Building a Hydrogen Society in the UK

Analysis by the Hydrogen Taskforce for the UK Hydrogen Strategy

05/02/2021

Glossary

Name	Definition
Blue Hydrogen	Hydrogen produced from fossil fuels with carbon capture and storage
Green Hydrogen	Hydrogen produced from renewable electricity through electrolysis
Grey Hydrogen	Hydrogen produced from fossil fuels without carbon capture and storage
Electrolysers	Technology which splits water into hydrogen and oxygen using electrical energy
Curtailment	Restricting or reducing something, in this case renewable energy generation due to a lack of grid capacity
Blending	Blending is a process by which hydrogen is blended with natural gas and then either injected into the gas grid or used in industrial or power applications. For the purposes of this report, the use of hydrogen blends in power is captured in the "power" figures, "blending" figures refer to hydrogen that is injected into the gas grid for use in domestic and commercial heating. This is distinct and separate from the 100% hydrogen heating which refers to new build or conversion projects that use 100% hydrogen.
Acronym	**Definition**
MW	Megawatt
GW	Gigawatt
TWh	Terawatt hour
Mt	Megaton
Gt	Gigaton
RTFO	Renewable Transport Fuel Obligation
GSMR	Gas Safety Management Regulations
BSOG	Bus Service Operators Grant
REDII	Renewable Energy Directive recast
CC(U)S	Carbon Capture (Utilisation) and Storage
FID	Final Investment Decision
CfD	Contracts for Difference
R&D	Research and Development
CCGT	Combined Cycle Gas Turbine
OCGT	Open Cycle Gas Turbine
HGV	Heavy Goods Vehicle
CCC	Climate Change Committee
CAPEX	Capital Expenditure
BEV	Battery Electric Vehicle
FC	Fuel Cell
OEM	Original Equipment Manufacturer
LDV	Light Duty Vehicle
HRS	Hydrogen Refuelling Station
RAB	Regulated Asset Base
FEED	Front End Engineering Decision
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
GVA	Gross Value Added
STEM	Science, Technology, Engineering and Maths
BEIS	Department for Business, Energy and Industrial Strategy
PEM	Polymer Electrolyte Membrane (electrolysis)
PPA	Power Purchase Agreement

Introduction

Hydrogen has a key role to play in meeting the UK's target of net zero emissions by 2050. It is a cost-effective way to achieve deep decarbonisation across a range of downstream applications. However, for hydrogen to play this role, the UK must act now to scale production of low carbon hydrogen.

The UK Hydrogen Strategy represents a vital opportunity for the Government to set out its ambition for hydrogen and explain how this ambition will be achieved. It will also be an opportunity to bring together the ambitions of the nations that make up the union into one coherent strategy. In a global landscape that has seen many economies set ambitious targets and commit substantial investment in the development and deployment of hydrogen solutions, the UK cannot afford to be timid in its Hydrogen Strategy. The UK has a strong foundation and is well positioned to take a global leadership role, delivering cost effective decarbonisation as well as jobs and economic growth. The huge potential will only be realised if the UK is bold and ambitious; if not, the UK risks being left behind. In short, the Hydrogen Strategy alone cannot win the hydrogen race for the UK; industry and government must work together to deliver. But a cautious strategy that does not set out suitable near-term direction will set the UK back in its ambition to create a world leading hydrogen industry.

Both blue and green hydrogen have an important role to play and the Taskforce supports the Government's plan to invest in both in tandem. The view of the Hydrogen Taskforce is that a sub-optimal roll-out is preferable to a 'wait and see' approach that delays the potential impact of hydrogen on UK emissions and puts the UK at a competitive disadvantage in a rapidly growing global market. The Taskforce supports the Government's approach of developing industrial "hubs where renewable energy, CCUS and hydrogen congregate" to drive the development of the hydrogen economy to 2030.[1]

This paper sets out the Hydrogen Taskforce's view on hydrogen uptake by 2030, the share of blue and green hydrogen production, the amount of CO_2 likely to be saved, and the role of supportive policy measures as an enabler to deploying hydrogen at scale.

Summary

For the UK to meet its 2050 net zero commitment, hydrogen solutions must be rapidly scaled through the 2020s. This will require action and coordination across the value chain. Production cannot be scaled without a market for hydrogen. Demand side technologies will not be developed and deployed without a source of hydrogen and most large-scale projects cannot come forward without both a network and storage assets.

These aspects are interdependent and must all be developed and scaled together, ensuring the optimum sequencing and prioritisation to enable the UK to build a solid foundation by 2030. Getting this right will provide the springboard for 2050 whilst ensuring that the UK realises the economic value from investment in hydrogen. Success will rely upon a strong partnership between the Government and business, including early alignment on business models and support measures.

2030 scenarios

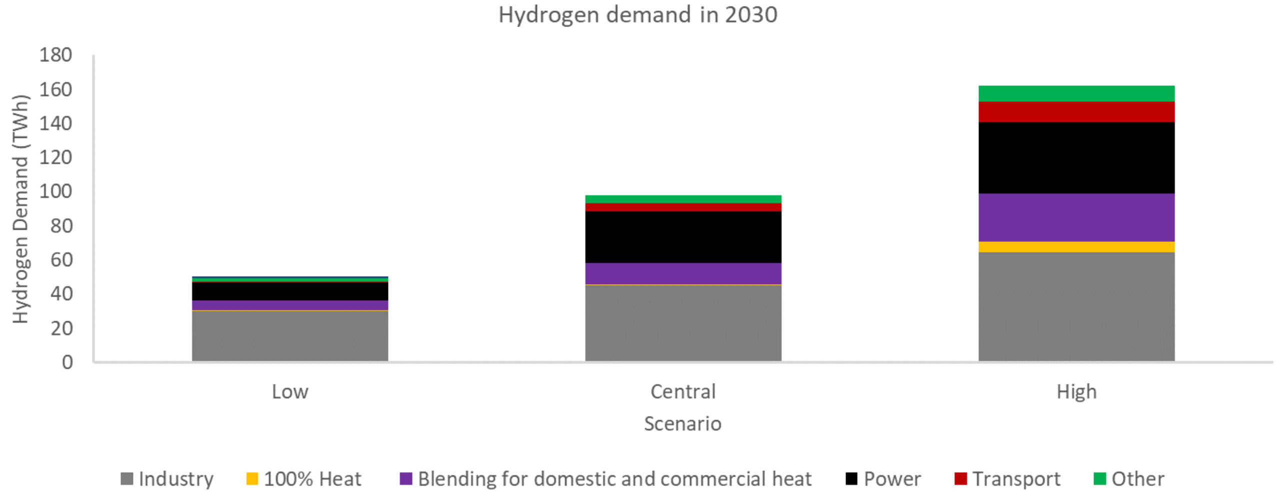
The Hydrogen Taskforce has developed three scenarios that outline what could be delivered in the UK by 2030 based on different assumptions. For context, these scenarios have been outlined alongside the Prime Minister's recent commitments to hydrogen in *The Ten Point Plan for a Green*

[1] HM Government (2020) The Ten Point Plan for a Green Industrial Revolution

Industrial Revolution. The high scenario has been developed by aggregating the 2030 ambitions of the projects in the UK pipeline and assumes that they all deliver 100% of their projected targets.[2] The central and low scenarios have been developed based on sensitivity analysis of the end use sector technologies. Full breakdowns can be found in the Appendix.

	10pt Plan	Low	Central	High
Production – installed capacity (GW)	**5**	**7.6**	**14.8**	**22.9**
Blue		5.2	9.1	14.0
Green		2.3	5.7	8.9
Demand - TWh		**49.7**	**97.9**	**161.9**
Industry		30.3	45.1	64.7
Blending for domestic and commercial heat		5.6	12.7	28.5
Power		10.4	30.1	41.6
Transport		0.8	4.6	12.1
100% domestic and commercial heat		0.2	0.7	6.1
Other (i.e. CHP, ammonia)		2.2	4.7	8.9
Impact				
Carbon abatement ($MtCO_2e$)	41	9.7	18.4	30.8
GVA - £bn		7.2	14.2	23.6
Jobs	8,000	29,700	58,500	96,800

**figures may not add due to rounding*



The 2020s must focus on scaling production of hydrogen which will require the unlocking of end use sectors with high demand as quickly as possible. It will also require investment in infrastructure, such as storage, pipelines and refuelling stations. Actions must also be taken in end use sectors where hydrogen has a key role to play by 2050 to prepare the sector for large scale roll out post 2030.

The Hydrogen Taskforce has set out a timeline of the actions that we believe are necessary to deliver the central scenario.

[2] In practice, it is unlikely that the high scenario will materialise, as it implies the achievement of maximal estimates for both green and blue production as well as for demand across all sectors. However, it is a way of demonstrating the potential supply of and demand for hydrogen in the UK economy.

Production

2021: Development of standards for blue and green hydrogen

2021: Offshore Wind framework adjusted

2021: Grid fees waived for green hydrogen

2021: Development of guidance on PPAs

2022: CCUS support scheme/ business models launched

2022: Blue and green production support scheme begins

2023: 4-5 blue production projects reach FID

2023: Large scale green production projects reach FID

2021-2030: Small scale green production projects

2023-2030: Large scale green production projects

2023-2026: Delivery of 1st phases of clusters, including large-scale blue production

2026-2030: Expansion of clusters

Infrastructure

2021: Development of regulatory framework to enable investment in networks and storage

2022: Define system operator requirements

2022: Introduction of "green gas" tariffs

2022: Amendment of GSMR

2022: Rough FID

2025: All networks have plans in FEED stage

2024-2030: Construction of hydrogen pipelines

2023-2030: Blending

2022-2026: Development of local/regional network plans

2021-2022: Rough FEED

2022-2026: Redevelopment of Rough

2022-2030: Development of H2 Salt Caverns

2022-2030: Development of Hydrogen Transmission Systems

Transport

2021: Amendment of BSOG to incentivise hydrogen

2021: Signalling on diesel phase out from 2035

2022: Subsidy support for buses begins

2024: Subsidy support for HGV and LCVs vehicles begins

2025: 100 hydrogen stations deployed

2026: Subsidy support for trains begins

2026: Production of blue ammonia for shipping begins

2030: 500 hydrogen stations deployed

2020-2030: R&D and Innovation funding for hydrogen shipping and aviation applications

2021: Amendment of RTFO to incentivise green hydrogen

2022-2026: Train Demonstration

2023-2027: Industry HGV and LCV aggregated procurement programme

2022-2026: HGV Demonstration

HYDROGEN TASKFORCE

Industry

2021: Target 75% Low Carbon Hydrogen in existing industrial hydrogen applications by 2030

2022: Industrial business models launched

2022: Capex support for early stage projects

2023: Signalling of fossil fuel phase out scheme e.g. carbon CfD/ tradeable performance standards/carbon leakage/public procurement

2022-2030: Grey hydrogen displacement

2020-2022: Fuel switching demo

2023-2026: Fuel switching in clusters

2027-2030: Fuel switching in expanded clusters

2022-2025: Hydrogen in reactivity processes demonstration

2027-2030: Hydrogen use in steel production begins

2025-2030: Hydrogen in reactivity processes in clusters

Power

2022: Power business models launched

2022-2030: Power blending

2022-2025: Development of peaking plan

2027-2030: New-build CCGTs running on 100% H2

2021-2030: Electrolysers participate in grid balancing

100% D&C Heat

2021: Signalling on "hydrogen ready" gas appliances and metering from 2025

2021: Case for Safety/ QRS for occupied pilots

2022: Heat business models launched

2025: "Hydrogen ready" gas appliances and metering

2022-2025: Live Trials of H2 Heating

2025-2030: 5 x 10,000 home pilots of H2 Heating

2021-2025: Development and trials of commercial heating technologies

Production targets

The Taskforce welcomed the inclusion of a 5GW production target within the Prime Minister's *Ten Point Plan for a Green Industrial Revolution*. This marked the first major target announcement on hydrogen by the UK and is an important first step. It is the view of the Taskforce that this 5GW target represents a very conservative view of what is possible in the UK and that the UK must look to be more ambitious if it is to compete internationally. The Taskforce has been undertaking analysis to develop 2030 scenarios that could be used to update the production target.

In order to develop production targets for 2030, the Taskforce has identified the projects and potential sources of hydrogen that could feasibly be delivered by 2030 across both green and blue. In each of these projects, we have identified the demand sectors and cross-matched these with technology readiness and pathway projections from other sources. Through this analysis, we have developed three core scenarios: high, central and low. The high scenario is derived from the most optimistic assessments of the potential of each end use sector. However, the Taskforce recognises that not all of these are likely to happen concurrently by 2030. All scenarios will require significant levels of government support. The central scenario represents an ambitious target, but one that the Taskforce believes is achievable. It would provide the necessary platform to build to 2050 whilst realising economic value for the UK. The low scenario would see some progress made in the decade but would leave the UK lagging behind other countries and would make the task of reaching net zero 2050 difficult. More detail on these scenarios can be found in the Appendix.

Green Hydrogen

The potential for green hydrogen production in the UK is vast. The UK has more offshore wind capacity than anywhere else in the world, currently over 10GW.[3] It also has a large offshore wind potential of approximately 6000TWh via a potential capacity of 1300GW, which is over three times the UK's current consumption of all forms of energy. Green hydrogen has a key role to play in enabling further deployment of renewables and avoiding constraint payments. The Government should also consider the role of hydrogen generated from nuclear.

In addition, green hydrogen has a key role to play in providing resilience and flexibility to the wider energy system. Green hydrogen can buffer both power generation and heat by enabling energy storage at scale. Electrolysers can be used to provide grid services and in demand side response through time varying operating profiles and balance the system without causing CO_2 emissions. As the UK moves towards an increasingly electrified energy system, this capability will become more essential.

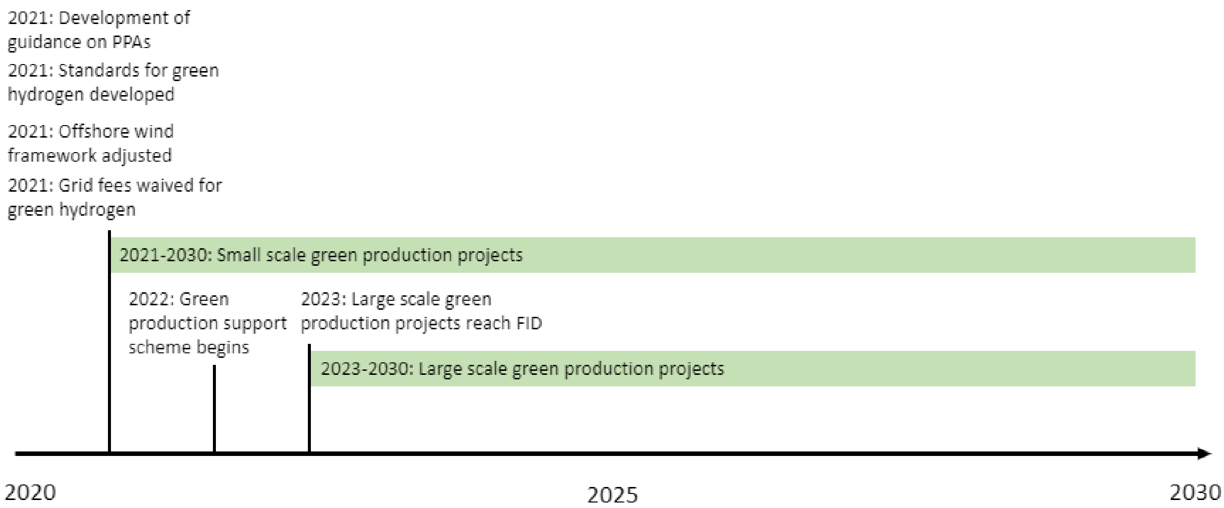
There is significant export potential for green hydrogen, with the EU targeting 80GW by 2030, 50% of which will be imported. The UK is well placed to capitalise on this opportunity. The UK is already expanding its exploitation of renewables and it has a strong leadership position in green hydrogen. It is home to the world's largest electrolyser factory and with a strong domestic market this could see further development of the UK supply chain. With other European countries setting ambitious green hydrogen production targets and substantial support packages, it is vital that the UK maintains its leadership position through strong support for green hydrogen.

[3] BEIS (2020) Energy Trends UK, July to September 2020

2030 production target

	Low	Central	High
Green hydrogen target (GW)	**2.3**	**5.7**	**8.9**
Offshore Wind Capacity (GW) with storage[4]	**3.2**	**7.9**	**12.4**
Offshore Wind Capacity (GW) without storage	**7.1**	**17.9**	**27.9**

Constraints and policy recommendations



ITM Power's electrolyser factory will have 1GWpa capacity by 2023, meaning that electrolyser manufacturing capability is unlikely to be a constraint on green hydrogen capacity. However, whilst the UK is currently a global leader in electrolyser technology, an ambitious target for green hydrogen and a corresponding support scheme will be critical to the UK maintaining its advantage in the market. The UK should have a support scheme in place by the end of 2021 to meet the central and high targets.

The offshore wind sector is targeting 40GW of generation capacity by 2030 meaning that raw generation capacity is unlikely to be a constraint on green hydrogen production, particularly if deployed with storage. However, the offshore wind framework will need to be adjusted to account for green hydrogen production. Such an adjustment will need to recognise multiple assets and the policy trade-offs involved in diverting electricity generated from offshore renewable assets away from the grid and into green H2 production. From a market perspective, the amount of low-priced and curtailed production will be a constraint. A review of the regulatory changes required to unlock green hydrogen's potential will need to include revision of network charges. BEIS, Ofgem and industry will need to coordinate on this activity.

The Hydrogen Taskforce is engaging in BEIS's business model workstream for hydrogen production. We would be supportive of a system based on a Contracts for Difference (CfD) mechanism, underpinned by revenues from the capacity market to reflect hydrogen's potential in supplying firm power to back up intermittent sources. CfDs are well understood by industry and have worked well with the offshore wind industry, delivering significant capacity and technology cost down over the

[4] The offshore wind capacity required to deliver green hydrogen is decreased if electricity storage is deployed alongside electrolysers. Turbines coupled with storage provide more consistent electricity than turbines alone, allowing electrolysers to operate at a higher load factor with the same capacity of offshore wind.

past five years. The 2019 CfD auction delivered 5.8GW of capacity at £39/MWh, a reduction of 66% compared to the prices in the first CfD auction in 2015. Hydrogen has similar cost down potential and the Taskforce considers that CfDs would support technologies down the cost curve. However, the system implemented would need to involve direct negotiation with projects rather than an auction style during the price discovery phase. The system implemented would also need to include a mechanism to give producers flexibility to supply a range of end uses which would all have different counterfactual costs.

Furthermore, any potential support scheme should align with regulatory instruments being developed, to ensure that the full value of renewable hydrogen production is realised. For instance, the development of Power Purchase Agreement (PPA) guidance to facilitate the effective use of PPAs to demonstrate 100% renewable electricity going to the electrolyser is one of the regulatory solutions for green hydrogen production that should be established in 2021.

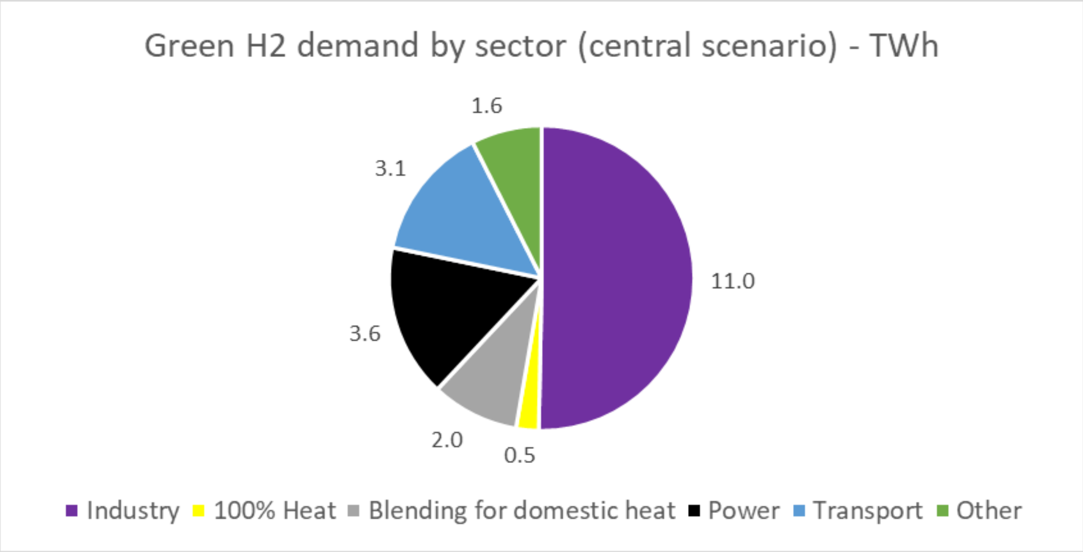
A PPA could address an existing regulatory barrier whereby the value of renewable hydrogen is eroded due to power from grid-connected electrolysers being scaled by the carbon intensity of the grid, as the electrolysers may need to import some power not only directly from the wind asset but also from the grid, if it were to run at, or close to 100% utilisation throughout the year. This scaling effect reduces the value of any support to the renewable hydrogen business case. PPAs would allow grid-connected renewables and grid-connected electrolysers to establish the green relationship and unlock full value to electrolysers whilst allowing renewable generators access to alternative markets and delivering additional value to consumers through green electricity sales.

Both on grid and off grid green hydrogen production should be considered within any support scheme allowing for small scale decentralised production as well as large centralized production attached to offshore wind. For on-grid small scale decentralised production, the government should consider waiving grid fees and the use of grid service payments as additional incentive mechanisms to support small scale green hydrogen production. Operating expenditure accounts for the majority of the cost for green hydrogen, where electricity costs are dominant and particularly affected by grid charges, taxes and levies. These issues could form part of a wider review of the electricity system and grid utilisation.

It is worth reiterating that in order for production to scale, there must be a market for hydrogen and the enabling infrastructure must be in place first, as a result of credible anchor projects, located in strategic industrial hubs, covering both the supply and demand side. This will open the market for wider nationwide applications and associated infrastructure. The most important markets to unlock to enable green hydrogen to scale are industry, power, blending and transport. Business models and policies associated with these sectors will be key including:

- Signals and business models for industries including refineries and power generation
- Amendment of the RTFO
- Amendment of the Bus Service Operator Grant (BSOG) and capital support for vehicles
- Amendment of the GSMR and business models for blending
- Development of a PPA guidance suitable for renewable hydrogen production.
- Waiving of grid fees and the provision of grid services by electrolysers

More detail on this can be found in the sections on industry, power, infrastructure and transport.



International examples

A number of policies developed in EU countries have stimulated green hydrogen production:

- Germany has indicated that it will set a target beyond that outlined in RED II for the minimum quota of renewable energy to be used in the transport sector and have included green hydrogen in this policy. This policy has been used to realise some early pathfinder green hydrogen projects in refineries. This could be replicated for some projects using the RTFO in the UK.
- Similarly, in France, a 2x multiplier has been added to exchangeable credits for the use of green hydrogen in refineries for producing transport fuels.
- Germany is also moving to exempt electricity required for producing green hydrogen from taxes, levies and surcharges. This should be replicated in the UK.
- France has signed into law that that renewable and low-carbon hydrogen should amount to 20% to 40% of hydrogen consumption by 2030.
- Germany is setting up a Carbon Contracts for Difference (CfD) model to stimulate demand in the industrial sector and is exploring the use of demand quotas for climate friendly products such as "green steel".

Blue Hydrogen

The UK is well positioned to take a leadership role in blue hydrogen, with a strong oil and gas sector and existing expertise and assets. There is significant potential to develop a UK based supply chain for the delivery of blue hydrogen projects, creating and protecting high value jobs. UK CO_2 storage potential is significant, estimated to be around 78GT.[5] No major technical hurdles to storing industrial scale CO_2 offshore exist. Blue hydrogen production is likely to be able to deliver large volumes of hydrogen at low cost in the short term.

Few EU countries are currently targeting blue hydrogen, which gives the UK an opportunity to take a leadership position. The EU has already indicated that it will likely look to import blue hydrogen in order to meet its hydrogen targets. There will be few nations able to provide this blue hydrogen and the UK could realise a large export market in the future. In addition, it is likely that blue hydrogen

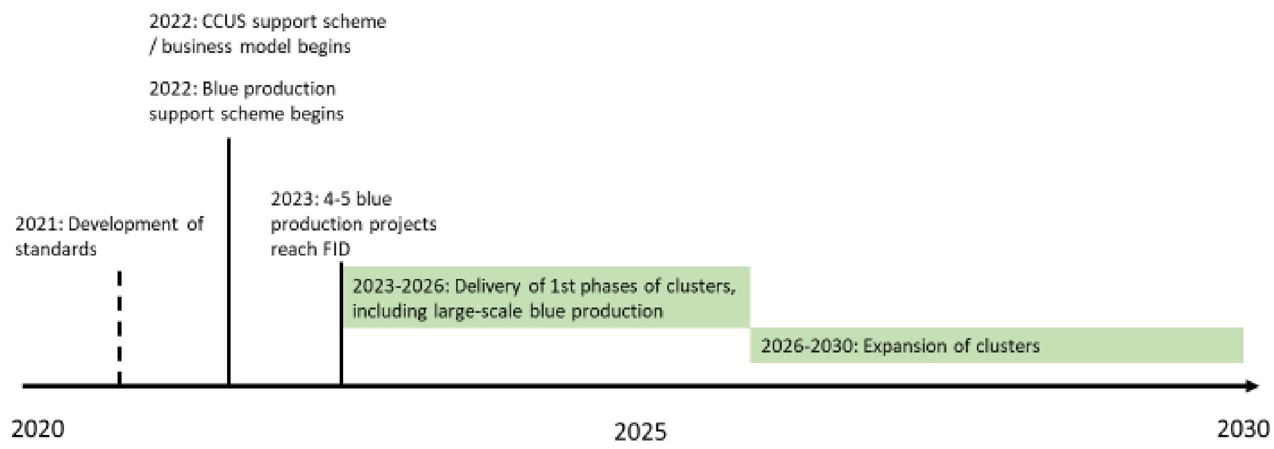
[5] Energy Technologies Institute (2016) Strategic UK CCS Storage Appraisal

production will increase globally and there will be significant export opportunities for technology and services if the UK takes a leadership position.

2030 production target

	Low	Central	High
Blue hydrogen target (GW)	**5.2**	**9.1**	**14.0**

Constraints and policy recommendations



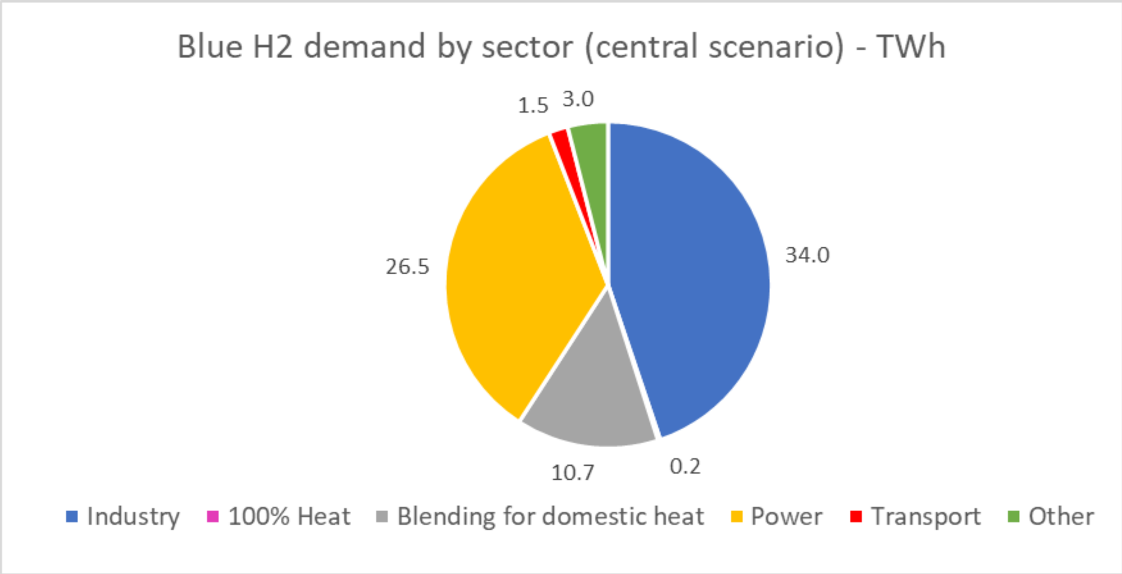
Any business model for blue hydrogen must consider the requirement for CCUS. The Government has committed £1bn for the delivery of a CCUS programme. However, there is currently no guidance on how this funding, as well as the planned £250m Zero Carbon Hydrogen Fund, will be used for projects that deliver blue hydrogen, e.g. split between CAPEX support for early-phase projects and long-term production supports. The Hydrogen Taskforce contends that a similar scheme to the CCUS Infrastructure Fund should be developed for hydrogen projects. Coordination on timings for blue hydrogen and CCUS development will be important.

Delays in the development of the business model for blue hydrogen will have a substantial impact on the industry's ability to deliver decarbonisation and realise economic value. In addition, it should be noted that the CCUS programme alone is not enough to kick start blue hydrogen production. Blue hydrogen will require support for production over and above that which might be committed through the CCUS programme.

As with green hydrogen, the Hydrogen Taskforce supports a negotiated support programme potentially in the form of a CfD during price discovery stage. The Taskforce recommends that the UK should aim to take 3-5 blue hydrogen projects across several industrial clusters to FID by 2023.

Industry and regulators must work together to develop standards for blue hydrogen including setting a 95% minimum CO_2 capture level. This work should take place as early as possible to allow industry to design processes and to give public confidence in blue hydrogen.

The key demand sectors required to allow blue hydrogen production at scale are industry, ammonia blending and power. Development of business models that would unlock these sectors will be critical to the delivery of blue production projects.



Demand

Hydrogen has a key role to play in UK energy. Cost effectively decarbonising much of the energy system is simply not possible without hydrogen. The priority during the 2020s should be to target end use sectors which can provide initial demand, allowing hydrogen production to scale. Technology development will follow as the market builds up. Developers will add more resources and funding to develop new and better hydrogen technology for industrial energy processes as confidence in value chains builds up. Alongside this, we must also ensure that sufficient progress is made by 2030 in areas where we know hydrogen will be essential to meeting net zero.

The first mover offtake demand sectors will be those that require no conversion of end use technologies or where end use technology already exists. These include displacement of grey hydrogen within industry, blending into the gas network for use domestically and in power applications and transport applications such as buses and ammonia production.

Industry

Industrial users will be key to providing initial demand volume. There are four main uses of renewable and low carbon hydrogen within industry: to replace grey hydrogen as a feedstock in refineries and chemicals production; to replace grey hydrogen in the merchant hydrogen market; for use in high grade heat processes; and for use within reactivity in processes such as steel and glass manufacturing.

Widespread industrial decarbonisation is simply not possible without clean hydrogen[6], both for feedstock and high-grade heat, especially where the flame (and subsequent combustion gases) needs to come into direct contact with the material or product being produced (e.g. in furnaces and kilns) and no other viable options exist. Hydrogen boilers could easily replace current boilers within industrial processes.

In cases where electrification is possible, the need to upgrade equipment and local grid connections is likely to make this more expensive than clean hydrogen for industrial users, with the Committee

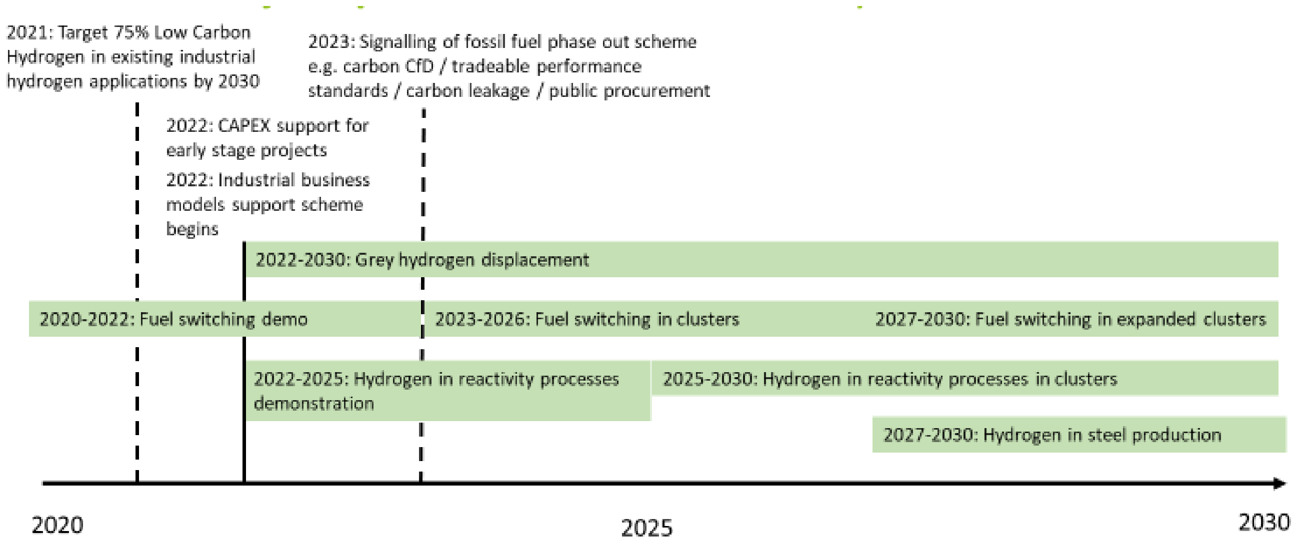
[6] CCC (2019) Net Zero Technical Report

on Climate Change concluding that "*hydrogen options may be cheaper than electrification*" for most industrial sites, excepting the use of electrical heat pumps used to space heat buildings.[7]

There are significant differences between the use of hydrogen for low- and high-grade heat and the use of hydrogen in reactivity. Many heat applications present fewer technological challenges than reactivity. For example, for some applications, changing burners or making small adaptations that would represent around 10% of CAPEX costs could be implemented to move to a hydrogen solution. There will be some regulatory reform required to enable these changes.

	Low	Central	High
Demand (TWh)	**30.3**	**45.1**	**64.7**
Blue hydrogen (TWh)	**27.2**	**34.0**	**45.4**
Green hydrogen (TWh)	**3.1**	**11.0**	**19.3**
Carbon abatement (MtCO_2e)	**6.4**	**9.3**	**13.7**

Constraints and policy recommendations



The UK currently uses 27TWh of grey hydrogen within industrial processes.[8] This demand comes from large-scale chemical processes such as refineries, ammonia, chemicals, plastics production, float glass and small-scale processes such as epitaxy, heating atmospheres, specialist metal and glass work and laboratories. The users are familiar with hydrogen and there are no technical barriers to switching to low carbon hydrogen. The UK should target displacing grey hydrogen as a feedstock with low carbon hydrogen as a first mover demand sector. This should be implemented by setting a 75% low carbon hydrogen target in 2030 for processes that currently use grey hydrogen.

For the sector to invest in hydrogen fuel switching solutions, it needs to deliver successful demonstration projects in the early 2020s. Moving from natural gas to hydrogen presents a significant risk to operators, so cost parity alone between natural gas and hydrogen is not enough in itself to stimulate a move towards hydrogen. First movers will require upfront grants alongside the ongoing subsidy support scheme to support the transition through to 2030.

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[7] CCC (2019) Net Zero Technical Report
[8] CCC (2018) Hydrogen in a low carbon economy

The challenges presented using hydrogen in reactivity processes are greater and less uniform. The extent to which we will see large scale decarbonisation of this sector in the 2020s rather than in the 2030s is unclear. However, R&D and demonstration should occur in order to position the sector for large scale decarbonisation in the 2030s.

Industrial users will require signaling from government to drive a move towards decarbonisation. This could be implemented through several different mechanisms such as tradable performance standards, carbon border adjustments, carbon CfDs, carbon pricing. Government and industry must work together in the early 2020s to develop the correct mechanism.

Power

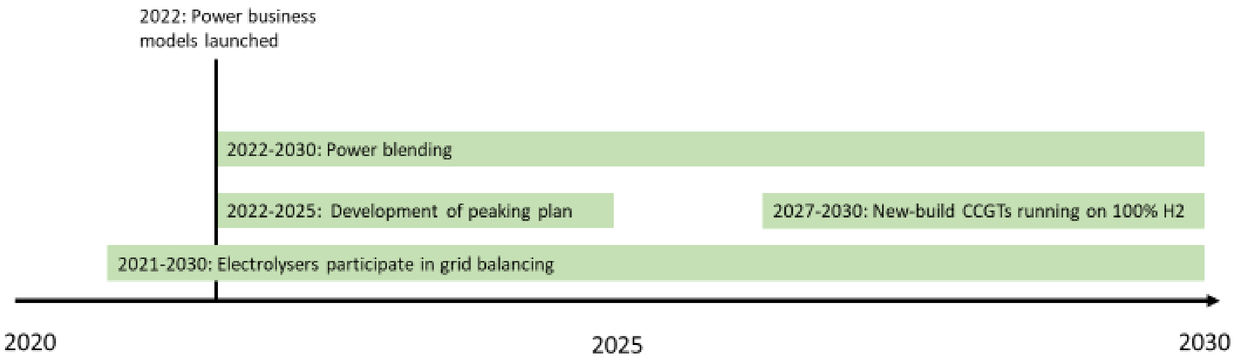
Power has a key role to play in providing anchor demand that will allow hydrogen production to scale. Anchor demand is particularly relevant for early stage blue hydrogen projects, several of the which have identified the power sector as a key early offtaker. As such developing the right policies and business models to unlock this market should be an early priority.

Hydrogen has a key role to play within the decarbonisation of power. As the UK moves towards an increasing reliance on renewables, hydrogen can provide several functions that will result in a more resilient, flexible and cost-effective power domain. These functions include:

- Providing storage to reduce costs of renewables - In order to hit target costs for renewables the UK will need storage to avoid curtailment. Hydrogen can provide largescale storage.
- Providing clean firm power generation – Hydrogen fired CCGT can be used as a replacement for the valuable role that gas fired CCGT currently plays in the energy system.
- Providing peaking generation – Hydrogen fired OCGT complements the deployment of renewables by providing peaking generation capacity
- Providing demand side response – electrolysers can be utilised to balance the grid, avoid curtailment and provide demand side response including frequency response.
- Enabling sector coupling to reduce electricity infrastructure costs – the heat and transport domains are 4 times larger than the current power domain with peak demand for gas also 4 times that of electricity. The use of hydrogen for sector coupling can assist renewables deployment, reduce infrastructure costs and improve reliability.

	Low	Central	High
Demand (TWh)	**10.4**	**30.1**	**41.6**
Blue hydrogen (TWh)	**8.8**	**26.5**	**35.4**
Green hydrogen (TWh)	**1.6**	**3.6**	**6.2**
Carbon abatement (MtCO_2e)	**1.8**	**5.2**	**7.2**

Constraints and policy recommendations



Early stage demand for hydrogen within the power sector will come from blending hydrogen into existing CCGT assets at low percentages. This can be done in the early 2020s as soon as hydrogen is available. It should be noted that power production facilities will prefer a constant blend and will have low tolerance for deviation from this fixed blend percentage. As a result, there are limits to the power sector's ability to act as a flexible off-taker of hydrogen when using it as a blended component.

Pure hydrogen power is currently in development, and this will need to continue over the early 2020s. In the long run, CCGTs using 100% hydrogen have an important role in providing firm power to complement intermittent renewables in addition to nuclear power generation and conventional thermal power generation with CCS. Alongside technology development, a plan for the use of hydrogen in providing peaking generation should be developed. This application has the added advantage of not having large seasonal variation which will enable facilities to run closer to maximum, improving economics.

100% Domestic and Commercial Heat

Decarbonising domestic heat is arguably the biggest challenge facing the UK as it looks to meet net zero. The UK has the oldest and leakiest housing stock in Europe and the vast majority (85%) of homes use natural gas for heating and cooking. A switch to electric solutions requires not only upgrading grid and generation capacity but also in many cases whole house retrofits given the combination of low temperature heat pumps and historically poor UK fabric energy efficiency.[9] The Hydrogen Taskforce therefore, endorses the Committee on Climate Change's conclusion that there is "no silver bullet to decarbonising heat", with the condition of local housing stock, population density (important for heat networks), the availability of green gases such as hydrogen and consumer preferences all playing important roles in what are likely to be local solutions.

From the consumer perspective, hydrogen offers a decarbonisation solution that requires minimal disruption in the home. It is a like for like replacement that consumers understand. A study on public perceptions on hydrogen[10] found that there was general support for hydrogen conversion amongst the public, particularly once provided with clear information on the hydrogen conversion. Consumers were prepared to pay a small premium for "green" gas, particularly if there was minimal disruption.

[9] Tado (2020) UK homes losing heat up to three times faster than European neighbours
[10] Newcastle University (2019) Blended Hydrogen: The UK Public's Perspective

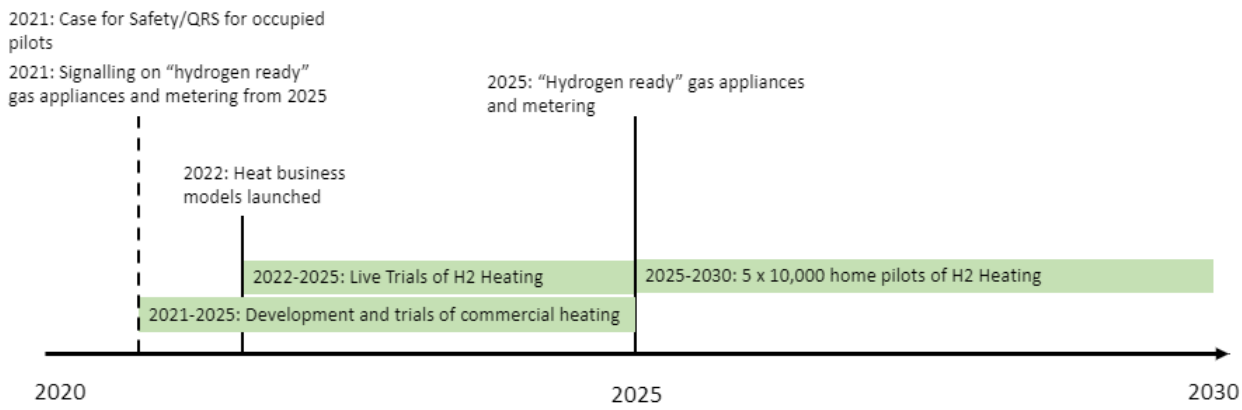
A further advantage of utilising hydrogen alongside electricity as an energy carrier is that it will result in a more resilient energy system. On a small scale, electrification, with its greater efficiency is the more cost-effective approach. However, at large scale, the energy system considerations mean that a mixed approach including a substantial role for hydrogen will result in greater resilience and lower costs. In 2018 gas hourly demand peaked at 214GW whilst electricity peaked simultaneously at 53GW. The electricity distribution network is currently not designed to manage the demands of the heat and transport sectors and, whilst the electricity distribution network will inevitably need to be upgraded to support the roll out of battery electric vehicles, there would be significant challenges in attempting to use the electricity network to support the entire transport and heat domains.

From a cost perspective, the Energy Networks Association (ENA) has developed analysis showing that a balanced scenario (replacing natural gas with an increasing amount of biomethane and hydrogen, with some further electrification) could save energy billpayers around £13 billion a year compared to a scenario that relies upon electricity alone.[11] Utilising the potential of hydrogen to decarbonise heat is a cost-effective pathway to achieving net zero by 2050.

The UK is already well set up for a hydrogen solution. The country has an existing supply chain, existing manufacturing and a large installer base that has expertise in boilers and wet central heating system. Moving to a hydrogen solution would cause minimal disruption to existing manufacturing and installation and would be a simple transition for the market. In addition, the UK has the most extensive gas distribution network in the world, 85% of the UK homes are connected to the grid. The UK has expertise to transform the grid to take hydrogen and all initial studies have shown that there is no technical reason why 85% of homes couldn't be decarbonised using hydrogen, should a source of low-cost clean hydrogen become available.

	Low	Central	High
Demand (TWh)	**0.2**	**0.7**	**6.1**
Blue hydrogen (TWh)	**0.0**	**0.2**	**5.2**
Green hydrogen (TWh)	**0.2**	**0.5**	**0.9**
Carbon abatement (MtCO_2e)	**0.0**	**0.1**	**1.0**

Constraints and policy recommendations



[11] Navigant (2019) Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain

The priorities for the 2020s should be:

- Live hydrogen heating community trials to demonstrate safety case (2022-2025)
- A series of hydrogen pilots across a range of different conditions (2025-2030)
- Building up the stock of "hydrogen ready" boiler to reduce the cost of conversion
- Prepare consumers for conversion through consumer engagement

The Prime Minister's Ten Point Plan included a commitment for live community trials of 100% hydrogen heating with a view to scaling up deployment to a town with 10,000s of homes by 2030. The Hydrogen Taskforce welcomes this announcement. Upon completion of the two hydrogen trials under the H100 and H21, the Government should target a series of hydrogen pilots across hydrogen clusters. A hydrogen transition, by necessity, will also need to explore electrification options of some buildings, consumer interaction, building retrofit needs and logistics. Multiple pilots will allow industry to test the roll out in several different settings and with several different networks.

As recommended by the CCC, the Government should mandate that all appliances sold after 2025 should be "hydrogen ready". This will reduce the cost of conversion as homes with hydrogen ready boilers can be converted in under an hour by changing a small number of components. The average lifetime of a boiler is 12 years and as such it will be important to mandate "hydrogen ready" boilers as soon as possible.

Consumers must be engaged early on the conversion to hydrogen heating. The value of early engagement can be seen in the move to Battery Electric Vehicles where Government and industry engaged early before implementing a ban on new vehicles powered by ICEs.

Transport

Hydrogen will have a key role to play in transport decarbonisation, particularly in larger vehicles which are less suited to electrification and where consumers demand rapid refuelling and long ranges. Hydrogen is expected to be the dominant choice for HGVs and shipping and is also likely to see deployment in buses, rail, cars and vans, particularly those that travel large distances or have high utilisation. Hydrogen's use in aviation is also being explored. During the 2020s, the UK should prioritise:

- Scaling deployment of HGVs, buses, trains
- Development and demonstration of hydrogen in maritime and aviation applications

In addition, the UK should consider targeting passenger cars, where consumers are often less sensitive to economics and light commercial vehicles where sensitivity to payload may make hydrogen the more attractive option for many use cases.

HGVs

The CCC, in its review of HGV options, found that the most cost-effective option in terms of infrastructure costs is the hydrogen scenario, which has a cumulative CAPEX cost of £3.4bn in 2060.[12] This is compared to £21.3bn for the BEV scenario. Hydrogen HGVs are being trialled in the US, Korea and in Switzerland and are likely to become more widely available in the late 2020s.

[12] CCC (2019) Zero Emission HGV Infrastructure Requirements

Hydrogen with its high energy density is more suited to HGVs than batteries as it has minimal impact on the payload capacity of the vehicle.

Buses

Hydrogen is an attractive option for bus operators due to the high energy density of hydrogen that allows for longer distances and faster refuelling. It is likely that FC buses will reach cost parity with both electric and diesel in the early 2020s. Wrightbus have stated their ambition to produce 3000 buses in the UK by 2024, which will deliver economic benefit and jobs to the UK. Buses will provide much of the initial volume of hydrogen demand in the early 2020s.

Trains

Electrification is likely to be the solution for low range local train services. However, hydrogen is the most cost-effective solution for regional trains as it has fewer infrastructure requirements than overhead lines. Hydrogen trains have been developed by Alstom and are in operation in Germany. The company has announced a £1 million investment in developing hydrogen trains for the UK with Evershot Rail. Demonstration projects for trains in the UK are underway with Porterbrook and University of Birmingham.

Maritime

The most promising fuels for decarbonising shipping are based on blue or green hydrogen. Hydrogen could be used directly on ships in liquefied or compressed state or alternatively bound in liquid organic hydrogen carriers (LOHC). Hydrogen could also be used as the building block molecule for chemical conversion to fuels like ammonia or synthetic fuels (e-fuels). Conversion of hydrogen to zero carbon fuels with higher energy density and better storage and handling properties could reduce the shipping cost impact for fuel storage. It could also reduce the cost of infrastructure and distribution through the value chain. Batteries are a good solution for coastal shipping but are limited by shorter endurance. Systems based on zero carbon fuels in combination with internal combustion engines or fuels cells are required for ship segments requiring weeks or more of endurance between bunkering operations.

Both MAN and Wartsila are committed to conducting a development and test program for ammonia fueled internal combustion engines in 2021, aiming to deploy on ships with ammonia engines in 2024. For hydrogen, development work is also ongoing, enabling partial combustion of hydrogen in engines. Fuel cells for marine use are also being developed by several manufacturers.

According to the International Council on Clean Transportation, 99% of transpacific shipping could be powered by liquid hydrogen by replacing 5% of cargo space with clean fuel storage.[13] To date, there have been trials of smaller vessels including the world's first dual fuel hydrogen ferry which will be trialed in Scotland in 2021. Significant R&D and demonstration alongside international coordination will be required for the decarbonisation of shipping.

Aviation

Hydrogen can play a role in decarbonising aviation where energy density is particularly important. Advanced biofuels and synthetic fuels made from hydrogen are the two major decarbonisation pathways open to aviation. In addition, hydrogen fuel cells have been demonstrated on a small scale, ZeroAvia recently completed the first hydrogen fuel cell powered flight in a commercial grade

[13] ICCT (2020) Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?

aircraft at their R&D facility in Cranfield.[14] Like shipping, further R&D will be required to explore all options for decarbonising aviation.

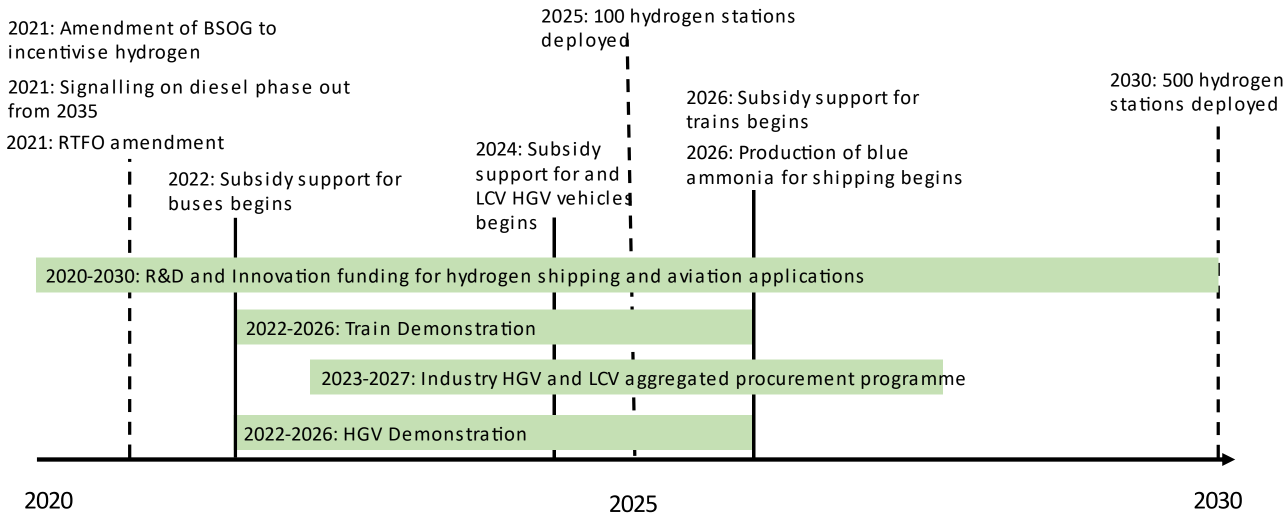
Cars and Light Commercial Vehicles

Hydrogen is an attractive option for consumers based on the experience that it offers. Hydrogen gives a greater range and faster refueling times whilst delivering on zero emissions. It offers a solution for consumers that don't have off street parking and home charging. For high utilisation users such as taxis or delivery vehicles, where waiting for charging has an impact on income, hydrogen is a more attractive option. Although battery electric vehicles will play a more central role in the passenger car sector, there is value in giving consumers choice based on their user requirements and feasibility of home charging. Car OEMs are investing heavily in FC development currently and there will undoubtably be a large global market. The UK should recognise this global trend and position the UK to capitalise on it.

The operational requirements of users may make hydrogen the preferred choice for many light commercial vehicle users.

	Low	Central	High
HGV deployment	**1,500**	**11,500**	**30,000**
Bus deployment	**500**	**6,000**	**10,000**
Train deployment	**175**	**600**	**2,000**
LDV deployment	**10,000**	**16,000**	**30,000**
Car deployment	**20,000**	**30,500**	**300,000**
HRS deployment	**155**	**500**	**1,756**
Demand (TWh)	**0.8**	**4.6**	**12.1**
Blue hydrogen (TWh)	**0.7**	**1.5**	**2.9**
Green hydrogen (TWh)	**0.1**	**3.1**	**9.2**
Carbon abatement ($MtCO_2e$)	**0.2**	**1.1**	**2.9**

Constraints and policy recommendations



[14] Green Car Congress (2020) ZeroAvia completes first hydrogen-electric passenger plane flight

HGVs, buses and trains

The availability of vehicles provides a constraint for transport demand. The UK is in a global race to encourage OEMs to bring their vehicles to the UK, rather than to other markets. OEMs will make decisions based on the domestic policy and market environment as well as the availability of refueling infrastructure.

Industry must develop an HGV aggregated procurement programme to deliver economies of scale on vehicle procurement in line with a commitment on infrastructure development. To initiate this programme, industry requires a signal from Government on decarbonisation of HGVs. This should come in the form of a ban on sales of new diesel HGVs from 2035. This will encourage users to act and encourage HGV OEMs to include the UK in the early target markets for vehicles.

The UK must also declare its ambition now to build a network of hydrogen refueling stations to support vehicles. It must put the policy frameworks in place to support the deployment of vehicles as well as the production of hydrogen.

Similarly, whilst UK OEMs have declared their ambition to produce large volumes of hydrogen buses to support the transition, the infrastructure for buses must be deployed, and a framework developed to support bus purchase whilst the technology delivers cost down. This could also be supported through amending the Bus Service Operators Grant (BSOG) to incentivise operators to move away from diesel to hydrogen.

For trains, the Government must commit to trials and develop a business model that enables manufacturers and operators to invest. R&D and demonstration activity must continue through the early 2020s to develop rail solutions that are appropriate for UK applications.

The Hydrogen Taskforce supports UK H2 Mobility's Hydrogen Strategy which calls for a subsidy to support vehicle purchase[15].

Shipping and Aviation

The UK should invest in R&D activity in shipping and aviation to develop solutions that can be deployed both domestically and exported. This should also include the production and use of hydrogen-derived fuels (e.g., green ammonia and kerosene) in applications where hydrogen itself cannot provide a net zero solution (e.g., long-range ships and planes).

Cars and LCVs

Like buses and HGVs, for cars and LCVs, the UK is in a global race to encourage OEMs to bring their vehicles to the UK, rather than to other markets. OEMs will make their decision based on the policy and market environment as well as the availability of refueling infrastructure. The UK should include hydrogen fuel cell cars and LCVs in any subsidy scheme for zero emission vehicles and ensure that benefit in kind legislation takes account of hydrogen correctly.

Distribution, transmission and blending

As the Prime Minister's Ten Point plan recognises, large-scale hydrogen development is likely to first take off in large industrial clusters with significant scale-up potential and where large prospective off-takers already exist to justify and de-risk investment in hydrogen supply, including critical infrastructure such as pipelines and storage. Early stage projects will require new dedicated

[15] UK H_2 Mobility (2020) Accelerate H_2

hydrogen infrastructure to transport hydrogen from the point of production to early stage end users. All hydrogen clusters will require investment in new infrastructure. This is essential to the improving the economics of using hydrogen as the use of trucks to transport hydrogen for many projects will be prohibitively expensive at scale. Early investment in this infrastructure will also encourage new production projects, stimulate innovation and stimulate interest amongst potential end users.

The UK must also capitalise on the existing gas infrastructure and leverage this asset to enable hydrogen to scale, alongside investment in new hydrogen infrastructure (e.g. trunk transmission pipelines and storage). Over 80 per cent of UK homes and businesses are connected to the gas network, giving the UK a world-leading level of gas network coverage. The regulatory framework has already been developed for the network. The gas network represents not only a high value asset that consumers have already paid for, but also a highly valuable industry that develops and maintains it. It is important that we leverage the gas network and the industry that supports it as the UK decarbonises.

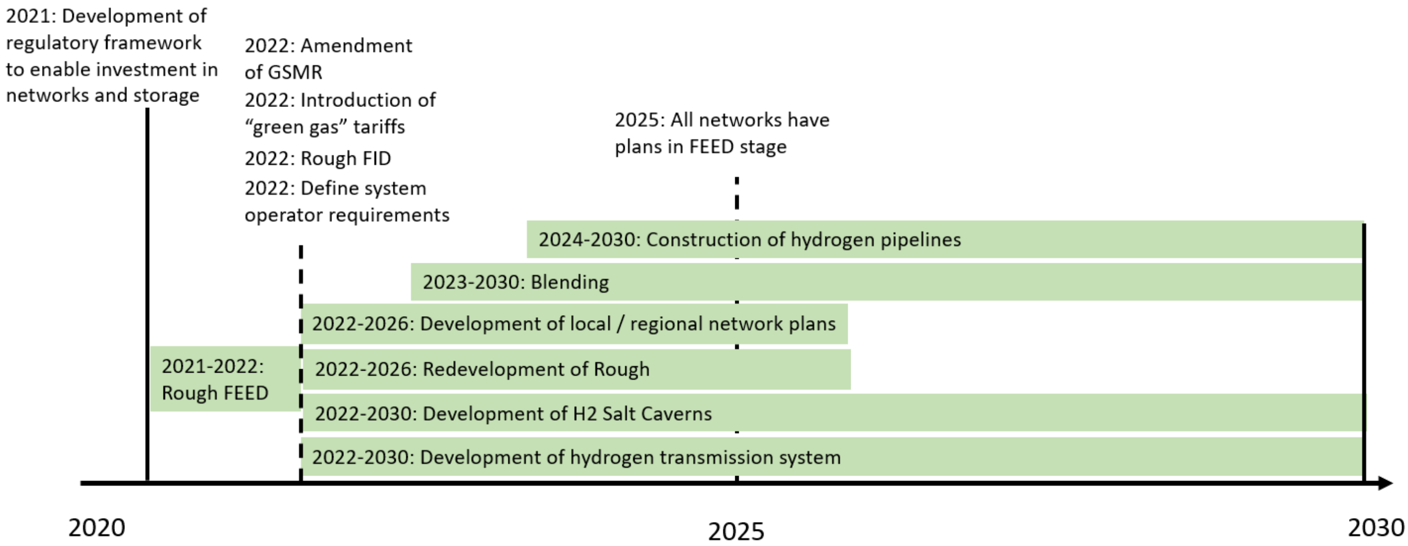
The use of hydrogen in the gas network delivers many energy system benefits. Hydrogen, through the use of electrolysers, can provide a link between the electricity system and the gas system allowing energy to be stored in times of surplus. The gas network itself is already one of the largest providers of energy storage and continued use through hydrogen will provide resilience to the wider system.

The gas network can provide an initial reliable market for hydrogen which will allow production to scale. Industrial users alone are not enough to deliver the required demand volume and the gas network offers a supporting high-volume offtake stream that will enable producers to deliver cost down. This approach is particularly important for blue hydrogen production which can only be delivered at scale and needs a large offtaker, but it would also enable green hydrogen to be injected into the grid. This would enable consumers to buy “green gas” in the same way that they currently buy green electricity.

The future of heat in the UK and, therefore, the future of the gas network has not yet been determined. However, blending is future proof and not dependent on the future of the gas network itself. If, once the case for hydrogen heat is proven, a decision is made to fully decarbonise large parts of the grid using hydrogen, then the existing blend provides a strong initial foundation to build upon. Alternatively, the UK could decide to transition away from gas towards electrification of heat and decommission much of the gas network. In this case, there will be a need for additional power generation to support electrification and blue hydrogen production can be diverted to gas turbines to provide this capacity.

	Low	Central	High
Demand (TWh)	**5.6**	**12.7**	**28.5**
Blue hydrogen (TWh)	**5.4**	**10.7**	**21.4**
Green hydrogen (TWh)	**0.3**	**2.0**	**7.1**
Carbon abatement (MtCO_2e)	**1.0**	**2.2**	**5.0**

Constraints and policy recommendations



There are few technological constraints to the introducing blending into the gas network and to starting to develop 100% hydrogen distribution networks. As such, there is little need for pilots for hydrogen distribution. However, a regulatory framework must be established that enables investment in networks. This could be delivered under a Regulated Asset Base (RAB) model.

Whilst some small changes are likely required to the existing gas regime to enable blending into the existing networks, a new regime will be required for full hydrogen networks or clusters. The existing gas regime which covers the large, interconnected UK network is probably not best suited for the inception and growth of initially isolated and discreet hydrogen networks. All networks and clusters must have a network plan in FEED stage by 2025. By 2030, a system operator and shipper must have been appointed to manage storage and settlement of these hydrogen networks, recognising that multiple SO's may be appointed to operate the multiple, and unconnected, hydrogen networks. To facilitate this a centrally administered "Hydrogen Code" or other such licensing regime will need to be established. Hydrogen meters are being developed under the Hy4Heat programme, but these will need to be in place in any homes that are converted.

Blending will help provide early markets to scale production and provide storage whilst salt caverns are being developed. The GSMR must be amended to enable blending. In order to stimulate demand for blending, a green gas programme could be introduced, similar to that of renewable electricity whereby consumers can purchase "green gas" through their energy provider. This system has been implemented for biomethane and could be built upon for hydrogen.

Another option may be to incentivise system operators to balance their networks with green gas. The costs of these balancing actions would be socialised across all users as per the existing arrangements.

Hydrogen Storage

Hydrogen storage, like dedicated hydrogen transmission and distribution pipes, is absolutely essential for the scaling of hydrogen in the UK in all scenarios. Government must include storage in its plans for hydrogen over the 2020s and enable investment in largescale storage capacity. Storage assets will be required for managing both seasonal and diurnal demand variation and for storing excess hydrogen that could be produced at times of high renewable electricity output. Hydrogen cannot be utilised at scale without storage. The UK has a number of existing assets that could be utilised for storing hydrogen.

- Rough, a former gas storage facility located off the East Coast of England. Due to be decommissioned in 2023, the facility supports around 1000 jobs in the North East. Its natural characteristics make it well suited to storing hydrogen and has the capacity to store up to 12.6TWh of hydrogen. This asset could be redeveloped at a cost of £650m.
- Aldbrough, an existing gas storage facility, with potential for expansion to incorporate hydrogen storage serving industrial clusters in the North-East.
- Underground cave-like structures have historically been used for storing gases and provide a well-established and relatively cheap way of storing hydrogen. It is estimated that 60 caverns may eventually be required if all storage was to be delivered through caverns. Costs per cavern would reduce from £45m to £25m as the technology is standardised.
- The gas network can provide storage, this will be particularly important in the short term when assets such as salt caverns and Rough have not been developed yet.

	Low	Central	High
Storage requirement (TWh)	**5.0**	**9.8**	**16.2**

Constraints and policy recommendations

In order for Rough to be redeveloped, a Cap and Floor regime should be introduced to enable investment. This should be developed in 2021 with a view to completing the FEED study from 2021-22 and reaching FID in 2022. The redevelopment build time would be 3-4 years, meaning that the asset would come online in 2025/26. It could be used flexibly to store natural gas, blends, or pure hydrogen depending on the progress that has been made in scaling production.

Hydrogen storage in salt caverns has not been demonstrated at scale in the UK. A demonstrator would require close to 100% public funding as the project would have negative EBITDA over the foreseeable future. A better alternative would be to develop a RAB model that would minimise upfront public funding while ensuring return for investors in what will be required assets moving forwards. The lead time for salt caverns is up to 7 years and as such, work must start by end of 2023 if construction/conversion is to be complete by the time hydrogen heating conversion takes place. In the meantime, storage can be provided by the gas network, provided that the GSMR allows for blending.

Jobs and skills

Hydrogen solutions have a critical role to play in the UK, not only in helping the nation meet its net zero target, but in creating the economic growth and jobs that will kickstart the green recovery. An effective Hydrogen Strategy is necessary to enable hydrogen to scale over the 2020s, thereby ensuring that the UK capitalises on the opportunity presented by hydrogen and builds a world-leading industry.

COVID-19 has caused significant economic upheaval across the country. The UK must identify those areas of the economy which have significant economic growth potential and can deliver long-term and sustainable increases in GVA and jobs. It will be important to consider regional factors and ensure that investment is targeted in those areas that have been hardest hit by the crisis.

Many major economies have identified hydrogen as a key part of both decarbonisation and economic recovery. As part of its stimulus package, Germany announced a €9bn investment in green hydrogen solutions, aiming to deploy 5GW by 2030. It is worth noting that this is the same capacity target as the UK but with significantly greater funding support committed. The Hydrogen Council estimates a future hydrogen and equipment market worth $2.5tn globally by 2050, supporting 30 million new jobs. Hydrogen offers the UK a pathway to deep, cost-effective decarbonisation while delivering economic growth and job creation. Hydrogen should therefore be at the heart of the Government's green recovery programme, ensuring that the UK builds back better and greener.

Hydrogen has the potential to drive economic growth and create jobs:

	Low	Central	High
GVA (£m)	**7,200**	**14,200**	**23,600**
Jobs	**29,700**	**58,500**	**96,800**

Constraints and policy recommendations

The UK needs to invest in training to ensure that the UK has a skilled workforce to effectively scale hydrogen solutions in the UK. Industry commitment options:

- Investment in training programmes to upskill/reskill workers for hydrogen related jobs
- Investment in STEM programmes for young people

Consumers

It is important that consumers are engaged and considered in any transition towards hydrogen solutions. This is particularly important in areas where consumers play a more active role such as heat and transport. Industry must take on responsibility for communicating the benefits of hydrogen and how the transition will take place as well as ensuring that vulnerable consumers are protected.

One of the challenges of decarbonisation is ensuring that it does not exacerbate inequality, benefiting those with higher incomes who are able to invest in low carbon technologies whilst leaving behind those on lower incomes. For example, a low-income household living in a mid-terrace with no off-street parking currently cannot access battery electric vehicles until on-street charging is widespread. Low income households or homes with space constraints cannot access heat pump technology.

Decarbonisation of industry, heat and transport will come at a cost. It is important that this cost does not fall on vulnerable customers. Hydrogen has the advantage of requiring little upfront investment on the part of the consumer. Hydrogen boilers will be of comparative cost as a natural gas boiler, FCEVs will reach cost parity with ICE vehicles. Users will not be required to have their own charging points but can refuel in the same way that they do currently.

Communication

Consumers are important stakeholders in the conversion to hydrogen and it is important that they are an integral part of the conversation. Industry must commit to communicating the benefits of hydrogen and how it will impact consumers now in order to prepare them for the transition. This may look different for different end users.

The Hydrogen Taskforce recommends that industry and Government come together to develop a public information programme for hydrogen.

Vulnerable consumers

One in ten homes in the UK are in fuel poverty[16], meaning that they have required fuel costs that are above average and were they to spend that amount they would be left with income below the poverty line. The average fuel poverty gap in the UK is £334, meaning that these households would need a fuel bill £334 lower to be lifted out of fuel poverty.

It is important that as part of any conversion process, vulnerable consumers are supported, and that the cost of conversion or the subsequent fuel costs do not push more households into fuel poverty.

ENDS

[16] BEIS (2020) Annual Fuel Poverty Statistics in England, 2020 (2018 data)

Appendix: Method note

Desk-based research was conducted to ascertain the different blue and green hydrogen projects across the UK. The purpose was to understand how much hydrogen is estimated to be produced from these projects by 2030 and how this demand is split across various end-use sectors (i.e. industry, transport, heat, power).

<u>Blue Hydrogen</u>

Since it is highly likely that each project will communicate that they can produce as much hydrogen as possible – for competition and funding purposes – we assumed that the total potential hydrogen demand from each project by 2030 represented an upper or 'high' scenario. To develop the 'low' and 'central' scenarios, we assigned a percentage to each sector to effectively determine the level of hydrogen demand that could be produced under each scenario. For example, for industry, the evidence-base suggests this sector is relatively more likely to use hydrogen demand before other end-use sectors. This is mainly because industry, particularly heavy industry, doesn't have many alternative decarbonisation options. On average, the percentage uptake under the low scenario ranged from 0% to 60%. For the central scenario, the average percentage uptake ranged from 4% to 75%. For the high scenario, we assumed that the projects were able to produce 100% of the demand they estimated. The percentages applied under each scenario were developed and informed by using a range of sources. This included utilising the existing evidence base (CCC, BEIS and industry reports) and feedback and intelligence from various Taskforce members. This is presented in the table below.

Blue H2 Sensitivity assumptions	**Low**	**Central**	**High**
Industry	60%	75%	100%
100% Heat	0%	4%	100%
Blending for domestic heat	25%	50%	100%
Power	25%	75%	100%
Transport	25%	50%	100%
Other	25%	50%	100%

For industry we have assumed that in the low scenario around 60% of overall blue industrial hydrogen demand is realised by 2030. This increases to 75% in the central scenario as more policy levers are unlocked (see main report for these policies for industry and for the other end-use sectors). In the 100% heat sector, 4% of the total potential is used for the central scenario to reflect the 0.7 TWh of demand from 5 trials of 10,000 homes on 100% hydrogen heating as this paper requests to be in place by 2030.

Across all these projects we assume advanced reforming (with CCS) is the preferred technology to produce the hydrogen. Specifically, these technologies could be a combination of Autothermal Reforming with CCS, Steam Methane Reforming (CCS) and Johnson Matthey's Low-Carbon Hydrogen technology. We assume the average load factor is ~95% and an average carbon capture rate of ~95% (this could increase to >97% as deployment increases).

<u>Green Hydrogen</u>

The Gigastack project provides estimates of hydrogen demand by end-use sector to 2030 and we use these values in their entirety. The main end-use sectors are industry, transport and blending. In addition to this, the Gigastack report suggests the UK could export significant amounts of green hydrogen to Europe and the Rest of the World in 2030. In discussion with Taskforce members, it was argued that given the time period in question (2020 to 2030), any hydrogen produced would be better suited to meet demand in end-use sectors. The classic 'chicken and egg' conundrum surfaces where we must ask: do we produce the hydrogen first to create the demand? Or do you create the demand and produce hydrogen to meet this? Our assessment is the former, and we assume that hydrogen is produced first, and this leads to the creation of demand (end-use) markets.

For H2H Saltend and Zero Carbon Humber (Green) projects, capacity was scaled back to 50% for the low scenario and 75% for the central scenario. As the Dolphyn and H100 Fife projects are comparably much smaller and more certain in size, no sensitivity was applied to create scenarios and the whole project was assumed to come to fruition in each scenario.

The report by the International Renewable Energy Agency (IRENA) is used to establish the average load factor of PEM electrolysis across the different scenarios. We assume average load factors of 40%, 60% and 80% in low, central and high scenarios respectively. This leads to an assessment that around 2GW of green hydrogen is needed by 2030 in the low scenario. This almost triples to over 5GW by 2030 in the central scenario.

Hydrogen demand from both blue and green is then summed across each end-use sector to provide an assessment of overall hydrogen demand across the three scenarios by 2030.

Appendix: Blue and Green hydrogen projects

The overall assessment of hydrogen demand has been developed using bottom-up analysis of the various blue and green hydrogen projects across the UK.

Blue hydrogen projects:

Projects	Location	Project leader	Other key stakeholders	Projected H2 demand / installed capacity
HyNet	Merseyside	Progressive Energy	SNC-Lavalin, Johnson Matthey, Essar Oil, Cadent, ENI	30.9 TWh / 3-4 GW
Zero Carbon Humber (Blue)	Humberside	Equinor	Drax, National Grid Ventures, SSE, Uniper	30.0 TWh / 3-4 GW
Humber Zero	Humberside	VPI	P66 and Uniper	8.3 TWh / 1 GW
Acorn	St. Fergus	Pale Blue Dot	Chrysaor, Shell, UK and Scotland Govt	12.6 TWh / 1-2 GW
Net Zero Teeside	Teesside	Oil and Gas Climate Initiative	BP, Shell, ENI, Total, Equinor	~20.0 TWh / 2-3 GW
Cavendish	Isle of Grain LNG terminal	Arup, National Grid Ventures, Shell, SSE, Uniper, Drax	National Grid, SGN, Cadent	~12.5 TWh / 1.5 GW
Zero Carbon South Wales	South Wales	National Grid, Arup and Wales & West Utility	Regen, Progressive Energy, Cardiff	2.0 TWh / 200 MW

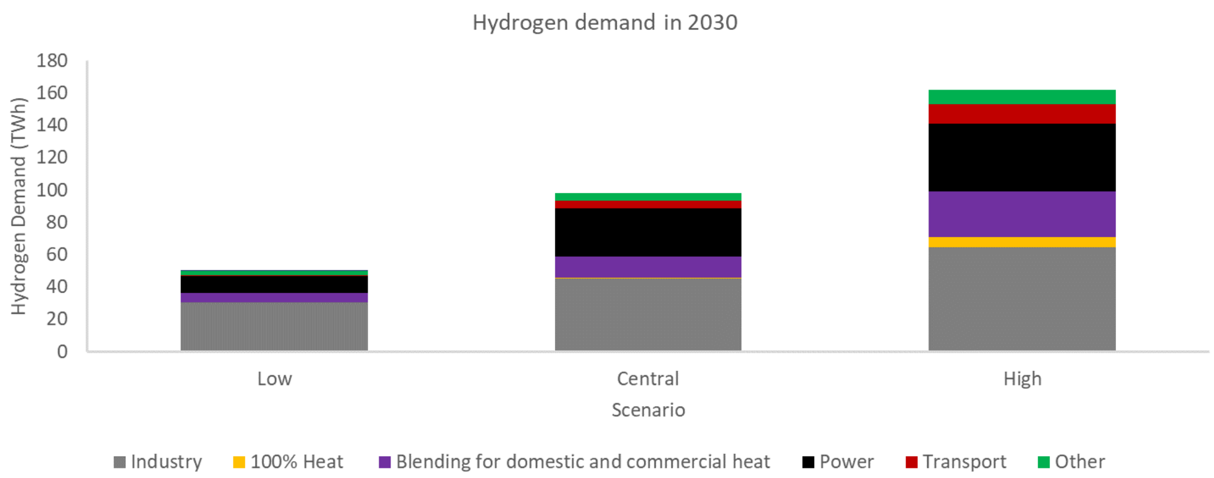
			University, Burns & McDonell	
HyPER	Cranfield University	GTI and Doosan Babcock	Cranfield University	0.01 TWh / 1.5 MW_{th}

Green Hydrogen Projects:

Projects	**Location**	**Project leader**	**Other key stakeholders**	**Projected H2 demand / installed capacity**
Gigastack	Humber (refinery)	ITM Power, Orsted and Phillips 66	Element Energy	27.0 TWh / 5.3 GW
Dolphyn	Aberdeen	Environmental Resources Management	National Grid Ventures	0.4 TWh / 100 MW
H2H Saltend	Humberside	Equinor		3.1 TWh / 600MW
Zero Carbon Humber (Green)	Humberside	Equinor	Drax, National Grid Ventures, SSE, Uniper	10.0 TWh / 2 GW
H100 Fife	Fife	SGN		0.02 TWh / 4 MW
Additional Green	N/A	ITM		5.1 TWh / 1 GW

Total hydrogen demand by type of hydrogen and end-use demand

	Blue Hydrogen - TWH			**Green Hydrogen - TWh**			**Total Hydrogen - TWh**		
	Low	**Central**	**High**	**Low**	**Central**	**High**	**Low**	**Central**	**High**
Industry	27.2	34.0	45.4	3.1	11.0	19.3	30.3	45.1	64.7
Blending	5.4	10.7	21.4	0.3	2.0	7.1	5.6	12.7	28.5
100% Heat	0.0	0.2	5.2	0.2	0.5	0.9	0.2	0.7	6.1
Power	8.8	26.5	35.4	1.6	3.6	6.2	10.4	30.1	41.6
Transport	0.7	1.5	2.9	0.1	3.1	9.2	0.8	4.6	12.1
Other	1.5	3.0	6.1	0.7	1.6	2.9	2.2	4.7	8.9
Total	**44**	**76**	**116**	**6**	**22**	**46**	**50**	**98**	**162**



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