hydrogen's greater flame speed and lower volumetric calorific value (when compared against natural gas), with the result that modifications/retrofit will be needed. There can also be material incompatibilities at higher concentrations of hydrogen.

While blends of natural gas and hydrogen up to 20% hydrogen may become available via the gas grid in the coming years - or mixes of this composition may be contemplated at sites with compressed natural gas and hydrogen deliveries – it should be pointed out that there is not a 1:1 relationship between the extent of hydrogen substitution and the reduction in carbon intensity of the resulting mixture. The lower volumetric calorific value of hydrogen means that, for the same energy delivered, a mixture of 20% green hydrogen will reduce the carbon intensity of the gas mixture by about 7%. The relationship between extent of hydrogen substitution in natural gas and CO_2 intensity of the resulting gas mixture per unit heat delivered is shown in Figure 3.

Figure 3 CO_2 reduction by percentage hydrogen blend (volume percentage)



Source: Ricardo calculations

A 100% hydrogen boiler is estimated to have a 22% higher capital expenditure than a natural gas boiler of the same capacity. This additional cost is driven by having a suitable burner for firing hydrogen with low NOx emissions[41]. However, some project developers engaged with indicated that buying a hydrogen ready boiler could be cost competitive with retrofitting an existing one for hydrogen, notwithstanding the issues mentioned above about loss of capacity. The likelihood that replacement is more cost competitive than retrofit increases with boiler age, especially since new boilers are likely to be more efficient than old boilers. Therefore, distillery operators should carefully consider their own individual circumstances regarding existing boiler capacity, present and future demands for steam and current boiler age when evaluating options to switch to hydrogen.

There are a range of industrial suppliers beginning to roll out boilers and burners, capable of running on blends of hydrogen up to 100%, in the anticipation that fossil fuels will be phased out gradually in favour of hydrogen once it becomes more widely available and cost competitive. Some organisations involved in this space include Byworth, Limpsfield, Bosch, Clean Burner Systems and Cochran.

3.3 PRODUCTION AND STORAGE OF HYDROGEN AT DISTILLERIES

3.3.1 Space Required for Production and Storage

3.3.1.1 Production

The generation of hydrogen on site will require space for electrolysers. There are mainly two types of electrolysers which are commercially available now. These are alkaline electrolysers and Proton Exchange Membrane (PEM) electrolysers. Alkaline electrolysers are much more established in the marketplace than PEM electrolysers and the two electrolyser types differ from each in terms of efficiency of turning electrical energy into hydrogen energy, operating pressures and temperatures, lifetimes, responsiveness to load changes and, of course, costs. This is discussed in further detail below.

However, as we have discussed elsewhere in this report, space availability is a determining factor for the hydrogen supply arrangements that are most suitable for a site; and the physical footprints of the two types are quite different. As a rule of thumb, for every 1 MWe of electrolyser capacity, an alkaline model will require 95m^2 of space, compared against 48m^2 for a PEM electrolyser[42].

For site with good land availability, either within the distiller site or adjacent to it, the generation of renewable electricity to power the electrolyser is a possibility. It is difficult to assess the amount of land required to generate renewable electricity of a meaningful quantity for the generation of hydrogen without doing a detailed assessment of land resources. However, it is possible to get an approximate feel for this using some rules of thumb, as follows:

For ground mounted PV, approximately 1 MWp of power can be installed in every 4 acres of land. The output of the installed PV array in terms of electricity generated in a year can be estimated by multiplying the capacity that can be installed by the number of hours in the year (8,760 hours) and multiplying again by the capacity factor. The capacity factor is highly location specific, but there are a number of tools available for finding this, including the following:

- **World Bank Solar Atlas (https://globalsolaratlas.info/map)**
- **Helioscope (www.helioscope.com)**
- **Renewables Ninja (www.renewables.ninja)**

Data from these sources can give greater levels of granularity on the variation of capacity factor across the year so a more detailed picture of hydrogen generation potential against hydrogen demand for specific periods of time can be built up.

For wind turbine generated electricity, once a wind turbine of interest has been identified, the efficient distribution of these across an area of available land, such that wind shadows do not impair the outputs of other turbines in the array which are down wind, can be determined by employing the rule of thumb that no wind turbine should be closer than 5 times the diameter of the wind turbine blades. The diameter of the wind turbine will be known. Then the annual yield can be estimated by multiplying the total capacity of the wind

[41] External research study hydrogen-ready industrial boilers (publishing.service.gov.uk)
[42] IEA The Future of Hydrogen – Seizing Today's Opportunities (2019).

turbine array by the number of hours in the year (8,760 hours) and multiplying the result by the capacity factor. The capacity factor is highly location specific, but there are tools that can be used to estimate this, including the following:

- **Renewables Ninja (www.renewablesninja.com)**
- **World Bank Wind Atlas (www.worldbank.com)**

Again, data from these sources can give greater levels of granularity on the variation of capacity factor across the year so a more detailed picture of hydrogen generation potential against hydrogen demand for specific periods of time can be bult up.

For Scotland as a whole, the average capacity factors for onshore wind and solar PV are shown below, based upon the total electricity generation figures for each source across the country in 2019 as defined in the Annual Compendium of Scottish Energy Statistics 2020[43].

Table 3 Annualised 2019 capacity factors for Scottish onshore wind and solar PV

Renewable Electricity Source	Installed Capacity (MW)	Capacity Factor 2019
Onshore Wind	8,400	26.1%
Solar PV	372	10.6%

3.3.1.2 *Storage*

A number of distilleries in Scotland are off the gas grid and therefore rely heavily on liquid fossil fuels and LPG to generate their heat. Sites in this position are therefore accustomed to taking delivery of fuels and setting aside space for storing them. Each distillery will have its own policy on the fuel inventory it needs to retain to guarantee continuity of distilling operations in the face of potential disruptions to delivery. In the absence of hydrogen being delivered via the existing gas grid, supply disruptions could be interruptions to physical deliveries of hydrogen to the distillery site or interruptions to the ability of the site to generate renewable electricity to produce its own hydrogen. Distilleries will likely wish to mitigate these situations by retaining back-up fuel supply (e.g. natural gas) and by retaining an adequate store of hydrogen.

This raises the question of how much hydrogen would a typical distiller need to store. Assuming that a malt distillery site producing 2 million Litres of Pure Alcohol (LPA) per annum currently consuming fuel for heat generation of 8 kWh/LPA wishes to have hydrogen storage to cover one week's operations, it would need to store about 8 tonnes of H_2. When stored as gas this would occupy the area taken up by 9 state-of-the-art tube trailers, each storing 900 kg at 300 bar. This is a significant inventory and distilleries will have to consider whether they have the space for this and, if not, would have to strike the right balance between storage space and the minimum delivery frequency necessary.

3.3.2 Water Requirements for Electrolyser

When carrying out water electrolysis on site to generate hydrogen, significant quantities of water may be required. The stoichiometric balance of water in electrolysis is for 9 kg of water to be used to generate 1 kg of H_2, with the remaining 8 kg generated as oxygen. But this is not the true requirement of water, as more water is needed to cool the electrolyser. While water and water treatment typically does not have a significant cost associated with it, it is nevertheless important to understand at the outset what the true water requirement might be, so that the existing situation at the site regarding water availability and wastewater treatment can be understood in proper context of hydrogen generation.

Water fed to the electrolyser has to be very pure and deionised. Reverse osmosis is typically used to first purify water being sent to the electrolyser and the electrolyser cooling system. About 20% of the water intake to feed these two would be sent to waste as water with concentrated contaminants at too high a level to be usable. Water destined for the electrolyser will then have to undergo a deionisation step, and this might reject about 20% of water fed to it, again as water with high levels of contaminants. Of the water actually sent to the electrolyser, a proportion of this would be rejected as wastewater (and therefore not used to generate

[43] ACSES+2020+-+December.pdf (www.gov.scot)

hydrogen) in order to manage the concentration of contaminants in the electrolyser. In all, for every 1 kg of H_2 produced by the electrolyser, about 15 kg of water may have to be extracted.

However, the largest demand for water in electrolysis would likely be cooling of the electrolyser. The demand for cooling water will depend on whether the electrolyser is cooled by evaporative or air cooling. If evaporative cooling is used then, for every 1 kg of hydrogen produced, around 40 kg of water might have to be extracted to balance losses from evaporation and the necessary blowdown of the system. If air cooling is used, then less water will be needed but at the expense of higher cost, more power consumption and larger physical footprint. In the worst case, with evaporative cooling, 55-60 litres of additional water may be needed for each 1 kg of H_2 produced[44]. However, the figures are based on international studies and the water requirement for evaporative cooling in Scotland will be lower.

It is useful to place these figures into the context of a distillery's current water use. What follows is an illustrative example of the additional water consumption that might result from hydrogen production at a distillery. For a malt distillery producing 2 million LPA per annum with a specific fuel consumption for heat of 8 kWh/LPA, assuming a worst case of 60 litres of water are needed per 1 kg of H_2, an additional 24 million litres of water might be needed, or 12 litres per LPA. Given the Scotch Whisky Association's water use range aspiration for water consumption in the range 12.5 to 25 litres water per LPA by 2025[45], attention should be paid to the water consumption for hydrogen production from electrolysis especially the component of water consumption associated with electrolyser cooling.

There are innovations taking place which could reduce freshwater consumption used as the feedstock for water splitting in electrolysis. Developments are underway of electrolysers which could be run on lower grade water feed, such as waste streams, allowing water recycling. Moreover, hydrogen combustion options, whereby pure water products of combustion are fed back to the electrolyser, are also under development.

Production And Storage of Hydrogen at Distilleries – Summary

Space Requirements for Production and Storage

- for every 1 MWe of electrolyser capacity, between 48 and 95 m^2 of space is required depending upon the electrolyser type chosen
- Assuming that a malt distillery site producing 2 million Litres of Pure Alcohol (LPA) per annum currently consuming fuel for heat generation of 8 kWh/LPA wishes to have hydrogen storage to cover one week's operations, it would need to store about 5 tonnes of H_2. When stored as gas this would occupy the area taken up by 9 state-of-the-art tube trailers, each storing 900 kg at 300 bar.

Water Requirement for Production

- For a distillery producing 2 million LPA per annum with a specific fuel consumption for heat of 8 kWh/LPA, assuming a worst case of 60 litres of water per 1 kg of H_2, an additional 24 million litres of water might be needed beyond what is required for distilling, or 12 litres per LPA

3.4 METHANATION

The challenges to employing hydrogen, particularly in a distillery, focus around the safety and capital expenditure to modify equipment to be fueled by hydrogen. As seen in the sections above, substitutions of natural gas with hydrogen beyond about 20% by volume involve changes requiring capital expenditure. Moreover, there are additional safety requirements arising from the storage of significant quantities of hydrogen and many distilleries will simply want to avoid the technical and administrative implications of this and concentrate on making whisky.

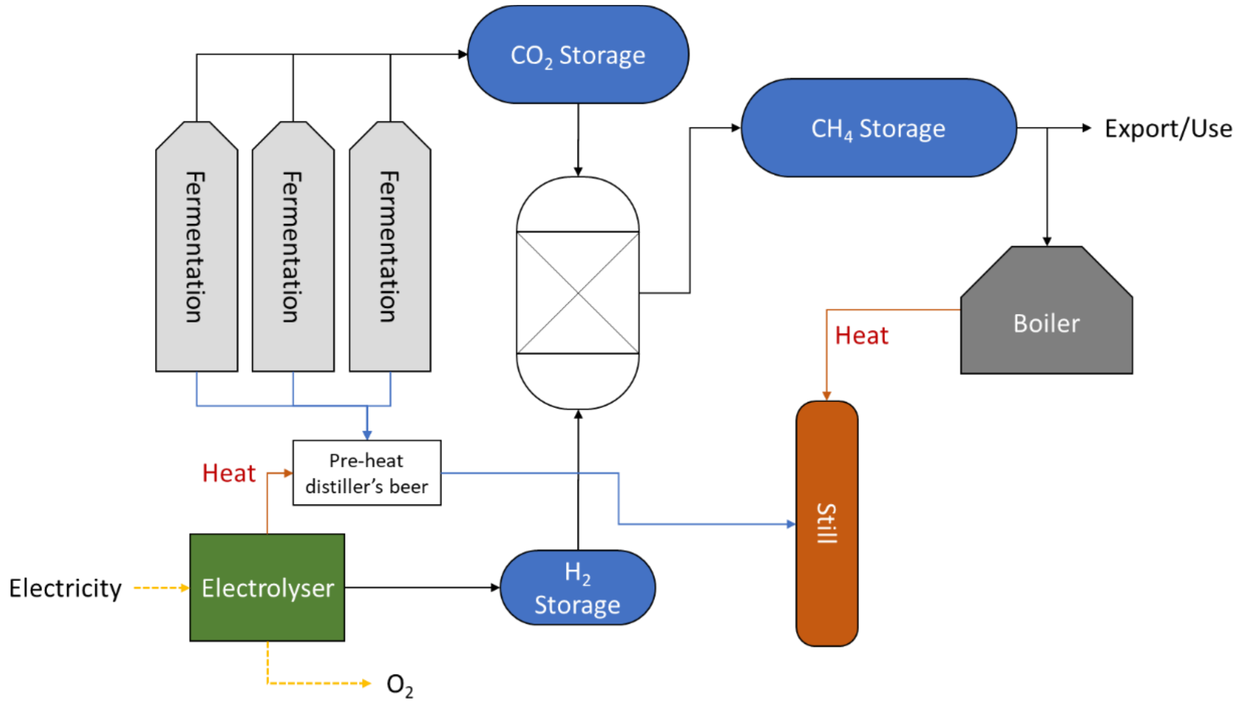
Methanation is an option that can simplify the transition by producing Synthetic Natural Gas (SNG) from hydrogen that is either imported or generated on-site. The SNG can be stored on-site – far simpler than the storing of green hydrogen produced on site – and can be used in existing combustion infrastructure. Sites off

[44] Water for Hydrogen - GHD
[45] Scotch Whisky: Water Use (scotch-whisky.org.uk)

the gas grid and using delivered compressed natural gas will essentially be replicating their current fuel storage arrangements, but this time with zero carbon methane.

The fermentation of wort to produce the wash, which is eventually distilled,produces carbon dioxide as a by-product. This carbon is effectively net-zero and many large scale breweries already recover it to utilise in downstream processes to remove the requirement to import CO_2. The reaction to produce SNG is called the Sabatier reaction, the reaction is either a catalytic chemical reaction that occurs between 200 and 500 °C at up to 30 bar, with a higher pressure favouring the thermodynamics[46]; or a biological process where bacteria metabolise the H_2 and CO_2 at 35-65 °C at pressures less than 10 bar[47]. Both processes are exothermic reactions reducing the heating requirement. The process is shown in Figure 3, which illustrates a potential integration of the methanation process with an electrolyser.

Figure 3 Process flow diagram and potential integration of a methanation process for a distillery



Methanation systems are currently being deployed at scale and have a Technology Readiness Level (TRL) of 7-9 with a number of demonstrations existing. Most notably is the Store&Go test site in Falkenhagen in Germany which has a 1 MW electrolyser and receives pure carbon dioxide from a bioethanol plant[48]. The referenced commissioning report provides greater detail of the processes including a detailed process flow digram. The Falkenhagen plant uses a catalytic process and reached an overall Power-to-Gas efficiency of 53%[49]. Store&Go have other demonstrations in Switzerland and Italy that are smaller, Audi have also had an e-gas project.

The catalytic process may be ahead as the process is effectively the reverse reaction of reforming which is used to generate blue or grey hydrogen, the latter being a widely deployed process. There is a commercial scale biological methenation process demonstrated in Switzerland by Hitachi Zosen Inova, they are now building a biological methanation process with a 2.5 MW Electrolyser and they also sell the technology[50]. Johnson Matthey produce catalysts for the catalytic methanation process and are likely to work with companies who can undertake EPC work to deploy the technology.

[46] Methanation of CO2 - storage of renewable energy in a gas distribution system | Energy, Sustainability and Society | Full Text (biomedcentral.com)

[47] Full article: Biological hydrogen methanation systems – an overview of design and efficiency (tandfonline.com)

[48] 2019-03-28_STOREandGO_D2.3_UST_accepted.pdf

[49] Germany | STORE&GO (storeandgo.info)

[50] Plant Construction - Schmack Biogas (schmack-biogas.com)

Other companies that have announced their own methanation systems include: Electrochaea, who produce the methanogenic biocatalyst for the Store&Go project[51]; ThyssenKrupp, who produce reactors, provide process design and can sell the whole packaged product[52]; Wood, who produce a catalytic system called VESTA that utilises syngas from gasification[53]; and also IHI Corporation of Japan, who produce a catalytic system[54].

The challenge for the technology is the electricity demand, Goffart de Roeck states that '... the electricity demand per MWh of SNG is 1.82 MWh to the electrolyser and 1.89 and 1.90 MWh electricity to the whole biological and catalytic pathway, respectively' and then they highlight the effect this can have on the (scope 2) emissions[55]. It can be concluded that a site would need excess low GWP electricity. There is extensive amounts of heat produced from either process due to the exothermic nature of the reaction. The biological and catalytic pathways produce 0.3 and 0.28 kWh/kWh_{HHV} H_2 from the exothermic reaction and exhaust heat from chillers, the waste heat from the biological pathway is available at 65 °C whereas the catalytic pathway produces heat at 270 °C.

Figure 3 highlights potential synergies of the production of SNG in a distillery as there is potential heat recovery that can be used in the process. The incorporation of an electrolyser on-site means that the operators can utilise cheap electricity to generate the hydrogen for use on-site (to convert to SNG) and in some cases continue to use grid gas to provide demand side cost control and site energy security. Glenmorangie distillery in Tain, Ross-shire, won funding from the Scottish Industrial Energy Transformation Fund to undertake a study on the potential for methanation and have been successfully trialling a methanation system produced by Hydrogen Green Power Ltd[56]. The plant has an output of 2 MW and generates 57 Nm^3/h of SNG.

Assuming the hydrogen is available and there is sufficient space for a methanation plant, then a distillery will likely produce enough biogenic CO_2 from fermentation to support the production of enough SNG to meet the majority of its heat demand. Other sources of CO_2 available at the distillery may include CO_2 from anaerobic digestion of distillery co-products, like pot ale, spent lees and draff.

[51] Electrochaea GmbH - Power-to-Gas Energy Storage | Technology
[52] Synthetic Natural Gas (SNG) | Power-to-X | thyssenkrupp (thyssenkrupp-industrial-solutions.com)
[53] VESTA methanation for renewable natural gas production | Wood (woodplc.com)
[54] IHI Launches Methanation System to Produce Fuel from Carbon Dioxide and Hydrogen | 2022FY | News | IHI Corporation
[55] Comparative life cycle assessment of power-to-methane pathways: Process simulation of biological and catalytic biogas methanation - ScienceDirect
[56] Michelin Development Supports Hydrogen Green Power's Green Growth (h2gp.co.uk)

3.5 HEALTH AND SAFETY AND HYDROGEN

The use or storage of hydrogen on site will require compliance with certain regulations and may introduce new ways of doing things for sites. Below we highlight the salient characteristics of hydrogen which must be taken into account when designing and operating plant, to ensure safe operations. From there we introduce and briefly discuss the regulations that would have to be complied with.

3.5.1 The Behaviour of Hydrogen

The following characteristics of hydrogen have the potential to pose health and safety risks which are new to a distillery:

Ignition range – The ignition range describes the composition range of hydrogen / air mixtures which can ignite. Outside of this range combustion cannot be sustained, either because there is too little oxygen or too little fuel. The ignition range of hydrogen is very wide at 4%-77%, in other words hydrogen air mixtures where hydrogen is present in volume percentages greater than 4% and less than 77% can ignite. The range for natural gas is 4%-17%. This means that, in theory, explosive atmospheres of hydrogen are much easier to create than explosive atmospheres with natural gas.

Ignition energy – The ignition energy of hydrogen is low at 0.02 MJ and this is about 1/10th that of methane. This means that hydrogen is much easier to ignite than natural gas. This low ignition energy means that building infrastructure features like lighting and heating could be viable ignition sources.

Density – The density of hydrogen is 1/14th that of air. This means that hydrogen will disperse rapidly out in the open and make it less likely that explosive atmospheres will be generated. However, in confined, inadequately vented spaces, the low density of hydrogen means that it will collect in elevated areas. This, combined with the wide ignition range and low ignition energy poses a risk. This risk is exacerbated by the tendency for lighting and heating infrastructure to be at higher levels.

Molecular size – Hydrogen is the smallest molecule and so the challenges of containing it in tanks and pipework is appreciable when compared to natural gas and this must be taken into consideration when selecting materials for tanks and pipework and making pipe joints.

Flame properties – Hydrogen burns very hot and with a colourless flame that radiates far less heat than a natural gas flame. The high flame temperature means that the creation of the pollutant NOx is more likely than for a natural gas flame and primary abatement measures need to be taken to reduce this, such as dilution with oxygen or the flue gases. The colourless flame means that it is difficult to detect by eye and this, combined with the low levels of heat radiated by the flame, means that it is possible to get very close to a hydrogen flame without detecting that it is there.

In spite of these risks, hydrogen is used very safely on many industrial sites, owing to adherence to a well-developed health and safety framework which identifies points of risk and measures to eliminate or mitigate the risk to safe levels. Part of the risk elimination and mitigation will likely include staff training and the use of equipment that is ATEX[57] compliant.

3.5.2 Relevant Health and Safety Regulation

The generation, storage and use of hydrogen on a site in Scotland has, depending on the extent of operations and other site specifics, the potential to bring the site under the following regulations. Only some of these may apply for a given distillery, but all relevant regulations are listed for the purposes of completeness. Some distilleries with on-site maturation warehousing may already have to comply under the DSEAR and COMAH regulations, but the storage of hydrogen on site could result in the site becoming regulated under a higher COMAH tier.

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[57] ATEX refers to the requirements set out in two Directives: (1) 99/92/EC, which relates to measures to protect the health and safety of employees at risk from explosive atmospheres, and (2) 2014/34/EU which relates to the type of equipment that can be used in areas where explosive atmospheres could develop.

Table 4 Potentially relevant health and safety regulations applying to the generation, storage and use of hydrogen

Name	Description
Dangerous Substances & Explosive Atmospheres Regulations (DSEAR) 2002[58]	These regulations provide approved codes of practice to protect employees AND members of the public from risks posed by fire, explosions gases under pressure and materials corrosive to metals. Employers are required to: • Identify dangerous substances and associated risks. • Apply control measures to control, reduce and/or eliminate the identified risks. • Apply control measures to reduce the impact of any event or incident involving dangerous substances. • Write and prepare plans and procedures to deal with incidents, accidents and emergencies involving dangerous substances. • Ensure employees are appropriately informed and/or trained to control and/or deal with the risks identified. • Classify and demarcate areas of a site where explosive atmospheres may occur and remove / reduce ignition sources in those areas. Typical areas included are point of use areas and storage areas. DSEAR also gives effect to two EU directives for controlling explosive substances, together known as ATEX, which indicate the required equipment and protective systems which must be used in zoned areas.
Town and Country Planning (Hazardous Substances) (Scotland) Regulations 2015	Storage or use of any hazardous substances above the designated threshold limits requires hazardous substance consent. Application approval and threshold limits are determined by your Local Planning Authority (via ePlanning Scotland). Threshold limit for Hydrogen is 2 tonnes gross mass storage, which equates to about 78 MWh (HHV) of fuel.
COMAH 2015[59] (Control of Major Accident Hazards)	Sites that fall under the COMAH regulations must take all necessary measures to prevent major accidents involving dangerous substances including: • Outlining general duties for operators • Major accident prevention policies • Preparation, review and testing of internal and external emergency plans (where applicable) • Provision for information to the public • Trans-boundary requirements • Measures in place to regulate documentation for safety reporting (where applicable) and inspections / investigations. Hydrogen tier thresholds: Lower tier status (gross Hydrogen storage) • 5 tonnes (~195 MWh HHV) Upper tier status (gross Hydrogen storage) • 50 tonnes (~1950 MWh HHV)

[58] DSEAR in detail - Fire and explosion (hse.gov.uk)
[59] COMAH - Guidance (hse.gov.uk)

Name	Description
	Note that an aggregation rule applies for the determination of the relevant tier when more than one dangerous substance is present. This means that, even though the storage quantities of two substances are individually both below tier thresholds, when considered in aggregate they may place the site into the upper tier. The obligations falling on the site within the lower tier are set out in COMAH Regulations 5, 6, 7, 17, 19, 23, 24 and 26. The obligations falling on the site within the upper tier include all those set out for the lower tier plus 8-13, 16 and 18.
The Pressure Systems Safety Regulations 2000 (PSSR)	This concerns actions for the prevention of injury arising from failure of a pressurised store of energy or component parts.
Industrial Emissions Directive	Combustion plant of capacity >3 MWth will have to comply with acceptable emissions levels for NOx. As discussed elsewhere in this document, due to the high flame temperature of hydrogen the chances of generating NOx are high.
Environmental Protection Act 1990	The act outlines provisions for the requirement to handle and dispose of hazardous waste appropriately and accordingly. In the context of hydrogen production in an electrolyser, the electrolyser will require a maintenance and servicing regime. Depending on the technology, hazardous waste may be generated (e.g. spent electrolyte in the case of an alkaline electrolyser), and the Environmental Protection and environmental permitting legislation will apply.

How Hydrogen can be used to Decarbonise Distilleries – Summary

From the proceeding sections, we can make the following summary about distilleries in Scotland

- Distilleries have heat intensive energy requirements
- Most of the heat demand at distilleries is for distillation, with some other lower grade demands for heat, including mashing. Demand for heat for malting occurs at a small number of distilleries where malting is collocated
- The majority of demand is currently met by natural gas and fuel oil, with about two-thirds of fuel for heat generation being from natural gas across the sector.
- Heat is predominantly generated and carried to process as steam
- Owing to an exacting clientele, there is an innate reluctance to make changes to the process which might have an impact on the characteristics of the product.

Given these characteristics of heat demand at distilleries, hydrogen has good potential to displace incumbent fuels because:

- It can generate the temperatures needed for steam raising
- Hydrogen is a gaseous fuel that can raise steam in a hydrogen ready boiler in the same way as incumbent fuels like natural gas and fuel oil
- Steam can be raised in the boiler with the same response times as existing boilers, which is important for process control
- The steam raised can be used with the existing steam distribution system (pipes and heat exchanges), maintaining existing levels of heat flow.

Therefore, viewing the issue technically as a heat generation and supply issue inside the distillery, hydrogen can be expected to work well as a decarbonisation option, if it has been produced with zero-carbon or low-carbon methods. However, this presupposes that hydrogen can be obtained on a reliable basis, at reasonable cost and can be stored in sufficient quantities to ensure continuity of operations. It is against these supply and storage criteria that distilleries will vary in how convenient a fuel hydrogen turns out to be, and differences in the supply and storage situation will be determining factors of the price of hydrogen.

To help distilleries understand the utility of hydrogen, we have developed archetypes in Section 5.2 relating to supply and storage possibilities which should cover the range of distillery types. We explain the considerations that distillery operators, falling into a particular archetype, should make when evaluating the potential use of hydrogen on their sites

4. CASE STUDIES

4.1 GRANT FUNDED PROJECTS TO DECARBONISE DISTILLERIES

Two of the major mechanisms that have allowed distilleries to study decarbonisation options are the Scottish Industrial Energy Transformation Fund (SIETF) and BEIS Green Distilleries Competition Phase 1 and Phase 2.

4.1.1 Scottish Industrial Energy Transformation Fund (SIETF) – Distillery Examples[60]

Table 5 SIETF examples relevant to the distilling sector

Organisation	Year	Study or Deployment	Technology
Glenmorangie	2021	Study	Synthetic methane from hydrogen and fermentation CO_2
Chivas Brothers Ltd	2021	Deployment	Deployment of mechanical and thermal vapour recompression
Whyte & Mackay	2022	Deployment	The installation of a steam boiler on Jura with biomass fuel burner and flue gas purification
Diageo	2022	Study	Electrification of heat that utilises on-site renewables to displace current natural gas use
GlenAllachie Distillery	2022	Study	MVR technology to recover vapour, compress it using renewable electricity and re-use to heat the still in the whisky distillation process.
Diageo	2022	Deployment	High temperature heat pump (HTHP) to use hot water from both the spirit condenser and wash condenser, conversion to low pressure steam for use within the stills, thereby reducing demand on the NG and biomass boilers

SIETF is expected to reopen for further rounds but there are no formal dates released at present.

4.1.2 BEIS Green Distillery Phase 1 Competition[61]

The purpose of the Green Distillery Phase 1 Competition feasibility studies was to develop the fuel switching concept to understand solution performance, market potential and to develop a costed pilot trial. A list of these, which total £1.01 million of funding, is shown in Table 6. Projects highlighted in **bold** were awarded Phase 2 funding to continue the development of their solution through to demonstration[62].

[60] Scottish Industrial Energy Transformation Fund (SIETF): winners and case studies - gov.scot (www.gov.scot)
[61] Green Distilleries Competition: Phase 1 feasibility reports - GOV.UK (www.gov.uk)
[62] Green Distilleries Competition: Phase 2 (Demonstration) successful projects - GOV.UK (www.gov.uk)

Table 6 BEIS Green Distilleries Competition Projects

Projects involving hydrogen	Projects not involving hydrogen
Awarded Phase 1 & 2 Funding Arbikie Distillery On-site electrolysis from on-site renewables and hydrogen boiler Ardmore Distillery WhiskHy: On-site supercritical electrolysis and hydrogen boiler Bruichladdich Distillery Project HyLaddie: Electrolysis using grid electricity and hydrogen boiler Colorado Construction (Livingston Test Centre) Gasification of waste biomass (with hydrogen, or others, as potential reactive fuel)	**Awarded Phase 1 Funding only** Highland Park Distillery HTHP to recover heat from wash still to offset malting kiln energy demand Uist Distilling Company Grid Scale High Temperature Energy Store (GSHTES) Sunamp Phase Change Material for high temperature thermal storage Cornish Geothermal Distillery Company HTHP utilising waste heat from geothermal power plant Atlantic Brewery and Distillery Switching fuel to carbon negative fugitive methane captured from slurry-lagoon AD Eden Mill Distillery Biomass District Heating[63] Highland Park Distillery High Temperature Heat Store
Awarded Phase 1 Funding only Colorado Construction (Livingston Test Centre) Hydrogen/biofuel burners Inchdairnie Distillery Hydrogen production from electrolysis and catalytic reforming of AD gas Uist Distilling Company Using hydrogen to heat thermal oil Environmental Resources Management Ltd Liquid Organic Hydrogen Carrier (LOHC) for transport to distilleries Edrington and Orkney Distilling Ltd HySpirits 2: Hydrogen supplied from Eday tidal energy site to fuel hydrogen boiler	

While Inchdairnie were not awarded Phase 2 funding, the distillery is in the process of purchasing a hydrogen-ready boiler that will initially run on natural gas but switch to hydrogen as soon as this becomes available[64].

[63] Hydrogen was assessed but ruled out in favour of biomass district heating
[64] 'This is an exciting time!' How Scotland's whisky industry went from bust to boom | Whisky | The Guardian

4.1.3 BEIS Green Distilleries Competition Phase 2

Four of the above projects were awarded Phase 2 funding and, of these, three focus exclusively on hydrogen. The exception is a project led by Colorado Construction and Engineering Ltd which aims to develop biofuel gasifiers that can be retrofitted to existing steam boilers.

Funding for Phase 2 will run until summer 2023, after which redacted reports are expected to be published on the Department for Energy Security and Net Zero (DESNZ) website. Details on the three hydrogen-only Phase 2 projects are provided below:

Table 7 Hydrogen focused BEIS Green Distilleries Competition Phase 2 projects

Distilleries Involved	Project Partners	Project Description
Arbikie Distillery	Locogen Logan Energy	Arbikie Distillery, located on a farm in Montrose, have installed a 1 MW onshore wind turbine, having received planning permission last year. Having been awarded up to £3 million, the wind turbine will provide power to an on-site alkaline electrolyser which will initially be sized at 500 kW before scaling up to 1 MW over time. An alkaline electrolyser was chosen based on cost and reliability compared to alternative electrolyser types. According to the Phase 1 feasibility study, the hydrogen will be compressed from 30 bar to 200 bar prior to storage. The current steam boiler's chamber is too small to permit the combustion of hydrogen and fall within Medium Combustion Plant Directive (MCPD) regulations[65]. Therefore, a new hydrogen-ready dual fuel burner and boiler has been installed, as of February 2023, to work alongside the existing oil-fired steam boiler to reduce the need for fossil fuel combustion gradually. No significant impacts to the day-to-day operation of the distillery are expected with the new boiler. Emissions of NOx will be kept to well under MCPD regulation limits through the adoption of flue gas re-circulation. From August 2023, the distillery expects to be using hydrogen.
Ardmore Distillery and Glen Garioch Distillery	Beam Suntory Supercritical Manufacturing Technology Centre (MTC)	WhiskHy[66], a consortium led by Supercritical, were awarded up to £2.94 million for Phase 2. Supercritical have developed lab-scale high pressure electrolysers which, once scaled-up to industrial scale, have the advantage of not requiring compression, thus potentially saving space for a distillery site. While the Phase 1 feasibility study focused on Ardmore Distillery, Phase 2 aims to scale-up the supercritical electrolyser to conduct an industrial trial at Beam Suntory's Glen Garioch Distillery. Glen Garioch has recently returned to direct-firing on its wash still. Therefore, it is expected that Phase 2 may involve a trial of hydrogen as the fuel for direct-firing applications. A further strand to the project involves investigating whether distillery wastewater can be used as part of the feed for the electrolyser to reduce the quantities of freshwater required.

[65] Arbikie Distillery begins work on hydrogen heating installation - Heating and Ventilation News (hvnplus.co.uk)
[66] WhiskHy project awarded £2.94M to advance high pressure zero emission hydrogen technology (supercritical.solutions)

Distilleries Involved	Project Partners	Project Description
		Beam Suntory, who operate five distilleries in Scotland, envisage green hydrogen as playing a role in their commitment to reduce emissions by 50% by 2030
Bruichladdich Distillery	Protium Green Solutions Ltd	Bruichladdich Distillery, and project partner Protium, were awarded up to £2.65 million for the HyLaddie[67] Phase 2 project. Located on the remote island of Islay, the distillery hopes to encourage wider adoption of hydrogen across the island's distilleries through a successful demonstration project. There is an aim to decarbonise Bruichladdich by 2025. Initially, Project HyLaddie intends to use renewable grid electricity to power an on-site electrolyser, with a longer-term plan to use a larger commercial scale electrolyser located off-site. One of the main challenges is the electricity grid constraints on Islay. Therefore, dedicated renewable power generation is being explored for large scale green hydrogen production to support island-wide decarbonisation. Phase 1 explored the feasibility of a Dynamic Combustion Chamber (DCC™) boiler whereby steam from combustion is condensed and returned to the electrolyser in a closed-loop fashion.

4.2 FURTHER CASE STUDIES FOR HYDROGEN AT DISTILLERIES

While the use of hydrogen as a fuel switching option for distilleries is still at a relatively early stage, there has been significant progress in the last few years. While the North of Scotland Hydrogen Programme at Cromarty Firth is the most high-profile project in development, there are some examples outside Scotland, in Japan, England and Ireland, that are worth highlighting

4.2.1 Cromarty Firth

The North of Scotland Hydrogen Programme, established through Opportunity Cromarty Firth, is an initiative in Northern Scotland to develop a green hydrogen hub in the Cromarty Firth Area for industrial, transport and domestic applications. The project is led by a consortium of companies with support from the Scottish Government.

The project will construct and operate one of the largest electrolyser plants in the UK at 30-35 MW, with the goal to produce up to 14 tonnes of green hydrogen per day by 2024[68]. The electrolyser will be located directly east of the Beinn Tharsuinn Windfarm and be solely powered by renewable energy. The development of this electrolyser project has completed its scoping stage with the planners at Highland Council[69].

Cromarty Firth, in 2023, won its bid to become one of Scotland's first green freeports, in addition to the Firth of Forth. A new initiative aimed at creating designated areas in ports that will promote sustainable economic growth, create new jobs, and support the transition to a low-carbon economy. These freeports will operate within a set of guidelines and incentives that are designed to encourage investment in renewable energy, low-carbon technologies and sustainable infrastructure. As a result, Cromarty Firth will be granted special economic status, allowing tax break benefits (such as reliefs on Land and Business Transaction Tax[70] and

[67] Bruichladdich Distillery Announces £2.65M Funding to Partner with Protium and Jericho Energy Ventures on Major Step Towards Decarbonisation Distillation — Protium

[68] Green Hydrogen | Opportunity Cromarty Firth | Low Carbon

[69] 22/04169/PAN | Erection and operation of a hydrogen electrolyser plant and associated infrastructure | Land 2480M East Of Beinn Tharsuinn Windfarm Edderton (highland.gov.uk)

[70] Land and Buildings Transaction Tax - Green Freeports Relief: consultation on proposed legislation - gov.scot (www.gov.scot)

non-domestic rates) and simplified customs procedures within designated sites to encourage businesses to invest and grow.

The North of Scotland Hydrogen Programme 'Distilleries project' identified several distilling sites in the region suitable for the offtake of hydrogen. Support for the project includes ScottishPower, Storegga, Glenmorangie, Whyte & Mackay, and Diageo. Scaling up the electrolyser capacity to 300 MW is a future target for the project.

4.2.2 Project Examples Outside Scotland

Hakushu Distillery[71] - Suntory is a Japanese beverage company that has produced whiskey for many years and has now, in collaboration with Yamansahi Prefecture, signed an agreement to develop a hydrogen production plant to run the Hakushu Distillery, as well as a nearby water processing plant. Plans include the installation of Japan's largest 16MW Yamanashi Model Power-To-Gas system to be completed by 2025 and produce enough green hydrogen to completely power the distillery and water treatment plant, with surplus hydrogen said to be utilised by surrounding communities. Of the approximately £87 million investment cost, £62 million will be paid by Japan's New Energy and Industrial Technology Development Organisation (NEDO) through its Green Innovation Fund.

Pernod Ricard Midleton Co. Distillery, Ireland[72] **-** In 2022, Pernod Ricard announced it will invest €250 million to build a new, state-of-the-art distillery. The distillery will be situated on a 55-acre site and distil pot still and grain whiskey and, should planning applications run smoothly, construction will begin in 2023 and be operational by 2025. Plans have been confirmed to incorporate green hydrogen (transported to site) and biogas into its energy mix, and to employ MVR technology thus demonstrating a mix of decarbonisation options.

Surrey Copper Distillery, England[73] **-** Through the deployment of AFC Energy's H-Power Tower fuel cell, the Surrey Copper Distiller has produced gin using green hydrogen supplied from a 3rd party. Normally, the batch distillation takes place by an electrically driven steam boiler. In the case of a special edition gin, the electricity for the steam boiler was provided from a fuel cell

[71] Suntory | News Release | Suntory and Yamanashi Prefecture Sign Basic Agreement to Decarbonize Suntory Hakushu Distillery and Suntory Minami Alps Hakushu Water Plant Using Green Hydrogen

[72] Irish Distillers announces plans for Midleton Distillery to become carbon neutral by 2026, using break-through emissions reducing technology | Pernod Ricard (pernod-ricard.com)

[73] Hydrogen powered gin - AFC Energy

5. TECHNO-ECONOMIC IMPLICATIONS

This chapter presents the techno-economic implications of distilleries adopting hydrogen. It is broken down into the following items:

- Hydrogen Requirements for Distilleries
- Fuel Supply Archetypes
- Hydrogen Prices and Forecasting

5.1 HYDROGEN REQUIREMENT FOR DISTILLERIES

Whisky distilleries can be divided into two main categories, grain and malt, with the latter generally requiring more energy for each litre of pure alcohol (LPA) produced. As a rule of thumb, typically 80-90% of energy consumed is related to process heat. The estimated hydrogen demand for distilleries, shown in Table 8, was determined using the typical energy requirement for grain and malt distilleries, as expressed in the Scotch Whisky Pathway to Net Zero report[74]. It must be noted that energy requirements vary significantly from distillery to distillery. Therefore, individual sites would require an assessment of their current energy efficiency levels to ascertain future hydrogen requirements.

Hydrogen uptake in distilleries will take place in a phased manner. The annual hydrogen requirement for distilleries to switch to 100% hydrogen is shown in Table 9. For the purposes of this study, it is assumed that the efficiency of a hydrogen boiler is the same as a natural gas boiler.

Table 8 Estimated hydrogen demand for heat per LPA produced

Distillery category	Hydrogen demand (kg/LPA)
Grain	0.093
Malt	0.177

Table 9 Requirement of hydrogen for heating purposes in distillery categories

Distillery category	Typical spirit production (million LPA/year)	Estimated hydrogen demand (tonne/year)
Grain	20 – 100	1,900 - 9,300
Large Malt	>5	900 - 3,500
Mid Malt	1 – 5	180 - 900
Small Malt	<1	18 - 180

In a recent study conducted by Element Energy on behalf of Scottish Enterprise[75], the potential use of hydrogen in Scotland was estimated across a range of industrial sectors, including whisky distilleries. The annual theoretical potential hydrogen demand for distilleries is estimated to be 1.4 TWh. After fossil fuel refining and the chemical/pharmaceutical sector, distilleries are identified as the third largest potential demand source for hydrogen.

5.2 FUEL SUPPLY ARCHETYPES

As discussed in Section 3, heat is usually delivered to the distilling process via steam generated in a boiler. Therefore, the production process adaptations that must be made for a site switching from fossil fuels to hydrogen do not vary greatly from site to site beyond what has been described in 3.2.

[74] Scotch Whisky Net Zero Report

[75] Element Energy and Scottish Enterprise, *Hydrogen Demand in Scotland – Industrial Applications* (2023)

The major difference between sites is the means by which hydrogen could be supplied. Six fuel supply options have been identified as part of this study. A distillery selecting the hydrogen route can choose one or more of these options, depending on its characteristics. The most important considerations that determine which options are most applicable for a given distillery are electricity constraints, land availability, water resource and whether a site is on or off the mains gas grid.

Hydrogen may be deployed in conjunction with other low carbon fuels, as discussed in Section 2. Three options relate to on-site hydrogen production via electrolysis and three options relate to the supply of hydrogen from a 3rd party. The fuel supply archetypes are summarised below:

Figure 4 Schematic of fuel supply archetypes for distilleries

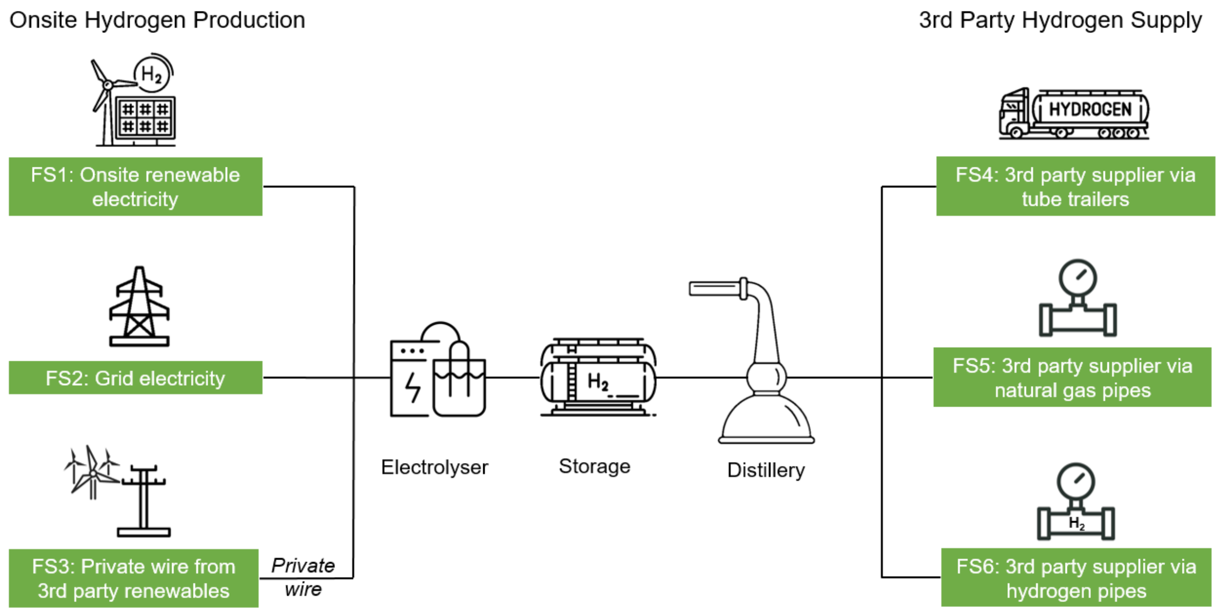

Table 10 Fuel Supply Archetypes

On-site hydrogen production via electrolysis	FS1: On or near-site renewable electricity
	FS2: Grid electricity
	FS3: Private wire electricity from 3rd party renewables
3rd party hydrogen supplier	FS4: Via tube trailers
	FS5: Via dedicated hydrogen pipes
	FS6: Via hydrogen injected into natural gas pipes

5.2.1 On-site hydrogen production via electrolysis

For distilleries that have sufficient land availability and water resource, on-site hydrogen production by electrolysis is an option. This solution has been proposed by several of the BEIS Green Distilleries projects, most notably the Arbikie Distillery, which will comprise a 1 MW onshore wind turbine, electrolyser, compressor, and hydrogen storage facility as part of the Phase 2 grant funded project.

On-site hydrogen production means sites do not incur transportation costs from a third party. Sites with renewable electricity generation assets, such as wind turbines or solar PV, in rural locations, often cannot export excess electricity due to grid constraints. Therefore, having on-site hydrogen production and storage can avoid curtailment of electricity generation. Distilleries could become self-sufficient in terms of their fuel supply, and this can greatly reduce exposure to external factors determining the price.

A potential drawback to on-site production is that it may become a distraction to a site's core business activities, which is of course making spirits of high, consistent quality.

For distilleries that are unable to install their own renewable electricity generation plant, either due to land availability or other planning constraints, the use of electricity from the grid or from a private wire connected to a third-party renewable energy supplier, such as a wind farm, could be an option. Adopting the first of these means that the generated hydrogen will not be 100% green, until such time as the electricity grid is fully decarbonised, although it is possible to purchase electricity from the grid that is certified as zero carbon by the supplier. A combination of on-site renewable power generation and grid electricity could be an option for sites who cannot produce sufficient hydrogen from on-site renewables alone.

5.2.2 3rd party hydrogen supplier

Rather than producing hydrogen on-site, an alternative solution is to purchase low carbon hydrogen from a third-party supplier which could be either green or blue hydrogen. The most common and simplest way hydrogen is supplied to end-users is via tube trailers. A typical trailer has a capacity of around 300 kg of hydrogen, with higher capacity trailers at 600kg and 900 kg starting to become available on the market[76]. In the short term, this is the most likely supply route for distilleries.

Another option for third-party supply is through gas pipelines, which could be achieved through a new private hydrogen pipeline now or, in the future, by connection to the national gas grid. Many distilleries in Scotland are off the national gas grid - for example island distilleries - and therefore the grid fuel supply option is not open to them. In 2023 the UK government is intending to make a policy decision on whether to allow up to 20% hydrogen blending by volume in the UK gas networks[77]. The aim is to ensure there is demand from hydrogen produced in the industrial clusters, to drive investment into infrastructure and equipment. The decision is likely to be approved and may lead to some older equipment needing to be replaced or upgraded. Figure 3 shows the limited reduction in CO2 emissions that a 20% hydrogen blend would create, however at a national scale it has the potential for large savings in emissions. Production quantities mean that a blend as high as 20% is unlikely to be seen in the short term. Towards the latter half of the decade, sites in proximity to the Acorn project at St Fergus may see percentages of hydrogen up to 20% in the gas grid if it is delivered by pipeline, and this will create a modest decrease in emissions of up to 7%. By the early 2030s, 25% of the UK's transmission network (high-pressure long-distance transport) will have been converted by National Grid to connect industrial clusters around the country. This is part of *Project Union* which is currently assessing pipeline routes and the readiness of existing assets to incorporate hydrogen[78]. The project will form the UK's hydrogen backbone and may also connect to the European Hydrogen Backbone. One example of such a route will connect clusters in Grangemouth to the Acorn production terminal at St Fergus. At this point, some gas grid connected distilleries may be able to connect to a hydrogen cluster, however future policy detail is required to know how other sites receiving gas will connect. Further to this, it should be noted that the Scottish Hydrogen Action Plan states that some parts of the gas grid in Scotland will be converted to 100% hydrogen in the 2030s and subsequent decades. This is subject to decisions that will be made at the UK level, currently set at 2026 (as stated in UK Hydrogen Strategy[79]) but a recent Hydrogen Champion's Report recommends that the government adopts a "minded-to" position by 2023[80].

An advantage of hydrogen supplied via pipework and used directly in a boiler is that storage of hydrogen would not be required. Hence, this supply option is highly relevant to sites which have space constraints. However, uncertainty remains about the likelihood and timeframes for hydrogen blending in the gas grid.

5.2.3 Factors influencing Fuel Supply Archetypes

The most important factors influencing the appropriateness of the six fuel supply archetypes were determined through stakeholder engagement and literature review. A summary of these, alongside each archetype, is shown in Table 11.

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[76] Hydrogen - UKPIA

[77] BEIS (2022), *Hydrogen Strategy update to the market: December 2022.,* Hydrogen Strategy update to the market: December 2022 (publishing.service.gov.uk)

[78] National Grid Gas Transmission (2022), *Project Union Launch Report.,* https://www.nationalgas.com/document/139641/download

[79] UK Hydrogen Strategy (publishing.service.gov.uk)

[80] Hydrogen Champion Report: Recommendations to government and industry to accelerate the development of the UK hydrogen economy (publishing.service.gov.uk)

Table 11 Factors influencing fuel supply archetypes

	Fuel Supply Archetype	Access to gas grid	Electricity grid constraints	Space/Land Availability	Water Resource	Other factors
FS1	On-site hydrogen production – on- or near-site renewable electricity	Not applicable	Required for export of excess renewable electricity to the grid or to import grid electricity when renewables unable to satisfy hydrogen demand. Additional grid capacity may need to be secured	Requires most land availability of all archetypes Space needed for • Renewables • Electrolysis • Compression • Hydrogen Storage	Requires adequate water supply for electrolysis beyond what is required for distilling operations. Some additional wastewater treatment will be necessary.	Excess hydrogen could be exported off-site or used for other purposes such as transport applications or for ammonia production Requires planning consents for wind and/or PV on-site owned by distillery
FS2	On-site hydrogen production – grid electricity	Not applicable	Site required to have substantial grid connection or ability to increase grid capacity	Space needed for • Electrolysis • Compression • Hydrogen Storage	Requires adequate water supply for electrolysis beyond what is required for distilling operations. Some additional wastewater treatment will be necessary	Electricity grid will take time to fully decarbonise Applicable for sites where there is no access to renewable electricity. Although it is possible to purchase electricity from the grid that is certified as zero carbon by the supplier. Cost of electricity will be high.
FS3	On-site hydrogen production – private wire electricity production from 3rd party renewables	Not applicable	Requires installation of private wire to 3rd party renewable energy project May require substantial grid connection capacity to make-up for shortfall in renewable electricity supply	Space needed for • Electrolysis • Compression • Hydrogen Storage	Requires adequate water supply for electrolysis beyond what is required for distilling operations. Some additional wastewater treatment will be necessary	Requires renewable energy supply (e.g. onshore wind farm with high levels of curtailment) that can be connected to distillery Requires strong and long-term relationship with 3rd party renewable energy supplier

	Fuel Supply Archetype	Access to gas grid	Electricity grid constraints	Space/Land Availability	Water Resource	Other factors
FS4	3rd party supplier via tube trailers	Not applicable	Not applicable	Requires space for storage, either in the form of trailer bays or fixed storage Requires less space than archetypes 1, 2 and 3	Not applicable	Requires suitable transport links for regular tube trailer deliveries. More applicable for sites with experience of fuel deliveries by road. Transporting hydrogen from mainland to island site could be challenging and costly compared to local, island scale H2 generation and road distribution.
FS5	3rd party supplier via hydrogen in natural gas pipes	Requirement This archetype is not suitable for any distillery off the gas grid e.g. island distilleries	Not applicable	Not applicable	Not applicable	High degree of uncertainty surrounding when and to what extent the gas grid will decarbonise using hydrogen. Initial proposed blend is 20% by volume. If approved by legislation, any distillery on the gas grid would receive some hydrogen via this route Not appropriate for distilleries with time-sensitive net zero targets i.e. net zero by 2030
FS6	3rd party supplier via dedicated hydrogen pipes	Not applicable	Not applicable	Not applicable	Not applicable	Best when in proximity to a hydrogen production project or part of low carbon hydrogen cluster. Otherwise, installation of new hydrogen pipeline for long distances could be expensive.

Fuel Supply Archetypes – Summary

- Any distillery connected to the national gas grid will likely receive some hydrogen in future -up to 20% by volume blending is expected, depending on UK Government policy decision in 2023, but may increase above this in future.
- On-site hydrogen production requires land availability for electrolysis, compression, and storage. Where on-site renewable power generation is feasible, this can be used to produce hydrogen.
- Where on-site renewable power generation is not feasible or insufficient to meet hydrogen demand, the alternatives include using grid electricity or a private wire from a third-party renewable energy project to power the on-site electrolyser.
- The capacity of electrical grid connection will likely require upgrading should grid electricity be used to power an on-site electrolyser.
- Water resources, beyond those required for distilling, must be considered for on-site hydrogen production.
- Hydrogen supplied from a third-party via tube trailers is the most likely option where land or water constraints prohibit on-site hydrogen production. In this scenario only space is required for storage, either as tube trailer bays or fixed storage.
- Distilleries which are part of a low carbon hydrogen cluster could potentially receive hydrogen by a dedicated pipeline.

5.3 HYDROGEN PRICES IN SCOTLAND AND FORECASTS

The cost structure of hydrogen, required to decarbonise heat applications for distilleries in Scotland, is composed of several systems with different costs. A discussion of the different cost structures is presented below through literature review. Section 5.3.5 presents cost ranges for the fuel supply archetypes and three periods of time (pilot phase until 2030, development and growth phase between 2030 – 2040 and mature phase after 2040). These cost figures can vary greatly and there are a number of uncertainties associated with each component, including market upscaling, technical maturity, variations due to different sizes and supply chain. This section aims to familiarise Scottish distilleries with the different cost components and the expected future cost per kg of hydrogen. Each distillery can use its own specific fuel consumption (kWh/LPA) to derive an understanding of hydrogen costs relevant to their distillery

Our findings in costs and prices come from publicly available economic assessments. It is expected that commercial contracts will find price levels that differ from these economic assessments for commercial reasons. These commercial factors include:

- The need for commercial benefit for the hydrogen producer and hydrogen user
- The producer's need to comply with the requirements of the support mechanisms accessed
- The user's need to remain competitive
- The assessment of risk and how this is priced

Hydrogen commercial prices, whereby hydrogen is supplied by a third party, are subject to a number of variables. In the long run they generally reflect supply and demand. Commercial prices differ from the levelised costs of production as they include profits, contingencies, mark-ups, and other financial metrics which are difficult to predict during the current period when the market for hydrogen is being established. After assessing several literature sources and other publicly available media, we have arrived at the following observations:

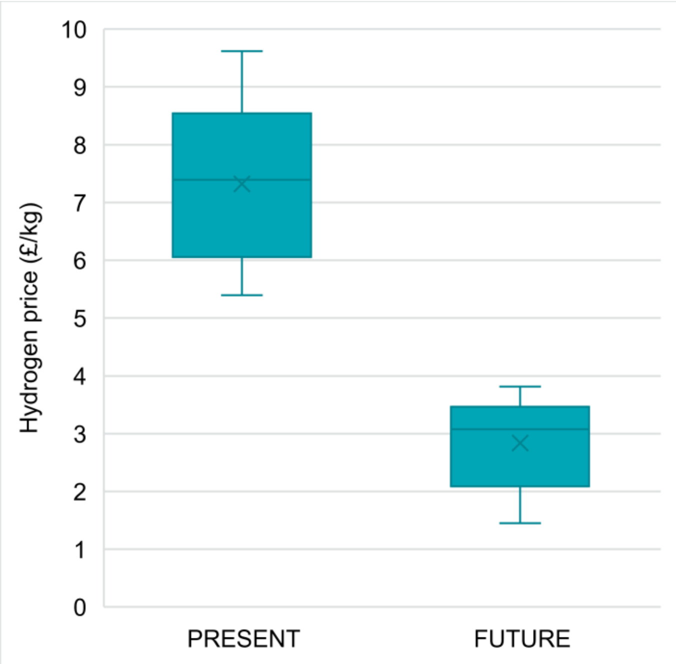
- At present, mainly grey hydrogen is available at scale which is not suited for the decarbonisation of distilleries. Because grey and blue hydrogen prices are dependent on natural gas prices, they are liable to current affairs like war and Covid-19 influencing their price. As ING[81] illustrates, blue and grey hydrogen prices have tripled from £1.75 to £5.30 per kgH_2 in recent times. The grey hydrogen commercial price is also affected by carbon taxation and other policies.
- Distillery owners must be aware that both blue and green hydrogen costs are linked to the price of gas and electricity feedstocks, respectively, and so they will depend upon the contractual arrangements that the producers and suppliers have made with their feedstock providers.
- Until market formation, distilleries are expected to secure fixed hydrogen price contracts backed by potential subsidies so that the business case can capture the high volatility of other markets (gas and electricity). This is shown in S&Ps Hydrogen Platts Assessment[82] which present a high volatility in green hydrogen prices ranging between £4 – 6.4 per kgH_2 within a one-month period. Another example is that of December 2022, when a combination of low wind resource and cold weather brought the hydrogen price to around £25 per kg in the UK. Price volatility and broad price ranges are also seen in retail hydrogen prices for mobility applications.
- Limited evidence of green hydrogen commercial prices exists which makes it challenging to draw concrete conclusions. An article by FuelCellWorks[83] from January 2023 indicated that Octopus was marketing its supplies starting at £5.5 per kg of green hydrogen. A survey of hydrogen sale prices published on the Mission Innovation Hydrogen Valley Platform[84] in Europe indicates the most common sale price of hydrogen is €6-8 per kg at present. Meanwhile, CE Delft[85] reports a 10% profit margin on green hydrogen production costs, resulting in 2030 commercial prices of €4.3 - 7.2 per kg. Distilleries will need to engage with a number of suppliers to identify the most commercially advantageous offers available.

[81] High gas prices triple the cost of hydrogen production | Article | ING Think
[82] Hydrogen Price Assessments | S&P Global Commodity Insights (spglobal.com)
[83] Cold December Boosts Hydrogen Production Costs, As Market Price Indications Emerge (fuelcellsworks.com)
[84] Hydrogen cost and sales prices | H2Valleys
[85] CE_Delft_210426_50_percent_green_hydrogen_for_Dutch_industry_FINAL.pdf (cedelft.eu)

- Most opinions and forecasts from stakeholders in the hydrogen supply chain agree that the commercial price of hydrogen will drop in the future as a result of market upscaling, improvements to technology and reductions in electricity costs from larger renewable electricity generation. For example, Fraunhofer[86] indicates that a financially favourable use of hydrogen is feasible at wholesale prices below €90/MWh (~€3.5 per kg) in 2045 depending on the end-use application. The report from the Gas Goes Green[87] project shows that green hydrogen from excess renewables will be competitive with blue hydrogen towards 2030 and green hydrogen from dedicated renewables will be competitive with blue hydrogen between 2040 and 2045. The report suggests that the levelized cost trajectory for green hydrogen will follow a similar trend that solar and wind have over the past decade.

The foregoing, in addition to further literature review, allows us to estimate indicative current (now until 2025) and future (from 2040 to 2045) commercial price ranges for renewable and low carbon hydrogen. These are presented in Figure 5 and show the range of expected prices using a box and whisker diagram. If distilleries can secure longer term supply contracts, then prices towards the lower end of these ranges could be possible.

Figure 5 Range of commercial prices of renewable and low carbon hydrogen found in public sources for present (until 2025) and future years (2040-45)



5.3.1 Green Hydrogen Production Costs

Green (or renewable) hydrogen production depends on the cost of electricity (often the highest cost component), investment cost for the electrolyser plant, load factor of the electrolyser, scale of production and cost of ancillary equipment. For distilleries, hydrogen production can take place on site depending on renewable electricity generation potential, water resource and land availability at the location. If these conditions are not met, grid electricity can be used to produce hydrogen on site, with a Purchase Power Agreement (PPA), or an agreement from a specific provider to certify that the electricity is from renewable sources, as per the *Low Carbon Hydrogen Standard*[88]. Off-site hydrogen production supplied by 3rd parties could also be favourable to distilleries where land, water and renewable sources are constrained. Such production facilities can be set up next to medium size onshore wind farms or solar energy plant, or at a site where a mix of grid electricity (of renewable origin) and renewable electricity is available.

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[86] How could the demand for hydrogen and its price develop up to 2045? - Fraunhofer ISI

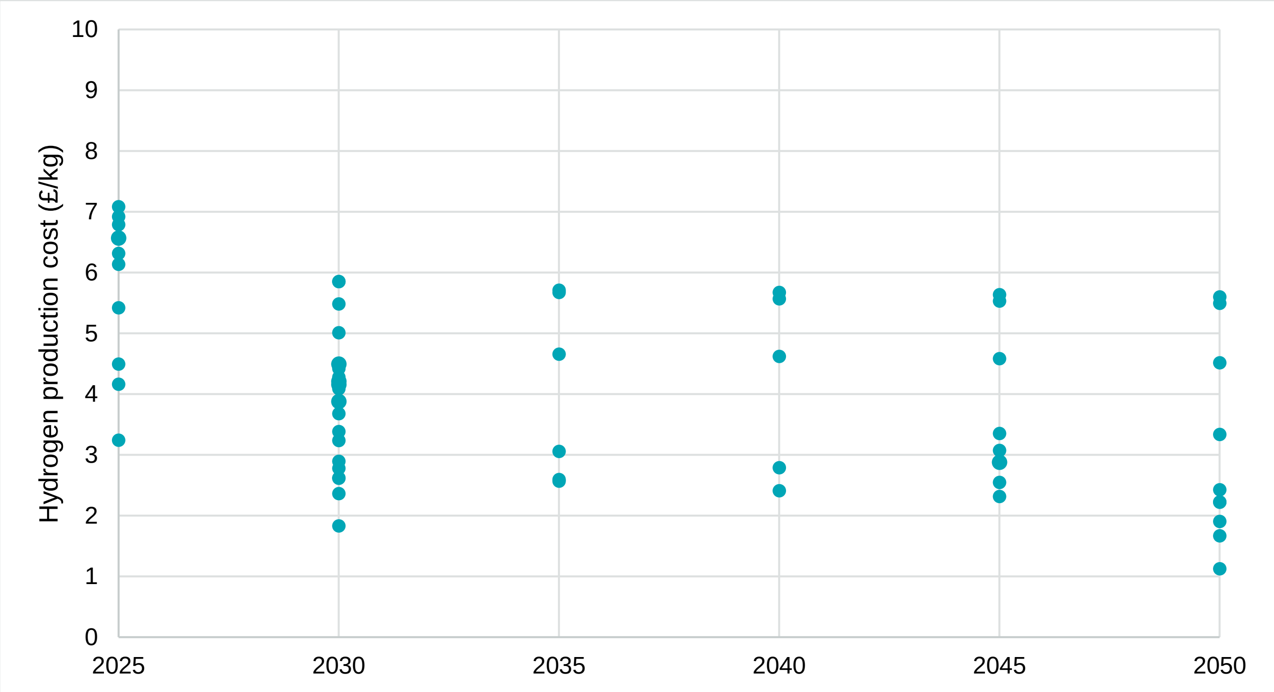
[87] Gas Goes Green Report: Hydrogen Cost to Customer

[88] *see Section 4.4* in Annexes - guidance on the greenhouse gas emissions and sustainability criteria under the low carbon hydrogen standard (publishing.service.gov.uk)

Literature shows that hydrogen production costs will decline in the future. Currently there is a wide range of costs attributed to market immaturity and scale. The projected future cost reductions[89] are based on technological advancements and market upscaling. Figure 6 has been compiled using data from various literature sources for the different types of green hydrogen production. These sources are listed in the Appendices. These ranges are from distributed electrolysis plant (1 – 20 MW) adjacent to a small or medium sized wind farms, up to large scale hydrogen production facilities, comprising multiple MW, which are fed from large scale offshore wind farms with contracts for curtailed electricity.

Hydrogen production costs are obviously a key consideration for Scottish distilleries. Distilleries differ in scale and in the proximity to hydrogen sources. A number of hydrogen production projects have been announced in Scotland and these could supply hydrogen to distilleries. Therefore, the 3rd party route, via a large-scale production centre, is the most likely scenario for most mainland distilleries in the short-term. These could benefit from larger scale hydrogen production, thus achieving lower costs. For island distilleries, where infrastructure presence is limited (these distilleries typically use heavy or medium fuel oil) the on-site hydrogen production route is a possible scenario via private wire connection to a 3rd party renewable electricity generator, on-site renewable electricity generation or importation from the grid. However, these distilleries might experience higher hydrogen costs if hydrogen is produced at a smaller scale than the mainland.

Figure 6 Literature estimates for green hydrogen production costs from 2025 to 2050 in £GBP$_{2022}$ per kgH_2



5.3.2 Hydrogen Transport Costs

When hydrogen is not produced within the distillery facility it must be transported from the point of production to the distillery site. Hydrogen can be transported either in compressed or liquified form. In the UK, hydrogen is normally transported as a compressed gas, via tube trailers or pipelines. Some reports highlight the range of these costs expressed as a function of volume and distance travelled[90]. For distances of up until 100km, transportation costs make tube trailers the rational choice, unless pipeline infrastructure exists or becomes available. Between ranges of 0 – 100 km and daily requirements of 0 – 10 tons per day (hence covering nearly all categories), the transportation costs range between £0.62 to £1.64[91] per kg of hydrogen[92] . For the grain distilleries, tube trailer transport appears more complex, as daily requirements could be between 4 to 19 tons of hydrogen, equivalent to 7 to 32 tube trailers per day (assuming 600kg carrying capacity). There is, however,

[89] Cost-competitive-green-hydrogen-how-to-lower-the-cost-of-electrolysers-EL47.pdf (oxfordenergy.org)
[90] BNEF Hydrogen Economy Outlook
[91] £GBP 2022 average
[92] Hydrogen Economy Outlook- BloombergNEF

progress in increasing capacities to 1,000kg[93], thus lowering driver and fuel costs per kg H_2. For longer distances, and when gas grid infrastructure is available, the use of pipelines may be the better option. Pipelines can transfer either blends or pure hydrogen. The costs of pipeline transportation range from £0.05 to £1.73[90] per kg of hydrogen.

Some whisky distilleries are located on islands, like the nine distilleries on Islay. These are usually mid-sized malt distilleries. In the case of Islay and Jura, 181 GWh of heavy fuel oil (HFO) is estimated to be used in distilleries[94]. This translates to about 90 - 100 tonnes of hydrogen requirements per week, which in turn means ~150 tube trailers (600 kgH_2 capacity) every week. M/V Finlaggan Roll on Roll Off ferry (Ro-Ro) visits the island 5 times a day and can accommodate 85 cars. However, whether a Ro-Ro ferry would be permitted to carry hydrogen and, if so, in what quantities, is an issue that would need to be discussed with the relevant ferry operators[95]. There are already COMAH regulations for stationary hydrogen storage for quantities above 5 tonnes, which means that there could be stricter rules for maritime transport, especially any with simultaneous passenger use. Transport of hydrogen via Ro-Ro ferries will be subject to the Maritime and Coastguard Agency (MCA) regulations. Currently there are rules governing the carriage of cylinders of gas[96,97] adopting the International Maritime Dangerous Goods (IMDG) Code for special packing provisions. The IMDG Code has recently been updated, for implementation 2024, and it will contain an amendment related to hydrogen. Another option is to charter a dedicated ship to transport hydrogen either in tube trailers or other means of hydrogen storage and off-loading to the island, but regulations and island-related business cases should be thoroughly examined, as costs could be high. In conclusion, the case for transporting hydrogen via tube trailers to different islands may only be suited to small scale demonstrations, and most likely it will be restricted by relevant maritime safety regulations. In the long run, local hydrogen production for multiple island distilleries appears to be a less complex scenario than importing from the mainland. The costs for transporting via ship to island-based distilleries is subject to case-specific techno-economic factors and to strategic decisions made by island clusters regarding the chartering of dedicated vessels to transport hydrogen to the islands.

5.3.3 Hydrogen Costs from Gas Networks

Hydrogen blending is currently limited to 0.1% by volume[98] in the gas network in Great Britain by the Gas Safety Regulations. The Department for Energy Security and Net Zero (DESNZ) is aiming to reach a policy decision in 2023 on whether to allow blending of up to 20% hydrogen by volume in the gas distribution networks. Safety trials were recently concluded for distribution level blending and are due to be concluded by late 2023 for transmission level blending. It is envisaged that a policy decision on blending into the gas transmission network will follow these trials. Hydrogen could arrive at distilleries via the distribution and transmission gas networks when policy, regulations and implementation decisions are aligned. Since 2002, the Iron Mains Replacement Programme has replaced 63% of iron pipes with polyethylene, which are more suitable for carrying hydrogen safely. This concerns the gas distribution level. Multiple demonstrations of hydrogen blends have been commenced in UK with ratios up to 20%. Some programmes are in development for 100% hydrogen gas networks such as SGN H100 Fife. However, no mandates have been given to allow hydrogen in all parts of the networks, but only in demonstrations. These decisions are expected to be taken between 2023 and 2026. Therefore, there is still an uncertain landscape for these options and therefore costs.

5.3.4 Hydrogen Storage On-site

Hydrogen will need to be stored near the distillery facilities when continuous supply via pipelines cannot be ensured. This is especially critical for the archetypes that involve on-site hydrogen production. A number of hydrogen tanks could store hydrogen when there is excess electricity generation. With an electrical grid connection, on-demand hydrogen production is possible as electrolysers have very fast cold-start up times (few minutes) and second based ramping-up and down of production. The temporal 30-min correlation of green electricity production, needed to justify that the hydrogen produced is green hydrogen, dictates the need for hydrogen storage. This applies in times of excess renewable electricity production to produce hydrogen for use at times when there is a demand for hydrogen for heat but there is limited green hydrogen production.

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[93] Spain's Calvera develops big hydrogen tube trailer for Shell (renewablesnow.com)

[94] Islay Energy Options Appraisal - DocsLib

[95] For example, CalMac (for the Clyde & Hebridean Isles network) and Northlink (for Orkney and Shetland)

[96] MGN 340 IMDG code and cargoes carried in cargo transport units - GOV.UK (www.gov.uk)

[97] MGN 341 Ro-ro ships' vehicle decks: accidents and access - GOV.UK (www.gov.uk)

[98] Hydrogen Champion Report: Recommendations to government and industry to accelerate the development of the UK hydrogen economy (publishing.service.gov.uk)

Storage can provide flexibility as well for the more traditional distilleries which do not have continuous operation.

A rough indication of hydrogen storage costs is a future levelized cost of storage of over £0.15 per kg of compressed hydrogen and around £0.86 per kg of liquified hydrogen. Storage size requirements would vary for each distillery. In terms of CAPEX figures, data from different vendors[99] suggest that a 250-bar tank with ~600kgH_2 would cost around £200-250k. This cost is considered a small fraction of the total cost for production, but it should still be taken into consideration.

Tube trailers, which transport the hydrogen into the distillery, already provide a form of storage which can be left at the site and picked up when empty and swapped. This might work well with small distilleries with low hydrogen demand. Large distilleries or distilleries that cannot find business models where a tube trailer company can lease the trailer for long periods, could consider investing in buffer tanks of various pressure levels (typically between 200 – 500 bar). The size of the storage tank needed depends on what can be achieved from the electricity sourcing scenarios, the size of the electrolyser, the demand profile of hydrogen and other techno economic parameters, which will vary from distillery to distillery.

5.3.5 Levelised Hydrogen Cost for each Fuel Supply Archetype

The levelised cost of hydrogen (LCOH) for distilleries using various fuel supply options has been estimated using literature sources examined and stakeholder consultation as shown in Figure 7. Where explicit costs are not available for a particular fuel supply option, an estimate is arrived at by combining production, transportation, and storage costs from different sources. Costs are presented in box and whisker plots to show the range of costs, with the range attributed to:

- different production technologies and sizes of plant
- different distillery hydrogen demand requirements
- different transportation characteristics (distance, volumes, pressure)
- different storage characteristics and sizes

These costs are presented for each fuel supply (FS) archetype for three periods of time: Pilot Phase (period to 2030), Development and Growth Phase (2030-2040) and Mature Phase (after 2040).

5.3.5.1 On-site hydrogen production using on or near-site renewable electricity (FS1)

This fuel supply option is ideal for distilleries with limited electrical grid connectivity and without “hydrogen-ready” gas grid availability. Typically, these are distilleries which use heavy fuel oil for their heating demand. These distilleries should have adjacent land area to install solar or wind energy assets and be in favourable locations where planning consents are possible. A small to medium size distillery could follow this path. For larger distilleries, larger wind and solar farm capacities would be needed to produce enough hydrogen, and water requirements should be considered. This option can complement power purchase agreements with 3rd party electricity suppliers when on-site solar and wind electricity production costs are lower than market retail prices.

These costs are adapted from pathways 2 and 4 described by ClimateXChange[100] for 1-20MW onsite hydrogen production co-located with on-site renewables, removing the transportation costs, and from onsite hydrogen production cost in the report by ICCT[101].

5.3.5.2 On-site hydrogen production using grid electricity (FS2)

This fuel supply option is ideal for distilleries with sufficient electrical grid availability and without “hydrogen-ready” gas grid availability. Typically, these are distilleries which use heavy fuel oil for their heating demand. These distilleries are also expected to have limited land in their premises to produce enough electricity from on-site solar and wind assets, but enough land area to install their electrolyser plant. A grid electrical connection could be the sole source of electricity or complement on-site electricity production, always complying with the Low Carbon Hydrogen Standard requirements. In principle, a distillery of any size could adopt this path if there is enough grid capacity, water resource and land for siting the electrolyser and storage.

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[99] Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration (nrel.gov)
[100] Cost reduction pathways of green hydrogen production in Scotland (climatexchange.org.uk)
[101] Cost of renewable hydrogen produced onsite at hydrogen refueling stations in Europe - ICCT

The range of costs for the different phases include electrolyser costs for different technologies and small to medium capacity ranges (1-20MW) and different electricity retail prices (with the majority likely coming from large scale offshore/onshore wind). The costs are adapted from the ClimateXChange reports and BEIS cost projections.

5.3.5.3 On-site hydrogen production using private wire electricity from 3rd party renewables (FS3)

This option applies to distilleries with very limited electrical grid availability and without "hydrogen-ready" gas grid availability. Also, it is necessary for there to be a reasonable quantity of exportable renewable electricity generated at projects located at a distance for which it is feasible to lay cables. These distilleries are usually in remote areas and use heavy fuel oil for their heating demand. These distilleries are also expected to have limited land on their premises for on-site solar and wind assets, but sufficient land for siting an electrolyser and storage. These distilleries are most likely to be located outside urban settings and close to onshore wind or solar farm developments. In principle any distillery size could adopt this path so long as there is enough renewable electricity generation in the vicinity, water resource and land availability for electrolysers.

Costs are adapted from the BEIS hydrogen production costs report for different electrolyser technologies, obtaining electricity from dedicated wind energy projects. A range of electricity retail prices is used - with a majority likely coming from large scale offshore/onshore wind. These estimates omit a cost for a grid connection, since the electricity is sourced via a private wire.

5.3.5.4 3rd party hydrogen supply via tube trailers (FS4)

This option applies to distilleries with very limited electrical grid availability and without "hydrogen-ready" gas grid availability. Distilleries should also be within a reasonable exportable distance of green hydrogen projects (50 to 100 km range). These distilleries can be in remote areas or near large industrial or urban settings. These distilleries are already using either heavy fuel oil or natural gas and are expected to have limited land on their premises for on-site solar, wind, and electrolyser systems. Distilleries of this type should have sufficient space for a hydrogen storage tank. In principle, any distillery size could adopt this path, but the current COMAH regulations which apply to 5 tonnes of hydrogen on-site storage may add complexities for distilleries where storage at this scale is needed. Moreover, 5 tonnes of hydrogen storage implies a total of nine tube trailers would have to visit every day, either to discharge hydrogen in a tank or simply be swapped with empty ones. This could represent a logistical challenge requiring significant space.

The range of costs presented in the figure below covers years 2022 to 2045. Costs are adapted from ClimateXChange Pathway 2 and BEIS data for different hydrogen production technologies, including electrolysis and CCUS enabled methane reforming, a range of transport distances and electricity prices.

5.3.5.5 3rd party hydrogen supply via natural gas pipelines (FS5)

This option applies to distilleries with limited electrical grid connectivity but with access to a "hydrogen-ready" gas grid. These distilleries are most probably already using natural gas for their operations and are expected to have limited land on their premises for setting up solar, wind, and electrolyser systems. They potentially do not require hydrogen storage systems as the gas grid presence provides supply resilience. Any distillery size could adopt this path, but it is most likely that these distilleries will select this path in the long run after the government announces its decision regarding the blending of hydrogen in the gas transmission and distribution networks.

Because the volumetric flow of hydrogen is almost three-times higher than for natural gas, new compressors are needed for repurposed transmission systems supplying hydrogen in gas pipelines. In energy terms, a repurposed hydrogen pipeline could transport around 80-90% of the energy compared to a 100% gas pipeline. The cost of hydrogen transportation over 1000km using repurposed hydrogen pipelines will be about £0.09 per kg when the pipeline operates at 100% capacity[102]. We find that there is a gap in the literature relating to costs of hydrogen transmission using existing natural gas networks.

Due to the uncertainty surrounding the timeframes and extent of blending hydrogen into the gas network, which is likely to be 20% by volume initially, a levelised cost for this fuel supply arrangement has not been included in Figure 7.

[102] A 100% of the theoretical maximum throughput capacity, for a 48-inch pipeline the theoretical maximum capacity is 16.9 GW of hydrogen

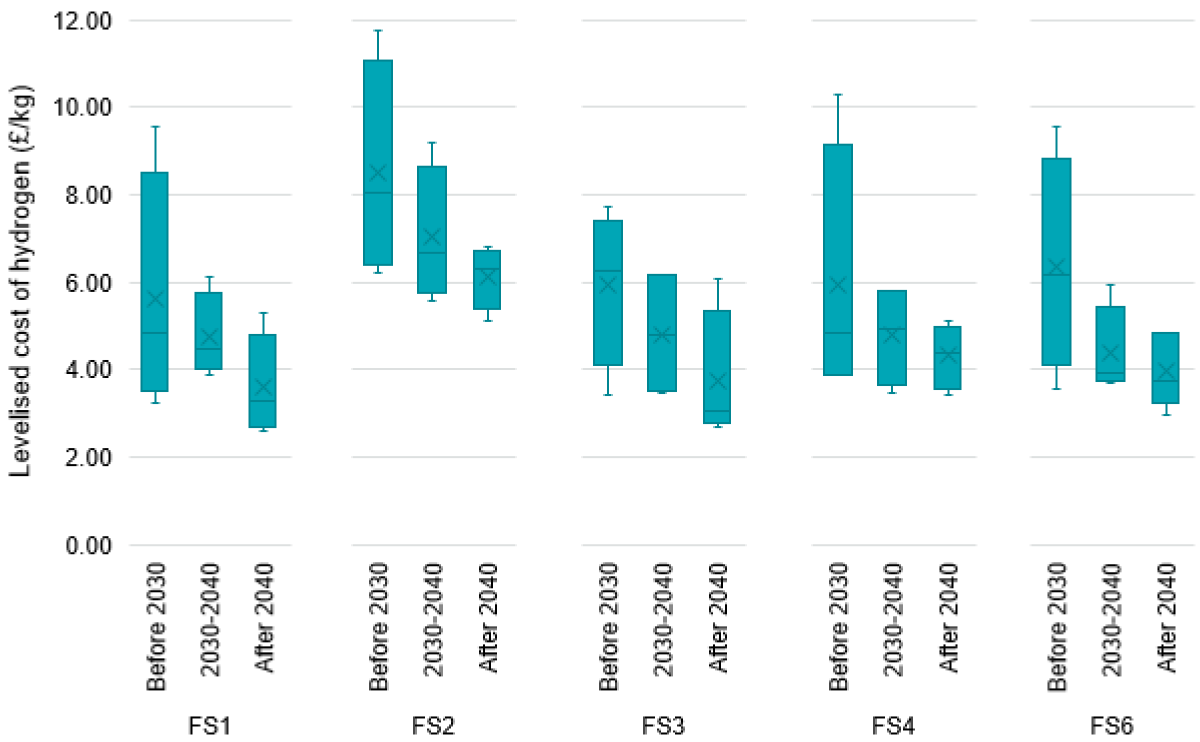
5.3.5.6 3rd party hydrogen supply via dedicated hydrogen pipes (FS6)

This option applies to distilleries with limited electrical grid connectivity and with access to a "hydrogen-ready" gas grid. These distilleries could be in remote areas which expect to have access to private hydrogen production projects with dedicated hydrogen pipeline networks. These distilleries are probably expected to have limited land on their premises for on-site renewable energy generation and hydrogen production facilities. They potentially do not require hydrogen storage.

The cost of hydrogen comprises the hydrogen production cost from BEIS and ClimateXChange combined with the cost of transportation by hydrogen pipeline from Bloomberg and IEA reports. Hydrogen pipes require high capital investment. For a hydrogen pipeline operating at 100% capacity the cost of transmission for 1000 km is over £0.25 per kg of hydrogen. This cost includes the cost of compressor, cost of pipeline and electricity needed for compression.

5.3.5.7 Cost Comparison between Fuel Supply Archetypes

Figure 7 Estimated levelised cost of hydrogen for each fuel supply archetype



The estimated LCOH values, shown above, for each supply archetype indicate that FS2 is likely to be the most expensive. This is attributed to the high cost of projected industrial retail grid electricity. In the long-term, estimates suggest FS1 as having the lowest levelised cost, marginally lower than FS2. However, as discussed in Section 5.2, FS1 is only applicable for sites with a high degree of land availability to accommodate on-site renewable power generation.

The two 3rd party hydrogen supply archetypes in Figure 7, FS4 and FS6, are both estimated to follow a similar trend to the three on-site hydrogen production archetypes. FS5 has not been included in the LCOH comparison figure due to the uncertainty surrounding the timeframes and extent of blending hydrogen into the gas network. Furthermore, given that a proportion of natural gas will remain in the gas grid, it would not be equitable to compare a mixed fuel to that of the five 100% hydrogen archetypes.

5.3.6 Comparison to Natural Gas and Fuel Oil

Taking a malt distillery that produces 2 million LPA per year and requires fuel for heat at 8 kWh/LPA we can illustrate the estimated annual fuel costs of switching to 100% hydrogen in comparison to natural gas and fuel oil for 2025 and 2045. This is shown in Table 12. A further illustration is possible for electricity, where steam is generated in an electric boiler, using either resistive or electrode technology. As discussed earlier in this report, High Temperature Heat Pumps (HTHPs) are not yet proven as a technical alternative for steam generation without significant retrofit issues for the stills.

The retail fuel prices are based on those projected by BEIS in November 2022 as part of supplementary guidance to Treasury's Green Book[103] which are inclusive of Climate Change Levy but exclusive of the cost of carbon in the UK Emissions Trading Scheme. Due to the high level of uncertainty, ranges of retail prices are provided in these UK Government projections.

Industrial retail gas prices in the UK in 2025 are expected to be in the range 3.6-8.1 p/kWh in 2025, rising to 4.2-8.3 p/kWh in 2045[104]. The central scenario has been taken for the purposes of estimating the total annual fuel costs. The central scenario for industrial retail electricity prices has also been assumed in which BEIS project a 2% rise between 2025 and 2045.

The National Grid Future Energy Scenarios (FES) 2022[105] analysis, forecasts the UK total carbon price to 2050 under three scenarios – low, base and high. The base carbon prices in 2025 and 2045 were applied to natural gas and fuel oil to arrive at a total cost for each of these fuels.

The average estimated commercial hydrogen prices (which encompasses both renewable and low carbon hydrogen) from Figure 5 have been used as a comparison to fossil fuel prices. These are £7.32/kg in 2025 falling to £2.84/kg by 2045.

Table 12 Annual estimated fuel costs for a 2m LPA distillery at 8 kWh/LPA fuel demand for heat in £(2022) (incl. projections for Climate Change Levy and carbon price)

Fuel	Estimated annual fuel cost in 2025	Estimated annual fuel cost in 2045
Natural Gas	£810,000	£900,000
Fuel Oil	£1,250,000	£1,600,000
Electrification	£1,660,000	£1,690,000
Hydrogen (renewable and low carbon)	£1,980,000	£1,150,000

Under the above assumptions, hydrogen will not be competitive in terms of price compared to any fossil fuels in 2025. In the short-term, financial incentives are likely necessary to encourage hydrogen adoption as a decarbonisation route. Due to reductions in hydrogen costs and the application of carbon prices to fossil fuels, our estimates conclude that hydrogen will have a lower cost than fuel oil in 2045, with cost parity expected sometime between 2030 and 2040. This furthers the case for rural distilleries off the gas grid to consider hydrogen as a potential fuel switching option. The estimations in Table 12 show that hydrogen will be slightly more expensive than natural gas in 2045. This is in alignment with the '*Cost reduction pathways of green hydrogen production in Scotland'* published on behalf of ClimateXChange[106] which indicates green hydrogen is unlikely to be price competitive with natural gas before 2045 in the absence of government support.

It must be noted that, given the high degree of uncertainty surrounding hydrogen, natural gas and carbon prices, cost competitiveness between the two fuels could be achieved prior to 2045. In 2045, steam generation using electric boilers is the most expensive of the fuel options considered above.

[103] Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal - GOV.UK (www.gov.uk)
[104] Based on the averages presented for Scenarios B and C, taking the central scenario.
[105] Future Energy Scenarios 2022 | ESO (nationalgrideso.com)
[106] Cost reduction pathways of green hydrogen production in Scotland (climatexchange.org.uk)

6. HYDROGEN FUNDING MECHANISMS

In order for hydrogen to become cost competitive with conventional fuels, the UK and Scottish Government have announced a series of funding mechanisms to drive the hydrogen sector forward. The relevance of these funding mechanisms to distilleries is outlined below.

6.1 SUPPORT FOR HYDROGEN PRODUCTION

The UK Government's Net Zero Innovation Portfolio (NZIP) includes the £240m Net Zero Hydrogen Fund (NZHF) which was designed to provide grant funding (DEVEX and CAPEX) for hydrogen production projects across the UK and a Hydrogen Business Model (HBM) to encourage private sector investment out to 2025.

The NZHF[107] targets new build blue or green hydrogen projects of at least 5MW production capacity, intended to be operational by 2025.

The HBM[108] involves a revenue support, where the government will help producers of green or blue hydrogen to bridge the gap between their operating cost and the lower hydrogen sell price (similar to Contracts for Difference). The UK Government has stated its ambition to run yearly electrolytic allocation rounds for the hydrogen business model and to move to price competitive allocations as soon as market conditions and legislation allow. Projects need to meet the Low Carbon Hydrogen Standard (LCHS) to be eligible, which requires producing hydrogen below a threshold of 20 $gCO2e/MJ_{LHV}$.

Distillers may find these funds relevant if they wish to: a) produce hydrogen on site and the project meets the eligibility criteria, b) purchase hydrogen, and so may enter into an agreement with a hydrogen producer who is applying for these funds, since the producer must demonstrate they have secured an off-taker. It should be noted that the funding requires a 25-year offtake agreement. Distillers who buy hydrogen are likely to be buying from a producer using one or both of these support mechanisms.

There are four funding strands

Strand 1: NZHF - Up to 50% co-funding DEVEX support for FEED studies for electrolytic hydrogen projects that do not require revenue support. The first round of access to this support closed on 23rd of June 2022.

Strand 2: NZHF - Up to 30% CAPEX co-funding support for projects that do not require revenue support. These are more likely to be smaller electrolytic projects that interact with the Renewable Transport Fuel Obligation. Access to this support closed on 13th of June 2022.

Strand 3: NZHF and HBM – For electrolytic projects (green hydrogen), providing up to 20% CAPEX support combined with the ongoing revenue support mechanism. The first window closed on the 12th of October 2022. It aims to support at least 250MW of production capacity. The first contracts were expected to be in place early 2023

The second window opens in 2023 and aims to stimulate a total of 1GW of electrolytic hydrogen in construction or operation by the end of 2025.

Strand 4: NZHF and HBM - For projects that are CCUS enabled (blue hydrogen) and are part of the phase 2 cluster sequencing process. These projects can access CAPEX support and the revenue support mechanism. Access windows for this support have yet to be announced.

Other completed supply funds (which could indicate potential future funds) included:

The £33m low-carbon hydrogen supply competition which funded 5 projects providing low carbon bulk hydrogen supply solutions.

The £60m low-carbon hydrogen supply 2 competition which funding to 28 projects. A total of £6m went towards 23 projects to conduct feasibility studies on innovative hydrogen supply solutions. Five projects went on to receive £38m of funding to support physical demonstration of the solutions.

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[107] UK Government - Net Zero Hydrogen Fund applications
[108] UK Government - Hydrogen production business model

6.2 GREEN FREEPORTS

Green Freeports[109] will benefit from a package of measures, comprising tax reliefs, customs advantages, business rates retention, planning, regeneration, innovation and trade and investment support. Details are yet to be confirmed; however, sources suggest select businesses in freeports will benefit from tax relief on Import duty, import VAT and customs duty in certain cases.

Inverness and Cromarty Firth Green Freeport and Forth Green Freeport were jointly selected by the Scottish and UK governments to become Scotland's first Green Freeports in January 2023. The bids reflected plans to enable renewable energy projects, including green hydrogen production at a larger scale and lower cost to customers. The Cromarty Firth bid in particular was supported by distillers Diageo, Glenmorangie and Whyte & Mackay who also form part of the Opportunity Cromarty Firth partnership which is planning a hydrogen hub in the Highlands.

6.3 ONGOING SUPPORT FOR INDUSTRY

Emerging Energy Technologies Fund (EETF)

The Scottish Government allocated £100 million from the EETF[110] towards hydrogen. The fund is set to be delivered over a 4-year period ending in 2026.

Within this fund, £10 million is allocated by the Hydrogen Innovation Scheme (HIS) which opened in 2022. It is a capital funding stream for the development and demonstration of innovative renewable hydrogen technologies. In 2023, £7 million were allocated to 32 innovation projects and for R&D centres[111].

The allocation of the remaining £90 million is being determined and may represent opportunities for industry.

Scottish Industrial Energy Transformation Fund (SIETF)

The SIETF[112] provides grant funding from 2021 through 2026 (£34m available) with annual competition rounds. Aimed at Scottish manufacturing businesses with high energy demands, the grant is design to support the reduction of energy costs and emissions through increased energy efficiency and decarbonisation. The fund is split into competitions which focus on:

- Energy efficiency and deep decarbonisation deployment projects (min. £100,000)
- Feasibility and FEED studies

Winners from prior competitions include distilleries like Glenmorangie (Synthetic methane from hydrogen and fermentation CO_2) and Chivas Brothers Ltd (for Mechanical and thermal vapour recompression).

SIETF is expected to reopen for further rounds but there are no formal dates released at present.

Business Energy Scotland's SME loan scheme

This scheme[113] offers an interest-free loan up to £100k for solar PV or wind turbines and grant of 75% of the cost (up to £20k of grant) on energy efficiency or 75% (up to £10k of grant) on renewable heat technologies. It is a two-stage process where BES provides an energy audit with a report, which allows access to the loan/grant. It is restricted to SMEs, and therefore applicable to many smaller distilleries.

CO_2 Utilisation Challenge

This fund covers up to 50% of grant funding towards the costs of R&D projects looking at converting CO_2 into a commercially useful or valuable product[114]. Scottish distilleries may be a relevant setting for these projects led by an innovation partner, for processes such as methanation. The fund runs between 2022 and 2024.

Horizon Europe – Clean Hydrogen Partnership programme

The Clean Hydrogen Partnership coordinates an annual programme of funding for collaborative European hydrogen innovation projects, which Scottish organisations can participate in. While there is no guarantee that future calls will cover topics specific to distilleries, there is an ongoing requirement for industrial sites in which

[109] Scottish Government - Green Freeports
[110] Scottish Government – Emerging Energies Technologies Fund
[111] Emerging Energy Technologies Fund - Hydrogen Innovation Scheme: successful projects
[112] Scottish Industrial Energy Transformation Fund
[113] Business Energy Scotland's SME loan scheme
[114] Scottish Enterprise - CO2 Utilisation Challenge

to test and demonstrate new hydrogen technologies. Distilleries could form part of relevant consortia, either as receptors of funding or in an advisory capacity.

6.4 PREVIOUS FUNDING ROUNDS

Examples of previous funding rounds (which could indicate potential future funds):

- The £10m Green Distilleries Fund provided funding to distilleries to test and demonstrate a range of decarbonisation solutions including hydrogen. Phase 1 supported 16 feasibility studies and Phase 2 awarded funding to four demonstration projects.
- The Low Carbon Manufacturing Challenge Fund (LCMCF), on pause at the time of this publication, provided funding to Scottish businesses to develop new low carbon products, services or business models based on Circular Economy principles. There was no restriction on industry sectors or company size. The support could be used for capital investment to improve processes and carbon savings and technically innovative R&D activities. The minimum grant amount was £150,000 and the intervention rate varied between 15-60% depending on individual project, applicant and subsidy route used.
- As part of the NZIP, a £55m Industrial Fuel Switching 2 Competition ran in 2022, funding the demonstration of fuel switching and fuel switch enabling technologies within an industrial setting.
- The £26m NZIP Industrial Hydrogen Accelerator Programme aimed to identify, support and then develop credible integrated hydrogen production and fuel switching systems by providing innovation funding.
- Hydrogen storage and distribution supply chain Collaborative R&D Competition provided a grant of up to £1 million for the total costs of UK projects focused on innovation in storage and or distribution within the hydrogen value chain. End users of hydrogen, such as distilleries, could find a role as an advisor or grant-receiving partner. The call closed on 26 April 2023.
- As part of the 2017 Clean Growth Strategy, a £20m Industrial Fuel Switching Competition was launched. It was a 3-phase competition, initially beginning with research and then competitions for demonstrator projects. The funding aimed to stimulate early investment in fuel switching processes and technologies.

7. MAP OF DISTILLERIES AND HYDROGEN PRODUCTION

A map of distilleries and hydrogen production projects has been produced as shown in Figure 8. The yellow circles denote all active Scotch whisky distilleries as of September 2022[115]. While there is a large cluster of sites in Speyside, distilleries are located across the country in a range of geographies, from urban areas which are heavily space constrained to remote island locations. The challenges and opportunities for hydrogen are varied depending on their location and specific site constraints.

At present, no distillery in Scotland actively uses hydrogen on site. Circles coloured orange denote distilleries that, to our knowledge, are either considering or actively developing plans to switch to hydrogen. For mapping purposes, Scottish distilleries involved in BEIS Green Distillery Competition Phase 1 and Phase 2 have been included as well as distilleries who could potentially receive hydrogen from the North of Scotland Hydrogen Programme at Cromarty Firth. Furthermore, a distillery based in the Borders who were part of the stakeholder engagement, signalled interest in adopting hydrogen and are shown on the map.

The "*Hydrogen Demand in Scotland – Industrial Applications*" study, produced by Element Energy, outlines a map of distilleries designated by LPA capacity.

Table 13 Scottish distilleries involved in the transition to hydrogen

Involved in BEIS Green Distillery Competition Phase 1 and/or Phase 2 which include hydrogen	North of Scotland Hydrogen Programme at Cromarty Firth
Arbikie Highland Estate Distillery	Glenmorangie
Beam Suntory's Ardmore Distillery and Glen Garioch distillery[116]	Whyte & Mackay's Invergordon and The Dalmore[117]
Inchdairnie Distillery	Diageo's Teaninich distillery[118]
Bruichladdich Distillery	
Highland Park	
Orkney Distilling Limited	
Benbecula Distillery	

Distilling in Scotland is an ever-growing industry with locations opening year on year. Locations of new or planned distilleries in the public domain[119] are shown as red circles. It must be noted this is a non-exhaustive list based on public knowledge at the time of publication.

To achieve Scotland's 5 GW by 2030 and 25 GW by 2045 hydrogen production ambition, a number of hydrogen production projects either exist or are in development. Some examples of green hydrogen projects in Scotland include H100 Levenmouth, Dolphyn, and Green Hydrogen for Glasgow. Blue hydrogen projects are also in development such as the Acorn project at St Fergus and at INEOS Grangemouth. Hydrogen production projects are shown as squares on the map depicted by colour of hydrogen.

Many of the successful applicants to the recent ScotWind leasing round, such as the Flotta Hydrogen Hub, are considering production of green hydrogen[120]. The offshore wind sites are not mapped, as they represent more long-term projects and a higher degree of uncertainty as a source of hydrogen for distilleries. The UK Government has at this time allocated grants to 15 hydrogen production projects[121] under the Net Zero Hydrogen Fund, several of which are Scottish-based such as Kintore Hydrogen, The Knockshinnoch Green

[115] list-of-current-operating-scotch-whisky-distilleries-sept-2022.pdf

[116] WhiskHy project awarded £2.94M to advance high pressure zero emission hydrogen technology (supercritical.solutions)

[117] Whyte and Mackay backs Cromarty green freeport | HeraldScotland

[118] How Scottish whisky's fuelling the energy transition (scottishrenewables.com)

[119] 14 new whisky distilleries opening in Scotland soon | Scotsman Food and Drink

[120] Scotland's bold offshore wind leap sets up global hydrogen role | Reuters Events | Renewables

[121] UK allocates grants to 15 low-carbon hydrogen projects and unveils shortlists for further funding | Hydrogen news and intelligence (hydrogeninsight.com)

Hydrogen Hub, and Lanarkshire Green Hydrogen, thus exemplifying the growth of the hydrogen sector in Scotland.

By far the largest cluster of distilleries can be found in Speyside. While there is not a hydrogen hub there at this time, a Moray Hydrogen Strategy has recently been devised in conjunction with Highlands and Islands Enterprise[122] which has identified opportunities for hydrogen production and demand in the region. A future multi megawatt hydrogen production project in Speyside could deliver hydrogen to several distilleries in the region in a similar fashion to the proposed Cromarty Firth Regional Hydrogen Hub.

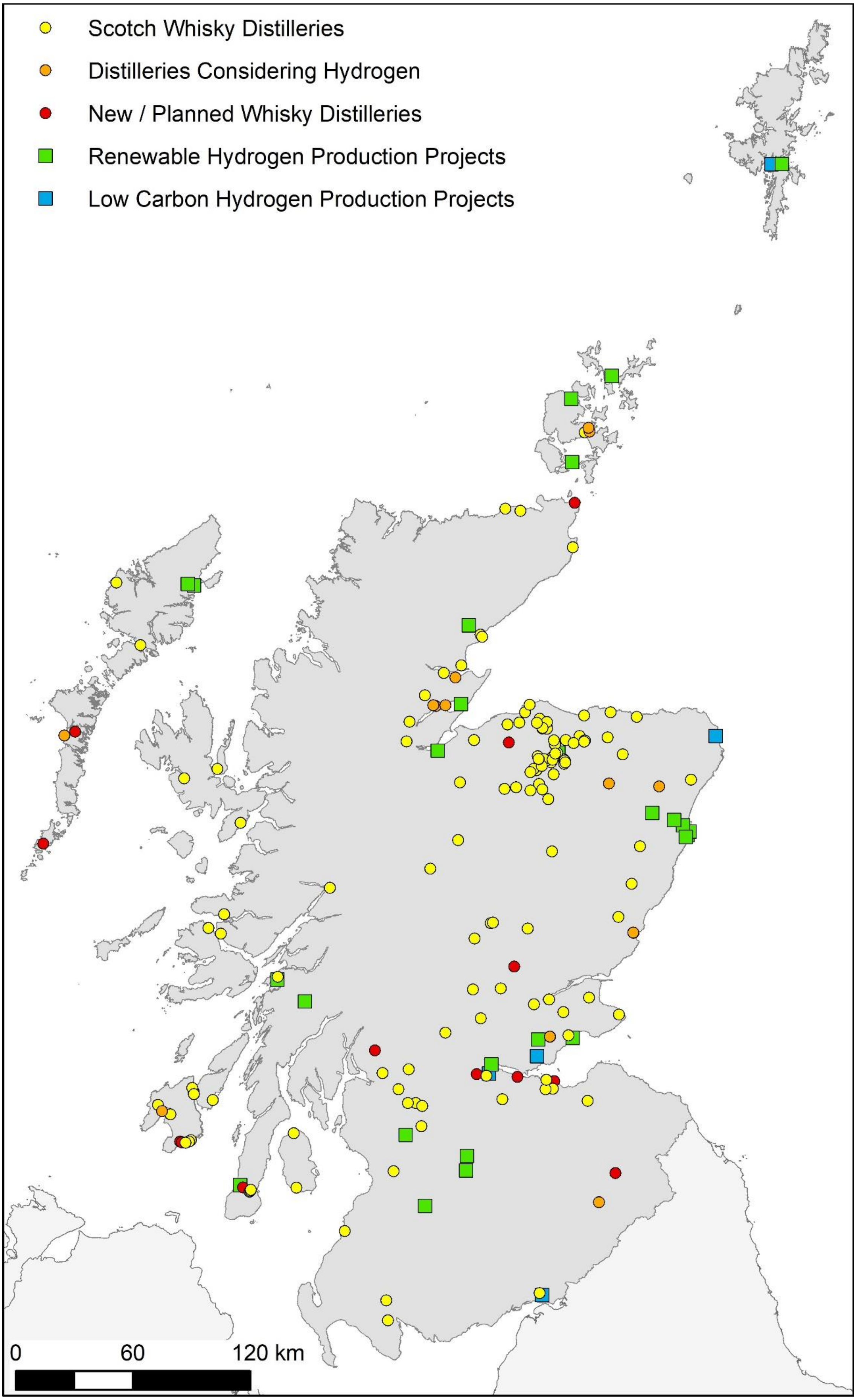
The Isle of Islay is the second significant cluster of distilleries. As indicated in Section 4: Case Studies, a successful demonstration project at the Bruichladdich distillery could encourage wider adoption of hydrogen across the island. The Islay Energy Systems Options Appraisal[123] outlines scenarios for island-wide decarbonisation. It includes hydrogen as a fuel option for distilleries in the long term (2030+) with short to medium term measures focusing on bioenergy and electrification, where feasible.

Distilleries in Scotland's central belt could potentially become off takers for hydrogen production projects in the region, within hubs like Glasgow, Grangemouth and Fife.

The pipeline of planned hydrogen production projects is continuously changing. Scotland's economic development agencies (SE, HIE and SoSE) maintain a database of projects which is available on request.

[122] Moray Council adopts hydrogen strategy
[123] islayenergyoptionsappraisal-full-report-jan-21.pdf (localenergy.scot)

Figure 8 Map of Distilleries and Hydrogen Production Projects in Scotland



8. RECOMMENDATIONS AND CONCLUSIONS

Conclusions

- A wide range of decarbonisation options are available to distilleries, the most common of which to date has been the use of bioenergy. There is often not a ‘one size fits all’ approach to decarbonisation, but rather the selection of the most appropriate fuel is site-specific.
- Scotland has a strong ambition to produce hydrogen (5 GW by 2030) and distilleries are featured within the second highest category in the hierarchy of hydrogen use cases.
- Hydrogen can be adopted in conjunction with other options or as a sole fuel switching option, depending on the availability of different energy sources and the efficiencies of alternative fuels.
- For most distilleries, decarbonising heat is largely associated with decarbonising steam generation. It is technically feasible to use hydrogen in a broadly similar way to natural gas, but its different physical characteristics must be accounted for.
- Most current gas boilers can handle up to 20% by volume of hydrogen (equivalent to 7% carbon savings, if the hydrogen is green hydrogen) without major modifications being required. Boilers that can combust up to 100% hydrogen are beginning to become available at ca. 22% higher capital expenditure than an equivalent natural gas boiler.
- Given the choice to retrofit an existing gas boiler or acquire a new hydrogen-ready boiler, distilleries should evaluate the overall energy efficiency gains against cost. The lower volumetric calorific value of hydrogen, compared to natural gas, should also be accounted for when determining whether the retrofit of an existing boiler can satisfy a site’s heat demand.
- Decarbonisation studies involving hydrogen for distilleries in Scotland have largely been driven by the BEIS Green Distilleries Competition and the SIETF.
- The major difference between distilleries is in how hydrogen could be supplied, determined by characteristics such as:
    - Availability of gas network
    - Land availability for production of hydrogen
    - Land available for storage of hydrogen
    - Water resource o Electricity grid constraints
- It is necessary for prospective hydrogen users to acknowledge the different safety and emission regulations and infrastructure requirements which apply to hydrogen when compared against incumbent fuels. It is strongly advisable for each site to undertake a detailed assessment of all relevant options before proceeding with a hydrogen project.

Suggestions for Distilleries

- Distilleries interested in hydrogen as a decarbonisation option can begin to consider the most relevant fuel supply archetypes featured in this report in relation to their site’s particular characteristics. Distilleries could also note the estimated Levelised Cost of Hydrogen (LCOH) for each supply archetype, to obtain an initial view of long-term hydrogen prices.
- If considering supply from a 3rd party, the map in this report, as well as the interactive online map being developed by Scottish Enterprise, can help distilleries identify the nearest hydrogen production projects in planning.
- Economic development agencies can provide confidential and bespoke decarbonisation and funding advice to distilleries.

Barriers to deployment

- In Scotland and the wider UK there are funding mechanisms to support hydrogen innovation as well as hydrogen production projects with Devex, Capex and a Business Model. However, at the time of publication there is uncertainty around the continuation of schemes like the Scottish Industrial Energy Transformation Fund and the Low Carbon Manufacturing Challenge Fund. There are gaps in funding for industrial hydrogen offtake projects without an innovative or hydrogen production element.

- As of June 2023, a low carbon hydrogen certification scheme is still being developed in the UK. There remains for now a lack of certainty regarding the emissions credentials of hydrogen which is purchased or produced.
- Engagement with stakeholders suggested that there is also uncertainty about how distilleries should report emissions associated with hydrogen production and use on site, e.g. whether NOx produced from the combustion of hydrogen must be considered similarly to carbon emissions.
- In the short term, hydrogen will not be cost competitive with either fuel oil or natural gas. While there is a high degree of uncertainty with respect to future fuel prices and carbon prices, a literature review of studies suggests that hydrogen will achieve cost parity with fuel in the 2030s, but natural gas will remain slightly cheaper than hydrogen even until 2045. Both policy decisions and market conditions will determine the relative future prices between these fuels.

Recommendations to address barriers

- Decarbonisation projects often need to involve several interconnected elements for greater efficiency and to meet site-specific requirements (e.g. renewable power generation, electrolysis, storage, bioenergy). Policy and guidance across several areas should be reviewed to take account of new energy developments, including hydrogen specifically, with the aim of allowing a whole-systems approach to planning, environmental reporting, safety permitting and business taxation.
- As hydrogen is a very new activity, it would be beneficial to communicate any new or relevant guidance on hydrogen projects widely among decision-makers at local level, the industry and the supply chain.
- New funding or policy mechanisms may be required to incentivise implementation of full-scale commercial hydrogen projects in distillery settings for on-site consumption beyond the pilot stage. This would encourage a wider rollout of integrated proven solutions which could in turn improve the cost competitiveness of hydrogen in the longer term by overcoming technical challenges and achieving economies of scale.
- The UK Low Carbon Hydrogen Certification Scheme will help to provide reassurance of the low carbon credentials of hydrogen purchased or produced. It will be important that the certification aligns with other energy and climate change mitigation schemes businesses need to comply with (both mandatory and voluntary) such as Streamlined Energy and Carbon Reporting and that clarity is provided on its alignment with the UK Emissions Trading Scheme (UK ETS).
- Geographical proximity between hydrogen supply and demand is one of the important factors to reduce the fuel's cost. This report's map of Scotch Whisky distilleries and hydrogen production projects suggests potential for agreements in areas like the Central Belt, Cromarty Firth and the North East. However, there is an open opportunity for new production projects to supply to Speyside and Islay distilleries, which could be stimulated with more targeted planning at national and local level through the Scottish Government's Hydrogen Hubs approach. The voice of the Scotch Whisky industry will be vital to shape the preferred solutions.

APPENDICES

Table A-1 Long list of energy efficiency measures applicable to distilleries

Measure	Energy Source
Compressed air improvements	Electricity
General site energy management/efficiency - staff behaviour etc.	Electricity
Lighting	Electricity
Variable Speed Drives	Electricity
Voltage optimisation	Electricity
Dewatering before drying	Heat
Digital Combustion Control	Heat
Drying improvement technologies	Heat
Economisation on fossil-fuel plant	Heat
Energy management & maintenance	Heat
Heat recovery - waste heat from process and cooling	Heat
HVAC systems improvement	Heat
Insulation to avoid heat loss	Heat
Mechanical Vapour Recompression (MVR)	Heat
Process optimisation	Heat
Steam production, distribution and end-use	Heat
Thermal fluid heating	Heat
Thermal Vapour Recompression (TVR)	Heat

Table A-2 Hydrogen Production Costs in £GBP2022 per kg - 2025 to 2050

Source	2025	2030	2035	2040	2045	2050	Comment	Link
American Petroleum Institute		5.49					For 1 MW PEM electrolyser	The Potential Role of Blue Hydrogen in Low-Carbon Energy Markets
American Petroleum Institute		4.17					For 20 MW PEM electrolyser	
American Petroleum Institute		3.68					For 100 MW PEM electrolyser	
BEIS	6.14	5.85	5.71	5.67	5.64	5.60	For alkaline electrolyser with load factor 98% and grid electricity	Hydrogen production costs 2021
BEIS	6.31	5.85	5.67	5.57	5.53	5.49	For PEM electrolyser with load factor 98% and grid electricity	
BEIS	5.42	5.01	4.66	4.62	4.58	4.51	For SOE electrolyser with load factor 90% and grid electricity	
Bloomberg NEF		1.83				1.13	For large projects	BNEF Hydrogen Economy Outlook
Climate Exchange Report	6.57	3.88			2.88		For 100 MW electrolyser plant	Cost reduction pathways of green hydrogen production in Scotland
Climate Exchange Report	7.08	4.28			3.35		For 200 MW electrolyser plant	
Climate Exchange Report	6.79	4.09			3.08		For 500 MW	

Source	2025	2030	2035	2040	2045	2050	Comment	Link
							electrolyser plant	
Energy Network	2.64	2.15	1.94	1.77	1.62	1.54	Hydrogen from dedicated renewable energy source	Hydrogen: Cost to customer Energy Networks Association
International Council on Clean Transportation		4.35				3.29	Onsite hydrogen production cost	Cost of renewable hydrogen produced onsite at hydrogen refueling stations in Europe
International Energy Agency		2.62				2.22	Hydrogen production using wind onshore energy	Global Hydrogen Review 2022 – Analysis - IEA
International Energy Agency		2.90				1.90	Hydrogen production using wind offshore energy	
International Energy Agency		2.36				1.67	Hydrogen production using energy from solar PV	
Scottish Enterprise	4.49	2.62					Cost of hydrogen in Europe	Development of early, clean hydrogen production in Scotland
Scottish Enterprise		4.49					For 200 MW electrolyser plant	
Scottish Enterprise		4.21					For 500 MW electrolyser plant	
Scottish Enterprise		4.16					For 1 GW electrolyser plant	

Source	2025	2030	2035	2040	2045	2050	Comment	Link
Scottish Government	6.81	3.19	2.53				Offshore wind energy plant of 14MW, 500MW and 1GW	Offshore wind to green hydrogen: opportunity assessment
World Energy Council	3.19	2.74	2.55	2.37	2.28	2.19	Based on different sources	Working Paper: Hydrogen Demand and Cost Dynamics | World Energy Council

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