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Abstract

This ELEGANCY report presents the application of the WP3 business model and business case framework, templates and tools to the UK case study.

The UK case study addresses the delivery of a Hydrogen-CCS infrastructure network for domestic and commercial heating across the northern regions of England as articulated in the H21 North of England (H21 NoE) report completed by Cadent, Equinor and Northern Gas Networks and issued in November 2018. That study built on an earlier study, H21 Leeds City Gate, and presented the engineering details of the most cost effective and realistic options for converting the north of England to hydrogen over a 7-year period between 2028 and 2034. The report also provided a vision for decarbonisation of 70% of meter points by 2050 using a subsequent regional roll out strategy and argued there is a realistic potential to expand production and infrastructure to enable a transition to 100% replacement of UK natural gas demand with hydrogen by 2050.

This report focusses on an assessment of the H21 system-level investment barriers and risks, and the mitigation measures needed to enable delivery of the H21 Roadmap vision. The government policies and support mechanisms that will be required to achieve the investment in, and deployment of, H21 are presented. An example business model based on collaboration between the government, and public and private sector institutions is defined taking account of realistic risk sharing and strategic drivers consistent with the UK government's legal 2050 net zero emissions target. The ELEGANCY WP3 business case template is populated at a conceptual level to summarise the findings of this analysis.

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1 INTRODUCTION

This report applies the business model and business case development and assessment methodology developed by ('**SDL**') in ELEGANCY Work Package 3 (WP3) to the UK case study in WP5 task 5.4. The report reviews the work presented by the H21 North of England project team in its 2018 report[1] and sets it in a business and investment context for large-scale decarbonisation of the UK energy system. Key risks and barriers to investment in the Hydrogen-CCS (H_2-CCS) integrated value chain are identified and ways to overcome these are suggested so that the time to market for hydrogen and CCS at business segment, regional and system levels can be reduced. A high-level business case strategic rationale and definition is developed that focuses on public/private collaboration for removal of investment barriers and mitigation of risks through the design of system business models.

The UK case study is led by BGS with contributory members Imperial College, Sustainable Decisions Limited, INEOS, and Scottish Enterprise. The study aims to provide technical information and an infrastructure planning and development strategy as evidence to support the H21 Roadmap, ahead of a 'key policy decision' and possible commitment to progress further engineering and design in 2021. The ELEGANCY research results should increase confidence in the provision of process technologies, transport infrastructure and storage capacity (in the absence of an existing 'over-the-fence' operation). This includes business investment and optimization of strategies for integrating H_2-CCS with a wider CCS system, as planned by H21 for rollout at regional and national level. Learnings gained will also be applicable to the development of hydrogen and CCS in other regions of the UK and EU.

In 2016, evidence was presented in the H21 Leeds City Gate report[2] that conversion of the UK gas distribution network to hydrogen integrated with CCS can reduce the UK emissions from heating by as much as 73%. The evidence also indicated that an H_2-CCS infrastructure for heating by converting the UK gas network to 100% hydrogen is both technically feasible and economically viable when the currently externalised costs of emissions are taken into account. Planning was in progress to implement 'next steps' as a programme of works (2017 to 2022), to deliver the UK H21 Roadmap and provide identified outstanding technical evidence. The vision for the H21 Roadmap is the incremental rollout of gas network conversion and CCS in phases across UK cities and regions and their industrial clusters. The H21 Roadmap assumes CCS is available 'over the fence' as and when it is required and is therefore not considered in detail in the H21 assessment. Further work was completed in 2018 and presented in the new report H21 North of England which extended the earlier work for Leeds to the North of England. This work did include solutions to the provision of CO_2 transport and storage (T&S) infrastructure.

The H21 reports have highlighted that the conversion of the UK gas distribution network to hydrogen cannot occur under current regulatory and policy frameworks, however they

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[1] Northern Gas Networks, Cadent and Equinor, 2018, *H21 North of England*, https://www.northerngasnetworks.co.uk/event/h21-launches-national/, accessed 31st March 2020

[2] Northern Gas Networks, 2016, *H21 Leeds City Gate*, https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf, accessed 31st March 2020

did not consider the changes that are necessary for the system level infrastructure chain integration with CCS. Without addressing these, significant market barriers and market failures will remain that discourage and prevent investment in CO_2 capture, transport and storage infrastructure as well as the development of hydrogen markets even if the required gas network regulatory changes are made. Future investment in common-use infrastructure is essential for enabling lower cost industrial, transport and heat decarbonization to meet the UK government's net zero emissions target by mid-century. This is not likely to materialize if the policy emphasis during the 2020's is fragmented and only focussed on delivering individual 'cost competitive' low carbon projects associated with natural gas power generation or industrial CCUS demonstration projects.

The business case assessment for the UK case study presented in this report has been undertaken at the 'concept definition' level. This is typical of all the ELEGANCY case studies and a characteristic of the research process for non-specific investment or policy proposals and decision-making. Nevertheless, this report presents a very detailed analysis of the strategic rationale, investment barriers and collaborative public-private system business model required for delivering the first phase of the H21 North of England Roadmap. The recommendations should support the establishment of an enduring government policy and support framework that can facilitate the further infrastructure build-out and investment optionality in subsequent phases of the H21 Roadmap. This system framework is also consistent with the techno-economic network modelling of heat decarbonisation of the entire UK performed by Imperial College for this UK case study[3].

The business case concept definition for the UK H21 case study is directed at the objective to achieve:

> *A commitment to phased investment in H_2-CCS infrastructure to cost effectively decarbonise residential heating in the north of England and to support UK energy system decarbonisation to meet a net zero emissions target by 2050.*

This study concludes that an initial commitment by 2023 to construction and funding of a first phase H_2-CCS network in the north of England is necessary to prepare for a gas network conversion commencing in 2028-29 and the development of markets for H_2 and CO_2. The initial H_2-CCS system would be commissioned in 2026 and composed of:

a. a modular H_2 production facility at scale [initial capacity 1.35 GW];
b. associated H_2 transmission pipeline(s) and geological cavern storage;
c. facilities and market appliance upgrades for H_2 blended with methane up to 20%;
d. conversion or construction of a power station capable of burning blended hydrogen and natural gas up to 90% hydrogen [initial capacity of 2 or 3 440 MW turbines];
e. connection to a large industrial cluster [Humber, Teesside, Manchester/Liverpool];
f. oversized CO_2 T&S infrastructure in the Southern North Sea [initial pipeline capacity of 15-20 Mt per annum].

[3] Sunny, N., Mac Dowell, N. and Shah, N., 2019, November. Large Scale Deployment of Low Carbon Hydrogen and CCS Value Chains for the Decarbonisation of Heat: Novel Methods and Insights. In 2019 AIChE Annual Meeting. AIChE.

The principal recommendations from this research to achieve the business case definition are:

1. A successful business case for H21 North of England requires a narrative supported by the public.
2. The 2050 Net Zero policy has to be the overarching system strategic direction to evaluate all projects and technologies. The business case for H21 North of England should be defined and evaluated in the context of Net Zero policy and not in the context of separate strategies for decarbonisation of power, industry, heat or transport.
3. Any Net Zero pathway/business case needs to plan for the development and deployment of innovative ‘negative emissions’ technologies because many emissions sources cannot be reduced to zero, leaving residual emissions in 2050. Negative emissions technologies, such as Direct Air Capture with Carbon Capture and Storage (DACCS) and Biomass Energy with Carbon Capture and Storage (BECCS), should be planned.
4. A delivery body/organisation is required with a clear mandate to coordinate the UK system-wide business case and deployment across all regions and sectors. The UK has governance expertise for governing and delivering the H_2-CCS system spread throughout a number of organisations including the Infrastructure Commission, the Infrastructure and Projects Authority, HM Treasury, Ofgem, the Low Carbon Contracts Company, the Oil and Gas Authority, and the Health and Safety Executive.
5. Government will need to be responsible, with public sector intervention and participation, for creating and developing new low carbon markets and sustained demand for hydrogen and for CCS. Decision making will need to be based on the principles of low regrets and creation of real options.

2 METHODOLOGY

2.1 Summary

This chapter provides a high-level summary of the business model and business case methodology, framework and tools developed in ELEGANCY work package 3 (WP3) that have been utilised in the UK H21 North of England case study with the results reported in the main body of this current report. The following sections give brief descriptions of the main elements of the WP3 methodology along with flowcharts and references to all of the relevant interim reports[4]. The full Excel spreadsheet toolkit developed in WP3 is listed in Table 4-1 of report D3.3.4 and can be found on the ELEGANCY website[5]. The toolkit uses 'heatmaps' and matrices for the display of complex data and information relationships. Green-amber-red 'traffic light' colour-coding is employed and also used in this report. Depending on context green represents a positive or good impact, outcome or value; amber represents neutral or adequate; and red represents negative, poor or deficient.

2.2 Business Model Development Methodology (Recap)

The flowchart in Figure 2-1 presents the overall methodology developed and applied by WP3 to select business models for H_2-CCS opportunities (see ELEGANCY reports D3.2.1, D3.3.2 and D3.3.3). A business case can be defined and assessed once a business model is selected. The ELEGANCY business case assessment methodology (presented in report D3.3.4) is therefore applied to business models chosen through the process described herein. As business model preferences can change with changing business contexts as well as with the maturity of a project, the combined selection and assessment process is iterative, but follows the same steps and analysis at fit-for-purpose levels of detail.

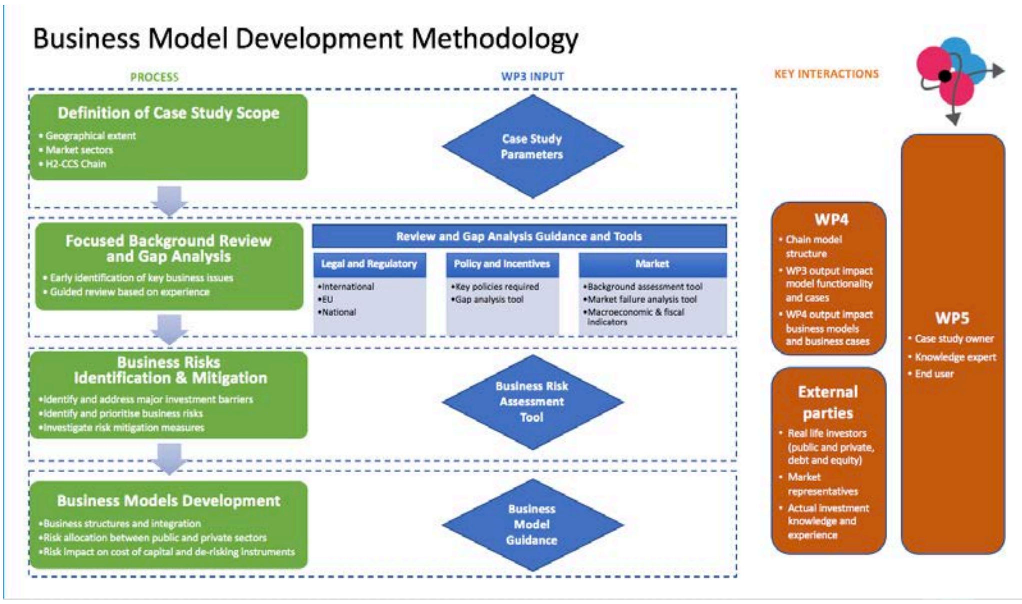

Figure 2-1 Business Model Development Methodology

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[4] ELEGANCY Publications, 2020a, https://www.sintef.no/projectweb/elegancy/publications/
[5] ELEGANCY Publications, 2020b, https://www.sintef.no/projectweb/elegancy/programme/wp3/business-case-development-toolbox/

The Business Model Development process is divided into four distinct steps:

Step 1: *Definition of the scope of the particular H_2-CCS chain for the relevant case study*

The process commences with an initial focus on the specific H_2-CCS chain technical sub-components, business segments, and associated market sectors of main interest, the geographical extent (including industrial hubs, production facilities, storage areas, end-users, cross-border interactions, etc.), and market potential.

First Climate and Sustainable Decisions have created a standardised framework for any case study lead organisation to use in this first step that matches the needs of the scope definition exercise described above. This framework comprises the technology elements and market sectors, a H_2-CCS chain business tree, and an extensive set of potentially relevant case study parameters (described in report D3.2.1). This framework and analysis are to be used side-by-side with the scenarios and quantitative estimates of market potentials undertaken in Work Package 5 *Task 5.1 Interfaces* and reported in D5.1.1[6].

Step 2: *Focussed market background review and gap analysis*

The purpose of this second step is to guide an overall assessment of the market background for any case study in preparation for the third step of understanding the investability and handling of major business risks. The major barriers and business risks that are faced by potential developers and financiers in the H_2-CCS business chain have been identified by stakeholders to be non-technical, and robust economic scrutiny is essential for any large-scale infrastructure investment. Technology components within the H_2-CCS infrastructure chain and end markets exist and have proven functionality. Hence, investing in, and delivering, low-carbon hydrogen using CCS at scale requires an understanding of the risks associated with government policy, market development, and regulatory frameworks. Full chain operability issues are another area of risk that is dealt with in Step 3 below.

The ELEGANCY WP3 toolkit has been designed and produced, based on the project development experience gained over a number of years in countries such as Netherlands, Norway and UK, to facilitate a simple high-level analysis of the major drivers for each of the H_2-CCS chain market sectors and business segments. The market background includes the legal and regulatory environment, the market fundamentals and applicable market failures, key macroeconomic drivers, the policy status and financial support mechanisms. An important aspect of this assessment method is the requirement to include thinking and review of the interactions between different market players reflected in the H_2-CCS chain business segments.

[6] ELEGANCY Publications, 2020a, op.cit.

Step 3: *Business and investment risk identification and mitigation*

Based on the information gathered during step 2, the third step is to identify and quantify the major business risks that impact the level of investment potential for each of the market sectors and business opportunities from both a public and a private sector perspective. A bespoke risk assessment spreadsheet tool has been designed (Report D3.3.2 Appendix A.2) that can be applied to any individual or bundled business opportunities along the H_2-CCS chain selected from the standardised business tree.

Section 2.4 of report D3.3.2 describes the risk assessment methodology in more detail. In summary, assessable risks are divided into:

1. Investment Barriers: these are circumstances or facts that raise the risk of detrimental investment outcomes to an unacceptable level for any type of investor. Generally, these barriers will affect multiple segments along the chain, or the whole chain, and require a ‘system view’ and multi-party (often in collaboration with government) approach to mitigation measures. These barriers need to be addressed in priority for any investment to be possible; and

2. Major Business Risks: these are risks that impact cost, revenue, liabilities, financing, schedule and therefore the risk/return equation for a final investment decision (FID). Individual businesses will generally be capable of mitigating these operational risks through familiar technical, commercial, insurance and other standard measures.

This step facilitates an early identification and prioritisation of risks to be addressed by a case study lead organisation and guide the subsequent communication and conversations with potential private investors and public/government organisations.

Step 4: *Business model development*

The fourth step in the method focuses on how to remove the investment barriers and mitigate business risks and to select appropriate business models for any given case study. Chapters 4-7 of Report D3.3.2 deal with the principles and elements used in the methodology. Report D3.3.3 completed the methodology with a description of the business model selection process, its relationship with preparing and assessing a business case, and a business model selection tool. When applied to case studies, the outcome will be the development of a number of viable commercial structures and business models, investigating the potential investor mix and the allocation of risks between those investors for each of the market opportunities, the de-risking mechanisms required from the financial and carbon markets and from the EU and national governments.

2.2.1 System and Operational Business Models

In order to create further clarity about business models the ELEGANCY WP3 methodology differentiates between system or macroeconomic business models and business segment or micro-economic business models (Figure 2-2). System business models are the principal means for the mitigation of exogenous risks (including political, policy, social and outcome risks) that cannot in general be managed by the private sector alone and provide a macroeconomic solution that can overcome barriers to investment by both the public and private sectors into the various operational segments of a full chain H_2-CCS infrastructure. Operational business models focus on the risks and delivery of the outputs and services for a particular business segment within the H_2-CCS chain.

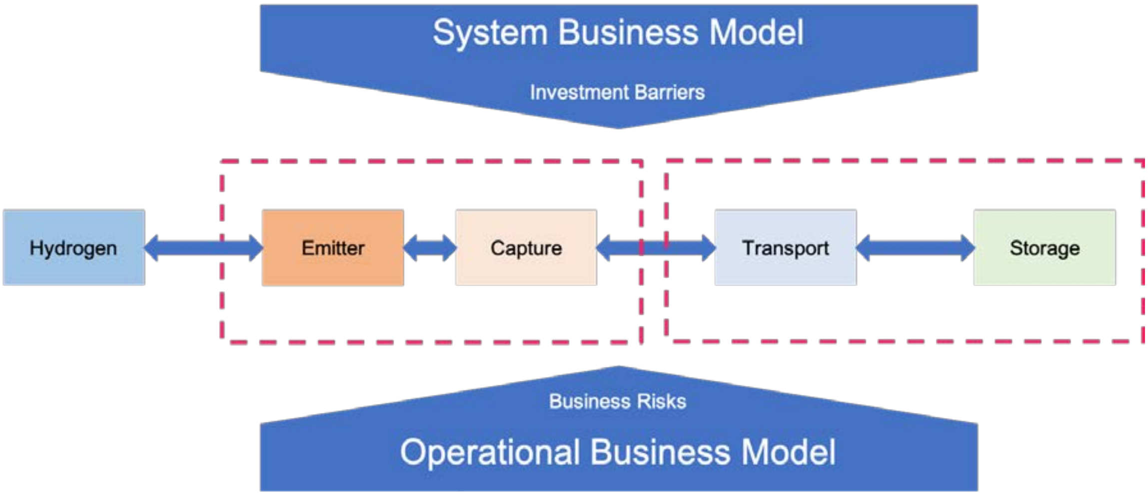

Figure 2-2 Business Model Characterisation

Unlike renewable energy entering mature electricity networks, CCS infrastructure and its applications have not in general been supported by fit-for-purpose holistic ‘programmatic’ government interventions. In large part this has been because of an inertia to commit to CCS as a climate mitigation technology. This in turn has created barriers to investment which extend beyond the business risks that an individual project may experience, even with government financial or fiscal incentives.

The combination of ELEGANCY WP3 and WP5 case study research has led us to the conclusion that a viable system business case is a pre-requisite for achieving an investable project business case. The development and selection of sector- or project-specific business models is dependent on an over-arching system business model that, at a minimum, must address the following:

a. System-level strategic rationale and objectives;
b. Cross-sectoral synergies and sector coupling;
c. Development of ‘low carbon’ end use markets;
d. Enduring system governance and oversight until markets are self-sustaining;
e. Public-private risk sharing reflecting system characteristics/properties;
f. Public-private collaboration and capacity/capability building;
g. Societal and social acceptance with removal of moral hazard; and
h. Development of real options for low regrets transition pathways.

2.3 Business Model Selection

The Business Model Selection Process is illustrated in Figure 2-3 below. Additional guidance (including recommended activities and supporting tools) is provided for each of the process steps in Sections 5.2 to 5.9 of report D3.3.3 and a list of the relevant WP3 tools is provided in Section 5.10.

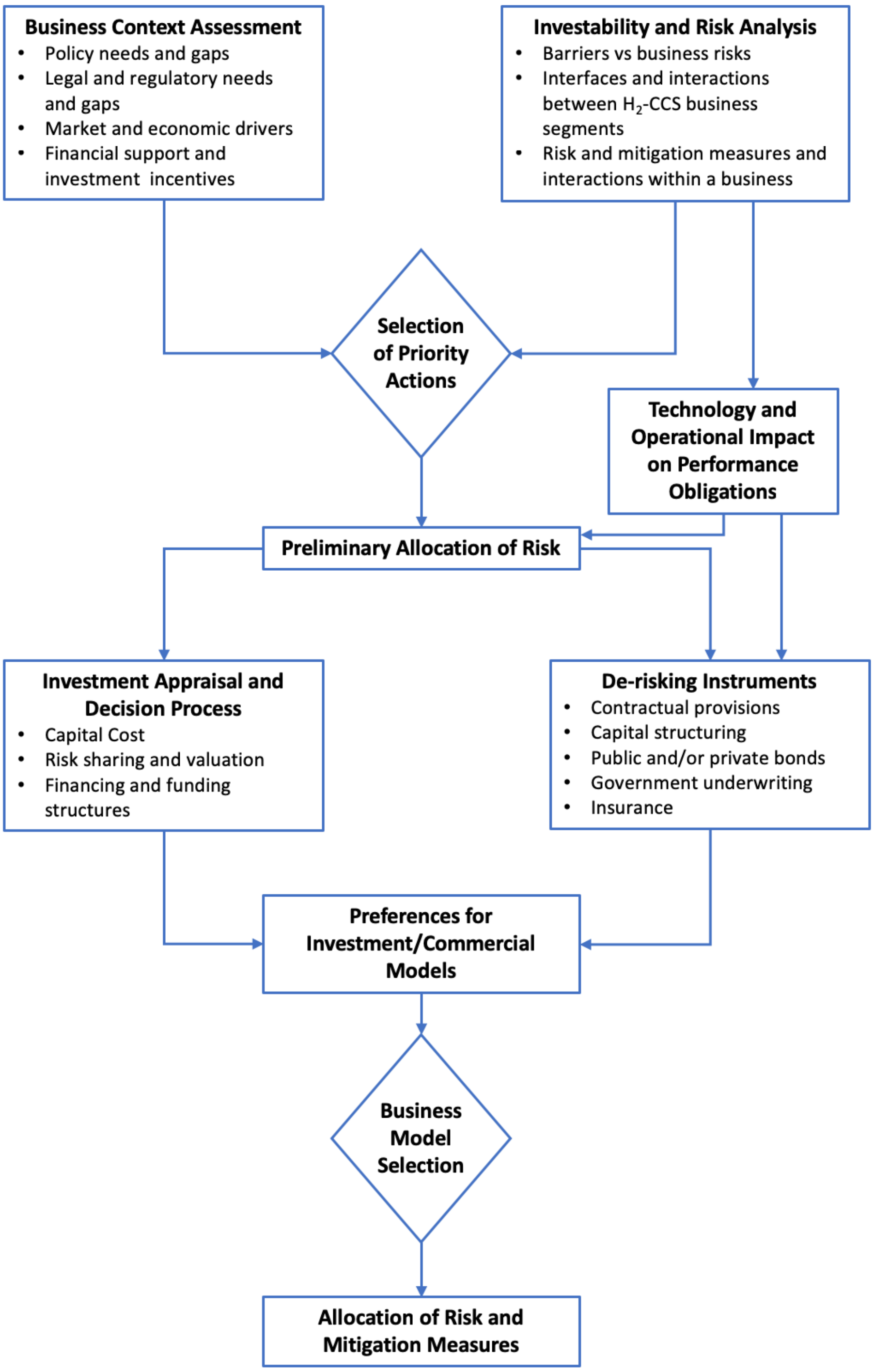

Figure 2-3 Business Model Selection Process

2.4 Business Model Selection and Business Case Development

The business case development and assessment processes are the subject of report D3.3.4 *Detailing the guidelines for the assessment and application of the business case templates in WP5*. The iterative interaction between selecting a preferred business model and developing its associated business case is shown below in Figure 2-4.

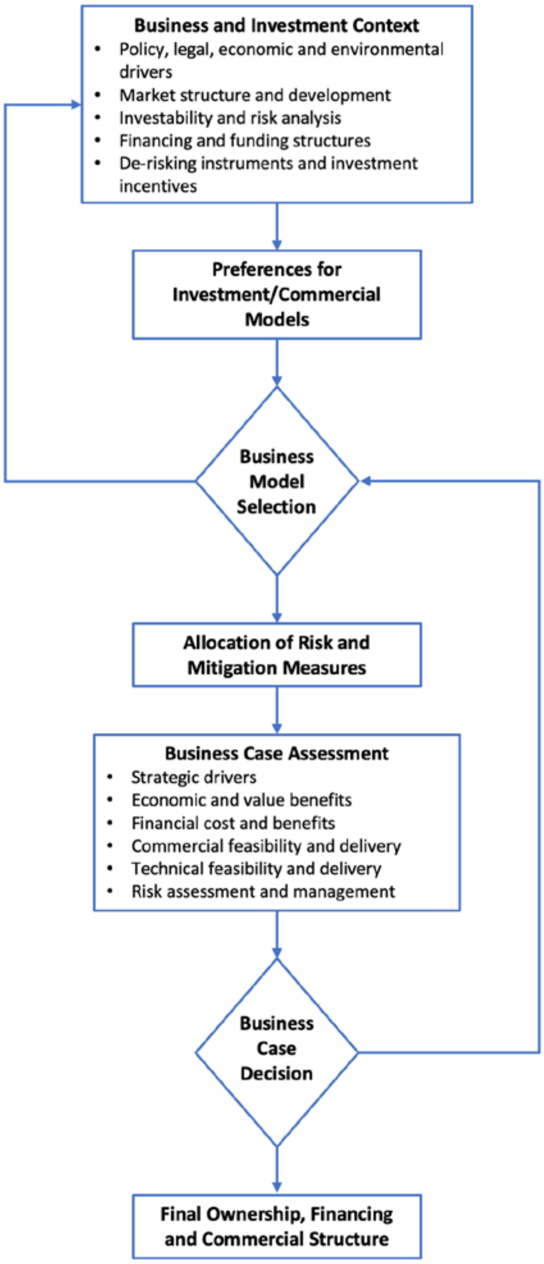

Figure 2-4 Business Case Development Process

2.5 Business Case Assessment

A flowchart of the ELEGANCY business case assessment process is provided in Figure 2-5 below and further guidance on the assessment for each of the business case dimensions can be found in report D3.3.4.

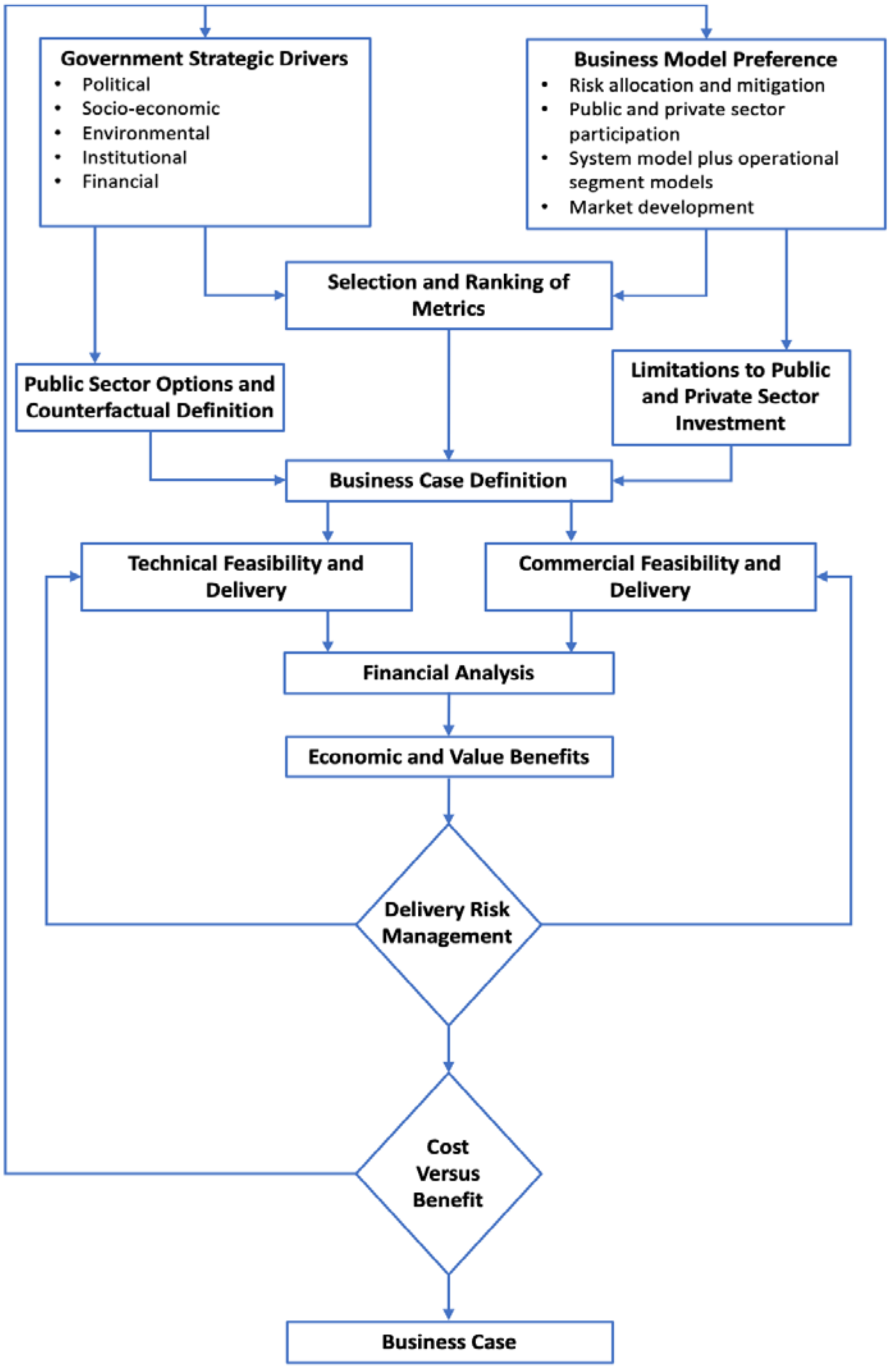

Figure 2-5 Business Case Assessment Process

2.5.1 Business Case Dimensions

A complete business case at either H_2-CCS chain system level or for an individual business segment within the chain is characterised in the ELEGANCY framework by the six dimensions illustrated in Figure 2-6 and described in detail in the report D3.3.4.

Figure 2-6 ELEGANCY Business Case Dimensions

2.5.2 Business Cases for ELEGANCY Case studies

The ELEGANCY case studies can be considered 'concept definition' studies in business parlance, and as such it is not possible to apply a full assessment to each one of the six business case dimensions of the methodology. The dependence of a business case on project maturity and business model selection has been discussed in detail in ELEGANCY report D3.3.4. and shown in both Figure 2-4 and Figure 2-5 above.

The subset of business case templates applied to the UK H21 North of England case study focus on a system level assessment including:

a. Business Case Definition;
b. Strategic Drivers and Rationale;
c. Technical Feasibility and Delivery;
d. Financial Costs and Benefits; and
e. Outcome Management, including risk and risk mitigation.

3 H21 NORTH OF ENGLAND BUSINESS CASE SCOPE

3.1 Overview

The aims of this case study are to:

1. Provide a conceptual business model, business case and infrastructure planning and development strategy to support the H21 North of England objective that enables:

   A commitment to phased investment in H_2-CCS infrastructure to cost effectively decarbonise residential heating in the north of England and to support UK energy system decarbonisation to meet a net zero emissions target by 2050.

   This includes providing conceptual solutions and potential government interventions to address the investment barriers and facilitate early market creation ahead of the development of profitable business models for clean and sustainable energy processes.
2. Provide a system perspective to facilitate the investment and optimisation of strategies for integrating H_2-CCS with a wider CCS system for the broader decarbonisation of the UK economy.
3. Demonstrate the practical application and use of the WP3 tools and methodology for future users in other regions/countries;

3.2 Business Sectors

The H_2-CCS business sectors included in this study are:

a. Centralised H_2 production (with CCS capture)
b. H_2 transport at transmission and distribution level
c. H_2 intra-seasonal and inter-seasonal storage
d. H_2 end use sectors:
   - Decentralised (domestic and non-domestic) heating (distribution level)
   - Centralised power generation
   - H_2 for industrial use

   The latter are considered in support of the business case for the H21 project and as part of the broader system decarbonisation.
e. CO_2 transport and storage

Hydrogen retail is not included in this case study as a separate business sector. The assumption is that free enterprise retail businesses for hydrogen supply will be the same or similar to those currently existing for natural gas and electricity. Commercial and industrial customers of hydrogen producers will be able to negotiate direct sales and purchase agreements as appropriate.

3.3 Geography and Scale

This study builds on the work completed by Leeds City Gate[7] and subsequently by the H21 North of England project team[8]. The overall scope of the H21 report is the conversion of the UK gas networks across the north of England within 7 years - between 2028 and 2034. This covers the Yorkshire and Humber region, Teesside and Manchester/Liverpool regions.

This ELEGANCY report focuses primarily on the early phases of market creation and H_2-CCS infrastructure deployment. Therefore, the timeline includes a Final Investment Decision (FID) in 2023 and a deployment and 'commissioning' phase commencing with first hydrogen production and CO_2 injection in 2026. This is consistent with the findings of the H21 North of England report that a Southern North Sea offshore CO_2 storage site could be ready for first injection in 2026.

The conclusions and recommendations presented in this report aim to remain agnostic in terms of the specific geography or cluster for each of the investments. The focus is on the collaborative strategic considerations for the public and private sector decision-making processes rather than articulating preferences for one region over another.

[7] Northern Gas Networks, 2016, op. cit.
[8] Northern Gas Networks, et. al., 2018, op. cit.

4 H21 BUSINESS AND INVESTMENT CONTEXT

4.1 UK Energy System

4.1.1 Strategic Rationale and Overcoming Investment Barriers

The UK Committee on Climate Change has advised the government[9] that Carbon Capture and Storage (CCS) is essential to achieve a net zero emissions objective by 2050. There are a number of technical challenges which are widely acknowledged but the real barriers to implementation of a first-of-a-kind (FOAK) infrastructure in the UK lie in the commercial, legal, financial and policy requirements. However, it should be understood that such barriers can be overcome by government intervention supported by society as a whole if there is a real coherent strategic rationale for the investment proposition.

A business and investment context assessment should clarify the overarching system objectives and priorities, beyond any regional, cluster or project objectives. It should test the various counter-scenarios (i.e other decarbonisation pathways), gather relevant information on the various economic sectors and regions to facilitate the development of a business case which fits synergistically within an energy system context.

4.1.2 System Decarbonisation

Fossil fuels are now widely recognised as an economically expensive commodity due to the cost of the externality arising from CO_2 emissions and environmental impacts created during their production, transportation and use. At the same time there is a huge reliance of modern society on fossil fuels, both economically and materially. The UK is fortunate to have a large number of options to decarbonise its economy, which is now heavily geared towards the provision of services (approx. 80% GDP in 2018) rather than manufacturing (approx. 14% GDP in 2018)[10]. The service sector is responsible for substantial distributed emissions, some of which can be abated at source by distributed technologies but many need to be ‘aggregated’ and abated using centralised technologies with ‘clean’ energy carriers such as renewable electricity or hydrogen gas. Small distributed CO_2 emissions sources (such as domestic and commercial heating[11], road and rail transport, shipping and air transport) are the most difficult of all to abate at a large aggregated scale.

Achieving the objective of an energy system and economy with net zero emissions will require a combination of all options currently available plus substitution over time with potential new technologies and solutions. The urgency of the physical implementation of an emissions reduction pathway to net zero in a period of 30 years means facilitating and encouraging reduced energy consumption, creating a circular economy, capturing emissions from existing industrial and power generation processes, introducing and developing new clean energy sources (renewable electricity, low carbon hydrogen, heat

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[9] Committee on Climate Change, 2019, *Net Zero: The UK's contribution to stopping global warming*, https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf, accessed 18th March 2020
[10] House of Commons Library, 2020, *Economic Indicators No. 02787*, 11th March, https://commonslibrary.parliament.uk/research-briefings/sn02787/ , accessed 25th March 2020
[11] Imperial College, 2018, *Analysis of Alternative UK Heat Decarbonisation Pathways*, Report for the Committee on Climate Change, https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf , accessed 31st March 2020

pumps etc.), new feedstocks to replace fossil fuels (such as for synthetic fibres and plastics), and negative emissions technologies (direct air capture with CCS known as DACCS, and bio energy with CCS known as BECCS). The latter will be required because it is impossible to eliminate all emissions in a cost-effective way (residual emissions).

Continued use of low carbon (net emissions free) gas (biogas, biomethane, hydrogen from electrolysis and reformed methane) as an energy carrier will require substantial effort and time to transform the gas system at scale including new and modified regulations, market functioning, infrastructure, and long term planning in both the public and private sectors[12].

In the UK, our context assessment suggests that the societal objective (which may at times clash with the contemporary political objective) is to transition away from fossil fuels and as such, the business case should build on the likely role of natural gas[13] in this transitioning energy system to net zero emissions by 2050.

4.1.3 Valuing Societal Benefits Not Only Evaluating Costs

To date there has been a strong focus in UK government policies on cost reduction for CCS technologies, project and infrastructure investment. Further, energy system transformation pathways tend to be assessed from a traditional least cost perspective using sectoral levelised cost of energy metrics. However, in the context of achieving net zero emissions, the key metrics need to be broadened to include the greater value for society delivered by undertaking the investment. The system outcomes are not only about economic growth or value for money, but rather sustainable growth and a circular economy with minimal dependence on fossil fuels. Evaluation of policy, investment, and financing decisions therefore requires taking into account:

a. The cost of pollution on health, environmental degradation and long-term societal impact;
b. The economic multiplier effects of different activities;
c. The value of creating flexibility and optionality for future technology deployments;
d. The facilitation of synergies between different energy consuming activities and economic sectors; and
e. Management of the decline in fossil fuel industry in UK at the same time as creating new opportunities for technology development and an alternative energy system.

4.1.4 First of a Kind Investment - Three Key Principles: ‘anchor’ users, low regrets and optionality

It is clearly not possible to predict the future and experts disagree on the best decarbonisation technologies and fuels, and about their future contributions. All do agree

[12] Stern, J., 2019, *Narratives for Natural Gas in Decarbonising European Energy Markets*, The Oxford Institute for Energy Studies, Paper NG 141, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/02/Narratives-for-Natural-Gas-in-a-Decarbonisinf-European-Energy-Market-NG141.pdf?v=79cba1185463, accessed 31st March 2020

[13] Stern, J., 2017, *The Future of Gas in Decarbonising European Energy Markets: the need for a new approach*, The Oxford Institute for Energy Studies, Paper NG 116, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2017/01/The-Future-of-Gas-in-Decarbonising-European-Energy-Markets-the-need-for-a-new-approach-NG-116.pdf, accessed 31st March 2020

that there is a need to take action on energy system change without delay. Clearly there is not one definitive solution and one technology that holds all the answers. The focus for UK policy should be, and is, on the development of a portfolio of flexible technology and infrastructure options. However, UK policy has not fully dealt with the actions and drivers that would make this portfolio synergistic and low regrets so that a flexible decarbonisation pathway with emergent options can develop over time and adapt to technology performance and cost improvements, societal preferences and consumer demand. A business case for Hydrogen-CCS must therefore be developed in the context of being a low regrets decarbonisation option facilitating synergies with other decarbonisation pathways and technologies.

This H21 North of England case study is about a first of kind H_2-CCS infrastructure investment which will support further decarbonisation over the long term. The concept of sustained ‘anchor’ demand is an essential requirement to justify the first investment with minimum regrets and maximum optionality. The choice of the ‘right’ strategic early infrastructure users will allow selection of a business model and creation of a business case which can be supported by local communities, society and private investors. Key factors will be:

a. minimise complexity of implementation (number of users, regulatory changes, technical risks, skills development and training, etc.);
b. select market(s) where investment costs can be socialised;
c. select support mechanisms or levies that do not penalise intermediate or final use and disadvantage low carbon products; and
d. minimise risk of stranded asset from volume uncertainty.

The lessons learnt from the UK CCS competitions and commercialisation programmes for the delivery of transport and storage infrastructure (see Section 4.3.3 below) also show that this is necessary to create optionality for industrial decarbonisation as an evolving add-on market in the future.

4.1.5 Market Development

Pro-active market development is critical to create demand for new low carbon products and energy sources, and to transition from an early phase of government supported infrastructure development to a sustainable market-driven (even with some limited government intervention) expansion. Key concepts in market development are the notion of captive and competitive markets, and mechanisms to bring costs to a competitive level to facilitate long term sustainable development by market pull.

In the UK, the domestic and commercial heating and electricity markets are captive markets. Such markets can allow for an easier implementation and transition of a product or energy change. However, understanding the overall costs of the change and how to socialise those initial costs is essential for business case development. The UK has a proven track record and experience in facilitating market transformations. A high penetration of cost effective low-cost renewable electricity has been realised over the last decade through the captive electricity market and supported by a number of transitionary funding mechanisms, socialised across all the users. The UK also carried out a full system change of domestic heating from town gas to natural gas in the 1970’s.

On the other hand, most industrial companies in the UK operate in competitive international markets and need to assess not only the cost but the financial benefits (product premium, reputation, attractiveness to investors) and short term and long term risks to their operations (such as reduced volume from change in consumer demand or competition from new products, policy changes, operational disruption, negative public opinion, etc.). At the moment, there is insufficient premium (if any) for low carbon 'green' products in the UK and across Europe so UK-based companies cannot justify the additional investment costs and risks for carbon capture without government support and guarantees. Nevertheless, opportunities do exist for fuel switching to hydrogen or electricity, but these are dependent on supply of low carbon hydrogen/electricity at a competitive price[14].

4.1.6 Collaboration versus Competition

A key theme which should be assessed and considered when developing the business case for investing in FOAK infrastructure and initial markets is the choice of collaboration versus competition between projects, regions or clusters. The capability to deliver, and the likelihood of success, will require a strategic rationale and public sector involvement coherent with the overall energy system decarbonisation objective.

Feedback from the ELEGANCY stakeholder meetings, workshops (Appendix I.A.1.a)(1)A) and published materials highlight that:

a. Each private sector party is generally only interested in their core business and expect other parties to deliver the other segments of the infrastructure;
b. There is little or no value in a single company being fully integrated along the industrial CCS value chain at this FOAK stage, and few companies have the financial capability and the business rationale to do so;
c. Large scale H_2-CCS infrastructure development will require multiple regional entities to be involved to create a low regrets solution for both industrial decarbonisation and domestic heating; and
d. There is a need for inter-regional leadership, governance, cooperation and cross-sectoral integration in order to develop a complete energy system decarbonisation framework.

At the time of writing a healthy amount of collaboration is occurring between private sector companies and with the UK government (providing grant funding) for a number of innovation, feasibility and concept definition projects (See Appendix B). While this is a positive step, questions remain as to how the UK government will select and support viable FOAK infrastructure, including where it will be located, and whether the primary policy principle will be collaboration or competition. Government policy is reviewed in Section 4.5 below.

[14] Element Energy Limited, 2018, *Industrial Fuel Switching Market Engagement Study*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/824592/industrial-fuel-switching.pdf , accessed 31st March 2020

A study performed by Summit Power in 2017[15] also demonstrated the positive impact on the UK economy of a systems approach to CCS infrastructure on the east coast of the UK. In addition, the national gas transmission system operator, National Grid, is working both in collaboration with others and separately in its HyNTS programme on projects to understand and prepare for network conversion to hydrogen as well as its end use in established markets[16,17].

4.2 North of England Energy Sub-system

The H21 North of England case study focuses on the H_2-CCS chain based on the decarbonisation of distributed residential and commercial emissions sources in cities across the north of England but is not limited to that scope. It takes into full consideration why and how such a project can be structured to support the UK system decarbonisation and facilitate such a transition away from fossil fuels.

4.2.1 Active CCS Projects

The Net Zero Teesside project[18] is an active CCUS project to kick start the use of the technology at scale by developing a CO_2 T&S infrastructure anchored on a new-build large natural gas fired power station with CCS. The premise is that this will support the future decarbonisation of the industrial cluster. The project is sponsored by OGCI Climate Investments and is being developed on its behalf by five members (BP, ENI, Equinor, Shell and Total) in partnership with local industry.

There is an active project sponsored by the Zero Carbon Partnership[19] (National Grid Ventures, Drax and Equinor) which is proposing to integrate BECCS at scale at the Drax power station with hydrogen production, decarbonisation of the cluster and CO_2 T&S into the Southern North Sea.

4.2.2 Industrial Clusters

The H21 North of England conversion roadmap comprises three primary industrial emissions clusters, each of which has progressed (and continues to undertake) studies of its own over the last 12 years to understand its decarbonisation needs and options, and what role there may be for CCS infrastructure. These clusters are shown in Figure 4-1 and

[15] Caledonia Clean Energy Project and Summit Power, 2017, *Clean Air – Clean Industry – Clean Growth, How carbon capture will boost the UK Economy, East Coast UK Carbon Capture and Storage Investment Study*, http://www.ccsassociation.org/news-and-events/reports-and-publications/clean-air-clean-industry-clean-growth/, accessed 26th March 2020

[16] National Grid, 2019, *Network Innovation Allowance Annual Summary 2018/2019*, https://www.nationalgridgas.com/document/127991/download, accessed 31st March 2020

[17] National Grid, 2020, *High Hopes for Hydrogen*, https://www.nationalgrid.com/high-hopes-hydrogen, accessed 31st March 2020

[18] Net Zero Teesside website, https://www.netzeroteesside.co.uk

[19] Zero Carbon Humber website, https://www.zerocarbonhumber.co.uk

are: Teesside[20,21,22,23], Humberside[24,25,26] , Merseyside[27,28]. H21 includes an additional connection with the Grangemouth cluster in south east Scotland.

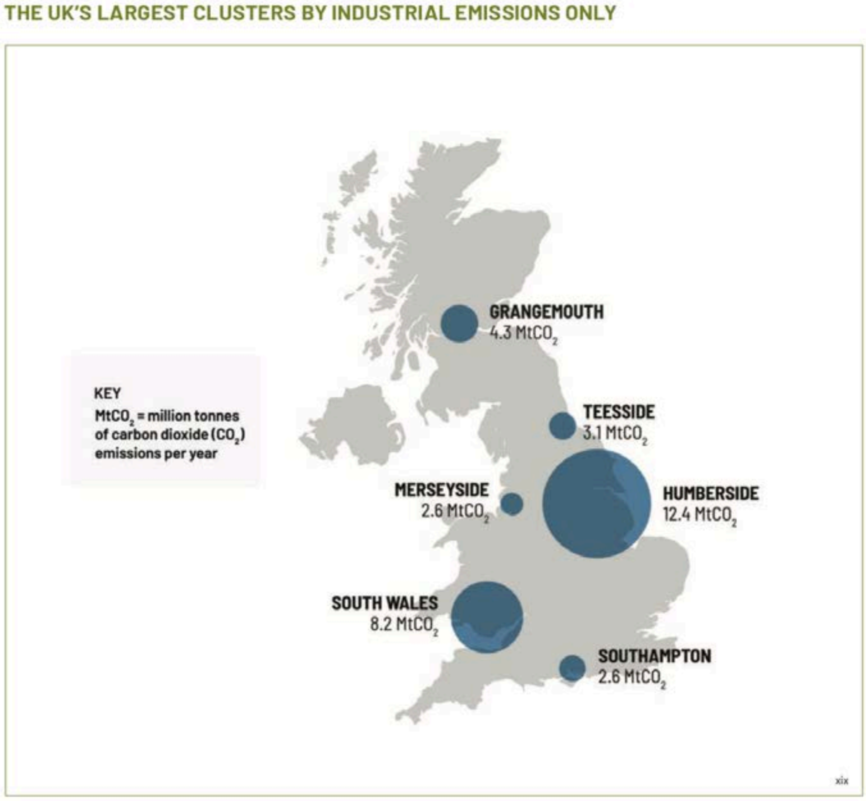

Figure 4-1 UK Industrial Emissions Clusters[29]

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[20] Teesside Collective website, http://www.teessidecollective.co.uk

[21] Cambridge Econometrics, 2015, *The Economic Impact of developing a CCS Network in the Tees Valley, A report for Tees Valley Unlimited*, http://www.teessidecollective.co.uk/wp-content/uploads/2015/06/Teesside-Collective-Economic-Impact-Report.pdf, accessed 26th March 2020

[22] Pale Blue Dot, 2015, *Industrial CCS on Teesside – The Business Case*, http://www.teessidecollective.co.uk/wp-content/uploads/2015/06/Teesside-Collective-Business-Case1.pdf, accessed 26th March 2020

[23] Pöyry and Teesside Collective, 2017, *A Business Case for a UK Industrial CCS Support Mechanism*, http://www.teessidecollective.co.uk/wp-content/uploads/2017/02/0046_TVCA_ICCSBusinessModels_FinalReport_v200.pdf, accessed 26th March 2020

[24] Zero Carbon Humber website, op. cit.

[25] Yorkshire Forward, 2008, *A Carbon Capture and Storage Network for Yorkshire and Humber*, http://i.thisis.co.uk/274676/binaries/carboncapturebros8_4_14410.pdf, accessed 26th March 2020

[26] Yorkshire Forward, 2010, *Carbon emission in the Yorkshire and Humber region*, Written evidence to the House of Commons Yorkshire and the Humber Regional Committee, https://publications.parliament.uk/pa/cm200910/cmselect/cmyork/438/43812.htm , accessed 26th March 2020

[27] HyNet website, https://hynet.co.uk

[28] Progressive Energy Ltd, 2017, *The Liverpool-Manchester Hydrogen Cluster: A Low Cost Deliverable Project*, Technical Report for Cadent, https://hynet.co.uk/app/uploads/2018/05/Liverpool-Manchester-Hydrogen-Cluster-Technical-Report-Cadent.pdf, accessed 23rd March 2020

[29] Drax, Equinor and National Grid Ventures, 2019, based on *Capture for Growth*, http://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/803086/industrial-clusters-mission-infographic-2019.pdf, accessed 31st March 2020

The Humberside industrial cluster is the largest emissions cluster in the UK. Its activities include: gas processing (Perenco, Centrica, Gassco), refineries (Lindsey and Phillips66 refineries which provide 27% of UK's oil refinery production), chemical plants (Saltend, Novartis, Tronox), many manufacturing plants (glass, cement, industrial gases, gypsum) and a number of large gas fired power stations (see Section 4.2.4). The Humber region has access to the Aldbrough gas storage facility. 1/5 of the UK's gas imports and 1/3 of UK's coal and sustainable biomass come through the Humber to be converted into energy.[30]

The Teesside industrial cluster is the largest chemical complex in the UK with more than 1,400 companies directly involved in the chemicals and process industry. All types of chemicals are produced including those from petroleum processing, petrochemical manufacture, specialty chemicals, and pharmaceutical intermediate and active chemicals. Some of the major international companies located in the Tees Valley are Huntsman, Ineos, Sabic, CF Fertilisers and Sembcorp. Of particular note is the Linde BOC hydrogen production facility using steam methane reforming.

4.2.3 Natural Gas

The UK benefits from a strong historical domestic oil and gas industry albeit with declining reserves, an extensive natural gas infrastructure transmission and distribution system and a competitive supply market with large import capabilities by pipeline and by ship in the form of LNG. Oil and gas production companies are actively involved in a number of projects across the UK to promote the use of CCUS as a necessary technology to decarbonise the economy.

As can be seen from the gas and electricity transmission network map in Figure 4-2, the north of England benefits from substantial infrastructure connections for gas. The Easington gas terminal located in Humberside is one of the 6 main gas terminals in the UK and is connected to the Southern North Sea gas fields and to Norway via the Langeled pipeline. Teesside benefits from a gas reception and processing facility from the Central North Sea, and Manchester/Liverpool has access to the gas fields in the East Irish Sea.

All sectors of the gas market are privately owned and managed. Gas transmission and distribution companies operate in a deregulated market under an established regulated asset base model. Network companies (Northern Gas Networks, Cadent, SGN, National Grid) are actively working on a number of government funded projects to convert their networks to hydrogen and protect their business interests at risk from electrification of their markets.

[30] InvestHumber website, https://investhumber.com/growth-sectors/energy-renewables/oil-gas

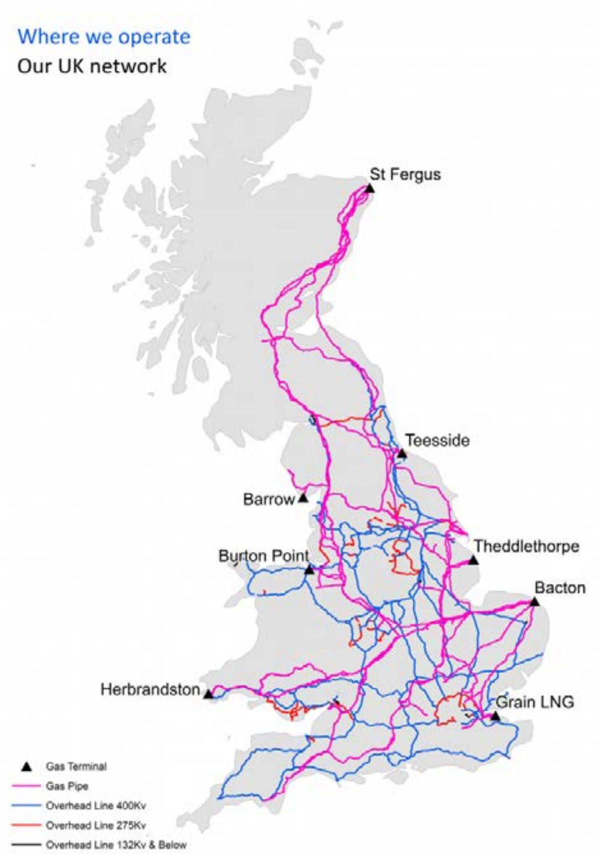

Figure 4-2 Map of UK National gas and transmission network[31]

4.2.4 Electricity Generation

The total installed capacity of major UK power stations was 84.8GW at the end of May 2019[32]. The UK has an excellent resource potential for renewable electricity from its wind resource (and solar to a lesser extent) and has successfully implemented policies to build a substantial renewable electricity capacity. The share of total electricity generation from renewables was 38.9% in Q3 2019 and marginally exceeded the share of generation from gas for the first time. The share of gas was 38.8% and the share of fossil fuel was 40.1%, a record low. Renewable electricity capacity was 46.9GW[33].

There is an extensive number of power generation installations operating in the North of England, primarily in the Humber region and in the Manchester/Liverpool region (see Figure 4-3). The Humber region is home to 1/6 of the UK power generating capacity. The Yorkshire and Humber region is also a major entry point for offshore wind electricity and a major hub of regional activity with 900MW in operation, over 4GW consented or under construction (see Figure 4-4).

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[31] National Grid website, 2020, https://www.nationalgridgas.com/land-and-assets/network-route-maps, accessed 31st March 2020

[32] Department for Business Energy and Industrial Strategy (BEIS), 2019, *Digest of UK Energy Statistics (DUKES): Electricity (Chapter 5)*, https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2019, accessed 31st March 2020

[33] National Grid website, 2020, op. cit.

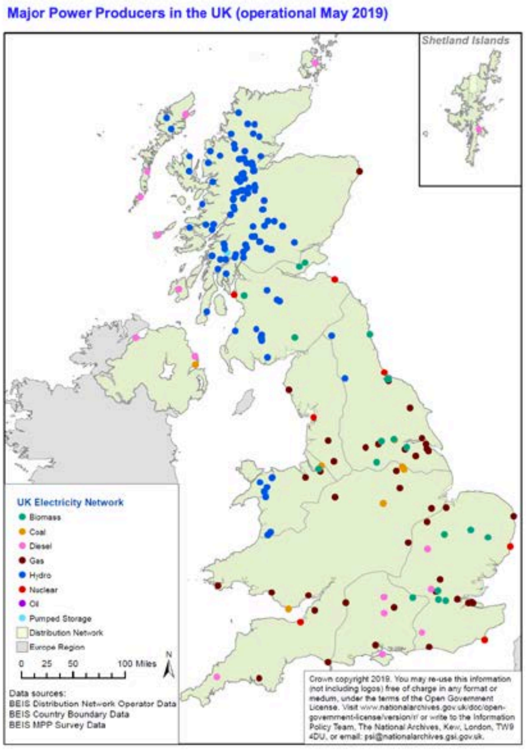
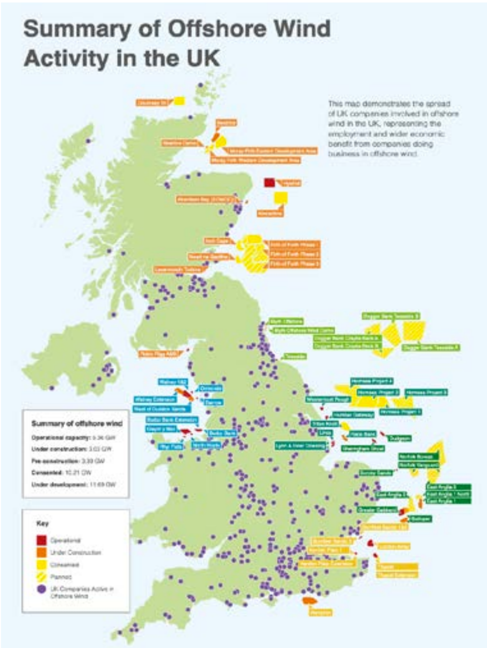


Figure 4-3 Map of Major power producers in the UK[34]



Wind farms		Owner/Operator	Capacity (MW)
Operational	Humber Gateway	E.ON	219
	Lincs	Centrica, Ørsted, Siemens Project Ventures	270
	Lynn & Inner Dowsing	Centrica	194
	Westermost Rough	Ørsted, Marubeni, Green Investment Group	210
Under construction	Race Bank	Ørsted	580
Consented	Triton Knoll	Innogy Renewables UK Ltd	860
	Hornsea Project One	Ørsted	1218
	Hornsea Project Two	Ørsted	1386
Planned	Hornsea Project Three	Ørsted	2400
	Hornsea Project Four	Ørsted	1200

Wind farms		Owner/Operator	Capacity (MW)
Operational	Barrow	Ørsted	90
	Burbo Bank	Ørsted	90
	Gwynt y Mor	Innogy Renewables UK Ltd, Green Investment Group, Stadwerke Munchen GmBH, Siemens AG	576
	North Hoyle	Innogy Renewables UK Ltd	60
	Ormonde	Vattenfall, AMF	150
	Rhyl Flats	Innogy Renewables UK Ltd	90
	Walney	Ørsted, SSE, Green Investment Group, Marubeni	367
	West of Duddon Sands	Ørsted, ScottishPower Renewables	389
	Burbo Bank Extension	Ørsted	258
Under construction	Walney Extension	Ørsted	660

Figure 4-4 Offshore Wind Activity UK and offshore wind projects in Yorkshire and Humber (top) and North West and Wales (bottom) [35]

[34] Department for Business Energy and Industrial Strategy (BEIS), 2019, op. cit.

[35] RenewableUK, 2017, *Offshore Wind Regenerating Regions - Investment and Innovation in the UK*, https://cdn.ymaws.com/www.renewableuk.com/resource/resmgr/publications/reports/OWW17_Regenerating_Regions.pdf, accessed 31st March 2020

4.3 H_2-CCS Business Sectors and Potential Markets

4.3.1 Hydrogen Sectors

Hydrogen has enjoyed a resurgence in interest and momentum in the past few years as a carbon free energy carrier with the potential to decarbonise multiple sectors, especially industrial and distributed emissions. According to the Committee on Climate Change[36], "*hydrogen is a credible option to help decarbonise the UK energy system, but its role depends on early Government commitment and improved support to develop the UK's industrial capability.*"

Some of the main advantages of hydrogen use for system decarbonisation are:

a. Hydrogen can be used with existing technology (burners, fuel cells) to decarbonise many business sectors either through blending with natural gas or as a direct fossil fuel replacement. There are, however, varying levels of complexity in transitioning from natural gas to hydrogen for the different sectors to be taken into consideration;
b. Hydrogen can be produced at scale centrally using proven technology from natural gas, and transitional pathway options to clean hydrogen (from electrolysis) exist;
c. Natural gas is already a major energy source for heating and power generation and the UK benefits from the availability of an expansive gas network connected to local sources of natural gas and import locations across the country;
d. The UK benefits from substantial geological potential for large-scale hydrogen storage capacity; and
e. Hydrogen offers opportunities for technology development, building on existing expertise in industrial clusters.

4.3.1.1 Hydrogen for heat

As hydrogen can be combusted in hydrogen burners or be used in fuel cells, it offers a zero or low-emissions alternative for both domestic and commercial heating and for many industrial facilities.

In the UK, domestic and commercial fuel combustion (primarily heating) accounted for approximately 33% of total CO_2 emissions in 2018[37]. Hence meeting a net zero emissions target means that natural gas, which is used for heating in over 85% of homes, will have to be replaced with either a decarbonised gas, or an electric-heating option with minimum disruption such as heat pumps[38]. There are 21 million homes with central heating and hot water from natural gas-fired boilers and a further 2 million commercial boilers[39]. The

[36] Committee on Climate Change, 2018, *Hydrogen in a low carbon economy*, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/, accessed 31st March 2020

[37] UK Government, 2020, *Final UK greenhouse gas emissions national statistics*, https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2018, accessed 31st March 2020

[38] Energy Research Partnership, 2016, *Potential Role of Hydrogen in the UK Energy System*, https://erpuk.org/wp-content/uploads/2017/01/ERP-hydrogen-report-oct-2016.pdf, accessed 31st March 2020

[39] Dodds, P. E. and Hawkes, A. (Eds.), 2014, *The role of hydrogen and fuel cells in providing affordable, secure low-carbon heat.* H2FC SUPERGEN, http://www.h2fcsupergen.com/wp-content/uploads/2014/05/H2FC-SUPERGEN-White-Paper-on-Heat-May-2014.pdf, accessed 31st March 2020

demand for heating is characterised by considerable intra-day and inter-seasonal variation requiring an energy supply with substantial flexibility. The UK benefits from a number of specific advantages for a gas network conversion which makes hydrogen an attractive practical proposition to facilitate decarbonisation, either by blending with (up to 20%), or 100% replacement of, natural gas:

a. A substantial part of the gas network has been replaced with modern polyethylene pipes, which can operate safely with high blends of hydrogen and therefore significantly reduce the cost of any infrastructure upgrades.
b. The UK can also make use of existing proven geological underground natural gas storage structures (salt caverns, aquifers, depleted gas fields) at the multi-terawatt hour (TWh) scale.
c. The UK has the prior experience of a large-scale network conversion when town gas was replaced by natural gas during the 1960s-1980s following the discovery of North Sea gas.

There is also substantial potential for use of hydrogen combustion in heat applications for industrial decarbonisation either directly in hydrogen burners or to provide heat and power in fuel cells. Today, hydrogen is already used for some low temperature direct and indirect heating applications such as process heating and drying especially when it is produced as a by-product of a local chemical process. For high temperature process and heat applications, i.e 240^oC – 2000^oC, hydrogen can provide a cost-effective solution with technology availability likely before 2030[40]. Hydrogen burners require only minimum capital investment as existing equipment can be adjusted to the new fuel. On the other hand, fuel cells benefit from higher efficiency but require sizeable investment.

4.3.1.2 Hydrogen for transport

Hydrogen can be used in a range of transport applications in fuel cells. Hydrogen fuel cells for road transport, primarily passenger cars, industrial trucks and buses are at the most advanced stage whilst other applications (marine, rail, aviation applications) are only either at an early development or demonstration stage. Hydrogen fuel cell electric vehicles (HFECV) have similar refuelling characteristics and distance ranges to conventional vehicles, therefore offering a consumer-friendly alternative to Battery Electric Vehicles (BEV). In the UK, major economic benefits could also be derived from local vehicle technology development and manufacturing given the contribution of the car industry to the UK manufacturing sector.

However, to achieve market uptake and affordability it is estimated that production of hundreds of thousands of passenger cars is required per year plus cost-effective production and distribution of hydrogen. The scale of investment required for large-scale HFCEV production and the roll out of a hydrogen delivery/refuelling infrastructure are currently considered to be the two main barriers to the introduction of hydrogen in transport, rather than technology development. This is especially so in the face of supportive government policy towards electric vehicles and re-charging networks as well as the increasing

[40] Element Energy Limited, 2018, op. cit.

numbers and gradual price reduction of BEVs. Furthermore, there is currently uncertainty in the consumer response to, and uptake of, HFCEVs.

The UK has two of the largest refuelling stations (by volume) in Europe serving the bus fleets in London and Aberdeen, with further plans to expand the current number of locations. There are also currently a number of UK and European targeted programmes (UK H_2Mobility, Hydrogen for Transport Programme (HTP), the JIVE and MEHRLIN European Collaborative projects, HyFive) to support introduction of hydrogen-fuelled vehicles and the early growth of refuelling infrastructure alongside the deployment of new vehicles. If demand growth above 10,000s vehicles beyond 2020-2025, the large-scale deployment of hydrogen for transport would be facilitated by the availability of cost competitive hydrogen through centralised hydrogen production and infrastructure.

4.3.1.3 Hydrogen for power generation

Hydrogen can be used in turbines (similar to natural gas) for electricity generation[41]. If low carbon hydrogen can be made available in the medium term it can offer a means to transition away from natural gas in gas-fired power stations without the need to deploy CCS on each individual power station. This offers an alternative pathway to provide demand management capability until battery or other electrical storage can be coupled with renewable energy, or until the low carbon hydrogen can be replaced with hydrogen produced competitively from hydrolysis.

4.3.2 Industrial Decarbonisation

Industrial decarbonisation is a very difficult part of energy and climate policy, and cross-sectoral synergies need to be taken into account when selecting solutions. The delays and slow progress resulting from the risks and complexity of carbon capture in industrial facilities and clusters may be best mitigated with options that facilitate partial decarbonisation at reduced cost. Some key lessons from published reports and ELEGANCY and ALIGN stakeholder interviews[42] applicable to the UK H21 case study are:

a. Many challenges exist to decarbonise industrial processes through carbon capture:
   - Carbon capture is a large additional financial cost (transport and storage are a minor cost component) and there is currently no market ‘premium’ on low carbon products to drive any change. The establishment of any premium is outside the control of the industrial companies. For commodity traded businesses, global trade agreements are not foreseen in the short term.
   - Carbon capture presents additional risks which must be addressed and justified for shareholders: operational risks (impact of downtime by integrating a new complex process across a site), T&S penalty risks (CO_2 volume risk due to exposure to market), and government penalty risk (e.g. subsidy repayment if plant closes for economic reasons).
   - Carbon capture is technically and commercially complex: it is application-specific with minimum scope of optimisation between industries.

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[41] See for example the Nuon Magnum project in Netherlands, https://www.nsenergybusiness.com/projects/nuon-magnum-power-plant/, accessed 31st March 2020
[42] See Appendix A

- It is not possible to develop a one-for-all business model to achieve economies of scale for technology, operational and market reasons. Each industrial sector faces different market risks and has different capture technology requirements which impact on the scalability of any carbon capture solutions.
- The risk of locking-in expensive carbon capture technology should be assessed given the availability of other decarbonisation options (see below).
- It is difficult for governments to justify the socialisation of any subsidy costs offered to privately owned profitable polluting companies.

b. Decarbonisation opportunities through fuel switching:
  - Access to hydrogen at reasonable cost would facilitate significant fuel switching opportunities[43]. This solution can be easily replicated and scaled up with minimum cost and risk for industrials.
  - Fuel switching applications in regions where emissions are smaller and/or distributed (carbon capture or gathering complexity) and electricity use cannot be cost competitive (e.g. the Rotterdam project is assessing the replacement of natural gas/process gas by hydrogen for the production of high temperature heat in refineries).

c. Other industrial decarbonisation or emissions abatement options to consider:
  - Circular economy: policies to encourage recycling and reuse of products.
  - Feedstock changes: emissions reduction through use of new feedstocks and new processes.
  - Shut down industrial production and import products.

[43] Element Energy Limited, 2018, op. cit.

4.3.3 CO_2 Transport and Storage

As a result of the UK governments' 2007-2015 CCS competitions and commercialisation programme a wealth of experience has been built up on market failures, investment barriers, risk and liability, and business models for handling the disposal of captured CO_2 using transport and geological storage infrastructure[44,45,46,47,48,49,50,51]. Ultimately a sustainable market for CO_2 transport and storage services will only emerge once end-use markets for low carbon products, including hydrogen, relying on capture technologies have been created and have become self-sustaining themselves. While consensus has generally been reached that FOAK transport and storage infrastructure should be combined in one business segment, this does not have to be the case in a mature market for CO_2 disposal services.

The early phases of the H21 roadmap will need to be supported by FOAK CO_2 transport and storage infrastructure built ahead of full market demand. Selecting optimal initial capacity and locations will be an important part of the investment decision making and business case. Hence the application of the anchor, low regrets and optionality principles described in Section 4.1.4 will be key to risk mitigation. Building the CO_2 T&S business segment as part of H21 will require addressing:

a. Economies of scale:
   - Cost reduction can be achieved through initial investment at scale in transport and storage with options to expand from initial infrastructure by connecting additional pipelines/reservoirs. The additional costs for oversizing initial transport infrastructure are not large overall.
   - Shipping can provide flexibility for hubs with lower CO_2 volumes and higher uncertainty with regard to volume commitment.

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[44] CCS Cost Reduction Taskforce, 2013, *The Potential for Reducing the Costs of CCS in the UK*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/201021/CCS_Cost_Reduction_Taskforce_-_Final_Report_-_May_2013.pdf, accessed 31st March 2020
[45] Pöyry and The Crown Estate, 2013, *Options to Incentivise UK CO_2 Transport and Storage*, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.694.547&rep=rep1&type=pdf, accessed 31st March 2020
[46] Goldthorpe, W., Ahmad, S., Eldering, L., Sannes, O., Baker, A., Grosvenor, D., .Dean, T., 2016, *A need unsatisfied - Blueprint for enabling investment in CO_2 storage.* London, UK: Deloitte/The Crown Estate.
[47] Carbon Capture and Storage Association, 2016, *Lessons learned - Lessons and evidence derived from UK CCS programmes, 2008-2015*, http://www.ccsassociation.org/press-centre/reports-and-publications/, accessed 31st March 2020
[48] Advisory Group, Committee on Climate Change, 2016, *CCS in the UK: A new strategy*, https://www.theccc.org.uk/wp-content/uploads/2016/07/CCS_Advisory_Group_-_CCS_in_the_UK.pdf, accessed 31st March 2020
[49] Goldthorpe, W., Ahmad, S., 2017, *Policy Innovation for Offshore CO_2 Transport and Storage Deployment*, Energy Procedia, Volume 114, July 2017, Pages 7540-7549, https://doi.org/10.1016/j.egypro.2017.03.1886
[50] Pale Blu Dot, Arup, Pinsent Masons, 2018, *CO_2 Transportation and Storage Business Models Summary Report*, 10251BEIS-Rep-01-04, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/677721/10251BEIS_CO2_TS_Business_Models_FINAL.pdf, accessed 31st March 2020
[51] CCUS Advisory Group, 2019, *Investment Frameworks for Development of CCUS in the UK*, http://www.ccsassociation.org/files/4615/6386/6542/CCUS_Advisory_Group_Final_Report_22_July_2019.pdf, accessed 31st March 2020

b. Anchor use:
   - T&S operators need 'anchor' users with minimum risk with regard to volume commitments (unless protected by government) to secure the initial infrastructure investment. The selection of the early users and location of the infrastructure needs to consider the phasing of future additional users.
   - The lowest volume risk would be from hydrogen production plant(s) where the hydrogen is used for city conversion. This can be a large and long-term captive market and guaranteed demand. Hydrogen for electricity generation or natural gas power plants with carbon capture would provide a good alternative option as they can achieve sizeable scale in the captive electricity market using existing revenue support mechanisms to secure minimum volumes.
   - Industrial users are a less attractive anchor proposition because the T&S operator would need multiple industrial companies to secure sufficient volume, with risk of CO_2 supply volume variability due to market dynamics of the industrial customer. Any agreement would require flexibility. There is a high risk of 'regret' by basing FOAK infrastructure development on industrial users.

c. Cost proportionality:
   - T&S cost is generally a small component of the total CCS chain. For industrial users and hydrogen producers, it represents only about 10% of the overall cost of capturing and disposing of CO_2.

d. Minimising Complexity:
   - Reuse of infrastructure has the potential to be more complex than a greenfield investment due to regulatory and availability constraints.
   - Selection of initial storage sites that can easily be developed in phases and with nearby options for expansion or backup will help mitigate performance risks in early H21 phases.

4.4 Market failures

ELEGANCY WP3 has defined a number of generic market failures for testing the achievability of case study objectives against the barriers and inertia to infrastructure investments and market development. The subset of these market failures that were found to be of importance to the UK H21 case study are listed below with their definitions:

1. ***Missing Market:*** No demand/market exists for the goods or services, thus creating a lack of price signals and preventing investment or even business interest in the activity.
2. ***Coordination Failure:*** Investment and business activities are dependent on synchronised or coordinated planning, design, financial investment decisions and construction in other related activities in order to mitigate counterparty or stranded asset risk. No coordination results in no market activity.
3. ***Low-Priced CO_2 Emissions:*** Insufficient carbon price signal exists to effectively value the environmental impact of emissions and as a consequence impacts negatively investment interest in low carbon technologies or market-making activities.
4. ***Positive Externality Environmental and Social Value of Hydrogen Utilisation:*** The positive environmental and social value of the activity is not taken into account in individual consumer decisions, nor priced into alternative goods and services

based on traditional technologies. For example, hydrogen fuel cell electric vehicles (HFCEVs) improve city air quality but the social cost of pollution is not included in the price of conventional vehicles.

5. ***Natural Monopolies:*** The business activity is naturally non-competitive or creates a high barrier to entry thus providing the first mover or operator with a dominant position, allowing market control and the ability to set higher prices.
6. ***Location Immobility:*** H_2-CCS infrastructure is highly location dependent (e.g. geological storage of H_2 and CO_2, pipeline corridors, industrial clusters) - this is a significant cost constraint for broader deployment. The free market won't deliver beyond locational preferences without government intervention.

Table 4-1 summarises the results of data collected for the UK H21 case study. The colour coding shows the 'extent' of the failure, defined as the severity of its effect, impact or consequence on the market sector. Red is high, amber medium, and green low impact. A full matrix including CO_2 infrastructure and services is included in Appendix C.

Table 4-1 Impact of market failures on development of H_2 sectors in the UK

Market Sector	Missing Market	Coordination Failure	Low priced CO_2 Emissions	Enviro-social Benefit of Hydrogen not Valued	Natural Monopolies	Location Immobility
H_2 for Heat	Red	Amber	Red	Amber	Green	Amber
H_2 for Power	Red	Red	Green	Amber	Green	Red
H_2 for Mobility	Red	Red	Red	Amber	Amber	Green
H_2 Industrial Use	Green	Green	Red	Amber	Green	Amber
Power-to-X	Amber	Red	Red	Red	Amber	Amber

Legend: green=low; amber = neutral; red = high

The high impact failures in the table are consistent with the findings of many UK studies (see Chapter 5) as well as more general recommendations of the private sector, such as those from the Hydrogen Council[52]. In particular, the maturity of the existing industrial sector stands out, but expansion into new low-carbon products is held back by the negative macro-economic effects of not appropriately pricing emissions or the competition from products that are environmentally detrimental. For the ELEGANCY UK H21 case study, the focus of delivering hydrogen heat markets should in the first instance address areas where the market failures are greatest: overcoming the lack of a market; coordinating the market creation and its supporting infrastructure; and minimising the impact of the location dependence of that infrastructure.

[52] Hydrogen Council, 2017, *How Hydrogen Empowers the Energy Transition*, https://hydrogencouncil.com/wp-content/uploads/2017/06/Hydrogen-Council-Vision-Document.pdf , accessed 23rd March 2020

4.5 UK Government Policies and Actions

4.5.1 Newly Announced UK Policies in Budget 2020

The UK government 2020 March Budget[53] has included funding for a number of relevant policies for delivering CCS and other low carbon activities that on face value support the objective of achieving net zero emissions by 2050. Although the budget is heavily focused on essential infrastructure as well as innovation to support future economic activity, it is silent on a coordinated and strategic approach to energy system decarbonisation that includes hydrogen as well as cross sectoral synergies, low regrets government participation or intervention, and real options for both public and private sector collaboration and investment. Policies and structural delivery mechanisms are left to follow from the comprehensive spending review to be completed by July 2020. The executive summary states:

"*The Budget launches the Comprehensive Spending Review 2020 (CSR), setting out the overall level of public spending within which the CSR will be delivered. The CSR will conclude in July and will set out detailed spending plans for public services and investment, covering resource budgets for three years from 2021-22 to 2023-24 and capital budgets up to 2024-25.*

The CSR will prioritise improving public services, levelling up economic opportunity across all nations and regions, strengthening the UK's place in the world and supporting the government's ambitions to reach net zero carbon emissions by 2050. It will focus on linking departments' spending proposals to the real-world outcomes they seek to achieve and delivering value for money for taxpayers."

Table 2.1 of the 2020 Budget document[54] summarises links between policy decisions and funding that will potentially be available to government departments. Primary policy areas in the budget that may have an impact on the delivery of the H21 Roadmap (in terms of timing, prioritisation and commitment) include:

a. The budget spending envelope for the CSR:
    - Since the publication of the 2020 Budget further budget announcements have been made to support the population and economy to mitigate the effects of the COVID-19 virus pandemic. The impact of these on overall government spending and the policy programmes already outlined is not knowable at the time of writing.
    - The government's election spending commitments within the funding envelope include research and development. If carefully targeted some of this could be beneficial to H21 and energy system decarbonisation. For example, the government intends to double the size of the Energy Innovation Programme.

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[53] HM Treasury, Budget 2020, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/871799/Budget_2020_Web_Accessible_Complete.pdf , accessed 23rd March 2020

[54] HM Treasury, Budget 2020, p65, op. cit.

b. Growing a greener economy:
   - The government is allocating an additional £10 million in 2020-21 to support the design and delivery of net zero policies and programmes.
   - The Climate Change Levy businesses pay on gas will be increased in 2022-23 and 2023-24. The stated logic behind this policy is that electricity is considered a "cleaner energy source" and that the government must continue to remove incentives to choose gas over electricity.
   - Carbon price support will be frozen for 2021-22 at the current level of £18/tonne CO_2e.
   - Introduce a Green Gas Levy to support introduction and deployment of biomethane in the gas grid.

c. The government intends to legislate in the 2020 Finance Bill to prepare for a UK Emissions Trading System (ETS), which could possibly be linked to the EU ETS. The government also intends to legislate for a carbon emissions tax as an alternative carbon pricing policy to the existing carbon price support mechanism and will consult on the design of such a tax in spring 2020.

d. Carbon Capture and Storage (CCS):
   - The government has announced its intention to create a Carbon Capture and Storage Infrastructure Fund to establish CCS in at least two UK sites – one by mid 2020s and one by 2030 with a budget of at least £800M budget to be decided in the CSR.
   - At least one privately financed gas fired power station with CCS will be supported (timeframe not specified) using consumer subsidies.

e. A review of HM Treasury's Green Book will be undertaken in collaboration with stakeholders, including users and academics, and revisions will be published at the same time as the CSR. The objective of the review is to: "*enhance the strategic development and assessment of projects, consider how to assess and present local impacts and look to develop new analytical methods for transformative or place-based interventions*."

Finally, the Budget document highlights that the UK government has £192 billion of contingent liabilities on the state balance sheet. HM Treasury has published a report[55] with proposals to improve the management of contingent liabilities. These proposals will be taken into account in the CSR and may have an impact on the implementation details of business models suited to H21 at both system and business segment level. For example, the proposals for improving risk sharing between government and the private sector, and for seeking compensation for providing insurance or guarantees, may directly affect collaboration and public-private partnership (PPP) structures needed for delivering the H21 Roadmap.

In summary, the key policies that can heavily impact on the H21 vision and delivery are the availability and mode of funding under the CCS Infrastructure Fund and associated

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[55] HM Treasury, 2020, *Government as insurer of last resort: managing contingent liabilities in the public sector*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/871660/06022020_Government_as_Insurer_of_Last_Resort_report__Final_clean_.pdf, accessed 31st March 2020

policies, the design of net zero policies and programmes, the outcomes of the review of the Green Book, and the willingness of, and methods used by, government to underwrite and support uninsurable private sector risks. The opportunity clearly exists within the 2020 Budget and CSR to establish a supportive set of system-level energy policies that can facilitate hydrogen and CCS projects and deliver on the low regrets and optionality requirements described in Section 4.1.4.

4.5.2 Existing UK Policies and Programmes

The key UK government policies and programmes currently in place that are relevant to the H21 Roadmap are detailed in Appendix B. In summary, these fit within a structured institutionalised framework comprising:

a. Various Environmental Acts including climate change legislation[56,57] with its net zero 2050 emissions target and oversight by the Committee on Climate Change;
b. Various Energy Acts targeting growth of renewable energy, energy efficiency and mechanisms for public sector subsidy support such as electricity market contracts-for-difference (CfD) and capacity market payments. These acts have also been used for the establishment of institutions such as the Low Carbon Contracts Company (managing CfDs) and the Oil and Gas Authority (mandated to maximise the economic value of North Sea oil and gas resources);
c. The UK National Infrastructure Commission (an executive agency of HM Treasury) and the Infrastructure and Projects Authority (which reports to the Cabinet Office and HM Treasury);
d. Fit-for-purpose regulations across a broad range of energy sectors and activities (including CCS) and gas and electricity market regulation by Ofgem;
e. The government's 2017 Clean Growth Strategy;
f. The government's 2017 Industrial Strategy;
g. Innovation programmes funded and managed through government departments and public bodies – of particular relevance to H21 are the Department for Business, Energy, and Industrial Strategy and Ofgem; and
h. International cooperation across a broad range of sectors, technologies and programmes.

[56] UK Climate Change Act, 2008, http://www.legislation.gov.uk/ukpga/2008/27/contents, accessed 31st March 2020
[57] The Climate Change Act 2008 (2050 Target Amendment) Order 2019 https://www.legislation.gov.uk/uksi/2019/1056/contents/made, accessed 31st March 2020

5 DEVELOPMENT OF UK HYDROGEN MARKETS

5.1 Summary

A consensus view of the requirements to develop hydrogen markets in the UK has begun to emerge over the last few years. A number of studies and reports[58,59,60,61,6263,64,65] have analysed hydrogen production, infrastructure and potential market characteristics as well as the policy and support mechanisms needed for delivery at economic scale. Perhaps one of the most important conclusions was articulated by Imperial College[66] in its work on heat system decarbonisation:

> *"The most important precondition for using hydrogen would be the development of large-scale, low-cost production facilities."*

Hydrogen production by autothermal or steam methane reforming (ATR or SMR) with carbon capture and storage, costs approximately 2.5 to 3 times less than hydrogen production by electrolysis using renewable electricity sources[67]. Therefore, the vision of developing hydrogen utilisation markets in the UK heat and transport sectors during the 2020s will require deployment of CCS infrastructure in the first instance. The infrastructure investment must be at low or no-regrets capacity levels that will be utilised and remain in place for a period of at least 20 years. Hence such infrastructure will need to be a backbone service for heat decarbonisation in the regions it is deployed. This, in turn, will only be achievable if a strategic approach is taken by the UK Government in conjunction with regional authorities[68]. Projections of hydrogen production cost by electrolysis suggest price parity with ATR/SMR plus CCS could occur in the mid-2030s[69]. A time horizon of 15 to 20 years for CCS infrastructure to support a hydrogen transition could therefore reasonably be considered a low-risk option.

The following sections summarise some important aspects of infrastructure and development of end-use hydrogen markets in the UK. It has been compiled from the UK studies already referenced as well as data collected in workshops and interviews conducted within the ERA-NET ACT ELEGANCY and ALIGN projects from over 60 project and

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[58] Energy Research Partnership, 2016, op. cit.
[59] Imperial College, 2016, *Managing Heat System Decarbonisation: Comparing the impacts and costs of transitions in heat infrastructure*, https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/icept/Heat-infrastructure-paper.pdf, accessed 31st March 2020
[60] Energy Research Partnership, 2017, *The transition to Low-Carbon Heat*, https://erpuk.org/wp-content/uploads/2017/10/ERP_heat_transition-Oct-2017.pdf, accessed 31st March 2020
[61] Northern Gas Networks, 2016, op. cit.
[62] Northern Gas Networks, et. al., 2018, op. cit.
[63] Progressive Energy Ltd, 2017, op. cit.
[64] Cadent Gas, 2017, *The Liverpool Manchester Hydrogen Cluster*, . https://cadentgas.com/about-us/innovation/projects/liverpool-manchester-hydrogen-cluster, accessed 31st March 2020
[65] E4Tech and Element Energy, 2016, *Hydrogen and Fuel Cells: Opportunities for Growth: A Roadmap for the UK*, https://www.e4tech.com/resources/126-hydrogen-and-fuel-cells-opportunities-for-growth-a-roadmap-for-the-uk.php, accessed 31st March 2020
[66] Imperial College, 2016, p3., op. cit.
[67] Zero Emissions Platform (ZEP), 2017, *Commercial Scale Feasibility of Clean Hydrogen*, https://zeroemissionsplatform.eu/zep-launches-commercial-scale-feasibility-of-clean-hydrogen-report/, accessed 31st March 20202
[68] E4Tech and Element Energy, 2016, op. cit.
[69] ZEP, 2017, op. cit.

external stakeholder organisations[70]. CO_2 infrastructure and related services have also been assessed as part of the above exercise. However, clearly investment in these requires development of end-use markets that can support revenue streams to the CO_2 infrastructure service providers. Hence in this UK market section we have focussed on hydrogen market development.

5.2 Strategic Planning and Carbon Budgets

The pace and scale of hydrogen market development in the UK required to assist meeting carbon budgets in the 2030s and to contribute to net zero emission in 2050 is such that government decisions on the integrated energy system, and hydrogen's role within it, will need to be made in the period up to the early-mid 2020s[71]. Government value-for-money decisions and commitments to support infrastructure and manufacturing investments will also require further data gathering. However, because of the large scale of activities like H_2-CCS demonstration, hydrogen production, blending in the gas network or city conversions (e.g. H21 Leeds and North of England), there will be a classic missing market 'chicken-and-egg' problem facing decision makers. This coupled with the need for coordination identified by stakeholders (Table 4-1), highlights the importance of strategic planning in a collaboration between the private sector and government[72,73,74,75].

The UK Government and gas market regulator (Ofgem) are undertaking a data collection process with regards to hydrogen and CCUS through financial support for a number of major investigation projects in conjunction with various interested parties (See Appendix B). Some of the more relevant ones for H21 North of England are:

a. H21 NIC Project (Phases 1 and 2) - Northern Gas Networks' continuation of work undertaken on the H21 Leeds City Gate Project to provide evidence on the viability of converting natural gas distribution networks to hydrogen[76,77];
b. Hydrogen 100 Project - SGN (formerly Scotia Gas Networks) hydrogen demonstration network[78];
c. HyDeploy Project - led by Cadent Gas exploring the potential of injecting zero-carbon hydrogen into the natural gas network[79,80];

[70] See Appendix A: A summary of findings has been documented in ELEGANCY project milestone report M5.4.5.
[71] E4Tech, UCL Energy Institute, Kiwa Gastec, 2015, *Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target*, Committee on Climate Change, https://www.theccc.org.uk/publication/e4tech-for-ccc-scenarios-for-deployment-of-hydrogen-in-contributing-to-meeting-carbon-budgets/, accessed 31st March 2020
[72] Energy Research Partnership, 2016, op. cit.
[73] Northern Gas Networks et.al., 2018, op. cit.
[74] E4Tech and Element Energy, 2016, op. cit.
[75] Hydrogen Council, 2017, op. cit.
[76] Northern Gas Networks, 2017, https://www.northerngasnetworks.co.uk/2017/11/30/ofgem-awards-9-million-innovation-funding-northern-gas-networks-pioneering-clean-energy-project-h21/, accessed 31st March 2020
[77] Ofgem, 2019, https://www.ofgem.gov.uk/gas/transmission-networks/network-innovation, accessed 18th March 2020
[78] SGN, https://www.sgn.co.uk/about-us/future-of-gas/hydrogen/hydrogen-100, accessed 18th March 2020
[79] Cadent Gas Ltd, 2018, https://cadentgas.com/media/press-releases/2018/pioneering-uk-gas-project-aims-to-reduce-domestic, accessed 31st March 2020
[80] https://hydeploy.co.uk, accessed 31st March 2020

d. Hydrogen for Heat Programme Hy4Heat - commissioned by the Department for Business, Energy and Industrial Strategy (BEIS) focused on gas quality standards, safety and metering, and the development of residential, commercial and industrial hydrogen appliances[81,82]; and
e. HyNet Industrial Fuel Switching and Low Carbon Hydrogen Production Projects - led by Progressive Energy[83,84,85].

With these projects and some of the other elements of the 2017 Clean Growth Strategy[86] and the 2017 Industrial Strategy[87], the UK Government is taking a cautious fact-finding and innovation-supporting approach to its hydrogen policy development. However, the independent analysis of the Committee on Climate Change (CCC)[88] has concluded that gaps still exist in meeting the fifth carbon budget (2028-2032) due to the need for further commitments to policies and mechanisms focussed on timely delivery of key technologies and infrastructure. Lead times for new hydrogen and CCS infrastructure combined with development of supply chains, including manufacturing capability and appliance installation capability, will be long (5 to 10 years). Industry has expressed very clear requirements that will need to be fulfilled if hydrogen markets are going to materialise and achieve their full potential in the second half of the 2020s.

The CCC[89] has also emphasised that:

> *"The Government will need to be prepared to act to reduce UK domestic emissions with existing technologies and should not rely on its success in promoting innovation."*

and

> *"The Government should not plan to meet the 2050 target without CCS."*

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[81] Arup, https://www.arup.com/news-and-events/news/arup-and-kiwa-gastec-appointed-to-explore-potential-for-using-hydrogen-to-heat-uk-homes, accessed 31st March 2020
[82] BEIS, https://www.gov.uk/guidance/innovations-in-the-built-environment#investing-in-hydrogen-innovation-for-heating, accessed 31st March 2020
[83] https://hynet.co.uk
[84] Progressive Energy Ltd., 2019, *BEIS Hydrogen Supply Programme HyNet Low Carbon Hydrogen Plant* Phase 1 Report for BEIS, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866401/HS384_-_Progressive_Energy_-_HyNet_hydrogen.pdf, accessed 31st March 2020
[85] Progressive Energy Ltd., 2020, *HyNet Industrial Fuel Switching Feasibility Study*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866402/Phase_2_-_Progressive_Energy_-_HyNet.pdf, accessed 31st March 2020
[86] BEIS, *The Clean Growth Strategy: Leading the way to a low carbon future*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf, accessed 31st March 2020
[87] BEIS, *Industrial Strategy: Building a Britain fit for the future*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf, accessed 31st March 2020
[88] Committee on Climate Change, 2018, *An independent assessment of the UK's Clean Growth Strategy: From ambition to action*, https://www.theccc.org.uk/publication/independent-assessment-uks-clean-growth-strategy-ambition-action/, accessed 31st March 2020
[89] Committee on Climate Change, 2018, p10, op. cit.

The CCC went on to recommend that the government should create plans to commence building a UK CCS industry in the 2020s. Neither hydrogen production and networks, nor CCS require major technological innovation[90,91,92]. However, hydrogen and CCS infrastructure will not be deployable in small and incremental steps, such as with onshore wind farms and solar installations and, as previously discussed, investments will be for long time horizons (20+ years). This is one of the key reasons why hydrogen and CCS industry stakeholders are interested in a coordinated planning, governance and decision-making framework which includes national, regional and local government, that:

a. enables large scale hydrogen use and transformation;
b. covers heat, transport and industrial sectors;
c. takes account of cross sector benefits/synergies and efficiencies;
d. makes links between direct hydrogen use and fuel cell use; and
e. includes value metrics based on whole system sustainability criteria.

The following sections summarise the consolidated findings of the studies referenced in Section 5.1. There is a specific focus on the outcomes needed during the next five and following years to deliver hydrogen into the UK energy system and for the development of the heat and transport market sectors. Domestic heating is the primary focus of the UK ELEGANCY case study since it informs the H21 Roadmap assessment for decarbonisation of heating of large UK cities. The timeframe fits with the CCC recommendations for both achieving the fifth carbon budget and deploying CCS infrastructure. In addition, the H21 Leeds City Gate project highlighted how low-cost hydrogen delivered through the gas network could revolutionise the availability and take-up of hydrogen vehicles[93]. The hydrogen and CCS sectors have the potential for substantial synergistic benefits that also meet UK carbon budgets.

5.3 Hydrogen in the Energy System

As discussed above, hydrogen has the potential to make a very substantial cost-effective contribution to a low-carbon UK energy system. In order to avoid losing that option over the coming decade a number of priority actions at the system level by both public and private sector actors are required. Academics, analysts and industry have all recognised the need for pro-activity from trade associations and individual companies to ensure momentum is built across potential hydrogen market sectors. Continuing collaboration between stakeholders with different interests and with the CCS community, building on the programmes that have been initiated to date, will be essential to establish the integrated system-level knowledge and community buy-in that will be needed to support decision-making and long-term planning. Stakeholders include gas producers, network operators, utilities companies, appliance manufacturers, other supply chains, government departments, etc.

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[90] Northern Gas Networks, 2016, op. cit.
[91] Northern Gas Networks et. al., 2018, op. cit.
[92] Carbon Capture and Storage Association (CCSA), *Lessons Learned: lessons and evidence derived from UK CCS programmes, 2008 – 2015*, http://www.ccsassociation.org/press-centre/reports-and-publications/, accessed 31st March 2020
[93] Northern Gas Networks, 2016, p2, op.cit.

Priority actions required to develop hydrogen in the UK energy system are (as highlighted in Chapter 4 and Appendix B some are already a work-in progress):

1. Existing regulations governing electricity and natural gas markets, networks and operators need to be reviewed and modified where necessary to ensure an enabling environment for hydrogen-based activities and the possible interactions with the remainder of the energy system;
2. Energy system safety standards, specifications and regulations that are currently in place for equipment, handling and use of conventional liquid fuels and natural gas require broadening to deal with the specific characteristics of hydrogen. Also, an agreed specification for 'low-carbon' hydrogen will need to be developed as soon as possible in order to enable engineering of H_2-CCS chains and development of H_2-derived liquid fuels;
3. Policies to support delivery will need to ensure a stable investment environment for an extended period of at least a decade and include a commitment to a designed, coordinated build-out and transformation from natural gas to hydrogen. A national body (public and/or private) will be required for oversight of first projects and conversions;
4. An economic market of sufficient size will have to be created that can be supported by a no/low regrets scale of production, transmission and distribution infrastructure. For example, through city and/or regional conversion as proposed in Leeds[94]. Specific market-making policies for different sectors are required (see below for heat and transport);
5. Hydrogen and CCS are nascent global markets with similar characteristics and synergistic potential for export of UK expertise and products. Japan[95] and China[96] are both making major commitments to explore hydrogen as part of their low carbon economies. Further to point 4 above, the UK will need a national trade position and policies to support increasing the critical mass of a combined domestic and export markets for UK manufacturers and supply chains;
6. Underground hydrogen storage site selection and engineering feasibility studies will need to be conducted and concluded before 2026;
7. On-going support for innovation, research and development across the entire hydrogen chain, including electrolysis from renewable energy, will be essential to maintain a cost reduction trajectory and prevent stranded assets from initial deployments;
8. Training and development programmes for relevant trade skills will need to be in place by the early 2020s in order to have a sufficiently large and skilled workforce to undertake city and regional conversion to hydrogen in all potential market sectors;
9. Many of the key delivery activities relate to networks and will need to be carried out by regulated monopolies as there is no market pull (cf. missing market) for the private sector. These organisations will have to be established or contracted by the early 2020s; and

[94] Northern Gas Networks, 2016, op. cit.
[95] Japan Ministry of Economy, Trade and Industry, 2014, *Strategic Energy Plan*, http://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf, accessed 23rd March 2020
[96] Xinhuanet, 2018, *"Hydrogen city" to be built in central China*, http://xinhuanet.com/english/2018-01/21/c_136913339.htm, accessed 23rd March 2020

10. Public engagement and education will be critical to any hydrogen market development. Government will need to work in collaboration with regional and city authorities, trade associations, Non-Governmental Organisations (NGOs) and private sector organisations to develop communication and education strategies that build familiarity and trust in the community.

5.4 Heat and Power

5.4.1 Domestic and Commercial Heating

When the UK Government does come to make decisions on heat decarbonisation and the role of hydrogen, Imperial College has advised that[97]:

> *"The choice of options and/or the rate of deployment may well be determined by the non-cost impacts and customer acceptance issues, rather than being made on the basis of least cost, market allocation principles."*

The Imperial College comparison of domestic heat decarbonisation options is shown in Table 5-1. This work does not include the potential for hydrogen fuel cell CHP but does note that CHP will be a future candidate for district heating systems. It is very clear from a sector view that there is no obvious winner between any of the potential technology solutions, and in fact some combination of all is likely to emerge. In this context government policy should enable all, and not hinder any technological solution.

Table 5-1 Cost/impact comparisons of different domestic heat decarbonisation options

Urban and suburban properties	Repurposed gas grids (hydrogen)	Electrification (heat pump)	District heating
Cost/impact of decarbonised heat supply	[red]	[green]	[green]
Cost/impact of network activities	[green]	[amber]	[red]
Cost/impact of activities in customer premises	[green]	[red]	[green]
Need for new regulation	[amber]	[green]	[red]

Legend: green=low; amber = neutral; red = high

The critical issue for hydrogen for heat, compared to the alternatives, is the cost of supplying the fuel. In other words, the production, decarbonisation (with CCS or via electrolysis), and transmission of low-carbon hydrogen. This hydrogen and CCS infrastructure need to be built before the market exists (cf. missing market and coordination failures in Table 4-1). However, as discussed previously and pointed out in all the studies on hydrogen, individual sectors cannot be evaluated in isolation. The options opened up by a hydrogen infrastructure for the entire energy system need to be valued with

[97] Imperial College, 2016, p3., op. cit.

holistic metrics. Large-scale use of hydrogen for domestic and commercial heating in the UK will, therefore, be dependent on the actions described in the previous Section 5.3.

Kiwa[98] noted that the single most important factor for manufacturers in the development of the hydrogen appliance market is an agreed and signed off plan for the local deployment of bulk pipeline hydrogen through the existing natural gas network. This is entirely consistent with the need for bulk hydrogen production and a long-term strategic plan as described in Section 5.2 above. Without the clear signals given by a government mandate, the supply chain, equipment and appliance manufacturers cannot invest in their own businesses and innovation. Development of standards and codes of practice, and training for installation and maintenance personnel are essential and need to be in progress/completed to allow roll-out of products by the time infrastructure is ready. Northern Gas Networks[99] and E4Tech and Element Energy[100] have suggested this government mandate should be in place by about 2021.

5.4.2 Smaller Scale Stationary Applications

Small-scale (mini- and micro-scale) fuel cell CHP has potential both as a transition technology (using natural gas, later to be converted) in on- and off-grid applications. Government support will be required to help create markets for hydrogen fuel cells. This could be achieved through feed-in-tariffs, research, development and demonstration grants, market pull mechanisms, such as rebates to consumers, and to provide clarity over the scope and role of CHP within the energy system. Assistance with access to international markets such as Europe, Japan and China will help UK manufacturers develop economies of scale for their investments. If hydrogen fuel cell CHP is to be a viable UK manufacturing and service sector it will need to compete for its place against countries like Germany and Japan over the next five and following years.

5.5 Transport

The UK Office for Low Emissions Vehicles (OLEV) is providing funding "*to position the UK at the global forefront of ULEV [ultra-low emissions vehicles] development, manufacture and use*" and runs a Hydrogen for Transport Programme including public refuelling infrastructure and hydrogen fuel cell vehicles. The government has stated in its Industrial Strategy[101] that zero-emission transport, including vehicle manufacture and supply chains, is a high priority. Hydrogen vehicles and CCS are mentioned as long-term options, also with a link to possible domestic shale gas production. However, the strategy does not provide a level playing field for HFCEVs competing against the more mature BEV market.

A budget of £400 million in the Clean Growth Strategy[102] to extend the EV re-charging network compares unfavourably with £23 million allocated for H_2 refuelling

[98] Kiwa, 2016, *Desk study on the development of a hydrogen-fired appliance supply chain*, Report for Department of Energy and Climate Change, https://www.gov.uk/government/publications/hydrogen-appliances-desk-study-on-the-development-of-the-supply-chain-for-100-hydrogen-fired-domestic-and-commercial-appliances, accessed 31st March 2020
[99] Northern Gas Networks et. al., 2018, op. cit.
[100] E4Tech and Element Energy, 2016, p18, op. cit.
[101] BEIS, 2017, *Industrial Strategy*, op. cit.
[102] BEIS, 2017, *The Clean Growth Strategy*, op. cit.

infrastructure. Further support for re-charging networks (increased to £500 million over 5 years from 2020) has been announced in the UK Budget 2020. There is a risk that positive feedback between increasing market demand and investment by EV vehicle manufacturers will result in increased inertia to the development and take-up of passenger HFCEVs. The market failures identified by stakeholders in Appendix C will be exacerbated without targeted policies. Transport applications for hydrogen are as dependent as domestic heating on a coordinated effort across industries, with a need to remove the 'chicken-and-egg' mismatch between infrastructure deployment (re-fuelling stations) and market demand for hydrogen (HFCEVs).

In its assessment of the Clean Growth Strategy, the CCC states[103]:

> *"The Government has set out an ambition for 30-70% of car sales and up to 40% of van sales in 2030 to be ultra-low emission vehicles (ULEVs). It will be necessary to deliver towards the upper end of the range for cars, and greater ambition will be needed for vans. There is little concrete action on emissions from HGVs [heavy goods vehicles]. More is also needed on shifting travel demand from passenger cars to lower-emission modes."*

Commercial, heavy goods vehicles, and buses can provide the core market for a backbone hydrogen re-fuelling station (HRS) network built out from a converted natural gas grid, which would also promote further development of HFC technologies. This would require availability of public funding and coordinated procurement with a focus on high-volume hydrogen users, a tightening of the air regulations for transport, a continued industry coordination to resolve any practical issues (such as vehicle certifications), and coordination of policy efforts at national and European level.

Meeting the CCCs recommendations will require a more aggressive approach to hydrogen use in transport. One key issue is the requirement for higher purity hydrogen for fuel-cell applications than is necessary for heat applications[104]. Technology development for distributed de-blending or purifying technologies, and cost reduction for the production of hydrogen meeting the higher quality specifications (for example further development of electrolysis technologies), will need to be an important focus of innovation funding. Therefore, in addition to the coordinated ten priority energy system actions in Section 5.3, there will need to be priority actions to develop hydrogen use in the UK transport market:

1. A government-supported early phase of an HRS network in strategic locations with funding assistance, e.g. subsidies and tax rebates, enabling initial FCEV sales. Industry can coordinate these larger-scale deployments to reach a target for a seed HRS network in the early 2020s;
2. Sufficient fuel demand in order to de-risk investments. This can be enabled by early sales of passenger vehicles, buses, and municipal refuse vehicles for public sector use via government procurement programmes;

[103] Committee on Climate Change, 2018, Box 4. p16, op. cit.

[104] Shell Deutschland, 2017, *Shell Hydrogen Study: Energy of The Future? Sustainable Mobility through Fuel Cells and H_2*, https://www.shell.de/medien/shell-publikationen/shell-hydrogen-study.html#vanity-aHR0cHM6Ly93d3cuc2hlbGwuZGUvaDJzdHVkeQ, accessed 31st March 2020

3. Increasingly stringent emissions regulations for vehicle use within city limits (the government has provided for an additional £175 million of funding to assist regional authorities improve air quality);
4. Completion of national and European programmes for regulations and standards (fuel, handling, transport, storage tanks, refuelling stations, and HFCs), permitting, licensing, and certification;
5. RD&D funding for the production and distribution of high purity hydrogen suitable for fuel cells, including technologies and facilities for de-blending (or purifying) from distribution networks and cost reduction for electrolysis;
6. RD&D funding for the continuing development of hydrogen-based technologies for trucks, articulated vehicles, also rail, ships, and aircraft. If hydrogen supply is secured, incremental build-out of the HRS network will be demand-driven by the progressive reduction in HFCEV costs and increasing profitability of hydrogen fuel retailing[105];
7. Encourage expansion of hydrogen vehicle and fuel cell manufacture by integrating export market development in an industrial strategy with the use of hydrogen for transport in a domestic ULEV strategy; and
8. National, regional and local communication plans to inform and prepare consumers to understand and support HFCEVs and hydrogen refuelling station networks.

Based on the review conducted here, ideally most of the above actions for initiating HRS build-out and market creation would be achieved by 2025 to begin benefitting from a first substantial deployment of H_2-CCS infrastructure[106,107] in 2026.

[105] UK H_2Mobility, Communication Pack, 2017, http://www.ukh2mobility.co.uk/wp-content/uploads/2017/09/Communication_pack_January_2017.pdf, accessed 31st March 2020
[106] E4Tech and Element Energy, 2016, op. cit.
[107] UK H_2Mobility, 2017, op. cit.

6 H21 NORTH OF ENGLAND REPORT: KEY IMPLEMENTATION FINDINGS

6.1 Summary

This chapter summarises and reviews the H21 North of England (H21 NoE) study report[108] completed by Cadent, Equinor and Northern Gas Networks and issued in November 2018. The report presents the engineering details and the most cost effective and realistic options for converting the North of England to hydrogen over a 7-year period between 2028 and 2034. The report also provides a vision for decarbonisation of 70% of meter points by 2050 using a subsequent regional roll out strategy and argues there is a realistic potential to expand production and infrastructure to enable a transition to 100% replacement of UK natural gas demand with hydrogen by 2050. This report followed the 2016 H21 Leeds City Gate report by Northern Gas Networks, Kiwa Gastec, Wales and West Utilities and Amec Forster Wheeler. That study concluded the UK natural gas networks had the capacity for 100% conversion to hydrogen.

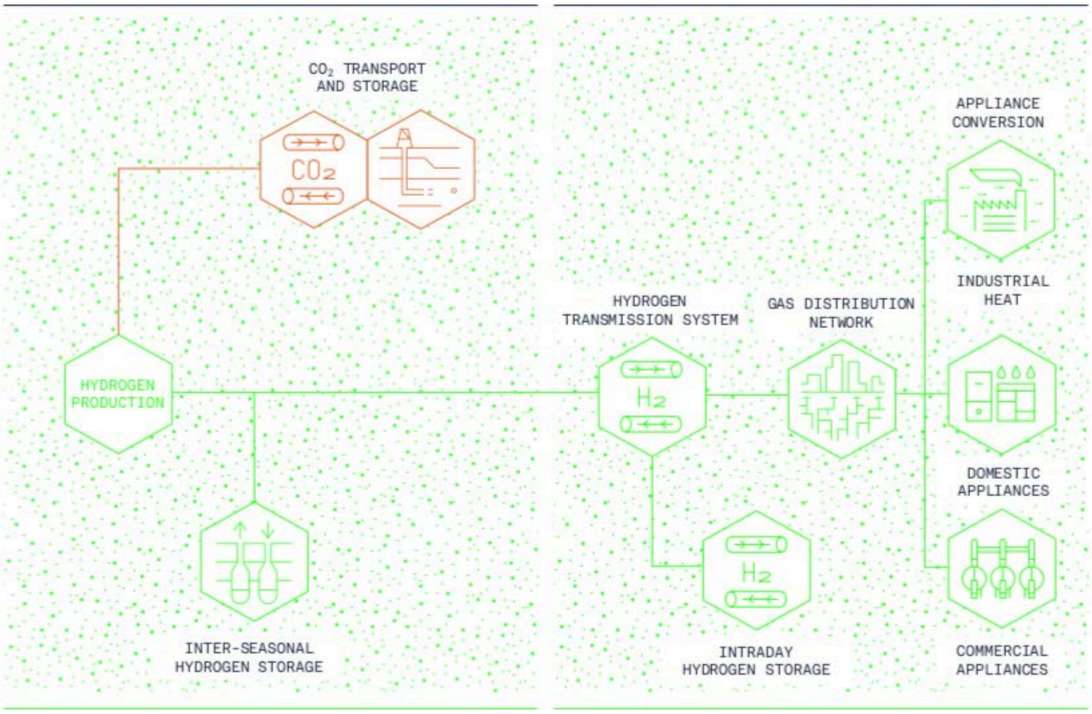

Figure 6-1 Project Scope of Work[109]

The H21 NoE project concept is based on the use of proven at-scale hydrogen production technology and existing in-country technical expertise. The technical solution relies on 12.15GW of natural gas-based autothermal reforming (ATR) hydrogen production in one or more facilities (HPF) delivering low carbon heat for Tyneside, (Newcastle, Gateshead), Teesside, York, Hull, West Yorkshire (Leeds, Bradford, Halifax, Huddersfield, Wakefield), Manchester and Liverpool. The project infrastructure includes 8TWh of inter-seasonal hydrogen storage, a 125GW capacity hydrogen transmission system and a CO_2 transport and storage system capable of storing up to 20Mtpa of CO_2 by 2035.

[108] Northern Gas Networks, et. al., 2018, op. cit.
[109] Northern Gas Networks, et. al., 2018, op. cit.

In its first phase the project would achieve the decarbonisation of 14% of UK heat and reduce CO_2 emissions by 12.5 Mtpa or 92% compared to business-as-usual natural gas use. The H21 NoE study authors aim to present a realistic delivery timeline and deliverables which fit with UK policy for heat decarbonisation and the obligations and timescales of the Climate Change Act.

The H21 project concept includes CCS infrastructure as a necessary enabler for hydrogen manufacture at scale in the delivery timescales required to meet UK carbon budgets. The study advocates CCS as an essential transitional step to facilitate a longer term sustainable domestic and global hydrogen economy. The project would also enable the decarbonisation of industrial clusters by default and provide the backbone of a system to provide flexible power to back-up renewable electricity.

The study is a detailed and thorough technical fact-based analysis which describes a robust engineering solution for cost effective deep decarbonisation of heat in the UK. However, the report does not set out to:

a. present, analyse and mitigate non-technical investment risks and barriers to implementation;
b. develop a business case and potential business model for the H_2-CCS chain and the multiple business sectors;
c. analyse in detail how and why the project will facilitate the UK system decarbonisation synergistically with the other decarbonisation pathways; and
d. carry out any Cost Benefit Analysis (economic impact, air quality/health impact) or Cost Effectiveness Analysis beyond a traditional cost analysis.

6.2 Analysis and Conclusions

The project completed a detailed technical engineering review of how a hydrogen project could be defined in a cost effective and realistic manner to meet the required heat demand for the UK north of England by converting from natural gas. It analysed all the relevant aspects of the energy sub-system including heat demand, low carbon hydrogen production, transport and storage (for demand management), and customer conversion.

6.2.1 Hydrogen

1. The study completed a detailed heat demand analysis and modelling to ensure security of supply issues would be addressed by the project technical configuration.
2. The study included a thorough hydrogen technology selection exercise based on cost, security of supply/reliability, proven technology, timescale for delivery and concluded that hydrogen production by ATR (with integrated CO_2 capture) in combination with storage in salt caverns in the north of England is the optimum solution.
3. The report presents a final hydrogen production capacity of 12.15GW, configured over 9 units of 1.35GW. This capacity allows 125% of the peak year average demand to be met. This flexible configuration is built at a rate of one ATR unit per year between 2026 and 2035. The capacity guarantees meeting the annual demand with any excess hydrogen production being via inter-seasonal storage, turn-down of units or in preference exporting as power. Such a technical configuration is possible through it ultimately requires a land area of 1.5km x 600m if built on one site.

4. The study identified an inter-seasonal hydrogen storage requirement of 8,052GWh. It reviewed the technical options for storage and concluded that geological storage in the deep salt strata in the north of England in the Yorkshire and Aldbrough area would be the best solution. This would avoid the need for recompression and would be based on 56 caverns operating between 275 and 85 bar with 8 surface facilities.
5. The study identified a preferred strategic location for the Hydrogen Production Facility (HPF) on the coast in the Humber region because of:
   a. its proximity to a major entry point of natural gas (the Easington Terminal) with long time horizon (30 GW and 40 years plus);
   b. its proximity to the preferred CO_2 geological storage solution offshore in the Southern North Sea;
   c. its proximity to future hydrogen storage caverns in the Aldbrough area (25 km away);
   d. its proximity to the shore for seawater outfall and ease of design of CO_2 transport;
   e. its proximity to a major HVAC electricity system and to an entry point for the large offshore wind HVDC cables to maximise future use of excess renewable electricity for hydrogen production from hydrolysis; and
   f. the availability of industrial land.
6. A split location between the Humber and Teesside was also considered. This would incur additional costs for the HPF (losses of economies of scale and duplication of some facilities), additional CO_2 pipeline transport costs and compression costs for hydrogen transport.
7. The report concludes that the hydrogen transportation system (HTrS) would require the following new infrastructure: 520km of 80bar Hydrogen Transmission System (HTS) without any additional compression, 334km of 40bar Local HTS (LHTS) and 605km of below 7bar Hydrogen Intermediate Pressure System (HIPS). Putting the scale of this in perspective, the required HTS and LHTS represents only 4% of the existing gas National TS and Local TS, and the HIPS represents only 0.2% of the gas distribution network.
8. With regard to customer conversion, the project plans for the conversion of 3.7 million meter points over a 7-year period. To implement this the study concluded that 3,000 plumbers per summer period and 1,500 per winter period would be required. This is in comparison to a total of 128,000 gas safe registered engineers and 250,000 plumbers working in the UK. In 1971-1972, at the peak of the UK gas network conversion from town gas to natural gas (which occurred between 1966 and 1977), 2.3 million-meter points were converted per year.

6.2.2 CO_2 Transport and Storage

The study reviewed the technical viability and cost of CO_2 transport and storage on the UK Continental Shelf to meet the H21 NoE project requirements. It was not the objective of the study to attempt to define or recommend an optimised transport and storage solution. Up to 20 Mtpa of transport and storage injectivity would be needed along with a total storage site capacity of 516 Mt for H21 NoE. The UK has a theoretical storage capacity of 78GT with key areas in Central and Northern North Sea (C-NNS), Southern North Sea (SNS) and the East Irish Sea (EIS). Substantial knowledge of the storage resource has been developed over the years and a number of alternatives could be selected for different phases of H21 NoE.

1. The study reviewed the Bunter sandstone closures BC36, BC40 and BC3 (saline aquifer formations) and a depleted gas field (Viking A) in the SNS for the CO_2 storage solution. These sites are a good strategic fit for a FOAK infrastructure due to the large storage potential, suitability for co-development or staged expansion, ability to share offshore transportation infrastructure, proximity to the shore, and proximity to large concentrated emissions sources. The SNS also allows for optionality to serve as a hub for other neighbouring countries, such as the Netherlands.
2. The study concluded that the SNS storage options are technically feasible and would provide a good basis upon which to conduct more detailed FEED studies for the H21 NoE project. The cluster of sites provides additional scope for risk and uncertainty management associated with capacity and injectivity at the rates required by H21.
3. Equally as important to the technical feasibility, the conclusion was reached that the technically most mature storage sites could be ready for commencement of injection operations in 2026. This would enable the achievement of Committee on Climate Change recommendations to have FOAK CCS infrastructure operational by 2026.
4. The H21 NoE project CO_2 transport and storage concept delivers a substantial cost benefit from economies of scale compared to the H21 Leeds City Gate project by increasing the stored emissions volumes from 1.5Mtpa to over 15Mtpa. The cost estimates for transport and storage reduced from £22/t CO_2 to £6/t CO_2 (Figure 6-2).
5. The study concluded that 15Mtpa is a 'sweet spot' and economies of scale benefits are significantly less at higher volumes.

Figure 6-2 Summary H21 unit transport and storage cost estimates per tonne CO_2 – all UK Continental Shelf and Norwegian Continental Shelf cases[110]

[110] Northern Gas Networks, et. al., 2018, op. cit.

6.2.3 Costs and Finance

The study H21 project cost estimates are presented in the figure below:

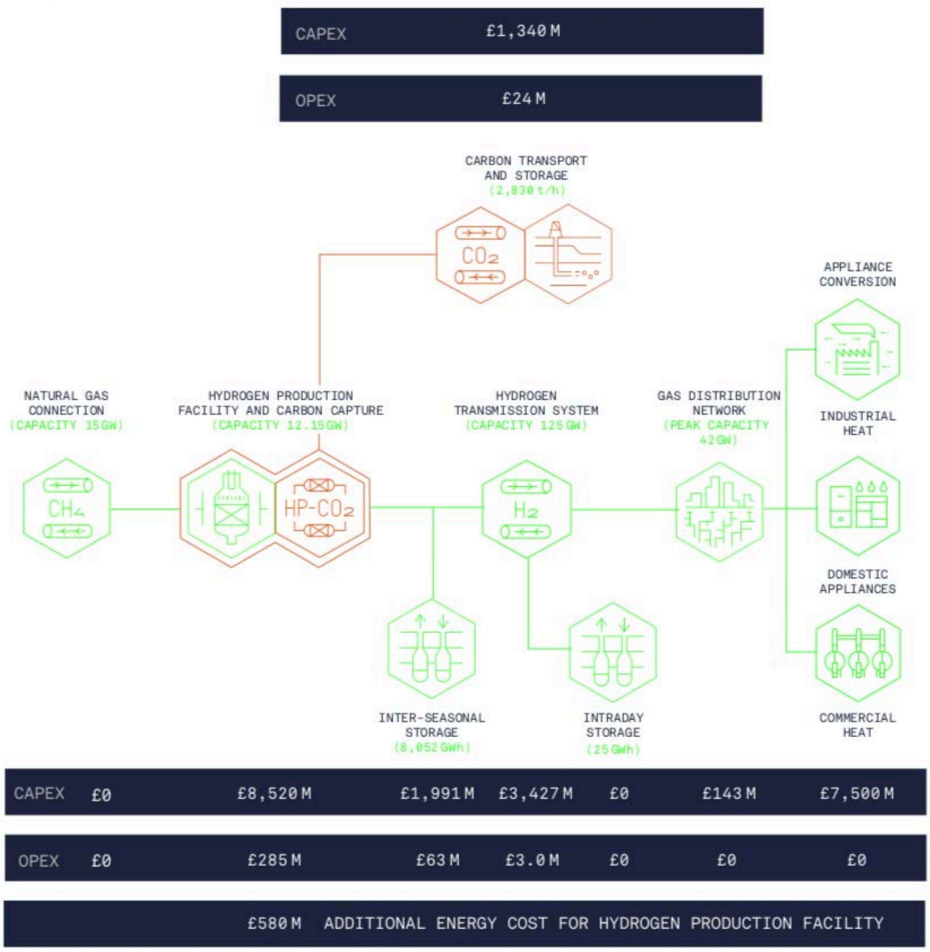

Figure 6-3 H21 NoE Project Costs (Capex and Opex)[111]

The main conclusions of the study are:

1. The expanded H21 project concept can realise 25% capex savings and 50% opex savings compared to the H21 Leeds City Gate study due to the economies of scale.
2. The study assumed a simple regulatory financing model whereby all new hydrogen infrastructure including H_2 production, inter-seasonal storage, H_2 transportation system, CO_2 transport and storage and appliances would form part of a new national 'hydrogen regulated asset' class and all costs would be socialised over the customers.
3. The final cost for the complete system conversion represents £3.8 per MWh or an increase of £53pa (7%) for a standard customer gas bill of £780 (using 2035 gas prices).
4. The CO_2 transport and storage component would cost £5.54/tonne based on such a regulated asset finance model

[111] Northern Gas Networks, et. al., 2018, op. cit.

7 H21 SYSTEM INVESTMENT BARRIERS AND RISK ASSESSMENT

The full H21 system risk matrix including investment barriers and mitigation options is presented in Appendix E and Appendix F. This risk assessment, and the completion of the associated risk matrix, were undertaken using the methodology developed in ELEGANCY WP3 and the risk assessment tool from the WP3 toolkit.

7.1 Policy Needs for H21 Roadmap Investability and Delivery

Based on stakeholder feedback (Appendix A), the assessment of the H21 business and investment context (Chapter 4), market development (Chapter 5), and the findings of the H21 North of England report (Chapter 6), a policy needs heat map (Figure 7-1) has been created using the ELEGANCY WP3 toolkit for the UK H21 Roadmap case study (a larger format version can be found in Appendix D). The synthesis of missing policies and stakeholder demand for solutions in this heatmap informs the H21 system investability analysis and risk matrix.

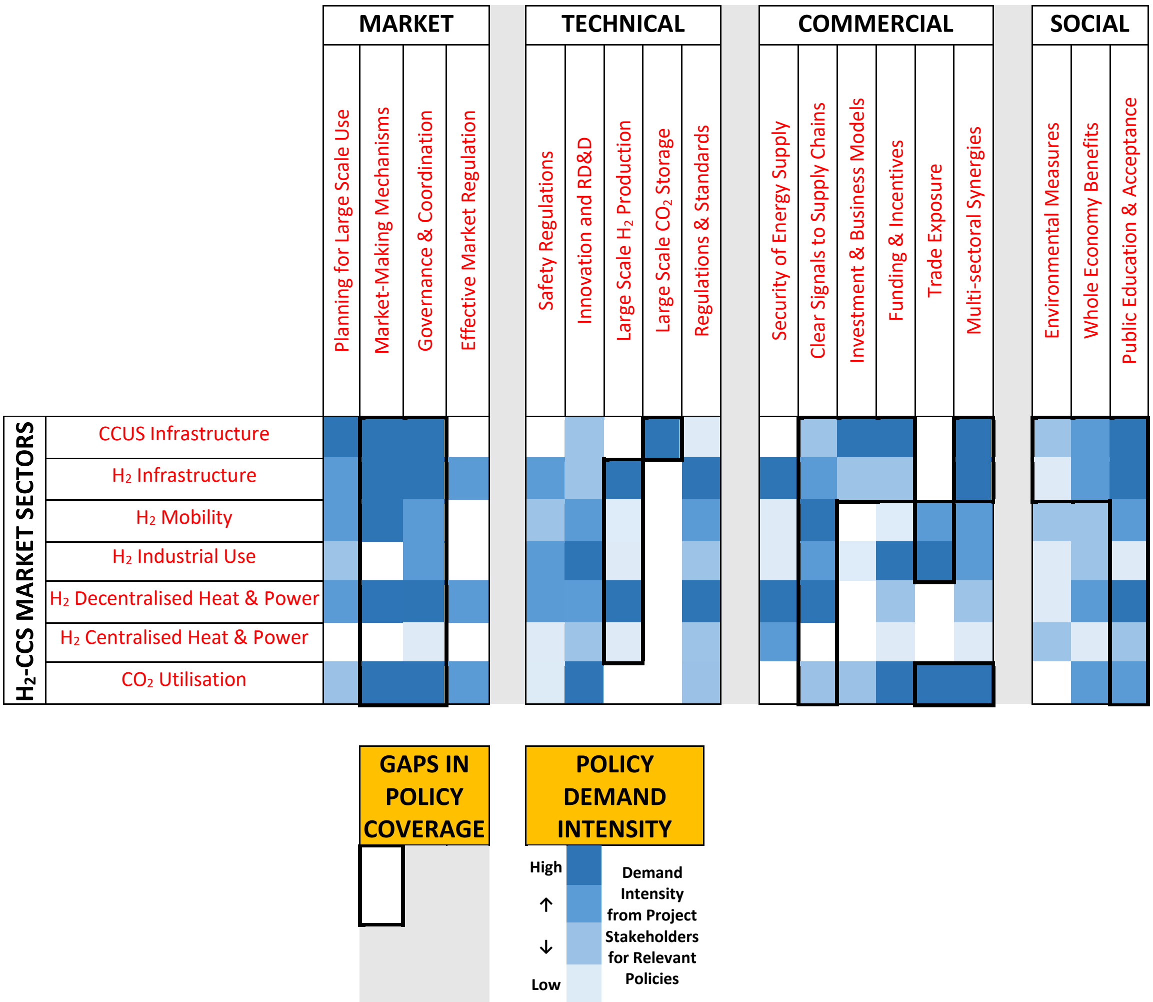

Figure 7-1 H21 Policy Needs Heatmap

The principal policy gaps shown in the heatmap are barriers to private sector investment and need to be resolved by government intervention beyond the Budget 2020 measures. Some gaps are already being partly addressed through work in progress in various government departments, but systems thinking with a net zero emissions outcome needs to become the framework in which all policy is developed going in to the 2020 Comprehensive Spending Review and subsequent programmes.

7.2 System Investment Barriers & Risk Mitigation Options

The H21 system investment barriers and mitigation options are presented in the matrix in Appendix E. The following is a high-level summary of the investment barriers dealt with in the matrix.

7.2.1 Political, Policy and Social Barriers

Details in Appendix E.1

7.2.1.1 Policy Change

1. Uncertainty of UK commitment to pace and evolution of low carbon or circular economy matching the net zero climate target
2. Missing binding government mandate for delivering the first cluster decarbonisation project and associated integrated full chain infrastructure

7.2.1.2 Permitting and Consenting

1. Long term leakage liabilities defined in EU Directive and national regulations with front loaded Financial Security

7.2.1.3 Reputation and Social

1. Unknown public acceptance of a city hydrogen conversion and gas network re-purposing
2. Cost of emissions abatement using CCS in the first phase of H21 is too high compared to competing technologies (renewable electricity, heat pumps) to warrant public funding support
3. Objections and moral hazard arguments related to continuing use of fossil fuels and financial support to O&G industry

7.2.1.4 Political and Governance

1. Lack of confidence in long term financial commitment by government

7.2.2 Technical and Physical Barriers

Details in Appendix E.2

7.2.2.1 Output and Service Reliability

1. Guaranteed intra-chain counterparty performance is required between H_2 retailer/DNO/TNO/producer and CO_2 capturer/gatherer/transporter/storer

7.2.2.2 Operations

1. Operational complexity of multi-party integrated system both during commissioning and early full-scale operations

7.2.3 Market and Commercial Barriers

Details in Appendix E.3

7.2.3.1 Market Development and Demand Uncertainty

1. Missing markets for large-scale clean (low carbon) hydrogen
2. Missing markets for large-scale use of CO_2 transport and storage infrastructure
3. Uncertainty of market demand over 20 years
4. Regulated rate of return is insufficient to attract oil and gas companies to invest only in CO_2 T&S service

7.2.3.2 Access to Capital

1. The level of financial risk related to integrated full chain infrastructure (cross chain default, political risk, delivery risk) is too high for lenders with conventional risk mitigation measures

7.2.4 Outcome Barriers

Details in Appendix E.4

7.2.4.1 Co-impact or Negative Impact

1. Early stage hydrogen supply system does not have sufficient capacity and is not sufficiently robust (compared to the natural gas system) to avoid customer outages

7.2.4.2 Asset Underperformance or Stranded Asset

1. Potential for CO_2 T&S infrastructure to be underutilised or not utilised after first capture project

7.3 System Business Risks & Risk Mitigation Options

The detailed H21 system business risks and mitigation options are presented in the matrix in Appendix F. The following is a high-level summary of the business risks dealt with in the matrix. Different stakeholders (public, private or joint) are best able to mitigate these risks, and the matrix indicates whether government intervention is required or not in order to implement the proposed mitigation options. The risk sharing and proposed public-private collaboration for delivering the H21 Roadmap is dealt with further in Section 7.4 below.

7.3.1 Political, Policy and Social Risks

Details in Appendix E.5

7.3.1.1 Regulatory

1. A functional regulatory framework agreed between government and the private sector to govern the system business model and investments in the H21 system is not in place in time for FID by 2023.
2. Inconsistent laws and regulations between end use markets and those governing CCS permitting and operations affect construction and/or service delivery.
3. Mandatory third-party access to infrastructure leads to operational and commercial problems such as controlling CO_2 and/or H_2 quality specs and inability to meet regulations and performance guarantees.

7.3.1.2 Policy Change

1. Government policy of supporting critical and strategic evidence gathering for H_2 in general and H21 in particular does not extend to the H21 FEED and live trials before 2023.
2. Government de-prioritises H_2-CCS in Clean Growth and Industrial Strategies in the period to 2023.
3. The functional regulatory framework agreed between government and the private sector to govern the investments in the H21 system is unilaterally changed by government before the second phase of H21 investment.

7.3.1.3 Legal and Ownership Rights

1. Outstanding legal issues in 2023 prevent integration of the collective investment decisions for the first H21 full chain system components and city conversions using results of the NoE FEED study.
2. Statutory remedies including compensation and penalties for defined and limited events (incl. death) result in expensive insurance for operators.
3. Agreed public-private sector system business model with segment business models and ownership rights is not in place in time for FID in 2023.

7.3.1.4 Permitting and Consenting

1. Onerous FOAK permit conditions on geological H_2 or CO_2 storage result in loss of private sector investment appetite or post-commissioning compliance difficulties.
2. H21 first phase consents, permits, leases or licences are not easily obtained (delayed, conditional or not granted due to FOAK issues such as technical and/or safety uncertainty).

7.3.1.5 Reputation and Social

1. Any initial public support existing during H21 FEED and trials is lost prior to taking FID in 2023.
2. Insufficient education and skills training programmes to provide workforce needed to implement H21 phases 1 and 2.
3. Problems with hydrogen delivery during commissioning and first phase of H21 result in loss of public support for phase 2.

7.3.1.6 Political and Governance

1. Impact of BREXIT is deeper and more negative than expected causing extended economic slow-down and/or reduced growth disincentivising conversion to hydrogen.
2. Carbon price on ETS or domestic tax stays too low for too long to incentivise decarbonisation investments in industry (incl hydrogen production and use).
3. UK and international climate change efforts fail to address disparity between carbon content of goods and services produced in different regions and jurisdictions as well as territorial versus extraterritorial emissions resulting in disequilibrium in global markets and disincentives for industry decarbonising with hydrogen and/or CCS.

7.3.2 Technical and Physical Risks

Details in Appendix E.6

7.3.2.1 Construction

1. Delays in construction, re-purposing, and commissioning including appraisal and characterisation of H_2 and/or CO_2 storage sites.
2. Full chain technical/technology integration and performance don't meet design criteria requiring re-design, remediation, or re-engineering.

7.3.2.2 Operational

1. Uncertainty and/or variability with the consistency of either the H_2 production stream or the CO_2 capture streams in terms of volume, purity, rate and cost.
2. Short term outages (including mechanical damage, maintenance delays, facilities problems etc.) of one part of the H2-CCS chain impact operations of another part of the chain.

3. Existing MMV technologies for use with CO_2 storage operations are not able to provide necessary or sufficient data for regulatory compliance purposes at bearable costs

7.3.2.3 Output and Service Reliability

1. Unknown performance reliability of scaled up ATR + capture technology operating in real world conditions.
2. Underperformance of CO_2 geological storage site (incl. capacity, lifetime injectivity, migration).
3. End user appliance performance and usability does not achieve the same standard and service level that natural gas customers are used to.

7.3.2.4 Environmental Impact

1. Release of CO_2 to atmosphere from capture, transport or storage operations, outages or leaks.
2. Hydrogen leak and explosion in the first phase of H21.

7.3.3 Market and Commercial Risks

Details in Appendix E.7

7.3.3.1 Currency and Exchange

1. Significant increase in costs due to currency fluctuations and therefore increase in tariffs and government subsidies/end user charges.

7.3.3.2 Market Development and Demand

1. Market demand declines from, or doesn't meet, projection in investment case.
2. Initial Leeds city conversion and/or foundation cluster customers delayed in start-up and use of hydrogen.
3. Industrial customers become insolvent / close business.

7.3.3.3 Access to Capital

1. Lenders conditions incompatible with regulatory regime designed for H21 NoE making finance essentially unavailable.
2. Lack of confidence from banks in operability of full system and availability of segment services plus potential financial impact from non-availability - Lenders require repayment guarantees from government or public authority.
3. Lenders seek onerous termination provisions or step-in rights making finance essentially unavailable.
4. Lack of confidence from banks in end user hydrogen market development beyond initial phase H21 captive customers.
5. Extended non-availability or non-performance of CO_2 transport and storage makes investment into ATR Hydrogen production 'dirty' and therefore non-ethical for banks.

7.3.3.4 Counterparty

1. Uninsurable components of the H21 infrastructure and operations require alternative and novel underwriting and guarantee mechanisms for intra-chain counterparty performance obligations.
2. New technology/supplier guarantees and warranties of insufficient quality to cover developers and operator's construction and operation risks.

7.3.4 Outcome Risks

Details in Appendix E.8

7.3.4.1 Emissions Reduction

1. Emissions reductions in H21 phase 1 do not meet expectations.

7.3.4.2 Negative Indirect Impact

1. H21 Phase 1 creates unintended disruptions across broader community and economy.

7.3.4.3 Public Budget

1. Potential for significant cost overruns and calls on government underwriting and support for delivering H21 city conversions and H_2-CCS infrastructure.
2. Significant cost improvements in other technologies make H_2-CCS chain with city conversion less cost effective for government.

7.3.4.4 Asset Underperformance

1. Premature CO_2 storage site closure during H21 phase 1.
2. Utilisation of the full capacity of initially oversized infrastructure in North of England does not materialise in the timeframe envisaged at FID.

7.4 Risk Mitigation Heat Map and Collaboration

7.4.1 Risk Mitigation Heat Map

The H21 risk mitigation heat map below can also be found in Appendix F.1 and F.2 in a larger format. This heat map has been created using the ELEGANCY WP3 methodology for summarising the risk matrix mitigation measures and responsible mitigating parties. A brief description on how to read the heat map and the conclusions from this analysis are provided in the following sections.

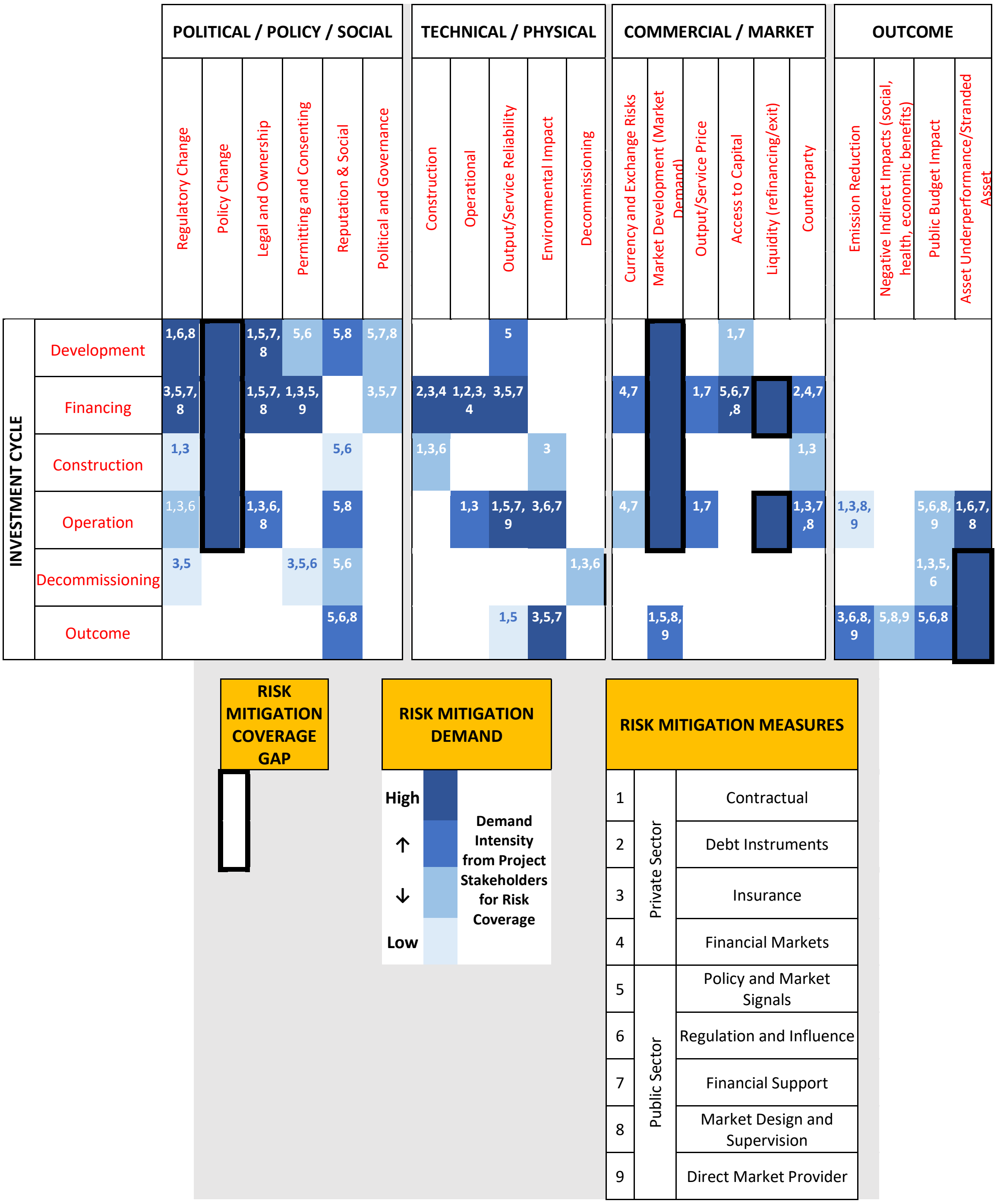

Figure 7-2 H21 Risk Mitigation Heat Map

7.4.2 Reading the Risk Mitigation Heatmap

The risk mitigation heat map is comprised of four dimensions:

1. On the left-hand axis is the stage in the development cycle of a given project or programme (in this case the H21 Roadmap);
2. Across the top axis are the risk categories and their sub-divisions contained in the full risk matrix;
3. The cell at the intersection of the development stage and the risk sub-division contains two pieces of information:
   i. The ‘demand intensity’ (on a scale from low to high) from stakeholders involved in the project or programme for a risk mitigation measure, and
   ii. The preferred classes of risk mitigation measure provided in the legend (divided between public and private responsibility).
4. The bold outline of cells indicates that there is currently no mitigation class or measure existing to manage that risk situation.

7.4.3 Risk Sharing and Collaboration Matrix

The H21 risk sharing and collaboration matrix below can also be found in Appendix F.3 in a larger format. This collaboration matrix reflects the risk sharing needed to deliver the H21 Roadmap and indicates the party or parties best placed to manage and mitigate the risks in the different stages of the H21 lifecycle based on the preferences for mitigation measures contained in the heat map in Figure 7-2. The next step in the ELEGANCY WP3 methodology is to select a collaborative business model that reflects these risk sharing requirements. An H21 system business model is defined and presented in the next chapter.

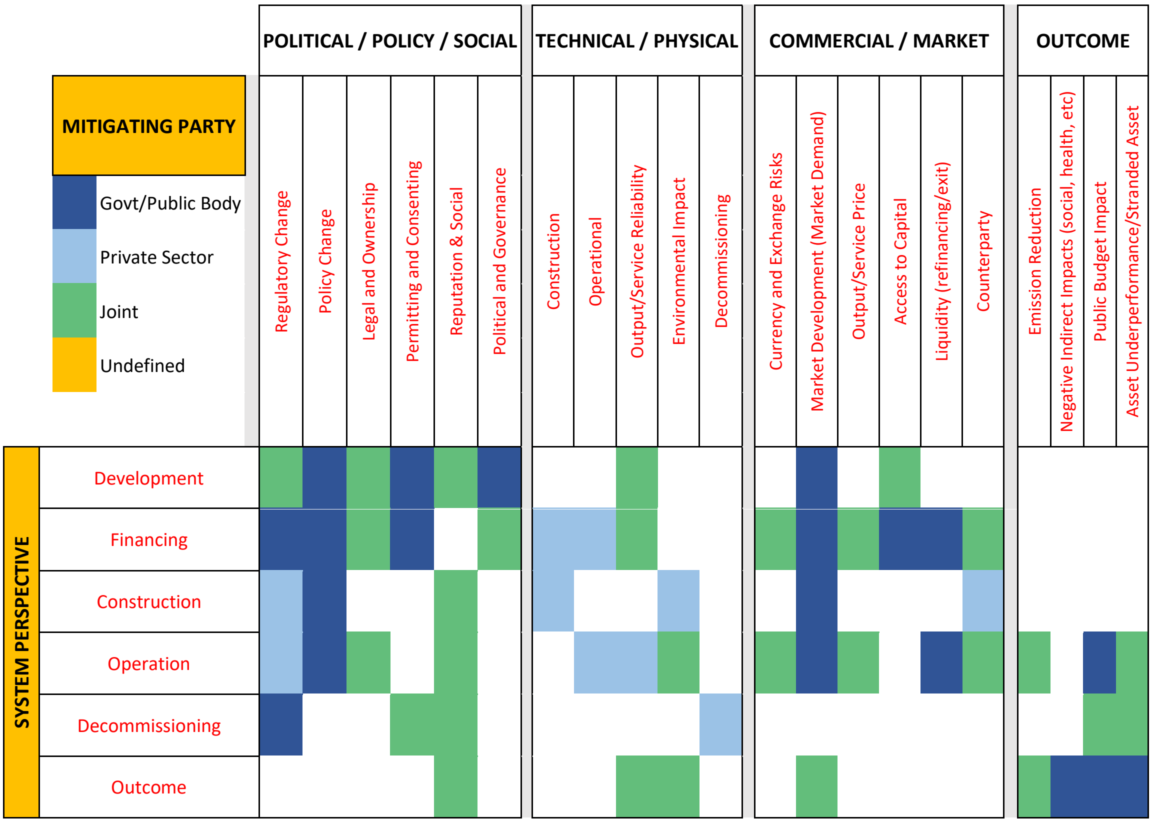

Figure 7-3 H21 Risk Sharing and Collaboration Matrix

8 H21 SYSTEM BUSINESS MODEL

In this chapter, a conceptual business model at system level for delivery of the H21 Roadmap is presented with proposed government interventions to address the system investment barriers presented in Section 7.2 and the major risk gaps highlighted in the risk mitigation heat maps in Section 7.4. The system business model described in Section 8.3 below has been developed taking into account the business and investment context including the policy and market analysis (presented in Chapter 4), and the system business drivers (presented in Section 8.1 below). Hydrogen retail is not included as a separate business sector. The assumption is that free enterprise retail businesses for hydrogen supply will be the same or similar to those currently existing for natural gas and electricity.

The Business Model Selection tool developed in ELEGANCY WP3 was used to support the definition of this conceptual business model.

8.1 System Business Drivers

A high-level qualitative assessment of the system business drivers was carried out using the business model selection tool. Extracts from the Excel tool are provided below with commentary for each of the system driver categories. Sectoral business drivers were also assessed using the relevant section of the business model selection tool and the results are included in Appendix G.1.Sector Drivers

8.1.1 Government Policies

CATEGORY	ASPECT TO BE RATED	RATING
Government Policies (energy & climate change)	**CURRENT:** Extent of energy and climate change mitigation policies for large scale energy transformation and relevant government's current commitment to low carbon development	Medium
	FUTURE: Confidence in the country's development of energy and climate change policies and relevant government's commitment for large scale societal low carbon energy transformation	Medium
	Availability of energy and/or climate change mitigation policy incentives for large scale energy projects	Low
	Alignment of energy policies with climate change targets	Medium
	Experience of different levels of government (central, regional, local) collaborating together to implement energy and climate policies	High

Key political and policy drivers are:

a. the obligation to meet the UK and international binding climate targets, translated in the recent policy of Net Zero Emissions by 2050[112]; and

[112] The Climate Change Act 2008 (2050 Target Amendment) Order 2019, op. cit.

b. to address the increasingly strong societal pressures (and associated economic disruption) to respond to the global climate crisis.

There is a growing recognition of the need for a complete energy system change rather than isolated sectoral actions, some of which include the necessity to deploy a CO_2 T&S infrastructure. This infrastructure can facilitate negative emissions technologies and strategic decisions to orchestrate a transition away from fossil fuels as the main energy source in the economy. However, the policy gap analysis in this case study highlighted the lack of actual climate mitigation policies to support the deployment at scale of infrastructure for clean fuels or decarbonisation of existing technologies.

Despite many headline policy announcements, policies with firm energy system commitments and interventions are still needed to provide certainty and stability for investors. Interventions in the form of policies and incentives for large scale infrastructure development now need to be structured and coordinated in a way that incorporates the three key principles defined in this study: system focussed anchor projects, low regrets investment, and creation of real options for the decarbonisation pathway.

System change through regional collaboration will require a structured approach coordinated by a government body or collective of government bodies with a governance mandate.

8.1.2 Institutional Drivers

CATEGORY	ASPECT TO BE RATED	RATING
Institutional (infrastructure)	**CURRENT:** Status and strength of large-scale energy infrastructure creation/development policies	Low
	FUTURE: Confidence in the evolution of the country's large-scale energy infrastructure creation/development policies	Medium
	Availability of large-scale infrastructure investment incentives	Low
	Availability of contractual frameworks for infrastructure investments	High
	Existing market and infrastructure regulation capability	High
Institutional (Business Models & PPP)	Level of pre-determined government preference for a specific business model (or infrastructure service provision and delivery)	High
	Level of experience with PPPs in the country	High
	Strength of the organisational and sectoral capacity of the public sector to implement different types of PPPs	High
	Adequacy of the country's governance framework for implementing different types of PPPs	High
	Flexibility of public sector to engage with private sector and to define and/or adapt PPP models for new sectors	Medium

The UK has vast experience of public-private partnerships for infrastructure investment and the necessary governance with in-country capability to deliver a broad range of public-private structures. The UK government's infrastructure development model is based on a strong preference for construction and delivery of infrastructure services through the private sector, which somewhat limits its options for delivery.

The business sectors of the H_2-CCS chain have the potential to be privately owned with varying levels of government oversight, support and regulation. The private sector has shown an active interest in early participation in the decarbonisation of the energy system albeit limited to their respective core activities and shareholder interests. Investment therefore remains subject to satisfactory government interventions to remove investment barriers and mitigate major business risks.

The private sector has traditionally and understandably sponsored projects consistent with their own company's objectives and it is critical that mechanisms to achieve the system objectives are fully integrated in the system business model.

8.1.3 Financing (Private and Public)

CATEGORY	ASPECT TO BE RATED	RATING
Financing (private sector)	Country attractiveness for infrastructure/low carbon energy investment (equity)	High
	Availability of bank financing (debt)	High
	Cost of financing for infrastructure investments	Low
Financing (public sector)	National debt level	Medium
	Extent of budgetary constraints (negative impact on financing capacity)	Medium
	Impact of fiscal rules (negative impact on financing capacity)	Medium
	Impact of public sector accounting rules (negative impact on financing capacity)	High
	Availability of public financing (bonds)	Medium

The UK has good historical access to private infrastructure financing at competitive cost and is an attractive country for private sector investment. The UK has some limitations on public sector financing as a result of budgetary constraints, national debt level and the impact of fiscal rules. This situation is likely to worsen and reduce the flexibility for government financing as a result of the COVID-19 crisis.

8.1.4 Market Development

CATEGORY	ASPECT TO BE RATED	RATING
Market Development	**CURRENT:** Status and strength of low carbon market creation/development policies	Medium
	FUTURE: Confidence in the evolution of the country's low carbon market creation/development policies	Low
	Government willingness to intervene in creation of new low carbon markets	Medium
	Government willingness to socialise costs of developing new markets and infrastructure	Medium
	Government willingness to use centralised system design, planning and coordination for market development	Low
	Institutional experience with delivering/managing market support and development mechanisms	High
	Private sector ability to undertake low carbon market development without government support	Low

The market failure analysis (presented in Section 4.4) has highlighted the major gaps across the proposed H21 H_2-CCS chain. There is a need for substantive government intervention both to centralise and coordinate market development and to create coherent long-term public sector funding mechanisms, backed by the public, that will encourage the private sector to invest and deliver the new infrastructure.

The UK has the necessary institutional experience to proactively deliver and manage such market development mechanisms though it is has not so far shown the willingness to intervene at scale and to socialise the early market creation costs. The lack of a strong strategic rationale and the pressure to act in the short term combined with the outcome risks and technology/market uncertainty have delayed any real decision and market making action.

8.1.5 Macroeconomic Drivers

CATEGORY	ASPECT TO BE RATED	RATING
Macroeconomic	**CURRENT:** National carbon pricing model: robustness, positive impact on private sector business decisions to decarbonise	Low
	FUTURE: Uncertainty of carbon pricing and impact on private sector business decisions	High
	National GDP per capita and trend	High
	Level of inflation	Low
	Unemployment Rate (national)	Low

Overall, the UK has good macroeconomic indicators – before the COVID-19 pandemic – with high GDP per capita, low unemployment and low inflation indicating a strong ability to finance (directly or indirectly) new infrastructure investment. However, the carbon pricing model, uncertain in its current form with the departure of the UK from the European Union, is insufficient to drive major business sector decisions to decarbonise. The time required to develop and implement a UK ETS (coupled or not to the EU ETS) as well as other carbon tax mechanisms proposed for review in the 2020 Budget is not likely to be fast enough to have a positive impact on the public and private investment decisions for the H21 Roadmap that should be made before 2023 (before the end of the current parliament).

A strong preference is now emerging across Europe for the concept of sector coupling whereby infrastructure development should fully integrate the synergies between economic sectors, between the existing and emerging decarbonisation technologies, and retain optionality over time for changes in technology trajectory. Underlying this principle is the avoidance of locking in traditional fossil fuel technologies. The H21 Roadmap will be well served by similar system-level thinking about the economy and pathway to net zero emissions.

8.1.6 Legal and Regulatory Drivers

CATEGORY	ASPECT TO BE RATED	RATING
Legal and Regulatory	Adequacy of legal / regulatory / policy framework in the country to implement different types of PPPs	High
	Cross border waste management - extent of legal constraints on structure of H2-CCS chain	Low
	European State Aid legislation - Extent of constraints on public sector incentivisation	Medium
	Environmental liability legislation - Extent of constraints on private sector investment	Medium

The legal and regulatory landscape in the UK is very mature for the type of infrastructure and market functioning required by H21. A functional regulatory framework agreed between government and the private sector to govern the business model and investments in the H21 system is currently being worked on with additional funding and cooperation from Ofgem. Nevertheless, a number of issues still need to be addressed to prevent problems during the implementation phase and subsequently during the development of markets and operation of the infrastructure. An example is the need to ensure consistent laws and regulations between end use hydrogen markets and those governing CCS permitting and operations so that construction and/or service delivery are not affected. It is unlikely that such matters will not be handled effectively, given the institutional capability in the UK, if there is a coordinated oversight and governance of the process leading to FID for H21.

A legal review conducted in ELEGANCY WP3 notes that although Brexit may present challenges to the H21 Roadmap, it also presents an opportunity to develop much more ambitious policies, market development and funding mechanisms (free from EU State aid constraints) which target UK-specific market conditions and better fast track H_2-CCS deployment. One of the opportunities may well be to revisit the regulations governing offshore CO_2 storage to make them more 'user friendly' to the private sector. Indeed, the UK would have the scope to construct a more fit-for-purpose regime to handle a number of CCS-related liability and regulatory barriers to investment.

8.1.7 Societal Drivers

CATEGORY	ASPECT TO BE RATED	RATING
Societal	How positive is the public opinion with regard to hydrogen as a future low carbon energy source?	Medium
	Extent of public education and training programmes directly related to the energy transformation required to meet climate targets	Low
	Extent of trust in oil and gas companies to deliver low carbon energy future	Low
	Extent of public sentiment to address climate change and environmental issues	High
	Willingness to pay for related health and environmental benefits	Medium

Key societal drivers include:

a. Increasing public pressure for action to address the worldwide climate crisis by moving away from a fossil fuel economy – through direct action and pressure on companies, investors and governments. A number of cross-European movements are gaining momentum and beginning to successfully create disruptions (for example a recent UK Court of Appeal ruling found that the new Heathrow runway national planning statement did not take into account the government's legal climate commitments).
b. Low confidence in the private oil and gas companies to manage such a system change in the interests of the public – given the financial risk of underutilising their existing assets and booked hydrocarbon reserves.
c. Lack of awareness of CCS across the public, and a general association that CCS supports the continuation of the fossil fuel economy.

Creating a H_2-CCS business case/business model which will gain societal acceptance is critical. The H_2-CCS proposition needs to address the moral hazard of locking in a fossil fuel future by using and subsidising CCS and needs to ensure that the role and development of CCS is strictly governed and restricted to facilitating a transition to a resilient 'fossil-fuel' free economy. Education and communication will be required to raise awareness first, followed by articulating the social, health and economic benefits of a clean energy system.

8.2 H_2-CCS System Deployment

The system business model for the gas network conversion is structured so the deployment pathway is executed over a number of phases to be consistent with the H21 North of England (NoE) study. This allows for management of outcome risk and investment barriers with regard to unreliable H_2 supply and underutilised H_2 and CO_2 infrastructure assets whilst offering flexibility for the future use of those assets. A conceptual system deployment is presented in the sections below. The timing and duration of the first phase needs to be such that Phase 2 commences in 2028-29. Based on the H21 NoE study this could be achieved with phase 1 lasting 2-3 years and first CO_2 injection commencing in 2026.

8.2.1 Phase 1: Early Infrastructure Deployment and Proving

8.2.1.1 Objectives

1. Deployment of H_2 as a new clean energy source with sustainable production pathways which can be used to decarbonise all business sectors of the economy utilising existing technology.
2. Proving the technical operability and potential of H_2-CCS to decarbonise the UK energy system. Reducing the commercial and operational complexity and mitigating the risks ahead of a full network conversion.
3. Create competitive alternative fuel for customers (industry, power generation and residential customers).
4. Anchoring the investment with an oversized infrastructure at scale and service to dispose of CO_2 cost effectively and with minimum risk.
5. Creating future optionality for energy system decarbonisation, including negative emissions technologies and offset markets.

8.2.1.2 Key Sectoral Activities

1. H_2 Production Facility: H_2 is produced at scale using proven technology in a modular plant which can be easily expanded. H_2 volumes are secured through a combination of low risk/low regrets guaranteed market uses including injection into the gas network (blending), decarbonisation of conventional power station(s) (through blending with or replacement of natural gas) and low-cost fuel switching opportunities in large industrial clusters in the north of England.
2. CO_2 capture: centralised capture at scale integrated with the H_2 production facility, which offers potential for economies of scale as H_2 production is expanded further in the north of England and capture technology is replicated at scale.
3. T&S infrastructure: deployment of oversized T&S infrastructure at scale using large capacity reservoirs in the Southern North Sea to support the production of low carbon 'blue' hydrogen. Design includes optionality for further expansion, satellite fields, injection back-up and shipping connections.
4. Local H_2 storage developed, reliability tested and proven through supply to a flexible power plant.
5. Collaboration with other industrial clusters to maximise early opportunities to connect infrastructure and synergies in technology deployment (such as fuel switching).

8.2.2 Phase 2: First City Conversion and Infrastructure Expansion

8.2.2.1 Objectives:

1. Execution and proving of first city conversion - Leeds (1GW).
2. Connection of additional local industrial clusters to H_2-CCS infrastructure.
3. Deployment of renewable-generated 'green' hydrogen production at scale wherever possible.

8.2.2.2 Key Sectoral Activities

1. H_2-CCS chain: expansion for first city conversion when initial H_2-CCS infrastructure has been proven and gas network conversion project is ready and supported by public opinion.
2. H_2 production:
    - expansion of existing facility to supply H_2 for city conversion.
    - optionality for further expansion to supply other business sectors: power, industrials, transport.
    - deployment of first 'green' hydrogen production facility integrated with offshore wind transmission entry point in Humberside.
3. H_2 storage: development and build out of new storage facilities.
4. T&S infrastructure:
    - connection of other regional industrial clusters to initial CO_2 T&S infrastructure by pipe or ship depending on volumes.
    - connection of new users supported by government intervention: e.g. DACCS and BECCS.

8.2.3 Phase 3: NoE Network Conversion and Flexible Infrastructure Expansion

8.2.3.1 Objectives

1. Executing the North of England Gas Network Conversion (12GW)
2. Building on existing CO_2 T&S infrastructure to support further decarbonisation by either increased H_2 usage or direct carbon capture.
3. Connection of other regional clusters across the country and/or potential development of additional T&S infrastructure in East Irish Sea.
4. Further deployment of green hydrogen production.

8.2.3.2 Key Sectoral Activities

1. H_2-CCS chain: further expansion of H_2-CCS chain for gas network conversion of NoE when city conversion has been proven.
2. H_2 production: further expansion of initial H_2 production facility and/or construction of separate facility.
3. H_2 storage: development and build out of new storage facilities across the north of England.

8.3 H21 System Business Model Example

The System Business Model presented in this section is based on the methodology developed for ELEGANCY WP3 and uses four main components of risk transfer (or sharing) between the public and private sector:

1. Assets and Rights Ownership;
2. Capital Sourcing;
3. Market Development (including revenue support mechanisms); and
4. Physical Delivery (including facilitating commercial structures).

Figure 8-1 Example H21 system business model

	Conceptual System Business Model	Asset & Rights Ownership	Capital Sourcing	Market Development		Physical Delivery	
				Responsibility	Remuneration	Responsibility	Business Structure
H_2 INFRASTRUCTURE	H_2 Production with Integrated CO_2 Capture	PRIVATE	PRIVATE	PUBLIC	Targeted Revenue Support	PRIVATE	Free Market Enterprise
	H_2 Transmission	PRIVATE	PRIVATE	PUBLIC	Price Regulated Revenue + Construction Support	PRIVATE	Regulated Asset Base (New)
	H_2 Distribution	PRIVATE	PRIVATE	PUBLIC	Price Regulated Revenue	PRIVATE	Regulated Asset Base (Existing)
	H_2 Storage	PUBLIC	PRIVATE	PUBLIC	Performance Based Revenue	PRIVATE	Public Concession (Design-Build-Finance-Operate)
CO_2 INFRASTRUCTURE	CO_2 Transmission	JOINT	JOINT	PUBLIC	Price Regulated Revenue	PRIVATE	Joint Venture
	CO_2 Storage	JOINT	JOINT	PUBLIC	Price Regulated Revenue	PRIVATE	Joint Venture
H_2 END USE MARKETS	Industry	PRIVATE	PRIVATE	PUBLIC	Targeted Revenue Support	PRIVATE	Free Market Enterprise
	Centralised Heat & Power	PRIVATE	PRIVATE	JOINT	Targeted Revenue Support	PRIVATE	Free Market Enterprise

8.3.1 Asset and Rights Ownership

1. Private ownership is envisaged for most sectors – this solution builds on the established ownership models for gas transmission, distribution and supply, gas processing and power generation.
2. A joint public-private ownership is suggested for the CO_2 T&S infrastructure to facilitate the management and delivery of this critical chain component for the overall outcome of system decarbonisation. At a minimum government underwriting of uninsurable storage risks and assistance with the structuring of the financial security is essential to remove the investment barriers for the private sector. A joint venture can also allow government to steer infrastructure expansion, have full transparency over performance and pricing, ensure fair access to all users at the appropriate cost and collaboration with all the regions. The government can demonstrate its commitment to long term infrastructure use and net zero policy delivery to facilitate investor participation and capital sourcing from the private markets.
3. Until such time as end-use markets for hydrogen have reached a critical level of demand and become self-sustaining the investment in, and provision of, H_2 storage services will be highly uncertain and risky. In this system model, government ownership of initial H_2 storage facilities is proposed as a 'public-good' infrastructure with a public concession awarded to the private sector through a competitive bid process.

8.3.2 Capital Sourcing

Private capital sourcing is envisaged though government intervention may be required for the CO_2 T&S infrastructure and for the H_2 production facility, as necessary to support private capital sourcing and reduce investors' and banks' financial exposure.

8.3.3 Market Development

1. In all markets the government would be responsible for the market development of both H_2 and CO_2 through the implementation of a number of government interventions via policy, regulatory, fiscal and financial means.
2. Hydrogen infrastructure remuneration.
   i. *H_2 production* in this business model follows a similar free enterprise model as with power generation supported by targeted revenue support in a form similar to a CfD with an entity such as LCCC, with all the capital and O&M costs of the facility covered initially. The gate price of hydrogen would be the same or lower than that of natural gas. The model could include some contractual flexibility for initial underperformance of the facility (especially the carbon capture component) and also performance and availability-based incentives/penalties.
   ii. *H_2 transmission and distribution* would use a similar price regulated revenue model as currently in place for natural gas – possibly with some additional construction support for the new parts of the H_2 transmission system.
3. CO_2 infrastructure remuneration.
   i. *CO_2 infrastructure* would be structured through a public/private sector joint venture with price regulated revenue to cover the capital investment cost and O&M costs for the initial oversized capacity at an agreed rate of return. Government partial ownership would offer flexibility in the negotiation of

risk/return with the co-investors and regulatory backed revenue would provide guarantees for the investors with regard to the market demand uncertainty, i.e infrastructure usage. Regulation would define the apportionment of the service charges between the initial H_2 production facility and additional and future users.

4. Hydrogen end use markets.
   i. *Commercial and domestic customers* would be serviced by free enterprise retail businesses for hydrogen supply that will be the same or similar to those currently existing for natural gas and electricity.
   ii. *Industrial decarbonisation through H_2 fuel switching* would be the responsibility of the privately-owned industrial companies. The combination of hydrogen being offered at the same cost as natural gas, EU ETS (or similar UK ETS) pressures, branding and reputational value may be sufficient to justify the fuel switching capital expenditure. Additional support may be necessary in the form of capital grants for specific industries.
   iii. *H_2 (or blended) power generation* would be structured on the traditional free enterprise business model already established in the power generation sector. The investors in a new or refurbished facility would be remunerated using a targeted revenue support mechanism based on the existing CfD mechanism with LCCC and the capacity market to cover the additional capex and opex costs. Commissioning delays and technical issues related to the technology could be handled contractually and contractual mechanisms could be defined to cover the risks of plant unavailability (or higher emission costs if natural gas is burnt) due to H_2 unavailability.

8.3.4 Physical delivery

Delivery of the infrastructure, facilities and services is allocated to private investors, and is consistent with the established models in the UK. The technologies proposed are relatively proven and there has been interest expressed in the ongoing sponsored projects supported by experience and expertise available in the private sector.

8.4 Government Intervention

A number of key government interventions are presented in this section as part of the conceptual system business model developed in this case study. This is not intended to be an exhaustive list of the interventions required to address all the business risks identified in the investability and risk analysis.

8.4.1 Market Development

Four market development mechanisms are suggested and presented conceptually below. These are intended to address the market development investment barriers and focus on creating markets respectively for hydrogen, CO_2 and for hydrogen fired power generation. The purpose is to help establish early markets for emissions-free production technologies in order to allow and facilitate the development and evolution of profitable business models for clean and sustainable energy.

1. Clean(er) Power Plant Support Mechanism:
   - Hydrogen power plant (burning a blend of natural gas and H_2 or 100% H_2 depending on technology availability) supported by contract-for-difference (CfD) mechanism (and capex support mechanisms as appropriate) with additional guarantees.
   - Financial guarantees against unavailability of hydrogen and EU/UK ETS penalties if there is a need to burn natural gas.
   - The mechanism would support the life extension of old power plant with modern 'clean' technology or the construction of new hydrogen power plant.
2. Hydrogen Market Mechanism:
   - Government intervention to create an initial market for hydrogen as a 'clean' fuel by offering hydrogen at a competitive price to natural gas/fossil fuel.
   - Implementation of a producer responsibility support mechanism[113] for waste management and system change to support the financing of initial H_2-CCS infrastructure. An example is a CO_2 levy on natural gas/fossil fuel-based products for the management of the resulting waste (emissions).
   - A CO_2 levy/tax would cover all the capital and operating costs of 'blue' H_2 production (including CO_2 T&S). A levy exemption would be available for H_2 production and for other users as appropriate (low income customers, specific business sectors).
3. Green Hydrogen Development Mechanism:
   - Creating a pathway using innovation funding to a clean 'green' hydrogen obligation.
   - Initially focus on provision of innovation and demonstration funding for green hydrogen technology.
   - Funding of construction of first clean hydrogen plants (by capital grants, or the fossil fuel levy for example).
   - After the gas network conversion is completed and H_2 is being supplied to the captive residential market, creation of a 'clean hydrogen obligation' - an obligation for suppliers to source a percentage of hydrogen from clean sustainable sources which increases over time. This is a similar mechanism to the Renewable Obligation.
4. CO_2 Market Mechanism:
   - Government intervention to create a long-term market for CO_2 disposal services to maximise use of T&S infrastructure and provide future stable funding for CCS.
   - Implementation of producer responsibility mechanism for carbon[114] by introducing a statutory obligation on oil and gas producers/importers in the UK to store a certain amount of CO_2 each year and if this is not possible, an obligation to purchase storage evidence through a fund – with increasing levels over time.
   - The fund can be an investor in CCS infrastructure or a direct buyer of CO_2.
   - The fund would be able to contract with emitters to justify funding for their decarbonisation projects. This would create a market mechanism to choose the most cost-effective projects and supplement the EU/UK ETS price.

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[113] Zero Emission Resource Organisation, 2019, *New business models for carbon capture and storage*, p17, https://zero.no/wp-content/uploads/2019/09/rapport-eng-ccs-v6.pdf, accessed 31st March 2020
[114] Zero Emission Resource Organisation, 2019, p18, op. cit.

8.4.2 Policy Change

A number of government interventions and contributions forming part of the collaborative approach to the system business model are suggested below to help mitigate the private sector attitude to the risk of policy change once investment decisions are made. These can provide guarantees and increased certainty for improving private sector investability in the development of H_2-CCS infrastructure:

1. Strengthened UK government policies to build credibility with private investors for 4th and 5th carbon budgets and 2050 net zero target.
2. Government and parliament commitment to first H_2 conversion in statute with mandate and budget given to Infrastructure and Projects Authority (or similar).
3. Utilise a binding umbrella (State) agreement split between H_2 and CCS chain with the government providing state mandates and assurances to enable financing for the integrated H21 full chain infrastructure (including guarantees on coordinated investment, delivery and intra-chain counterparty performance).
4. Gas network conversion and H_2 storage and transmission can be funded by legally binding and established network funding mechanisms (e.g. regulated asset base model).
5. Setting up an executive committee to drive H_2-CCS across UK with engagement of all key parties and oversight of regional sub-committees for market and infrastructure delivery.

8.4.3 Outcome Management

Government participation in the system business model can help address key investment barriers for the government itself related to uncertainty in achieving the desired H21 outcomes. Some of these have synergies with the needs of the private sector investors and operators.

1. Coordination, steering and governance:
   - Government body to be set up to coordinate regional availability of H_2 to potential key users, deployment of T&S infrastructure, and facilitate collaboration between regions and industrial clusters.
   - Part public ownership of T&S infrastructure.
2. System design flexibility and decarbonisation optionality:
   - H_2 system: flexibility on early H_2 use through blending in gas networks and/or in power plant and flexibility through deployment phases with modular H_2 production to fit with demand.
   - CO_2 T&S: selection and permitting of initial storage reservoir with high readiness level and with back up and expansion options in proximity.
3. Remuneration and ownership models:
   - Capacity and performance-based remuneration for H_2 production facility and power plant.
   - Regulated asset base model for H_2 and CO_2 transport and storage with penalties for underperformance.
   - Part public ownership of T&S infrastructure to ensure transparency, securitisation and performance.

9 H21 SYSTEM BUSINESS CASE TEMPLATE

9.1 Summary

The H21 business case template summarises the analysis contained in the previous chapters of this report. It provides an early stage snapshot of the justification to proceed with the H21 Roadmap beyond the concept definition study already undertaken by Northern Gas Networks et.al.[115], and the research and data collection currently being progressed in the government-sponsored collaborations described in Appendix B. The business case summary is a view from an objective observer of the system development proposition and therefore does not distinguish between preferences of the potential public and private sector participants. Hence, where appropriate, the templates of the WP3 methodology are modified to reflect this independent perspective.

The relevant components of the full business case template summarising this case study are included in Appendix H.

9.2 Business Case Definition

9.2.1 Investment Proposition

> *A commitment to phased investment in H_2-CCS infrastructure to cost effectively decarbonise residential heating in the north of England and to support UK energy system decarbonisation to meet a net zero emissions target by 2050.*

An initial commitment by 2023 to the construction and funding of a first phase H_2-CCS network in the north of England is necessary to prepare for a gas network conversion commencing in 2028-29 and the development of markets for H_2 and CO_2. The initial H_2-CCS system would be commissioned in 2026 and composed of:

a. a modular H_2 production facility at scale [initial capacity 1.35 GW];
b. associated H_2 transmission pipeline(s) and geological cavern storage;
c. facilities and market appliance upgrades for H_2 blended with methane up to 20%;
d. conversion or construction of a power station capable of burning blended natural gas up to 90% hydrogen [initial capacity of 2 or 3 440 MW turbines];
e. connection to a large industrial cluster [Humber, Teesside, Manchester/Liverpool];
f. oversized CO_2 T&S infrastructure in the Southern North Sea [initial pipeline capacity of 15-20 Mt per annum].

This system will be supported by the creation of a new fossil fuel levy and CO_2 storage obligation on oil and gas producers/importers combined with a government commitment to the deployment of green hydrogen production technology (electrolysis) commensurate with an eventual minimum captive market size for H_2 use.

The subsequent phases of investment will focus on the decarbonisation of the gas network through the further expansion of the H_2-CCS infrastructure and will be adjusted to reflect

[115] Northern Gas Networks et. al., 2018, op. cit.

the outcome from the first investment phase and the evolution of system decarbonisation pathways.

9.2.2 Case Study Parameters and Business Drivers

The parameters defining the metrics for this UK business case assessment were originally outlined in ELEGANCY report D3.2.1[116] as:

a. Climate Business Context
  - National policies
  - H21 Project Roadmap viability for multiple stakeholders
  - CO_2 sources

b. Markets
  - Hydrogen potential and expansion
  - CO_2 transport and storage service

c. Delivery
  - H_2-CCS infrastructure
  - Regulatory
  - Customer
  - Government subsidies

These parameters were expanded during the course of this study as a result of stakeholder engagement to further include:

d. Collaboration and institutional capability
  - Public-private sector risk sharing
  - Governance
  - Outcome management

e. Financing
  - Public sector
  - Private

f. Sector coupling
  - Low regrets investment
  - Real options

g. Societal acceptance
  - Safety
  - Fossil fuel moral hazard

[116] ELEGANCY Publications, 2020a, op. cit.

9.3 Dimension 1: Strategic Rationale

In this section, the key strategic dimensions for the H21 Roadmap investment proposition are assessed using the WP3 business case assessment tool. Justification is provided below with a high-level alignment rating.

9.3.1 Meeting the Government Strategic Objectives

1. Environmental:
   - The project supports UK policy of heat decarbonisation and obligations of the Climate Change Act. Hydrogen has the potential to facilitate decarbonisation with minimum cost and disruption to customers while using established gas infrastructure to manage supply. H21 North of England presented a vision for decarbonisation of 70% of meter points by 2050 using a regional roll out strategy (the first phase would achieve 14% of UK heat and 12.5Mtpa of CO_2 avoided by 2034).
   - It facilitates the use of hydrogen across all business sectors as an alternative 'clean' fuel and supports decarbonisation through use and further expansion of oversized CO_2 T&S infrastructure.
2. Economic:
   - Facilitates development of a new H_2 supply chain.
   - Sustains the existing gas distribution/transmission businesses for the long term.
   - Protects the economic interests of industrial clusters with cost effective optionality between fuel switching and carbon capture.
   - Sustains economic value from oil and gas in country through energy transition.
3. Financial:
   - Initial infrastructure is created at scale in line with recommendations to achieve cost effectiveness.
   - Technical risks are minimised through use of proven technology, initial use of H_2 in sectors with operational/fuel flexibility.
   - Government funding is minimised through private sector ownership and delivery in most business sectors and use of regulated returns.
4. Political:
   - Low regrets proposition with phased system deployment.
   - Optionality and flexibility are built-in and there is minimum risk of under-utilisation. Anchoring the CCS infrastructure on hydrogen allows optionality for end users to either use a clean fuel (hydrogen) or use carbon capture (dependent on specifics of industry).

9.3.2 Sources of Value (Public Sector)

The proposition incorporates considerable optionality to access additional sources of value in a number of business sectors:

1. Industrial: the project would create the ability for industrials to decarbonise partially at minimum cost, commitment and complexity through fuel switching. This could create a competitive advantage for UK manufacturing.
2. Power generation: the project would both facilitate the decarbonisation of the existing conventional power sector without large and complex investments in stand-alone carbon capture facilities for plants with limited life span. It would

support further renewable electricity penetration by acting as a backbone for new clean flexible back-up generation and energy storage.
3. It creates opportunities for the UK to import CO_2 from other countries by building on the competitive advantage of owning large scale CO_2 storage sites.

9.3.3 Justification for CCS

1. Short term: a reliable large-scale CCS infrastructure is necessary for the decarbonisation of the NoE gas networks by hydrogen – even limited to the first deployment phase - and needs to be fully proven ahead of any decision to carry out large scale conversion of residential heating.
2. Medium term: the CCS infrastructure is needed both to create optionality for the decarbonisation of existing fossil fuel-based technology (industry, conventional gas fired power generation) with no clear other alternatives and to facilitate the deployment at scale of negative emission technologies such as biomass energy with CCS. It will also enable testing and early deployment of technologies such as direct air carbon capture (and other innovative technologies). The decision to anchor the infrastructure on hydrogen production offers the government time and flexibility to assess the relevant industries in the light of market and technology development and to choose the most appropriate decarbonisation pathway.
3. Long term: a reliable large-scale CCS infrastructure is essential both for the decarbonisation of the NoE gas networks by hydrogen and to support the broader system decarbonisation required to achieve net zero emissions and the transition to a sustainable clean economy.

9.3.4 Societal Acceptance

1. CO_2 transport and storage is presented as a waste disposal service to support the deployment of hydrogen as a new energy source (for heating and power generation) with the potential to be produced sustainably at scale and to replace natural gas. It is clearly articulated as a shift away from CCS supporting the business as usual fossil fuel technologies.
2. The infrastructure is to be paid for by charges on natural gas/fossil fuel by all users to make hydrogen price competitive with natural gas – rather than charge the public to develop an initial infrastructure which would benefit the fossil fuel industry without creating new sustainable energy pathways.
3. The project incorporates the planned transition away from fossil fuel through the deployment and development of clean hydrogen production technology in a committed but gradual manner proportional to the penetration of hydrogen into the energy market. This will be supported by a number of specific legal and regulatory interventions.

9.3.5 Competition and Collaboration

1. This project is designed to support a broader system decarbonisation and integrate all the regions in a phased development rather than focus on development of a specific region. It is initially focused on the north of England for strategic reasons: concentrated geographic location of emission intensive sectors (heat, industry, power), existing assets (H_2 and CO_2 storage potential, gas and electricity network infrastructure). The selection of an initial region/hub for the project would be made

based on system deployment considerations and ensure that the benefits are shared and that other regions are not at a disadvantage.
2. The H21 project activities are being progressed by the gas network companies and focused on the gas network conversion with government support to test and develop a safety case.
3. This project proposition which incorporates the full H_2-CCS chain would be in competition with the existing Net Zero Teesside project, the Merseyside HyNet project, the Zero Carbon Humber project, and other projects around the country (the Acorn project in Scotland for example). However, the government would be expected to act to support a coordinated approach between all those projects and investors.

9.3.6 Scaling Up

1. The planned system deployment in Section 8.2 articulates how the project could be scaled up from an early proving phase to a city conversion and later to a North of England conversion.
2. The project would easily integrate other energy intensive sectors for a further expansion of the use of the CCS infrastructure: industrials and power generation (fuel switching or carbon capture), BECCS and DACCS.
3. The project is planned around a coordinated decarbonisation approach of the regions of the north of England. It integrates regions and cities, and connects Teesside, Humberside, the Manchester/Liverpool clusters, and Grangemouth cluster through a shared infrastructure.

9.3.7 Low Regrets and Optionality

This investment proposition is designed to create maximum optionality and enable low regrets decisions:

1. Each investment phase is designed to be modular with optionality for expansion and adjustments with market and technology developments.
2. Optionality for decarbonisation through disposal of CO_2 from access to T&S oversized infrastructure where the reliability and safety has been proven in the first phase and which can be easily expanded gradually to match demand:
    - Existing fossil fuel-based technologies with no alternatives;
    - Support for deployment of negative emission technologies such as BECCS and early DACCS technology.
3. Optionality for the development and deployment of clean/green hydrogen across the country by creating an early market for hydrogen which can be regulated and allow the future development of cost-effective green hydrogen options whether in-country or imported.

9.4 Dimension 2: Financial Costs and Benefits

The H21 North of England report provided a detailed analysis of the financial costs of each of the components of the H_2-CCS chain for the UK NoE gas conversion, which are summarised in Section 6.2.3. This study has not focussed on reviewing in detail and challenging any of the cost assumptions and models used by H21.

The conceptual business case presented in this report proposes an alternative hydrogen system deployment programme to address the investment barriers. This alternative is based on initial use of H_2 blended in gas networks and in regional power stations. The additional costs for this alternative are reviewed briefly below. In addition, an order of magnitude estimate is presented for the CO_2 tax or levy on natural gas.

9.4.1 Power Station Costs

We have assumed that the new combined cycle gas turbines (CCGTs) with a Development Consent Order in the North of England Humber region will be built in the 2020's with the latest turbine technologies and will be capable of burning high hydrogen blends (up to 90% by volume) by 2025-2030 without requiring new capital investments. This is consistent with the technical review and findings published in November 2019 by Element Energy[117].

9.4.2 CO_2 Levy

The numbers in this section are provided to illustrate the extent of funding available for initial H_2-CCS infrastructure through the proposed waste management producer responsibility mechanism of a CO_2 levy on natural gas.

Total UK gas consumption was 876TWh in 2019[118] and a 1p/th levy would therefore provide funding of £300m annually. Depending on fuel prices, this would correspond to a 4% increase at 25p/th (Sep 2019 prices) or 7% at 15p/th (March 2020 prices)[119]. In comparison, the proposed CCS infrastructure for the H21 project would have an estimated total capital cost of £1.34 billion and operating cost of circa £24 million per annum.

9.5 Dimension 3: Economic Value and Benefits

Economic value and benefits were not considered in this study beyond any of the emissions saving analysis carried out by the H21 project and the economic and societal benefits which have been carried out in relation to sponsored projects in Teesside and the Humber region. Summit Power completed a study[120] as part of their project in Grangemouth in 2017 and Equinor commissioned a report from Element Energy in 2019 about the direct benefits to the UK economy of various decarbonisation scenarios utilising hydrogen[121].

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[117] Element Energy Limited, 2019a, *Hy-impact series study 3: Hydrogen for Power Generation Opportunities for hydrogen and CCS in the UK power mix*, http://www.element-energy.co.uk/wordpress/wp-content/uploads/2019/11/Element-Energy-Hy-Impact-Series-Study-3-Hydrogen-for-Power-Generation.pdf, accessed 31st March 2020

[118] UK Government , *Gas Q4 2019 Statistics*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875527/Gas_Q4_2019.pdf, accessed on 31st March 2020.

[119] Ofgem website, February 2020, Day ahead gas prices at NBP, https://www.ofgem.gov.uk/data-portal/all-charts/policy-area/gas-wholesale-markets, accessed 31st March 2020

[120] Caledonia Clean Energy Project and Summit Power, 2017, op. cit.

[121] Element Energy Limited, 2019b, *Hy-impact series study 1:Hydrogen for Economic Growth, Unlocking jobs and GVA whilst reducing emissions*, http://www.element-energy.co.uk/wordpress/wp-content/uploads/2019/11/Element-Energy-Hy-Impact-Series-Study-1-Hydrogen-for-Economic-Growth.pdf, accessed 31st March 2020

9.6 Dimension 4: Commercial Feasibility and Delivery

This study has focused on the system level investment barriers and business risks, and the definition of a conceptual business model structure with system-level risk mitigation measures to address those. The detailed analysis of the commercial feasibility and delivery at a business sector and operational level (details of contractual terms and financing structures for example), as envisaged in this dimension was not undertaken as part of this research.

Risk mitigation measures are presented in Chapter 7 and the business model with proposed system deployment and government interventions are presented in Chapter 8.

9.7 Dimension 5: Technical Feasibility and Delivery

Similar to Dimension 2 above, the H21 North of England report provided a detailed analysis of the technical feasibility and delivery of each of the components of the H_2-CCS chain for the UK NoE gas conversion. These have been summarised in Chapter 6. This study has not focussed on reviewing in detail and challenging any of this work. Some additional technical feasibility points are made with regard to hydrogen use for power generation.

9.7.1 Power Stations

Element Energy[122] reviewed the existing hydrogen and gas power generating technologies and their likely evolution and concluded that:

- large scale H_2 gas turbines (H_2GTs) will be available by 2029-2030 at similar efficiencies to current natural gas CCGTs and very low NOx emissions, which would not require additional NOx capture investment; and
- many CCGT plants can run on a blend of hydrogen of natural gas and such an option is expected to be a lower cost than outright hydrogen turbine retrofits. Current gas turbines can use 30% (by volume) blending and the newer gas turbines that would be built in the mid 2020s can be expected to be capable of running on 90% blending.

Alternative options for extending the life of old CCGTs by either retrofitting H_2GT technology or refurbishing them with the latest technology are available but are likely to be more expensive. It may be preferable to defer the timing of such decisions until the H_2-CCS system is proven, the H_2 market is initiated and H_2 technology has developed further to minimise capex investment in the first phase of H21.

[122] Element Energy Limited, 2019a, op. cit.

9.8 Dimension 6: Outcome Management

Barriers and risks to achieving the desired outcomes for both public and private sector stakeholders in H21 have been reviewed in Sections 7.2.4, 7.3.4, 7.4 and Appendix E. In summary, the four principal outcomes assessed in this study are:

a. Emissions reductions;
b. Negative indirect impact;
c. Public budget impact; and
d. Asset underperformance, including stranded assets.

The following outcome management plan is consistent with the business model and business case presented in this report and is proposed to mitigate the system-level barriers and risks to achieving the desired H21 objectives through to 2035:

9.8.1 Emissions Reductions

1. Government to contract in partnership through an umbrella agreement with developers and operators of sufficient capability and financial strength; and
2. Modular design for the H_2 production and capture facilities to enable technology improvements/substitutions

9.8.2 Negative Indirect Impact

1. Create and execute a combined market and infrastructure development plan designed to incorporate the proposed phased system deployment including lower risk operations such as H_2 blending or use of H_2/Clean Gas Power station to prove the H2-CCS chain, build sufficient hydrogen production redundancy and establish back-up/seasonal storage facilities; and
2. Utilise an Executive Steering Committee to drive the H21 Phase 1 process with engagement of all key parties (grouped in regulatory, regional and functional expert working groups).

9.8.3 Public Budget Impact

1. Government to contract in partnership through an umbrella agreement with developers and operators of sufficient capability and financial strength to deliver H21 phase 1; and
2. Modular design of H_2 plant combined with H_2-CCS chain based on multiple users offers sufficient flexibility to adjust or stop further expansion.

9.8.4 Asset Underperformance

1. Utilise centralised hydrogen production combined with designed market development to provide more options for use of CO_2 T&S infrastructure than individual CO_2 capture projects/facilities;
2. Utilise an extended CO_2 storage site pre-FID appraisal and characterisation period including injection testing, pressure monitoring and 4D seismic surveying. Establish pre-appraised and characterised back-up storage sites prior to FID; and
3. Implement the government net zero, clean growth and industrial policies through a rigorous coordinated strategy comprising real options to ensure full utilisation of infrastructure that includes dealing with residual emissions via BECCS and DACCS technologies.

APPENDICES

A STAKEHOLDER ENGAGEMENT

This appendix summarises the outcomes from a programme of meetings, interviews and workshops held with a broad range of public and private sector stakeholders during the course of the ERA-NET ACT ELEGANCY and ALIGN projects. Meetings and interviews specifically targeting the H21 Roadmap were held with a number of public and private sector stakeholders in the period November 2018 to July 2019 around seven key themes described below. The meeting format used was free-flowing discussions on a confidential basis focussed on these themes and driven by participants' direct experience, the principal barriers and issues faced by stakeholders, and exploration of public-private solutions. In addition, the feedback and recommendations from the more general workshops were reviewed and distilled in order to extract the key points of relevance for the H21 UK Case Study.

A.1 Stakeholder Engagement Themes

A.1.1 Theme 1: Strategic rationale for Hydrogen/CCS

- What are your objectives and priorities?
- What is your strategic rationale and vision for hydrogen use and contribution to decarbonisation in your region or industrial cluster?
- How does it fit with the UK energy system decarbonisation? Competition or integration with other economic sectors?
- What are the main industrial sectors in the cluster? (chemical, refining, cement, steel, other)
- What are the key drivers for CCU/CCS decarbonisation for each sector? How do they differ?

A.1.2 Theme 2: Investment risks and investment barriers

- What do you think are the main investment barriers to H_2-CCS development?
- How do you see the impact of Brexit on H_2-CCS development?
- What do you think are the risks and main investment barriers to region or cluster decarbonisation? (commercial/market risks, technical/operational risks, political/policy/social risks, outcome risks)
- Sectoral versus system risks and barriers: key commonalities and differences for each hydrogen market or industrial sector. (for example: market uncertainty, international competition, technical complexity, age)

A.1.3 Theme 3: Market development

- How to address market failures
- Market enabler - discussion on role and value of market enabler/market maker
- Role of hydrogen as carbon free energy source vs individual sectoral decarbonisation
- Sectoral priorities - What are the sectoral priorities for decarbonisation in the region or cluster? why?
- How to address market failures for CCS as waste management service?

A.1.4 Theme 4: Preferences for risk mitigation/risk allocation

- Discussion on a number of investment barriers, discussion on options/preferences to address them, allocation between private and public sector. For example:
  - Slow hydrogen market development
  - CO_2 Storage liability
  - Cross chain default
  - Industrial downtime
  - International competitiveness

A.1.5 Theme 5: Public/private sector collaboration

- What is currently happening?
- How to facilitate engagement and develop joint solutions?
- How to address the mismatch between political mandate and the long-term H_2-CCS investment timeline
- Regional and cross-country collaboration

A.1.6 Theme 6: Region or cluster competition and phasing

- Advantages and risks of competition
- Coordination with other regions or clusters
- How to phase development across regions, clusters and nationally?

A.1.7 Theme 7: Financing structure

- Any preferences for financing? public/private sector
- Perspective on EIB or similar financing
- Differences between H_2 Production-Capture and CO_2 Transport& Storage? Individual subsidies vs central funding

A.2 Stakeholder Engagement Outcomes

A.2.1 Systems Thinking

A.2.1.1 System Strategic Priorities and Rationale

a. *The 2050 Net Zero target has changed the pathways and the decisions required*
   - Impossible to reach 100% decarbonisation without CCS – residual emissions from normal industrial/power generation processes (maintenance time, downtime, even emissions from hydrogen production).
   - Direct Air Capture with Carbon Capture and Storage (DACCS) and other negative emission technologies such as Biomass Energy with Carbon Capture and Storage (BECCS) will be necessary. They will require a CCS infrastructure but will not be able to fund it initially given the low capture volumes.
   - Any Net Zero pathway/Business Case needs to plan for the development and deployment of these innovative technologies.

b. *Clarity of strategic prioritisation is critical*
- There are multiple decarbonisation and economic policies and objectives across many sectors, contributing to the difficulty to make strategic decisions on large scale financial commitments: industrial strategy, individual sectoral. decarbonisation strategies, economic growth, infrastructure planning, land use etc.
- Net Zero policy can be the overarching system strategic direction to evaluate all projects. The business case for H21 North of England should be defined and evaluated in the context of Net Zero policy and not in the context of industrial strategy or decarbonisation of heat and/or transport.
- Net Zero and the long-term diversification away from fossil fuel - There needs to be a conscious realisation that implementing and funding the net zero emissions policy requires a move away from fossil fuel utilisation and steps need to be taken accordingly.
- Net Zero policy will naturally deliver economic growth opportunities through development and export of innovative low carbon technologies, opportunities for regional economic revival, transfer of Oil &Gas knowledge and infrastructure.
- Anchor infrastructure (CO_2 and/or hydrogen) offers opportunities for further deployment of new technologies (BECCS, DACCS) at lower cost.

c. *Focus on synergies between hydrogen and electrification instead of competition*
- There is real embedded value in synergies between hydrogen and electrification (from renewable electricity). Each pathway is dependent on the other to achieve Net Zero; the uncertainty lies in the balance between both due to external factors.
  - Greater penetration of renewable energy generation capacity requires low carbon flexible power plants – these can be fuelled by hydrogen in the context of a strategy of diverting away from fossil fuel.
  - Future production of clean hydrogen will require a greater capacity of renewable electricity.
- Electrification or hydrogen for heating? The answer is likely to be a combination of both technologies. There are major issues with electrification of heating – expensive network reinforcement, very large installed capacity for peak demand, increase in requirements for renewable power generation capacity and for electricity storage, issues of customer behaviour (reluctance to change).
  - There is a need to develop low regret options where there are synergies and optionality to move between alternatives rather than making a choice – criticality of developing both pathways in parallel synergistically.
  - System Synergies: ultimately need to look holistically and include farming vs biomass, use of land

A.2.1.2 System Coordination

a. There is recognition of a need for a delivery body/organisation with a clear mandate to coordinate the UK system wide business case and strategic rationale across all regions and sectors
- This oversight and governance can be implemented in a learning-while-doing mode in the north of England.

- Each business is focused on their core activity and expects other components of the H_2-CCS chain to be delivered and made available by others. Business planning is based on individual business needs.
- Each region is equally focused on their own regional development and their specific circumstances (economic situation, emissions profile, existing infrastructure, etc.)
- Many project groups are working at individual business/regional level but not at system level. Sectoral prioritisation for the UK is not being managed proactively.
- This is different from an organisation to coordinate and manage the delivery of a specific H_2-CCS chain at regional cluster level.
- The UK has expertise for delivering the H_2-CCS system spread across a number of organisations including the Infrastructure Commission, the Infrastructure and Projects Authority, Ofgem, the Low Carbon Contracts Company, the Oil and Gas Authority, and the Health and Safety Executive.

b. There is a need for coordination without picking any winners - the development of a plan with shared benefits
- There is a view that a competitive approach can be unbeneficial as it incurs a lot of costs and is often demoralising to the losers.
- However, early movers need to ensure they are fairly compensated for their risks.

A.2.1.3 Hydrogen as clean fuel versus natural gas with post-combustion CCS

It is critical that government defines clear strategic priorities on fossil fuel/clean fuel pathway in the context of 2050 Net Zero at national level.

- Is a decarbonised fossil fuel industry acceptable for the public in the long term?
- Decision to move away from fossil fuel will require development of a market for hydrogen as a new clean fuel.
- Clarity is required to guide the system business case, to define the long-term actions required for the development of a market for a new clean fuel/energy source and to guide the project developers and potential investors in defining and structuring individual business and investment cases.

A.2.2 Market Failures

A.2.2.1 Market Development

a. There is a need for a public sector driver initially to create a demand for CCS and for hydrogen
- Market creation requires intervention – gas networks/wholesalers cannot create a hydrogen market and a regulatory framework, hydrogen plants will not be built without demand for hydrogen, industrials cannot create demand for low carbon products.
- There is also a need for consistency and confidence in the long-term direction and intervention from the public sector.

b. *Market development and the necessary interventions need to be consistent with the overarching strategic objectives for the UK energy system*
   - Should the focus be the creation of a market for decarbonisation services or should the focus be the creation of a market for competitively priced clean energy sources for heat and electricity as well as clean feedstocks which can replace fossil fuels and avoid direct emissions?
   - CCS can become a transition technology which initially allows the decarbonisation of an economy based on fossil fuels whilst other energy sources/feedstocks/technologies emerge with government intervention and are supported to compete with fossil fuels.
   - The framework at system level must be designed to allow for transition from subsidised market creation to self-sustaining market operation.
   - Financial mechanisms have been created to fund early project analysis and technology development, but no real mechanisms are available for deployment/implementation.

c. Customer behaviour has a big impact on market development
   - Electricity market is a captive market with existing regulatory framework – lower complexity, no change in customer behaviour is required.
   - Heating market is a captive market with existing regulatory framework – 22 million homes, no change in customer behaviour for blending, minimum impact for conversion to hydrogen boilers.

d. *There is a need to have CO_2 Transport & Storage (T&S) services available for all users, designed and developed strategically for the overall system decarbonisation*
   - There is a need to separate “universal” CO_2 T&S services from market development for new low carbon energy sources, low carbon products, low carbon technologies.
   - For example, the H-vision project (The Netherlands) and the role of a central T&S organisation (Porthos project) which has the responsibility to provide T&S infrastructure to all users. The H-vision project is a feasibility study involving sixteen parties, predominantly from the port of Rotterdam industrial area, collaborating to explore the centralised large-scale production of blue hydrogen (from natural gas and refinery fuel gas) in the Rotterdam industrial area to replace natural gas and coal in a large-scale power plant and a number of combustion applications in the major local refineries/chemical plants. Additional hydrogen users (industrials, gas customers, etc.) and suppliers may be connected in later stages. The H-vision project is relying on a second project - the Porthos project - to provide the transportation and storage infrastructure. Porthos is made up of three government owned organisations (Port of Rotterdam Authority, Gasunie and EBN) which are centrally planning the possibility of a T&S network taking into account all relevant sectors and the strategic priorities and cost effectiveness. Decisions about which party(ies) will construct or run this T&S network have not been taken yet.

e. *The concept of a market maker/enabler*
   - It is acknowledged that the shared use of CCS infrastructure by multiple sectors/markets increases the value (financial, economic, social, environmental) of making an initial investment and is the overall long-term

justification for that investment. However, the initial investment proposition is usually based on a limited scope with one sector acting as a market enabler for the other sectors. Future potential upside is always value-at-risk. The investment proposal and business case therefore need to present both a competitive base case (the initial investment) and demonstrate how the sources of future value can be realised by enabling the decarbonisation of other sectors through synergies. Decisions by companies and governments are made on the strategic rationale, total potential realisable value and associated optionality but need to be justifiable to the shareholders and public based on the value of a low regrets base case. This conundrum must be resolved collaboratively otherwise experience has shown neither private nor public parties can justify the FOAK projects.

f. Sectoral priorities for market development

- The government has a vital responsibility to define and communicate its priorities for sectoral market development to help developers understand how to structure their business case accordingly. For example, is CCS for power generation the immediate priority and will it be an enabler for decarbonised heating using hydrogen? Or is the immediate priority to build a hydrogen network with CCS which will enable in the future decarbonised power and then industrial CCS? Only early collaboration between government and interested developers can reconcile such choices, and for the H21 roadmap these should be made before 2021 to enable a live trial to commence in 2022 and a policy decision for hydrogen in heat by 2023.

A.2.3 System Funding

Market creation and initial infrastructure funding requires government support/funding.

a. The complexity of allocating costs to users

- The RAB model is based on the principle of providing a service to a body of consumers (market) who are willing to pay for that service.
- CO_2 T&S will be a shared infrastructure servicing multiple end-use markets, which leads to the complex problem of determining how to socialise the costs through the different markets. There need to be mechanisms and policies to reconcile how to split consumer contributions (and benefits) in different proportions and at different times without certainty on who the users will be and in which proportions they will use the system. The UK has used that consumer contribution model successfully for the Thames Tideway (wastewater crossing under the Thames) but the costs and benefits can be directly allocated to one set of customers.
- A further issue is the difference between what the initial user(s) of the infrastructure can pay and the return on the investment expected by private sector investors - for an infrastructure built at a sufficient scale for further market growth this might be very large.
- One issue with RAB is that such a model is usually low risk/low return. This is the opposite of the business of oil and gas exploration and production, which has a high risk/high return profile. These companies are the only ones who have the capability to build and operate CO_2 T&S projects. So private oil and

gas companies are unlikely to be interested in such an investment proposition without some incentive such as securing a continuing market for natural gas.

b. Use of a levy

- Use and adapt existing funding mechanisms where possible.
- Potential for use of a levy funding mechanism. The levy is applied directly to achieve the required strategic objective and to ensure that there is a contribution from the responsible parties/equipment/product to remediating the impact (decarbonisation, development of clean fuels, etc.)
- Existing mechanisms to drive development of clean electricity generation and reduction in energy consumption: e.g. Fossil Fuel Levy, Climate Change Levy.
- The levy can be applied to the input fuel (natural gas, oil) rather than the output product (electricity, industrial product, consumer service).
- The levy can be used to fund any part of the H_2-CCS chain.
- There needs to be a transparent structuring of any levies consistent with the phasing of deployment for the H21 project, presenting how the project and the levy fit with public preferences and society's objectives.

A.2.4 Societal Acceptance: A Major Investment Risk/Barrier

A.2.4.1 Principal Social Issues

a. A successful business case for H21 requires a narrative supported by the public.

- It must be recognised that the public represents a collective which is different from the state.
- The public is a strong driving force for change/lack of change.
- Support from the public is essential as infrastructure development will be paid by customers/public and significant amounts of money will be required

b. The importance of education and communication of the value of CCS/Hydrogen for society as a whole (economic, social, environmental).

- Consumers' willingness to pay comes down to education and communication (i.e. awareness of the costs of decarbonisation and the costs of meeting a net zero 2050 target). It is recognised CCS is a least cost and (in some cases) least disruptive option, but the full social and economic value of the investment needs to be better communicated. It is important to realise that CCS provides multiple services:
  - To the emitter - CCS takes care of emissions;
  - To the public - CCS contributes to mitigate climate change by allowing the decarbonisation of multiple sectors and distributed emissions sources over the long term through a balanced just transition. CCS does not only 'deal with waste from industry' but also deals with the side effects of the products that consumers are using. This is a wider social and sustainability dimension, which directly involves consumers. Therefore, putting the responsibility of consumers at the core of what CCS provides and communicating a business case and a narrative that explains what CCS will deliver to the public consistent with their expectations is critical.
- Community engagement should not only be limited to the proposed H21 clusters, or regions. Education and communication should be systemic throughout the entire UK in order to provide a level of knowledge,

understanding and support in society consistent with the task of achieving net zero emissions by 2050.

c. *The "Moral Hazard" is a major risk/barrier – a new narrative is necessary on Hydrogen with CCS*
   - The production of hydrogen for H21 from natural gas can be seen as "keeping the oil and gas companies in business".
   - Business models which provide financial support for the fossil fuel industry and which do not challenge the status-quo on the long-term use of fossil fuel are unlikely to be acceptable to the general public. A narrative by the fossil fuel industry based on CCS as climate mitigation has been unsuccessful as CCS is perceived cynically as a means to sustain the fossil fuel industry. Electrification has gained public support as the public perceives that electricity is increasingly sourced from renewable sources, away from fossil fuel sources.
   - Business models which expect the taxpayer to fund the decarbonisation of polluting industries which make large profits worldwide for their owners/shareholders are expected to be challenged.
   - In most countries, the moral hazard argument is a major barrier to be addressed to gain public support. There can be spillovers from public climate activism to the UK and there is a need to see a path away from fossil fuel.
   - Poor or inconsistent public acceptance of utilisation of CCUS technologies for decarbonisation has been identified as an investment barrier by the Zero Emissions Platform (ZEP) Technical Working Group.

d. *The mismatch between political mandate and the long-term CCS investment timeline is a barrier to private sector investment*

Investing in CCS is a long-term process which goes beyond the length of a political mandate. It is also harder to sell the value of FOAK projects because there is less visibility on the project lifetime and therefore the business case must demonstrate both the need for urgency (why now?), reasonable short term value and long term optionality/incremental value (but with some guarantee that a developer will at least get their money back at an agreed return).

A.2.4.2 What can be done?

The points below are a list of suggestions/recommendations extracted from the discussions and workshops:

a. *Engagement with NGOs (WWF, Greenpeace…) to develop a clear message about the role of CCS infrastructure in the long-term energy transition to a low carbon economy*
   - NGOs can help educate, connect and integrate with the public's emotions and desire for change and for a low carbon future away from fossil fuels to gain support for critical political decisions.
   - For example, Bellona described its engagement work in Germany between government and NGOs to the extent that Greenpeace is now locally advocating for CCS in industry and the German government ministry has started considering CCS for industry.

- In the UK, it was agreed that NGOs are being less negative and understand better the role of CCS in energy transition. But for the moment, NGOs are NOT sending proactive messages on CCS.

b. *Presenting a green vision of the future and not a grey vision of the future.*
   - The H21 business case needs to incorporate and present blue hydrogen as an enabler for green hydrogen, and an enabler for industrial decarbonisation.
- Importance that *the narrative around CCS should not be seen as competing with renewables* but being complementary.
- Importance of *an assessment framework/protocol which takes into account the economic value argument* (just transition, job creation, costs of the energy transition, economic multipliers).

A.2.5 Sector Analysis and Drivers

A.2.5.1 Industrial Sector

a. *Investment drivers*
   - No real driver from market demand – Some customers are interested in low carbon products but do not want to pay a premium for them.
   - Exposure to Emission Trading System (ETS) and uncertainty of future CO_2 prices is one of the main potential drivers but the ETS price is too low and too uncertain to justify any investment.
   - Business threat from government intervention or negative public reaction is a potential business driver in decarbonisation. It justifies participation and interest in programmes for contingency planning and innovation projects but is insufficient for large scale investment.
   - CO_2 T&S cost represents a minor cost in the overall decarbonisation and is not a significant factor in an industrial company's investment decision. Main cost is the investment in carbon capture plant (in the absence of alternative fuel/feedstock).

b. *Key System Considerations*
   - Technical Complexity:
     - capturing process emissions from industrial plants is expensive and requires different technologies for different processes. It is difficult to achieve substantial economies of scale and consistency across even one industrial sector.
     - Issue of CO_2 stream purity/quality: CO_2 emissions from combustion are of different purity from emissions from processes.
   - Two main sources of industrial emissions
     - Process emissions
     - Emissions from fuel consumption for heat or electricity
   - How is decarbonisation of industry best achieved? A number of options are available and need to be evaluated and selected in the context of an overall system strategic rationale.
     - Capture of CO_2 emissions from current process plants/boilers/furnaces
     - Reducing/phasing out use of fossil fuel as feedstock through innovative changes in feedstock/manufacturing processes and increase in proportion of recycling of products?

- Utilisation of alternative clean fuel or electricity for heat/electricity applications at competitive price
- Offsetting emissions by purchasing certificates from alternative negative emission technologies (DACCS, BECCS)
- Moving industry out of country/Exporting products

c. *Major Investment Risks/Barriers*

- Major financial risk on sizing and operation of CO_2 capture plants due to exposure to market uncertainty for future product demand and manufacturing process (changes in feedstock, proportion of product recycling) - Risk of being penalised by the government: repayment of subsidies or obligation to run the plant at a loss for example.
- Market Complexity
  - Trade exposure and no market demand (final users do not want to pay premium)
  - Market development of low carbon industrial products cannot be supported and achieved by the UK on its own.
- Even with subsidies, any decarbonisation project needs to compete with other investments internally on the basis of rate of return.
- Risk of business disruption

A.2.5.2 Hydrogen Transport & Distribution

a. *Investment drivers*

- At the moment, there is no demand pull/market signal to change the current business model of gas distribution.
- The business threat from electrification is the main potential driver. This is driving participation in hydrogen project concepts and feasibility studies funded by the government and Ofgem under the current regulatory framework but is not sufficient to justify large scale investment. Interest is limited to participation in the core business of transportation and distribution.
- Hydrogen transport and distribution business is consistent with the core business of the natural gas incumbents.
- A clear government mandate is required to change the gas distribution and supply model and to drive the demand for hydrogen.

b. *Key System Considerations*

- Challenges on ability to produce sufficient hydrogen from renewable sources – large quantities of renewable electricity would be required for electrolysis compared to capacity required in heat pumps.
- System benefits from hydrogen storage: heating requires sizeable storage capacity and the UK benefits from large scale underground storage. On the other hand, electricity battery storage requires import of rare metals such as nickel
- Hydrogen conversion offers convenience for customers (minimum disruption) and use of existing infrastructure with minimum changes.
- Hydrogen production with capture of CO_2 emissions allow centralisation of emission capture at specific purity

- Blending versus 100% hydrogen: possibility to blend hydrogen into existing gas supply to prove hydrogen supply and initiate with lower cross chain risk but much lower environmental impact on emission
- Segmentation within hydrogen market - different fuel quality/purity

c. *Major Investment Risks/Barriers*
- Lack of a standard for hydrogen (being developed)– critical for hydrogen transport and supply
- Authenticity and self-interest: is the hydrogen narrative being developed by gas distribution companies out of self-interest to keep their existing business alive? The narrative needs to be independent.

A.2.5.3 CO_2 Transport and Storage

a. *Investment drivers:*
- Opportunity to create a new business using existing skills and know-how.
- Response to a business threat – recognition of critical risk of major business model disruption to standard fossil fuel supply business (e.g. what happened to across Europe with the nuclear phase out and the rise in renewables). The threat is driving interest and participation but is not sufficient to justify investment.
- Reuse of infrastructure is not a critical driver for investment – it adds complexity.

b. *Major Investment Risks/Barriers*
- Acceptable rate of return:
  - Regulated rate of return does not fit with the core business of oil and gas companies.
  - CCS/T&S projects need to compete internally with other corporate projects. A lower rate of return may be acceptable to facilitate strategic development of a new market opportunity or to help with internal environmental KPIs.
- Uncertainty of revenue:
  - It is difficult to value business opportunity over 20years.
  - There is a need for guarantees – as a minimum for the capex to be recovered.
- Cross chain default – this is a major risk for a FOAK project and needs to be addressed by government intervention.
- Government exposure
  - Confidence and credibility in the government is critical
  - Need for a clear government mandate
- Technical storage risk
  - The storage performance risk remains an important though manageable risk. It is greater for an early mover because of the impact on others in the chain as a result on their dependence on a single store.
- Regulatory and Permitting Risk - Storage Liability (EU Directive)
  - This major risk/investment barrier is applicable to all EU countries and has been discussed in many workshops across the industry and in the WP3 workshops.

- There is a need for both public and private sector to work together to define the mechanisms that they can put in place to address this investment barrier.
- General recommendations include:
  - Engagement with public sector to highlight the issue, to reinforce that European law only provides guidelines and that there is a need for government to take action to cap limited liabilities at an investable level.
  - Likely events and worst-case scenarios should be dealt separately with from one another.
  - Class risks could be addressed through a mutual fund, which would involve the participation of countries who intend to use CCS. But this requires cross-Europe government support for the initial projects when there is not enough pool for the industry to fund.

B UK GOVERNMENT HYDROGEN & CCUS ACTIONS

B.1 The Industrial Strategy November 2017[123]

The following list comprises a high-level summary of relevant elements of the UK Industrial Strategy:

a. The industrial strategy identifies clean growth as one of the four biggest challenges for the UK and therefore embeds this strategy released in October 2017 (described below);
b. Recognises the need to "*work with industry to stimulate further market investment in clean and efficient technologies and process*", and re-affirmed £162 million of innovation funding contained in the Clean Growth Strategy;
c. Support for 'smart' energy systems to "*link energy supply, storage and use, and join up power, heating and transport to increase efficiency*";
d. New technologies for greater storage of electricity and demand management are another focus area;
e. The government aims to encourage local smart grids in order to facilitate decarbonisation of the heating and transport sectors;
f. Zero emission transport is a high priority, including vehicle manufacture and supply chains. Although an initial focus is on supporting further electric vehicle charging infrastructure, hydrogen and CCS are mentioned as long-term options also with a link to domestic shale gas production.

B.2 Clean Growth Strategy October 2017[124]

Relevant elements for H_2-CCS extracted from the strategy include:

a. Demonstrate international leadership in carbon capture usage and storage (CCUS), by collaborating with global partners and investing up to £100 million in leading edge CCUS and industrial innovation to drive down costs [*The policy principle behind this is focussed on technology cost reduction rather than benefits from economies of scale and multi-sector synergies –detail provided in the CCUS Roadmap published in December 2018 was very limited. The main message is: work with industry to identify cost effective private sector-led ways of developing, financing and delivering CCUS*];
b. Work in partnership with industry, through a new CCUS Council, to put the UK on a path to meet its ambition of having the option of deploying CCUS at scale,

[123] UK Department for Business, Energy & Industrial Strategy, 2017, https://www.gov.uk/government/publications/industrial-strategy-building-a-britain-fit-for-the-future, accessed 31st March 2020
[124] UK Department for Business, Energy & Industrial Strategy, 2017, https://www.gov.uk/government/publications/clean-growth-strategy, accessed 31st March 2020

and to maximise its industrial opportunity [*Creation of a Cost Challenge Taskforce, which delivered a report to Government in July 2018 entitled 'Delivering Clean Growth: CCUS Cost Challenge Taskforce Report'. Creation of a CCUS Advisory Group, which delivered a report to Government in July 2019 entitled 'Investment Frameworks for Development of CCUS in the UK'.*];

c. Develop a strategic approach to greenhouse gas removal technologies, building on the Government's programme of research and development and addressing the barriers to their long-term deployment [*Some such as air capture would likely require CCUS*];
d. Invest around £162 million of public funds in research and innovation in Energy, Resource and Process efficiency, including up to £20 million to encourage switching to lower carbon fuels [*This includes transforming manufacturing and heavy industry side by side with CCUS – hydrogen is a focus fuel*];
e. Invest in low carbon heating by reforming the Renewable Heat Incentive, spending £4.5 billion to support innovative low carbon heat technologies in homes and businesses between 2016 and 2021;
f. Invest around £184 million of public funds, including two new £10 million innovation programmes to develop new energy efficiency and heating technologies to enable lower cost low carbon homes [*Includes the £25 million programme looking at converting networks from NG to* H_2*. Side by side with £195 million from Ofgem for gas network companies to introduce new technologies and operating/commercial arrangements.*];
g. Spend £1 billion supporting the take-up of ultra-low emission vehicles (ULEV), including helping consumers to overcome the upfront cost of an electric car [*Primarily focussed on EVs but some HFC funding including £23 million for* H_2 *refuelling infrastructure*];
h. Announce plans for the public sector to lead the way in transitioning to zero emissions vehicles;
i. Invest around £84 million of public funds in innovation in low carbon transport technology and fuels [*£246 million earmarked for development and manufacture of electric batteries*];
j. Phase out the use of unabated coal to produce electricity by 2025;
k. Target a total carbon price in the power sector, which will give businesses greater clarity on the total price they will pay for each tonne of emissions;
l. Invest around £900 million of public funds, including around £265 million in smart systems to reduce the cost of electricity storage, advance innovative demand response technologies and develop new ways of balancing the grid.

B.3 CCUS Action Plan December 2018

The UK Government made the following statement in its CCUS Action Plan published in December 2018:

“The main barriers now are not technological: rather, government and the sector need to work together to build the frameworks to enable CCUS to deploy at scale. This is a partnership, but one in which we must be clear that government can only be expected to bear the irreducible risks, and where market mechanisms must come to bear to deliver best value solutions for taxpayers.

The companies involved, many of whom rely on fossil fuels for the bulk of their revenues, must see finding routes to deploying CCUS solutions as essential to their license to operate, as well as a chance to share in the economic rewards of leading in this burgeoning sector. This report delivers a plan to work with them to deliver on this opportunity.”

Summary of actions needed to deliver our 2030s ambitions

Address policy barriers	Review barriers to deploying CCUS and consult on emerging findings	Identify infrastructure re-use opportunities and set out HMG policy	Set out policy options for responsibly developing GGRs
Delivery capability	Assess delivery capability required for projects during the 2020s	Examine delivery implications of deploying at scale during the 2030s	Industry to build delivery capability in the private sector
Delivery of infrastructure	Commence detailed engagement with industry on the critical challenges to delivering CCUS in the UK	Examine the opportunity of shared CO² infrastructure	Consult on the design of the Industrial Energy Transformation Fund
Innovation	Deliver £40 million innovation programmes focused on CCUS	Set out next steps for UK CCUS innovation	Develop new, innovative R&D projects and collaborative partnerships with academia and industry
International collaboration	Progress outcomes of the global Accelerating CCUS Summit	Deliver an action plan to advance the Mission Innovation CCUS Challenge	Work with other Governments to identify and address barriers to cross border transport of CO²
CCUS Council		CCUS Council to advise on priorities and progress	

2019 | Early 2020s | Ongoing

Key Messages:

- Option to deploy at scale in 2030s => possibly 10+ years after first infrastructure is built
- Sequential ‘staged’ approach to learning and deployment

- Strong emphasis on innovation for cost reduction
- Emphasis on private sector developing capability to deliver
- Emphasis on industrial decarbonisation
- No real strategic plan for government beyond 12-18 months (no market development)

After the publication of the CCUS Advisory Group report in July 2019, the Department of Business, Energy and Industrial Strategy (BEIS) opened a consultation on CCUS Business Models. This consultation closed on 16th September 2019 and at the time of writing BEIS is analysing the responses. The consultation covered the following subjects[125]:

- "*options on CCUS business models for industry, power, and carbon dioxide transport and storage;*
- *a framework for future evaluation of models to support hydrogen production with CCUS;*
- *the CCUS-specific risks inherent in first of a kind CCUS projects;*
- *the possible delivery and coordination challenges of deploying CCUS at scale*".

B.4 CCU Demonstration Projects

The BEIS website describes[126] this programme as follows:

"*This programme is designed to encourage industrial sites to capture carbon dioxide which could then be used in industrial applications. It will provide a learning opportunity for the development of capture technologies at an intermediate scale, thus reducing costs and risks.*

Overall programme aims:

- *to demonstrate carbon capture and utilisation at a number of key industrial sites in the UK*
- *to demonstrate and accelerate cost reductions of about 20-45% in carbon capture technology, or about £10-20/MWh*
- *to encourage a project pipeline of follow-on CCU projects that will help less mature, but more novel technology to be demonstrated at scale*
- *to improve understanding of the cost and performance of carbon capture technology*
- *to de-risk the capture technology*

[125] Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/consultations/carbon-capture-usage-and-storage-ccus-business-models

[126] Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/carbon-capture-and-utilisation-demonstration-ccud-innovation-programme

Organisations of any size are eligible to apply for funding. Projects may involve working with international partners, but the work funded must be conducted predominantly in the UK."

£5M funding June 2019 from total £20M:

a. Drax – Fuel Cell Biogenic Carbon Capture Demonstration, £500,000 towards a £1 million project
b. Origen Power – Oxy-Fuelled Flash Calciner Project, £249,000 towards a £356,000 project
c. Tata Chemicals Europe – Carbon Capture and Utilisation Demonstration, £4.2 million towards a £17 million project

A further funding call for construction and demonstration projects closed in September 2019. At the time of writing no announcement had been made on award of grants.

B.5 CCUS Innovation Programme

The BEIS website describes[127] this programme as follows:

"*BEIS launched a call for CCUS Innovation in July 2018 to offer grant funding for world-leading research and innovation projects that offer:*

- *a significant reduction in the cost of capturing and sequestering carbon dioxide; and / or*
- *a quicker, more widespread deployment of CCUS in the UK and internationally*

Up to £24 million of grant funding was made available under this programme to support:

- *feasibility studies*
- *industrial research*
- *experimental development projects*
- *infrastructure projects*

The project funding period is up to 24 months, with projects finishing by 31 March 2021.

The call closed to applications in November 2018."

£21M funding June 2019 from total £24M:

a. C-Capture – Negative CO_2 emissions from BECCS at Drax Power Station in North Yorkshire to enable Drax to become the world's first negative emissions power station in the 2020s: £4,915,070 towards an £11.1 million project

[127] Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/call-for-ccus-innovation

b. Pale Blue Dot Energy – Acorn storage site. The BEIS funding is progressing the detailed engineering for this project towards a final investment decision in 2021: £4,795,017 towards an £8.1 million project
c. TiGRE Technologies Limited - Integration of CCUS technology to a 200MW OCGT TiGRE Project located in the North Sea by assessing the feasibility of integrating conventional best-practice carbon capture and sequestration technology into a real-life production facility: £163,909 towards a £243,000 project
d. Translational Energy Research Centre (PACT-2) - Led by University of Sheffield / Pilot-Scale Advanced Capture Technology (PACT). The centre's state-of-the-art facilities will enable UK companies to develop, de-risk, and accelerate their innovations under realistic operating conditions: £7 million toward a £21 million project
e. Progressive Energy – HyNet Industrial CCS. The HyNet project consortium of Progressive Energy, Essar Oil UK, CF Fertilisers, Peel, Cadent and the University of Chester is undertaking the 'pre-FEED' study which will confirm technical viability of the project, mitigate engineering risks, and provide robust cost estimates for subsequent project development: £494,626 toward a £765,500 project
f. OGCI Climate Investments – Clean Gas Project feasibility study. OGCI Climate Investments has entered into a strategic partnership with BP, ENI, Equinor, Occidental Petroleum, Shell and Total: £3.8 million toward an £18 million project

B.6 Industrial Fuel Switching Programme and Competition

The aim of the £20 million Industrial Fuel Switching Competition has been to identify and test the processes and technologies required for industries in the UK to switch to low carbon fuels.

The Competition has been technology-neutral, however, it has taken a portfolio approach to funding a range of solutions in scope. For this competition, projects that facilitate switching industrial processes to electricity, biomass or hydrogen have been considered in scope. Projects focused on biomethane, synthetic methane, carbon capture, usage and storage (CCUS) or energy efficiency were considered out of scope.

- Phase 1: Market engagement and assessment study; this was completed by Element Energy[128].
- Phase 2: Feasibility studies (total budget of up to £3m; up to £300k for each feasibility study); this phase provided an opportunity for successful applicants to demonstrate the feasibility of their proposed technology or approach "*to enable the use of a low carbon fuel for a particular industrial process or across an*

[128] Element Energy Limited, 2018, op. cit.

entire site". Completed reports can be found on the BEIS website[129] and include, of relevance to the ELEGANCY UK case study, the HyNet proposal for Industrial Fuel Switching in the North East.

- Phase 3: Demonstration studies (total budget of up to £16.5m, up to £7.5m contract for each demonstration project.) Four projects have been awarded funding for progressing fuel switching feasibility demonstrations. These projects are:
  - HyNet North West – practical demonstration of switching a number of industrial processes from natural gas to hydrogen, including direct firing, boiler and refinery technologies. Funding awarded £5.24 million
  - Fuel mixing for UK cement production – will investigate through physical trials the use of biomass, hydrogen and electricity in cement production. Funding awarded £3.2 million
  - Alternative fuel switching technologies for the glass sector – evaluation of the technical, economic and environmental aspects of electric, hydrogen, bio-fuel and hybrid-fuel melting technologies for general use in the glass sector. Funding awarded £7.12 million
  - Hydrogen alternatives to natural gas for calcium lime manufacturing - examination and demonstration of using hydrogen as an alternative to natural gas for manufacturing high calcium lime that can then be used in diverse markets including iron and steel manufacturing. Funding awarded £2.82 million

B.7 Investing in hydrogen innovation for heating: Hy4Heat

BEIS is undertaking a £25 million project to explore the potential use of hydrogen gas for heating UK homes and businesses. Following a competition, BEIS has appointed Arup+, a team of contractors led by Ove Arup to run this project.

This project Hy4Heat will run from 2017 to 2021 and will aim to define a hydrogen quality standard, and to explore, develop and test domestic and commercial hydrogen appliances.

B.8 Hydrogen for Transport Programme

The Office for Low Emission Vehicles (OLEV) is a cross-Government, industry-endorsed team combining policy and funding streams to simplify policy development and delivery to support the early market for ultra-low emission vehicles (ULEV). OLEV aims to provide almost £1.5 billion to position the UK at the global forefront of ULEV

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[129] Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/industrial-fuel-switching-to-low-carbon-alternatives, accessed 31st March 2020

development, manufacture and use. This will contribute to economic growth and will help reduce greenhouse gas emissions and air pollution on our roads.

Based in the Department for Transport, OLEV is part of the Department for Transport and the Department for Business, Energy & Industrial Strategy.

The Hydrogen for Transport programme has two primary objectives:

1. to increase the number of publicly accessible UK hydrogen refuelling stations and;
2. to increase the number of fuel cell-powered electric vehicles on UK roads.

In early 2019 the government announced the winners of a £14 million funding competition to progress the deployment and demonstration of hydrogen-fuelled transport[130]:

Project	Stations	Vehicles	Grant request
Project: Tees Valley Hydrogen Transport Initiative, Consortium: Tees Valley Combined Authority (UK), Materials Processing Institute, Northern Gas Networks	2 – Middlesbrough & Stockton on Tees	5 cars	£1,303,500
Project: Hydrogen Mobility Expansion Project II, Consortium: Element Energy, ITM Power (trading) Ltd, Toyota (GB) Plc, Hyundai Motor UK Ltd	1 - Crawley	51 cars	£3,070,000
Project: Northern Ireland Hydrogen Transport, Consortium: Viridian Energy Supply Limited, Translink (Ulsterbus), HyEnergy Consultancy Ltd	1 – Belfast	3 buses	£1,953,937
Project: Riversimple Clean Mobility Fleet, Consortium: Riversimple Movement Ltd, Monmouth County Council	-	17 cars	£1,249,670
Project: Towards commercial deployment of FCEV buses and hydrogen refuelling, Consortium: BOC Ltd, Merseytravel (Liverpool City Region, Aberdeen City Council and Arcola Energy)	1 – St Helens	30 buses – [5 in Aberdeen and 25 in Liverpool]	£6,419,038

130 FuelCellsWorks https://fuelcellsworks.com/news/uk-government-announces-winners-of-14-million-competition-to-fund-hydrogen-fuel-cell-vehicles-and-hydrogen-refuelling-infrastructure/

B.9 Low Carbon Hydrogen Supply Programme and Competition

The following description of the low carbon hydrogen programme and closed competition is provided on the BEIS website[131]:

"*Low carbon hydrogen could play an important role in decarbonising industry, power, heat and transport. However, for a market to grow, potential users (in any application) need to be confident in supply of sufficient amounts of low carbon hydrogen at a competitive price.*

The £33 million Low Carbon Hydrogen Supply competition aimed to accelerate the development of low carbon bulk hydrogen supply solutions in the above sectors. It was aimed at projects at a technology readiness level (TRL) of 4 to 7, which could result in lower capital or operating costs when compared to Steam Methane Reformation with Carbon Capture & Storage (SMR+CCS) or improve the carbon capture rates at a comparable cost.

Phase 2 of the competition aimed to accelerate the development of low carbon bulk hydrogen supply solutions by providing funding for demonstration projects.

Phase 1 funded feasibility studies looking into accelerating the development of low carbon bulk hydrogen supply solutions."

Bulk low carbon hydrogen solutions to support large scale energy system changes include: low carbon production (through fossil fuel reformation with CCS), zero carbon production (using zero carbon energy such as electrolysis, nuclear, or biomass with CCS), the import infrastructure for hydrogen, the storage of hydrogen, or the bulk provision of hydrogen closer to the end user. These solutions could also include the use of hydrogen carriers such as ammonia.

Completed Phase 1 project reports are available from the BEIS website at the link in footnote 131. Both onshore and offshore production methods were studied in these projects. Some of the reports more immediately of relevance to the UK case study include:

- HyNet Low Carbon Hydrogen Plant – Led by Progressive Energy
- Acorn Hydrogen Feasibility Study – Led by Pale Blue Dot Energy
- Project HySecure (H_2 geological salt cavern storage) – Led by Inovyn (Ineos)
- Methilltoune Phase 1 (Offshore wind and onshore electrolysis) – Led by SGN

5 projects have been successful in obtaining funding under Phase 2 of the programme competition. Details can be found on the BEIS website[132]. Both the HyNet and Acorn

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[131] Department for Business, Energy and Industrial Strategy https://www.gov.uk/government/publications/hydrogen-supply-competition
[132] Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/hydrogen-supply-competition/hydrogen-supply-programme-successful-projects-phase-2

projects have progressed to Phase 2 to deliver engineering designs rather than demonstration.

B.10 Ofgem Innovation Programme and Funding

Ofgem conducts gas network innovation competitions with funding available up to approximately £20 million per annual competition.

Funding awarded in the Gas Network Innovation Competition (NIC) 2018:

- Cadent: HyDeploy2 - Further testing of blending hydrogen with natural gas supplied to homes and businesses with a view to deploying it across Britain's gas networks. Awarded £13.28 million

  The project aims to demonstrate the injection of hydrogen into the public gas network, building upon the learning of Cadent's ongoing NIC project, HyDeploy, taking place at Keele University. This includes testing the safety case and trialling the injection of hydrogen into untested parts of network, as will be required for the GB-wide deployment of blended hydrogen. The UK Health & Safety Executive gave permission in November 2019 to run a 10-month live test of blended hydrogen (up to 20%) and natural gas in the private gas network at Keele University campus.

Funding awarded in the Gas Network Innovation Competition 2019[133]:

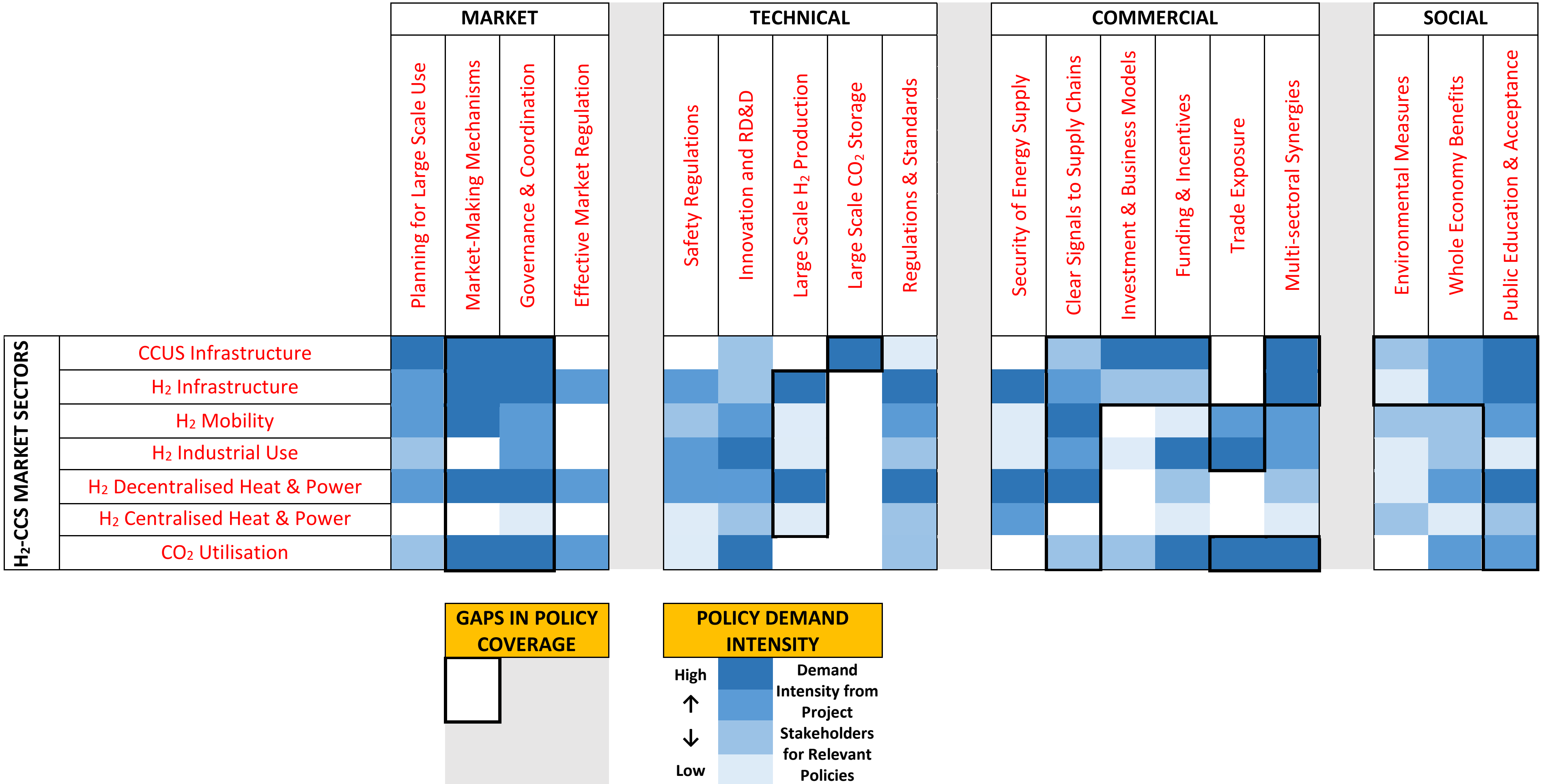
- Northern Gas Networks and collaboration partners were awarded £6.8 million to progress phase 2 of the H21 natural gas to hydrogen conversion project concept, building on the work undertaken in H21 Leeds City Gate and H21 North of England. The H21 Network Operations project aims to expand the safety-based evidence for 100% hydrogen conversion in the below 7 bar GB gas distribution network. The results of this work will provide an important foundation to the Hy4Heat investigation of hydrogen as a potential heat source for homes. Project partners are Cadent Gas, Wales & West Utilities and National Grid.

[133] Ofgem, 2019, op. cit.

C UK H21 MARKET FAILURE ASSESSMENT

Market Opportunities/Market Failures	Missing Market	Coordination Failure	Negative Externality Low Priced CO2 Emissions	Positive Externality Improved Air Quality	Natural Monopoly	Merit Goods Hydrogen	Merit Goods CO2 Utilisation	Merit Goods Appliances & Equipment	Location Immobility	Social Inequality Fuel Poverty	Information Failure and Asymmetry	Knowledge Creation Spillovers
H_2/CO_2 End Use Markets												
Large Stationary Power	High	High	Low	Low	Low	Medium			High			
Small Stationary Power	High	High	High			Medium		Medium	Low	Medium	Low	Medium
Mobility - Vehicles	High	High	High	Medium	Medium	Medium	Medium		Low	Low	Low	Medium
Mobility - Other												
Heat	High	Medium	High	Medium	Low	Medium		High	Medium	High	Low	Medium
Chemicals and Industry	Low	Low	High	Medium		Medium	High		Medium		Low	High
Power to X (Storage)	Medium	High	High		Medium	High			Medium		Low	High
H_2-CCS Chain												
H_2 Retail	High	High	High	High	Low	High		High		High	Low	Low
H_2 Distribution	High	High	High	High	Medium	High			Medium			Low
H_2 Storage	High	High	High	High	High	High			High		High	Medium
H_2 Transmission	High	High	High	High	High	High			High			Low
Low Carbon H_2 Production	Medium	High	High	High	Medium	High			Medium		Low	Low
CO_2 Capture	Medium	High	High	Medium	Low		High		Low		Low	Medium
CO_2 Gathering	High	High	High		High		High		Medium		Low	Medium
CO_2 Transmission	High	High	High		High				High		Medium	Medium
CO_2 Storage	High	High	High		High				Medium		High	Medium

D UK H21 POLICY NEEDS HEATMAP



E H21 NORTH OF ENGLAND SYSTEM RISK MATRIX

E.1 Investment Barriers: Political, Policy and Social

Risk Category	Investment Barriers (investability Rating 5)	Scope of Chain Impact	Proposed Measure	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
Policy Change	Uncertainty of UK commitment to pace and evolution of low carbon or circular economy matching net zero climate target	H2-CCS Chain	Strengthened UK government policies to build credibility with private investors for 4th and 5th carbon budgets and 2050 net zero target	Control of Cause: Likelihood Reduction	Policy and Market Signals	Early stage of development	yes	3
Policy Change	Missing binding government mandate for delivering the first city natural gas to H2 conversion and associated integrated full chain infrastructure	H2-CCS Chain	Parliament commitment to first H2 conversion in statute with mandate and budget given to Infrastructure and Projects Authority (or similar)	Recovery from Consequence: Impact Reduction	Contractual	Non-Existing	yes	3
Political and Governance	Lack of confidence in long term financial commitment by government	H2-CCS Chain	Long term political and financial commitment to first clean H2-CCS infrastructure project in statute and cross-party consensus on energy policy	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	2
			Setting up Executive Committee to drive H2/CCS across UK with engagement of all key parties and oversight of regional sub-committees for market and infrastructure delivery	Recovery from Consequence: Impact Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3
Permitting and Consenting	Long term leakage liabilities defined in EU Directive and national regulations with front loaded Financial Security	CCS Chain	Joint public-private solution to provision of transport and storage service with risk and liability sharing, appropriate guarantees, and government underwriting of liabilities private sector cannot carry	Recovery from Consequence: Impact Reduction	Ownership Structure / Investor Type	Early stage of development	yes	3
			Post BREXIT UK government modifies regulations to include capping mechanisms on liabilities and an improved compliance and penalty regime	Recovery from Consequence: Impact Reduction	Regulations, Legal and Influence	Non-Existing	yes	2
Reputation and Social	Unknown public acceptance of a city hydrogen conversion and gas network re-purposing	H2-CCS Chain	Long term proactive education, communication and engagement plan and actions	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	3
			Promotion and development of socio-economic benefits (UK industry for hydrogen boilers/fuel cell micro CHP, trade for installers, exports, GVA)	Control of Cause: Likelihood Reduction	Policy and Market Signals	Early stage of development	yes	3
			Promotion and development of environmental benefits (CO2 reduction, clean air, ULEV vehicles etc)	Control of Cause: Likelihood Reduction	Policy and Market Signals	Early stage of development	yes	3
			Create a clear overall UK system narrative/strategic rationale which incorporates value of hydrogen city conversion alongside electrification (rather than in competition) in the context of Net Zero objective	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	3
Reputation and Social	Cost of emissions abatement using CCS in the first phase of H21 is too high compared to competing technologies (renewable electricity, heat pumps) to warrant public funding support	CCS Chain	Create strategic plan/roadmap with diversified low regrets options for the future where sufficient volume of CO2 is abated at lowest cost from multiple sectors to justify initial full-scale T&S system. For example, one central large-scale hydrogen plant to provide clean hydrogen (emissions centrally captured) to a combination of cities, hydrogen power plant and key industrials.	Recovery from Consequence: Impact Reduction	Policy and Market Signals	Non-Existing	yes	3
			Policy commitment to develop CO2 transport and storage at scale for the FOAK phase of H21 that will have a low regrets capacity able to account for future residual emissions requiring offsets using greenhouse gas removal technologies	Recovery from Consequence: Impact Reduction	Policy and Market Signals	Early stage of development	yes	3
Reputation and Social	Objections and moral hazard arguments related to continuing use of fossil fuels and financial support to O&G industry	H2-CCS Chain	Develop and communicate long term strategic rationale with CCS as a transitional technology and which includes early committed pilot deployment of other emissions reduction technologies (DACCS, BECCS, hydrogen from electrolysis, etc.)	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	3
			Engage and collaborate with NGOs in communications to the public	Control of Cause: Likelihood Reduction	Regulations, Legal and Influence	Non-Existing	yes	3
			Develop acceptable financing structure - apply principle of producer pays and finance clean disposal service from fossil fuel industry	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	3

E.2 Investment Barriers: Technical and Physical

Risk Category	Investment Barriers (investability Rating 5)	Scope of Chain Impact	Proposed Measure	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
Output and Service Reliability	Guaranteed intra-chain counterparty performance is required between H2 retailer/DNO/TNO/producer and CO2 capturer/gatherer/transporter/storer	H2-CCS Chain	Utilise a binding umbrella agreement that guarantees intra-chain counterparty performance with government providing state step-in, guarantor of last resort, assurances and underwriting as required	Control of Cause: Likelihood Reduction	Contractual	Non-Existing	yes	3
Operational	Operational complexity of multi-party integrated system both during commissioning and early full-scale operations	H2-CCS Chain	Develop a business case with a phased deployment including lower risk operations such as H2 blending or use of H2/Clean Gas Power station to prove the different elements of the H2-CCS chain and remediate early operational issues with minimum impact	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Early stage of development	yes	3
			Government underwrites emissions penalties associated with outages and early operational issues/delays	Recovery from Consequence: Impact Reduction	Financial Support	Non-Existing	yes	2

E.3 Investment Barriers: Market and Commercial

Risk Category	Investment Barriers (investability Rating 5)	Scope of Chain Impact	Proposed Measure	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
Market Development/ Demand (uncertainty of revenue)	Missing markets for large-scale clean (low carbon) hydrogen	H2-CCS Chain	Parliament commitment to first H2 conversion in statute with mandate and budget given to Infrastructure and Projects Authority (or similar)	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3
			Government setting up policies for financial support/funding structure to make cost of hydrogen competitive with alternative fossil fuels	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	3
Market Development/ Demand (uncertainty of revenue)	Missing markets for large-scale use of CO2 transport and storage infrastructure	H2-CCS Chain	Government underwriting the provision of affordable disposal service (at scale) to CO2 emitters during market development	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	3
Market Development/ Demand (uncertainty of revenue)	Uncertainty of market demand over 20 years	H2-CCS Chain	Government policies and enduring mechanisms to support evolution of hydrogen markets of sufficient scale to support infrastructure investment	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	3
			Government provides guarantees for capex repayment (irrespective of market demand) for initial infrastructure	Recovery from Consequence: Impact Reduction	Financial Support	Non-Existing	yes	3
Access to Capital	The level of financial risk related to integrated full chain infrastructure (cross chain default, political risk, delivery risk) is too high for lenders with conventional risk mitigation measures	H2-CCS Chain	A binding umbrella (State) agreement split between H2 and CCS chain with the government providing state mandates and assurances is required to enable financing for such an integrated full chain infrastructure (guarantees on coordinated investment, delivery and intra-chain counterparty performance)	Control of Cause: Likelihood Reduction	Contractual	Non-Existing	yes	3
			An integrated public-private system business model recognising the joint and separate responsibilities and capabilities for delivery of outcomes	Control of Cause: Likelihood Reduction	Ownership Structure / Investor Type	Non-Existing	yes	3
Market Development/ Demand (uncertainty of revenue)	Regulated rate of return is insufficient to attract O&G operators to invest in CO2 T&S service	CCS Chain	Create a societally acceptable CO2 T&S funding structure whereby O&G industry, as a whole, pays for higher regulated rate of return for the first projects. Future projects with lower risk profile may attract infrastructure investors with lower RoR requirements	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	3
			Obligation on O&G companies as industry group to participate in T&S investment and operation	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3

E.4 Investment Barriers: Outcome

Risk Category	Investment Barriers (investability Rating 5)	Scope of Chain Impact	Proposed Measure	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
Co-impact/ negative indirect Impact (social, health, economic benefits)	Early stage hydrogen supply system does not have sufficient capacity and is not sufficiently robust (compared to the natural gas system) to avoid customer outages	H2-CCS Chain	Combined market and infrastructure development plan designed to incorporate a phased system deployment including lower risk operations such as H2 blending or use of H2/Clean Gas Power station to prove the H2-CCS chain, build sufficient hydrogen production redundancy and establish back-up/seasonal storage facilities	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3
Asset underperformance/ stranded asset ("white elephant")	Potential for CO2 T&S infrastructure to be underutilised or not utilised after first capture project	CCS Chain	Centralised Hydrogen production combined with designed market development provides more options for use of CO2 T&S infrastructure than individual CO2 capture projects/facilities	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3

E.5 Business Risks: Political, Policy and Social

Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
REGULATORY	A functional regulatory framework agreed between government and the private sector to govern the business model and investments in the H21 system is not in place in time for FID by 2023	✗	✗	✔	✔	✗	H2-CCS Chain	4	5	20	4	Utilise an Executive Steering Committee to drive the process with engagement of all key parties (grouped in regulatory, regional and functional expert working groups)	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Early stage of development	yes	3
	Inconsistent laws and regulations between end use markets and those governing CCS permitting and operations affect construction and/or service delivery	✔	✗	✔	✔	✔	H2-CCS Chain	3	4	12	3	Establish an oversight council including Ofgem, IPA, HSE, OGA and others to ensure laws and regulations are consistent, compatible and fit-for-purpose in liaison with the executive steering committee	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
	Mandatory third-party access to infrastructure leads to operational and commercial problems such as controlling H2 and CO2 quality specs and inability to meet regulations and performance guarantees	✗	✔	✗	✗	✔	H2-CCS Chain	3	4	12	3	Regulator/Competent Authority implements evidence-based pragmatic and flexible compliance regime and penalty response	Recovery from Consequence: Impact Reduction	Regulations, Legal and Influence	Early stage of development	yes	2
												Contractual gas quality specifications with performance guarantees and contractual liabilities from counterparty operators	Control of Cause: Likelihood Reduction	Contractual	Existing	no	2
POLICY CHANGE	Government policy of supporting critical and strategic evidence gathering for H2 in general and H21 in particular does not extend to the H21 FEED and live trials before 2023	✔	✗	✗	✔	✗	H2 Chain	3	5	15	4	Minimise value at risk from project development activities and seek necessary guarantees from government	Recovery from Consequence: Impact Reduction	Contractual	Existing	yes	2
												Create H2-CCS business case optionality with flexibility to adjust if city conversion is not progressed: flexibility in sizing of hydrogen plant and storage, other hydrogen users (power plant, industry)	Recovery from Consequence: Impact Reduction	Policy and Market Signals	Early stage of development	yes	3
	Government de-prioritises H2-CCS in Clean Growth and Industrial Strategies in the period to 2023	✗	✗	✔	✔	✗	CCS Chain	3	5	15	4	Minimise value at risk from project development/FEED activities, ensure shared government contribution to fund FEED, and seek necessary guarantees from government	Recovery from Consequence: Impact Reduction	Contractual	Existing	yes	3
	The functional regulatory framework agreed between government and the private sector to govern the investments in the H21 system is unilaterally changed by government before the second phase of H21 investment	✔	✔	✔	✔	✔	H2-CCS Chain	2	5	10	3	Remuneration structure is sufficient for stand-alone investment in 1st phase infrastructure investment. Return on investment in oversizing of infrastructure is covered by an appropriate contractual mechanism and guaranteed/protected by the government.	Recovery from Consequence: Impact Reduction	Financial Support	Non-Existing	yes	2
												Business Case for H2-CCS chain is not linear and includes flexibility and optionality in terms of sizing and hydrogen users for future development - so that long term commitment of city conversion is not critical for investment decision - for example modular and expandable hydrogen plant, key future users identified (industry, hydrogen power plants, etc.), staged development of CO2 storage reservoirs	Recovery from Consequence: Impact Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2

Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
LEGAL AND OWNERSHIP RIGHTS	Outstanding legal issues in 2023 prevent integration of the collective investment decisions for the first H21 full chain system components and city conversions using results of the NoE FEED study	✗	✔	✔	✔	✗	H2-CCS Chain	3	4	12	3	Establish an oversight council including Ofgem, IPA, HSE, OGA and others to ensure laws and regulations are consistent, compatible and fit-for-purpose	Control of Cause: Likelihood Reduction	Regulations, Legal and Influence	Non-Existing	yes	2
LEGAL AND OWNERSHIP RIGHTS												Integrated project development by government and regional authorities to manage investment timing and remove legal barriers	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	1
LEGAL AND OWNERSHIP RIGHTS	Statutory remedies including compensation and penalties for defined and limited events (incl. death) result in expensive insurance for operators	✔	✗	✗	✗	✔	H2-CCS Chain	2	3	6	2	Ongoing and transparent engagement between all the parties to understand the implications of statutory requirements on investment costs	Recovery from Consequence: Impact Reduction	Market Design, Supervision, Market Provider	Early stage of development	yes	1
LEGAL AND OWNERSHIP RIGHTS												Socialise the cost of early infrastructure funding widely to minimise potential impact of early risk premium on a specific group of users for the first project.	Recovery from Consequence: Impact Reduction	Policy and Market Signals	Non-Existing	yes	1
LEGAL AND OWNERSHIP RIGHTS	Agreed public-private sector system business model with segment business models and ownership rights is not in place in time for FID in 2023	✔	✔	✔	✔	✔	H2-CCS Chain	3	5	15	4	Focus on high level business case and business model issues starting in early 2020 between overall government steering group and individual regional project teams.	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Early stage of development	yes	3
LEGAL AND OWNERSHIP RIGHTS												Establish government steering group in liaison with regulatory oversight council with necessary funding and mandate to coordinate and define business case and business model for H2-CCS infrastructure chain investment	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3
PERMITTING AND CONSENTING	Onerous FOAK permit conditions on geological H2 or CO2 storage result in loss of private sector investment appetite or post-commissioning compliance difficulties	✔	✗	✔	✔	✔	H2-CCS Chain	4	4	16	4	Use of lowest risk storage sites	Control of Cause: Likelihood Reduction	Technology	Early stage of development	no	3
PERMITTING AND CONSENTING												Ongoing and transparent engagement between all the parties to understand the implications of permit conditions on investment costs	Recovery from Consequence: Impact Reduction	Market Design, Supervision, Market Provider	Late stage of development	no	3
PERMITTING AND CONSENTING												Socialise the cost of early infrastructure funding widely to remove potential impact of early risk premium on a specific group of users for the first project.	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
PERMITTING AND CONSENTING	H21 first phase consents, permits, leases or licences are not easily obtained (delayed, conditional or not granted due to FOAK issues such as technical and/or safety uncertainty)	✔	✗	✔	✔	✗	H2-CCS Chain	2	4	8	3	Use of proven technology, pipeline corridors, existing re-usable infrastructure, low impact geographical locations	Control of Cause: Likelihood Reduction	Technology	Early stage of development	no	2
PERMITTING AND CONSENTING												Coordinated project development with government oversight/steering to ensure permitting/licensing issues are addressed early	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2

Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
												Capability of permitting and licencing authorities such as HSE, EA, OGA, Ofgem, Crown Estate, BEIS, DEFRA etc is established by 2021 to ensure knowledgeable decision-making	Control of Cause: Likelihood Reduction	Regulations, Legal and Influence	Early stage of development	no	2
REPUTATION AND SOCIAL	Any initial public support existing during H21 FEED and trials is lost prior to taking FID in 2023	✗	✗	✔	✔	✗	H2-CCS Chain	2	5	10	3	Proactive and coordinated public engagement programme with support from relevant NGOs	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	2
REPUTATION AND SOCIAL	Insufficient education and skills training programmes to provide workforce needed to implement H21 phases 1 and 2	✔	✗	✗	✔	✗	H2-CCS Chain	3	4	12	3	Ensure relevant training and skills development with sufficient funding is incorporated into clean growth and industrial strategies at the sector level and into overall project programme	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	1
REPUTATION AND SOCIAL	Problems with hydrogen delivery during commissioning and first phase of H21 result in loss of public support for phase 2	✔	✔	✗	✔	✔	H2-CCS Chain	3	5	15	3	Critical to select and structure order and timing of development of components H2-CCS to minimise risk for end users. Hydrogen delivery and storage is proven and tested with other end users before actual city conversation and timing of city conversation is adjusted accordingly.	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
POLITICAL AND GOVERNANCE	Impact of BREXIT is deeper and more negative than expected causing extended economic slow-down and/or reduced growth disincentivising conversion to hydrogen	✗	✔	✔	✔	✗	H2-CCS Chain	3	5	15	3	Trade deals include goods and services such that UK carbon budgets can be credibly met, not placed at risk, and low carbon and climate business investments are facilitated/supported. "Green" and circular economy is prioritised.	Recovery from Consequence: Impact Reduction	Policy and Market Signals	Non-Existing	yes	2
POLITICAL AND GOVERNANCE	Carbon price on ETS or domestic tax stays too low for too long to incentivise decarbonisation investments in industry (incl hydrogen production and use)	✗	✔	✔	✗	✗	H2-CCS Chain	4	4	16	3	UK carbon price floor and/or a new carbon tax increased in line with a credible price trajectory to meet carbon budgets and value the CO2 externality for the UK economy, with compensatory mechanisms for the disparity between domestic and global markets.	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	2
POLITICAL AND GOVERNANCE	UK and international climate change efforts fail to address disparity between carbon content of goods and services produced in different regions and jurisdictions as well as territorial versus extraterritorial emissions resulting in disequilibrium in global markets and disincentives for industry decarbonising with hydrogen and/or CCS	✗	✔	✔	✔	✗	H2-CCS Chain	5	5	25	4	Support measures for industry introduced (including import border adjustment, export price compensation) in accordance with a designed timeline consistent with meeting UK carbon budgets	Recovery from Consequence: Impact Reduction	Financial Support	Non-Existing	yes	2
POLITICAL AND GOVERNANCE												Funding mechanism for clean energy conversion to include socialisation of costs across all population not just immediate customers of individual low carbon products or services	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	3

E.6 Business Risks: Technical and Physical

Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
CONSTRUCTION	Delays in construction, re-purposing, and commissioning including appraisal and characterisation of H2 and/or CO2 storage sites	✔	✗	✗	✔	✗	H2-CCS Chain	4	3	12	2	Comprehensive public and private sector collaboration on integrated project governance, coordination, monitoring and risk analysis	Control of Cause: Likelihood Reduction	Technology	Non-Existing	no	1
												Build contingency and optionality in overall H2-CCS chain project development	Control of Cause: Likelihood Reduction	Contractual	Early stage of development	no	1
	Full chain technical/technology integration and performance don't meet design criteria requiring re-design, remediation, or re-engineering	✔	✗	✔	✔	✗	H2-CCS Chain	3	5	15	4	In depth reviews of global lessons learnt, detailed and comprehensive risk analysis, audits	Control of Cause: Likelihood Reduction	Technology	Early stage of development	no	3
												Technical collaboration between EPCMs and technology suppliers across the chain to stress-test integrated designs	Control of Cause: Likelihood Reduction	Technology	Early stage of development	no	2
OPERATIONAL	Uncertainty and/or variability with the consistency of either the H2 production stream or the CO2 capture streams in terms of volume, purity, rate and cost	✔	✗	✗	✗	✔	H2-CCS Chain	3	4	12	2	Contractual gas quality specifications with performance guarantees and contractual liabilities from EPCM and counterparty operators	Control of Cause: Likelihood Reduction	Contractual	Existing	no	1
												Build contingency and optionality in overall H2-CCS chain project development	Control of Cause: Likelihood Reduction	Technology	Non-Existing	no	1
	Short term outages (including mechanical damage, maintenance delays, facilities problems etc.) of one part of the H2-CCS chain impact operations of another part of the chain	✔	✔	✗	✗	✔	H2-CCS Chain	3	3	9	3	Ensure sufficient hydrogen storage capability combined with system level redundancy and segment operational back-up measures, including CO2 sequestration contingency	Control of Cause: Likelihood Reduction	Technology	Existing	no	2
												Insurance cover for BAU events and government underwriting where insurance unavailable	Recovery from Consequence: Impact Reduction	Insurance	Early stage of development	yes	1
	Existing MMV technologies for use with CO2 storage operations are not able to provide necessary or sufficient data for regulatory compliance purposes at bearable costs	✔	✗	✗	✗	✔	CCS Chain	1	4	4	2	Regulator/Competent Authority implements evidence-based pragmatic and flexible compliance regime and penalty response	Recovery from Consequence: Impact Reduction	Regulations, Legal and Influence	Early stage of development	yes	1
OUTPUT AND SERVICE RELIABILITY	Unknown performance reliability of scaled up ATR + capture technology operating in real world conditions	✔	✔	✔	✗	✔	H2-CCS Chain	2	4	8	2	In depth reviews of global lessons learnt, detailed and comprehensive risk analysis, collaboration between EPCMs and technology suppliers	Control of Cause: Likelihood Reduction	Technology	Existing	no	1

Risk Category	Business Risks	Nature of Impact: Cost	Revenue	Financing	Schedule	Liabilities	Scope of Chain Impact	Risk Quantification: Likelihood	Impact	Rating	Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
												Modular H2 plant design with step by step performance testing with early users (with flexibility on fuel consumption) prior to full city conversion	Recovery from Consequence: Impact Reduction	Technology	Existing	no	1
	Underperformance of CO2 geological storage site (incl. capacity, lifetime injectivity, migration)	✔	✔	✗	✗	✔	H2-CCS Chain	3	5	15	4	Extended pre-FID appraisal and characterisation period including injection testing, pressure monitoring and 4D seismic surveying. Engineered redundancy in wells and storage formations. Pre-appraised and characterised back-up storage sites prior to FID	Control of Cause: Likelihood Reduction	Technology	Existing	no	3
												Public sector underwriting where no insurance available, underwriting beyond limits on carbon pricing (guarantees for capped carbon penalties for geological storage), no-fault compensation mechanisms, guarantor of last resort for financiers	Recovery from Consequence: Impact Reduction	Financial Support	Non-Existing	yes	2
	End user appliance performance and usability does not achieve the same standard and service level that natural gas customers are used to	✔	✔	✗	✗	✔	H2 Chain	2	4	8	3	Critical safety evidence gathered, appliance standards developed and world best practice implemented in regulation in sufficient time to enable incorporation in FEED ahead of FID	Control of Cause: Likelihood Reduction	Technology	Early stage of development	yes	2
ENVIRONMENTAL IMPACT	Release of CO2 to atmosphere from capture, transport or storage operations, outages or leaks	✔	✗	✗	✗	✔	CCS Chain	2	4	8	4	Use of proven technology and designs in H21 phase 1	Control of Cause: Likelihood Reduction	Technology	Existing	no	3
												Counterparty indemnities and remedies including compensation up to defined caps with remainder underwritten by government during H21 phase 1. Requires umbrella agreement including government and relevant authorities	Recovery from Consequence: Impact Reduction	Contractual	Non-Existing	yes	2
	Hydrogen leak and explosion in the first phase of H21	✔	✗	✗	✔	✔	H2 Chain	1	5	5	3	Use of proven technology and designs in H21 phase 1	Control of Cause: Likelihood Reduction	Technology	Existing	no	2
												In depth reviews of global lessons learnt, detailed and comprehensive risk analysis, collaboration between EPCMs and technology suppliers	Control of Cause: Likelihood Reduction	Technology	Early stage of development	no	1
DECOMMISSIONING	N/A																
	N/A																
	N/A																

E.7 Business Risks: Market and Commercial

Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
CURRENCY AND EXCHANGE	Significant increase in costs due to currency fluctuations and therefore increase in tariffs and government subsidies/end user charges	✔	✗	✔	✗	✔	H2-CCS Chain	4	4	16	3	Agree contractual risk sharing and pass through between private investors and government in competitive procurement exercise	Recovery from Consequence: Impact Reduction	Contractual	Existing	yes	2
												Standard currency risk management: currency swaps, procurement terms, maximise local content	Recovery from Consequence: Impact Reduction	Financial Markets and Debt Instruments	Existing	no	2
MARKET DEVELOPMENT AND DEMAND RISKS	Market demand declines from, or doesn't meet, projection in investment case	✗	✔	✔	✗	✗	H2-CCS Chain	3	5	15	3	Take-or-pay contract with baseload H2 offtaker(s) with sufficient capacity reserved and secured market demand and government revenue support to cover a threshold return on investment. Appropriate pass-through if third party capture provider.	Recovery from Consequence: Impact Reduction	Contractual	Early stage of development	yes	1
												Focus on demand from captive markets (power, residential heating, large industrials) to anchor initial infrastructure	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	1
												Create demand by designing hydrogen market to ensure hydrogen is more competitive than alternative fossil fuels	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	1
												Choose counterparties with secure market demand or implement appropriate public-private collaborative business model for a required minimum period	Control of Cause: Likelihood Reduction	Contractual	Early stage of development	yes	2
												Design CO2 T&S and H2 storage infrastructure development to match secure demand and have flexibility for expansion. Government support to act as underwriter of last resort for minimum return on capital investment.	Recovery from Consequence: Impact Reduction	Market Design, Supervision, Market Provider	Early stage of development	yes	2
	Initial Leeds city conversion and/or foundation cluster customers delayed in start-up and use of hydrogen	✗	✔	✗	✔	✗	H2-CCS Chain	4	4	16	3	Terms of take-or-pay hydrogen supply contracts with energy supplier(s) and CO2 T&S contracts include public sector underwriting with revenue/cost compensation mechanism for segments in full system delivery	Recovery from Consequence: Impact Reduction	Financial Support	Non-Existing	yes	2
												Public sector market-maker that carries coordination responsibility and is guarantor of last resort	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
	Industrial customers become insolvent / close business	✗	✔	✔	✗	✔	H2-CCS Chain	3	4	12	4	Support measures for industry introduced (including import border adjustment, export price compensation) in accordance with a designed timeline consistent with meeting UK carbon budgets	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	3

Risk Category	Business Risks	Nature of Impact: Cost	Nature of Impact: Revenue	Nature of Impact: Financing	Nature of Impact: Schedule	Nature of Impact: Liabilities	Scope of Chain Impact	Risk Quantification: Likelihood	Risk Quantification: Impact	Risk Quantification: Rating	Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
												Design hydrogen market so that hydrogen conversion for industrial customers is not an added cost and does not impact their competitiveness. Create a pull for hydrogen from multiple industrial customers by making hydrogen competitive with alternative fossil fuel	Recovery from Consequence: Impact Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
												Choose H21 first phase counterparties with secure market demand or business model for a required minimum period (e.g. 15 years)	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
ACCESS TO CAPITAL	Lenders conditions incompatible with regulatory regime designed for H21 NoE making finance essentially unavailable	✗	✗	✔	✗	✔	H2-CCS Chain	3	4	12	4	Utilise umbrella agreement to establish required statutory provisions and regulations for private sector finance to be available in collaboration with banks and private sector investors	Control of Cause: Likelihood Reduction	Regulations, Legal and Influence	Non-Existing	yes	2
												Structure H2 system network infrastructure under existing gas distribution RAB model with Ofgem oversight	Control of Cause: Likelihood Reduction	Regulations, Legal and Influence	Early stage of development	yes	2
	Lack of confidence from banks in operability of full system and availability of segment services plus potential financial impact from non-availability - Lenders require repayment guarantees from government or public authority	✔	✔	✔	✔	✔	H2-CCS Chain	4	5	20	4	H2-CCS infrastructure umbrella agreement between state/public authority and private sector providing loan guarantees/debt repayment, revenue compensation at agreed threshold, insurer of last resort, regulatory review as necessary	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	3
	Lenders seek onerous termination provisions or step-in rights making finance essentially unavailable	✗	✗	✔	✗	✔	H2-CCS Chain	3	4	12	4	Under a H21 umbrella agreement mandate relevant public authorities to perform step-in functions as part of regulatory oversight including permit/licence suspension or termination. Include cost capping and underwriting minimum repayment thresholds as required	Control of Cause: Likelihood Reduction	Regulations, Legal and Influence	Non-Existing	yes	3
	Lack of confidence from banks in end user hydrogen market development beyond initial phase H21 captive customers	✔	✗	✔	✔	✗	H2-CCS Chain	3	4	12	3	Parliament commitment to a subsequent phase H21 conversion using CCS if first phase successful with mandate and budget given to Infrastructure and Projects Authority (or similar)	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
												Overall infrastructure development designed in distinct modular phases - each phase is independent and can be funded separately	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Early stage of development	yes	2
	Extended non-availability or non-performance of CO2 transport and storage makes investment into ATR Hydrogen production 'dirty' and therefore non-ethical for banks	✗	✗	✔	✔	✗	H2-CCS Chain	3	4	12	3	Parliament commitment to first phase H21 conversion using CCS in statute with mandate and budget given to Infrastructure and Projects Authority (or similar)	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	2
												Structure overall timing of project with CCS proven on lower scale (using hydrogen with power plant or industrials) prior to full hydrogen plant for H21 city conversion	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	2
												Funding support for initial CCS infrastructure (pipeline, reservoir) provided on the basis of minimising risk with options to develop alternatives for worst case scenario	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	2

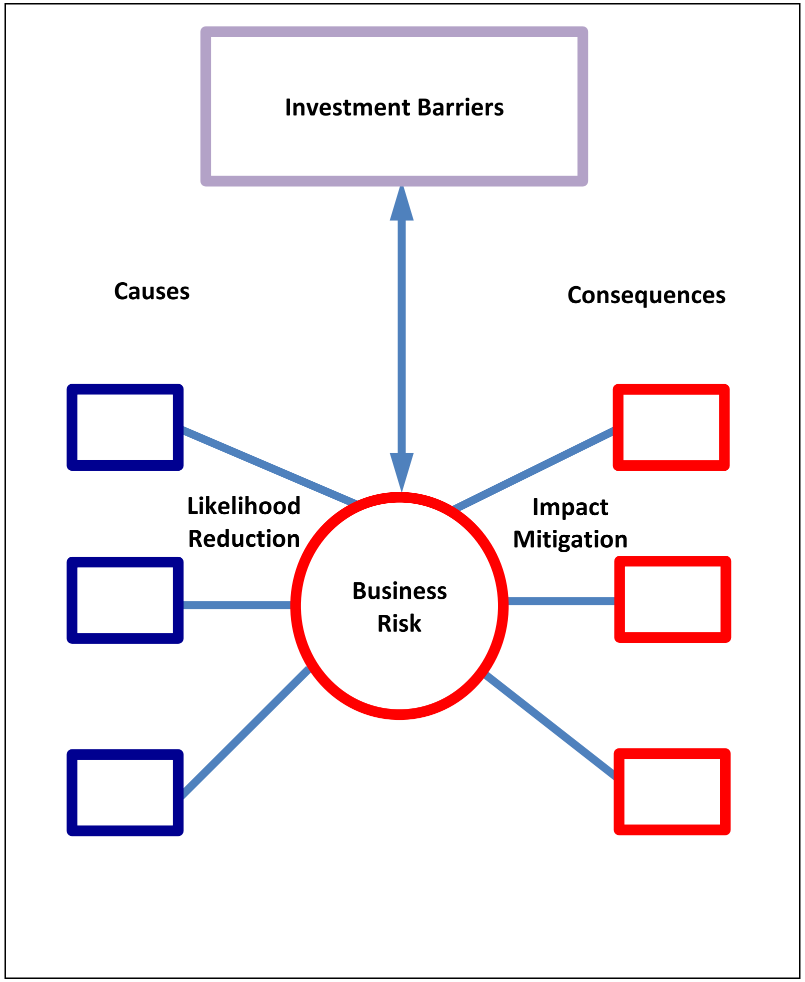
Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
COUNTERPARTY	Uninsurable components of the H21 infrastructure and operations require alternative and novel underwriting and guarantee mechanisms for intra-chain counterparty performance obligations	✔	✗	✔	✗	✔	H2-CCS Chain	5	5	25	4	Public sector underwriting where no insurance available, underwriting beyond limits on carbon pricing (guarantees for capped carbon penalties for geological storage), no-fault compensation mechanisms, guarantor of last resort	Control of Cause: Likelihood Reduction	Financial Support	Non-Existing	yes	3
COUNTERPARTY	New technology/supplier guarantees and warranties of insufficient quality to cover developers and operator's construction and operation risks	✔	✗	✔	✗	✔	H2-CCS Chain	5	4	20	4	Contract with technology suppliers who can provide substantive warranties and guarantees within a partnership structure under the terms and conditions of a suitable umbrella agreement	Recovery from Consequence: Impact Reduction	Ownership Structure / Investor Type	Early stage of development	no	2
COUNTERPARTY																	
EXIT/LIQUIDITY/ REFINANCING RISKS	N/A																
EXIT/LIQUIDITY/ REFINANCING RISKS	N/A																
EXIT/LIQUIDITY/ REFINANCING RISKS	N/A																

E.8 Business Risks: Outcome

Risk Category	Business Risks	Nature of Impact					Scope of Chain Impact	Risk Quantification			Investability Rating	Mitigation Measures	Target of Mitigation Measure: Cause or Consequence?	Category	Current Status of Mitigation Measure	Government Intervention Required (y/n)	Investability Rating (Post Mitigation)
		Cost	Revenue	Financing	Schedule	Liabilities		Likelihood	Impact	Rating							
EMISSION REDUCTION	Emissions reductions in H21 phase 1 do not meet expectations	✗	✗	✗	✗	✓	H2-CCS Chain	2	5	10	2	Government to contract in partnership through an umbrella agreement with developers and operators of sufficient capability and financial strength to deliver H21 phase 1	Control of Cause: Likelihood Reduction	Ownership Structure / Investor Type	Non-Existing	yes	1
												Modular design for the H2 production and capture facilities to enable technology improvements/substitutions	Recovery from Consequence: Impact Reduction	Technology	Early stage of development	no	1
NEGATIVE INDIRECT IMPACT (SOCIAL, HEALTH, ECONOMIC, etc.	H21 Phase 1 creates unintended disruptions across broader community and economy	✗	✗	✗	✗	✓	H2-CCS Chain	1	5	5	1	Utilise an Executive Steering Committee to drive the Phase 1 process with engagement of all key parties (grouped in regulatory, regional and functional expert working groups)	Control of Cause: Likelihood Reduction	Market Design, Supervision, Market Provider	Non-Existing	yes	1
	N/A																
	N/A																
PUBLIC BUDGET	Potential for significant cost overruns and calls on government underwriting and support for delivering H21 city conversions and H2-CCS infrastructure	✓	✗	✓	✓	✗	H2-CCS Chain	3	4	12	4	Government to contract in partnership through an umbrella agreement with developers and operators of sufficient capability and financial strength to deliver H21 phase 1	Control of Cause: Likelihood Reduction	Ownership Structure / Investor Type	Non-Existing	yes	3
	Significant cost improvements in other technologies make H2-CCS chain with city conversion less cost effective for government	✓	✗	✗	✓	✗	H2-CCS Chain	3	4	12	4	Modular design of H2 plant combined with H2-CCS chain based on multiple users offers sufficient flexibility to adjust or stop further expansion	Recovery from Consequence: Impact Reduction	Technology	Existing	no	3
ASSET UNDERPERFORMANCE/ STRANDED ASSET	Premature CO2 storage site closure during H21 phase 1	✓	✓	✓	✗	✓	H2-CCS Chain	2	5	10	4	Extended pre-FID appraisal and characterisation period including injection testing, pressure monitoring and 4D seismic surveying. Pre-appraised and characterised back-up storage sites prior to FID	Control of Cause: Likelihood Reduction	Technology	Early stage of development	no	3
	Utilisation of the full capacity of initially oversized infrastructure in North of England does not materialise in the timeframe envisaged at FID	✓	✓	✗	✓	✗	H2-CCS Chain	3	5	15	3	Government net zero, clean growth and industrial policies are implemented through a rigorous coordinated strategy comprising real options to ensure full utilisation of infrastructure that includes dealing with residual emissions via BECCS and DACCS technologies	Control of Cause: Likelihood Reduction	Policy and Market Signals	Non-Existing	yes	2

E.9 Risk Matrix Guidance and Legend

ASSESSMENT METHODOLOGY



PRIVATE SECTOR INVESTABILITY RATING GUIDANCE

Investability Rating	Guidance
1	Established business opportunity with standard business risks. Investment open to standard market players with standard financing and insurance available
2	Medium risk investment with debt financing available at short tenor and high interest, higher than standard IRR required, risk profile acceptable to more than 50% of market players
3	High risk investment with low debt ratio bank financing available, proven technology and acceptable regulatory and legal environment
4	Investment requires high risk appetite - First mover investor - No debt financing available, strategic investment, company with large balance sheet
5	No Investment possible - uncapped or unmanageable liabilities, high uncertainty of revenue and cost, unacceptable performance guarantees and warranties

PUBLIC SECTOR INVESTABILITY RATING GUIDANCE

Investability Rating	Guidance
1	Established public sector investment activity and/or risk profile
2	Medium risk to Government, small number of previous public sector investments with similar risk profile, general community support for the activity, infrastructure, or service
3	High risk investment with potential for stranded or under-performing assets left in public sector hands
4	Investment requires high risk appetite from Government with Treasury buy-in, very strong or new policy support, likely a need for new legislative mechanisms, possible need for bi-partisan agreement in parliament
5	No public investment possible - political or financial exposure too high

RISK MITIGATION MEASURE CATEGORY GUIDANCE

Mitigation Measure Category	Guidance
Contractual Terms	Examples include: take or pay, bank guarantees, pricing structure, change of control and change of law provisions, risk allocation, liability limits for specific events, consequential damages
Financial Market and Debt Instruments	Minimum repayment levels, debt service cover ratio, step in rights, swaps, derivative instruments, new technology guarantees/requirements
Insurance	Insurance cover to protect against specific risks and cap liabilities
Technology	Improvements in technology to improve reliability, improve efficiency, reduce capex/opex, reduce uncertainty of unplanned operational events
Policy and Market Signals	Policy commitments, targets and carbon budgets, Principles for evaluating investment – (social economic benefits), decision-making structure
Regulations, Legal and Influence	Legislative changes to define, allocate and reduce liabilities, legal requirements for permitting and planning consent including financial guarantees and liability for decommissioning, pollution…
Financial Support	Financial support mechanisms (grants, tax allowances, FITs, subsidies, CfDs, etc.), public sector underwriting, Third Party Access policy, Regulated/Unregulated business
Market Design, Supervision, Market Provider	Intervention for competition, tradeable permits, competitive tendering, direct service or goods provision,
Ownership Structure / Investor Type	Joint ventures, strategic partnerships and vertical integration of value chain, impact of government participation, public-private ownership/operating model

RISK LIKELIHOOD RATING GUIDANCE

Risk Likelihood	Guidance
1	Very unlikely
2	Unlikely
3	Possible
4	Likely
5	Very Likely

RISK IMPACT RATING GUIDANCE

Risk Impact	Guidance
1	Insignificant
2	Minor
3	Moderate
4	Major
5	Severe

F H21 SYSTEM RISK MITIGATION

F.1 H21 System Heat Map

		POLITICAL / POLICY / SOCIAL						TECHNICAL / PHYSICAL					COMMERCIAL / MARKET						OUTCOME			
		Regulatory Change	Policy Change	Legal and Ownership	Permitting and Consenting	Reputation & Social	Political and Governance	Construction	Operational	Output/Service Reliability	Environmental Impact	Decommissioning	Currency and Exchange Risks	Market Development (Market Demand)	Output/Service Price	Access to Capital	Liquidity (refinancing/exit)	Counterparty	Emission Reduction	Negative Indirect Impacts (social, health, economic benefits)	Public Budget Impact	Asset Underperformance/Stranded Asset
INVESTMENT CYCLE	Development	1,6,8		1,5,7,8	5,6	5,8	5,7,8			5						1,7						
	Financing	3,5,7,8		1,5,7,8	1,3,5,9		3,5,7	2,3,4	1,2,3,4	3,5,7			4,7		1,7	5,6,7,8		2,4,7				
	Construction	1,3				5,6		1,3,6			3							1,3				
	Operation	1,3,6		1,3,6,8		5,8			1,3	1,5,7,9	3,6,7		4,7		1,7			1,3,7,8	1,3,8,9		5,6,8,9	1,6,7,8
	Decommissioning	3,5			3,5,6	5,6						1,3,6									1,3,5,6	
	Outcome					5,6,8				1,5	3,5,7			1,5,8,9					3,6,8,9	5,8,9	5,6,8	

F.2 Legend for H21 System Heat Map

RISK MITIGATION COVERAGE GAP

RISK MITIGATION DEMAND

High	Demand Intensity from Project Stakeholders for Risk Coverage
↑	
↓	
Low	

RISK MITIGATION MEASURES

1	Private Sector	Contractual
2		Debt Instruments
3		Insurance
4		Financial Markets
5	Public Sector	Policy and Market Signals
6		Regulation and Influence
7		Financial Support
8		Market Design and Supervision
9		Direct Market Provider

F.3 Risk Sharing and Collaboration Matrix

MITIGATING PARTY

- Govt/Public Body
- Private Sector
- Joint
- Undefined

POLITICAL / POLICY / SOCIAL

SYSTEM PERSPECTIVE	Regulatory Change	Policy Change	Legal and Ownership	Permitting and Consenting	Reputation & Social	Political and Governance
Development	Joint	Govt/Public Body	Joint	Govt/Public Body	Joint	Govt/Public Body
Financing	Govt/Public Body	Govt/Public Body	Joint	Govt/Public Body		Joint
Construction	Private Sector	Govt/Public Body			Joint	
Operation	Private Sector	Govt/Public Body	Joint		Joint	
Decommissioning	Govt/Public Body			Joint	Joint	
Outcome					Joint	

TECHNICAL / PHYSICAL

SYSTEM PERSPECTIVE	Construction	Operational	Output/Service Reliability	Environmental Impact	Decommissioning
Development			Joint		
Financing	Private Sector	Private Sector	Joint		
Construction	Private Sector			Private Sector	
Operation		Private Sector	Private Sector	Joint	
Decommissioning					Private Sector
Outcome			Joint	Joint	

COMMERCIAL / MARKET

SYSTEM PERSPECTIVE	Currency and Exchange Risks	Market Development (Market Demand)	Output/Service Price	Access to Capital	Liquidity (refinancing/exit)	Counterparty
Development		Govt/Public Body		Joint		
Financing	Joint	Govt/Public Body	Joint	Govt/Public Body	Govt/Public Body	Joint
Construction		Govt/Public Body				Private Sector
Operation	Joint	Govt/Public Body	Joint		Govt/Public Body	Joint
Decommissioning						
Outcome		Joint				

OUTCOME

SYSTEM PERSPECTIVE	Emission Reduction	Negative Indirect Impacts (social, health, economic benefits)	Public Budget Impact	Asset Underperformance/Stranded Asset
Development				
Financing				
Construction				
Operation	Joint		Govt/Public Body	Joint
Decommissioning			Joint	Joint
Outcome	Joint	Govt/Public Body	Govt/Public Body	Govt/Public Body

G H21 SYSTEM BUSINESS MODEL

G.1 Sector Drivers

CATEGORY	ASPECT TO BE RATED								
	MARKET SECTOR	H_2 INFRASTRUCTURE				CCS INFRASTRUCTURE		H_2 END USE MARKETS	
		H_2 Production	H_2 Transmission	H_2 Distribution	H_2 Storage	CO_2 T&D	CO_2 Storage	Industry	Centralised Heat & Power
MARKET DEVELOPMENT	Government willingness to intervene in creation of new low carbon markets	Medium	Medium	Low	Low	Medium	Medium	Low	Medium
	Opportunity to adapt and reuse existing market development mechanisms	medium	high	high	Medium	low	low	low	Medium
	Government willingness to socialise costs of developing new markets and infrastructure	Medium	high	high	Medium	Medium	Medium	low	High
	Government willingness to become an active market actor to facilitate market development	Low	low	low	low	medium	medium	low	low
	Private sector interest in investing early into sector	Medium	high	high	Low	high	high	medium	medium
	Private sector ability to undertake market development without government support	low	low	low	low	low	low	low	low
PHYSICAL DELIVERY	Existing physical assets and opportunities for re-use	Medium	high	high	low	low	low	Medium	high
	Clustering of potential customers, demand and/or assets	High	high	high	high	high	high	high	high
	Technology maturity (incl. CO2 capture)	Medium	Medium	Medium	Low	High	medium	high	medium
	Capacity of private sector to manage physical assets and manage unforeseen construction or operation activities	High	high	high	medium	high	high	high	high

CATEGORY	ASPECT TO BE RATED								
	MARKET SECTOR	H_2 INFRASTRUCTURE				CCS INFRASTRUCTURE		H_2 END USE MARKETS	
		H_2 Production	H_2 Transmission	H_2 Distribution	H_2 Storage	CO_2 T&D	CO_2 Storage	Industry	Centralised Heat & Power
SOCIETAL	Extent of positive public support for contribution of each sector to system decarbonisation		Medium	Medium		Medium	Medium	Medium	Medium
	Public acceptance of safety and environmental impact of activity	High	Medium			Low	Low	Medium	Medium
	Extent of public awareness of potential sector contribution to system decarbonisation and value to community	Low	Medium	Medium		Low	Low	Medium	Medium
	Willingness to pay to subsidise relevant sectors to decarbonise energy system	Low	Low	Low		Low	Low	Low	medium
		Note that a blank means the response is unknown							

H H21 SYSTEM BUSINESS CASE TEMPLATES

H.1 Business Case Definition

A. PROJECT PRESENTATION

H2-CCS Sectors	Full H_2-CCS chain, H2 for gas network conversion and other sectors
Project Status	Concept
Project Type	First of a Kind Large Scale Infrastructure Deployment
Project Scale (financial)	CAPEX: £22.78 billion OPEX: £955 million per annum post 2035
Project Scale (emissions)	CO_2 emissions reduction 12.5 Mtpa

Geographical Extent	North of England
Implementation Timeline	2023-2035
Market Maturity	Market creation
Main Public Sector partners/stakeholders	General government - to be defined later
Main Private Sector partners/stakeholders	Gas distribution companies (Northern Gas Networks, Cadent), H2 production companies (BOC, Air Liquide), oil and gas companies (BP, Shell, Total, Equinor, ENI, National Grid, Power generation companies

INVESTMENT PROPOSITION
An initial commitment to construction and funding of a first phase H_2-CCS network in the north of England is necessary to prepare for a gas network conversion commencing in 2028-29 and the development of markets for H_2 and CO_2. The initial H_2-CCS system will be composed of: 1. a modular H_2 production facility at scale [initial capacity 1.35 GW]; 2. associated H_2 transmission pipeline(s) and geological cavern storage; 3. facilities and market appliance upgrades for H_2 blended with methane up to 20%; 4. conversion or construction of a power station capable of burning blended natural gas up to 90% hydrogen [initial capacity of 2 or 3 440 MW turbines]; 5. connection to a large industrial cluster [Humber, Teesside, Manchester/Liverpool]; 6. oversized CO_2 T&S infrastructure in the Southern North Sea [initial pipeline capacity of 15-20 Mt per annum]. This system will be supported by the creation of a new fossil fuel levy and CO_2 storage obligation on oil and gas producers/importers combined with a government commitment to the deployment of green hydrogen production technology (electrolysis) commensurate with an eventual minimum captive market size for H2 use. The subsequent phases of investment will focus on the decarbonisation of the gas network through the further expansion of the H_2-CCS infrastructure and will be adjusted to reflect the outcome from the first investment phase and the evolution of system decarbonisation pathways.

B. BUSINESS CONTEXT SUMMARY

DIMENSION	SUMMARY
Institutional	The UK has experience of different levels of government (central, regional, local) collaborating together to implement energy and climate policies. Institutional capability is high to participate in delivery of H_2-CCS infrastructure and heat decarbonisation with organisations such as Ofgem, Oil and Gas Authority, Infrastructure and Projects Authority, Health and Safety Executive, Low Carbon Contracts Company. There is a high availability of contractual frameworks for infrastructure investments and existing market and infrastructure regulation capability. Additionally, the UK has a high level of experience in public-private business models.
Financing (private & public)	The UK has good historical access to private infrastructure financing at competitive cost and is an attractive country for private sector investment. The UK has some limitations on public sector financing as a result of budgetary constraints due to austerity measures and national debt level and the impact of fiscal rules. This situation is likely to worsen and reduce the flexibility for government financing as a result of the COVID-19 crisis.
Market Development	There are major market failures across the H_2-CCS chain and there is a need for substantive government intervention both to centralise and coordinate market development and to coherent long-term public-sector funding mechanisms, backed by the public to encourage the private sector to invest and deliver the new infrastructure. The UK has the necessary experience to proactively deliver and manage such market development mechanisms though it is has not so far shown the willingness to intervene at scale and to socialise the early market creation costs. The lack of a strong strategic rationale and the pressure to act in the short term combined with the outcome risks and technology/market uncertainty have delayed any real decision and market making action.
Macro-economic	Overall, the UK shows strong macroeconomic indicators – before COVID-19 crisis – with high GDP per capita, low unemployment and low inflation indicating a strong ability to finance (directly or indirectly) new infrastructure investment. However, the carbon pricing model, uncertain in its current form with the impending departure of the UK from the European Union, is insufficient to drive significant business sector decisions to decarbonise.

DIMENSION	SUMMARY
Legal & Regulatory	The UK has a high adequacy of legal / regulatory / policy framework in the country to implement different types of PPPs and collaborate with the private sector. There are few legal constraints on the structure and operation of a H_2-CCS chain for providing a cross-border waste management service to other countries (the contracting parties to the London Protocol have agreed in 2019 to allow provisional application of the as-yet unratified cross-border transport of CO_2 between collaborating parties). The extent of constraints on public sector incentivisation under European State Aid legislation and the extent of constraints on private sector investment under environmental liability legislation post BREXIT are as yet undetermined.
Societal	Creating a H_2-CCS business case/business model which will gain societal acceptance is critical. It needs to address the moral hazard of locking in a fossil fuel future by subsidising CCS, and needs to ensure that the role and development of CCS is strictly governed and restricted to facilitating a transition to a resilient 'fossil-fuel' free economy. Education and communication will be needed to raise awareness first and then articulate the social, health and economic benefits of a clean energy system

Summary of Government's key policy objectives

1. Net zero emissions in 2050 under the Climate Change Act with a succession of legally binding carbon budgets
2. 'Clean Growth Strategy' to achieve a 'green' economy with sustainable growth
3. 'Industrial Strategy' to stimulate market investment in clean and efficient technologies and processes
4. Facilitating social and economic development of regions across the UK
5. Innovation funding to stimulate development and deployment of a range of low carbon technologies for heating, transport, energy storage, electricity generation, smart energy systems, and new low carbon products
6. Financing and delivery of low carbon infrastructure primarily by the private sector driven by carbon markets and appropriately structured carbon tax, carbon price support and competitive subsidy mechanisms
7. Socialisation of costs across consumer markets where appropriate (e.g. consumer electricity bills)
8. Establish CCS in at least two UK sites - one by mid 2020s and one by 2030
9. Facilitate at least one privately financed gas fired power station with CCS through consumer subsidies

E. BUSINESS MODEL PREFERENCE

Business Model	Ownership	Capital Sourcing	Market Development		Physical Delivery	
			Responsibility	Revenue Model	Responsibility	Business Structure
H2 Production	PRIVATE	PRIVATE	PUBLIC	Targeted Revenue Support	PRIVATE	Free Market Enterprise
H2 Transmission	PRIVATE	PRIVATE	PUBLIC	Price Regulated Revenue + Construction Support	PRIVATE	Regulated Asset Base (New)
H2 Distribution	PRIVATE	PRIVATE	PUBLIC	Price Regulated Revenue	PRIVATE	Regulated Asset Base (Existing)
H2 Storage	PUBLIC	PRIVATE	PUBLIC	Price Regulated Revenue	PRIVATE	Public Concession (Design-Build-Finance-Operate)
CO2 Capture						
CO2 Gathering						
CO2 Transmission	JOINT	JOINT	PUBLIC	Price Regulated Revenue	PRIVATE	Joint Venture
CO2 Storage	JOINT	JOINT	PUBLIC	Price Regulated Revenue	PRIVATE	Joint Venture
Mobility						
Industry	PRIVATE	PRIVATE	PUBLIC	Targeted Revenue Support	PRIVATE	Free Market Enterprise
Decentralised Heat & Power						
Centralised Heat & Power	PRIVATE	PRIVATE	PUBLIC	Targeted Revenue Support	PRIVATE	Free Market Enterprise

G. LIMITATIONS TO INVESTMENT

Post-mitigation investability rating (PMIR) provided in brackets (See Appendix E.9)

Principal Barriers to Private Sector:

1. Uncertainty of UK commitment to pace and evolution of low carbon or circular economy matching net zero climate target [PMIR = 3]
2. Missing binding government mandate for delivering the first city natural gas to H2 conversion and associated integrated full chain infrastructure [PMIR = 3]
3. Lack of confidence in long term financial commitment by government [PMIR = 2 - 3]
4. Long term leakage liabilities defined in EU Directive and national regulations with front loaded Financial Security [PMIR = 2 - 3]
5. Operational complexity of multi-party integrated system both during commissioning and early full-scale operations [PMIR = 2 - 3]
6. Missing markets for large-scale clean (low carbon) hydrogen [PMIR = 3]
7. Missing markets for large-scale use of CO_2 transport and storage infrastructure [PMIR = 3]
8. Regulated rate of return is insufficient to attract O&G operators to invest in CO_2 T&S service [PMIR = 3]

Principal Barriers to Public Sector:

1. Cost of emissions abatement using CCS in the first phase of H21 is too high compared to competing technologies (renewable electricity, heat pumps) to warrant public funding support [PMIR = 3]
2. Early stage hydrogen supply system does not have sufficient capacity and is not sufficiently robust (compared to the natural gas system) to avoid customer outages [PMIR = 3]

Principal Barriers to Public and Private Sectors:

1. Unknown public acceptance of a city hydrogen conversion and gas network re-purposing [PMIR = 3]
2. Objections and moral hazard arguments related to continuing use of fossil fuels and financial support to O&G industry [PMIR = 3]
3. Guaranteed intra-chain counterparty performance is required between H_2 retailer/DNO/TNO/producer and CO_2 capturer/gatherer/transporter/storer [PMIR = 3]
4. Uncertainty of market demand over 20 years [PMIR = 3]
5. The level of financial risk related to integrated full chain infrastructure (cross chain default, political risk, delivery risk) is too high for lenders with conventional risk mitigation measures [PMIR = 3]
6. Potential for CO_2 T&S infrastructure to be underutilised or not utilised after first capture project [PMIR = 3]

H.1.1 Drivers

H.1.1.1

Section I: Drivers of Business Case Definition

Category	Aspect to be Rated	Guidance	Rating
Government Policies (energy & climate change)	**CURRENT:** Extent of energy and climate change mitigation policies for large scale energy transformation and relevant government's current commitment to low carbon development	*Provide an indication of the robustness, diversity and impactfulness of energy and climate change policies in the country.*	Medium
	FUTURE: Confidence in the country's development of energy and climate change policies and relevant government's commitment for large scale societal low carbon energy transformation	*Provide an indication of the uncertainty around the future evolution of government policies on energy and climate.*	Medium
	Availability of energy and/or climate change mitigation policy incentives for large scale energy projects	*E.g. funding (direct or indirect)*	Low
	Alignment of energy policies with climate change targets	*Ability of policies to deliver stated or legislated emissions targets*	Medium
	Experience of different levels of government (central, regional, local) collaborating together to implement energy and climate policies		High

Category	Aspect to be Rated	Guidance	Rating
Institutional (infrastructure)	**CURRENT:** Status and strength of large-scale infrastructure creation/development policies	*Provide an indication of the robustness, diversity and impactfulness of infrastructure policies.*	Low
	FUTURE: Confidence in the evolution of the country's large-scale infrastructure creation/development policies	*Provide an indication of the uncertainty around the future evolution of government policies.*	Medium
	Availability of large-scale infrastructure investment incentives	*E.g. government guarantees and other forms of indirect support*	Low
	Availability of contractual frameworks for infrastructure investments		High
	Existing market and infrastructure regulation capability		High
Institutional (Business Models & PPP)	Level of pre-determined government preference for a specific business model (or infrastructure service provision and delivery)		High
	Level of experience with PPPs in the country		High
	Strength of the organisational and sectoral capacity of the public sector to implement different types of PPPs		High
	Adequacy of the country's governance framework for implementing different types of PPPs		High
	Flexibility of public sector to engage with private sector and to define and/or adapt PPP models for new sectors		Medium

Category	Aspect to be Rated	Guidance	Rating
Financing (private sector)	Country attractiveness for infrastructure/low carbon energy investment (equity)		High
	Availability of bank financing (debt)		High
	Cost of financing for infrastructure investments		Low
Financing (public sector)	National debt level	*Provide an indication of the country's debt level and as a consequence, its difficulty to finance large scale infrastructure and energy projects*	Medium
	Extent of budgetary constraints (negative impact on financing capacity)		Medium
	Impact of fiscal rules (negative impact on financing capacity)		Medium
	Impact of public sector accounting rules (negative impact on financing capacity)		High
	Availability of public financing (bonds)	*Provide an indication of how constrained the public sector budget is, i.e. surplus vs. deficit. Rating scale: surplus buget = low, balanced budget = medium, constrained buget (i.e. deficit) = high.*	Medium

Category	Aspect to be Rated	Guidance	Rating
Market Development	**CURRENT:** Status and strength of low carbon market creation/development policies	*Provide an indication of the robustness, diversity and impactfulness of low carbon market creation policies.*	Medium
	FUTURE: Confidence in the evolution of the country's low carbon market creation/development policies	*Provide an indication of the uncertainty around the future evolution of government policies.*	Low
	Government willingness to intervene in creation of new low carbon markets		Medium
	Government willingness to socialise costs of developing new markets and infrastructure		Medium
	Government willingness to use centralised system design, planning and coordination for market development		Low
	Institutional experience with delivering/managing market support and development mechanisms		High
	Private sector ability to undertake low carbon market development without government support		Low

Category	Aspect to be Rated	Guidance	Rating
Macroeconomic	**<u>CURRENT:</u>** National carbon pricing model: robustness, positive impact on private sector business decisions to decarbonise	*If carbon pricing is available in the country context, indicate the level of the carbon price as low / medium / high.*	Low
	<u>FUTURE:</u> Uncertainty of carbon pricing and impact on private sector business decisions	*If carbon pricing is available in the country context, provide an indication of the uncertainty around future carbon price levels.*	High
	National GDP per capita and trend		High
	Level of inflation		Low
	Commodity prices	*E.g. prices for natural gas*	High
	Unemployment Rate (national)		Low

Category	Aspect to be Rated	Guidance	Rating
Legal and Regulatory	Adequacy of legal / regulatory / policy framework in the country to implement different types of PPPs		High
	Cross border waste management - extent of legal constraints on structure of H2-CCS chain		Low
	European State Aid legislation - Extent of constraints on public sector incentivisation		Medium
	Environmental liability legislation - Extent of constraints on private sector investment	*E.g. Does the legal / regulatory / policy environment favour PPP application and the different components required for PPPs? Are PPPs consistent with other government policies? Is there sufficient legislative authority for entering into PPPs? Is there sufficient legislation to support the management and supervisory role of the public sector in PPPs?*	Medium

Category	Aspect to be Rated	Guidance	Rating
Environmental	Air quality	*Provide an indication of the air quality. Rating scale: poor air quality = low, decent air quality = medium, good air quality = high*	Low
	Management of natural resources	*Provide an indication of the effectiveness of natural resources management in the country. Rating scale: poorly managed = low, decently managed = medium, well managed = high*	High
	GHG emissions	*Provide an indication of the magnitude of GHG emissions relative to the size of the country*	High

Category	Aspect to be Rated	Guidance	Rating
Societal	How positive is the public opinion with regard to hydrogen as a future low carbon energy source?		Medium
	Extent of public education and training programmes directly related to the energy transformation required to meet climate targets		Low
	Extent of trust in oil and gas companies to deliver low carbon energy future		Low
	Extent of public sentiment to address climate change and environmental issues	*Public perception or social acceptance of the specific business opportunity along the H2-CCS chain. E.g. public perception of CO2 transport and storage. Rating scale: poor public perception = low, intermediate public perception = medium, good public perception = high.*	High
	Willingness to pay for related health and environmental benefits	*Public perception or social acceptance of the specific business opportunity along the H2-CCS chain. E.g. public perception of CO2 transport and storage. Rating scale: poor public perception = low, intermediate public perception = medium, good public perception = high.*	Medium

H.1.1.2

Section II: Drivers of Business Case Selection Specific to Business Opportunity and Sector being Considered

Category	Aspect to be Rated	Rating							
		H2 End Use Markets		H2 Infrastructure				CCS infrastructure	
		Chemicals & Industry	Centralised Heat & Power	H2 Production	H2 Transmission	H2 Distribution	H2 Storage	CO2 Transmission	CO2 Storage
		Conversion to chemicals or direct use via combustion for process heat.	*H2 power station or gas/H2 blended fuel*						
Physical and Technical	Existing physical assets and opportunities for re-use	High	High	Medium	High	High	Low	Low	Low
	Clustering of potential customers, demand and/or assets	High	High	High	High	High	High	High	High
	Technology maturity	High	High	High	High	Medium	medium	High	Medium
	Capacity of private sector to manage physical assets and manage unforeseen activities	High	High	High	High	High	High	High	High
Societal	Public perception of use case	High	High	Medium	Medium	Medium		Low	Low

H.2 Strategic Rationale

A. STRATEGIC RATIONALE - OBJECTIVE

OBJECTIVE: **JUSTIFICATION FOR CHANGE AND ASSESSMENT OF ALIGNMENT OF PROJECT WITH STRATEGIC OBJECTIVES AND MAJOR PRIORITIES OF PUBLIC SECTOR AND THE PRIVATE SECTOR PARTICIPANTS**

B. STRATEGIC ISSUES

KEY STRATEGIC ISSUES	QUESTIONS	ALIGNMENT RATING	RESPONSE
Demonstrate how proposal fits with the government's strategic objectives	Environmental	High	* Supports UK policy of heat decarbonisation and obligations of Climate Change Act. Hydrogen has the potential to facilitate decarbonisation with minimum cost and disruption to customers while using established gas infrastructure to manage supply. H21 North of England presented a vision for decarbonisation of 70% of meter points by 2050 using a regional roll out strategy (the first phase would achieve 14% of UK heat and 12.5Mtpa of CO_2 avoided by 2034). * Facilitates the use of hydrogen across all business sectors as an alternative 'clean' fuel and supports decarbonisation through use and further expansion of oversized CO_2 T&S infrastructure.
	Economic	High	* Facilitates development of a new H_2 supply chain; * Sustains the existing gas distribution/transmission businesses for the long term; * Protects the economic interests of industrial clusters by creating cost effective optionality for decarbonisation * Sustains economic value from oil and gas in country through energy transition.
	Financial	Medium	* Initial infrastructure is created at scale in line with recommendations to achieve cost effectiveness. * Technical risks are minimised through use of proven technology, initial use of H_2 in sectors with operational/fuel flexibility. * Government funding is minimised through private sector ownership and delivery in most business sectors and use of regulated returns.

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	Political	Medium	* Low regrets proposition with phased system deployment. * Significant optionality is built-in and there is minimum risk of under-utilisation. Anchoring the CCS infrastructure on hydrogen allows optionality for end users to either use a clean fuel (hydrogen) or use carbon capture (dependent on specifics of industry).
Sources of Value (Public Sector)	* How does the project support other ongoing decarbonisation activities? * What are the additional sources of value created by the project for the public sector? * Does the project support the acceleration/execution of other H2-CCS projects? How? What are the potential synergies?	High	* Industrial: the project would create the ability for industrials to decarbonise partially at minimum cost, commitment and complexity through fuel switching. This could create a competitive advantage for UK manufacturing. * Power generation: the project would both facilitate the decarbonisation of the existing conventional power sector without large and complex investments in stand-alone carbon capture facilities for plants with limited life span. It would support further renewable electricity penetration by acting as a backbone for new clean flexible back-up generation and energy storage. * It creates opportunities for the UK to import CO2 from other countries by building on the competitive advantage of owning large scale CO2 storage sites.
Demonstrate how proposal fits with private sector participants' strategic objectives	Financial	Low	There are currently no or low financial benefits for companies to invest in low carbon products or services
	Market and Product Development	High	Current private sector participation is high in innovation projects for low carbon technologies to address fossil fuel use in processes and substitution of energy use with hydrogen
	Environmental	Medium	Companies understand the imperative to transition to sustainable products and services in a net zero CO_2 emissions economy, but the slow pace of change is driven by perceptions of government commitment and consumer demand in end-use markets
	Reputation/Brand	High	Companies are keen to be perceived as addressing the climate crisis to both investors and consumers
	Other strategic objectives	High	Strategic objectives for the longer term related to business survival, location, transformation or profitability

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Sources of Value (Private Sector)	* Does the project support other ongoing activities in the company(ies)? How? * What are the additional sources of value created by the project for the company(ies)? * Does the project support the acceleration/execution of other projects for the company? How? What are the potential synergies?	High	* Supports preservation of existing business and offers new business opportunities for gas distribution and transmission companies. * Supports continuation of existing power generation facilities and new business opportunities at scale for power generators.
Justification for CCS	Why is CCS investment necessary in the short term?	High	A reliable large-scale CCS infrastructure is necessary for the decarbonisation of the NoE gas networks by hydrogen – even limited to the first deployment phase - and needs to be fully proven ahead of any decision to carry out large scale conversion of residential heating.
	Why is CCS investment necessary in the medium and long term?	High	**Medium Term:** the CCS infrastructure is needed both to create optionality for the decarbonisation of existing fossil fuel-based technology (industry, conventional gas fired power generation) with no clear other alternatives and to facilitate the deployment at scale of negative emission technologies such as biomass energy with CCS. It will also enable testing and early deployment of technologies such as direct air carbon capture (and other innovative technologies). The decision to anchor the infrastructure on hydrogen production offers the government time and flexibility to assess the relevant industries in the light of market and technology development and to choose the most appropriate decarbonisation pathway. **Long term**: a reliable large-scale CCS infrastructure is essential both for the decarbonisation of the NoE gas networks by hydrogen and to support the broader system decarbonisation required to achieve net zero emissions and the transition to a sustainable clean economy. Needed to achieve net zero policy objectives by 2050 to facilitate testing and deployment of negative emission technologies.

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	Why is the combination of CCS with the specific sector (industry, power, heating, transport) better than alternatives for that sector?	High	Anchoring CCS infrastructure with H_2 production allows the deployment of a new energy source with potential for clean sustainable production and avoids locking in fossil fuel-based technology (gas fired power station). It creates optionality.
Societal Acceptance	Does the proposal address concern that CCS is pushed by special interest groups? How?	High	* CO2 transport and storage is presented as a waste disposal service to support the deployment of hydrogen as a new energy source (for heating and power generation) with the potential to be produced sustainably at scale and to replace natural gas. It is clearly articulated as a shift away from CCS supporting the business as usual fossil fuel technologies. * The infrastructure is to be paid for by charges on natural gas/fossil fuel by all users to make hydrogen price competitive with natural gas – rather than charge the public to develop an initial infrastructure which would benefit the fossil fuel industry without creating new sustainable energy pathways. * The proposition has optionality built in so that the government is not locked into a specific technology and industry sector.
	Does the project fit with the public perception or social acceptance of the specific business opportunity along the H2-CCS chain? How? (E.g. public perception of CO2 transport and storage)	Medium	* Further work would be needed to raise awareness of hydrogen and educate the public. * There is no current rejection or negative opinion of hydrogen.
	Does the project incorporate a planned transition away from CCS and fossil fuels? How is this structured?	High	Yes - through the deployment and development of clean hydrogen production technology in a committed but gradual manner proportional to the penetration of hydrogen into the energy market. This will be supported by a number of specific legal and regulatory interventions.
	Does the proposal incorporate clean hydrogen? How?	High	Yes - phased development and deployment is incorporated through a number of regulatory interventions to fund and create obligations on suppliers.

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Competition & Collaboration (public sector)	* Does the project compete with other similar H2-CCS projects regionally/nationally? * What support does the project have from the public sector (local, regional, national)? * What is the rationale for government intervention?	Medium	* This project is designed to support a broader system decarbonisation and integrate all the regions in a phased development rather than focus on development of a specific region. It is initially focused on the north of England for strategic reasons: concentrated geographic location of emission intensive sectors (heat, industry, power), existing assets (H2 and CO2 storage potential, gas and electricity network infrastructure). The selection of an initial region/hub for the project would be made based on system deployment considerations and ensure that the benefits are shared and that other regions are not at a disadvantage. * The H21 project activities are being progressed by the gas network companies and focused on the gas network conversion with government support to test and develop a safety case. * This project proposition which incorporates the full H2-CCS chain would be in competition with the existing Net Zero Teesside project, the Merseyside HyNet project, the Zero Carbon Humber project, and other projects around the country (the Acorn project in Scotland for example). However, the government would be expected to act to support a coordinated approach between all those projects and investors.
Demonstrate how the project can be scaled up	Does the proposal offer a transition from a project approach to a system approach? How?	High	The planned system deployment articulates how the project could be scaled up from an early proving phase to a city conversion and later to a North of England conversion.
	Does the project facilitate the future integration of other energy intensive business sectors? How?	High	The project would easily integrate other energy intensive sectors for a further expansion of the use of the CCS infrastructure: industrials and power generation (fuel switching or carbon capture), BECCS and DACS.
	Does the project facilitate the expansion into other regions? How?	High	The project is planned around a coordinated decarbonisation approach of the regions of the north of England. It integrates regions and cities, and connects Teesside, Humberside, the Manchester/Liverpool clusters, and Grangemouth cluster through a shared infrastructure.

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Low Regrets & Optionality	Does the project offer optionality for decision making and minimise impact if no further projects are built or if future deployment is limited? How?	High	* Each investment phase is designed to be modular with optionality for expansion and adjustments with market and technology developments. * Optionality for decarbonisation through disposal of CO2 from access to T&S oversized infrastructure where the reliability and safety has been proven in the first phase and which can be easily expanded gradually to incorporate existing fossil fuel-based technologies with no alternatives and support the deployment of negative emission technologies such as BECCS and early DAC technology. * Optionality for the development and deployment of clean/green hydrogen across the country by creating an early market for hydrogen which can be regulated and allow the future development of cost-effective green hydrogen options whether in-country or imported.