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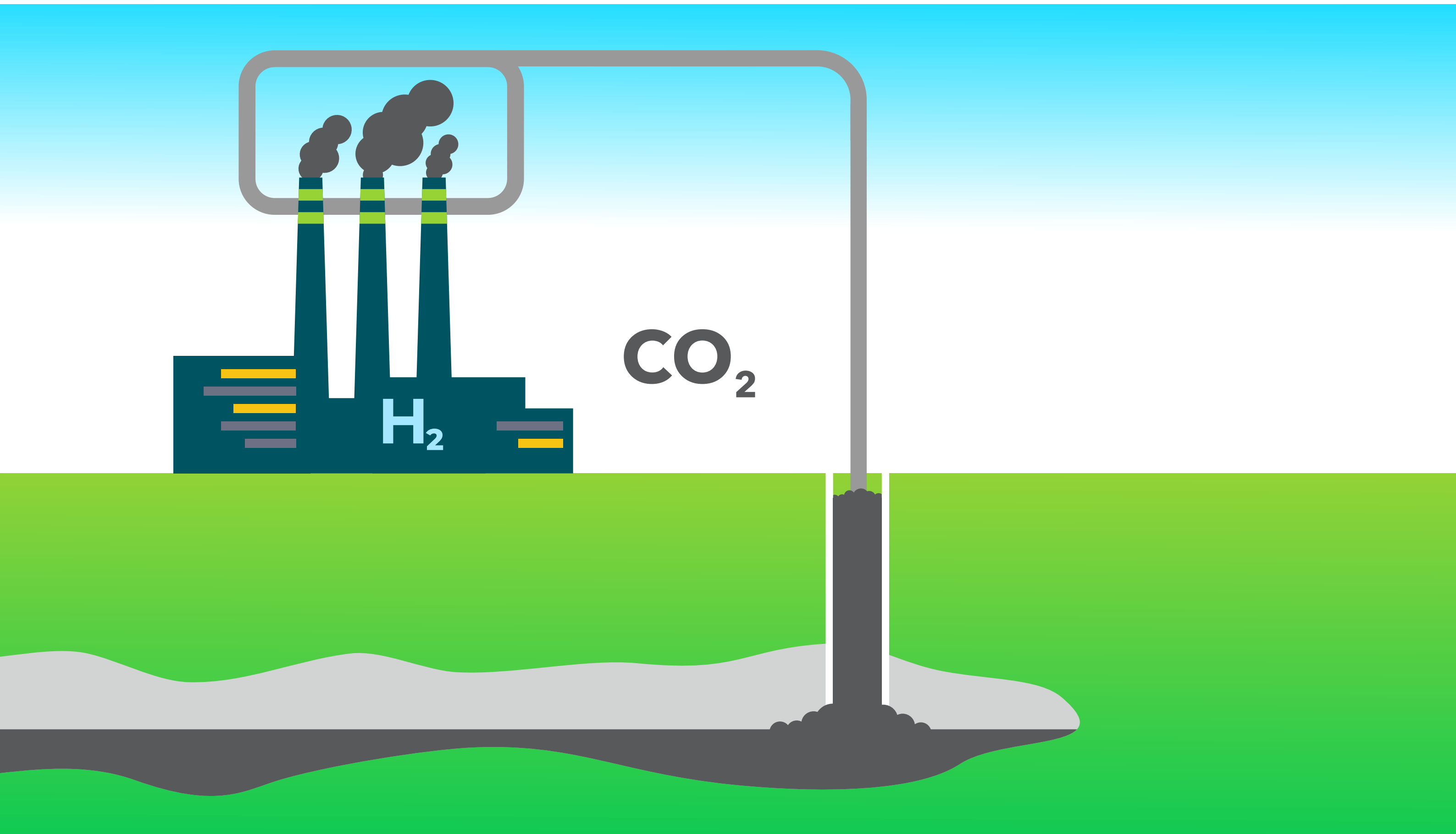
Hydrogen UK

CCUS-Enabled Hydrogen Production Report

Written By

CCUS-Enabled Hydrogen Production Working Group



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Executive Summary

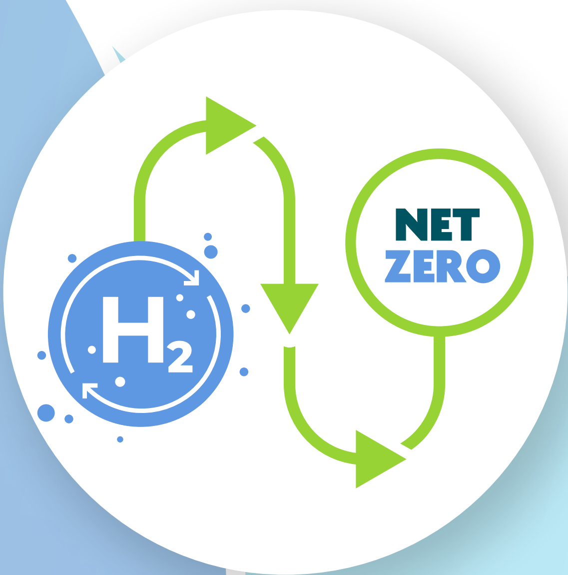
The UK has committed to achieving Net Zero by 2050. In all the major models of possible routes to Net Zero, hydrogen plays a significant role. To deliver the volumes of low carbon hydrogen required, the Government has pledged its support to both electrolytic and CCUS-enabled hydrogen, which is made from hydrocarbons with the carbon dioxide captured and used or permanently stored.

CCUS-Enabled Hydrogen is Low Carbon Hydrogen

DESNZ have produced a Low Carbon Hydrogen Standard (LCHS) to ensure that all hydrogen that receives government support is produced in a manner that is compliant with the UK's Net Zero targets. The LCHS is one of the most stringent standards in the world for carbon emissions, and hydrogen produced in the UK using CCUS-enabled technology, such as that being proposed for use in the industrial clusters, can easily meet the definition of 'low carbon'. Novel technologies currently being brought to market offer the capability of producing low carbon hydrogen that can be applied to decarbonising smaller industrial processes away from the major clusters.

CCUS-Enabled Hydrogen Delivers at Scale and Pace

CCUS-enabled hydrogen can deliver hydrogen production suitable for individual industrial facilities or on a gigawatt (GWs) scale in a relatively short space of time. The nature of the technology lends itself to large scale facilities that can be delivered in modules of 100s of MW, but the development of new production pathways that output solid carbon (rather than carbon dioxide gas) will mean that hydrogen can also be produced away from carbon dioxide networks and at smaller scales. When multiple projects are delivered concurrently, this kick-starts the hydrogen economy, allowing the UK to go further and faster in its efforts to decarbonise.



CCUS-Enabled Hydrogen Can Decarbonise Hard to Abate Industrial End Users

Many of the hardest to abate industries are found in industrial clusters. Many heavy emitting industrial processes will require significant volumes of reliable, baseload low carbon hydrogen. This makes them ideally located for access to large scale CCUS-enabled hydrogen production which can be deployed in clusters to aggregate demand and make use of shared infrastructure. Similarly, newer production pathways will also enable industrial decarbonisation away from the industrial clusters and carbon dioxide transport networks.

CCUS-Enabled Hydrogen Relieves Pressure on Renewable Deployment

Electrolytic hydrogen and renewable electricity have an important role to play in the decarbonisation of energy in the UK. However, the deployment of both will be limited by a variety of factors. CCUS-enabled hydrogen production provides a viable, low carbon alternative which can alleviate pressure on the already constrained electricity grid, allowing renewable electricity generation and electrolytic hydrogen production to scale at a more manageable pace. This benefit of CCUS-enabled hydrogen in the years out to 2035 has been explicitly recognised in the Committee on Climate Change's recently published '*Delivering a Reliable Decarbonised Power System*'[1].

Economic Growth and UK Expertise

There are significant economic benefits to the UK pursuing CCUS-enabled hydrogen. These include but are not limited to job creation, GVA and utilising the extensive UK expertise in the oil and gas industry. The UK is also home to a range of companies developing innovative production technologies which generate solid carbon products, as well as hydrogen, for use in other processes. Supporting production can foster the development of domestic supply chains, reduce reliance on imported low carbon hydrogen, and if supply exceeds demand, offer an opportunity to export to other regions.

Figure 1: A Steam Methane Reformation Unit

The Role of Hydrogen in Net Zero for the UK

Hydrogen is a fuel with zero direct carbon emissions at the point of use that can help to decarbonise multiple sectors of the UK economy. **Table 1** outlines some of the end-use applications that hydrogen can be used to decarbonise.

Sector	Prominent example	Technology	Replacing
Industry	Steel manufacture	Direct iron reduction using hydrogen	Natural Gas
	Glass manufacture	Hydrogen kiln	Natural Gas
	Food & Drink manufacture	Hydrogen boiler or hybrid	Natural Gas
Transport	Road (Light and Heavy Vehicles)	Fuel cell or hydrogen ICE	Petrol and Diesel
	Rail	Fuel cell	Diesel
	Maritime	Ammonia or synthetic methanol ICE or fuels cell	Bunker Fuel
	Aviation	Multiple prospects	Kerosene
Buildings	Domestic heating	Hydrogen boiler or hybrid	Natural Gas
	Commercial heating	Hydrogen boiler or hybrid	Natural Gas
Power Generation	Flexible power generation	Hydrogen CCGT / GT/ reciprocating engine	Unabated Natural Gas

Table 1: End Use Examples of Hydrogen

Hydrogen will play a crucial role in reaching the UK's mandated Net Zero ambition by 2050. The UK Hydrogen Strategy estimates that to meet Net Zero by 2050, hydrogen will make up 20-35% of the UK's final energy demand (250-460 TWh a year)[2], a significant increase from the 10-27 TWh currently being produced[3]. Hydrogen will enable the decarbonisation of hard to abate sectors including industry, heavy transport, dispatchable power generation and potentially heat. **Figure 2** from the UK Hydrogen Strategy[4] indicates what hydrogen demand could look like in 2030 and 2035 across the industrial, power, heat and transport sectors (note that these demand figures were issued before the Government doubled its hydrogen production capacity target for 2030).

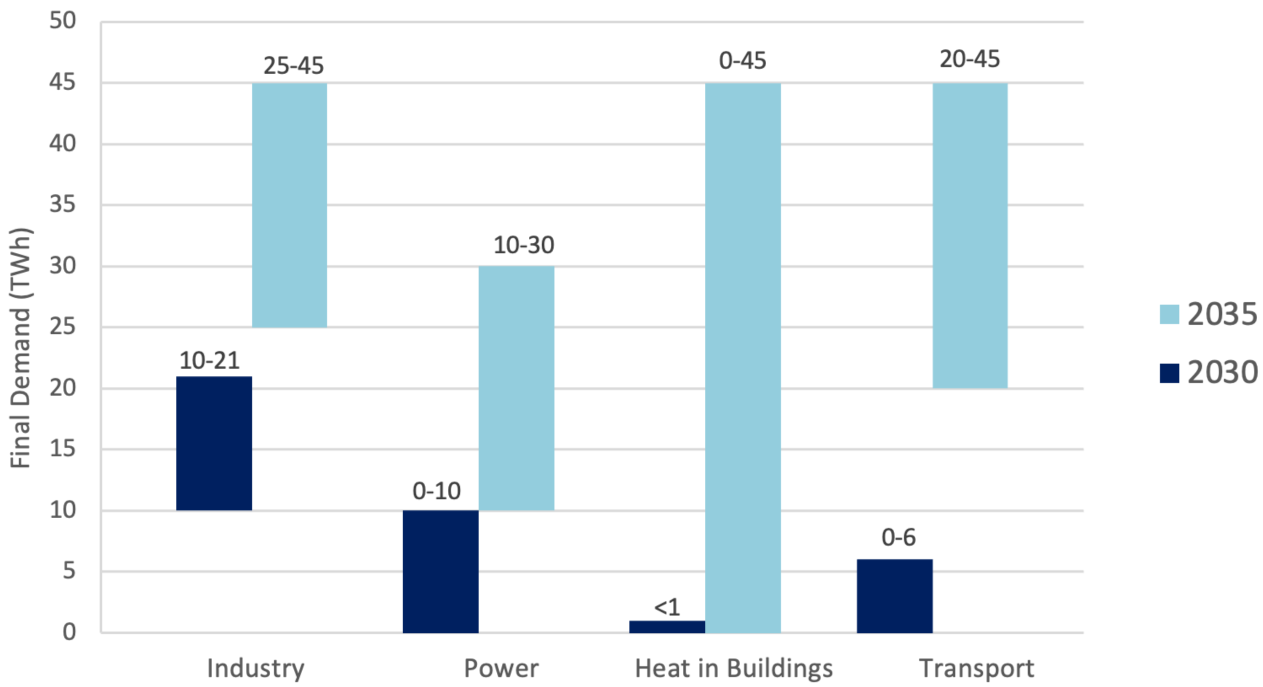


Figure 2: Estimated UK Hydrogen Demand for Hydrogen by Sector[3]

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This will be achieved via a twin track approach between electrolytic and CCUS-enabled hydrogen production. The Department for Energy Security and Net Zero (DESNZ), formerly the Department for Business, Energy and Industrial Strategy (BEIS), have supported CCUS-enabled hydrogen as a sector through legislation and support mechanisms. A crucial mechanism that DESNZ have developed is the Low Carbon Hydrogen Standard (LCHS). This standard details a maximum GHG emission intensity of 20g CO_2e/MJ_{LHV} in the production process of hydrogen for it to be deemed as 'low carbon'[5].

For CCUS-enabled hydrogen, the LCHS stands as a stringent threshold that must be met in order to access governmental funding, thus helping to make hydrogen production with higher levels of associated carbon emissions unaffordable.

CCUS-Enabled Production Methods

Methane Reformation with Gaseous CO_2 Product

A significant portion of hydrogen produced currently involves the reformation of natural gas (methane). The most common production method globally is via Steam Methane Reforming (SMR)[6]. This process involves heating methane to high temperatures in the presence of a catalyst to form a syngas mix of hydrogen, carbon dioxide, and carbon monoxide. Following this the carbon monoxide is further converted to create more hydrogen and carbon dioxide via a water gas shift reaction. The Auto Thermal Reforming (ATR) of methane is a process whereby partial oxidation and steam reforming are used to produce a syngas mix of carbon monoxide and hydrogen. The syngas can then be purified, similarly to SMR, to obtain hydrogen and carbon dioxide. The Partial Oxidation (POX) of methane can also be used to produce hydrogen in a separate process from ATR. Here, hydrogen is produced via a non-catalytic oxidative reforming process where methane is reacted with a limited amount of oxygen so complete oxidation cannot occur.

The reformation of natural gas for hydrogen production currently releases carbon dioxide, the main greenhouse gas emission contributing to anthropogenic climate change, as a by-product. To reduce the harm caused from this release, Carbon Capture, Utilisation and Storage (CCUS) technology can be incorporated with the aim of removing up to 97% of the carbon dioxide produced during hydrogen production[7]. The captured carbon dioxide can then be compressed and transported by pipeline or ship for permanent storage underground in geological formations. Hydrogen produced using these processes that do not implement CCUS technology are referred to as 'grey hydrogen'; with the introduction of CCUS, they are deemed as 'blue hydrogen'.

Figure 3: An Autothermal Reforming (ATR) Plant[4]

The UK Hydrogen Strategy details estimates for the levelized cost of SMR and ATR processes for 2050. A 300 MW ATR plant with Carbon Capture and Storage (CCS) in the UK is estimated to produce hydrogen at £65/MWh in 2050, whilst an equivalent capacity SMR plant with CCS will produce hydrogen at £67/MWh[8]. CCUS technology can be attached to both SMR and ATR plants, with expected carbon capture rates of 90% and 97% respectively.[9]

Methane with Solid State Carbon Product

CCUS-enabled production of hydrogen will include a range of novel technologies, particularly technologies that produce solid carbon. The pyrolysis of hydrocarbons, typically methane, is one example. Here, a hydrocarbon is pressurised and heated to a high temperature in the absence of oxygen and thus, hydrogen gas ('turquoise hydrogen) is produced alongside solid carbon[10]. Thermal Plasma Electrolysis (TPE) is another notable CCUS-enabled method of hydrogen production that outputs solid carbon rather than carbon dioxide gas. This process uses plasma torches to split hydrocarbon feedstocks (typically methane, flare gas or biomethane) into hydrogen ('emerald hydrogen') and carbon via the application of an intense electrical field rather than heat[11]. When biomethane feedstock is then coupled with the output of solid carbon in this way, TPE offers an attractive route to delivering negative emissions. Microwave plasma can also be used to crack methane into its constituent atoms, producing hydrogen alongside solid carbon.

The solid carbon produced by these technologies can be isolated, collected and then sequestered. Alternatively, the output may be used as a material in industrial and technological sectors, displacing solid carbon produced by existing highly emissive processes. Potential end uses range from graphene and other advanced materials to soil enhancement and agriculture feeds.

In the UK Hydrogen Strategy, the role of methane pyrolysis is described as 'nascent technology' that requires further research and development to play a major future role[12], yet it is already apparent that technologies such as thermal plasma electrolysis and methane pyrolysis will be vital as decentralised CCUS-enabled production methods delivering hydrogen away from industrial clusters.

Biomass Gasification

Greenhouse Gas Removal technologies (GGRs) have been highlighted by both the Intergovernmental Panel on Climate Change (IPCC) and the Climate Change Committee (CCC) as a necessity in reaching net zero targets[13]. The gasification of biomass coupled with CCUS technology allows for production of low carbon hydrogen alongside the potential of negative carbon emissions. The UK is pioneering the demonstration of CCUS with biomass power generation, with DRAX leading the efforts within Bioenergy CCS (BECCS) technology, submitting plans to build the world's largest carbon capture and storage plant last year[14]. The DESNZ funded Hydrogen BECCS Innovation Programme has awarded £30 million to nearly 30 organisations across feedstock pre-processing, gasification components and novel biohydrogen technologies[15].

Summarising the Benefits of CCUS-Enabled Hydrogen Production

Retrofit to Existing Hydrogen Production

At the end of 2021, 47% of global hydrogen production used natural gas as a feedstock in comparison to just 4% from electrolysis[16]. The remaining 49% relies on oil or coal as the feedstock for hydrogen production which are highly emissive of carbon dioxide, and thus needs to be replaced with low carbon hydrogen as soon as possible. Carbon Capture, Utilisation and Storage (CCUS) technology can be incorporated in not only new build but also existing hydrogen production plants. This offers a significant opportunity to decarbonise the current fleet of fossil-fuel based hydrogen production facilities, transitioning them, and their offtakers, from high to low carbon hydrogen.

Low Carbon Hydrogen at Scale

The deployment of CCUS-enabled hydrogen allows for production of low carbon hydrogen at significantly greater levels and at an earlier date than is going to be feasible without it. Gigawatt scale CCUS-enabled production will become operational sooner than equivalent electrolytic production projects, thus allowing the decarbonisation of hard-to-abate sectors to commence at an earlier date. CCUS-enabled hydrogen production can be used to produce baseload volumes of hydrogen from day one. This will enable electrolytic hydrogen, which will likely face initial challenges around the deployment and intermittency in of renewable electricity generation, as well as limited access to hydrogen storage, to scale alongside the development of hydrogen transport and storage infrastructure. This allows hydrogen supply to scale up rapidly during the 2020s, enabling the full hydrogen supply chain to be developed sooner than would be achieved without CCUS-enabled production, something that could in fact help early electrolytic projects come to market.

An early and large-scale hydrogen supply allows emitters who are looking to decarbonise their processes early, across a range of sectors, to choose a hydrogen pathway. This avoids emitters being forced to choose what may end up being a potentially sub-optimal solution in the long term simply because they lack access to a supply of low carbon hydrogen.

Since CCUS-enabled hydrogen can be scaled up quickly, it can provide the supply of low carbon hydrogen needed for early, consistent, and strong decarbonisation action to be taken where it will have the largest impact on meeting the UK's 2050 carbon budget. Furthermore, developing CCUS-enabled production infrastructure within the UK will lay the groundwork for opportunities across the entire CCUS sector. Industries such as industrial CCUS, power bioenergy carbon capture and storage (BECCS) and gas-CCS power generation are essential to reaching net zero and will be able to springboard off the large-scale deployment of CCUS-enabled hydrogen production infrastructure.

Achieving Interim Carbon Budgets

CCUS-enabled hydrogen allows for greater decarbonisation to occur during the 2020s when it is most effective for reducing the overall level of GHGs in the atmosphere. Ultimately net zero is just an end point target. The total level of emissions released by the UK between now and net zero 2050, and hence our impact upon the climate, will be determined in large part by the action we take to decarbonise in the 2020s and early 2030s. A steel mill decarbonised by hydrogen in 2040 will add ten more years to cumulative emissions than one decarbonised in 2030. Net Zero by 2050 still comes with a certain degree of temperature change so reducing carbon emissions sooner will limit this change and the potential damage that this could cause.

Making Use of the UK's Natural Resources and Existing Energy Infrastructure

To deploy large scale CCUS-enabled technology, a large capacity of carbon dioxide storage is required. **Figure 4**, from the Energy Technology Institute[17], overlays the top 50 carbon dioxide emitters in the UK with the location and capacity of potential

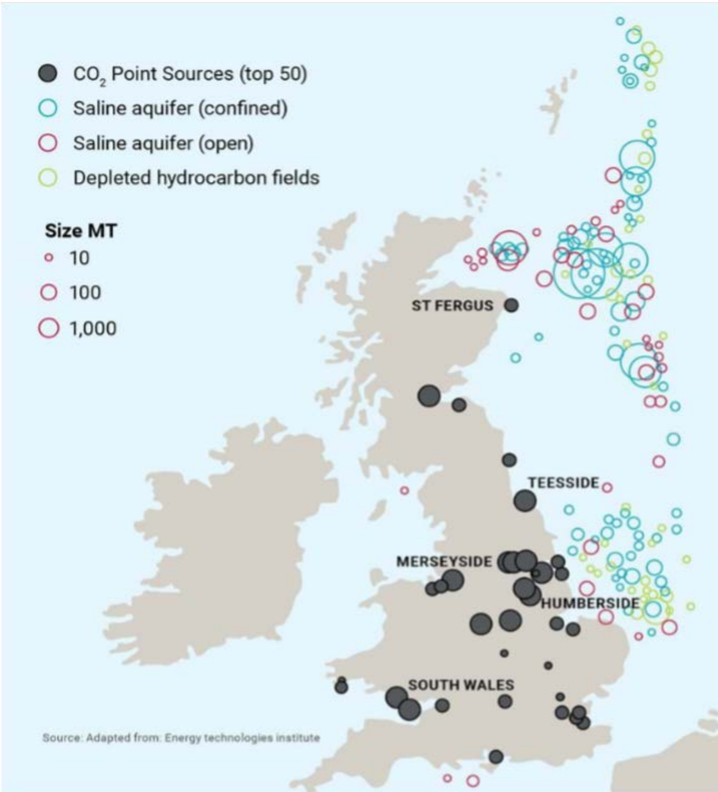

Figure 4: Top 50 carbon emitters – location relative to potential CO_2 storage[16]

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carbon dioxide storage. The UK is fortunate to have access to saline aquifers and depleted hydrocarbon fields close to industrial clusters enabling the large-scale deployment of CCUS-enabled technology. Meanwhile, nascent hydrogen with solid carbon production technologies can make use of existing natural gas and electricity networks to deliver low carbon hydrogen production close to the point of use, with solid carbon as a potentially valuable by-product. Initially, these technologies could provide hydrogen for discrete applications with a potential for future scale up.

Reducing the Pressure on Renewable Deployment

CCUS-enabled hydrogen further relieves pressure on UK renewable build out. Electrolytic hydrogen will be crucial to meeting net zero aims producing carbon free hydrogen. The UK's electricity demand is set to increase significantly due to the increase in electrolytic production alongside the increased electrification of sectors such as power generation, transport and heat. In National Grid's Future Energy Scenarios, peak electricity demand increases from c.60 GW in 2022 to c.100GW in 2050, within the System Transformation scenario[18]. Hydrogen UK has mapped the renewable power demand needed to meet total hydrogen demand if electrolytic hydrogen was the sole method of hydrogen production and using the CCC balanced pathways scenario. As **Figure 5** shows, between 60% and 114% of the total renewable capacity would be needed in 2050 to meet this demand[19]. CCUS-enabled hydrogen production can help alleviate the electricity demand required for hydrogen production and enable the decarbonisation of other sectors via electrification.

In the UK, 53% of industrial emissions come from industrial clusters[20]. Government has identified that UK clusters support high quality jobs that pay above the average national wage and are critical to the local economy[21]. However, these cluster sites need intervention to ensure they comply with net zero aims and can continue driving growth and export pportunities within the UKs industrial sector. CCUS-enabled hydrogen production provides a pathway for these cluster sites to continue generating the benefits they bring.

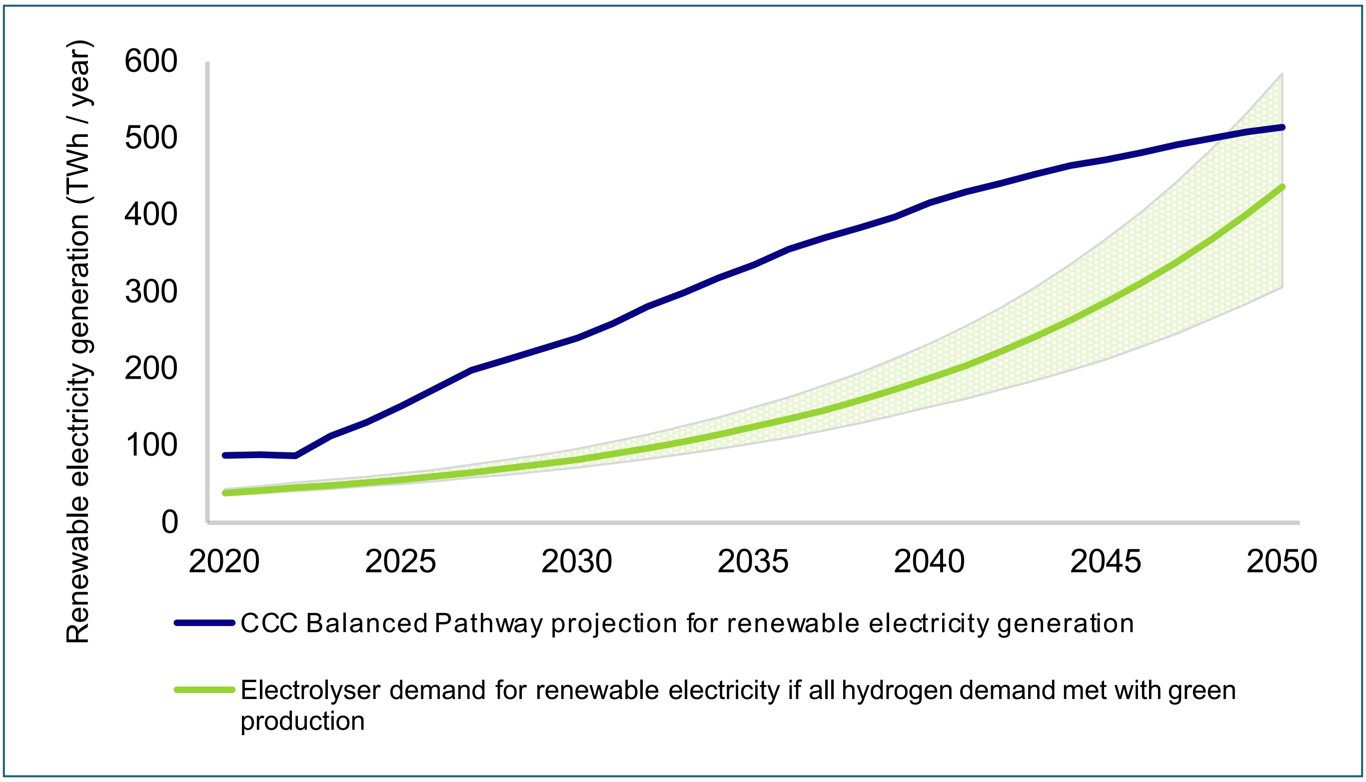

Figure 5: Range of renewable electricity generation required for projected[20].

DESNZ have stated their ambition to:

1. Have at least two low carbon clusters built and operating by 2025,
2. Have at least four low carbon clusters operating by 2030 capturing 10MtCO_2/year. In October 2021 the government increased the carbon capture ambition to 20-30MTCO_2/year by 2030[22].

Whilst the majority of industrial emissions are generated via these cluster sites, a significant proportion of emissions (47%) are dispersed outside of these cluster sites across the nation[23]. Hydrogen networks and dispersed electrolytic production will have a large role to play in the decarbonisation of these emissions as well as novel CCUS-enabled technologies, such as methane pyrolysis, that can be used to decarbonise industrial sites outside of clusters before hydrogen networks are operational. Moving to a low carbon industry is a significant opportunity for the UK to pioneer and seize a large share of a growing global market[24]. DESNZ estimate that UK industry contributes a GVA of approximately £150 billion per year to the UK economy, securing around 1.5 million jobs and exporting goods and services with a value around £320 billion[25]. CCUS-enabled technologies, specifically in low carbon hydrogen production, will be fundamental in the transition to low carbon industry and maximising this opportunity.

Economic Benefits and Utilising UK Expertise

There are significant economic benefits to the UK pursuing CCUS-enabled hydrogen. These include but are not limited to job creation, GVA and utilising the extensive UK expertise in the oil and gas industry.

In 2020, the Hydrogen Taskforce estimated that CCUS-enabled hydrogen could deliver £2.8bn in cumulative GVA and over 10,000 cumulative jobs by 2035[26].

A North Sea Transition Deal report, titled 'Integrated People and Skills Strategy', states that 90% of the UK's oil and gas workforce have skills transferability to adjacent energy sectors. One of the sectors identified as having high transferability is CCUS-enabled hydrogen[27]. Furthermore, a report by Element Energy for The Engineering Construction Industry Training Board (ECITB) suggests that hydrogen production from reforming natural gas will have similar skills requirements to the existing chemical and oil and gas industries with low requirements for training. The main upskilling requirements will be in CO_2 capture, infrastructure and storage[28]. The Green Jobs Taskforce made a similar finding of minor retraining requirements[29]. The skills requirements for CCUS-enabled hydrogen production are shown in more detail in the infographic reproduced in **Figure 6**.

Inevitably, skills requirements will be informed by the data that government has been gathering as part the cluster sequencing process[30]. These submissions contain a wide range of information including job title, activity type, skill level (NVQ), location, whether the job is created, safeguarded or displaced, direct or indirect, and salary.

Hydrogen technologies

	Key technology components	Relevant industries: Chemical	FEED & Design	Renewables	Power Generation	Oil & Gas	Nuclear	Water Treatment	Time-frame	Skills Impact	Comments on skills and industry similarities
Hydrogen Production – Adv. gas reform	Air separation unit, metallic structures, compressors	●	●	○	○	○	○	○	◔	●	Existing skills similar to the chemical and oil and gas industries

CCS technologies

	Key technology components	Relevant industries: Chemical	FEED & Design	Renewables	Power Generation	Oil & Gas	Nuclear	Water Treatment	Time-frame	Skills Impact	Comments on skills and industry similarities
CCS capture plants	Capture plant, compressors, exchange columns, pipework2	○	●	○	●	○	○	○	◔	●	Minor upskilling needed for welding, erection, testing and inspection; similar to chem ind.
CO_2 transport infrastructure	Onshore and offshore pipeline laying	○	●	○	○	●	○	○	◔	●	Minor technical upskilling for handling of new materials for CO_2 pipelines
CO_2 Storage	Offshore pipeline, injection wells, monitoring	○	●	○	○	●	○	○	◔	●	Minor upskilling might be needed for oil and gas personnel in FEED and monitoring stages

Industry Sector Key

Chemical | Food & Drink | Nuclear | Renewables | Oil & Gas | Pharmaceuticals | Power Generation | Water Treatment | FEED & Design

Figure 6: Skills requirements for CCUS-enabled hydrogen[29]

Export Opportunity

A significant export opportunity exists with the growth of the UK CCUS-enabled hydrogen production sector. The UK is home to pioneering companies within the CCUS sector, including world leading oil and gas companies and those developing CCUS-enabled hydrogen production technology, such as Johnson Matthey's LCH™ technology which is already licensed internationally. There is potential for the UK to not just export CCUS technology, but also to export technical expertise, especially to neighbouring nations within Europe. These benefits remain pertinent within the nascent solid carbon technology sector, where the UK hosts front-running companies like HiiROC[31] and Levidian[32]. The UK has the potential to pioneer on a global stage acting as a net exporter of both technological equipment and expertise, solidifying its reputation as global leader within the hydrogen and CCUS sector.

Emissions

Emissions Analysis of CCUS-Enabled Hydrogen

It is essential to recognise that achieving low emissions from CCUS-enabled hydrogen is not simply a pledge or an ambition. In the UK there is a regulatory requirement for low emissions for hydrogen producers to receive revenue support from the Hydrogen Production Business Models (HPBM) and capital funding from the Net Zero Hydrogen Fund (NZHF). Hydrogen production which fails to achieve the limit set by the Low Carbon Hydrogen Standard (LCHS), currently 20gCO_2e/MJLHV of produced hydrogen[i], is unlikely to be able to compete with supported hydrogen especially following the tightening of the emissions trading scheme in line with net zero[33]. **Figure 7** shows the carbon intensity of CCUS-enabled hydrogen under several scenarios using DESNZ's LCHS calculator[34]. The scenarios shown are:

- **Best Case** – this assumes very low upstream natural gas emissions with natural gas originating from Norway – it should be noted that producers cannot use this upstream emission factor in calculating their emissions intensity under the LCHS if natural gas is sourced through the UK gas network.
- **Central Case** – this assumes the UK weighted average natural gas upstream emissions with a CO_2 capture rate of 95%.
- **JM LCH** - this assumes UK weighted average natural gas upstream emissions but a higher CO_2 capture rate of 97.1% based on Johnson Matthey's LCH™ technology.

These CCUS-enabled hydrogen production emissions are then compared with grid electricity carbon intensity projections in 2025[35] and the Low Carbon Hydrogen Standard[ii]. In a more complete emissions comparison, the end use should be included as electric and hydrogen end uses are likely to have different efficiencies and therefore require different amounts of input energy. However, the graph shows that in 2025, it is expected that CCUS-enabled hydrogen is likely to have an emission factor less than half that of grid electricity. The graph also shows that the majority of CCUS-enabled emissions arise from the emissions associated with upstream natural gas supply.

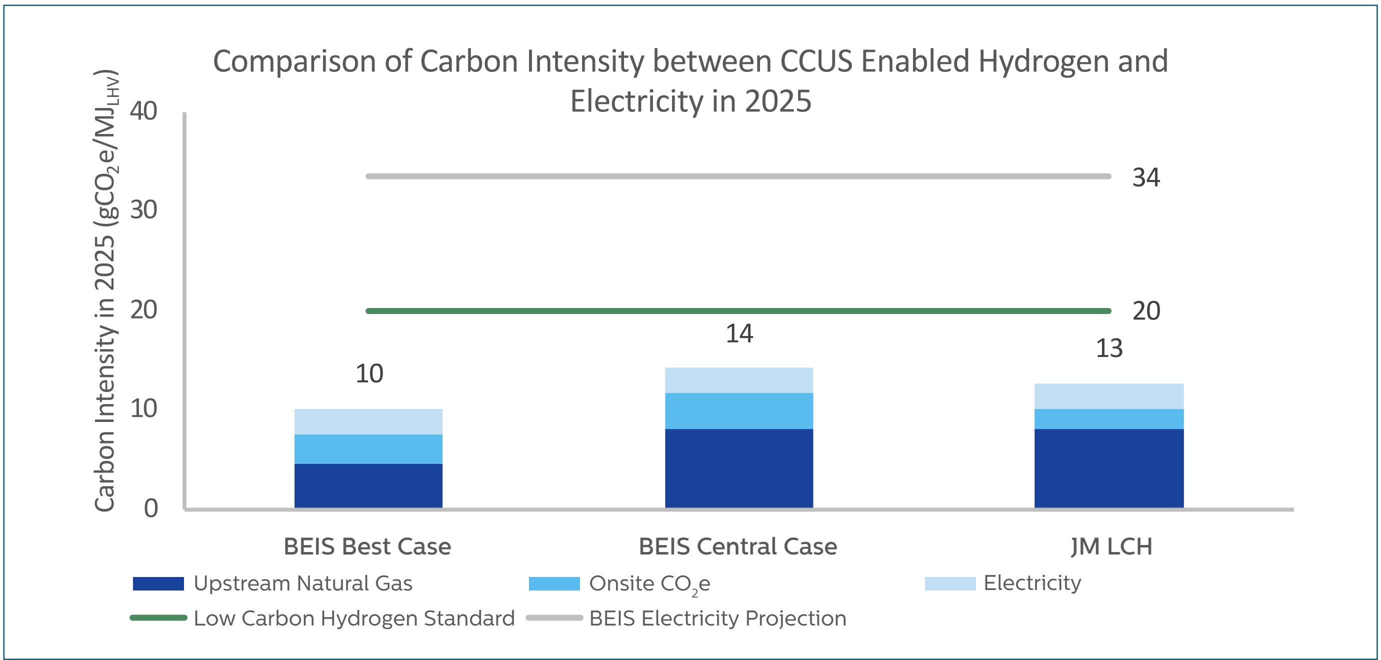

Figure 7: Comparison of Carbon Intensity between CCUS-Enabled Hydrogen and Electricity in 2025[35]

[i] 1gCO_2e/MJ = 3.6gCO_2e/kWh

[ii] Values used from version 1 of the Low Carbon Hydrogen Standard (LCHS) calculator. Due to an unresolved error within version 2 raised with DESNZ. Version 3 is expected to be published soon.

The emissions intensity of both grid electricity and hydrogen will reduce over time as upstream gas regulations are improved, curbing upstream fugitive methane emissions from the natural gas supply chain, and more low carbon electricity generation is deployed. It is expected that electricity will decarbonise at a faster rate than CCUS-enabled hydrogen production. However, with improving upstream natural gas regulation, the emissions associated with CCUS-enabled hydrogen can also be very low. If the UK can reduce upstream gas emissions to low levels comparable to Norway by 2030, **Figure 8**[iii] below shows that even in 2030 CCUS-enabled hydrogen would have much lower emissions than electricity.

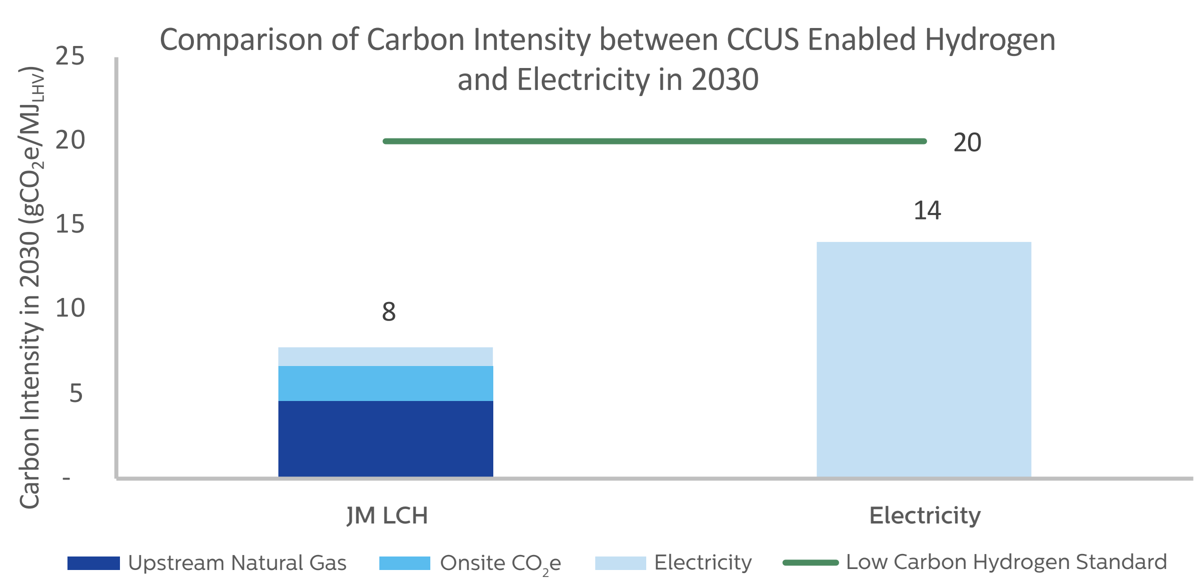

Figure 8: Comparison of carbon intensity between CCUS-enabled hydrogen and electricity in 2030 (DESNZ[34]) assuming improved methane leakage rates

Inevitably, electricity generation will have lower emissions than CCUS-enabled hydrogen from natural gas in the long term, as natural gas derived hydrogen will always have some residual emissions, unless produced with biomethane. However, the purpose of these graphs is to show that in the medium term CCUS-enabled hydrogen can deliver very significant emissions savings. In its recently published report, 'Delivering a Reliable Decarbonised Power System', the Committee on Climate Change stressed that: "Zero-carbon electricity must be prioritised for displacing unabated fossil generation and meeting increasing demands from electric vehicles and heat pumps"[36]. In order to decarbonise rapidly the UK will require a high degree of electrification, however CCUS-enabled hydrogen also has a significant role to play. A report by E4tech for BEIS (now DESNZ) which considers options for the Low Carbon Hydrogen Standard highlights how CCUS-enabled emissions can have considerable negative emissions. If using biomethane with ATR and CCS, the report estimates emissions to be approximately -60 gCO_2e/MJ H2 (LHV). Emissions are substantially lower if hydrogen is produced by wood gasification with CCS, which the report estimates to be approximately -160 gCO_2e/MJ H2 (LHV)[37].

[iii] Values used from version 1 of the Low Carbon Hydrogen Standard (LCHS) calculator. Due to an unresolved error within version 2 raised with DESNZ. Version 3 is expected to be published soon.

Time Value of Emissions

The social cost of carbon (SCC) is an estimate of the economic damage caused by emitting a tonne of carbon dioxide equivalent greenhouse gas emissions at a point in time. As concentrations of greenhouse gases in the atmosphere increase, each additional unit of emissions causes more damage than the last. This is reflected in the fact that SCCs tend to increase over time[38]. Therefore, carbon abatement now is worth more than carbon abatement in the future. CCUS-enabled hydrogen is one of the quickest ways to reduce emissions at scale in hard to decarbonise sectors.

In a similar way to the SCC, DESNZ produce carbon prices for policy appraisal. Instead of being based on the economic cost to society of the emissions, these are based on the Marginal Abatement Cost (MAC) of reducing emissions. **Figure 9** below shows this visually by showing DESNZ' carbon prices for policy evaluation[39] of carbon increasing over time. This shows that if a policy, such as deployment of CCUS-enabled hydrogen production, is beneficial using current carbon prices, it will be even more beneficial using future carbon prices.

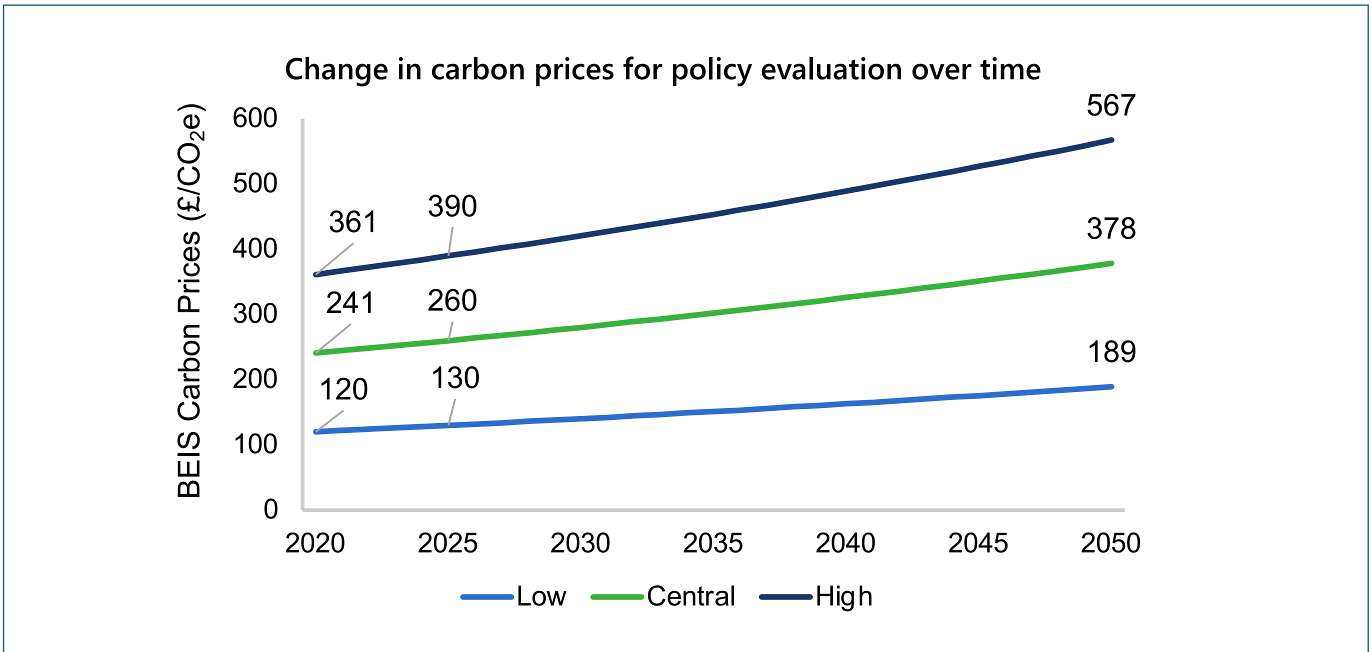

Figure 9: Change in carbon prices for policy evaluation over time[39].

Using the cost difference between natural gas and CCUS-enabled hydrogen from BEIS' Hydrogen Production Costs 2021, decarbonising natural gas costs approximately £33/MWh(LHV)[40]. Comparing the emissions when from moving from natural gas to hydrogen using BEIS' central CCUS-enabled emissions for 2025 of 51 gCO_2e/kWh(LHV)[34] and a natural gas emission factors of 237 gCO_2e/kWh(LHV)[41] implies an emission saving of 186 gCO_2e/kWh(LHV) when switching from natural gas to CCUS-enabled hydrogen. Combining these two figures gives an estimated cost of decarbonising natural gas of £177/tCO_2e. This is well below BEIS (now DESNZ) central carbon prices for policy appraisal in 2025 of £260/tCO_2e. For a complete comparison the costs of end use switching and any additional efficiency losses should be taken into account, however this shows that in scenarios with low fuel switching costs, switching from natural gas to CCUS-enabled hydrogen is effective value for money decarbonisation.

Addressing Criticisms of CCUS-Enabled Hydrogen Emissions

Several major news outlets have reported on an academic study titled 'How green is blue hydrogen?' which seeks to discredit the use of CCUS-enabled hydrogen. The study, which continues to receive media attention uses assumptions, some of which are implausible, to draw the conclusion that the life cycle greenhouse gas emissions from burning 'blue' hydrogen were more than 20% greater than emissions using conventional natural gas. As previously mentioned, CCUS-enabled hydrogen in the UK will need to meet the LCHS so will guarantee emission savings of at least 70% when switching from natural gas. The findings of the study are not applicable for CCUS-enabled hydrogen production in the UK for a wide range of reasons, including:

- **Assumed methane leakage rate of 3.5%** - the methane leakage rates in well-regulated markets such as the UK are much lower than this. As an example, the OGCI are targeting leakage rates well below 0.2% by 2025, already achieving this with 0.17% in 2021[42].
- **Assumed CO_2 capture rates of 85% and 65%** - ATRs with CCS should be able to achieve CO_2 capture rates above 90%; the CCC assume 95% and technology providers say 97%. SMR technology can also achieve capture rates of 90%.
- **Climate metric GWP20** – a GWP20 climate metric is used which ignores climate impacts beyond 20 years in the future. This puts a greater emphasis on methane emissions than CO_2 emissions which remain in the atmosphere far longer and coupled with the high methane leakage assumptions results in a very high emissions estimate for CCUS-enabled hydrogen.

A study produced by Equinor highlights the importance of good practice in the CCUS-enabled hydrogen production and explores emissions in more detail[43].

CCUS-Enabled Production in the UK

Hydrogen UK is compiling a database of all UK-based hydrogen projects that have been announced in the public domain. **Table 2** displays proposed production capacities, operational dates and peak capacity years. It must be noted that the entries in this section are project proposals, not production capacity.

Project Name	Location	Stage	Initial Prod. Capacity (MW)	Start Year	Peak Prod. Capacity (MW)	Peak Capacity Year
Acorn Hydrogen	Scotland	FEED	200	2026	TBC	TBC
H2Teesside (East Coast Cluster)	North East England	FEED	500	2027	1,000	2030
Humber Hub Blue Project	North East England	FEED	720	2027	720	2027
H2NorthEast (East Coast Cluster)	North East England	FEED (Q4 2023)	355	2028	1,000	2030
H2H Saltend (East Coast Cluster)	North East England	FEED	600	2027	600	2027
H2H Production 2	North East England	Concept	1,200	2028	1,200	2028
Acorn: Project Cavendish	South East England	Feasibility	700	2027	700	2027
Bacton Energy Hub	East England	Concept	355	2030	355	2030
South Wales Industrial Cluster	Wales	Concept	TBC	TBC	TBC	TBC
Southampton Hydrogen Hub (Solent Cluster)	South East England	Concept	1,000	TBC	2,000	TBC
Vertex Hydrogen HYNET	North West England	FEED	1,000	2026	4,000	2030
BOC Teeside Capture	North West England	FEED	150	2027	150	2027

Table 2: CCUS-Enabled Hydrogen Production Projects Data

Note: Dates and capacities are what have been stated publicly.

A key role CCUS-enabled hydrogen production has to play in the next few years is producing low carbon hydrogen at scale. **Figure 10** demonstrates how this production capacity increases from now until 2030, assuming all announced projects reach their maximum capacity at their stated operational date - only projects which have an operational date could be included in this figure. Furthermore, the government has framed the UK's hydrogen production targets as "up to 10 GW of low carbon hydrogen production by 2030, with at least half coming from electrolytic hydrogen" [44]. In Figure 10, we have assumed a 10 GW low carbon production target and a 5 GW electrolytic production target, however it's likely that this split may be different in 2030.

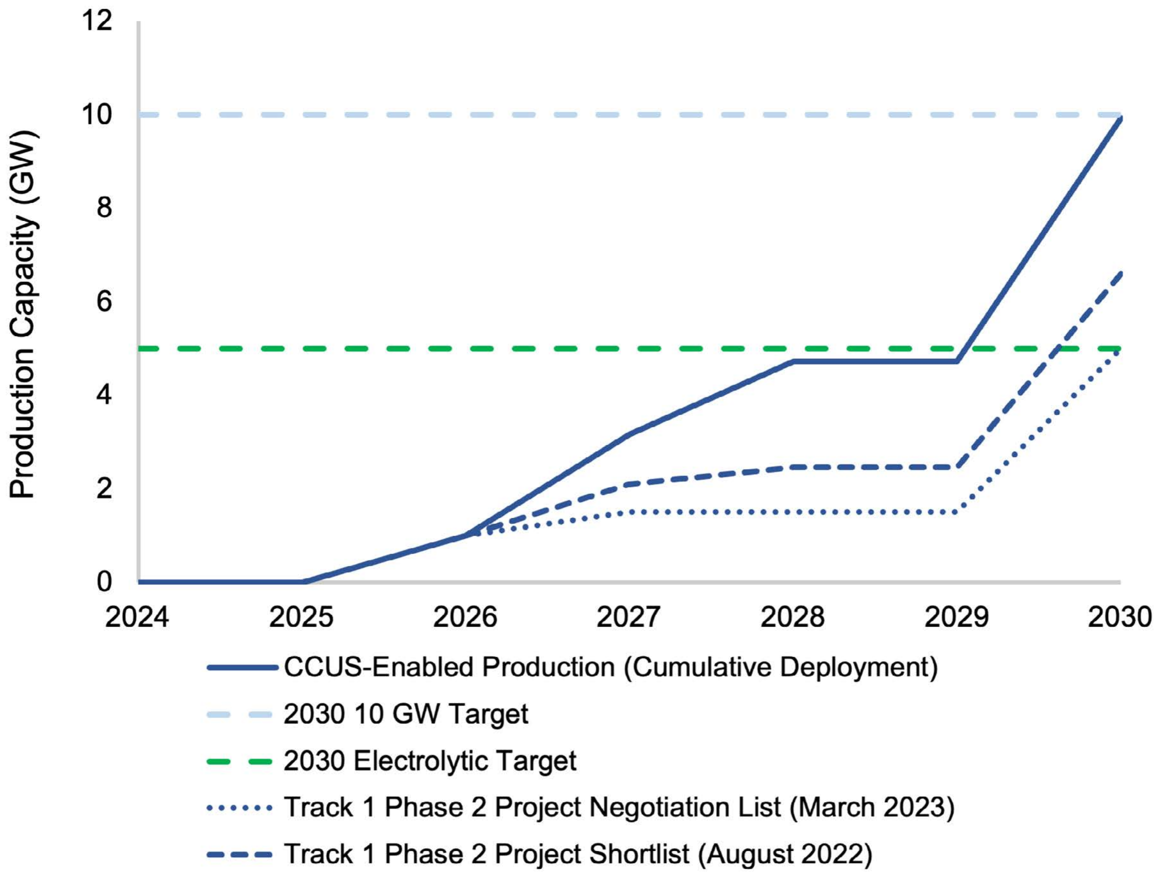

Figure 10: Cumulative CCUS-Enabled Hydrogen Production until 2030

Overview of the Cluster Sequencing Process

Background

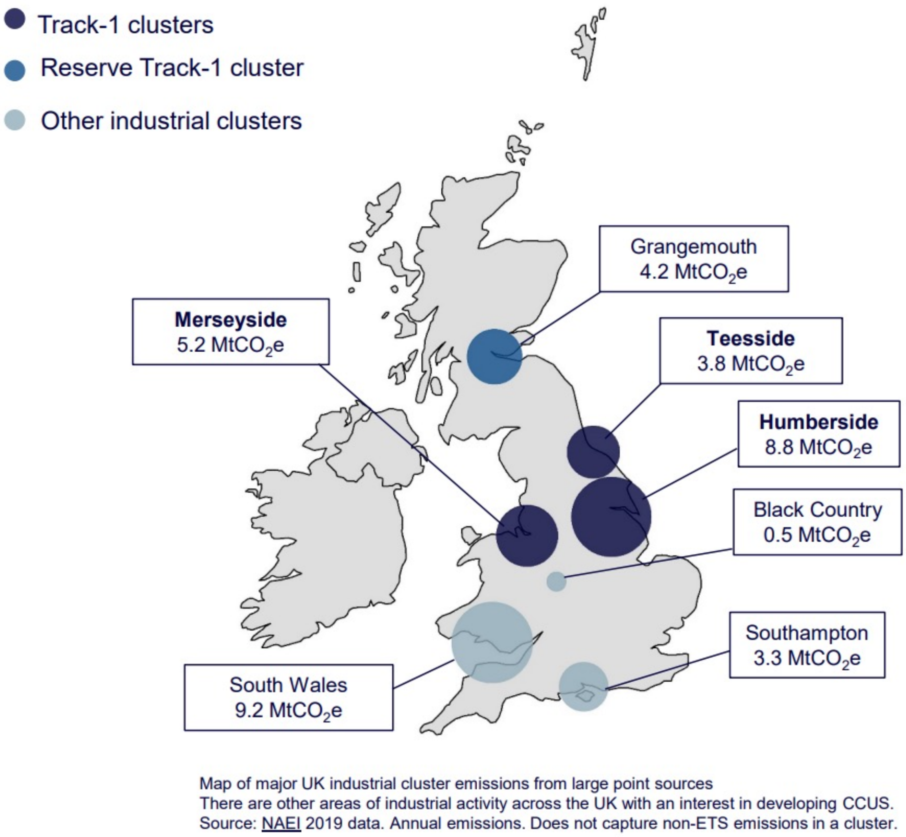

Figure 11: UK Industrial Cluster Map with Track-1 Status

Figure 11 shows the UK industrial clusters and their status within the Track-1 cluster sequencing process. On Energy Security Day (30th March 2023), DESNZ announced the Track-1 Phase 2 project negotiation list, containing just two hydrogen production projects. This announcement is the latest in the Track-1 cluster sequencing process, as demonstrated in **Figure 12** below[45].

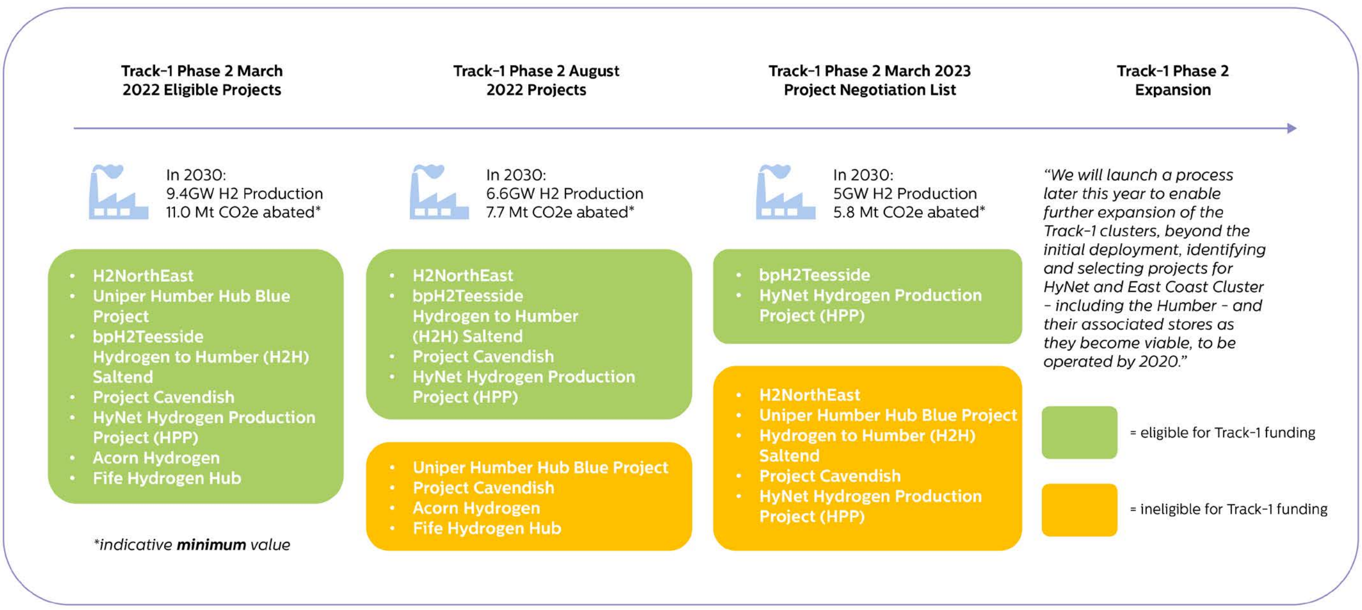

Figure 12: Track-1 Cluster Sequencing Process

Hydrogen UK

Concurrently, DESNZ invited Expression of Interest (EOI) submissions for Track-2 during April this year, aiming to select two clusters which can store at least 10 Mtpa of CO_2 by 2030. On 31st July, DESNZ confirmed that the Acorn and Viking CO_2 T&S systems, "due to their maturity, remain best placed to deliver our objectives for Track-2"and thus will commence engagement with both clusters.

Challenges

The cluster sequencing programme aims to enable the rollout of CCUS-enabled hydrogen within the UK. Pace and scale are needed to successfully achieve this. Hydrogen UK have ascertained some key challenges and learnings from the process so far on how to best accomplish this:

1. Investor Uncertainty

The phased nature of the rollout gives rise to a pertinent question – what happens to the projects not shortlisted? CCUS-enabled hydrogen developers face long lead times for planning, consenting, procurement and construction for their respective projects, meaning financial investment must be secured well in advance of any green light from government. To make investors and project developers consider waiting, a minimum level of certainty, in the form of timelines for projects both shortlisted and not, is urgently required. Without this basic level of detail, the level of uncertainty and confusion for the future can only be expected to cause investors to take their business elsewhere, losing the first mover advantage the UK has positioned itself in as a result of years of research, investment and project development. It is imperative that this minimum level of clarity is provided to industry.

2. Maximising Emissions Displaced

CCUS-enabled hydrogen projects have the capability to save million tonnes of carbon emissions from being released into the atmosphere and thus reducing the associated damaging environmental effects. As outlined in **Figure 13**, the Track-1 Phase-2 shortlisting process has gradually taken more and more CCUS-enabled hydrogen projects off the table, reducing the maximum potential level of carbon emissions that can be displaced within UK industrial clusters. Figure 13 displays the decrease in potential carbon emissions saved as a result of this shortlisting process.

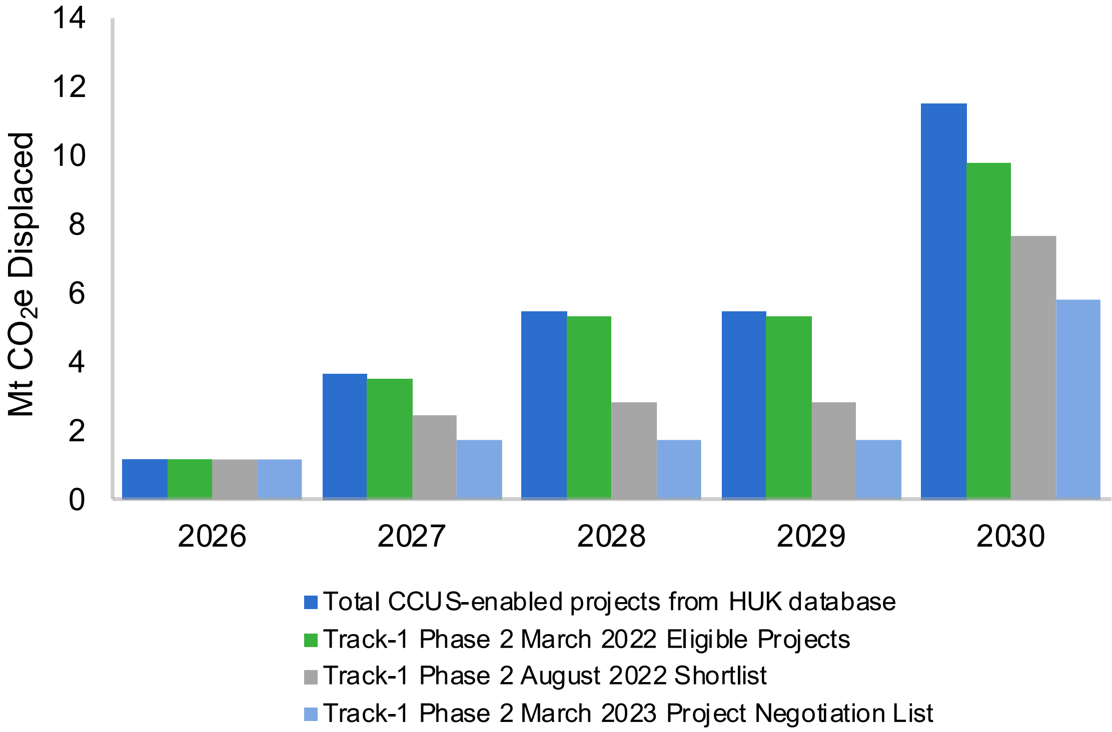

Figure 13: Indicative carbon emissions saved from CCUS-enabled hydrogen in clusters

It should be noted that the data displayed in figure 13 is a minimum indicative value of carbon emissions saved, due to the following assumptions:

- CCUS-enabled hydrogen is produced at the maximum emission intensity allowed under the LCHS up to 2030.

- The produced hydrogen only displaces methane from combustion applications, when other fuels and feedstocks with higher emission intensities will likely also be displaced.

Therefore, the savings missed out on will likely be considerably higher than those in Figure 13. Hydrogen UK acknowledges that there are further complexities to immediately funding all projects, however, recommends that the UK government provides a clear pathway for all cluster CCUS-enabled hydrogen production projects to be funded as quick as possible to maximize the associated environmental benefits.

3. *Ineffective Competition*

A major flaw of the cluster sequencing process is the overly competitive element it gives rise to. The competitive element requires developers to invest heavily without certainty over funding or timing. This points to the UK becoming a follower in deployment of CCUS technology, rather than a leader, especially when compared to other nations such as the United States. Here, initiatives such as the Inflation Reduction Act (IRA) and the Regional Clean Hydrogen Hubs Program encourage collaboration between a diverse range of stakeholders across the entire hydrogen value chain. In this environment, subsidies are provided for low carbon hydrogen production, storage and end-use applications, creating a fast moving, attractive landscape for CCUS-enabled hydrogen producers to locate their developments in. Comparing to the UK, it seems clear that the lack of collaboration between CCUS-enabled hydrogen production stakeholders will prove detrimental in the pace of rollout of the technology. It is vital that learnings and best practices are shared between industry to give the UK the best chance of developing into a world leading CCUS-enabled hydrogen nation and preventing international companies taking their business elsewhere.

In future, DESNZ should aim to reduce the level of ineffective competition from the cluster sequencing process, and instead focus on maximising carbon emissions at an acceptable value for money, by sharing learnings and fostering a more open environment.

4. *Carbon Dioxide Transport and Storage Requirements*

So far, a clear learning has been that the access CCUS-enabled projects have to CO_2 transport and storage infrastructure has proven to be critical in deciding which projects have been progressed. Only the four CCUS-enabled production projects which were listed on the August 2022 Phase-2 Cluster Sequencing shortlist have access to suitable CO_2 transport and storage infrastructure. This creates a portfolio risk for the remaining gaseous CCUS-enabled hydrogen production projects, currently with no visibility of the process for obtaining their necessary CO_2 transport and storage infrastructure connection or capacity. The Climate Change Committee's recent report 'Delivering a Reliable Decarbonised Power System' states "in the early days of its development blue hydrogen is likely to be located near a CCS sink to minimize the requirements for CO_2 transportation and storage"[46], highlighting the increased future requirements and potential bottlenecks for expansion away from already existing CO_2 infrastructure. To give some context to the CO_2 storage capacity required to meet the 2030 5GW CCUS-enabled[47] hydrogen production target, extrapolating the HyNet Low Carbon Hydrogen Plant performance data[51] gives a value of approximately 9 $MtCO_2$ pa.

As the implementation of transport and storage infrastructure comes with significant lead times, it is essential that direction is provided from the UK government on a strategy to connect non-shortlisted CCUS-enabled hydrogen production projects to either existing or new build CO_2 infrastructure, in turn providing the required confidence to investors and potential off-takers.

Case Studies

HyNet

Based in North West England and North Wales, the HyNet project is a successful Track-1 cluster that aims to become operational in 2025[48]. Within the project, hydrogen will be produced at the Stanlow Manufacturing Complex[49], operated by Vertex Hydrogen and transported around the cluster by the HyNet hydrogen network[50], developed by Cadent. HyNet partners INOVYN are repurposing salt caverns in the Northwich area of Cheshire to store 35,000 tonnes of hydrogen, providing security of supply. Beginning production in 2026, it will generate over 1GW of low carbon hydrogen, the equivalent to the energy used by a major British city region, for example Liverpool[51]. With the construction of a further three plants in the late 2020s, production capacity could increase to approximately 4GW, therefore playing a substantial role in helping to achieve the Government's 10 GW 2030 target. The resulting CO_2 captured at a target rate of 97% and a minimum rate of 95% by the CCUS-enabled hydrogen production process is to be stored underground in the nearby in the Liverpool Bay gas fields[52].

H2Teeside

bp is the lead operator of the East Coast Cluster, a group of projects including Net Zero Teesside and Zero Carbon Humber as part of the Northern Endurance Partnership (NEP)[53]. CCUS-enabled hydrogen production will provide c.160,000 tonnes of low carbon hydrogen per year. Furthermore, up to c.2million tonnes of CO_2 per year will be captured and sent to secure long-term storage – the equivalent of capturing the emissions from the heating of one million UK households[54]. The project aims to produce over 1GW of low carbon hydrogen production by 2030.

H2Teesside will supply hydrogen to a wide range of customers, including new businesses attracted to low carbon hydrogen produced at scale. The project will contribute towards levelling up due to the provision of high-quality jobs and upskilling opportunities. During construction, the project will support approximately 1200 jobs (both directly and indirectly) per year and approximately 600 jobs per year after the completion of phase 1 of the project.

Figure 14: H2Teesside Aerial View

The Solent Cluster

The Solent Cluster, founded by ExxonMobil, Solent Local Enterprise Partnership and the University of Southampton, is a collaboration of cross-sector organisations, businesses and industries with expertise in CCUS. Currently emitting approximately 3.2 million tonnes of carbon dioxide emissions from manufacturing processes, the Solent Cluster is regarded as a leading contributor to total CO_2 release in the UK[55]. The project aims to capture up to 10 million tonnes of carbon dioxide per year, the equivalent of taking 3.75 million cars off the road[56]. The project will be anchored by the development of new hydrogen facilities at the existing Fawley petrochemical complex alongside the necessary CO_2 capture technology and associated transport and storage infrastructure.

Novel Technology Case Studies

HiiROC

HiiROC use Thermal Plasma Electrolysis (TPE) to produce hydrogen and carbon black from a hydrocarbon feedstock[57]. The TPE technology uses 4-5 times less energy than electrolysis of water for the same volume of hydrogen output. Carbon black is used in multiple commercial applications such as tyres, rubbers, inks and toners. The technology can be used from industrial scale (hundreds of tonnes/day) down to small modular units (hundred kg/day).

Figure 15: HiiROC Hydrogen Production Unit

Levidian

Levidian have developed a novel technology, named LOOP, that cracks methane into hydrogen and carbon, locking the carbon into high quality green graphene[58]. The LOOP system is modular and can be deployed readily on a customer site, integrating with existing infrastructure to deliver a hydrogen-rich gas blend for immediate use. LOOP can also produce separated hydrogen for use in a variety of applications. The graphene produced can then be utilised to decarbonise other materials. LOOP systems are operational in Levidian's Cambridge headquarters and in the UAE; further deployments are planned in the UK, Europe, and elsewhere this year.

Figure 16: Levidian Hydrogen Production Unit

Recommendations

1. Provide further clarity and certainty on the process and funding envelope for cluster sequencing.

Hydrogen UK welcomes the latest announcements from the UK Government on the cluster sequencing process, including the shortlisting of the Track-1 Phase-2 projects and the outcome of the Track 2 EOI process. We now call for DESNZ to provide further clarity and certainty to the funding and timelines for projects both in and out of Track-1 and expected Track-2 shortlists. The UK has an abundance of projects looking to help the decarbonisation effort; however, uncertainty and potentially unnecessary competition is creating a situation where the value for money of the projects could be adversely affected. Projects may be forced to factor in sub-optimal designs to account for the uncertainty in the sequencing, and therefore availability of large-scale shared infrastructure, and competition between the projects is limiting progress rather than helping to drive costs down. DESNZ must ensure that learnings from the evaluation of the Track-1 cluster sequencing process are fed into the design for the Track-2 process without further delay, including reviewing evaluation criteria weightings under an industry-agreed, consistent methodology. It is essential that the UK maintains its early momentum in the CCUS-enabled production space, and that investment currently set aside for UK projects does not go elsewhere due to uncertainty and delays in an increasingly competitive global market.

2. The Heads of Terms for the HPBM must be fine-tuned to "break the chain of risk" for early movers.

With any nascent industry there exists the challenges and risks associated with reliability of supply and demand. For CCUS-enabled hydrogen production, this also extends to the availability of CO_2 transport and storage infrastructure, essential for ensuring the low carbon credentials of the produced hydrogen. In order to facilitate the realisation of early projects, it is necessary for Government to mitigate and break the chain of associated risks that are beyond the influence of hydrogen production projects, enabling them to concentrate on managing risks within their sphere of control. It is important to acknowledge that with the establishment of reliable infrastructure, the presence of multiple CO2 storage sites, the ability to blend hydrogen into gas networks, and a solid network of hydrogen consumers, these risks will fall away.

3. Ensure that novel technologies are supported in the Low Carbon Hydrogen Standard in advance of their commercial deployment.

The UK is home to the developers of several innovative hydrogen production technologies that deliver CCUS. However, they are 'not currently considered' within the LCHS. It is important that this stance is changed so that the deployment of these technologies is not hampered by inability to access government funding. In order to reach our Net Zero mandate, we will need every available technology, and delays to the deployment of technologies that can help decarbonise industrial emissions outside clusters must be avoided. In addition, the definition of CCUS by government should explicitly include production pathways that output solid carbon. This will remove the risk that rules and regulations relating to CCUS unwittingly exclude hydrogen production methods such as thermal plasma electrolysis and pyrolysis.

4. Provide clarity on CO_2 transport and storage infrastructure access for CCUS-enabled hydrogen production projects both inside and outside of industrial clusters

Gaseous CCUS-enabled production projects need access to the necessary CO_2 transport and storage infrastructure. Outside of the shortlisted Cluster Sequencing Phase-2 projects, CCUS-enabled production projects need visibility on how they will gain access to the necessary CO_2 transport and storage infrastructure connection and capacity. The UK government must provide clarity on this process to ensure there is no lag period where CCUS-enabled production projects are not able to operate due to a lack of access to CO_2 transport and storage infrastructure, and to provide the necessary confidence for projects to move ahead with current timelines.

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