Consultation Towards a Future Grangemouth Hydrogen Hub

Final Report

Scottish Enterprise

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1 Introduction

1.1 Background

Scotland's strategy for tackling climate change has rapidly evolved over the course of the last five years. In a series of strategic actions, the Scottish Government published the Climate Change Plan for 2018-2032 and passed the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 along with the declaration of a climate emergency in April 2019 and, therefore, established a commitment to achieving net-zero emissions of all greenhouse gases by 2045 in direct response to the international Paris Agreement.

Gradual reduction of the reliance on fossil fuels is the core element of Scotland's decarbonisation strategy. As such, all industrial and user sectors are considering an eventual strategic pivot away from traditional, carbon-intensive energy sources towards a more sustainable energy mix. Central to this transition is the growing recognition of low-carbon ('blue') and renewable ('green') hydrogen. Hydrogen, with its capacity to decarbonise sectors where electrification is not practical, such as oil and gas refining, chemicals, and other process industries, offers the potential to significantly reduce emissions on the way to net zero targets.

In 2020, the Scottish Government introduced the Scottish Hydrogen Assessment which outlined three potential scenarios of hydrogen integration into the energy mix. Building on this, the Hydrogen Action Plan (published in 2022) defined the ambition to achieve 5 gigawatts (GW) of installed hydrogen production capacity by 2030 and 25 GW by 2045. The achievement of these targets will require a rapid infrastructure expansion to enable the production of blue and green hydrogen; carbon capture, utilisation and storage, and hydrogen transportation and storage. End-user sectors will also need to adapt their infrastructure to benefit from fuel switching to hydrogen.

Despite the strong and consistent policy support, the economic activities in this nascent industry in Scotland have been, to date, limited to small-scale pilot projects, for example. the Aberdeen Hydrogen Bus Project; BIG HIT (Orkney) and Creed Hydrogen Skills and Innovation Centre (Western Isles). Meanwhile, larger projects are predominantly at the planning stage or awaiting final funding decisions.

Grangemouth is home to the biggest Scottish industrial complex accounting for 4% of Scotland's GDP and approximately 8% of its manufacturing base[1]. It is the largest carbon-emitting location in the country and, therefore, an obvious target for urgent decarbonisation activities. It has been predicted that the large emitters in Grangemouth are most likely to catalyse a net-zero solution in their own operations and drive a change in others due to the intrinsic links of infrastructure and the business needs of process industries[1]. Hydrogen is likely to become a critical element for Grangemouth's transition to net zero through the development of the Grangemouth Hydrogen Hub – a centralised place for hydrogen production, use and export. For the purposes of this study, a hydrogen hub is

1 Scottish Net Zero Roadmap. https://snzr.co.uk/the-report/

defined as a regional network of hydrogen producers, consumers, and connective infrastructure located in strategically close proximity.

In 2021, Scottish Enterprise commissioned research to baseline the current Grangemouth stakeholder position and planned integration of hydrogen in economic activities, illustrating hydrogen-enabled decarbonisation scenarios of the cluster, in alignment with the national strategies at the time[2]. The key insights from the study included the finding that unabated hydrogen is already produced as a co-product of polymer and olefin manufacture and used in the cluster, which is largely self-sufficient ('self-supply'). As such, there is a clear opportunity for sustainable hydrogen integration into processes and energy systems within the cluster. The extent of the demand for hydrogen from users is, however, unclear due to the lack of infrastructure and market-ready options in fuelling and logistics/haulage, and the price premium to drive hydrogen uptake.

2 Objectives and Methodology

The purpose of this study is to review and re-assess the status of hydrogen activities in the Grangemouth industrial cluster. It follows up on the study by Wood (2021), by providing an update on the current and planned projects in the region and nationally.

We carried out desk research to summarise industrial and policy developments with a focus on the time period from 2021 to date.

A semi-structured interview programme with key Grangemouth Hydrogen Hub industrial and public sector stakeholders was carried out to identify new and emerging hydrogen projects or interests, as well as to identify challenges and opportunities for strategic support and investment. We interviewed 20 organisations, as listed in Appendix A.

3 The Grangemouth Industrial Cluster in the Context of the Emerging Hydrogen Value Chain

3.1 Overview

The Grangemouth industrial complex is home to over 25 individual companies (across 32 sites in 2021) that have been identified as potential stakeholders in the future Grangemouth Hydrogen Hub. These companies include major fuel producers (Petroineos); chemical manufacturers (BOC, INEOS), transport businesses (Malcolm Logistics, Alexander Dennis) and other companies. In addition to the industrial companies, Forth Ports also operates out of Grangemouth and was recently awarded green freeport status[3]. Mossmorran is located close by and this is home to the Shell natural gas liquids plant and ExxonMobil ethylene plant. Across the Forth at Longannet, there is a brownfield site of Longannet

2 Grangemouth Hydrogen Hub. Wood, 2021.
3 Forth Green Freeport.

Power Station (Scottish Power) and the associated infrastructure assets, including a private railway that was used to deliver coal to the station. The cluster is located near Edinburgh Airport and the City of Edinburgh.

In principle, most of these regional stakeholders could become involved in the hydrogen value chain as producers, transporters and/or users of sustainable hydrogen for the decarbonisation of their activities. This assumption is based on the existing understanding of the industrial landscape in Scotland which has identified that the use of hydrogen as an energy carrier is a viable decarbonisation pathway for many industrial and transport sectors[4]. In addition, the Grangemouth process industry already produces non-abated hydrogen as a byproduct from polymer and olefin processing and uses it as a chemical for oil refining processes (oil hydrocracking and sulfur removal). This example shows that the cluster has a unique opportunity to pilot sustainable hydrogen integration into processes at an industrial scale by replacing non-sustainable hydrogen in chemical processes and deploying hydrogen as an energy carrier (fuel cells or hydrogen-fired turbines).

Despite the apparent potential of a self-contained hydrogen ecosystem, the Grangemouth cluster will depend on a range of developments elsewhere in the hydrogen value chain to enable the transition. The current understanding of the complexity of the hydrogen supply chain and its gaps in Scotland[5] and the wider UK[6] illustrates the multi-level nature of opportunities and challenges. The needs of the emerging Grangemouth hydrogen industry can be conceptually described on three levels of engagement:

- ***Micro level***: supporting individual companies within the future hub. These needs could include, for example, technological innovation (better efficiency of carbon capture solutions), availability of electrolysers, and integration of hydrogen into existing operations.
- ***Meso level***: addressing the needs of the future Grangemouth Hydrogen Hub ecosystem. These could include, for example, infrastructure needs, such as transport and storage logistics within the hub and outside the hub. More broadly, this includes most company-to-company interactions and commercial activities (supply/demand; export market).
- ***Macro level***: considering interactions with, and dependencies on, the broader hydrogen economy. These could include, for example, policy development, funding and investment, and regional skills availability.

These are discussed in more detail below, describing a selection of considerations that are relevant to the hydrogen economy as a whole and providing a broader context to the challenges of integrating hydrogen at different levels of industrial interconnectivity. These aspects illustrate choices that emerging hydrogen hubs, such as Grangemouth, need to make in order to create a sustainable hydrogen ecosystem.

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4 Hydrogen demand in Scotland: a mapping of industrial and transport applications (2023).
5 Mapping the current and forecasted hydrogen skills landscape (2023).
6 Supply chains to support a hydrogen economy (2022).

3.2 Micro-level

Within individual companies there are several challenges to address, including the three critical elements discussed below.

Technological uncertainty

Innovative technologies have a degree of uncertainty as they are being trialled at scale across the hydrogen value chain. A few relevant examples focusing on upstream production are discussed below.

Carbon capture is a technology with a long history, with the first methods of carbon capture being utilised to separate CO_2 from methane extracted from natural gas reservoirs. In 1972, Terrell Natural Gas Processing Plant (Texas, US) began capturing CO_2 with the purpose of supplying it to an oil field for oil extraction[7]. In the context of the hydrogen economy, carbon capture is critical for capturing CO_2 generated by steam reforming of natural gas to extract 'blue' hydrogen. Carbon capture is often referred to as 90+% efficient, based on small scale lab and pilot data. In practice, however, large scale industrial plants have, to date, failed to meet these capture targets. For example, Gorgon, a 3Bn AUD carbon capture and storage (CCS) project in Australia (Chevron, ExxonMobil, Shell), began operations in 2016 and by 2022, had underperformed on its original efficiency target of 80% capture efficiency by approximately 50% [8], with the shortfall being addressed by greenhouse gas offsets worth up to US$ 184M. One of the most recent carbon capture projects in the UK, at Tata Chemicals Europe's combined heat and power plant in Northwich, will convert 40,000 tonnes of CO_2 into sodium bicarbonate, representing the capture of 10% of its total CO_2 emissions[9].

In green hydrogen production, water electrolysis for hydrogen production at scale remains a novel process. The electrolyser technologies face some challenges, for example insufficient durability of electrodes (used to conduct electricity) and membranes (for the separation of gases). Some types of electrolysers require precious metal catalysts that dramatically increase operational costs[10]. Companies are rapidly innovating in this area to address these issues. For example, New Zealand-based startup Bspkl is developing catalysts that use 25 times less platinum, iridium, and ruthenium. Additionally, electrolysers are dependent on advanced water filtering to create ultrapure water[11]. This is achieved by filtering that can create a bottleneck in the process. Scotland-based companies such as sHYp and Evolve Hydrogen Ltd seek to address this bottleneck through innovative electrolyser design that will enable direct electrolysis of seawater without the need for desalination. The world's largest green hydrogen production facility at the moment is the 260 MW Kuqa project in Xinjiang, China[12]. Its initial output is 10,000 tonnes of hydrogen a year, with expected ramp up to 20,000 tonnes

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7 Lessons captured from 50 years of CCS projects. (2021)
8 https://ieefa.org/articles/if-chevron-exxon-and-shell-cant-get-gorgons-carbon-capture-and-storage-work-who-can
9 https://www.chemistryworld.com/news/uks-first-industrial-scale-carbon-capture-plant-opens-in-cheshire/4015867.article
10 An overview of water electrolysis technologies for green hydrogen production. (2022)
11 https://www.eurowater.com/en/references/water-treatment-for-alkaline-electrolysis
12 https://www.hydrogeninsight.com/production/worlds-largest-green-hydrogen-project-begins-production-in-china/2-1-1478233

supplemented by 210,000 m^3 tank storage capacity. The Kuqa project hydrogen is used to displace grey H_2 at Sinopec's Tahe facility and could reduce CO_2 emissions by 485,000 tonnes per year. It is unclear whether Kuqa hydrogen meets the definitions of green hydrogen as the capacity of renewables built for this facility are estimated to meet around 60% of the demand[13].

Hydrogen storage and its relation to the end use

Current methods for hydrogen production generate medium-to-high-pressure gas that typically requires high-pressure tank storage. It can also be cryo-compressed or liquefied (at -253 °C) which requires specialised insulated vessels[14]. These options are, currently, not sufficiently scalable.

Underground geological storage is a promising solution to address this issue. Several types of geological formations, such as salt caverns, saline aquifers, and depleted hydrocarbon reservoirs have the potential to be used for the bulk storage of hydrogen gas. In addition to scale, underground storage has benefits such as safety of stored gas and space management[15]. One example of projects in consideration is the potential Rough offshore storage conversion to enable storage of hydrogen at scale; the desired investment for this project is estimated £2 Bn[16]. Salt caverns are one of the most promising options due to their presence in a range of geographies across different countries. There are several salt cavern projects in the UK, such as HySecure (Cheshire)[17] and Teesside[18]. Unfortunately, salt cavern storage is not a feasible option in a range of regions due to geological characteristics, including London, the southeast England, South Wales, and Scotland[19].

There is a significant potential for hydrogen storage in material-based media. Hydrogen can be absorbed onto either a solid surface, such as metal-organic frameworks (MOF)[20], or reversible combination with other chemicals. One option for hydrogen storage as a chemical is as a liquid organic hydrogen carrier (LOHC). The LOHC pathway is being explored by, for example, HySCALE project (SGN)[21]; HySTOC project[22] and LHyTS project (a collaboration between the Net Zero Technology Centre and ERM to create a hydrogen export route from Scotland to Rotterdam)[23]. The appeal of chemical storage of hydrogen is in the ease of handling as it can use the same infrastructure as, for example,

13 https://www.hydrogeninsight.com/production/world-s-largest-green-hydrogen-project-chinas-260mw-kuqa-facility-to-be-commissioned-at-the-end-of-may/2-1-1457242
14 https://www.energy.gov/eere/fuelcells/hydrogen-storage
15 A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. (2022)
16 https://smarter.energynetworks.org/projects/nia2_sgn0024/
17 https://www.storengy.de/sites/default/files/mediateque/pdf/2021-11/HySecure%20EN.pdf
18 https://www.gaffneycline.com/sites/g/files/cozyhq681/files/2022-07/gaffneycline_underground_hydrogen_storage_article.pdf
19 Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations
20 Optimizing Hydrogen Storage in MOFs through Engineering of Crystal Morphology and Control of Crystal Size (2021)
21 https://smarter.energynetworks.org/projects/nia_sgn0164/
22 https://cordis.europa.eu/project/id/779694
23 https://www.erm.com/news/project-launched-to-create-hydrogen-highway-from-scotland-to-rotterdam/

liquid fuels or crude oil (e.g., liquid tankers). Hydrogen can also be stored as a component of methanol[24], ammonia (highlighted by the RSE[25]), and synthetic/e-fuels[26].

For producers to make a decision regarding the best storage strategy for hydrogen (and consequently invest in the production infrastructure), it is critical to understand the methods and priorities for the end use of hydrogen. As indicated previously, hydrogen gas is routinely produced and used in a range of processes in petrochemicals. These activities generally use grey (unabated) hydrogen which is not sustainable and represents an obvious displacement target. Hydrogen gas and hydrogen carriers can be used for energy generation via direct combustion. Examples include power and steam generation in hydrogen gas-powered turbines[27]; long-haul passenger planes using sustainable aviation fuels[28], and numerous technologies in development such as ammonia-powered ships (e.g., Nordic Green Ammonia-Powered Ships project[29]) and e-methanol-powered ships[30].

Renewable electricity – intermittency and curtailment

Sustainable electricity is the key component in the production of both blue and green hydrogen, as both processes are highly energy intensive. Renewable electricity, for example, generated via wind turbines, has an intermittent pattern of generation that is dependent on the weather conditions. This is a concern for hydrogen production facilities that are continuous processes. For example, in some common types of electrolysers, nickel electrodes critically erode after 5,000 stop-start cycles[31]. Other electrolyser designs have long start cycles (>12 hours) and suffer from embrittlement of ceramic elements[32]. As such, continuous access to electricity at a competitive cost is critical for a producer facility.

On the other hand, hydrogen production is often discussed in the context of storage of excess renewable electricity[33]. Renewable electricity sources can produce more electricity than is required or more than can be exported to the grid, resulting in curtailment – a deliberate reduction in power generation to balance supply and demand. Scotland, in particular, has very high levels of curtailed electricity, and these levels are predicted to continue to increase as new wind projects are developed following the recent Scotwind and INTOG leasing rounds that together will add over 30 GW of renewable electricity capacity[34]. Subsequently, some of the projects may have to pursue hydrogen as their route to market, either as primary (Flotta Hydrogen Hub) or secondary (Ocean Winds) value offering . Research shows that hydrogen has the potential to reduce the overall curtailment of

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24 https://orsted.com/en/media/newsroom/news/2023/05/13682622
25 https://rse.org.uk/wp-content/uploads/2022/04/RSE-AP-Scottish-Government-Draft-Hydrogen-Action-Plan-2022.pdf
26 Synthetic/Sustainable Aviation Fuel Mapping. (2023)
27 https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20Power%20to%20Gas%20-%20Hydrogen%20for%20Power%20Generation.pdf
28 https://www.greenbiz.com/article/sustainable-aviation-fuel-offers-flight-path-net-zero-air-travel
29 https://www.zerocarbonshipping.com/publications/nordic-green-ammonia-powered-ships-nogaps/
30 https://www.reuters.com/business/sustainable-business/maersk-agrees-project-with-spain-make-e-methanol-its-fleet-2022-11-03/
31 Alkaline Water Electrolysis Powered by Renewable Energy: A Review
32 Assessment of electrolysers: report (2022)
33 Large-scale electricity storage. (2023)
34 https://www.offshorewindscotland.org.uk/the-offshore-wind-market-in-scotland/scotwind-leasing-round/

renewable energy, but the expected lag time between the growth of wind energy generation and network reinforcement / hydrogen production capability increase is likely to lead to a significant volume of curtailed energy in the late 2020s[35].

3.3 Meso-level

This section discusses three core elements of meso-level, or inter-company, activity in the emerging Grangemouth Hydrogen Hub.

Transportation infrastructure for hydrogen and captured carbon

Post-production, hydrogen needs to be transported (for storage or to the end-user) using the most economically feasible options with consideration of the available infrastructure and capital costs for its installation and repurposing. In 2022, the International Renewable Energy Agency (IRENA) published a report 'Global Hydrogen Trade: Part 2'[36] that outlined the predictions for the most effective pathways of hydrogen transportation based on the project size and distance (Figure 1).

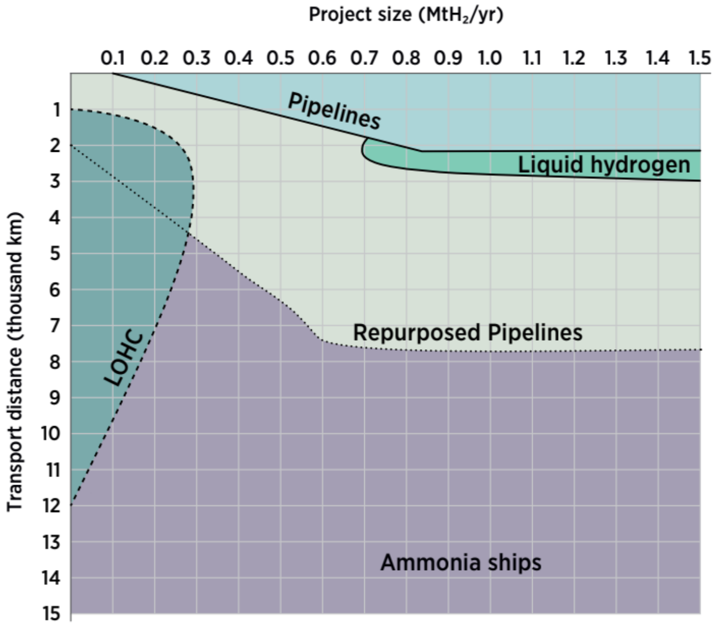

Figure 1. Predictions of the most cost-effective hydrogen transport pathways in 2050 as a function of project size and transport distance (IRENA).

Additionally, for production of blue hydrogen, the transportation of captured carbon is a critical prerequisite. In September 2021, INEOS announced the conversion of the Grangemouth petrochemicals plant and oil refinery to run on hydrogen at a cost of more than £1bn, to help make it

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35 The potential for hydrogen to reduce curtailment of renewable energy in Scotland. (2022)

36 Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers. (2022)

net zero for carbon emissions by 2045[37]. This will be achieved through the construction of the Low Carbon Hydrogen Manufacturing Plant (discussed in more detail in Section 5.1). As indicated in the press release, this project depends on infrastructure development defined within the Acorn project– a Scottish CCUS Cluster project that will enable INEOS to remove captured carbon and store it in the North Sea. In their recent conversations with the Scottish Government Economy and Fair Work Committee (December 2023), INEOS indicated that the vast majority of infrastructure assets can be repurposed to enable transportation of hydrogen and CO_2 with an additional need of 15-20 km of pipeline. These changes are happening within the context of announcements of the Petroineos investigation into the potential transition to the primary operations as an import and export oil terminal facility[38], suggesting that the cluster and INEOS and Petroineos asset operations might change considerably (depending on the commercial case of this transition that will be determined in the next 18 months). In collaboration with INEOS, two key projects – H2 Caledonia (SGN) and Project Union (NGT) - seek to create a hydrogen transportation system capable of transporting 100% hydrogen in Scotland and the wider UK, thus connecting hydrogen production centres to hydrogen consumers and key industrial cluster sites, including the Grangemouth cluster. In this way, the Grangemouth cluster has the potential of becoming a net producer or a net consumer of hydrogen, depending on the growth of the demand.

In this context, connectivity infrastructure between producers, users, and storage systems is a critical link that allows for the development of an integrated hydrogen ecosystem and network effects therein.

Supply-and-demand: business case

Fuel switching to hydrogen has a strongly persuasive and unequivocal sustainability argument. However, in order to accelerate industry activities to enable the hydrogen economy, there is a need for an equally strong business case in the context of supply and demand of hydrogen.

Presently, self-supply is the most reliable early opportunity for companies that use grey hydrogen in their processes already (such as INEOS's petrochemicals plant). Other large companies in the region, for example, Mossmorran-based Shell and ExxonMobil, could also produce and use hydrogen for their own operations.

Whilst self-supply is a stable model for kickstarting hydrogen production (as the same company is in full control of scale of production and use), such siloed cases are unlikely to establish a hub and, therefore, will not benefit from wider network effects. Other hubs, such as Cromarty Firth Hub[39] and HyNet North West (discussed in detail below) integrate non-producing users, as well as users outside the chemicals industry, as a core part of the proposition.

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[37] https://www.ineos.com/news/shared-news/ineos-grangemouth-moves-forward-on-the-next-phase-of-its-journey-to-reduce-greenhouse-gas-emissions-to-net-zero-by-2045-with-further-investment-in-excess-of-1-billion/

[38] https://www.bbc.co.uk/news/uk-scotland-tayside-central-67497023

[39] https://www.cromartyhydrogenproject.co.uk/

Some uncertainty about end users and, therefore, their integration into a hub proposition comes from the lack of clarity about hydrogen deployment priorities. The Scottish Hydrogen Action Plan (2022) indicated the hierarchy of H_2 uses (Figure 2), and, internationally, a range of organisations have created their own predicted priorities, such as the Hydrogen Ladder (Figure 3) . The true levels of market pull in these priority sectors remains unclear, and other low priority sectors remain hotly debated. For example, domestic heating is one of the most widely discussed opportunities. Whilst the use of hydrogen in domestic heating is considered to be a suboptimal use of hydrogen due to the presence of other alternatives (such as heat pumps), it could work as an anchor market to provide the producers with certainty of a single large offtaker, thus de-risking their investment in production infrastructure[40,41]. INEOS, for example, has engaged in a series of projects with SGN to investigate the opportunity to deliver hydrogen to SGN's end users for domestic heating. Conversely, the Second National Infrastructure Assessment called on the Government to rule out hydrogen for heating[42]. At the time of evidence gathering for this report, the UK Government was expected to make the final decision on the hydrogen role in heating by 2026[43]. In December 2023, the support for hydrogen and natural gas blending into the GB gas distribution networks (up to 20% by volume) was announced[44].

Lastly, the use of hydrogen in domestic heating will have a significant seasonal variation that might make this end user market less appealing to the producers than, for example, freight or export.

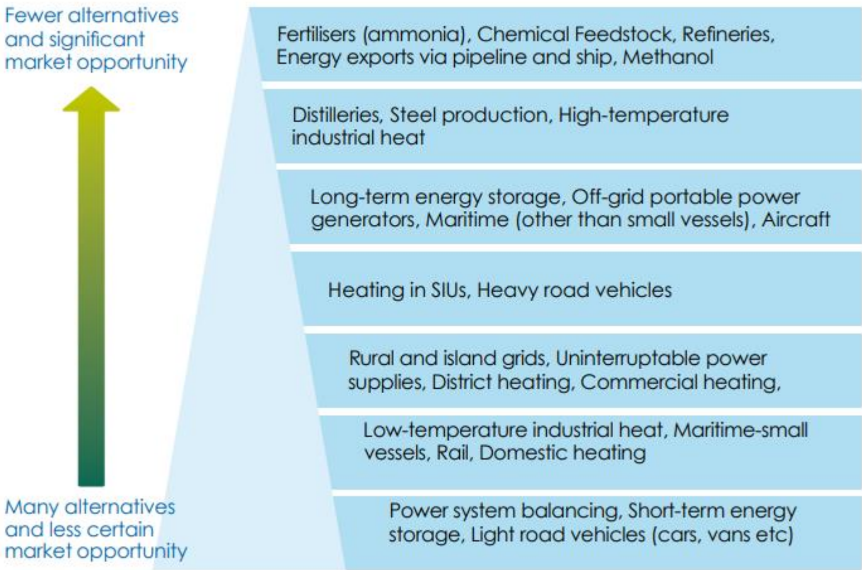

Figure 2. The hierarchy of hydrogen use in the Hydrogen Action Plan.

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40 [Hydrogen for heat? Eight critical questions for the UK Hydrogen Strategy. (2021)]
41 [The potential use of hydrogen for heating in Scotland. (2022)]
42 [Second National Infrastructure Assessment. (2023)]
43 https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-enabling-the-hydrogen-village-trial
44 https://www.gov.uk/government/publications/hydrogen-blending-in-gb-distribution-networks-strategic-decision

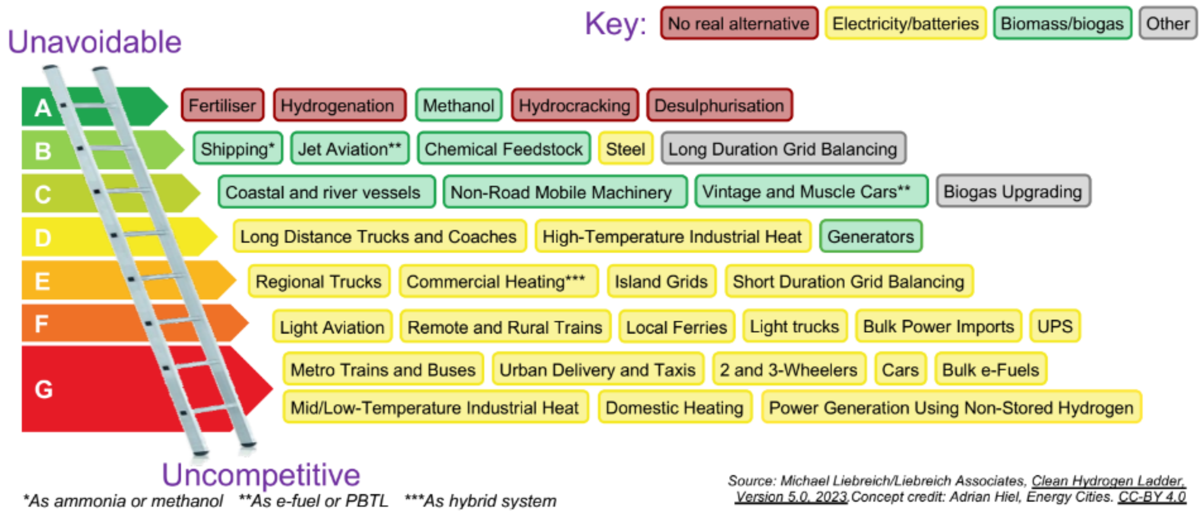

Figure 3. The Hydrogen Ladder (Revision 5).

Reaching export markets

Export markets are identified as key opportunities for the hydrogen value chain in Scotland. For example, the EU has already signalled a very high appetite to become an importer of sustainable hydrogen[45].

Hydrogen transport is a critical aspect to enable access to export markets. Aquaductus, a purpose-built hydrogen pipeline in development in the German North Sea, is likely to serve as the key infrastructure for connecting North Sea hydrogen producers to the European mainland[46]. However, a recent report about commercial models for future hydrogen production[47] for Crown Estate Scotland and the Net Zero Technology Centre's (NZTC) Hydrogen Backbone Link: Connecting Scotland to Europe project [48] do not include Grangemouth in their assessment of access points to export markets as all pipelines are modelled from the North East (Aberdeen / St Fergus). Nevertheless, Grangemouth is part of the Forth Green Freeport area, which offers a favourable tax environment, development land, and a suite of business and innovation support opportunities and, therefore, may attract investment that would enable connection into export markets. Indeed, Forth Ports have previously signalled their interest in H_2 and potentially CO_2 transport by ship, building on its current status as the Scotland's largest export and principal export hub[49].

Export market considerations have a close connectivity to macro-level policy developments. For example, a consideration must be given to sustainable hydrogen definitions and their

45 https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en
46 https://aquaductus-offshore.de/
47 Commercial models for future hydrogen production. (2023)
48 Hydrogen Backbone Link: Connecting Scotland to Europe. (2023)
49 https://falkirk.gov.uk/coins/viewSelectedDocument.asp?c=e%97%9Dc%90r%82%8A

standardisation[50]. The UK Government published a standard for low carbon hydrogen in 2022 and a new certification scheme is due in 2025[51]. For Scotland-produced sustainable hydrogen to have demand in European import market, these definitions must align.

In summary, there is a significant level of business case interdependence in the emerging hydrogen economy whereby a commercial interest of one company relies on the activities of another. This situation highlights that collaboration, strategic activity and geographic proximity of stakeholders (technology developers, producers, and early end-user adopters) in the early stages of the hydrogen economy could help the success of this emerging sector. This has been exemplified by the creation of the Energy Transmission Zone in Aberdeen that seeks to support hydrogen supply chain expansion in the North East of Scotland. Grangemouth has the potential to pivot the existing industrial strengths and expertise to capitalise on the hydrogen opportunity. More collaborative business models that share the research and innovation burden and financial risk across the industry supply chain can help move the nascent industry into an accelerated growth stage.

3.4 Macro-level

This section highlights three macro-level influences on the emerging Grangemouth Hydrogen Cluster.

Continuity in policy & support

The emerging hydrogen economy in the UK is supported by a series of policy developments.

Building on the announcement of the Ten Point Plan for a Green Industrial Revolution[52] (2020), that included ambitions to generate 10 GW of low carbon hydrogen production capacity by 2030, and the establishment of the Hydrogen Advisory Council; the UK's Hydrogen Strategy[53] was published in 2021. The key objective of the strategy is to support the development of a hydrogen economy with the potential to provide up to 35% of the UK's energy consumption by 2050, alongside development of a hydrogen business model and the launch of targeted funding sources (discussed below). The Scottish Hydrogen Assessment[54] (2020), followed by the Hydrogen Action Plan[55] (2022), defined Scottish ambition for installed sustainable hydrogen production capacity of 5 GW by 2030 and 25 GW by 2045. This commitment was further confirmed in the Net Zero Nation: Draft Energy Strategy and Just Transition Plan[56] (2023) as a part of a more integrated overview of the sustainable energy mix in the country. It is noted, however, that none of these policy documents have been made into law, unlike, for example, the legislative frameworks for emissions reduction / net zero whereby The Climate Change (Scotland) Act 2009 was amended by the Climate Change (Emissions Reduction Targets)

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50 Standardizing hydrogen certification. (2023)
51 https://www.gov.uk/government/publications/uk-low-carbon-hydrogen-standard-emissions-reporting-and-sustainability-criteria
52 The ten-point plan for a green industrial revolution. (2020)
53 UK hydrogen strategy. (2021)
54 Scottish hydrogen assessment. (2020)
55 Hydrogen action plan. (2022)
56 Draft Energy Strategy and Just Transition Plan. (2023)

(Scotland) Act 2019[57]. In contrast, a range of hydrogen-focused incentives in the US have been passed as federal public law[58].

Regionally, the Grangemouth Future Industry Board (GFIB) was established in 2020 to act as a unified group of stakeholders seeking to identify and address the changing needs of the region[59]. In line with the recommendations from the Scottish Government Economy & Fair Work Committee in Summer 2023, GFIB is undertaking a broadening of its membership to include industry and community voices and will co-develop a Just Transition Plan for the cluster by Spring 2024.

Public funding and private investment

In April 2022, the UK launched the £240 million Net Zero Hydrogen Fund (NZHF) to support the deployment of hydrogen production projects with a focus on capital and development grants[60]. This is part of the Hydrogen Production Business Model – a series of revenue support mechanisms to support hydrogen producers to overcome the operating cost gap between low carbon hydrogen and high carbon fuels[61]. This includes two CCUS-enabled hydrogen projects in Track-1 (HyNet North West and Teesside) and a shortlist of 20 projects undergoing due diligence for the first electrolytic hydrogen allocation round that includes four Scotland-based projects. The Track-2 CCUS fund is currently undergoing due diligence of the Acorn project and Viking Transport[62]. The second round of allocation for electrolytic hydrogen was announced in December 2023[63]. Additional funding sources relevant to hydrogen (but not specifically targeted to it) include the Energy Entrepreneurs Fund[64], £210 M Industrial Decarbonisation Challenge Fund (UKRI)[65], £20 M Clean Growth Fund (equity investment; part of the BEIS £1 bn Net Zero Innovation Portfolio)[66], and a range of other investments and funding opportunities[67]. The UK is home to at least three large venture capital funds with a substantial focus on hydrogen technologies – HydrogenOne Capital Growth[68] (10% owned by INEOS[69]); HyCap, and Hydrogen Ventures[70] (a subsidiary of Climate Change Ventures).

In Scotland, the £180M Emerging Energy Technology Fund[71] was announced as a part of the Climate Change Plan Update in December 2020. The strategic focus of this fund was divided into £80M for blue

57 https://www.legislation.gov.uk/asp/2019/15/contents/enacted
58 https://afdc.energy.gov/fuels/laws/HY?state=US
59 https://www.gov.scot/groups/grangemouth-future-industry-board/
60 https://www.gov.uk/government/publications/net-zero-hydrogen-fund-strand-1-and-strand-2
61 https://www.gov.uk/government/publications/hydrogen-production-business-model-net-zero-hydrogen-fund-shortlisted-projects/hydrogen-business-model-net-zero-hydrogen-fund-negotiations-list-for-allocation-round-2022
62 https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-track-2
63 https://www.gov.uk/government/publications/hydrogen-allocation-round-2
64 https://www.gov.uk/government/collections/energy-entrepeneurs-fund
65 https://www.ukri.org/what-we-do/our-main-funds-and-areas-of-support/browse-our-areas-of-investment-and-support/industrial-decarbonisation/
66 https://www.gov.uk/government/publications/clean-growth-equity-fund
67 Hydrogen Investment Roadmap. (2023)
68 https://hydrogenonecapitalgrowthplc.com/
69 https://www.ineos.com/news/ineos-group/ineos-energy-announces-cornerstone-backing-for-hydrogenone/
70 https://hydrogenventures.co.uk/
71 https://www.gov.scot/publications/emerging-energy-technologies-fund-hydrogen-innovation-scheme-successful-projects/

hydrogen and CCUS technologies (not yet awarded), and £100M for green hydrogen technologies[72]. As a part of the green hydrogen technology funding allocation, the Hydrogen Innovation Scheme (HIS; total value £10M) awarded £7M capital to a total of 32 projects for feasibility studies, technical demonstration, and development of test and demonstration facilities and equipment. The remaining £90M for the delivery of green hydrogen projects has not yet been released.

Regionally, the Falkirk-Grangemouth Investment Zone Growth Deal represents a strategic investment in the future of these regions, aiming to stimulate economic activity, support innovation, and enhance community well-being. This includes a Forth Green Port Freeport £25M seed funding (for the development of the Tax Sites). Some of the major energy companies that are based in the Grangemouth region have internal (private) investment branches, including INEOS Investments and Shell Ventures.

Skills

Scotland has a particularly strong knowledge and skills base in engineering and process industries built on the legacy of oil, gas, and renewables developments over the years. Skills needs across the emerging hydrogen value chain have been highlighted in several studies, with particular emphasis on the concentration of skills needs around production sites and augmentation of existing skilled technical roles to incorporate hydrogen[5,73]. In addition, the demand for a skilled workforce is predicted to rapidly increase across the whole energy sector. In 2022, the Royal Society of Edinburgh called for curricula updates to reflect this evolving job market[25]. A range of skills initiatives, including OPITO's Energy Skills Passport[74], the Hydrogen Skills Partnership[75], and the National Energy Skills Accelerator[76] are working to address the predicted skills shortage across the energy sector, including hydrogen.

3.5 Implementation of previously highlighted recommendations for Grangemouth

The Wood report (2021) identified several strategic recommendations towards the development of the future Grangemouth Hydrogen Hub. The implementation of these recommendations and comments on the relevant activities are summarised in Table 1 .

Recommendation	Status	Comments
Ensure ongoing studies (SNZI/SNZR, SGN Industrial Clusters, IDRIC) are used to develop a coherent further investment case for hydrogen.		Strong and consistent messaging in support of hydrogen as a decarbonisation technology.
Demand: SULEB III funding round for hydrogen buses.		Now replaced by ScotZEB (currently on Round 2). The Scottish Government has indicated to the public sector partners that further ScotZEB rounds are highly unlikely (no public statement has been made).

72 https://www.gov.scot/news/investing-in-green-hydrogen/
73 Landscape review of skills needed for an emerging hydrogen based economy. (2023)
74 https://opito.com/media/news/opito-awarded-5-million-through-just-transition-fund-to-deliver-energy-skills-passport
75 https://hydrogenskillsallaince.org/
76 https://the-nesa.org/

Fund FEED study for blue hydrogen production facility at Grangemouth.		INEOS Low Carbon Hydrogen Manufacturing Plant was announced, pending Acorn CCUS infrastructure – not yet funded as the Scottish Cluster is undergoing due diligence regarding CCS Infrastructure Fund Track 2 (timelines are unknown).
Support collaboration between manufacturers and haulage/rail sectors to determine fuelling station needs and aftercare packages for hydrogen.		Ofgem's Strategic Innovation Fund has some rail/haulage projects, but none explicitly associated with Grangemouth.
Support funding routes to attract sustainable aviation fuel (SAF) production and development of CCU Sustainable Manufacturing Campus at Grangemouth.		SE SAF study has investigated the regional market opportunity[26] . SAF funding available through the UK Government Advanced Fuel Fund (no Scotland-based projects in Round 1, Dec 22). Business case for the Sustainable Manufacturing Campus, funded by the Falkirk Growth deal, being prepared. SAF Working Group being convened by the SG and SE (work likely to include providing advice on how the Scottish Government could facilitate SAF production and use).
Fund FEED study for green hydrogen production facility at Grangemouth (including scope of offshore renewable generation).		Various funding sources available (Hydrogen Innovation Initiative's Seed programme (£6M), Net Zero Hydrogen Fund (NZHF funded four green H_2 projects; none in Grangemouth). Significant increase in renewable electricity capacity from ScotWind and INTOG but no information about their association with potential green hydrogen projects at Grangemouth to date. The Scottish Hydrogen Innovation Scheme predominantly focused on concept and feasibility; no green hydrogen projects in Grangemouth[77]. Forth Green Freeport funding (£25 M) regionally targeted investment does not focus on green hydrogen. Emerging Energy Technologies fund is a possible source for funding a study of this type (not yet released).
Convene logistics taskforce to study feasibility of decarbonising freight logistics in/out of Grangemouth cluster (road/rail/port) 'hydrogen zone'.		Potentially a topic of Grangemouth Future Industries Board (pending Board's update of strategic aims, Sept 2023).
Work with UK Government to incentivise hydrogen/BEV in revised fuel duty structure.		Hydrogen is not included in the fuel duty structure 2022-2023[78] .

Table 1. Recommendations from Wood (2021) report and comments on their implementation.

[77] https://www.gov.scot/publications/emerging-energy-technologies-fund-hydrogen-innovation-scheme-successful-projects

[78] https://www.gov.uk/government/publications/changes-to-fuel-duty-rates/fuel-duty-rates-2022-23

4 Key Messages from Interviews

The collection of the primary research data via semi-structured interviews with key stakeholders took place in September-October 2023. In December 2023, several strategic announcements from the UK Government were released which might have had an impact on some opinions and attitudes outlined in the report. We note the rapidly evolving environment in the hydrogen ecosystem and have provided, where appropriate, an indication of newest developments that might change the context of given statements.

4.1 Micro-level

The interviews indicated a range of activities relating to hydrogen ecosystem in Grangemouth and the wider region. Figure 4 summarises current and potential projects focusing on hydrogen production, self-supply, and transportation via pipeline network.

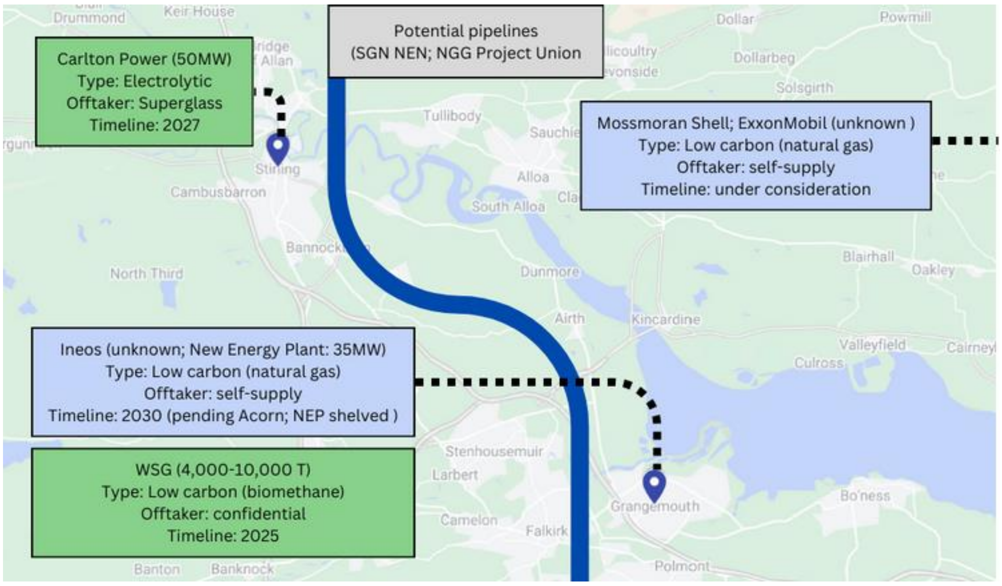

Figure 4. Hydrogen activity in Grangemouth and wider region.

Currently, hydrogen ecosystem development in the region is thought to be led mainly by producers. Potential users who do not produce hydrogen are generally interested in using it to replace grey hydrogen in their existing processes or for activities like industrial heat to help meet their net zero targets. Yet, many of these users remain open to various decarbonisation strategies, prioritising an energy solution that ensures steady supply and cost. Similarly, potential offtakers do not show a very strong preference for the source of hydrogen (electrolytic or natural gas), though blue hydrogen is seen as offering more short-term supply security until electrolytic production and storage capacity can meet future demand.

Grangemouth industrial cluster, such as a selection of companies outlined in Table 2, contains two major groups of companies with the highest potential to become early-to-medium-term hydrogen offtakers. This includes chemicals manufacturers and logistics companies. Chemical manufacturers are actively investigating hydrogen for low-carbon industrial heat and to replace grey hydrogen when suitable. This shift is mainly motivated by the need to cut emissions following the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019. For logistics, the zero-emission vehicle mandate by 2035[79] and net-zero HGV target by 2040[80] will likely push for faster decarbonisation, as petrol and diesel engines are phased out. It has been highlighted that the industrial base in Grangemouth will experience significant changes in near future as many chemicals manufacturers have announced their departure from site, and others will seek to integrate in the cluster.

Company	Primary operations	Consumer	Producer	Logistics	Notes
Celtic Renewables	Biorefinery		Medium		
Alexander Dennis	Bus manufacturing	Low			Involved in the hydrogen activities as a manufacturer of hydrogen fuel cell buses.
INEOS	Chemicals	High	High		Accounced Low Carbon Hydrogen Manufacturing plant in 2022. The timeline is under revison.
Versalis	Chemicals	High	High		Versalis to close chemical plant by April 2024.
Calachem	Chemicals	Medium	Medium		Announced the closure of the manufacturing arm in 2021.
Mossmorran NGL Plant	Chemicals	High	High		Primary interest in self-supply.
Fife Ethylene Plant	Chemicals	High	High		Primary interest in self-supply
Syngenta	Chemicals	Medium			
Piramal Healthcare	Chemicals (pharma manufacturing)	Medium			
BOC Gases	Gas distribution			High	Virtual pipeline
Avanti Gas Road Loading terminal	Gas distribution			High	
Polymer Logistics Scotland	Haulage	High		Medium	An opportunity to decarbonise the fleet by moving to hydrogen-powered machinery. Could become involved in hydrogen transportation via tube trailers
HWCoates	Haulage	High		Medium	
Malcom Logistics	Haulage	High		Medium	
John Mitchel	Haulage and warehousing	High		Medium	
Falkirk Council	Heavy fleet managers (local authority)	High			
Hewden	Lease of machinery	High			
Forth Ports	Logistics			High	Import and export markets.
Petroineos	Refinery	High	High		Announced the Refinery Transition Project to explore moving to primary operations as import/export site
International Timber	Timber import and distribution	High			

Size of opportunity		
	(green)	High
	(amber)	Medium
	(red)	Low

Table 2. Grangemouth industrial cluster companies and their potential activities in the emerging hydrogen cluster (Optimat views only).

Grangemouth is viewed as a highly promising contender to assume a leadership role in blue hydrogen production (from methane or biomethane), industrial utilisation and supply to various end-users. Its substantial power-hungry industrial user base and strategic location near significant urban and transport hubs, such as the City of Edinburgh and Edinburgh Airport, as well as its access to export

79 https://www.gov.uk/government/news/government-sets-out-path-to-zero-emission-vehicles-by-2035

80 https://www.gov.uk/government/news/uk-confirms-pledge-for-zero-emission-hgvs-by-2040-and-unveils-new-chargepoint-design

facilities at Forth Ports, contributes to this potential. However, the timelines of hydrogen production and transportation project development are seen as slow. The Grangemouth industrial cluster's appetite for hydrogen is believed to soon outpace the timelines (and, potentially, planned capabilities) of the planned production projects. This suggests that the regional industry might become a net importer of hydrogen from hydrogen production sites based elsewhere in Scotland, and, potentially, act as a regional hydrogen distribution hub (similarly to its activity in gas and fuel distribution).

The prospects for green hydrogen in the Grangemouth industrial cluster are currently considered less favourable, primarily due to constraints in available renewable power resources. Developments in the Scotwind and INTOG leasing round 2 sites, situated closer to Aberdeen than Grangemouth, suggest that infrastructure for green hydrogen, including cabling, will likely be established further north. The sustained viability and success of the Grangemouth hub, however, are considered to be intrinsically linked to the development of green hydrogen infrastructure as it is the preferred long term production strategy. Electrolytic hydrogen production is, therefore, actively considered for co-location with onshore wind capacity in the broader region (outside the Grangemouth industrial cluster), for example, Stirling and potentially Longannet. An emerging project for hydrogen production via biomethane steam reforming with carbon capture has been flagged within the cluster, with a unique value proposition that uses the captured carbon as a secondary product. Due to commercially sensitive nature, the end user market for this product was not disclosed; this could potentially include the use as a feedstock for Fischer–Tropsch-based processes (methanol, ethanol, SAF production). Overcoming the challenge of accessing renewable energy sources at scale is vital for diversifying the hub's hydrogen production capabilities and ensuring its long-term sustainability.

Opinions among stakeholders regarding the most strategic focus for hydrogen at Grangemouth are varied. Green hydrogen producers are showing a strong focus on domestic industrial decarbonisation that includes industrial heat and heavy transport. Some stakeholders contend that there is a significant opportunity for Grangemouth to break into the production of Sustainable Aviation Fuels (SAF), seizing the growing demand and market potential. Whilst Petroineos' announcement of the Refinery Transition Project has added considerable uncertainty about the short-term activity on side, the company has publicly stated that they are in the appraisal stage for a biorefinery producing SAF or HVO (hydrotreated vegetable oil, or renewable diesel)[81]. In contrast, others argue that prioritising the export of gaseous hydrogen to Europe should be the primary focus as a far more significant commercial opportunity. Venturing into hydrogen production for applications such as methanol or ammonia synthesis presents another potential pathway. However, this would necessitate navigating markets that are projected to have intense global competition, due to the relative ease of transporting and storing ammonia and methanol. This factor is crucial for stakeholders to consider in determining the strategic direction for hydrogen production and its storage medium at Grangemouth.

Overall, hydrogen producers have expressed strong opinions that in the short to medium term, the strategic priority should be meeting the domestic hydrogen demand (as opposed to the export market)

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81 https://www.energyvoice.com/oilandgas/north-sea/refining/541845/breaking-grangemouth-oil-refinery-could-cease-operations-by-2025/

as the local industries are accelerating their decarbonisation activities. In this way, considerations regarding the export of H_2 are perceived as a question to consider in the future when large gigawatt-scale facilities in Scotland become operational. This indicates the need for strong strategic policy leadership to ensure an optimal environment for this future activity. This could be achieved, in turn, by in-depth consideration of export scenarios that in the future will link large producers to key export target countries.

Additionally, the context of this question has recently shown significant changes, with Petroineos announcing an investigation into the potential transformation of the refinery into a fuel import site. As indicated previously, the final decision regarding the future of this site will be based on the results of the ongoing investigation of the Refinery Transition Project (over the next 18 months).

The Grangemouth cluster currently faces significant demand for power and steam, leading to potential bottlenecks in various processes (current and planned). This situation could potentially impede on-site hydrogen production and presents a challenge that must be addressed proactively. Implementing waste-to-power solutions equipped with carbon capture technology, emerges as a viable strategy to alleviate these challenges and bolster the energy supply, thereby supporting the broader objectives of the Grangemouth hydrogen hub.

4.2 Meso-level

The availability of renewable electricity and associated infrastructure constraints is seen as one of the key bottlenecks for hydrogen production. As highlighted earlier, new offshore renewable electricity projects are situated closer to Aberdeen than to Grangemouth, leading to the perception that hydrogen production will predominantly occur in the North East, subsequently flowing southwards to feed a blending and distribution hub at Grangemouth. Conversely, other stakeholders believe that the location of offshore wind projects is less relevant in this context because hydrogen production might be predominantly driven by onshore wind developments in the region. Additionally, the stakeholders indicate that the grid infrastructure is a major constraint in the development of green hydrogen projects, and potentially can affect blue hydrogen production projects depending on their source of steam and heat as fossil fuel-driven electricity generation might not meet the desirable low carbon standard.

Hydrogen transportation and storage remain crucial issues. Without substantial storage capacity to offset the seasonal availability of renewable energy, the hydrogen supply chain is likely to stay fragmented and vulnerable to disruption. This may necessitate using natural gas as a backup energy source. In the short term, hydrogen transportation from producers to end users will primarily use tube trailers. For high-volume end users in the medium term, a privately owned pipeline could be the most cost-effective transportation method. In both cases, the proximity of producers and end users is highly beneficial. Looking long-term, stakeholders anticipate that Grangemouth will connect to major hydrogen pipeline projects currently in development (H2 Caledonia, SGN North East Network & Industrial Cluster Development, Project Union). Interestingly, some stakeholders believe that

Grangemouth could eventually become a net hydrogen user and serve as a central hydrogen distribution hub in central Scotland.

There is a consensus that both the production and utilisation of hydrogen on-site necessitate a more robust market incentive to establish a compelling commercial case. The industry has weathered considerable uncertainty and fluctuations in gas prices over recent years, particularly since the onset of the war in Ukraine, engendering a cautious stance towards potential further increases in power costs and fluctuations in the availability of hydrogen to meet demand. Most stakeholders indicated that there is an immediate need for clear guidance on the strategic priorities for hydrogen utilisation. While blending hydrogen into gas networks for heating purposes is seen as having limited attractiveness (see Figures 1 and 2), it does provide access to a substantial anchor market almost instantaneously, giving potential producers some certainty of demand. Other stakeholders with interest in hydrogen production state that they are targeting offtakers that will use hydrogen for industrial heat and heavy transport, and that these applications should be more supported by the policy and public funding initiatives, moving away from a 'scattergun' approach.

Additionally, leveraging public sector procurement could serve to mitigate the business risks for producers. Export markets are seen as a key element in the hydrogen economy, including an opportunity for Grangemouth through Forth Ports. However, placing a disproportionate emphasis on export could potentially diminish the incentive for local infrastructure development. Stakeholders indicate that even the priority export markets do not yet have a hydrogen activity, and, therefore, the focus should be on domestic decarbonisation until circa 2030. This belief is surprising as other Scottish Enterprise sources indicate that there is a current demand for hydrogen import internationally, for example, into Germany. The reluctance of the consulted stakeholders may be based on the fact that the current cost of hydrogen production relies exclusively on the Government's Hydrogen Business Model subsidy, and, as such, is not yet competitive on an international market.

Perceptions of connectivity and collaborative efforts among industry entities within the Grangemouth region are suboptimal. This may be attributable to the real or perceived dominance of a single major organisation in the area, a situation that has been described as both Grangemouth's most significant strength and its most notable vulnerability. The reliance on a single company for hydrogen production is perceived as a risk, potentially undermining Grangemouth's prospects as a hydrogen hub in the context of its connectivity to non-producing end users and the broader hydrogen economy. Encouraging a diversity of producers and their interconnectivity in the area could distribute the risk more evenly, enhance the attractiveness of business propositions, and bolster user confidence in the consistent supply of hydrogen. Organisations responsible for hydrogen transport infrastructure are deemed essential for ensuring connectivity, not just amongst companies, but also between companies and end-users. It is anticipated that collaborative efforts will naturally evolve from the establishment of interconnected infrastructure. However, it has been highlighted that the industry needs to be more proactive in collaborative efforts to ensure that business risks are evenly spread and mitigated.

The industrial cluster in Grangemouth has such a substantial demand for power that in the short term, the hub is anticipated to become a net user of hydrogen—a scenario that presents significant opportunities for potential producers. However, due to the perceived lack of inter-organisational connectivity, this opportunity is currently underexploited. We would like to highlight that the collaboration ecosystem in Grangemouth requires a further, more balanced assessment as we have been unable to obtain commentary from the key organisation that has been highlighted by stakeholders as the critical element in the future Grangemouth Hydrogen Hub.

To evolve into a genuine hub, some stakeholders believe that there is a need for Grangemouth to integrate dynamic innovators and Research and Technology Organisations (RTOs). The challenge lies in attracting these innovation-driven industrial entities, particularly when the assets are predominantly controlled by a single company. Allocating additional space for development could be a viable solution. For instance, the local council might designate specific areas for this purpose, or depreciated assets could be repurposed and remediated. Despite ongoing concerns regarding the availability of land for developmental initiatives, projects focusing on land remediation for such purposes do not currently appear to be strategic investment priorities for targeted public funding.

4.3 Macro-level

The Hydrogen Business Model is considered to be the most significant macro-level enabler of hydrogen activities in the region, and all companies prioritise compliance with the business model's requirements in order to qualify for the subsidy and be able to sell hydrogen at a competitive price.

The Scottish Hydrogen Action Plan is widely regarded as robust and coherent, with a clear and consistent message being articulated. However, there is an undercurrent of uncertainty due to the UK general election scheduled to take place within the next 12 months, with industry experts anticipating potential shifts in the overarching policy landscape as a consequence. Additionally, the activity of Scottish Enterprise in the hydrogen is perceived positively, and SE resources such as Scotland's Hydrogen Asset map were referred to as very useful by project developers.

Compared to other hydrogen clusters in Scotland, such as those in Orkney, Cromarty Firth and Aberdeen, the progression of the Grangemouth cluster is perceived to be lagging behind. This disparity in development pace could potentially be attributed to the scale of the projects underway in Grangemouth, which are believed to be considerably larger in scope. Additionally, the local councils in these other areas are perceived to be more proactive in their approach to fostering cluster development.

Notably, the local authorities have indicated that the transition to hydrogen for the heavy fleet vehicles (e.g., council's heavy fleet and Grangemouth's logistics industry) is an obvious strategic priority, and action will be taken to ensure that infrastructure is in place to allow this transition after 2025. However, their current appetite for demonstrator projects is low, and the preference is for technologically mature projects that can guarantee the security and consistency of hydrogen supply. We note that this is in contrast to opinions expressed by hydrogen producers who understand that whilst fuel switching to hydrogen is a high risk for the offtakers, a high degree of collaboration between partners is critical for hydrogen project success. It was highlighted that the Forth Valley region has the potential to be more collaborative in its complementary hydrogen activities, noting the projects spearheaded in Fife.

One of the standout attributes of Grangemouth as a hydrogen hub is its highly skilled and experienced workforce, which is identified as one of its unique selling points. This wealth of expertise positions the hub favourably in the competitive landscape of hydrogen production and innovation.

However, a potential barrier to optimal collaborative endeavours in the region could be the nature of the public funding currently in circulation. An example of this is the £25 million seed funding provided by Falkirk Council for the development of the Tax Sites and Hydrogen Innovation Scheme. This funding model is perceived to inadvertently encourage a competitive rather than collaborative environment, leading to a proliferation of isolated, or 'siloed', projects. This, in turn, could be hampering the overall efficacy and synergistic potential of the region's hydrogen initiatives.

The Government has an opportunity to provide leadership and confidence by clarifying hydrogen use priorities and being more proactive and transparent in supporting companies that are committing to sustainable products and processes. Many stakeholders with interest in hydrogen production indicated that offtakers require more public support as they are taking on a greater risk when fuel switching to hydrogen compared to the established natural gas supply chains.

To truly capitalise on its assets and position itself as a leader in the hydrogen industry, there is a need for a strategic reassessment of funding models and incentives to foster a more collaborative and integrated approach to project development in the Grangemouth region. There has been an indication that the Grangemouth Just Transition plan will seek to aid the creation of a more collaborative focus within the region. By doing so, the cluster can unlock its full potential and contribute more significantly to Scotland's hydrogen economy.

5 Mapping Grangemouth Industrial Cluster Hydrogen Projects

To assess and contextualise the development of the Grangemouth Hydrogen Hub, short case studies of hubs elsewhere are provided.

5.1 Hydrogen Hub Case Studies

HyVelocity

HyVelocity Hub (US) is a hub recently chosen by the Department of Energy (DOE) Office of Clean Energy Demonstrations[82] for funding. It is now in negotiations, potentially receiving up to $1.2 billion from the Bipartisan Infrastructure Law. Led by seven main industry partners—AES Corporation, Air Liquide, Chevron, ExxonMobil, Mitsubishi Power Americas, Ørsted, and Sempra Infrastructure—the hub is managed by GTI Energy. It collaborates with various organisations, such as the University of Texas at Austin, The Center for Houston's Future and Houston Advanced Research Center[83]. This Gulf Coast cluster is already one of the world's largest hydrogen hubs, with 48 hydrogen production plants,

82 https://www.energy.gov/oced/funding-notice-regional-clean-hydrogen-hubs
83 https://www.hyvelocityhub.com/support/hyvelocity-selected-to-develop-gulf-coast-hydrogen-hub/

over 1,000 miles of dedicated hydrogen pipelines, and an annual production of 3.5M metric tons of H_2 (1/3 of the U.S.'s yearly production)[84]. Additionally, the hub boasts 51 GW of renewable energy capacity (solar and wind), 2.4 billion tonnes of CO_2 storage capacity in three hydrogen storage caverns, and access to affordable local natural gas. The hub is rapidly advancing, fuelled by its oil, gas, and hydrogen heritage, as well as bipartisan support that transcends specific government jurisdictions (with a funding mandate set in law), providing the industry with a high level of confidence. The HyVelocity hub also has a robust community benefits plan in line with the Justice40 initiative, ensuring that 40% of the investment's overall benefits aid disadvantaged communities affected by pollution[85]. It is projected that a hydrogen hub like HyVelocity may need 8-12 years from the funding opportunity announcement to reach full operation[86].

HyNet North West (UK)

HyNet North West[87] is a hydrogen production and a Track-1 CCUS NZHF project[88] in North West England and North Wales. Its plans encompass the entire infrastructure required for the blue hydrogen value chain, including production facilities, hydrogen and CO_2 pipelines, and storage[89]. HyNet is supported by the University of Chester as the project's academic lead[90]. Over 40 end-user organisations have committed to early adoption and decarbonisation through HyNet. Initially designed for blue hydrogen, HyNet's design also facilitates a transition to green hydrogen as renewable electricity capacity in the region grows. One of HyNet's founding partners, Statkraft, has shown interest in developing the parallel Cheshire Green Hydrogen project[91]. Key projects under HyNet include:

- Hanson Padeswood Cement Works Carbon Capture and Storage Project
- Viridor Runcorn Industrial CCS
- Protos Energy Recovery Facility
- Buxton Lime Net Zero
- HyNet Hydrogen Production Plant 1 (HPP1).

HEAVENN (Netherlands)

HEAVENN is a large-scale demo project under the umbrella of the European Hydrogen Valleys. Based on the EU definition, a hydrogen valley is "a geographical area – a city, a region, an island or an industrial cluster - where several hydrogen applications are combined together into an integrated hydrogen ecosystem that consumes a significant amount of hydrogen, improving the economics

84 https://www.hyvelocityhub.com/wp-content/uploads/2023/04/HyVelocity-H2Hub-FAQs-4_23.pdf
85 https://www.whitehouse.gov/environmentaljustice/justice40/
86 Hydrogen hubs: Is there a recipe for success? (2022)
87 https://hynet.co.uk/
88 https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-track-1-project-negotiation-list-march-2023
89 https://geos.ed.ac.uk/sccs/project-info/2165
90 https://www1.chester.ac.uk/news/university-powers-ahead-academic-lead-national-net-zero-mission
91 https://hynet.co.uk/green-hydrogen-portfolio-announced/

behind the project. It should ideally cover the entire hydrogen value chain: production, storage, distribution and final use"[92]. The valleys are eligible for additional subsidies as a part of the EU hydrogen strategy.

The HEAVENN project partners include Gasunie, Nobian, Engie, Getec, Groningen Seaports, Nederlandse Aardolie Maatschappij, QBuzz, TotalEnergies, Energie Beheer Nederland, Lenten Scheepvaart BV, Green Planet, Municipalities of Groningen, Hoogeveen and Emmen, HyEnergy TransStore, Shell, H2Tec and a range of political and research organisation sponsors. The investment volume of the project is currently at €2.8 Bn[93]. The project covers a range of value chain aspects: H_2 production electrolytically using PEM and ALK hydrolysers; compressed H_2 storage in caverns; H_2 transport by pipeline, trucking, and ship; H_2 distribution for transport sector (refuelling stations) but excludes primary energy sourcing that could potentially come from the neighbouring wind power projects such as NorthH2[94]. HEAVENN will be connected to the national hydrogen backbone and feed end users such as the first hydrogen-powered village Stad aan 't Haringvliet[95].

The project was initiated in 2014, with development starting in 2019 and expected finalisation in 2026. The full ramp-up of operations is predicted to happen in the timeframe by 2035.

5.2 Ongoing projects in Grangemouth

As the industry is legally obliged to continuously reduce its carbon emissions, the major companies in the region have begun exploring the opportunity of using sustainable hydrogen to meet their energy demands in processes that cannot be effectively electrified. Some companies, such as Shell and ExxonMobil (Mossmoran) have informally expressed interest in using, and potentially producing, low carbon hydrogen for their operations. The first regional company that made a public announcement indicating their commitment to low carbon hydrogen production was INEOS with their plans of the Low Carbon Manufacturing plant in early 2022[96]. In June 2023, Carlton Power released a statement regarding a collaboration with a large industrial offtaker Superglass (Stirling) in a project that will install a 10 MW electrolyser to produce approximately 1000 tonnes of hydrogen per year[97]. In December 2023, WSG released an invitation to tender for the supply, delivery and installation of the major hydrogen-related equipment and production plant with aim to produce 2,000 or 4,000 kg of hydrogen per day using biogas as feedstock. This plant will be equipped with carbon capture to remove and liquify CO_2. This activity indicates that the producers have the ambition to come online

92 https://www.clean-hydrogen.europa.eu/get-involved/mission-innovation-hydrogen-valleys-platform_en
93 https://h2v.eu/hydrogen-valleys/heavenn-0
94 https://www.rwe.com/en/research-and-development/hydrogen-projects/north2/
95 Excelling in Hydrogen: Dutch technology for a climate-neutral world (2022)
96 https://www.ineos.com/news/shared-news/ineos-at-grangemouth-announces-plans-to-construct-a-low-carbon-hydrogen-manufacturing-plant/
97 https://www.carltonpower.co.uk/news/carlton-power-agrees-partnership-with-scotlands-superglass-to-develop-green-hydrogen-project-in-stirling

around 2026, although timelines are subject to a range of factors, including the availability of public funding support.

INEOS Low Carbon Manufacturing plant

INEOS Low Carbon Manufacturing plant is highly likely to become the lead enabler of the future Grangemouth Hydrogen Hub as the first mover into the emerging market opportunity. Hydrogen produced in this plant will be used to power a new energy plant, as well as to be deployed across other assets on site, including the Combined Heat and Power Plant, the KG Ethylene Plant and elements within the Petroineos refinery. In June 2022, reports emerged that the construction of the new power plant was facing delays due to a range of factors including an increase in gas prices and supply chain interruption associated with the war in Ukraine[98]. It has been stated that whilst the company remains dedicated to the project, the delivery timeline requires reassessment.

The Scottish Cluster

The Scottish Cluster[99] is a collaboration of over 50 industrial and public sector stakeholders that was formed in 2021 and involves several industrial partners from the Grangemouth region. Within the cluster, stakeholders such as Storegga / the Acorn CCS project are some of the key infrastructure developers for CO_2 transport and permanent storage that would enable removal of CO_2 from blue hydrogen production sites (such as INEOS) to enable ongoing operations. The Acorn Project was unsuccessful in Track 1 of the UK Government's CCUS cluster sequencing in 2021 with the priority given to HyNet North West and the East Coast Cluster. In July 2023, the Acorn Project's entry was confirmed for Track 2 of the funding stream[100]. The timeline for project launch is currently unknown. As an indication, the East Coast cluster was confirmed in Nov 2021, and the work on Net Zero Teesside low-carbon natural gas power station (one of the cluster's beneficiaries) began in Oct 2023, indicating a two-year lag between the start of negotiations and the final funding decision.

The timeline of INEOS Low Carbon Hydrogen Manufacturing plant could, therefore, be further influenced by the progress of the Acorn capacity of transporting and storing CO_2.

Grangemouth-Granton project (LTS Futures)

SGN LTS Futures programme[101] is a series of £30M projects looking to research, develop, test and evidence the compatibility of the local transmission system assets (pipelines, plants, fittings) with hydrogen. The Grangemouth-Granton project[102], led by SGN in collaboration with INEOS, aims to use a decommissioned 30 km pipeline between the Grangemouth refinery and Granton for transmission of gaseous hydrogen. The work began in 2022, and the current project plan aims to deliver a live trial of the LTS pipeline for hydrogen carrying in March 2025. The project is likely to depend on the hydrogen

98 https://www.falkirkherald.co.uk/business/ineos-calls-a-halt-to-ps350-million-grangemouth-energy-plant-3744099
99 https://www.thescottishcluster.co.uk/
100 https://www.thescottishcluster.co.uk/acorn-to-enter-track-2
101 https://www.sgn.co.uk/about-us/future-of-gas/lts-futures
102 https://smarter.energynetworks.org/projects/nia2_sgn0001/

production capacity of INEOS at Grangemouth, and it is unknown whether delays in the Low Carbon Manufacturing plant construction will result in downstream delays in this project or, alternatively, whether unabated hydrogen will be used for piloting this pipeline. Additionally, SGN are leading on projects such as H100 Fife[103] for use of hydrogen in domestic heating.

5.3 Hydrogen Hub Features in Grangemouth

Table 3 summarises the common features of a hydrogen hub across the case studies outlined above and provides commentary on the strength of the future Grangemouth Hydrogen Hub in context of these features, as informed by insights from the consultation with key stakeholders.

Features	Grangemouth Hydrogen Hub context	Rating
Established oil, gas and renewables experience	Grangemouth's core strength is in its oil and gas heritage and the existing infrastructure that links Grangemouth to gas and fuel distribution networks. Feeders 10 and 12 are being assessed for H_2/ CO_2 transport. Access to experienced and highly skilled process industry workforce is a particularly strong aspect of Grangemouth.	
Port access	Forth Green Freeport (FGFP) is a very strong opportunity to reap logistic and taxation benefits for the developing hydrogen industry, particularly via export by ship. This opportunity is more immediate as gaseous hydrogen export to Europe is likely to occur via pipeline in medium-to-long term. Port access is critical for export of other media of hydrogen, such as SAF, methanol or ammonia.	
Strong local and central government-level policy support	Grangemouth has been identified as a critical location for decarbonisation activities via projects such as SNZR. Overall, the hydrogen economy in Scotland has strong policy support. However, there is a lot of uncertainty about hydrogen use and commitment to hydrogen in the changing political environment. This is further compounded by the expected UK General Election in the next 12 months. Unlike the US, hydrogen support in the UK is not made into law.	
Community buy-in	Stakeholders believe that the community support for hydrogen hub development in the region could be improved, especially in context of the themes of Just Transition. The H100Fife project was cited as a good example of public engagement in a hydrogen end user sector. The future Grangemouth Just Transition plan will seek to include more industry and community voices to address this aspect (in development).	
Significant levels of regionally concentrated public investment	FGFP seed fund (£25M) investment is regionally targeted and concentrated but perceived as insufficient for a hydrogen hub development. It is also believed that current models of funding encourage competition over collaboration.	
H_2 / CO_2 transport and storage	Grangemouth does not have options for H_2/ CO_2 storage on site and, therefore, will rely entirely on the removal of gases via pipeline. Feeders 10/12 have the potential to be used for H_2/CO_2 transport. The progress depends on the Acorn project that is currently undergoing due diligence for Track-2 funding. Timeline to final investment decision is unknown.	

103 https://www.sgn.co.uk/H100Fife

Committed early adopters in end-user sectors (industrial, public procurement)	Current discussions about hydrogen use in the area are focused on self-supply. Development of Grangemouth as a hydrogen hub and net producer is perceived as exclusively dependent on the market demand. Industry has appetite for decarbonised power – several stakeholders indicated that industrial end-users have little interest in hydrogen per se but urgently require cost-effective, more sustainable and abundant/consistent sources of power, and if hydrogen can provide it, there is a strong commercial reason to switch. This implies that hydrogen could become a preferred option if the price is competitive and consistent. Other large companies (e.g., in Mossmorran) could become major customers for a hydrogen producer in Grangemouth. The domestic heating market has potential to enable hydrogen take-off because blending could be kickstarted quickly as no major changes to the existing infrastructure are required. This remains hotly debated in terms of policy and public acceptance and more clarity is urgently needed. End-users cannot commit to hydrogen because of limited availability (leading to intermitted supply); lack of clarity about priority end-user sectors or timing for deployment. Nevertheless, Grangemouth industry remains power-hungry and is projected to become a net importer of hydrogen for decarbonisation of operations. It is noted that offtakers might require more support for fuel switching in terms of their in-house technological needs.	
Integration into the regional research and knowledge base and collaborative industrial environment	Insufficient collaboration between organisations and relatively low integration of research and knowledge base (compared to other hubs) is seen as one of the greatest threats for Grangemouth Hydrogen Hub development. Stakeholders stated that there is minimal conversation between major companies (potential producers) and other companies in the area, with indication that large companies are exclusively interested in collaborating with other large companies. There are, therefore, concerns that smaller, strongly innovation-driven and potentially more collaborative companies might struggle to integrate into the Grangemouth cluster because of low levels of collaboration, as well as a perceived lack of land for development.	
Collaborative effort among several major companies enabled and derisked by innovation-driven smaller companies		
Access to substantial amount of renewable electricity	It has been indicated that Grangemouth is increasingly power-hungry, and limitations in steam and power is already a bottleneck for some ongoing and proposed processes. Introduction of additional steam reformers for production of blue hydrogen at scale will further compound this issue.	

Table 3. Common features of a hydrogen hub and a commentary on Grangemouth context.

6 Conclusions

6.1 Current Position

The industrial leader in the region is anticipated to be at the forefront of blue hydrogen production. Their current commercial activities, however, are predominantly centred around self-supply and small-scale demonstrator projects with organisations involved in transport infrastructure. This results in a noticeable lack of direct interaction between potential producers and end-users, setting this region apart from other developing hubs in Scotland and elsewhere.

The progression towards blue hydrogen production could face delays due to the absence of adequate infrastructure for CO_2 removal at the production site. The Acorn project, positioned as a Track 2 CCUS project, is the most promising infrastructure initiative for transporting and storing CO_2 from Grangemouth. Nonetheless, it is still in the process of due diligence for funding, and the timeline for the final investment decision remains uncertain, introducing an element of unpredictability for potential producers in the region.

The hierarchy of uses for hydrogen is yet to be clearly defined. While the hydrogen action plan does provide some direction, there is a pervasive sense of uncertainty within the industry, prompting calls for more decisive leadership.

In its current state, the Grangemouth Industrial Cluster does not have sufficient assets to establish a comprehensive hydrogen hub capable of generating the desirable network effects. Without connecting infrastructure and collaboration with other hydrogen sites, Grangemouth is likely to remain focused on self-supply rather than participating in a wider hydrogen economy. To become a successful hydrogen hub, Grangemouth needs more committed end-users such as, for example, OI Manufacturing (Alloa), the City of Edinburgh or Edinburgh Airport, and it is imperative to integrate with the broader east coast of Scotland hydrogen ecosystem. Stakeholders are strongly advocating for a collaborative approach, urging Grangemouth to form partnerships with other hubs like Aberdeen. In this way, Grangemouth could establish itself as a core hydrogen transport hub due to proximity to the planned pipelines and port.

Regarding potential, the Grangemouth Hydrogen Hub is perceived to have a significant advantage in producing blue (methane or biomethane) gaseous hydrogen for local and regional applications. In contrast, green hydrogen is seen as a less viable option due to the considerable distance from the offshore wind sites identified in the recent Scotwind and INTOG leasing rounds and, critically, grid constrains. Smaller green hydrogen production sites will develop in the broader region as they co-locate with onshore wind sites, and could provide hydrogen to the industrial cluster users. If power demands are met in the medium term, Grangemouth could explore opportunities in e-fuel and sustainable aviation fuel production, potentially augmented by CO_2 imports from Europe, either for onsite utilisation or permanent storage via the Acorn project.

6.2 Recommendations

Based on the evidence collated and analysed during this study or recommendations are:

- Enable the market through dedicated end user pull:
    - Commit to 1-2 key priorities for hydrogen use: Given the uncertainty in the hierarchy of uses for hydrogen, it’s crucial to identify and commit to a small number of key applications where hydrogen can play a vital role. The commitment will provide a clear direction and focus for the industry and should be strongly supported through policy messaging. Based on the activity in the current project pipeline, these priorities could be heavy transport and industrial heat.
    - Increase the support for hydrogen offtakers to encourage fuel switching

    - Encourage collaboration through innovative public funding mechanisms: To bridge the gap between potential producers and end-users, foster collaborative projects through public funding. This could be in the form of grants, tax incentives, or public-private partnerships, specifically targeted at projects that encourage collaboration between different stakeholders in the hydrogen value chain.
- Link Grangemouth to non-producing end users: Establish connections and partnerships between Grangemouth and potential end-users within the cluster that cannot self-supply hydrogen, and those outside the cluster, such as the City of Edinburgh or Edinburgh Airport. This can help in creating a market for the hydrogen produced and ensure consistent demand.
- Increase capital funding through innovative mechanisms. For example, the EU Just Transition Fund is a targeted investment into regions that are most affected by the transition due to their dependence on fossil fuels. The eligibility includes national and local authorities, encouraging local proactivity in collaboration with the industry.
- Investigate the options to reconsider the curtailment subsidy model to encourage wind operator interest in hydrogen production and collaboration with potential hydrogen producers as a preferred option to curtailment.
- Foster innovation and collaboration:
    - Attract innovative companies: Encourage startups and innovative companies to set up operations in the region by providing incentives and creating a conducive environment for innovation. The proposed Sustainable Manufacturing Campus, when established, should offer such an environment.
    - Encourage major companies to collaborate: Investigate and implement strategies to promote collaboration between established industry leaders, other companies and innovative SMEs. This could involve creating platforms for knowledge sharing, co-development projects, or mentorship programs.
    - Develop activities towards East Coast of Scotland hydrogen backbone: Investigate the strategies for Grangemouth to collaborate with other hubs, such as Cromarty and Aberdeen to evaluate Grangemouth's potential as a blending and distribution hub.
- Provide clarity on funding timelines:
    - Clear communication on the Acorn project funding timeline: Provide regular updates and clear communication regarding the funding and development timeline of the Acorn project. This transparency is crucial to reduce uncertainty and help potential producers in their planning and investment decisions.
- Advocate for connectivity from Grangemouth to European infrastructure:
    - Capitalise on Forth Ports: Create strategies for hydrogen import/export through Forth Ports through series of strategic pilot projects.
    - Lobby for integration with the European Hydrogen Network: To maximise the export potential of hydrogen, the region should actively advocate for the establishment of pipeline connections to the European hydrogen infrastructure. This will open up new markets and enhance the economic viability of hydrogen production in the region.

Appendices

Appendix A: Participants in Interview Programme

	Companies
1	Calachem
2	Carlton Power
3	Celtic Renewables
4	Element Energy
5	Exxon Mobil (Mossmorran)
6	Fulcrum Bioenergy
7	National Gas
8	Petrolneos
9	Scottish Power
10	SGN
11	Shell (Mossmorran)
12	Wood
13	WSG
	Wider Stakeholders
14	Forth Valley College
15	Hydrogen UK
16	IDRIC
17	NECCUS
18	Net Zero Technology Centre
19	Scottish Enterprise
20	SHFCA
21	Falkirk Council

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