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The potential use of hydrogen for heating in Scotland

A REVIEW OF THE EVIDENCE RELATING TO THE POTENTIAL FOR THE LARGE-SCALE USE OF HYDROGEN FOR HEATING VIA CONVERSION OF THE NATURAL GAS NETWORK

INFORMING POSITIVE CHANGE

Client: WWF Scotland

Report title: The potential use of hydrogen for heating in Scotland

Subtitle: A review of the evidence relating to the potential for the large-scale use of hydrogen for heating via conversion of the natural gas network.

VERSION	DATE	VERSION SUMMARY	APPROVALS
RO	8/2/2022	V1.1	Principal author: Joanne Wade Approved by: Bill Kirkup
R1	25.3.22	V1.7	Principal author: Joanne Wade Approved by: Bill Kirkup
R2	18.4.22	V1.8a	Principal author: Joanne Wade Approved by: Bill Kirkup
R3	26.6.22	V1.9	Principal author: Joanne Wade Approved by: Bill Kirkup
R4	18.7.22	V1.10	Principal author: Joanne Wade Approved by: Bill Kirkup
R6	15.8.22	V1.11	Principal author: Joanne Wade Approved by: Bill Kirkup

FOR DIRECT ENQUIRIES ABOUT THIS PROPOSAL:
Name: Bill Kirkup
Partner
CAG CONSULTANTS

Mob: 07766 500054
Email: bk@cagconsult.co.uk
TO CONTACT CAG CONSULTANTS:
CAG CONSULTANTS
150 Minories
London EC3N 1LS

Tel: 020 8555 6126

hq@cagconsult.co.uk
www.cagconsultants.co.uk

CONTENTS

1 Introduction

1.1 Introduction

The potential use of hydrogen for heating is currently a much debated and somewhat contentious issue. Whilst, if UK and Scottish governments' decarbonisation targets are to be met, the need to decarbonise heating is unquestioned, there is some dispute over the most effective decarbonisation pathway. A focal point of recent debate is the extent to which the replacement of natural gas with low-carbon hydrogen might avoid, or reduce, the need for the large-scale electrification of heat, and how quickly this might happen.

It is understood that WWF Scotland is concerned that the 'hydrogen for heating' debate has become a distraction and perceives a risk that it may undermine Scottish government action and the activities of local authorities and other key stakeholders. The potential impact on the rollout of 'low regrets' solutions – such as increased energy efficiency and the electrification of heat – is of particular concern, as these measures can deliver the emissions cuts required to meet climate change targets to 2030, which can keep global temperature rise below the 1.5˚C threshold.

This report has been commissioned to inform WWF Scotland's engagement in discussions about the potential role of hydrogen in the decarbonisation of heating. The report is focused on the practicalities involved in a potential hydrogen transition only. As such, it does not consider the advantages and disadvantages of hydrogen relative to other low-carbon technologies.

1.2 Research questions

This report seeks to address a set of research questions relating to the practicalities – technical, economic and social – of displacing natural gas with hydrogen, via the conversion of the natural gas (hereafter referred to simply as gas) distribution network. The scope of the review was limited to the use of hydrogen for heating as WWF Scotland believes there is an emerging consensus on the role of hydrogen in the decarbonisation of industrial processes and heavy transport. However, some consideration of non-domestic uses of hydrogen in this report proved to be unavoidable.

In the original brief for this work, WWF Scotland stated that the study should provide:

> *a short review of the realistic timescales over which large-scale delivery of low-carbon hydrogen via converted gas networks could begin and be delivered at scale in Scotland.*

Specifically, it was requested that the research address the following questions:

- Where in Scotland is likely to be best suited for early deployment?
- What are the realistic timescales over which large-scale delivery of low-carbon hydrogen via converted gas networks (beyond demonstrators) could begin in Scotland?
- What are the estimated upfront conversion and running costs for homes heated by hydrogen in 2030 and 2045?

Over the course of the study, through close engagement between the research team and WWF Scotland, a set of sub-questions were developed to allow focused exploration of the key dimensions of each research question. These are presented in the following list, which provides the structure for Section 3 of this report

1. Where in Scotland is likely to be best suited for early deployment?

- Where in Scotland is likely to be best suited for the early mass deployment of hydrogen for domestic heating?

- What locational or other factors make these sites suitable for early deployment?
- What wider development scenarios are these sites associated with?
- What other development scenarios have been proposed?

2. What are the realistic timescales over which large-scale delivery of low-carbon hydrogen via converted gas networks (beyond demonstrators) could begin in Scotland?
   - What level of deployment is estimated to be deliverable by 2030?
   - What are the critical dependencies that will determine or inform the likely level of deployment by 2030 (and beyond)?
   - Based on the above, what appear to be the most realistic scenarios and timeframes for the large-scale delivery of low-carbon hydrogen?

3. What are the estimated upfront conversion and running costs for homes heated by hydrogen in 2030 and 2045?
   - What is the range of home conversion cost estimates in the literature? What are the reasons for any observed variations and which estimates appear to be the most robust?
   - Who would be expected to pay for the cost of home conversions?
   - What is the range of running costs for domestic consumers? What are the reasons for any observed variations and which estimates appear to be the most robust?
   - How do estimated running costs for hydrogen heating compare with current and projected running costs for gas consumers?
   - To what extent would consumers be expected to bear the cost of the conversion of the gas network to hydrogen?

1.3 Summary of method

This report is based on the findings of a literature review conducted between October 2021 and January 2022. The review involved two stages of activity. The first – effectively a scoping phase – comprised an in-depth review of 11 documents (listed in Appendix A) selected on the basis of their ability to provide the research team with an understanding of what would be involved in a large-scale transition from gas to low-carbon hydrogen. The scoping exercise also looked to identify critical dependencies and any assumptions that have been made regarding timing and cost. The primary output from the scoping exercise was a systems diagram illustrating the key components that need to be in place to enable a functioning domestic hydrogen supply chain.

During the course of the Stage 1 review, the research team kept a record of issues felt to require more detailed investigation, for example to fill apparent gaps in the evidence or to examine identified assumptions. This was discussed with WWF Scotland at the end of Stage 1, after which the research team finalised a list of topics and priority issues for investigation during Stage 2 work.

Stage 2 involved an in-depth review of an additional 20+ documents. A number of other documents were referred to where these seemed likely to generate useful additional insight. This activity was followed up with a small series (4) of expert interviews intended to address issues where the literature was felt to be incomplete, inconclusive or did not provide a clear picture on a given topic. This report is the primary output of this research, but the Stage 2 work also informed a review of the system diagram formulated during Stage 1.

1.4 Challenges and limitations of the research

The key challenges and limitations associated with this research include the following:

- The majority of this report and the evidence base it draws on pre-date the Russian invasion of the Ukraine, an event which has greatly changed the complexion of the national energy debate. The implications for hydrogen production are likely to be significant but it is considered unlikely that they will have a material impact on decisions regarding the near-term use of hydrogen for heating.

- There is a large volume of literature dealing with the potential use of hydrogen for heating. Given the breadth of the study and constraints on resources (time and funding) some important documents will have been overlooked.
- Although there is a large and rapidly expanding body of literature on the subject of hydrogen for heating, there is a relative lack of information specific to Scotland. This has constrained the research team's ability to provide detailed insight into some aspects of the research questions.
- There is a high degree of uncertainty over a number of key variables affecting the potential use of hydrogen for heating. Insight into some of these matters, in particular those relating to costs, may be held by the private sector and potentially government bodies, but is commercially confidential and therefore not accessible[1]. Significant unknowns include:
    - Uncertainty concerning the nature and scale of future government interventions, both in relation to hydrogen for heating and the hydrogen sector more generally
    - The likely future costs of production and unit costs of hydrogen (particularly green hydrogen).
- The listed uncertainties, in tandem with the politicised nature of the debate, means that care needed to be taken when selecting and reviewing the literature. There is clear bias in much of the grey literature (a key source for this study, given the nature of the research questions), with advocates both for and against the use of hydrogen for heating. We therefore looked to select literature from sources reflecting all shades of opinion and to tie our analysis to a whole system diagram to ensure, as far as possible, that consideration was given to all factors that would affect the large-scale use of hydrogen for heating (Table 2 summarises these factors).
- The level of attention being paid to hydrogen by the private sector, alongside forecast innovations that could radically reduce the cost of production, mean that significant new information will emerge in the near term. As a result some aspects of this report are likely to date quite quickly, however, the fundamental system requirements (dependencies) appear unlikely to change significantly.

[1] This has been mitigated somewhat by the release of commercial material for projects supported by the UK Government's Low Carbon Hydrogen Supply competition. We identified some projects that appear to be developing without public funding – for example, the proposed INEOS blue hydrogen production plant at Grangemouth – but very little detail is available in the public domain.

2 Policy Context

2.1 Introduction

Energy policy in the UK is the responsibility of the Department for Business, Energy and Industrial Strategy (BEIS). However, the Scottish Government is responsible for some matters that strongly interact with energy policy and practice, including planning and climate change policy (Hinson, 2020). Cairney et al. (2019) suggest that, in practice, there are a number of 'blurry' boundaries in relation to energy policy. There is evidence of this in hydrogen policy, where both the UK and Scottish governments have both produced strategies relating to hydrogen and heat decarbonisation. Whilst these documents are clearly linked, there are also some divergences, illustrating the desire of the Scottish Government to pursue a development path tailored to its wider policy objectives.

2.2 Context

This section provides a summary review of the key policy documents relating to hydrogen and its potential role in the decarbonisation of heat (see Table 1). In line with the objectives of this research, its focus is to draw out key information regarding the potential for converting the gas network to enable the provision of hydrogen for heating at scale.

Table 1: Key Scottish and UK government policies relating to hydrogen and heating

Date	Source	Name of document
December 2020	Scottish Government	Scottish Hydrogen Assessment.
December 2020	Scottish Government	Scottish Government Hydrogen Policy Statement
August 2021	UK Government	UK Hydrogen Strategy
October 2021	Scottish Government	Heat in Buildings Strategy: Achieving net zero emissions in Scotland's buildings
October 2021	BEIS	Heat and Buildings Strategy
November 2021	Scottish Government	Draft Hydrogen Action Plan

2.2.1.1 An explanation of the types of hydrogen

The literature refers to several different types of hydrogen. These are defined by the way they are produced and the level of carbon emissions that result. Hydrogen produced from the steam reformation of fossil fuels (primarily natural gas) without any carbon emissions abatement is commonly known as **grey hydrogen**, and accounts for the majority of hydrogen produced worldwide today. The UK currently produces 0.7Mt (27TWh) of grey hydrogen annually for use in industrial processes, for example in oil refineries, fertiliser production and food processing (CCC, 2018).

In this report we are concerned with the two main types of low-carbon hydrogen proposed for UK production and use: **blue hydrogen**, which uses the same process of production as grey hydrogen but incorporates emissions abatement through carbon capture and storage; and **green hydrogen**, which is produced by the electrolysis of water, powered by low-carbon and renewable electricity.

2.2.2 A summary overview of Scottish and UK government hydrogen policy (as of January 2022)

2.2.2.1 Scottish Hydrogen Assessment

In December 2020 the Scottish Government released its Scottish Hydrogen Assessment (Scottish Government, 2020a). This document is reported as having been informed by extensive stakeholder engagement and is described as being intended to inform the development of hydrogen policy in Scotland.

The Scottish Hydrogen Assessment states that hydrogen is expected to play a significant role in decarbonising Scotland's energy system, but notes that there is uncertainty regarding the nature and extent of this role. Key messages from the Assessment include the following:

- There is a significant economic opportunity, both in domestic and export markets, to be captured through the development of a hydrogen economy. Scotland is described as having a range of natural advantages, including access to a significant renewable energy resource and a well-established oil and gas sector that could provide both infrastructure and expertise to a new hydrogen production sector.
- Green hydrogen is the ultimate goal, but the development of blue hydrogen could offer significant short- to medium-term benefits.
- The development of a hydrogen sector will require a high level of coordination across the public and private sector.
- There is a need for a clear and ambitious strategy and to move at speed to ensure that Scotland captures the economic opportunities for developing manufacturing and service sectors able to export to global markets.
- There is a need to move beyond pilots and onto the establishment of commercial-scale projects.
- A whole system perspective is required, with consideration given to how hydrogen might best complement increasing electrification.
- There are low regrets opportunities for using hydrogen in industrial applications and heavy transport (HGVs, buses, rail and water).

In relation to hydrogen for heating, the Scottish Hydrogen Assessment states that the role hydrogen might play in the decarbonisation of heat is uncertain and that further development and demonstration work is required to determine this. In the meantime, it suggests that the option be left open:

> *At this stage all options, including blue and green hydrogen, or use of hydrogen in the gas heating networks should be kept open.*[2]

2.2.2.2 Scottish Government Hydrogen Policy Statement

Also published in December 2020, the Scottish Government's Hydrogen Policy Statement (Scottish Government, 2020b) was informed by the Scottish Hydrogen Assessment. The Policy Statement confirmed the Scottish Government's interest in the development of a hydrogen economy, both to help meet domestic decarbonisation targets and to secure new export markets. In pursuit of these objectives, it states that the Scottish Government will look to support the development of 5GW generation of renewable and low-carbon hydrogen by 2030, and that it has an ambition to see at least 25GW production capacity by 2045. To enable this development, the Policy Statement announces that the Scottish Government will produce a Hydrogen Action Plan and support its implementation with £100 million of funding support. In signalling this ambition, the Policy Statement notes that the

[2] Scottish Government. Scottish Hydrogen Assessment (December 2020), p. 98.

Scottish Government hopes to provide industry and private investors with the confidence needed to invest in Scotland's embryonic hydrogen sector.

The Scottish Government Hydrogen Policy Statement acknowledges that the Scottish Government will need to work together with the UK Government – which is identified as having control over several key legislative and regulatory levers – to build a successful hydrogen economy.

2.2.2.3 UK Hydrogen Strategy

The UK Hydrogen Strategy (HM Government, 2021), issued in August 2021, echoes, in general terms, many of the positions and ambitions in the Scottish Hydrogen Assessment and Scottish Government Hydrogen Policy Statement. In line with these documents, decarbonisation and economic opportunity are identified as being the primary drivers. One significant difference is that the UK Hydrogen Strategy contains a UK-wide target of 5W by 2030. It is not expected that all of this development will occur in Scotland, indicating that the Scottish Government – which has set its own target of 5GW – has greater ambitions in this regard. The UK Hydrogen Strategy notes the need for the UK Government to work in partnership with the Scottish Government. As in the Scottish Hydrogen Assessment, it highlights the strength of Scotland's wind resource and oil and gas sector as key assets that are expected to play a key role in the development of a UK hydrogen economy.

The UK Hydrogen Strategy lists a number of initiatives and interventions that are being taken forward by the UK Government to deliver its stated ambitions. Several of these are specifically intended to explore and enable the use of hydrogen for heating. As stated in the Strategy (pp. 111–115) these include:

- We will review the overarching market framework set out in the Gas Act 1986 to ensure appropriate powers and responsibilities are in place to facilitate a decarbonised gas future.
- We are reviewing gas quality standards with a view to enabling the existing gas network to have access to a wider range of gases in future, potentially including hydrogen.
- We will launch a Call for Evidence on the future of the gas system this year.
- We aim to consult later this year on the case for enabling, or requiring, new natural gas boilers to be easily convertible to use hydrogen ('hydrogen-ready') by 2026.
- We will engage with industry and regulators to develop the safety case, technical and cost effectiveness assessments of blending up to 20 per cent hydrogen (by volume) into the existing gas network. Subject to completion of safety trials, we aim to provide an indicative assessment of the value for money case for blending by Q3 2022, with a final policy decision likely to take place in late 2023.

Whilst the UK Hydrogen Strategy describes a number of measures associated with the use of hydrogen for heating, and in particular the use of hydrogen as a direct substitute for natural gas, it states that there is still considerable uncertainty about how best to deliver the UK's heat decarbonisation targets[3] and that the potential role of hydrogen, in particular, has yet to be determined. The Strategy identifies uncertainties regarding the costs, benefits, safety, feasibility, air quality impacts and consumer experience of using hydrogen for heating, referring to the work of the Hy4Heat programme on hydrogen-ready appliances, consumer receptiveness and skills, and a series of hydrogen for heat trials including the H100 Fife neighbourhood trial in Levenmouth, Fife (by 2023), a village-scale trial (by 2025[4]) and town-scale trial (by 2030). However, it notes that the development of the town-scale trial will be dependent upon the outcomes of the smaller scale trials and other wider

[3] On p. 61 the strategy suggests that to meet the 2050 net zero target would "require us to switch to low-carbon alternatives to heat the 30 million residential, commercial, industrial and public sector buildings in the UK."
[4] Ofgem proposed funding for detailed design work for two potential village trials in May 2021. The areas being assessed are both based in the north of England. https://www.ofgem.gov.uk/publications/hydrogen-village-trial-detailed-design-studies-decision

research, and that this decision will not be made until 2026 – this is defined as being a strategic decision point on the future of hydrogen for heat in the UK.

More generally, the Strategy acknowledges that there is a need to develop support mechanisms, described as a Hydrogen Business Model, to address the cost challenge of producing low-carbon hydrogen, most likely through a long-term revenue support mechanism. This mechanism will be critical in ensuring the supply of hydrogen and therefore, by default, to any hydrogen for heating initiatives. A consultation on the model closed on 21 October 2021; the final form of the model is expected to be completed by the end of 2022.

2.2.2.4 Scottish Government Draft Hydrogen Action Plan

In November 2021 the Scottish Government issued its draft Hydrogen Action Plan, intended as a companion document to the Hydrogen Policy Statement. The Action Plan describes the actions the Scottish Government proposes to take forward over the period 2021–26 in pursuit of the 5GW target announced in the Hydrogen Policy Statement. External stakeholders were provided an opportunity to feed back their views on the Plan; the consultation period closed on 26 of January 2022.

The Action Plan restates the ambitions of the Hydrogen Policy Statement and confirms the commitment of £100 million of funding support. It also highlights the Scottish Government's commitment to securing a 'just transition' to net zero and suggests that the development of the hydrogen sector has a role to play in ensuring this. The Hydrogen Policy Statement acknowledges that there are multiple challenges, not least the current high cost of hydrogen by comparison with fossil fuels, but also emphasises the need to move forward at pace so as not to concede competitive advantage.

The Hydrogen Action Plan contains multiple references to the possibility of using hydrogen to decarbonise heat, noting that the Scottish Government is working to identify those areas of the country best suited to a hydrogen for heat transition. It states that the first part of this work is underway and that this will establish a cost trajectory for renewable hydrogen over the period from 2030 to 2045. Once available, this will be used to inform future policy decisions. Beyond this, the Action Plan notes that the Scottish Government will:

- Continue to support the development of evidence relating to the potential role of hydrogen in decarbonising heat.
- Support Scottish Gas Networks (SGN) with their work on the conversion of section of network to accommodate hydrogen 'wherever those actions are commensurate with keeping options open and limiting consumer costs' (p.34).
- Continue to explore opportunities for the use of blended hydrogen (up to 20%) in the gas network.
- Look to support projects seeking to demonstrate how renewable hydrogen might be used in the gas network.
- Press the UK Government to progress the consultation work on hydrogen-ready boilers.
- Press the UK Government to move forward on the amendment of regulations and legislation required to support the use of hydrogen in the gas grid (a process described as being important in enabling the maximisation of the volumes of renewable hydrogen in the energy system).

2.2.3 The Scottish and UK governments' heat in buildings strategies

2.2.3.1 Scottish Government Heat in Buildings Strategy

The Scottish Government's Heat in Buildings Strategy, published in October 2021, addresses all aspects of heat decarbonisation in buildings. It stresses the need for action on decarbonisation whilst noting that such action must be consistent with the principles of a just transition. The Strategy is informed by the Hydrogen Policy Statement, and notes the uncertainties regarding the use of hydrogen for heating and the need to establish the safety and commercial case.

In relation to hydrogen, the framing of the Heat in Buildings Strategy is more bullish than the other reviewed policy documents. For example, it claims that that there is a 'need' for biomethane and hydrogen to be deployed in the mains gas network (up to 20% by 2030) to reduce its carbon emission intensity. Elsewhere, the document states that the Scottish Government has an objective to enable consumer use of hydrogen via the gas grid:

> *Our overarching objective is to ensure Scottish consumers are able to access low-cost hydrogen in the gas grid, should that become available in the late 2020s and early 2030s, and to maximise the volume, and accelerate the deployment, of hydrogen from renewable sources.* (p.57)

The Strategy notes the Scottish Government's commitment to decarbonise heat in 1 million homes by 2030. This has implications for the total number of homes that could eventually use hydrogen for heating, given that it will not be an option at any scale beyond pilots in the period to 2030. However, whilst the Strategy stresses the need to deploy low regrets solutions, such as heat pumps and heat networks, it notes that this must be planned to avoid undermining the business case for hydrogen in those areas where, in the longer term, it might be appropriate to supply hydrogen through the gas network.

The Heat in Buildings Strategy also notes that the Scottish Government lacks certain regulatory and legislative powers and, echoing phrasing used in the Scottish Government's draft Hydrogen Action Plan, urges the UK Government to accelerate hydrogen trials (neighbourhood, village and town), the consultation on enabling or requiring hydrogen-ready boilers, and its decision regarding the future use of hydrogen in the gas network. It also asks the UK Government to work with the Scottish Government on product standards for new gas boilers.

2.2.3.2 UK Government Heat and Buildings Strategy

The UK Government's Heat and Buildings Strategy was also published in October 2021, but shortly after that of the Scottish Government. It includes a number of references to the potential role of hydrogen for heating.

The Strategy notes the need to move away from the use of fossil fuels in heating. As with other policy documents, however, it states that the precise way forward, in terms of low-carbon alternatives, has yet to be determined. In common with the hydrogen policy documents, the Strategy stresses the need for further research to determine the potential role of hydrogen for heating and the intention to make a 'strategic decision' on this matter in 2026. In the meantime, in order to achieve decarbonisation targets, it stresses the need to accelerate the establishment of markets for low regrets solutions such as heat pumps and heat networks. It states that even if hydrogen is found to have a role in heat decarbonisation, it is unlikely to be suitable for all building types and locations and, in addition, there is an immediate need to install such technologies.

> *In all future heat scenarios – including if hydrogen is proven to be feasible and preferable to use in heating some buildings – 600,000 hydronic heat pump installations per year is the minimum number that will be required by 2028 to be on track to deliver Net Zero.* (p.16)

The Strategy identifies multiple forms of intervention and support activity. Most of those relevant to the use of hydrogen for heating have been identified in the preceding section and are not repeated here. Relevant activities not previously referenced, or referenced in greater detail, include:

- A stated intention to build markets for low-carbon sources of heat, such as heat pumps and heat networks, including by phasing out the installation of new natural gas boilers by 2035 in on-gas-grid housing.
- Additional detail relating to the development of standards for hydrogen gas installations and skills training (new standards are in development but are not yet finalised).

2.2.4 Hydrogen policy – A key points summary

The following summarises, in general form, some of the key points that inform current Scottish and UK government policy on hydrogen.

- It is accepted that there is a lack of clarity or certainty regarding the potential role of hydrogen in the decarbonisation of heat. Consequently, a cautious approach has been adopted, with evidence being gathered via multiple research exercises.
- The national hydrogen for heating pilot programme is expected to provide the information necessary to inform strategic decisions about the future of hydrogen for heating. The UK Government has identified 2026 – by which time information from the neighbourhood and village trials is expected to be available – as its key decision point. The development of hydrogen for heating in Scotland, or at least its scheduling, is to some extent dependent upon decisions made between now and 2026, and the policy review suggests that the Scottish Government is pushing for earlier action.
- Even if hydrogen proves to be a viable solution for heating, there is a need to deploy heat pumps and heat networks to ensure that decarbonisation targets can be met, and such activity needs to be scaled up and accelerated. Overall, however, no one solution is fit for all scenarios and solutions – including hydrogen – are expected to be tailored to local circumstance.
- The potential for generating economic benefit is a strong driver for hydrogen policy and there is an acknowledged need for early action at scale to ensure that economic opportunities, particularly in relation to export opportunities, are not lost. There are other and more obvious markets for hydrogen than heating – for example, in industrial processes and transport – but the use of hydrogen for heating (including in blended mixes) would help scale up demand. It is not, however, clear how necessary this is to the establishment of the wider hydrogen economy.
- The development of a hydrogen economy will require a high level of coordination between different UK administrations and the private sector. It is unclear how this might be organised.
- There is an expectation that hydrogen will, at least initially, be expensive in comparison with natural gas and electricity, which may preclude its use for heating in the short and medium term. The Scottish Government's Heat in Buildings Strategy appears supportive of the use of hydrogen for heating, but also stresses the need for a just transition to low-carbon heating. The hydrogen business model will be important in determining the market cost of hydrogen.

3 Findings

3.1 Introduction

This section presents the findings from the literature review. Specifically, it considers what is known, in terms of market readiness and key dependencies, about the key technical, economic and social components (described in Table 2) required for a functioning hydrogen-based mass heating system based on a repurposed gas network.

NB: The reader should note that the level of detail available in the literature varied widely by 'component' and this is, inevitably, reflected in this report. To date, more attention has been given to the technical challenges (i.e. can it be done) than to issues such as cost and consumer acceptance. However, as noted at various points in the Policy Context section, there is a significant programme of research underway and this includes work to address many of the current gaps.

Table 2: Main components required for a functioning low-carbon hydrogen system for home heating

Infrastructure	Requirements
Production	Sufficient (blue and/or green) hydrogen production and/or import to supply high-value hydrogen uses (hard-to-decarbonise uses and electricity system services) and a significant proportion of heating demand. Requires: land; production facilities; gas (for blue); carbon capture and storage/CCS (for blue); renewable energy (green).
Transmission	Hydrogen transmission pipelines, linked to production sites, reach a significant proportion of homes currently on the gas grid. Sufficient long-term storage (or excess production capacity) to enable peak heating demand to be reliably met.
Distribution	Local distribution networks capable of safely supplying hydrogen to a significant proportion of homes currently on the gas grid. Sufficient short-term storage (or excess production capacity) to manage short term demand fluctuations.
In-house pipes and appliances	Hydrogen-compatible home pipework and appliances in place.
Supply chain	**Requirements**
Materials and equipment	Availability of specialist material and equipment – electrolysers, hydrogen ready appliances, etc.
Labour	Sufficient capability and capacity within the labour force to enable the necessary levels of production of equipment and installation.
Economic case	**Requirements**
Production costs	Wholesale price of hydrogen is comparable with natural gas, assuming the application of a net zero compatible carbon price is being applied to all fossil fuels.
Viable investment models	Business models that enable infrastructure investment.
Retail pricing is competitive	Retail price of hydrogen is acceptable to all consumers (households, business and transport users and the electricity system); costs of hydrogen-compatible appliances are acceptable to consumers.

Social/political	Requirements
Carbon intensity	Hydrogen is sufficiently low carbon to be compatible with trajectories to net zero.
NOx emissions	End-use appliances are designed to be compatible with local air quality limits for NOx emissions.
Regulatory framework	Legislative and regulatory frameworks are in place to ensure safe and reliable provision of hydrogen to households and other users, and transport and storage of CO2 from blue hydrogen production.
Reliability	Hydrogen system provides an acceptable level of energy stability and security.
Consumer acceptance	Households are prepared to use hydrogen in their homes (and businesses) and prepared to accommodate the disruption associated with a changeover from natural gas.

3.2 Infrastructure

3.2.1 Blue hydrogen production

Key findings:

- Uses mature technology for hydrogen production (more efficient alternative coming through)
- Dependent upon access to natural gas and carbon capture and storage (CCS) facilities
- Plans for major developments in both production and a linked CCS facility, but both on hold awaiting public funding decisions
- Developments require large amounts of land
- Scotland's east coast is an ideal location for the development of blue hydrogen production facilities, combining proximity to gas import terminals and potential locations for carbon storage, with likely early uses for hydrogen in industrial clusters and urban transport decarbonisation schemes
- Cost estimates vary, but thought unlikely to alter significantly once initial production established
- Residual carbon emissions, from the natural gas supply chain and CCS, may be an issue when net zero requirement is considered

3.2.1.1 Production technology

Methane reformation is a technology that is already in use in the UK, in the production of grey hydrogen. Steam methane reformation (SMR) in particular is a well-proven hydrogen production technology. However, there is expected to be a move away from the use of SMR, which is most cost-effective for small to medium applications, towards advanced thermal reformation (ATR), which has better scalability and hence is better for larger scale plant (Barnes et al., 2021). Barnes et al. (2021) suggest that both SMR and ATR technologies are at Technology Readiness Level (TRL) 9[5]. Two proposed blue hydrogen plants, the Acorn Hydrogen Project at St Fergus (the natural gas terminal site) in north-east Scotland and the HyNet project in north-west England, expect to use ATR technology. One reason given for this is that it enables a more energy (and cost) efficient integration of carbon capture (Pale Blue Dot, 2019). The BEIS publication Hydrogen Production Costs (BEIS, 2021a) notes that as well as being cheaper than SMR, ATR enables higher levels of carbon capture, potentially up to 98% (Agora Energiewende, 2021). Whilst the production technology is proven, there

[5] The TRL scale is a widely accepted method of assessing the market readiness of a technology. The scale runs from1–9, with 9 meaning the technology in question is proven and market ready.

are multiple barriers to potential developers. The UK Government's Hydrogen Strategy (UK Government, 2021a) identifies a number of general barriers to increasing the capacity of hydrogen production (both blue and green), including high production costs relative to high carbon alternatives, high levels of technical and commercial risk, demand uncertainty, lack of market structure, distribution and storage barriers, and policy and regulatory uncertainty.

3.2.1.2 Carbon capture and storage

The production of blue hydrogen requires carbon capture and storage (CCS). Some engineering and scenario analyses anticipate that, due to current (pre-2022 fossil fuel price spikes) relative cost advantages, blue hydrogen supply will dominate (i.e. be more prevalent than green) in the earlier stages of hydrogen production scale-up, and perhaps even out to 2050 (CCC, 2018; IET, 2019; National Grid, 2021) ('system transformation' scenario). If this were to be the case, then hydrogen's future role in the UK energy system would be heavily dependent on the availability of CCS (CCC, 2018; IET, 2019). The Scottish Government's Hydrogen Policy Statement (Scottish Government, 2020b) refers to a 46Gt CO_2 storage opportunity in Scottish waters, and its draft Hydrogen Action Plan (Scottish Government, 2021b) notes the importance of CCS for decarbonising Scotland's industrial sector and for potential negative emissions technologies (e.g. use of biomass to produce hydrogen with CCS). At present, though, there are no operational CCS facilities in the UK (Trask et al., 2022) and the lack of CCS is a constraint factor on blue hydrogen production.

The Energy Transitions Commission[6] (ETC, 2021) suggests that if blue hydrogen is to play a significant role in a low carbon transition, there is a need for acceleration in the pace of development of CCS infrastructure. It notes, however, that the process of developing a CO_2 storage resource to commercial status can take between 5 and 12 years for depleted oil and gas fields. In addition, it suggests that understanding of the precise geological suitability for many potential CO_2 storage sites is lacking, that CCS projects face administrative and technical hurdles that can cause delays or cancellation[7], and that there may be public resistance to CCS development (ETC, 2021). In the UK, for example, there is uncertainty regarding the costs of carbon transport and offshore storage, with the UK Government undertaking further research to inform the design of future policy support (BEIS, 2021a).

3.2.1.3 Physical and geographic dependencies

Ideal siting for blue hydrogen production facilities involves proximity to a natural gas supply (Scottish Government, 2020a & 2020b; Barnes et al., 2021; Agora Energiewende, 2021), proximity to CO_2 transport and/or storage (Sunny et al., 2020; Scottish Government, 2020a & 2020b; Barnes et al., 2021), proximity to demand (for hydrogen) (Sunny et al., 2020; Barnes et al., 2021), ease of access to export markets (Barnes et al., 2021; Scottish Government, 2020b), proximity to underground storage for hydrogen (Sunny et al., 2020), and availability of skilled labour (Barnes et al., 2021).

Scotland's north-east coast has natural gas terminals and proximity to significant potential CO_2 storage opportunities offshore. Scotland's east coast is home to a number of energy-intensive industries, in particular around Grangemouth and Mossmoran, with the potential to provide the anchor demand for hydrogen that could make the establishment of localised hydrogen supply economically feasible (Agora Energiewende, 2021).

Scotland's east coast hosts a number of towns and cities that could offer demand at scale for hydrogen for heating and transport vehicles (ENA, 2020; Scottish Government, 2020a), and oil and gas/renewables sector supply chains with relevant skills are largely based around Aberdeen and

[6] The Energy Transitions Commission describes itself as "a global coalition of leaders from across the energy landscape working together to accelerate the transition to a zero-emissions future". It develops transition tools and road maps, and its focus areas include energy-intensive value chains and harder-to-abate sectors.
[7] The Scottish Government has committed to work on guidance for planning consent for large hydrogen production facilities.

Aberdeenshire (Scottish Government, 2020c). These circumstances lend support to suggestions that north-east Scotland is 'uniquely' suited to early development of low-carbon hydrogen (Frazer-Nash Consultancy, 2018), and explain why the area is seen by many as a clear starting point for hydrogen deployment (UK Government, 2021a; ENA, 2020).

The first UK CO_2 appraisal and storage licence has been awarded to Pale Blue Dot for its planned facility near St Fergus (IET, 2019), and is expected to be linked to its aforementioned blue hydrogen plant (Pale Blue Dot, 2019). The Acorn project plans to produce 50,000t hydrogen from a proposed 200MW blue hydrogen ATR production facility and to store 500,000t CO_2 a year by 2025 (Pale Blue Dot, 2019; Scottish Government, 2020b). It has been suggested that its CO_2 storage capabilities could increase to 10mt per year by 2030 and 20mt per year by 2034 (Scottish Government, 2020b). In addition to St Fergus, sites on the east coast of Scotland that have been identified as potential locations for early development of blue hydrogen, where CCS will be needed for industrial decarbonisation or where plans are being developed for the co-location of production and demand hubs, include Aberdeen (Pale Blue Dot, 2019; Scottish Government 2020a & 2021b; Moulli-Castillo et al., 2020), Grangemouth (Scottish Government, 2020c & 2020a), Greenock (Scottish Government, 2020c), Mossmoran (Scottish Government, 2020a), Cromarty Firth (Scottish Government, 2021b) and Fife (Moulli-Castello et al., 2020).

Other physical requirements for blue (and green) hydrogen production include access to land and water. According to Scottish Enterprise, a 1GW reformation plant requires 20,400m^2 of land that is zoned for industrial use and must meet COMAH Upper Tier regulations[8] (Barnes et al., 2021). Whilst substantial, this is not a large land requirement in terms of energy infrastructure – for example, the 1.25GW Sizewell B plant requires 20 times this land area (AEA, undated). Access to land, or securing the necessary planning permissions, has not been identified as a particular constraint on any of the currently proposed developments. This is likely partly due to their development on industrial sites where land is available and developments of this type actively encouraged.

Water use should also be noted: one source estimates that the production of 300TWh[9] blue hydrogen would involve water consumption equivalent to at least that of 300,000 households (IET, 2019). Water use on industrial sites is often constrained by permitting; however, projects currently in development do not appear to have been constrained by water access. Pale Blue Dot (2021) states that water for the Acorn facility will be supplied from the Scottish Water Network, whilst HyNet North West (2021) anticipates that water will be supplied via a combination of recycled water and rainwater harvesting, with any shortfalls made up by extraction from the River Dee.

3.2.1.4 Cost of production of blue hydrogen

Cost estimates for the production of blue hydrogen are shown in Table 3, below. Costs per tonne of blue hydrogen are likely to be minimised by use of large-scale production facilities near gas and CO_2 terminals, through economies of scale and minimisation of gas and CO_2 transport costs (Imperial College, 2018).

The range of costs shown in Table 3 reflects a number of uncertainties, including in the future cost of gas and the cost of CCS. Whilst some references suggest that costs may fall over time as the sector scales up (Pale Blue Dot, 2019; ETC, 2021), others think they will increase as potential cost reductions in some areas are more than offset by increases in gas prices, if carbon is priced in (Scottish Government, 2020a). The largest future cost uncertainty is linked to future gas prices (Baldino et al., 2020), which are estimated to represent nearly 60% of total costs between now and 2050 (Element Energy and E4Tech, 2018). Blue hydrogen has been estimated to be cost-

[8] Regulations governing sites handling hazardous chemicals. Upper Tier refers to sites that handle large quantities of such chemicals.
[9] For context, total UK gas use for heating in 2019 was approx. 479TWh (BEIS statistics: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2020).

competitive with grey hydrogen, with a carbon price of £42–£98/t[10] (Agora Energiewende, 2021). For reference, the EU ETS carbon price has varied over the past three years between €19.5 and €96.4 (approx. £16–£81); critically though, the general trend, particularly in recent years, has been upwards[11].

Table 3: Blue hydrogen production costs (£/MWh)*

Reference	Current	2025	2030	2035	2040	2045	2050
Levelised cost of production estimates							
UK Government, 2021a	59–62	–†	–	–	–	–	65–67
ETC, 2021 (production cost)	24.4–62	–	–	–	–	–	23.5–56.4
Pale Blue Dot, 2019	54–84	–	–	–	–	–	–
IEA, 2021	18.8–37.6	–	–	–	–	–	–
SGN, 2020a	41.85	–	–	–	–	–	–
CCC, 2018	–	28–57	–	–	27–57	–	–
Price estimates							
BEIS, 2021a (H_2, wholesale price)	46–51	47–52	45–53	46–54	46–54	46–54	46–55
Comparator: BEIS projected wholesale natural gas prices (BEIS, 2020)‡	*11–25*	*12–27*	*14–28*	*15–30*			
BEIS, 2021a (H_2, industrial retail price)	56–62	55–65	57–66	57–66	57–66	57–67	57–67

* Some references provided cost estimates in USD/kg; these were converted assuming $1=£0.74 and 1kg=39kWh

† Blank cells indicate that the reference did not provide an estimate for the year in question

‡ These price projections were made before the energy price crisis that began in late 2021. For comparison, current wholesale gas prices are around £65–70 per MWh[12]. Changing assumptions about gas prices would also affect projections of future blue hydrogen prices.

3.2.1.5 Prospects for blue hydrogen

The ENA (2020) argues that, in general, industrial clusters are planning to produce only enough hydrogen for their own use, not to provide additional capacity for domestic conversion – without policy support, potential suppliers did not see that there was a business model for producing hydrogen for domestic use.

The Acorn project, currently the most advanced blue hydrogen proposal within Scotland, is proposing a 200MW development. This project is atypical of those we have looked at as it is intended to produce hydrogen for use into the gas grid, initially via a 2% blend. The possibility of providing higher blends –

[10] Assuming €1=£0.84.
[11] https://sandbag.be/index.php/carbon-price-viewer/ (accessed 23/02/22).
[12] https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators (accessed 23/03/22).

up to 20%, and even a 100% stand-alone hydrogen distribution network – have been explored as part of the Aberdeen Vision project. Hydrogen production at the Acorn site could rise to 10GW (60TWh/yr) by 2045 to 'fully utilise the forecasted natural gas flows from the St Fergus Terminal', meeting around 50% of forecast UK hydrogen demand in 2050 (Pale Blue Dot, 2021)

However, the literature, including commercial studies for hydrogen production facilities funded through the UK Government's Low Carbon Hydrogen Supply Competition, suggests that greater policy and market certainty is needed to stimulate private investment and grow blue hydrogen production capacity (Sunny et al., 2020; Pale Blue Dot, 2021; ENA, 2020). For example, HyNet North West (2021) has indicated that a final investment decision regarding its proposed blue hydrogen plant is likely to be heavily dependent upon the level of support that will be made available through the Hydrogen Business Model (expected to be finalised by the end of 2022). Support mechanisms mentioned in the literature include: carbon pricing (National Grid, 2021; UK Government 2021a; ETC, 2021); investment support mechanisms including contracts for difference (SGN et al, 2020; HyNet North West, 2021) or an expanded scope of the Green Gas Levy (Scottish Government, 2020b); international standards, including to certify carbon content of hydrogen (ETC, 2021; IEA, 2021; UK Government, 2021a); adequate infrastructure planning (IEA, 2021); and demand-side policies that create identifiable markets (ETC, 2021; IEA, 2021). There also needs to be some support for supply chain development. Scotland is considered to be starting from a strong base in this respect (Scottish Government, 2020b) but there are acknowledged gaps in manufacture and maintenance of hydrogen production, storage and transport systems (Scottish Government, 2020c).

3.2.1.6 Carbon intensity

Carbon emissions[13] for blue hydrogen depend on the level of fugitive methane emissions in the gas supply chain, conversion efficiency of the reformation process, and the effectiveness of carbon capture at the point of production. Estimates of current and potential future direct emissions from the production process are in the range 11–25gCO_2/kWh (CCC, 2018; Siemens Gamesa, 2021; ENA, 2020). Fugitive methane emissions add very significantly to this[14], resulting in estimated total emissions between 60% and 85% lower than those from the existing use of natural gas (CCC, 2018). High use of blue hydrogen in the earlier period of National Grid's 'system transformation' scenario means that although the scenario delivers on the UK's 2050 net zero target, it is not consistent with the UK's Sixth Carbon Budget (National Grid, 2021).

Analysis for the National Infrastructure Commission suggests that, if the status quo is maintained, a scenario with total decarbonisation of the gas grid using blue hydrogen would result in cumulative emissions to 2050 at 64% of current levels, because large-scale roll out would not start for a number of years and properties off the gas grid are not addressed by this action (Element Energy and E4Tech, 2018). Whilst the CCC (2018) see a role for blue hydrogen in reducing carbon emissions, some commentators (e.g. Agora Energiewende, 2021) consider that blue hydrogen cannot be part of a fully decarbonised system because there will always be fugitive methane emissions in the supply chain and never 100% carbon capture at the point of production. They suggest that, with fugitive emissions at the current global average rate and a 98% carbon capture rate, lifecycle emissions would exceed the threshold defined in the European Commission's sustainable finance taxonomy[15] (Agora Energiewende, 2021). The Scottish Government's 2045 net zero commitment may therefore be an issue for investors because blue hydrogen production facilities built over the next decade will not have reached the end of their life by this point (Scottish Government, 2020a). There is the potential to produce hydrogen from bioenergy with CCS, which would result in negative emissions (Scottish Government, 2020b). The projected costs for this are much higher than for blue hydrogen,

[13] CO_2e – emissions of methane included.
[14] ENA (2020) states that gas supply chain emissions are 35.3gCO_2 per kWh hydrogen.
[15] This situation may change as details of the taxonomy are finalised.

ranging from £64–£127/MWh (CCC, 2018; BEIS, 2021a), although factoring in carbon pricing would make the economics of this option far more favourable (BEIS, 2021a).

3.2.2 Green hydrogen production

Key findings:

- Electrolyser technology for use at scale is an emergent technology and expensive, but costs are expected to fall rapidly and significantly. Future cost estimates (pre-energy crisis) vary considerably, but the industry view is that green hydrogen may become cost competitive with blue early in the 2030s.
- Production at scale depends on the availability of sufficient low-carbon electricity. The ability to secure such scale may be addressed, to some extent, by offshore production.
- Green hydrogen hubs are of interest to the Scottish Government, linked to energy access in the Islands and the potential development of hydrogen exports.

3.2.2.1 Critical dependencies

The electrolysers used in green hydrogen production are at a lower level of technological maturity than methane reformers (TRL level 4-9 (IEA, 2021) vs TRL level 9 for SMR and ATR (Barnes et al., 2021). However, smaller scale electrolysers (up to 10MW capacity) are available commercially and can be used in tandem to allow for large scale production (IET, 2019). ITM Power, a leader in electrolyser production, expects to able to provide modular production facilities of up to 1GW by the end of 2022. The global capacity of electrolysers doubled over the five years to 2021, reaching 300MW in total. There are around 350 projects currently under development which could potentially increase global capacity to 54GW by 2030, with a further 40 larger scale projects in the early stages of development that could add another 35GW (IEA, 2021). Industry estimates suggest that capital costs will reduce in the near future, potentially by as much as 50% (ETC, 2021; SGN et al., 2020c). The Scottish Government's Hydrogen Assessment (Scottish Government, 2020a) suggests that it is the scale-up and build-out rates of electrolysis plants worldwide, together with the strength of policy support in the UK and elsewhere, that will dictate the rate of growth in production of green hydrogen. This could, with optimistic assumptions, result in green hydrogen production that is a viable competitive option in the early 2030s. The Scottish Government's draft Hydrogen Action Plan expects that in the next five years the focus will be on engineering and technical design of production facilities, which will enable full costing and hence final investment decisions to be taken later this decade (Scottish Government, 2021b).

Production of green hydrogen also depends on the availability of sufficient zero carbon electricity. This appears unlikely to be a limiting factor on hydrogen production in Scotland (Scottish Government, 2020a; Hydrogen Taskforce, 2021). However, the rate of increase in generation capacity, in particular in offshore wind, will have to be accelerated to deliver hydrogen production at scale within the necessary timeframes to meet decarbonisation targets (Barnes et al., 2021). Whilst more capacity would be needed for a hydrogen-based heating scenario than for one based on heat pumps (due to lower overall system efficiency), the need for accelerated development of generation capacity likely holds true for any heat decarbonisation scenario, irrespective of the balance between electrification and the use of hydrogen (Imperial College, 2018). For example, National Grid's Future Energy Scenarios suggest the need for between 31 and 47GW of offshore wind across the UK by 2030 (National Grid, 2021).

The necessary acceleration in the development of offshore wind seems likely to happen. Current UK offshore wind capacity totals 11GW, with 0.9GW of this in Scottish waters (BEIS, 2021c). In 2020, the UK Government increased its target for 2030 for offshore wind generation capacity from 30GW to

40GW (UK Government, 2020). It has also promised to hold yearly auctions for contracts for new project capacity, into which the c.4GW presently in development in Scotland (Scottish Government, 2021b) could bid. Looking further ahead, the Scottish Government's recent auction of offshore wind development rights resulted in the award of rights to develop 25GW of capacity (FT, 2021), more than double the 10GW ambition set out in its plan for offshore wind energy (Scottish Government, 2020d).

3.2.2.2 Physical and geographic dependencies

Green hydrogen production is ideally sited in close proximity to renewable energy resources, where there is available land (if onshore) for industrial development and adequate water supply. Local demand, availability of skilled supply chains and ease of access to export markets are also beneficial (Barnes et al., 2021).

A number of commentators suggest that, for the UK as a whole, the scope for production of hydrogen from surplus renewable electricity may be limited. The situation may be somewhat different in Scotland, where grid constraints may lead to more frequent curtailment of renewables, and hence a higher proportion of potential renewable electricity that is currently unused. The Climate Change Committee estimates that a maximum of 44TWh hydrogen could be produced in this way in 2050 (CCC, 2018), and one other commentator notes that electrolysis will compete with other forms of flexibility for the use of low-cost electricity (Agora Energiewende, 2021).

The Scottish Government (2020c & 2021b) suggests that the production of hydrogen from offshore wind could help to reduce or avoid Scotland's grid constraints by providing a significant local demand for existing generation. There is also increasing interest in the offshore production of hydrogen through the use of integrated systems combining existing or new wind turbines with electrolysers and water desalination technologies, for example the Dolphyn project (summarised in Table 5 in Section 4.3, below). Perhaps importantly, this technology is also claimed (ERM, 2021) to provide opportunities to access wind resources in areas where long-distance underwater electricity transmission infrastructure would be prohibitively expensive.

The Scottish Government expects early work on where best to locate electrolysers to be published in 2022 (Scottish Government, 2020c). Island and rural communities have already been highlighted as potential sites for development, given their potential for co-location of production and use, high fuel costs (which makes green hydrogen a more competitive commercial prospect) and constrained infrastructure (Scottish Government, 2020a). This is consistent with the UK Government's view that first movers in this field in the early 2020s are likely to be relatively small scale, with production and use closely linked (UK Government, 2021a). Indeed, the green hydrogen cluster in Orkney is the first and only (as yet) green hydrogen project in the UK to move past initiation and into a growth phase; grid constraints and otherwise constrained renewable output are considered to have been drivers here (Mouli-Castillo et al., 2020). Other island locations where activity to develop and use green hydrogen is already in progress or planned include Shetland and the Outer Hebrides (Scottish Government, 2020a & 2021b; UK Government, 2021a).

Outside of rural and island settings, the Fife H100 project – reportedly a 'first-of-a-kind' [16] home heating demonstration pilot – is expected to become operational in the early 2020s (Scottish Government, 2021b). This project, the UK's national 'neighbourhood scale' hydrogen for heating pilot, includes plans to distribute green hydrogen from an electrolyser powered by an existing 7MW wind turbine to 300 properties in the Levenmouth area (SGN et al, 2020). A separate hydrogen distribution network will be built for this pilot, whereas proposals for wider rollout beyond pilots are based on repurposing the existing gas grid.

[16] https://h100fife.co.uk (accessed 23/03/22).

There is also the potential for development in Scotland's cities, although this may be less clearly beneficial than the situation for islands or industrial clusters (Scottish Government, 2020a). Both Aberdeen and Glasgow are mentioned as potential demand sources (Scottish Government, 2020b &2021b; UK Government, 2021a), with the latter focused on hydrogen (for use in transport) from an existing wind farm at Whitelee. An application for planning permission for the hydrogen production plant was submitted in April 2021 (East Ayrshire, 2021).

Green hydrogen production has high land (onshore production) and water (an essential component of the electrolysis process) requirements. In both cases, the amounts required are significantly higher than for methane reformers: a 1GW electrolyser may need 80,000–130,000m² zoned for industrial use and with COMAH Upper Tier permits (Barnes et al., 2021), and production of 300TWh could require water equivalent to the consumption of around 1.2 million households (IET, 2019). Neither issue has been identified as a major concern at this stage, but these needs could potentially constrain large-scale growth in the future. New developments, such as the Dolphyn project, may enable the development of offshore production systems that avoid such constraints.

3.2.2.3 Cost of production

Perhaps the biggest barrier to rapid increases in the production of green hydrogen is the cost, relative to current costs of natural gas and the cost of producing blue hydrogen. However, both UK and Scottish government documents present an expectation that green hydrogen will become cost competitive with blue at some point in the period 2025 to 2032 (Scottish Government, 2020a & 2020c; UK Government, 2021a). Comparing the latest BEIS cost projections for the two production routes (BEIS, 2021a, summarised in Tables 3 and 4) suggests that this is based on a green hydrogen production system that sources electricity from a mix of dedicated offshore wind and curtailed generation.

Table 4: Green hydrogen cost estimates (£/MWh)

Reference	Current	2025	2030	2035	2040	2045	2050
Levelised cost estimates							
CCC, 2018	–	–	–	–	72–77	–	–
ETC, 2021	–	37.6	–	–	–	–	18.8–28.2
Scottish Government, 2020c	–	–	73.7(2028)	58.4(2032)*	–	–	–
Barnes et al., 2021	96.8	–	–	–	–	–	–
IEA, 2021	55.4–150.4	–	24.4	–	–	–	–
Price estimates							
BEIS, 2021a (dedicated offshore, industrial retail price)	–	109–116	88–91	79–82	72–76	71–76	69–75
BEIS, 2021a (curtailed electricity, industrial retail price)	65–133	58–104	48–88	46–80	43–73	43–70	42–67

Reference	Current	2025	2030	2035	2040	2045	2050
Comparator: BEIS projected wholesale natural gas prices (BEIS, 2020)†	*11–25*	*12–27*	*14–28*	*15–30*			

* Analysis by the Scottish Government suggests that this price will deliver cost parity with natural gas, presumably with carbon costs factored into the gas price.

† These are wholesale prices, whereas BEIS estimates for green hydrogen are retail prices. Estimates were made before the current fuel price crisis.

The point at which green hydrogen becomes cost competitive (with blue hydrogen) depends on the cost trajectories of renewably generated electricity, natural gas (including any carbon pricing), and the cost of electrolysers, all of which have significant uncertainties. The necessity of reducing costs of wind generation is recognised by the Scottish Government (Scottish Government, 2020a & 2020b). Industry analysis suggests that such cost reductions will happen by the early 2030s (Siemens Gamesa, 2021; SGN et al., 2020c). As noted above the cost of electrolysers is forecast to reduce rapidly and sharply. For example, as a result of recent investments, ITM Power expect to secure a 40% reduction in costs over a three-year period through increased automation, product standardisation and economies of scale (Element Energy, 2019).

The Climate Change Committee estimates that an electricity cost lower than £10/MWh could make electrolysis paired directly with wind generation cost competitive with methane reformation (CCC, 2018). This is consistent with International Energy Agency analysis suggesting that electricity prices need to be below $20/MWh (IEA, 2021).

3.2.2.4 Prospects for green hydrogen

The Scottish Government view is that, with appropriate near-term government support, Scotland could become a leader in the production of green hydrogen (Scottish Government, 2020a). Supply targets and targets for production infrastructure feature in both UK and Scottish government policy and there are no clear physical constraints on growth. Currently, there is no electrolyser production capacity in Scotland, but there are no known constraints that would prevent the import of equipment as required. However, the Scottish Government recognises that to achieve its targets, consistent and long-term support will be needed for green hydrogen to be deployed at scale (Scottish Government, 2020).

In terms of support needs, the energy sector points to the need for supply and demand targets, carbon pricing, targets for production infrastructure and public investment in early large-scale projects (ETC, 2021). For example, ERM (2021) suggests that a contracts for difference mechanism or similar will be necessary to incentivise the development of the Dolphyn system. As with blue hydrogen, the Hydrogen Business Model is again likely to be a critical matter in determining future investments.

3.2.2.5 Carbon intensity

Increasingly ambitious carbon emissions targets seem likely to force an increased proportion of hydrogen to be produced via electrolysis (Imperial College, 2018). Siemens Gamesa (2021) suggests that the growth in global demand for hydrogen to decarbonise sectors that are hard to electrify will have to be met using green hydrogen if net zero targets are to be met.

Climate Change Committee analysis suggests that future grid carbon intensity will result in emissions of 11–14gCO_2 per kWh grid connected green hydrogen (CCC, 2018). This may be an overly cautious estimate: in the three National Grid Future Energy Scenarios that are compatible with net zero, the electricity grid reaches zero emissions in the early 2030s, and Scottish Government statistics show that in 2020 the equivalent of 98.6% of all electricity used in Scotland came from renewable sources[17].

3.2.3 Transmission, distribution and storage of hydrogen for home heating

Key findings:

- A new national transmission system for hydrogen is likely to be needed, as during the period of transition both natural gas and hydrogen will need to be supplied across the country.
- Distribution networks will be relatively easily converted to carry hydrogen once the Iron Mains Risk Reduction Programme, replacing iron pipework with plastic pipes, is complete in 2035.
- Short- and long-term storage will be needed. Long-term underground storage, in salt caverns or in depleted oil and gas fields, is at an early stage of development.

Hydrogen can be transported by road, rail or ship, but for home heating pipelines are the most cost-effective way to transport the significant volumes of hydrogen necessary to meet demand over the required distances (CCC, 2018; Agora Energiewende, 2021).

The UK has a nationwide gas transmission network of high-pressure pipes that transport natural gas from the points at which it comes ashore to most areas of the country. The transmission network connects, via intermediate and medium pressure pipes, to regional low-pressure distribution networks that carry gas to final users.

3.2.3.1 Transmission

In relation to the use of hydrogen for heating, hydrogen might be introduced initially into the gas network by blending small percentages into sections of the existing national gas transmission and distribution system. For example, the Acorn Hydrogen Feasibility Study (Pale Blue Dot, 2019) refers to an initial blend of 2% for the Aberdeen region, and the potential to build out to blend increasing percentages of hydrogen into the national grid (up to 20%).

The IEA (2021) notes that hydrogen blending at rates of between 2% and 10% by volume can occur without substantial retrofitting of the natural gas pipeline. Where there are polymer-based pipelines (as is now the case in much of the UK), blending up to 20% is possible with minimal or no modifications to the grid infrastructure.

However, the CCC notes: “blending of hydrogen is not a key stepping stone on the way to full conversion to hydrogen, as it fails to tackle key challenges associated with higher proportions of hydrogen supply” (CCC, 2018). Moving beyond blending to a 100% hydrogen system may require a new transmission network, as the existing network would be required to continue to supply natural gas until the transition was complete. Gas network operators suggest that a new transmission network may be required even for blending as some industries that use methane as a feedstock may

[17] https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2018/10/quarterly-energy-statistics-bulletins/documents/energy-statistics-summary---december-2021/energy-statistics-summary---december-2021/govscot%3Adocument/Scotland%2BEnergy%2BStats%2BQ3%2B2021.pdf (accessed 23/03/22).

not be able to cope with blending, and that more work on blending and deblending is needed in the period to 2025 (SGN, 2020; ENA, 2020).

The current UK national gas transmission network includes 7,660km of high and intermediate pressure pipes (National Grid, 2017). Analysis for the National Infrastructure Commission (Element Energy and E4Tech, 2018) suggests that building a new transmission network for hydrogen would cost around £4bn (discounted) although Scottish Enterprise capital cost estimates (of £1.7m–£3.5m/km) suggest that the cost of replacing the entire network could be as high as £13–27bn (Barnes et al., 2021).

Scottish Gas Networks suggests that a first step in the transition to a full hydrogen system (at scale, as opposed to the H100 pilot) could be the development of a new pipeline connecting Aberdeen with St Fergus, which could be used to supply the Aberdeen region, initially with a 20% blend of blue hydrogen and then converted to 100% blue hydrogen. The pipeline could later also be used to transport green hydrogen from offshore production sites to the Aberdeen region (SGN, 2020).

It is not clear when the transmission system as a whole will be ready to supply hydrogen to consumers across the gas grid in Scotland: Energy Networks Association (ENA) scenarios suggest that conversion/construction will happen in the period from 2030 to 2040 (ENA, 2020). This will be dependent on the successful completion of all the necessary preparatory studies and pilots, and on the speed with which the planning system approves the necessary infrastructure construction. Both the gas industry (ENA, 2020) and the Scottish Government (Scottish Government, 2021b) refer to the first half of the 2020s as the period during which work to support the establishment of this infrastructure will take place. Slow speed of planning approvals is an issue of concern raised by the gas industry (ENA, 2020) and as previously mentioned the Scottish Government is working to provide guidance on this (Scottish Government, 2021b).

There is little said about how investment in the new infrastructure will be paid for, although one report suggests that costs could be recovered from consumers over a 30-year period (Baldino et al., 2020).

3.2.3.2 Distribution

The UK natural gas distribution networks comprise around 280,000km of pipes, 233,000km of which are low pressure pipes installed over many decades of gas network development. Since the 1970s, polyethylene pipes have been used; prior to this, iron pipes were used and an estimated 89,000km of iron pipes are still in use (Dodds and McDowall, 2013). Polyethylene pipes are suitable for the distribution of hydrogen; iron pipes are not. Through the Iron Mains Risk Reduction Programme, the gas network operators are in the process of replacing iron pipes with polyethylene pipes to improve the safety of the network. This programme will be complete by 2035, meaning that by this point the pipework across the distribution system will be suitable for hydrogen (ENA, 2020). Conversion of the 'hydrogen-ready' distribution system to 100% hydrogen will, however, require replacement of some valves and regulators and potentially some work in gas users' properties.

Transition to a hydrogen-only network could be managed by isolating appropriately sized segments of the distribution network and purging the natural gas before filling the pipes with hydrogen. Such work would need to be undertaken at the same time that necessary in-house conversion work takes place in properties connected to that segment of the network (IET, 2019).

SGN & Wood (2021) list the following activities that would be needed for conversion of network segments:

- Industrial and commercial plant sensitivity assessments
- Planned sectorisation of the project area that ensures minimal disruption and costs associated with additional connections and strategically placed valves

- Disconnection, isolation and purging of the local natural gas system
- Conversion of burners and appliances to operate with 100% hydrogen
- Any additional changes to customers' gas systems
- Any additional network reinforcement or upgrades to district governors and/or removal of material that is not suitable for hydrogen
- Purging of the pipework system
- Connection to the local hydrogen system.

Uncertainties remains as to how this will work in practice, including the need for coordination between the supply chains that deal with appliances and systems in people's homes and the distribution grid operators (Frazer-Nash Consultancy (2018). The feasibility studies that have taken place and the pilots planned for the early- to mid-2020s are in part designed to better understand this. The H21 Leeds City Gate study suggests that only relatively minor upgrades to the medium- and low-pressure networks will be needed (IET, 2019).

Whilst trials and further studies are happening, the Scottish Government has stated that it will support SGN on the pathway to network conversion wherever this is consistent with keeping options open and limiting consumer costs (Scottish Government, 2021b). One area where UK-level policy work is needed is changing Gas Safety Management Regulations to make them appropriate for the distribution of hydrogen (Pale Blue Dot, 2019; SGN, 2020).

3.2.3.3 Storage

Hydrogen cannot be used at scale without storage. This is needed for managing both short-term demand fluctuations and any large inter-seasonal demand variations, such as those seen for heating (Hydrogen Taskforce, 2021).

Short-term demand fluctuations are presently dealt with using linepack[18] within the gas distribution and transmission networks. Annually, the networks store somewhere in the region of 100TWh energy using linepack, with a little more than half of this in the distribution network and the rest in the national gas transmission system (Wilson, 2022). The lower density of hydrogen would reduce the network's capacity to store energy in this way (Storenergy and Inovyn, 2019), but a significant amount of storage capacity would be retained in the system and this is likely to be sufficient to manage short-term demand fluctuations.

A more significant hurdle for the development of a hydrogen system is the need for long-term storage. HyStorPor (2021), a research group based at Edinburgh University, suggests that seasonal storage needs can only be met via geological storage. The two main options identified in the literature include salt caverns or depleted oil and gas fields. The issues associated with the use of salt caverns for storage are well understood, but the use of depleted oil and gas fields is an as yet unproven option. The ETC (2021) suggests that the TRL for depleted oil and gas field hydrogen storage is 2–3, whereas salt caverns are at TRL 9. The use of salt caverns and depleted oil and gas fields would both be expected to cost less than other storage options[19]. High capital costs would remain an issue, meaning that it would only be commercially viable to develop them once hydrogen is produced in significant quantities (Scottish Government, 2020a). However, development of storage may need to precede large-scale development of production capacity (Storenergy and Inovyn, 2019), leading to suggestions this should be enabled through the establishment of a Regulated Asset Base funding mechanism for hydrogen storage (ENA, 2020).

[18] Linepack refers to the volume of gas that can be stored within the gas pipe network.
[19] Space constraints on above-ground storage mean that hydrogen would have to be stored at high pressure to contain the amount of hydrogen that would need to be stored long term.

According to National Grid (2021), the UK currently stores 14TWh natural gas in salt caverns. In its Future Energy Scenarios[20], there is a need for at least 2TWh hydrogen storage by 2035, up to 24TWh by 2040, and up to 51TWh by 2050. Modelling by Imperial College (2018) suggests the need for up to 20TWh of hydrogen storage. Assuming that existing natural gas storage is given over to hydrogen, given the lower energy density of hydrogen, there would still be a need for a significant increase in storage capacity. At present, only one salt cavern is being used for hydrogen (grey) storage – located on Teesside, it has been operational since 1972. The feasibility of large-scale geological storage options is being considered by the HyStorPor (HyStorPor, 2021) and HySecure (IEA, 2021) projects. HyStorPor is also looking at consumer acceptance of hydrogen storage.

The time required to develop storage (new projects can take 5 to 10 years to develop) is noted in a number of analyses (National Grid, 2021; Scottish Government, 2021b; Agora Energiewende, 2021), and the Scottish Government's draft Hydrogen Action Plan (Scottish Government, 2021b) suggests there will not be sufficient storage to meet peak demand until 2045. The suggested solution in the interim is to build additional reformer capacity to supply the peaks (Scottish Government, 2021b). However, although storage is expensive (£6.4bn/yr to meet UK-wide peak winter demand, according to modelling by Imperial College (2018)), it is thought to be more cost-effective than building additional production capacity to meet peaks (which would likely sit unused for a significant proportion of the year). It is also likely that further government support would be needed if additional reformers were to be built to cover peak demand (Scottish Government, 2021b).

There are no onshore salt deposits in Scotland, but there are extensive offshore deposits which could, in theory, serve to provide storage. There is also significant potential for large-scale storage in depleted hydrocarbon reserves (Scottish Government, 2020c). One suggestion in the literature is that the former Rough gas storage facility, sited off England's east coast and due to be decommissioned in 2023, could be repurposed and expanded for hydrogen storage. This could potentially store up to 12.6TWh of hydrogen (Hydrogen Taskforce, 2021).

Decisions on policy support for the development of storage should consider not only its potential role in meeting peak demands for heat, but also the role it could play in the wider energy system in dealing with the intermittency of renewables (UK Government, 2021b). Proponents of salt cavern storage suggest that its costs compare favourably with other energy storage options such as pumped hydro or batteries (Storenergy and Inovyn, 2019).

[20] In the net zero compliant FES, total annual hydrogen demand in 2050 is between 149TWh and 475TWh. At the higher end of this demand range, hydrogen meets over 50% of total residential energy demand.

3.2.4 Use of hydrogen in the home

Key findings:

- Very little is known about consumer attitudes towards the use of hydrogen for heating. The planned trials at neighbourhood and village scales will have to be completed to address this.
- Initial safety assessments suggest that it will be possible to use hydrogen safely in the home. The trials will need to assess the costs and practicalities of delivering this in practice, including understanding how much work will be required to existing pipework systems and how easy it will be to add the required ventilation.
- Hydrogen-ready boilers could be introduced to the market in the mid-2020s, and existing natural gas boilers replaced by them as part of natural appliance turnover.
- Running costs associated with using hydrogen for heating are likely to be an issue.

One of the main claimed advantages of hydrogen for home heating is that it provides a familiar 'like-for-like' replacement that consumers understand and are comfortable with (Hydrogen Taskforce, 2021). Hydrogen boilers are able to deliver the same performance as those fuelled by natural gas and allow the same pipes and radiator system to be used for heat distribution (IET, 2019). Appliances that are 'hydrogen-ready', i.e. that can work when fuelled with natural gas but are easy to convert to use hydrogen fuel, are seen as a central enabler of a switchover of the gas grid (IET, 2019). Industry is calling for government to mandate hydrogen-ready appliances from 2025 (ENA, 2020; Hydrogen Taskforce, 2021). Hydrogen boilers are expected to cost a similar amount to natural gas boilers. One analysis suggests a cost premium of around £100 (Element Energy, 2021), but a more recent price promise from boiler manufacturers states that the cost of hydrogen-ready boilers would be the same as the cost of natural gas equivalents (The Engineer, 2021).

Trials of hydrogen for heating homes will be carried out in the first half of this decade (ENA, 2020; UK Government, 2021b). These aim to demonstrate that hydrogen can be distributed to and used in homes safely, securely and reliably, and that the process of conversion and use of hydrogen is acceptable to consumers (IET, 2019; BEIS, 2021b). Industry analysis suggests that there need to be trials of using hydrogen in 10,000 homes by 2030 (Hydrogen Taskforce, 2021).

3.2.4.1 Safety and environmental impacts

Hydrogen and natural gas have different physical and chemical properties[21], and the safety of the use of hydrogen in buildings requires careful consideration. Odorants will have to be added so that people can smell leaking gas (as is the case for natural gas); there may also be a need for flame colourants, although opinion is divided on this (IET, 2019; ARUP, 2021). A safety assessment carried out as part of the Hy4Heat project (ARUP, 2021) concluded that leaks from accidental damage to pipework were both more likely to cause incidents with hydrogen than with methane, and also that such incidents would on average cause injury to more people[22]. The assessment recommended, therefore, that two separate excess flow valves are fitted in any property being converted to hydrogen and sufficient non-closable vents installed close to ceilings in rooms with gas appliances or substantial pipework. The assessment suggests that with these measures in place, together with visual inspection of pipework, rectification of any faults, and tightness testing of the pipework before and after installation work, the

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[21] Hydrogen is a smaller molecule and hence leaks faster through a given sized hole; it is less dense and less energy dense, has a lower minimum ignition energy and wider flammability range, and has a much higher laminar burn velocity but otherwise burns similarly to methane. Like methane, it is odourless; unlike methane, it burns with a virtually colourless flame.

[22] The assessment assumed the same pipework in the home and the same behaviour by consumers, with safety certified appliances all fitted with flow failure devices and installed by fully competent tradespeople.

use of hydrogen in the home should be as safe as the use of natural gas. These recommendations will be applied in practice during the pilot trials. Until these have taken place, it is not possible to determine the likely cost and disruption implications of the measures, in particular the need for inspection and rectification of faults in pipework and tightness testing (ENA, 2020; Element Energy and E4Tech, 2018).

Burning hydrogen results in higher levels of emissions of nitrogen oxides (NOx) than burning methane, and this may be an issue for local air quality levels. The Climate Change Committee proposes that the implications of hydrogen combustion for NOx emissions, compared with fossil fuels and any low-carbon alternatives, should be established (CCC, 2018).

3.2.4.2 Trials and wider roll-out

The first UK neighbourhood-scale trial of hydrogen for heating, using a new dedicated hydrogen distribution network, will take place in Fife as part of the Fife100 project. This will be established by 2023 and will be followed by a village-scale trial by 2025, with plans developed for a possible hydrogen town that can be converted before the end of the decade (UK Government, 2021b). In March 2022, Ofgem proposed funding two detailed design studies for locations in England, rejecting an application from SGN[23].

If the trials are successful and a decision is taken to pursue a wider rollout of hydrogen for heating, there are a number of scenarios proposed for how this might happen and how long it may take. These are set out in more detail in Section 4, below, but what happens in practice will depend on a number of key constraints.

In all the scenarios, transition to a hydrogen grid, whether for the whole country or only some regions, would involve dividing the gas distribution network into segments that can be isolated from one another, and then isolating each in turn, disconnecting it from the natural gas transmission grid, converting it to hydrogen, and then connecting it to the hydrogen transmission system. Consumer cost and disruption will be minimised, and consumer acceptance likely increased, by maximising the number of hydrogen-ready appliances that are installed as part of natural replacement cycles rather than having to be replaced early. If such appliances are mandated by 2025 and replacement continues at similar rates to the present day, it will take until 2039 for around 90% of boilers to be hydrogen-ready[24]. A policy decision will be needed as to when a sufficient proportion of boilers are hydrogen-ready and hence when an area-by-area switch over programme can begin.

The switchover of a given segment of the grid to hydrogen needs to be completed sufficiently quickly for consumers to be happy with the amount of time their gas supply is disconnected. Working proposals at the moment suggest disconnection periods of a small number of days (CCC, 2018). For this to be feasible, sufficient appliance installers and associated trades will need to be available in the local area for the switchover period to adjust hydrogen-ready appliances, replace any remaining non-hydrogen-ready appliances, and carry out other necessary pre-conversion work to systems in people's homes. The H21 North of England team (NGN, 2018) estimates that converting the 3.7 million gas customers in their study area to hydrogen over a seven-year period would require an average of 3,000 plumbers in the summer and 1,500 in the winter, with an average of 240 management and administrative staff employed for the whole period.

Work for BEIS on the logistics of hydrogen conversion (Fraser-Nash Consultancy, 2018) estimated that a total of 44 million person days of work would be involved if all homes on the gas grid were converted to hydrogen. Using a range of scenarios on how the required workforce would develop and

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[23] https://www.ofgem.gov.uk/publications/hydrogen-village-trial-detailed-design-studies-decision (accessed 23/04/22).

[24] Estimated based on the statement in ENA (2020) that 1.5 million boilers are replaced each year and there are 23 million homes with gas boilers.

be deployed, they estimated a time period for complete switchover ranging from 3 to 16 years. Given the complexities of having the workforce in the right place, minimising disruption by carrying out conversions in the summer only, and avoiding a surge in the number of installers required followed by a steep drop-off once conversion is completed, the longer end of this timescale range seems more realistic. Indeed, the Scottish Government estimates that with a workforce of 13,000 and conversions carried out in the summer months only, a switchover of the entire network in Scotland would take 11 years (Scottish Government, 2021b). The Climate Change Committee (2018) suggests that the challenges involved mean that even two decades may not be sufficient time to complete the switchover.

The desire of investors to have some assured demand for hydrogen may influence the shape and speed of construction of a hydrogen transmission system. This could drive a pattern of conversion to hydrogen heating starting in clusters linked to other uses for hydrogen and subsequently spreading out (Element Energy and E4Tech, 2018). Equally, there may be small pockets of hydrogen use in relatively isolated communities linked to hydrogen production facilities (Scottish Government, 2020a).

Policy action may encourage or discourage the use of hydrogen for heat in some areas. As noted above, the Scottish Government wants to ensure that Scottish consumers can access low-cost hydrogen for heating should it become available, and to ensure that no-regrets action on heat pumps and heat networks is planned so that the business case for hydrogen is not undermined in those areas where it might be an appropriate option in the longer term (Scottish Government 2021a). The development of Local Heat and Energy Efficiency Strategies for all areas in Scotland by the end of 2023 and a national assessment to identify strategic heat decarbonisation zones (Scottish Government, 2021a) will have an impact. The UK Government, in planning to phase out gas boilers, also acknowledges the need to consider areas where hydrogen may later be introduced:

> *In the next decade we will have taken important strategic decisions on the role of hydrogen in heating and will know more about its regional suitability, therefore we aim that by 2035, hydrogen-ready boilers are not installed in areas that do not and will not have access to a supply of low-carbon hydrogen in the future.* (UK Government, 2021b)

The Scottish Government's target to decarbonise at least 1 million homes on the gas grid by 2030 would by default remove a proportion of these homes from the pool of potential users of hydrogen but if, as is proposed, the installation of heat pumps and heat networks is planned so as not to disadvantage future hydrogen developments, this should not be problematic. SGN & Wood (2021) suggest that hydrogen could make a significant contribution to meeting the 1 million homes target. However, this is dependent on significant investment in CCUS infrastructure in Scotland and reformers for the production of blue hydrogen, beginning within the next couple of years, which seems highly unlikely given that there is as yet no government support for such investments. It is also dependent on conversion of the gas grid beginning in 2024; again this seems unlikely given that government decisions on the use of gas for home heating will not be taken until the initial pilots have been completed, in the mid-2020s.

3.2.5 Cost and consumer acceptability

3.2.5.1 Total system costs

The Climate Change Committee suggests that, when capital costs are considered, any decarbonisation pathway is likely to almost double the cost of heating the UK's homes (CCC, 2018). Analysis for the National Infrastructure Commission notes that there are significant cost uncertainties across all heat decarbonisation pathways and that, as a result, it is not possible to say definitively which option will be cheapest (Element Energy and E4Tech, 2018). National Grid's latest Future Energy Scenarios (National Grid, 2021) notes that total system costs do not vary significantly between scenarios, indicating that technology pathway choices do not impact costs significantly.

In summary, all approaches to heat decarbonisation come with a significant cost. At the system level, at least based on current understanding, there is little difference between the potential pathways. However, there are projected to be significant differences between initial transition costs and ongoing running costs across the different low-carbon heating options. Compared with heat pumps, for example, current estimates suggest that the initial investment in hydrogen appliances for home heating would be cheaper, but annual running costs more expensive (Element Energy and E4Tech, 2018).

3.2.5.2 Initial costs of the conversion from natural gas to hydrogen

Estimates of cost per household for the initial hydrogen conversion process range from £750–£1,000 for labour only, i.e. if a hydrogen-ready boiler is already in place in the home and excluding the costs of any additional safety-related equipment (Frazer-Nash Consultancy, 2018), to £2,000-£4,000 if all appliances (boiler, oven and hob) need to be replaced (CCC, 2018). If hydrogen rollout were to lead to early replacement of many systems, one national analysis estimates the cost of a full UK-wide rollout to be £26bn (Element Energy and E4Tech, 2018). Some commentators suggest that these costs would have to be subsidised/socialised if consumers were forced to replace appliances earlier than they would otherwise have done (Fylan et al, 2020). There are also suggestions in the literature that consumers may have to be incentivised to take part in a natural gas to hydrogen conversion to counter any disruption they may experience (Frazer-Nash Consultancy, 2018).

3.2.5.3 Energy efficiency

Some hydrogen proponents claim that in comparison to heat pumps – which are generally viewed as the main alternative technology for domestic heating – the use of hydrogen reduces the need for consumers to invest in energy efficiency measures, thereby reducing cost and disruption (EUA, 2021).

However, the total system cost scenarios referred to in 3.2.5.1 generally assume similar needs for energy efficiency improvements, regardless of which low-carbon heat supply technology is used. National Grid (2021) argues that thermal efficiency is as important for hydrogen as for heat pumps: improvements in energy performance reduce the cost of energy security across all Future Energy Scenarios, reduce running costs and minimise total system costs to 2050. NIC analysis argues that the higher cost energy efficiency measures that are a prerequisite for heat pumps are also justified for pathways based on hydrogen heating (Element Energy and E4Tech, 2018), and the CCC states that there is a need to ensure that all homes are EPC Band C by 2035 (CCC, 2018). The Scottish Government's target to improve the energy performance of all homes to EPC C by 2033 and all homes occupied by fuel-poor households to EPC B by 2040 (Scottish Government, 2021a) is consistent with arguments for energy efficiency investment, irrespective of the route to decarbonising heat supply.

3.2.5.4 Ongoing running costs

The literature contains almost no estimates of annal running costs for a hydrogen heating system, but the consensus is that it would be more costly than alternatives. Sunny et al. (2020) suggest that, depending on how various elements of the hydrogen system are funded, the cost to consumers of blue hydrogen could be between 190% and 320% of the cost of natural gas. Element Energy (2021) assumes a retail price for hydrogen in 2050 of 9.8p/kWh. Their scenario with the highest deployment of hydrogen boilers has a lower proportion of homes spending less than £500 per year on fuel and a higher proportion spending more than £1,250 per year than any other scenario, suggesting that hydrogen will remain more costly for the foreseeable future.

The H21 North of England project (NGN, 2018) estimates that it would be possible to meet 14% of the UK's demand for heat by converting gas networks across the north of England to hydrogen and socialising the costs of the fuel across all users of the gas network. It estimates that this would result in fuel cost increases for all UK gas consumers of around 7%. The report does not consider what would happen once the remaining users of the gas network decarbonised their heat supply, either by converting to hydrogen or by disconnecting from the gas network.

The UK Hydrogen Taskforce suggests that consumers would be prepared to pay a small premium for ‘green gas’, particularly if this minimised disruption (Hydrogen Taskforce, 2021). However, other studies of consumer attitudes have highlighted concerns about the idea of increased fuel bills (Fylan et al., 2020; Gray et al., 2019).

In the current context, it seems likely that securing consumer buy-in to the prospect of increased running costs will be a serious hurdle for hydrogen to overcome. Applying carbon pricing to natural gas would reduce the expected gap between it and hydrogen but would also increase the attractiveness of other forms of low-carbon heat at the expense of hydrogen. It is worth noting that the Scottish Government is urging the UK Government to rebalance energy prices, shifting some policy costs away from electricity and onto gas, to reflect the falling carbon intensity of the electricity grid (Scottish Government, 2021a). The UK Government has stated its intention to do this (UK Government, 2021b).

3.2.5.5 Fuel poverty

The ENA (2020) notes: “Costs to consumers and the risks of fuel poverty matter, and hydrogen will cost more than natural gas today (as will all other options) – the issue of who pays and how much is therefore critical.”

Fuel poverty is a core concern for the Scottish Government, and the main policy response is to provide capital for investment in energy efficiency and low-carbon heat technologies. There is a commitment to deliver ‘measures to help those in fuel poverty to manage their running costs’ (Scottish Government, 2021a). A whole-system transition based on the use of hydrogen boilers, which will likely have significantly higher running costs than heat pumps or hybrid systems (Element Energy and E4Tech, 2018), would be likely to generate a need for more costly ongoing forms of intervention than would be incurred from a transition to alternative forms low-carbon heating,.

3.2.5.6 Acceptability of hydrogen heating systems

It is generally acknowledged in the literature that not enough is yet known about public attitudes towards the use of hydrogen for heating (e.g. Scottish Government, 2020a; Element Energy and E4Tech, 2018). What is known is based on hypothetical scenarios presented to research project participants, which relies on people being able to imagine using hydrogen heating or its alternatives. The reliability of the results of these studies depends on the quality of information being given to participants (Imperial College, 2018). Hydrogen trials over the next five to ten years will provide evidence on consumer reactions in real-world situations: as the CCC (2018) notes, these trials will need to be of sufficient scale and diversity to enable understanding of whether hydrogen can be a genuine option at larger scale.

4 Response to research questions

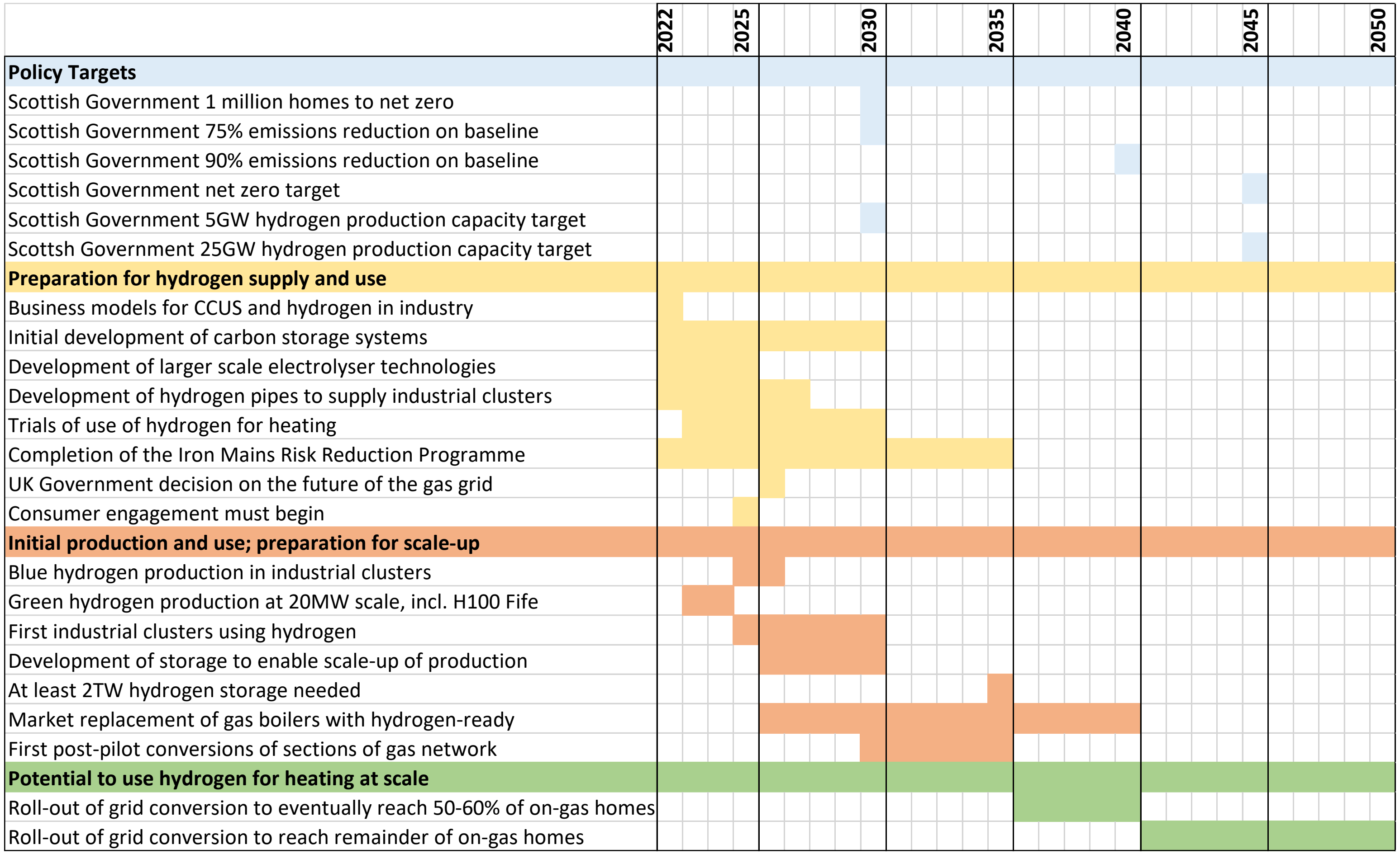
In this section we have drawn on the key information laid out in the policy context and findings sections to address the research questions set for this literature review.

4.1 What are the realistic timescales over which large-scale delivery of low-carbon hydrogen via converted gas networks (beyond demonstrators) could begin and be delivered at scale in Scotland?

The findings from our literature review identify a number of critical dependencies that will determine what the realistic timescale for large-scale delivery might be.

Table 2 (Section 3.1) presents the key components (in terms of infrastructure, supply chains, economics, and the social/political framework) that need to be in place to deliver a system of hydrogen for home heating. Figure 1, below, illustrates the timeframes suggested in the literature over which the critical elements may develop, given the right policy support, together with some of the key policy milestones.

Figure 1: Possible timeframes drawn from the literature



4.1.1 Policy milestones

Looking first at the Scottish policy context, the early targets for decarbonisation of 1 million homes on the gas grid and for an overall 75% emissions reduction come before any significant scale of hydrogen rollout will be possible.

Scenarios for the rollout of gas network conversion suggest it could take up to 20 years, starting after the completion of the planned area, village and town pilots, in 2030 (e.g. ENA, 2020). The overall Scottish Government net zero target date of 2045 is in the middle of the period when the latter 40–50% of on-gas homes could see their distribution network converted to hydrogen. Whether the whole of Scotland's gas distribution network can be converted in time to meet the net zero target will depend on cooperation between the Scottish Government and SGN, the network operator, and also more generally on how gas network operators and the regulator decide collectively on the most cost-effective pathway to conversion/how the conversion process will be funded.

If the Scottish Government targets for 25GW of hydrogen production capacity by 2045 are met, there would in theory be sufficient hydrogen to meet demand for heating homes: at a 50% load factor[25], for example, 25GW would produce around 110TWh of hydrogen per year. Total gas demand in Scotland in 2019 was less than half of this, at 47.6TWh (Scottish Government, 2021c). However, other competing domestic uses for hydrogen (in industry and the transport sector) and potentially the export market – both of which have been identified as priorities by the Scottish Government – could require a high proportion of the hydrogen produced.

4.1.2 Preparation for hydrogen supply and use

For the 25GW target to be met, a series of developments must happen; as noted in sections 3.2.1 and 3.2.2, government support will be needed for hydrogen production and CCS, to be made investable. A key proposed revenue support mechanism for hydrogen (blue and green) is the Low Carbon Hydrogen Business Model (LCHBM). A final decision on this mechanism is expected in 2022. However, initially at least, the scheme is understood to be unlikely to support projects focused on domestic heat decarbonisation (BEIS, 2022).

Assuming that financial support is forthcoming, some commentators suggest that carbon capture and storage systems could take up to a decade to develop to commercial status (ETC, 2021). This contrasts with more optimistic UK Government aspirations, as expressed in the prime minister's Ten Point Plan[26], which commits to the deployment of two Track 1 (priorities for support) carbon capture usage and storage (CCUS[27]) clusters in England by the mid-2020s. In Scotland, the proposed Acorn CCUS facility has been identified as a first reserve (i.e. a potential replacement project should one of the Track 1 projects fail to proceed), but is otherwise listed as a Track 2 project. At the time of writing, this appears to mean that it may not become operational until 2030 (unless alternative or additional support is made available), which would also delay the production of blue hydrogen from its proposed sister facility. For green hydrogen, the literature suggests that there is a need for the scaling up of electrolyser technology; the Scottish Government's hydrogen assessment (Scottish Government, 2020a) suggests that it is the scale-up and build-out rates of electrolysis plants that will dictate the rate of growth in production of green hydrogen. There is some evidence of movement in this area, most notably the establishment of a so-called Gigafactory in Sheffield (by ITM Power) in 2021. This is

[25] A 50% load factor has been chosen for illustrative purposes only. Note that offshore production from dedicated renewable resources will be subject to fluctuations in availability of renewable electricity and hence it is reasonable to choose a relatively low load factor here.
[26] The Ten Point Plan for a Green Industrial Revolution (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf (accessed 5.7.22).
[27] CCUS schemes may include the commercial use of CO2 as opposed to simply carbon storage.

reportedly the largest such manufacturing facility in the world and ITM are understood to have to have the necessary finance in place to build a second, even larger facility. ITM, however, produce for a global market and so the use of their technology in the UK will be determined by factors such as government support and competition for their product in other markets.

Before large-scale rollout of gas network sectoral conversion to hydrogen can begin, the Iron Mains Risk Reduction Programme must be complete so that the low-pressure network is suitable for transporting hydrogen. This programme will be complete by 2035 (ENA, 2020). There also needs to be a government decision on the future of the gas grid: the UK Government is planning to make this decision in 2026, after neighbourhood and village trials are carried out in the first half of the decade (UK Government, 2021b).

If a hydrogen for heating transition is to occur, significant consumer engagement must begin before the middle of this decade. It is generally acknowledged that not enough is yet known about public attitudes towards the use of hydrogen for heating (e.g. Scottish Government, 2020a; Element Energy and E4Tech, 2018), and what is known is based on hypothetical scenarios presented to research project participants, which relies on people being able to imagine using hydrogen heating or its alternatives. The aforementioned pilots are expected to help inform consumer engagement programmes, but as noted, evidence from these will not be available until the late 2020s.

4.2.3 Initial production and use

The UK Hydrogen Strategy (UK Government, 2021a) suggests that we should be looking to have the first blue hydrogen production in industrial clusters by the middle of this decade. These may be located in the north of England, given that HyNet in north-west England and the East Coast Cluster around Teesside and the Humber are the preferred locations for government support for CCUS[28]. The Fife 100 and Dolphyn plans suggest that, with appropriate government support, green hydrogen production at multiple MW scale, could be brought online within the next few years.

In the second half of the decade, development of sufficient storage capacity will be necessary to enable production to scale up. National Grid scenarios (National Grid, 2021) suggest that at least 2TW hydrogen storage will be needed by 2035.

Consumer cost and disruption will be minimised, and consumer acceptance maximised, by maximising the number of hydrogen-ready appliances that are installed as part of natural replacement cycles rather than having to be replaced early. If such appliances are mandated by 2025 and replacement continues at similar rates to the present day, it will take until 2039 for around 90% of boilers to be hydrogen-ready. A policy decision will be needed as to when a sufficient proportion of boilers are hydrogen-ready and hence when an area-by-area switch over programme can begin.

The gas industry (ENA, 2020) suggests that the first post-pilot conversions of sections of the gas network could begin in the first half of the 2030s. This suggests that the level of deployment by 2030 is at most restricted to local distribution networks around industrial clusters. Construction of dedicated distribution grids may be required as the proportion of domestic appliances that are hydrogen-ready will still be relatively low and 'forced' conversion of entire local areas – rather than the option to convert – could be unpopular and require significant subsidy.

4.2.3 Potential to use hydrogen for heating at scale

The gas industry suggests that wider conversion of the network could begin in 2035 and that the rollout could be largely completed by 2045 (ENA,2020). However as noted above, it will take until 2039 for a large majority of gas boilers to have been replaced with hydrogen-ready alternatives,

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[28] https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-1-expressions-of-interest/october-2021-update-track-1-clusters-confirmed (accessed 5.8.22)

assuming these are mandated from 2025. Therefore, there is a question over how the cost of early replacement of boilers in a significant proportion of homes would be funded if this rollout scenario happens. Scenarios in the literature suggest that widespread conversion of gas networks will not happen until the 2040s, and hence large-scale delivery of low-carbon hydrogen for home heating cannot happen until then.

4.2 What are the estimated upfront conversion and running costs for homes heated by hydrogen in 2030 and 2045?

Estimates of upfront conversion costs from reliable studies range from £750 to £4,000 per household (Frazer-Nash Consultancy, 2018; CCC, 2018). The lower end of the range assumes that existing appliances are hydrogen-ready and that there is little need for new equipment within the home's gas distribution system; the assumption at the upper end is that all gas-using appliances will have to be replaced.

Some proponents of hydrogen (e.g. EUA, 2021) suggest that there is no need for investment in the energy efficiency of homes to enable a transition to hydrogen for heating. However, National Grid (2021), the National Infrastructure Commission (Element Energy and E4Tech) and the Climate Change Committee (2018) all argue that properties should all be improved to EPC C standard to ensure that overall costs for consumers are minimised.

4.2.1 What is the range of running costs for domestic consumers? What are the reasons for any observed variations and which estimates appear to be the most robust?

There are almost no direct estimates in the literature for consumer running costs. This may be a result of the challenges of generating such estimates, given the large uncertainties around future technology costs (in particular for CCS and electrolysers) and future fuel (gas and renewable electricity) costs. However, even with optimistic assumptions about cost reduction, it seems clear that running costs for consumers using hydrogen will be significantly higher (potentially up to two or three times higher, according to Sunny et al. (2020) or based on UK Government estimates (see Tables 3 and 4)) than current running costs using natural gas. Future application of carbon pricing to gas could deliver cost parity between hydrogen and natural gas by the early 2030s. However, given that the issue of high gas prices is at present causing significant public and political concern, it is unlikely – even once energy prices normalise – that any government in the near future will be willing to implement policies that increase gas prices.

Fuel poverty is a core concern for the Scottish Government, and the main policy response is to provide capital for investment in energy efficiency and low-carbon heat technologies. There is a commitment to deliver 'measures to help those in fuel poverty to manage their running costs' (Scottish Government, 2021a). Hydrogen boilers will likely have significantly higher running costs than heat pumps or hybrid systems (Element Energy and E4Tech, 2018). Unless government policy reduces the price of hydrogen for consumers (e.g. through contracts for difference), it is difficult to see how their use by households suffering or at risk of fuel poverty can be seen to be consistent with fuel poverty policy.

4.2.2 To what extent would consumers be expected to bear the cost of the conversion of the gas network to hydrogen?

A significant proportion of the costs of converting the gas network are already being borne by consumers via regulatory funding of the Iron Mains Risk Reduction Programme.

Proposals in the literature for funding the remaining system transition costs refer to the potential need for Regulated Asset Base funding, so the expectation is that consumers will bear these future costs also. What is not clear is whether this will be the case if large numbers of consumers choose to decarbonise by electrifying their heating, thus significantly reducing the domestic customer base for the gas sector. It is also not clear where the balance would lie between recovering costs from domestic and non-domestic customers.

4.3 Where in Scotland is likely to be best suited for the early deployment of hydrogen for heating at scale?

Assuming a focus on the use of domestically produced hydrogen, our assessment is that the early deployment of hydrogen for heating (100% as opposed to blended) is expected to occur near to hydrogen production facilities. The likely geographic deployment of hydrogen for heating will therefore be dictated by the factors which determine the location of such facilities.

The literature review identified multiple locational factors that are important in determining where hydrogen production occurs. The most important of these are:

- Access to a large-scale energy source (gas for blue hydrogen, renewable electricity for green).
- Proximity of a viable market – Industrial and, to a lesser extent, transport were identified as the priority markets for most entities involved in hydrogen projects. Both forms of end use are subject to increasingly strong market drivers (in comparison to heating) and have lower capital requirements owing to the relatively low distribution costs.

Other locational factors include:

- Access to suitable land – Industrial sites offer both space and lower planning thresholds.
- Access to water.
- Access to storage.
- Access to CCS/CCUS for blue hydrogen.

The east coast of Scotland, particularly the north-east, hosts several sites that feature a suitable combination of locational factors. It is therefore perhaps unsurprising that it hosts many of the UK's actual and proposed hydrogen projects.

Table 5 provides summaries of several of these projects. It should be noted that the table only lists mainland projects and, in the main, only those known to have given some level of consideration to hydrogen for heating. For reference, the literature identifies over 40 hydrogen projects in Scotland, in various stages of development, but only a minority of these involve domestic heating. This is consistent with suggestions in the literature that the priority for hydrogen projects should be for use in industry and transport.

Table 5: Hydrogen projects in Scotland of significance for the potential use of hydrogen for heating

Project	Summary	Understanding of status
Aberdeen Vision	It is understood that the work of the Aberdeen Vision initiative is intended to position Aberdeen as a leading contender for the UK Government's hydrogen town pilot (2030). The project aims to provide new market opportunities for hydrogen in	Unclear – There is clear interest in developing a hydrogen economy in Aberdeen and Aberdeenshire, but in relation to the use of hydrogen for heating it is understood that the concept is dependent upon the

Project	Summary	Understanding of status
	Aberdeenshire, including the use of hydrogen for heating (both 20% blended and through a proposed 100% system), and is closely integrated with the proposed Acorn developments at St Fergus. There are also links to the ERM Dolphyn project.	supply of blue H2 from the proposed Acorn plant.
Aberdeen, ERM Dolphyn Hydrogen	A commercial development plan (CDP) has been produced for a potential 10MW commercial scale demonstrator by 2024. It is anticipated that this will be located offshore from Aberdeen and that it will supply one or more end users in the Aberdeen area. The possibility of blending green hydrogen into the gas network has been explored, but it could instead or also be used for multiple other purposes.	The CDP was funded by BEIS via the Low Carbon Supply Competition. Development of the demonstrator is dependent upon the scheme securing additional funding support. Further support is being sought from BEIS and ERM is in discussion with potential investors.
Cromarty Firth, Green Hydrogen Hub	The North of Scotland Hydrogen Programme aims to develop a green hydrogen hub in the Cromarty Firth to produce, store and distribute hydrogen. A feasibility study has been commissioned to consider opportunities for distilleries to use hydrogen. Publicity materials for the project reference the possibility of using green hydrogen for heating but provide no additional details.	A feasibility study to consider the viability of using green hydrogen in distilleries is described as a kick starter project. This study was due to be completed in June 2021.
Fife, East Neuk Power to Hydrogen	SGN produced a report (2020) which explores the power to hydrogen potential in the East Neuk of Fife. Heating was considered but the use of hydrogen for transport fuels was found to be the most effective option in the short term. The report suggests that blending could be economically viable with subsidies of around £0.7/kg H2.	The study is described as supporting the H100 Fife project but it is not clear whether or not the findings are informing any other form of practical initiative.
Fife (Levenmouth), H100 Fife	This neighbourhood pilot scheme (understood to be the first of the three national pilots identified in the UK Hydrogen Strategy) will supply 300 homes with green hydrogen produced using a single wind turbine. The hydrogen will be supplied to homes via a purpose-built pipe network.	According to a recent BBC report (16 March 2022), the scheme will be operating from 2023. This report suggests that participants will pay the same price for hydrogen as they would for gas, but acknowledges that, in reality, hydrogen is a more expensive fuel source.

Project	Summary	Understanding of status
Grangemouth-Granton, Future of the Local Transmission System (LTS)	SGN investigated how the LTS could be repurposed to allow for the transmission and storage of hydrogen and CO_2. This included a study of the feasibility of using the Grangemouth-Granton LTS as a desk top case study. The work found that 91% of the LTS pipework is likely to be suitable for storing and transporting hydrogen.	The final report was issued in July 2021. The project is informing the work of the Institute of Gas Engineers and Managers (IGEM) LTS Futures Group.
St Fergus Gas Terminal, Acorn blue hydrogen production plant	A blue hydrogen production development has been proposed for the St Fergus gas terminal. It is understood that development (assuming a favourable business case) would currently involve the deployment of 3 units of 200MW, 300MW and 300MW. The development of each would be staged at 18- to 24-month intervals. Production would use North Sea natural gas, with the carbon being directed to the proposed Acorn CCS development. It is proposed that the hydrogen would be blended into the National Transmission System (NTS), initially at 2% but with expectations that this will increase over time. It is also proposed to divert some of the hydrogen to supply the Aberdeen Vision of 20% and 100% hydrogen conversion.	A detailed concept evaluation study was completed in July 2021. The report states that funding has been secured to move the project through the next stage of development, to the point at which a final investment decision (FID) can be made. This exercise (desk-based) is expected to be completed in early 2024. If the FID is to proceed, the aim is to have an operational project by 2026. Government support is 'key' to the progress of this project.
St Fergus Gas Terminal, Acorn CCS project	Phase 1 of the proposed Acorn CCS would enable at least 5Mt/yr of CO_2 sequestration via the repurposing of the Goldeneye pipeline. The project is a key component in the embryonic Scottish hydrogen economy, being essential to blue hydrogen production. Through its role in market development, it is arguably also an important enabler of green hydrogen.	The Acorn CCS site was unsuccessful with a bid to the UK Government's CCS Infrastructure Fund, but the site has been named as a reserve and as such may attract funding should one of the two preferred sites fail to proceed. According to the Acorn CCS website, the project developers remain committed to the project, which is currently in the detailed engineering and design phase of development. If the business case is viable then the project could be operational by the mid-2020s.

4.3.1 Areas most likely to see the early deployment of hydrogen for heating at scale

4.3.1.1 Aberdeen and Aberdeenshire

Based on evidence gathered through the literature review and informed by the projects outlined in Table 5, we would suggest that the use of hydrogen for heating, at scale, is most likely to arise in Aberdeen and Aberdeenshire. There is considerable support for the hydrogen economy in this area and Aberdeen is understood to be positioning itself to become the UK's hydrogen town pilot. Work has been undertaken to identify markets for hydrogen in the area and to determine the feasibility and viability of both blended and 100% hydrogen use. As part of this, links have been forged with the proposed Acorn blue hydrogen and CCS facilities at St Fergus, with the former being seen as the initial main source of supply. The level of support for hydrogen in the area has meant that other projects, for example ERM Dolphyn, are also looking to locate their early developments here. This indicates a tacit recognition that moving to a hydrogen economy will require a whole-system approach and the alignment of activities by multiple players. We would note, however, that this means there are multiple interdependencies, and a failure of key projects to secure finance will mean that multiple others will be unable to proceed. At present, as noted in the main report, the future of several projects involved in the Aberdeen Vision is dependent upon future government support, in the short term at least.

4.3.1.2 Fife

Fife hosts the Fife H100 project, described by SGN as a 'world-first' hydrogen to homes heating project[29]. As noted in Table 5, it is a small-scale project with limited scope for expansion owing to its reliance on single turbine. SGN (SGN,2020b) has considered the possibility of larger scale hydrogen for heating developments in Fife but concluded that hydrogen for transport was the most economically attractive option, at least in the short term.

4.3.1.3 Grangemouth

Some scenarios (e.g. CCC, 2020b) suggest that a rollout of hydrogen in Scotland could start from the Grangemouth industrial cluster. INEOS has publicly stated that it will develop a 700MW blue hydrogen production plant at Grangemouth. The CO_2 is expected to be routed to the Acorn CCUS project. Hydrogen will be used to supply INEOS petrochemical businesses via a site-specific hydrogen distribution network. Currently, the site uses gas supplied by the Forties pipeline. It is anticipated that the blue hydrogen facility may also supply external sites and form the basis of a local hydrogen hub. The proposed plant could, in theory, provide an opportunity to provide hydrogen to domestic consumers in adjacent locations. However, we found no evidence to suggest that this was anticipated and in the short term – assuming the site proceeds – it may be that its focus will be on meeting the needs of INEOS and potentially other industrial users only.

4.3.2 Wider development scenarios

As stated above, the Acorn project is linked to the wider vision for the Aberdeen region. This is initially focused on transporting gas from the Acorn site at St Fergus to the city and using it to fuel transport fleets. It is consistent with the Scottish Government's idea of a Regional Hydrogen Energy Hub (Scottish Government, 2021b), which is defined as 'a geographical location (region, city, island, industrial cluster) that is host to the entire hydrogen value chain, from production, storage and distribution to end-use'. The extent to which this will lead on to use for home heating is not yet known, but this will depend on a number of factors including the results of home heating trials, scaling up of production facilities, conversion of the local gas network and development of sufficient storage for the system to manage the variation in demand caused by winter peaks. Many of these elements are considered in the feasibility work that has been carried out for the Aberdeen Vision, but all are at an early stage of development.

Assuming that all the unknowns resolve in favour of using hydrogen for heating, it is interesting to consider the range of views on the size of role it would eventually play. The literature presents a number of alternative scenarios for the future of hydrogen and its role in home heating. A selection of the main scenarios from the CCC (Element Energy, 2021; CCC 2020b & 2020c), National Grid (2021) and the Energy Networks Association (ENA, 2020) are summarised in Appendix A, with the key aspects discussed here.

[29] https://www.sgn.co.uk/H100Fife (accessed 5.4.22).

All the published scenarios tend to assume that blue hydrogen production in industrial clusters will be the starting point, with any rollout of hydrogen for home heating beginning close to these hubs. For Scotland, this might suggest a rollout from the industrial cluster in Grangemouth (e.g. as suggested in CCC, 2020b). As noted, however, early use for heating in Aberdeen seems more likely at the moment, given that the Acorn facility and the Aberdeen Vision generally are at a more detailed planning stage than the proposed Grangemouth facility. Potentially, use could subsequently expand out from both these locations.

The impact that island hubs could have on the geography of larger scale rollout scenarios may be small. Although there could be more local use in the islands, hydrogen not used locally or exported is perhaps more likely to be piped offshore to existing terminals, such as St Fergus, and then into a national transmission grid, rather than being distributed locally through newly built onshore pipelines.

The proportion of home heating that might eventually be met using hydrogen varies considerably between energy scenarios for the UK. National Grid (2021) presents three scenarios that deliver net zero, and the role played by hydrogen in home heating in 2050 varies from meeting a 'very small proportion' to meeting the equivalent of 60% of current home heating demand. Element Energy produced scenarios for the CCC's Sixth Carbon Budget work (Element Energy, 2021), where hydrogen's role in home heating in 2050 varies from nothing at all to 71% of all homes using hydrogen, either via hydrogen boilers (in the north of the UK) or hybrid heat pumps (in the south). The CCC's preferred scenario involved hydrogen use for heating in 3.9 million homes, all via hybrid heat pumps.

The way in which initial developments in Scotland might develop into one of these alternative scenarios is not clear at present.

4.4 Areas needing further research

There is an extensive body of literature on the future of hydrogen, but this all notes the significant degree of uncertainty surrounding estimates of costs and volumes of production and consumption. Further desk research would not be expected to change this at the present time.

Both the UK and Scottish governments are expected to produce a number of relevant studies and policy documents this year (2022), including the hydrogen business model, early work on where to locate electrolysers, guidance on planning consent for large hydrogen production facilities, and the Energy Strategy and Just Transition Plan. A review of these, when available, could be undertaken to update the findings of this document. Other newly emerged documents and research might also be accommodated should resource allow.

One issue that may fundamentally affect the evolution of the hydrogen economy is the impact of Russia's invasion of Ukraine and the subsequent decision by the EU to become independent of Russian gas supplies. A question in our mind is the extent to which there might be accelerated growth in renewables and whether this, in combination with potentially persistently high (relative to pre-invasion costs) gas costs, undermines the case for blue hydrogen.

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Appendix B: Scenarios

ENA full hydrogen rollout

Aim: Complete transition of gas grid and many gas users switch to hydrogen

Hydrogen demand: 140TWh supplied to buildings in 2050

Homes using hydrogen: Conversion spreads out from industrial clusters; total homes not specified but demand for hydrogen approx. half of current demand for gas in homes

Timeline: Network conversion starts from 2035; first 100% hydrogen for heating 2030–2035; widespread domestic conversion in the 2040s

Potential issues: Will the planning system move swiftly enough to support this level of hydrogen demand? Will decisions on hydrogen ready boilers and on business models be taken in early 2020s?

Likelihood for Scotland: Low
End point is possible, but unlikely to deliver net zero by 2045

National Grid System Transformation

Aim: Net Zero with minimal consumer disruption

Hydrogen demand: 475TWh in total in 2050 (mainly blue); residential sector is largest single element of demand at 155TWh

Homes using hydrogen: Not specified, but total heating demand is 250 TWh, so approx. the equivalent of 60% of homes

Timeline: First hydrogen town by 2030

Potential issues: As for ENA full hydrogen rollout, will the system develop swiftly enough to support this level of demand in 2050? Assumes a carbon price applied to all fossil fuels – will this happen in time to drive the necessary investment?

Likelihood for Scotland: Low
Not compatible with Scottish Government policy targets

National Grid Leading the Way

Aim: Net Zero via rapid decarbonisation with world-leading technology

Hydrogen demand: 297TWh total in 2050, all green. Aviation and shipping, and industry/commerce are the largest demand sectors

Homes using hydrogen: Hydrogen meets around 40% of home heating demand

Timeline: First industrial cluster development a little later than the government target of 2025; otherwise in line with government targets

Potential issues: Will a carbon price be applied to all fossil fuels in time to stimulate necessary investment? Will the high consumer engagement assumed here actually happen?

Likelihood for Scotland: Medium to High
Consistent with policy aims and the focus on technology leadership and green hydrogen is in line with Scottish Government; carbon pricing and consumer engagement are potential issues

National Grid Consumer Transformation

Aim: Net Zero with high consumer participation

Hydrogen demand: 149TWh total in 2050; 75% from green. Aviation and shipping are primary uses; road and rail transport second

Homes using hydrogen: Only a very small proportion of home heat demand is met using hydrogen

Timeline: One fully net zero cluster by 2040

Potential issues: Will a carbon price be applied to all fossil fuels in time to stimulate necessary investment? Will the high consumer engagement assumed here actually happen? Can heat pumps meet most home heating demand in Scotland?

Likelihood for Scotland: Low to Medium
Consistent with policy aims but the level of heat pump use may be an issue for Scotland, and carbon pricing and high consumer engagement are potential problems

CCC balanced

Aim: Reduce emissions in buildings to zero by 2050

Hydrogen demand: 13.5TWh for home heating in 2050

Homes using hydrogen: 3.9 million using hybrid heat pumps

Timeline: Rapid grid conversion possible from 2030; some hydrogen near industrial clusters from 2030; work as much as possible with existing technology lifetimes

Potential issues: Will heat pump and heat network supply chains ramp up quickly enough to deliver this?

Likelihood for Scotland: Medium to High

Meets policy aims but perhaps not ambitious enough: Scottish Government likely to want to develop demand in a wider area than suggested here

CCC headwinds

Aim: Reduce emissions in buildings to zero by 2050

Hydrogen demand: 130.9TWh for home heating in 2050

Homes using hydrogen: 71% of all homes (9.3 million hydrogen boilers in the north of the UK, 9.5 million hybrids in the south)

Timeline: Similar to balanced scenario, but much more ambitious ramp-up of hydrogen production during the 2030s

Potential issues: Difficult to meet higher levels of hydrogen demand, which leads to more reliance on blue hydrogen. This results in potential issues with residual carbon emissions and levels of natural gas imports

Likelihood for Scotland: Low to Medium

A high degree of hydrogen use in Scotland is possible, but probably more green than blue; affordability issues would have to be addressed

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