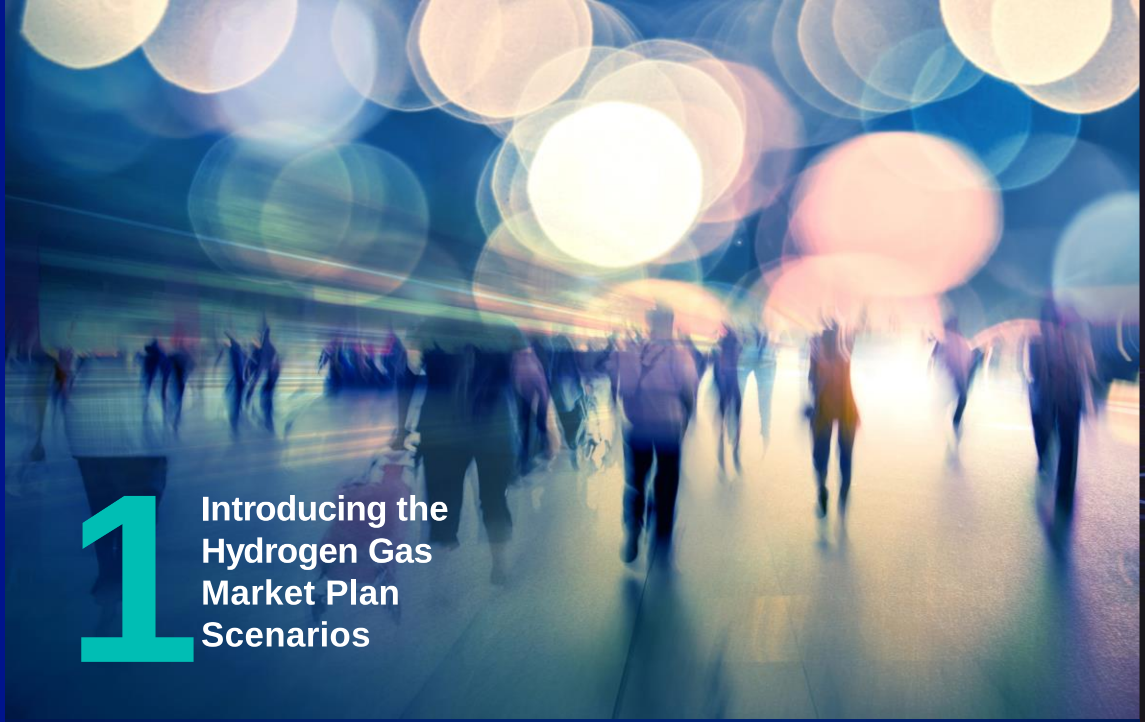
Gas Transmission

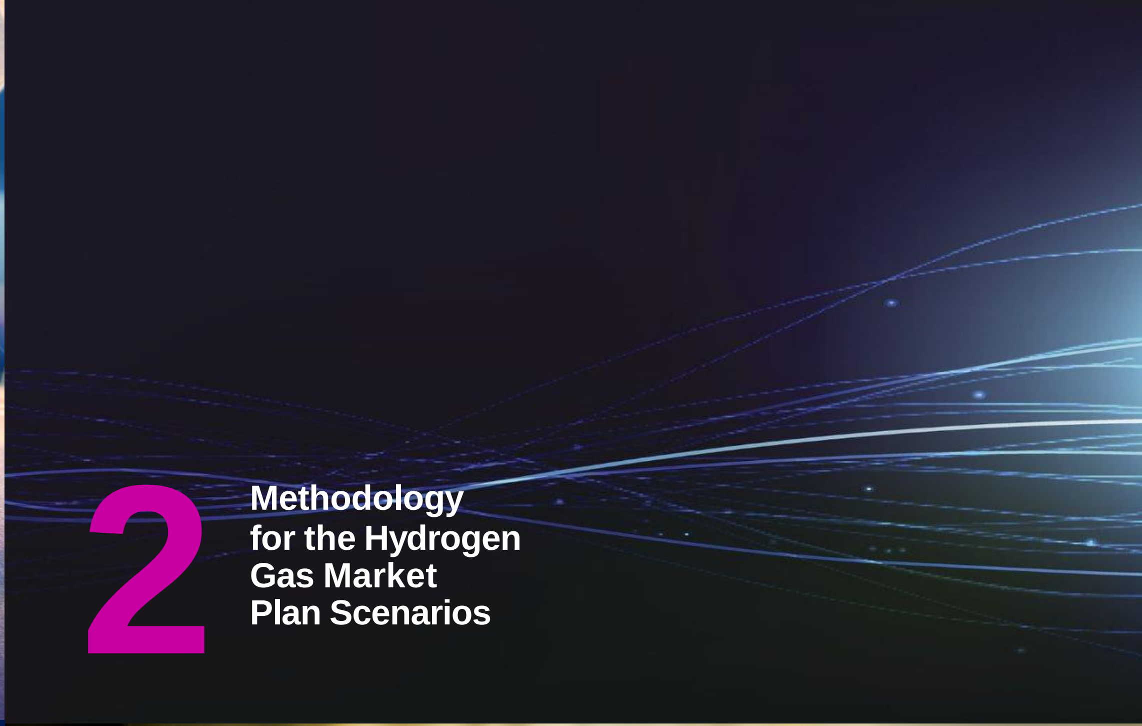
Hydrogen Gas Market Plan
Scenarios

nationalgrid

Hydrogen Gas Market Plan Scenarios
2021



1 Introducing the Hydrogen Gas Market Plan Scenarios



2 Methodology for the Hydrogen Gas Market Plan Scenarios

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1 Introducing the Hydrogen Gas Market Plan Scenarios

Introducing the Hydrogen Gas Market Plan Scenarios

We generated four hydrogen scenarios as the first stage of the Hydrogen Gas Market Plan (GMaP) project. We outlined potential hydrogen transition pathways to indicate to market participants the events or triggers that could lead to future market change.

National Grid Gas Transmission in collaboration with an expert cross-industry working group generated the hydrogen scenarios to demonstrate extreme examples of how Great Britain could transition to a future hydrogen economy. The scenarios explore the potential role of various hydrogen production and storage technologies, hydrogen transportation options and user conversion routes to full **(100%) hydrogen.**

We know there is no one winning technology or vector that could deliver our 2050 net zero carbon emissions target. However, because this project is focused on exploring how hydrogen could impact Great Britain's gas market, we have only focused on how hydrogen transition pathways could contribute towards delivering a net zero 2050.

No quantitative data was used in the generation of the following scenarios. Not focusing on quantitative data allowed for a broader assessment of the sequence of potential hydrogen developments. For example, the output of the following scenarios includes the locality of where hydrogen could emerge and how this could interact with existing gas networks or generate the need for new build networks. The scenarios also include how the emergence of hydrogen could influence which users convert to hydrogen first, and when hydrogen storage at scale could become critical.

Clearly, to generate hydrogen scenarios, there is much to consider in the envelope of possibilities that could make up our future hydrogen economy.

Introducing the Hydrogen Gas Market Plan Scenarios

We based the Hydrogen Gas Markets Plan scenarios on completed or ongoing hydrogen projects in Great Britain.

For example, we know that green hydrogen is already available at transport refuelling stations, and that in the short term (by 2030) it is looking promising that several industrial clusters will transition to using blue hydrogen.

We have reflected growing energy industry views that hydrogen will be deployed to users who are less suited to electrification, and could be used to provide flexibility the same way natural gas does today in supporting intermittent renewable electricity generation. We also recognized the growing momentum behind potential medium to longer term roles of hydrogen that could involve decarbonisation of domestic heat and the heavy goods transport sector.

While we do not know the boundaries of hydrogen deployment in the future of Great Britain's energy landscape, we have used the following scenarios to capture our current knowledge of completed and potential hydrogen development. Please section 4 for more information on the hydrogen projects we based the scenarios on.

Introducing the Hydrogen Gas Market Plan Scenarios

The purpose of generating the Hydrogen Gas Market Plan scenarios was to develop 100% hydrogen transition pathways to explore the events or triggers that could lead to market change.

A future hydrogen economy should adhere to the same core principles of today's natural gas market (i.e. competitive, liquid and liberalised). Therefore, the challenge will be the transition to this end state. We generated scenarios to show alternative pathways for hydrogen development, using timelines based on an earliest likely event basis, to signify the indicative tipping points into potential new styles of market arrangements.

Although the various stages of the following scenarios could all happen at the same time within different regions of Great Britain, they have been split into separate scenarios for the purpose of market impact analysis. Our aim was to outline lines of direction hydrogen markets could travel in, to allow market participants to plan for future market change depending on which hydrogen market triggers come to fruition.

Please continue to explore the methodology we used to generate the Hydrogen Gas Market Plan scenarios.

2 Methodology for the Hydrogen Gas Market Plan Scenarios

Hydrogen scenario generation methodology

1. Assumptions

Our assumptions drove how key variables played out through the different scenarios (i.e. when, where and how much)

Assumptions on…

- **Hydrogen production**
- **Hydrogen and Carbon storage**
- **Hydrogen transport**
- **Hydrogen market demand**

2. Key variables

We selected key variables that could make up a potential hydrogen economy including:

Scenario variables:

Hydrogen production technologies
- Methane reforming with carbon capture, usage and storage
- Electrolysis
- Biomass gasification

Hydrogen storage
Carbon storage
- Salt cavern
- Hydrogen carrier
- Pipe linepack
- Offshore gas fields

Method of Hydrogen transportation
- Transmission
- Distribution
- New build

Hydrogen consumers
- Transport
- Industry
- Power generation
- Heat

3. Potential time horizons

We explored how the selected key variables could interact in hydrogen transition pathways out to 2050:

National Grid Gas Transmission leveraged in-house scenario forecasting capabilities to generate scenarios that indicate transition pathways to 100% hydrogen by 2050.

These scenarios were reviewed, challenged and agreed by external market participants.

Assumptions and limitations to scope for the scenarios

01 Hydrogen production

(Assumption) The four hydrogen GMaP scenarios were established on the premise that Great Britain will comply with net zero carbon emissions by 2050, and that hydrogen will play a significant role in delivering this target.

Therefore, the hydrogen GMaP scenarios that include a supply of blue hydrogen production in 2050 are based on the assumption that negative emission technology will offset any fugitive emissions from blue hydrogen production.

(Limitations to scope) The hydrogen GMaP scenarios do not include volumes of hydrogen supply needed to meet hydrogen demand. However, multiple alternative industry reports have analysed potential required volumes of hydrogen in a decarbonised future, such as the Energy Networks Association Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain report and National Grid ESO's 2020 Future Energy Scenarios.

02 Hydrogen and Carbon storage

(Assumption) The following scenarios assume that sufficient storage capacity for both hydrogen and carbon emissions (due to hydrogen production) will be available.

Storage solutions for both hydrogen and carbon are assumed to include both the use of present mature technology as well as the development of new and/or currently low maturity technology to deliver storage at the scale needed for the scenarios.

03 Hydrogen transport methods

(Assumption) To provide the required envelope of realism, the hydrogen GMaP scenarios are broadly based on completed or ongoing hydrogen projects in Great Britain. This includes hydrogen projects that consider repurposing existing Transmission and Distribution pipelines, as well as new build pipelines in the transition to a hydrogen future.

While some consumers may not depend on network conversion to transition to hydrogen, the following scenarios have assumed the key role of networks is to support the scale up and further conversion of consumers to hydrogen.

04 Hydrogen pricing

(Limitations to scope) The price of hydrogen production, transportation, storage and consumer uptake was out of scope for the hydrogen GMaP scenarios.

However, information on hydrogen pricing can be found within alternative industry publications such as within the Energy Network Association's Hydrogen Cost to Consumer report.

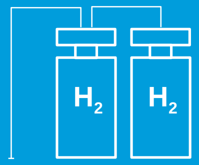
05 Range of uncertainty

(Limitations to scope): The following scenarios do contain, as expected, a range of uncertainty. Because we used the following scenarios to explore the events/triggers that could lead to market change and thus impact gas market participants, the following scenario timelines have been established on an earliest likely event basis to signify the indicative points tipping points into new styles of market.

We have not included any key dates for specific hydrogen projects, but rather used broader five year increments.

Key variables explored within the scenarios

In the journey to a net zero by 2050 target, we recognised there will be many variables of a hydrogen gas market value chain that will need to integrate and work well together. Below we have outlined the value chain variables explored within the hydrogen GMaP scenarios:



Upstream

Hydrogen production technologies

- Methane reformation with carbon capture usage and storage (CCUS)
- Biomass gasification with CCUS
- Electrolysis

Please note:
While there are many alternative low carbon hydrogen production technologies, we have selected higher maturity technology options for the purpose of this project.

Midstream

Gas network infrastructure

- Transmission network
- Distribution network
- Private gas network
- New build network

Storage infrastructure

- Salt cavern
- Hydrogen carrier
- Pipe linepack
- Offshore gas fields

Downstream

Hydrogen demand by sector

- Industrial and Commercial
- Power generation
- Transport
- Domestic heat

Upstream: Methane reformation hydrogen production

Within the hydrogen GMaP scenarios, blue hydrogen is defined as hydrogen produced through methane (natural gas) reformation with the additional process of carbon capture usage and storage (CCUS).

Reformation technology involves splitting methane (CH_4) into its components of Carbon and Hydrogen. In order to limit the carbon output, it is necessary to add the process of CCUS to capture and permanently store the carbon by-product. Likely locations for permanently storing carbon by-products include within emptying offshore oil and gas fields.

There are three primary methane reformation technologies at various technology readiness levels including:

- **Steam Methane Reformation (SMR)**
- **Auto Thermal Reformation (ATR)**
- **Low Carbon Hydrogen (LCH)**

Currently, Great Britain has no blue hydrogen production facilities, because no commercial CCUS facilities exist.

However, Figure 1 indicates the approximate locations of grey hydrogen (1) production facilities in Great Britain. Grey hydrogen is currently used predominantly for industrial processes.

In the following scenarios we only considered the deployment of ATR and/or LCH methane reformation technology, due to their design emphasis on limiting fugitive emissions (2).

It is key to note that current grey hydrogen production already has a commercial purpose, and requirements for blue hydrogen in a net zero future will likely need to be generated through additional production capabilities.

(1) Grey hydrogen technology produces hydrogen from fossil fuels, without the process of CCUS to capture the carbon by-product..
(2) Feasibility studies indicate that Low Carbon Hydrogen (LCH) technology has a high carbon capture rate at 97%.

Figure 1: Current grey hydrogen production facilities**

*Current UK hydrogen production methods
**Please note, the locations of grey hydrogen sites are approximate and limited to Great Britain, are not size representative or exhaustive.

Upstream: Electrolysis hydrogen production

Within the hydrogen GMaP scenarios, we defined green hydrogen as hydrogen produced through electrolysis technology, powered by renewable electricity.

Electrolysis technology uses electricity to split water (H_2O) into its components of Hydrogen and Oxygen. Electrolysis is sometimes referred to by the energy industry as Power-to-Gas (P2G).

There are currently three primary electrolysis technologies at various technology readiness levels including:

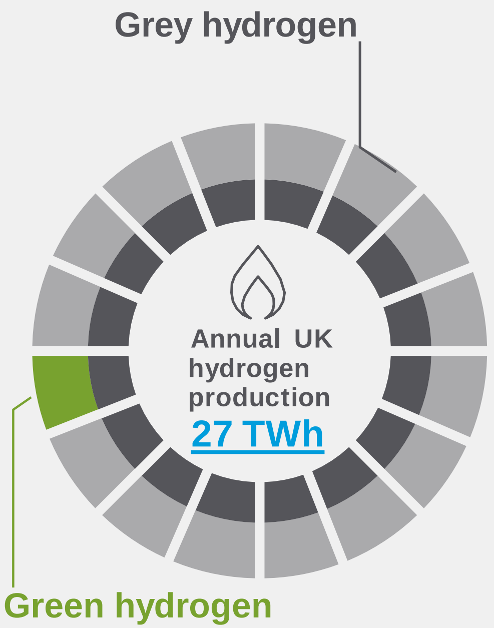
- **Proton Exchange Membrane (PEM)**
- **Alkaline electrolysis (ALK)**
- **Solid oxide electrolysis cells (SOEC).**

Figure 2 illustrates the approximate locations of green hydrogen production in Great Britain. The vast majority of these are currently meeting transport refuelling needs.

In the following scenarios, we do not specify which electrolysis technology makes up the proportion of green hydrogen production, although we do specify when green hydrogen is being produced solely from constrained renewable electricity or dedicated renewable electricity.

It is key to note that current green hydrogen production already has a commercial purpose, and requirements for green hydrogen in a net zero future will likely need to be generated through additional production capabilities.

Figure 2: Current green hydrogen production facilities**



*Current UK hydrogen production methods

**Please note, the locations of green hydrogen sites are approximate and limited to Great Britain, are not size representative or exhaustive.

Midstream: Hydrogen transportation

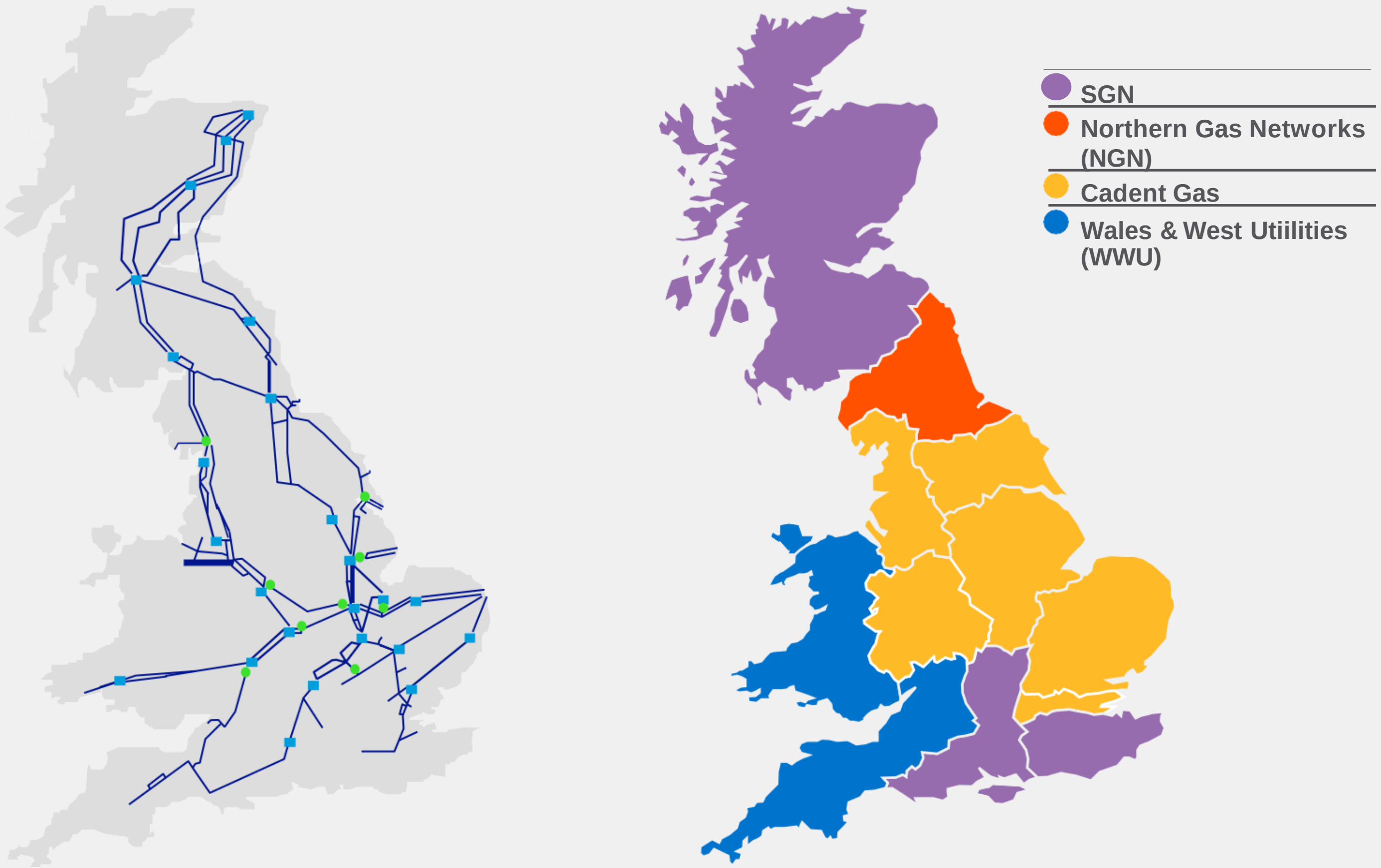
Capitalising on the existing gas networks could provide a least cost and least disruptive solution to decarbonise current and future gas network consumers.

Figure 3 illustrates the current gas Transmission (NTS) and Distribution (GDN) networks in Great Britain.

In the following scenarios, we recognised there could be a need for both repurposing the existing Distribution and Transmission networks, as well a need for new build networks to transport hydrogen throughout the transition to a hydrogen economy.

A need for new build hydrogen ready networks could be driven by many factors, including the current uncertainty surrounding converting all components of the current gas networks to 100% hydrogen.

Figure 3: National Transmission Network (NTS) and the Gas Distribution Networks (GNDs)



National Transmission Network (NTS)

Gas Distribution Networks (GDNs)

Downstream: Hydrogen demand

The hydrogen GMaP scenarios consider a wide variety of consumers on different 100% hydrogen transition pathways. We recognised that each consumer sector will have different opportunities and challenges to decarbonise, and the role of hydrogen in each sector has not yet been defined. With that uncertainty in mind, below we have illustrated the potential hydrogen demand sectors included within the scenarios:

Industrial and commercial

Across Great Britain there are several significant carbon emitting regions where large industrial and commercial consumers are clustered. These energy users are often referred to as hard to decarbonise due to their bulk high-grade heat requirements currently being met by fossil fuels. As it is unlikely these customers could decarbonise through electrification (because of their high-grade heat needs), these users are likely to transition to hydrogen.

Power generation

To support increasing intermittent renewable electricity generation, power derived from hydrogen (hydrogen that could be stored for long periods of time and used in times of electricity system stress) is likely to have an important role in the transition to a net zero future.

Transport

Large and heavy transport vehicles required to cover long distances, such as heavy goods vehicles, specific train routes, ships and light aircraft, are likely to transition to hydrogen. There is growing industry consensus that because it could be challenging for these users to use electric battery technology, due to their sheer size and weight, these forms of transport are likely to transition to hydrogen.

Domestic heat

As more than 80% of Great Britain's domestic properties are connected to the gas networks, repurposing all or parts of the existing gas network infrastructure to hydrogen could allow domestic gas users to decarbonise in a least cost and least disruptive way.

Bridging the gap

It's time to bridge the gap.

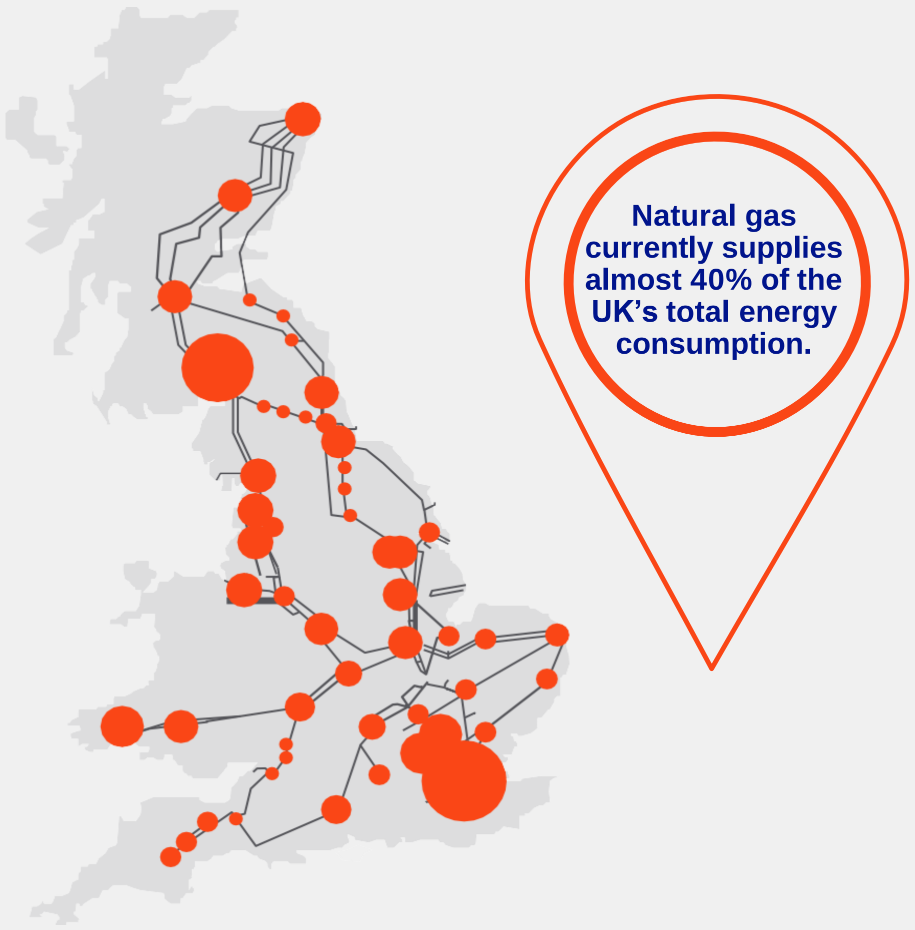
To meet our emission reduction targets, we will need to reduce our end-use of natural gas demand (Figure 4) to zero. Both blue, green and alternative hydrogen technologies could play a significant role in replacing our end-use of natural gas.

We have created the following scenarios as part of the hydrogen GMaP project to illustrate where hydrogen could be produced, how it could be produced, and by when through different hydrogen transition pathways to a net zero by 2050 target.

Figure 4 indicates data from the 2019 Gas Ten Year Statement (pre-pandemic) where the UK consumed ~876 TWh of natural gas.

Clearly, current levels of hydrogen production (27TWh) are no where near enough the levels that will likely be required on the journey to net zero.

Figure 4: 2019 aggregrated natural gas demand centres



3 Hydrogen Gas Market Plan Scenarios

Key market sensitivities explored within the scenarios:

As discussed, we developed the following scenarios to indicate to market participants the events or triggers that could lead to market change. Below we have indicated some of the key market sensitivities we explored:

Role of networks

- Networks will likely play a central role in connecting hydrogen supply to demand, improving security of supply through access to diverse supply sources and storage facilities and increasing supply resilience through intra-day storage (linepack) for consumers. The role of networks will also play a key role in determining whether hydrogen systems develop as isolated regions or become connected into a single system. Clearly, the role of networks will impact the evolution of hydrogen market frameworks. Some specific examples include:
  - The use of networks will influence whether the existing daily balancing regime is an appropriate basis for a hydrogen transition, or drive alternative balancing needs, such as city gate balancing (i.e. balancing different commodities at different pressure tiers).
  - If the existing gas networks are repurposed to hydrogen, market arrangements will need to consider the impacts of a growing hydrogen system and a shrinking natural gas system. This will include considering the security of supply market arrangements for consumers on both systems.

Regionalisation

- Depending on how hydrogen develops, based on factors such as the locality of where hydrogen is produced (i.e. clustered hydrogen production or distributed hydrogen production) and the role of networks, regional hydrogen systems could emerge. Regional isolated hydrogen systems could impact the evolution of hydrogen market frameworks, for example:
  - Regionalisation could drive the need to develop regional market arrangements, including potentially regionally priced hydrogen products.
  - On the other hand, without regionalisation (i.e. hydrogen systems are all connected), it is likely a single hydrogen market framework could be utilised, including for example hydrogen products bought and sold within a single market place.

Hydrogen product value mechanisms

- We largely included blue hydrogen as the bridge to green hydrogen in the following scenarios.
- We specified the emergence of different hydrogen technologies to explore their role in driving market change. For example:
  - If decarbonisation is the key driver for a hydrogen transition, it may be important for market participants to disclose hydrogen production technologies and any resulting carbon by-product. This could potentially drive the need for hydrogen product value mechanisms, such as the use of hydrogen Guarantees of Origin.

Whole system

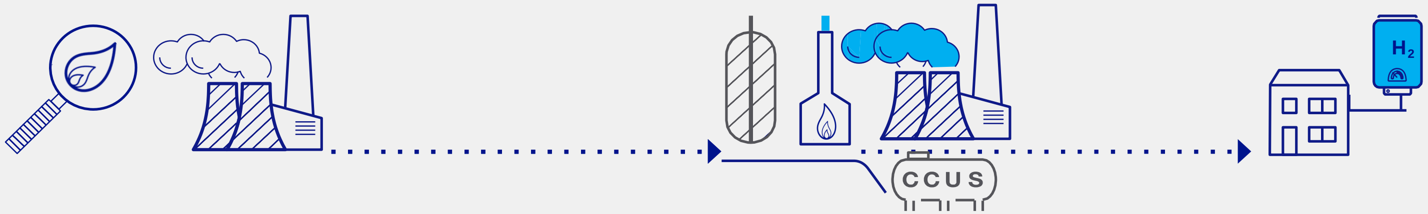
- A hydrogen transition will likely be highly interconnected with methane, biomethane and electricity systems. Interactions between gas and electricity systems and markets are likely to become much more closely interlinked in a decarbonised future, and whole system thinking will likely play an important role in influencing hydrogen market frameworks. For example:
  - A whole systems view of commercial framework changes could optimise low carbon hydrogen production across both the electricity and gas systems.
  - Market frameworks could be developed to optimise sector-coupling arrangements to benefit the decarbonisation of both electricity and gas systems.

Please continue to view the hydrogen GMaP scenarios and how we explored different hydrogen transition pathways.

Hydrogen GMaP Scenario 1

Initial focus on hydrogen converted: Industry

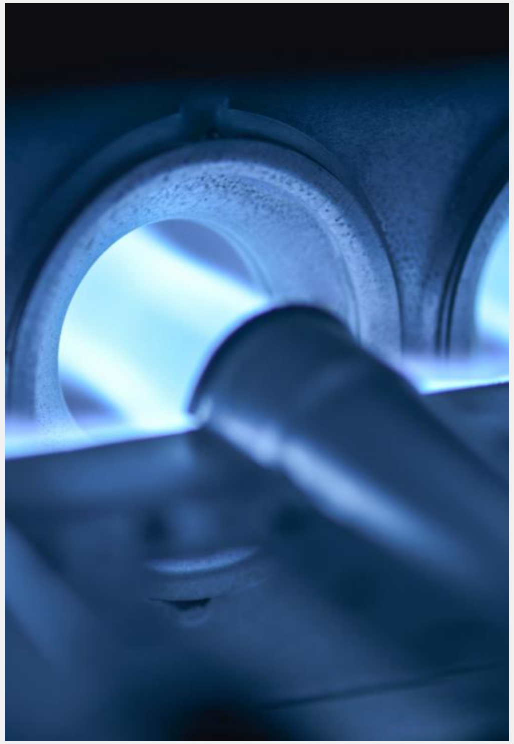
Hydrogen in industry



Development of 100% hydrogen gas burning equipment for industry

Industrial gas users within several industrial clusters transition to 100% blue hydrogen

Expanding industrial clusters enable Gas Distribution Networks to begin repurposing networks to hydrogen



2020 – 2025

Hydrogen trials continue at pace. Heavy emphasis from Original Equipment Manufacturers is on the development of hydrogen gas burning equipment for industrial and commercial users.

In addition, hydrogen trials continue to gather the safety and technical evidence needed to enable existing Transmission and Distribution networks to transport up to 100% hydrogen.

100% Hydrogen-ready boilers for domestic gas users are mandated by Government policy.

2025 – 2030

Blue hydrogen production facilities at coastal locations supply several (i.e. at least four) industrial clusters with 100% hydrogen. The hydrogen is transported within new build hydrogen-ready pipelines to industrial customers.

Industrial* customers act as the anchor demand for blue hydrogen facilities, although the hydrogen producers are able to blend up to 20% hydrogen by volume into the local Gas Distribution Networks (GDNs) and 2% hydrogen into the local National Transmission System (NTS).

In addition, sections of the NTS begin to be repurposed to 100% hydrogen to connect hydrogen clusters in close proximity.

100% Hydrogen-ready boilers begin to be rolled out to domestic consumers.

**Note: Initial industrial users supplied with 100% hydrogen also retain connection to natural gas network for supply resilience.*

2030 – 2035

Increasing blue hydrogen production at industrial cluster locations enables local GDNs to begin 100% hydrogen conversion of selected existing networks. The first customers to convert to 100% hydrogen on these GDN networks would be located in close proximity (i.e. ~ 20km) to the blue hydrogen facilities.

Conversion of domestic users triggers the need for medium scale hydrogen storage solutions (i.e. compressed hydrogen) to ensure resilience and security of supply.

Blue hydrogen also begins to be extracted from 100% hydrogen networks and purified to decarbonise heavy goods vehicles.

Hydrogen GMaP Scenario 1

Initial focus on hydrogen converted: Industry

All 100% hydrogen regions are connected by repurposed sections of the existing National Transmission System

2035 – 2040

All 100% hydrogen regions (i.e. expanding hydrogen industrial clusters) are connected by repurposed sections of the NTS.

Connecting 100% hydrogen regions together improves the security of supply for hydrogen converted customers, connects growing hydrogen regions to large scale hydrogen storage facilities (i.e. repurposed salt cavity storage) and enables additional hydrogen conversion for industrial customers and zonal GDN conversion.

Excess blue hydrogen supplies (in the form of ammonia) begin to be exported to the EU and global hydrogen market.

First net zero industrial cluster fuelled by negative emission hydrogen technology

2040 – 2045

Blue hydrogen production is capped, and all increasing hydrogen production is fuelled by zero or negative emission hydrogen production technology. For example, green hydrogen produced from curtailed renewable energy begins to connect in a distributed manner to the 100% hydrogen networks.

The first net zero industrial cluster in Great Britain is delivered through the supply of blue hydrogen offset by negative emission hydrogen production technology, including biomass gasification with carbon capture usage and storage (CCUS).

Accelerating integration of green hydrogen generated by offshore wind

2045 – 2050

Growing large-scale zero emission hydrogen production accelerates the transition from reliance on blue hydrogen to an increasing integration of zero or negative emission hydrogen production technology.

For example, large-scale green hydrogen production is fuelled by dedicated renewable electricity from offshore wind fleets, where hydrogen is generated offshore and transported by pipeline to coastal gas terminals.

Scenario 1 End State:

2045- 2050

Industrial clusters play a key role in anchoring an initial hydrogen economy. The coastal blue hydrogen clusters expand, and by 2040, all 100% hydrogen regions are connected.

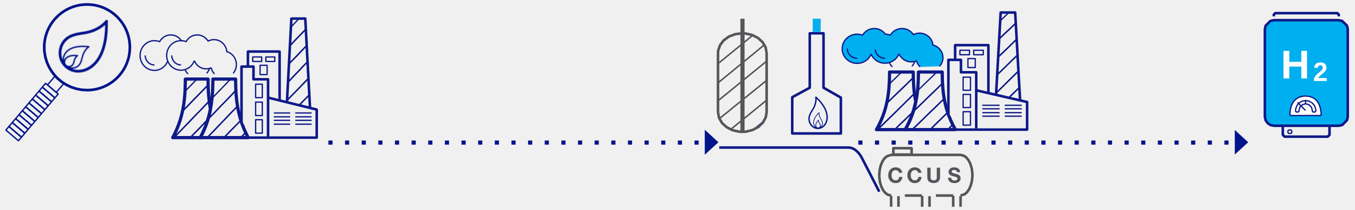
Hydrogen is transported across Great Britain through largely repurposed existing gas network (NTS and GDN) infrastructure.

Increasing integration of green hydrogen supply reduces reliance on blue hydrogen over time for the 100% hydrogen system in Great Britain.

Hydrogen GMaP Scenario 2

Initial focus on hydrogen converted: Power Generation

Hydrogen in power generation



Development of hydrogen gas burning equipment for power generation users

2020 – 2025

Hydrogen transition research and development continues at pace. Heavy emphasis from Original Equipment Manufacturers is on exploring the potential for converting existing power generation gas burning equipment to hydrogen.

100% Hydrogen-ready boilers for domestic gas users are mandated by Government policy.

Hydrogen blend (up to 20%) for power generation clusters and local networks

2025 – 2030

Blue hydrogen facilities sited at coastal hubs enable methane intensive power generation clusters to accept up to 20% hydrogen.

The coastal blue hydrogen production facilities are also able to blend up to 20% hydrogen by volume into both the existing local Gas Distribution Networks (GDNs) and National Transmission System (NTS).

De-blending technology is used to protect customers (i.e. industrial and commercial) on the hydrogen blended networks who are not yet able to accept hydrogen.

100% Hydrogen-ready boilers begin to be rolled out to domestic gas users.

Expanding power generation clusters enable local networks to begin repurposing to 100% hydrogen

2030 – 2035

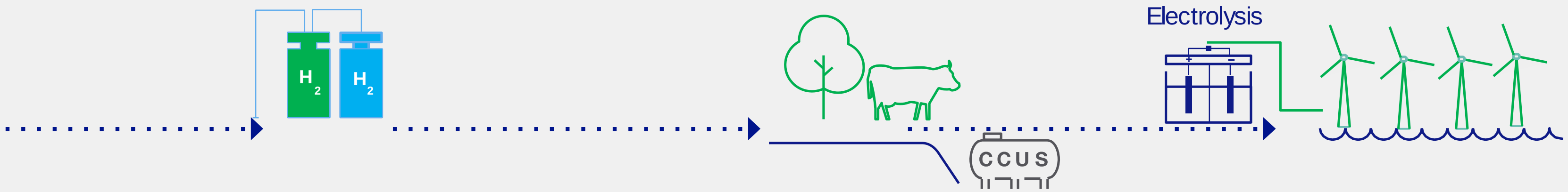
When the required technical evidence is achieved, power generation clusters begin accepting up to 100% hydrogen from the growing blue hydrogen coastal facilities.

In addition, repurposed sections of the NTS, or if required, new build hydrogen-ready pipelines, transport 100% blue hydrogen to in-land power generation and industrial users within a relatively short (~70km) distance. Newly connected high-demand hydrogen consumers would previously have had lack of access to blue hydrogen and/or carbon capture usage and storage technology.

The increasing build out of blue hydrogen production also enables GDNs to transition selected customers (within a ~20km radius) to 100% hydrogen. To ensure security of supply, medium scale hydrogen storage solutions (i.e. Liquid Organic Hydrogen Carrier) is critical.

Hydrogen GMaP Scenario 2

Initial focus on hydrogen converted: Power Generation



Blue hydrogen supply is capped, driving zero emission hydrogen production

2035 – 2040

Blue hydrogen production is capped. Expanding hydrogen production for the isolated hydrogen regions (i.e. expanding from power generation clusters) is fuelled only by zero emission hydrogen technology, including green hydrogen produced from curtailed onshore wind and solar.

Large scale storage solutions are in place (i.e. ammonia) to ensure hydrogen supply resilience from potentially intermittent green hydrogen production.

Hydrogen is also extracted from 100% hydrogen gas networks and purified to enable large transport vehicles to decarbonise. Hydrogen refuelling stations meet the needs of hydrogen trains, ships and heavy goods vehicles.

Accelerating integration of zero and negative emission hydrogen supply

2040 – 2045

Expanding hydrogen production for the isolated hydrogen regions includes zero and negative emission hydrogen production technology, including the integration of biomass gasification hydrogen production with CCUS.

In areas where Gas Distribution Networks (GDNs) have limited capacity, GDNs are able to reverse flow hydrogen supply onto NTS 100% hydrogen pipelines.

Expansion of 100% hydrogen networks driven by large scale green hydrogen supply from offshore wind

2045 – 2050

Increasing zero emission hydrogen is supplied to the hydrogen regions though green hydrogen. The green hydrogen is largely generated from curtailed renewable electricity from offshore wind.

Increasing green hydrogen supply enables existing gas networks (NTS and GDN) to continue zonal conversion programmes to 100% hydrogen within hydrogen regions, although these regions are not connected by 2050.

Scenario 2 End State:

2045- 2050

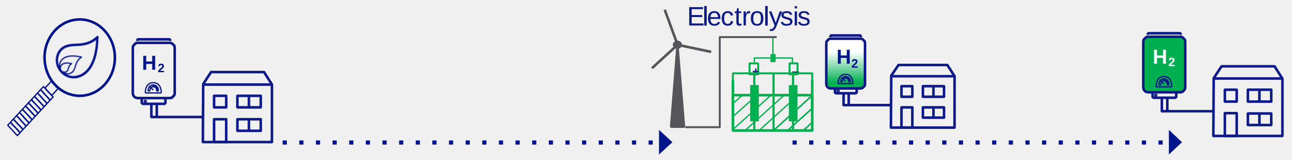
Several regional coastal blue hydrogen hubs emerge to decarbonise power generation clusters. Existing gas networks (NTS and GDN) are able to use excess blue hydrogen production for zonal 100% hydrogen conversion to connect more hydrogen consumers in close proximity.

Large scale green hydrogen supply emerges to aid regional 100% hydrogen networks expand and reduce emissions for the (isolated) hydrogen regions over time.

Hydrogen GMaP Scenario 3

Initial focus on hydrogen converted: Domestic heat

Hydrogen in heating



Hydrogen trials gather evidence to repurpose Gas Distribution Networks (GDNs) to 100% hydrogen

2020 – 2025

Trials continue at pace to demonstrate existing Gas Distribution Network (GDN) as well as gas burning equipment for domestic customers readiness and suitability for hydrogen conversion (including hydrogen blending).

Small-scale green hydrogen production is used to convert new build gas networks and off-grid consumers to 100% hydrogen. For example, green hydrogen is used to convert a new build GDN to 100% hydrogen by 2023, with the aim to gather the required evidence for a wider rollout of 100% hydrogen on the GDNs.

100% Hydrogen-ready boilers are mandated by Government policy and begin to be rolled out.

Hydrogen blending (up to 20%) begins within existing GDNs

2025 – 2030

Hydrogen blending, up to 20% by volume, is permitted within existing GDNs. The green hydrogen for network blending is supplied by electrolysis technology powered by curtailed renewable electricity from onshore wind and solar. Green hydrogen supplies connect in a distributed manner across the GDNs.

Distributed blue hydrogen production emerges solely to decarbonise industrial or power generation users connected to either the GDNs or National Transmission System (NTS), who would otherwise be challenging to decarbonise. For blue hydrogen production not located by the coast, the carbon by-product is transported via rail or road tanker to offshore permanent storage.

Zonal conversion program begins to repurpose existing GDNs to 100% hydrogen

2030 – 2035

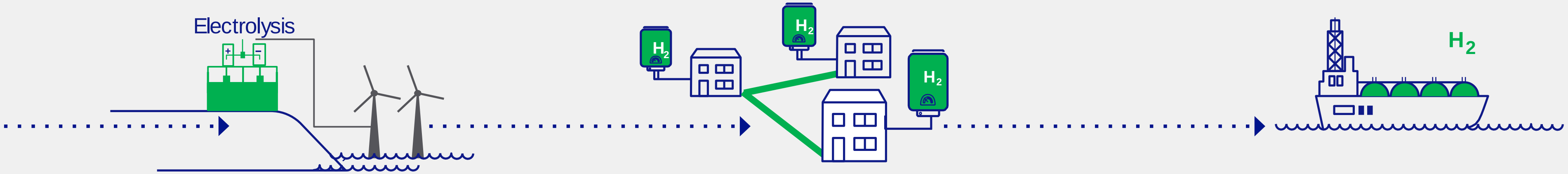
Zero emission hydrogen production scales up, driven by the development of hydrogen production from technologies such as SOEC [Solid Oxide Electrolysis Cells] connected to nuclear reactors.

The expanding zero emission hydrogen production enables existing GDNs to begin repurposing networks to 100% hydrogen in zonal conversion programmes. Large-scale hydrogen storage solutions (i.e. repurposed salt caverns) are critical to ensure inter-seasonal security of supply for hydrogen users.

Hydrogen begins to be extracted from hydrogen networks and purified for use at hydrogen refuelling stations for cars, buses and select rail routes.

Hydrogen GMaP Scenario 3

Initial focus on hydrogen converted: Domestic heat



Large scale green hydrogen production accelerates GDN zonal conversion to 100% hydrogen

2035 – 2040

Green hydrogen production ramps up, fuelled by dedicated renewable electricity (i.e. powered by offshore wind fleets) and green hydrogen imports from the global market.

Growing green hydrogen production enables increasing GDN networks to be repurposed to 100% hydrogen.

A new build hydrogen transmission network connects nearby GDN hydrogen regions

2040 – 2045

A new build hydrogen transmission network connects 100% hydrogen GDN regions together that are in close proximity to improve regional security of supply. Hydrogen regions would only be connected based on the return on investment to security of supply.

The NTS only operates a natural gas and biomethane backbone for industrial and commercial clusters relying on blue hydrogen. Some of these clusters also deploy pyrolysis technology (pyrolysis of natural gas to generate hydrogen and a solid carbon by-product) to decarbonise.

Excess green hydrogen supplies are exported to the global market

2045 – 2050

Great Britain is able to offer green hydrogen surplus production as an export product for global trade, by shipping hydrogen (i.e. in the form of ammonia) produced from oversized green hydrogen facilities.

Scenario 3 End State:

2045- 2050

Hydrogen development in Great Britain focuses on place-based solutions. Several existing GDNs convert all or parts of their networks to 100% green hydrogen.

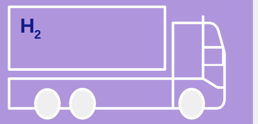
Some, but not all, 100% hydrogen regions are connected by a new build hydrogen transmission network to increase regional supply resilience.

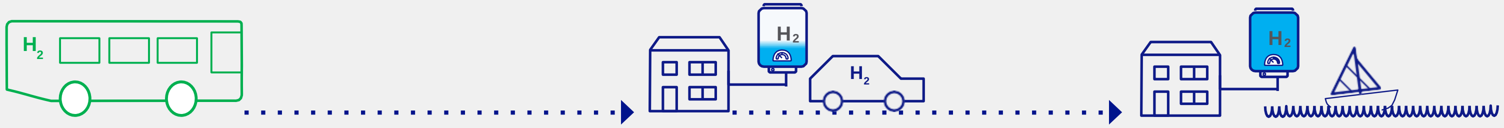
The existing NTS retains a natural gas and biomethane backbone to enable customers (that are challenging to electrify) generate blue hydrogen or deploy pyrolysis technology to decarbonise.

Hydrogen GMaP Scenario 4

Initial focus on hydrogen converted: Transport

Hydrogen in transport

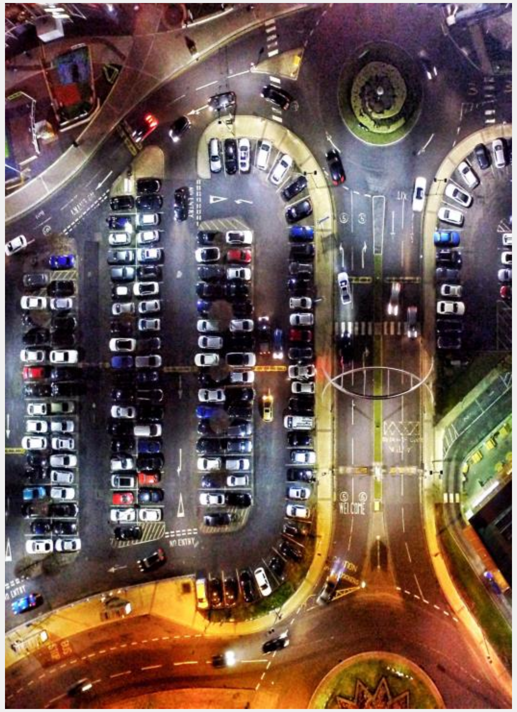




Small scale off-grid green hydrogen production is driven by transport demand

Initial blue hydrogen connections to the NTS enables a 20% hydrogen blend

The NTS begins to be repurposed to 100% hydrogen to supply hydrogen ready demand centres



2020 – 2025

Green hydrogen generated from curtailed renewables emerges across Great Britain to meet public transport refuelling needs within urban areas, and for small-scale industry fuel-switching (i.e. off-grid whisky producers fuel-switching to hydrogen).

Hydrogen production is largely not connected to the gas networks and emerges in a distributed manner across Great Britain, although trials continue at pace to demonstrate the safety and technical feasibility of converting the existing gas networks and gas network customers to 100% hydrogen.

100% Hydrogen-ready boilers for domestic gas users are mandated by Government policy and begin to be rolled out.

2025 – 2030

Blue hydrogen production facilities begin to connect to the existing National Transmission System (NTS) at coastal locations. At these locations hydrogen is blended at increasing levels (up to 20%) into the NTS (this in turn flows through to the Gas Distribution Networks (GDNs)).

De-blending technology is used to protect customers (i.e. industrial and commercial) on the hydrogen blended networks who are not yet able to accept hydrogen.

De-blending technology is also used to extract high purity hydrogen from the gas networks to support meeting demand from a sophisticated network of transport refuelling stations.

2030 – 2035

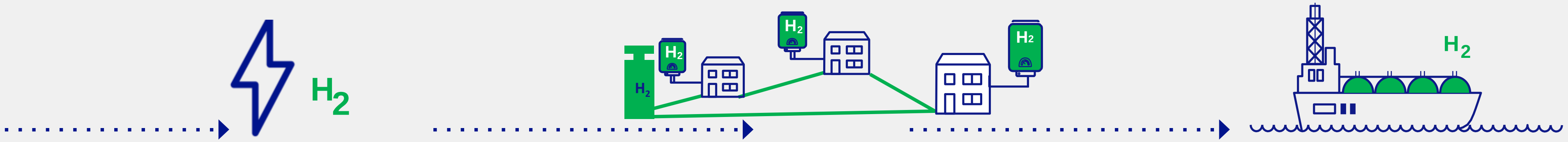
A coordinated increase of blue hydrogen production at coastal sites enables the NTS to begin repurposing selected pipelines to 100% hydrogen to enable select demand centres (i.e. industrial clusters or hydrogen ready GDNs) to transition to 100% hydrogen.

Large storage solutions are in place (i.e. ammonia or geological facilities) to ensure hydrogen inter-seasonal supply resilience.

Blue hydrogen is also extracted from the networks and purified to decarbonise maritime transport.

Hydrogen GMaP Scenario 4

Initial focus on hydrogen converted: Transport



Green hydrogen generated from the decarbonised electricity grid enables gas network conversion to 100% hydrogen	Large scale green hydrogen production enables increasing gas network zonal conversion to 100% hydrogen	Surplus green hydrogen supplies are traded on the global market	Scenario 4 End State:

2035 – 2040

Blue hydrogen production is capped, and zero emission hydrogen production technology increases in scale across Great Britain.

Increasing green hydrogen is produced from the decarbonised electricity networks. Electrolysers emerge in regions where hydrogen production can take advantage of available capacity in hydrogen networks, and prevent constraints in the electricity networks due to high renewable loads. The green hydrogen connects into Great Britain's gas networks (NTS and GDN) to support an increasing hydrogen rollout.

Hydrogen is also extracted from the gas networks and purified to fuel hydrogen converted rail routes as well as light aircraft hydrogen consumers.

2040 – 2045

Large-scale green hydrogen production from dedicated renewable electricity (i.e. from offshore wind fleets) begins to connect to the NTS at multiple coastal gas terminal locations. Green hydrogen imports also connect to the NTS through gas interconnectors.

Increasing green hydrogen supplies into the NTS supports an increasing rollout of 100% hydrogen onto repurposed gas pipelines. Green hydrogen integration rapidly reduces reliance on blue hydrogen production.

2045 – 2050

Great Britain begins to export (i.e. by shipping hydrogen stored as ammonia or Liquid Organic Hydrogen Carriers) excess hydrogen supplies from oversized green hydrogen facilities.

2045- 2050

Hydrogen development begins with blue hydrogen technology, followed by a coordinated ramp up of green hydrogen technology.

The existing gas networks are repurposed to hydrogen, following a coordinated hydrogen flow through the NTS to the GDNs.

Hydrogen for transport plays a key role in the development and movement of hydrogen supplies across Great Britain and globally.

The key variables we explored in the scenarios:

As indicated in the figure below, the Hydrogen Gas Market Plan scenarios explored many different combinations of the key variables that could make up a future hydrogen economy within Great Britain:

Upstream: Emergence of hydrogen production		Centralised blue H2 (i.e. Few, large scale facilities)	Distributed blue H2 (i.e. several small scale facilities)	Centralised green H2 (i.e. dedicated renewables)	Distributed green H2 (i.e. curtailed renewables)
	2025			Scenario 3, 4	Scenario 3, 4
	2030	Scenario 1, 2, 3, 4	Scenario 3		
	2035				
	2040				Scenario 2
	2045			Scenario 1, 2	Scenario 1
	2050				

Midstream: Emergence of hydrogen transport		NTS: 0% H2 GDN: 100% H2	NTS: H2 blend GDN: H2 blend	New build 100% H2 NTS GDN: 100% H2	NTS: 100% H2 GDN: 100% H2
	2025	Scenario 3			
	2030		Scenario 1, 2, 4		
	2035			Scenario 2	Scenario 1, 2, 4
	2040				
	2045			Scenario 3	
	2050				

Downstream: User transition to 100% hydrogen		Industry 100% H2	Transport 100% H2	Power 100% H2	Heat 100% H2
	2025		Scenario 4		Scenario 3
	2030	Scenario 1, 3		Scenario 3	
	2035	Scenario 2, 4	Scenario 1	Scenario 1, 2, 4	Scenario 1, 2, 4
	2040		Scenario 2, 3		
	2045				
	2050				

4 Supporting information for the Hydrogen Gas Market Plan Scenarios

Purpose of supporting information

The following slides provide an overview of key hydrogen projects across Great Britain and their approximate locations (1). We used these hydrogen projects as the basis to build out the hydrogen GMaP scenarios.

To provide an overview of Great Britain's completed or ongoing hydrogen projects, we split Great Britain into six regions including: Scotland, North East, North West, Midlands and East Anglia, South England and Wales. Although the included hydrogen projects are by no means exhaustive, they provide a helpful snapshot of the rapid pace of hydrogen development.

In addition, we used the key to the right to identify the primary **(2)** potential market role of each hydrogen project.

(1) Please note in some cases we used the lead company's head office for hydrogen projects that did not have clear locations.

(2) We recognise that hydrogen projects will likely play multiple market roles, however for the purpose of this exercise we focused on what we believe is the primary market role.

Key to the market role of the following hydrogen projects:

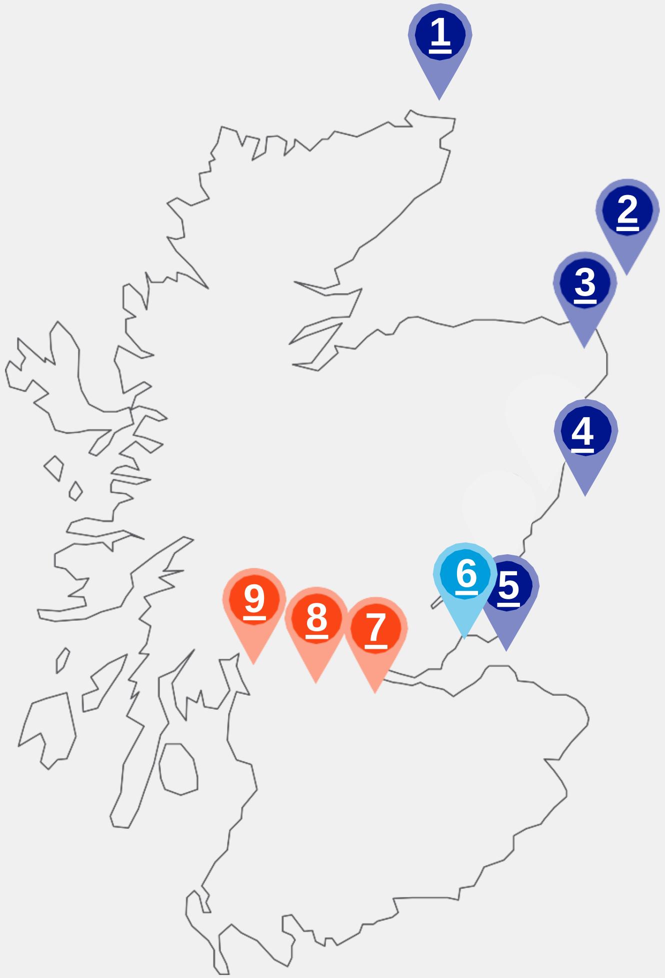
- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

Hydrogen in Scotland

Scotland aims to become a leading hydrogen nation. In December 2020 a Hydrogen Policy Statement released by Scottish Government included a target to deliver 5GW of hydrogen by 2030, a target previously set by the Prime Minister for the whole of the United Kingdom. Scotland's Hydrogen Policy Statement includes £100 million for investment in hydrogen technology and processes, aiming to take full advantage of local existing gas infrastructure and natural resources.

As seen in the figure*, Scotland has a wide range of hydrogen projects. From a market perspective, these projects focus largely on hydrogen production (both blue and green) that will generate a market push force to stimulate hydrogen demand. It will come as no surprise that Scotland is aiming to generate much more hydrogen than it could consume, with ambitions to participate in a future UK, EU and potentially global hydrogen market.

*Please note this figure is not exhaustive.



Key to the following hydrogen projects:

- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

Click the pins on the map to find out more information on the hydrogen projects.

Project key

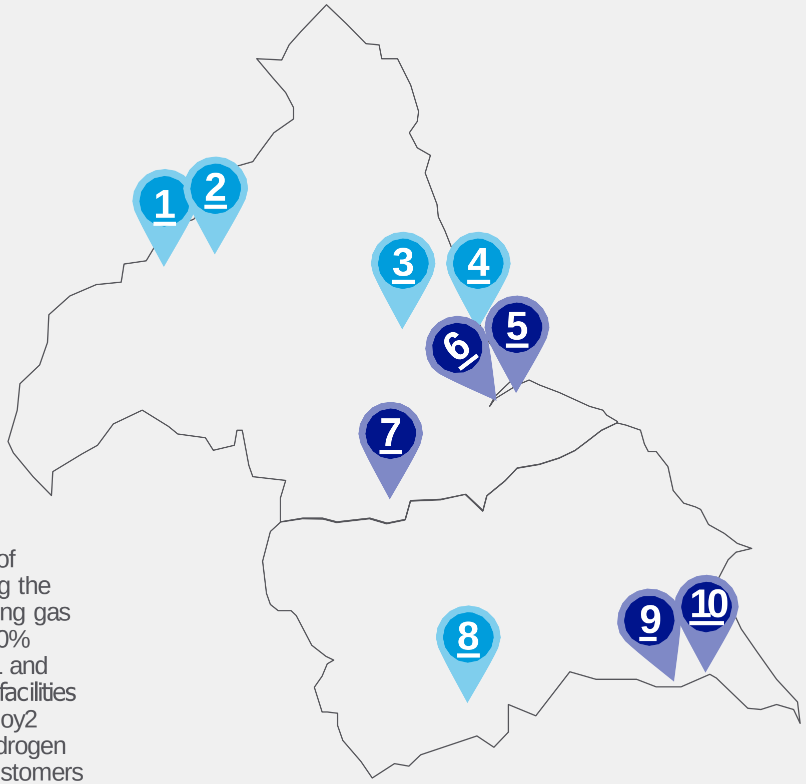
1. European Marine Energy Centre
2. Acorn project
3. Aberdeen Vision
4. Dolphyn project
5. Project Methiltoune
6. H100
7. HyScale
8. Scotland's Net Zero Infrastructure
9. Scotland's Net Zero Roadmap

Hydrogen in the North East

The North East of England currently produces 50% of the UK's hydrogen production (currently grey hydrogen) and maintains large hydrogen storage facilities. This clear opportunity, coupled with the fact the North East is home to the biggest carbon emitting industrial cluster in the UK (the Humber), means the region is rapidly developing a clean hydrogen agenda. For example, the Zero Carbon Humber partnership aims to reach a final investment decision by 2023 to deliver large scale blue hydrogen production by 2026.

From a market perspective, we note that the majority of hydrogen projects in the North East focus on gathering the safety and technical evidence needed to enable existing gas networks (Transmission and Distribution) to supply 100% hydrogen to consumers. This is evidenced by the H21 and FutureGrid programmes that have or will build testing facilities to flow up to 100% hydrogen. In addition, the HyDeploy2 project at Winlaton will be the first demonstration of hydrogen blending on a public gas network. Although not all customers converted to hydrogen will need hydrogen pipelines, from a markets perspective a clear role of the gas networks is to connect hydrogen supplies with hydrogen demand centres and thus generate increasing hydrogen demand.

*Please note this figure is not exhaustive.



Key to the following hydrogen projects:

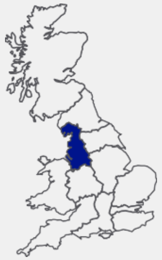
- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

Click the pins on the map to find out more information on the hydrogen projects.

North East key

1. FutureGrid
2. H21 NIC phase 1 and phase 2
3. HyDeploy 2 Winlaton
4. Gateshead hydrogen show homes
5. Net Zero Teesside
6. Tees valley net zero industrial cluster plan
7. Gigstack
8. H21 suite of projects
9. Zero Carbon Humber
10. Humber net zero industrial cluster plan

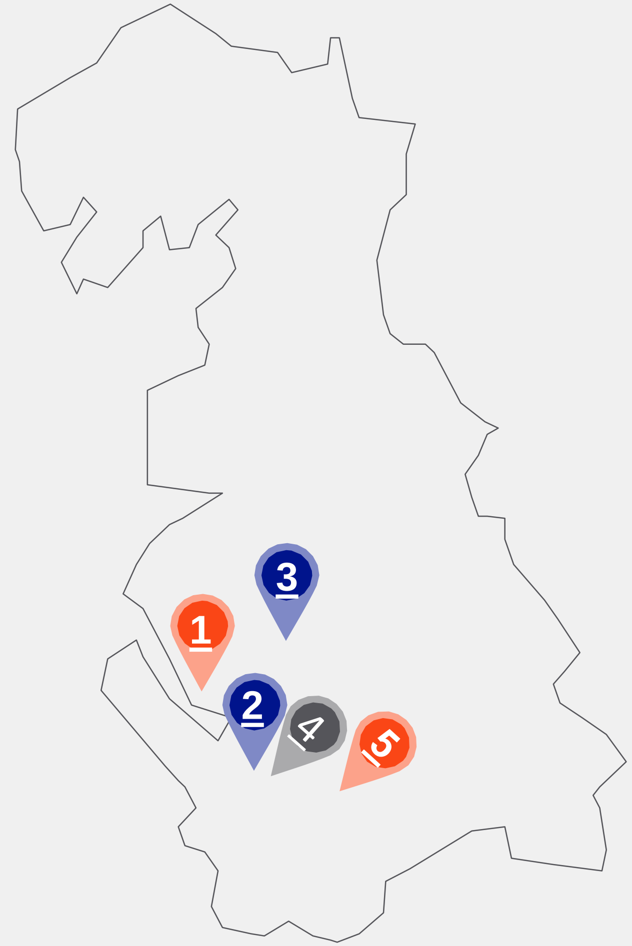
Hydrogen in the North West



The North West region has a combination of high emitting energy users (including some of the UK's largest manufacturers) and geological opportunities (such as salt cavities that could be repurposed for hydrogen storage) to drive hydrogen development. As a testament to this, the HyNet North West project aims to decarbonise the region through large scale blue hydrogen supply and new build 100% hydrogen pipelines.

From a market perspective, it is clear that the primary hydrogen supply project for the region, HyNet North West, should drive key commercial learnings for a hydrogen future. HyNet North West asserts it is readily extendible and could provide a blueprint to be replicated across the UK. HyNet North West has also received both private sector and public sector funding (including funding from Ofgem in the form of Cadent's GD2 final determination).

*Please note this figure is not exhaustive.



Key to the following hydrogen projects:

- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

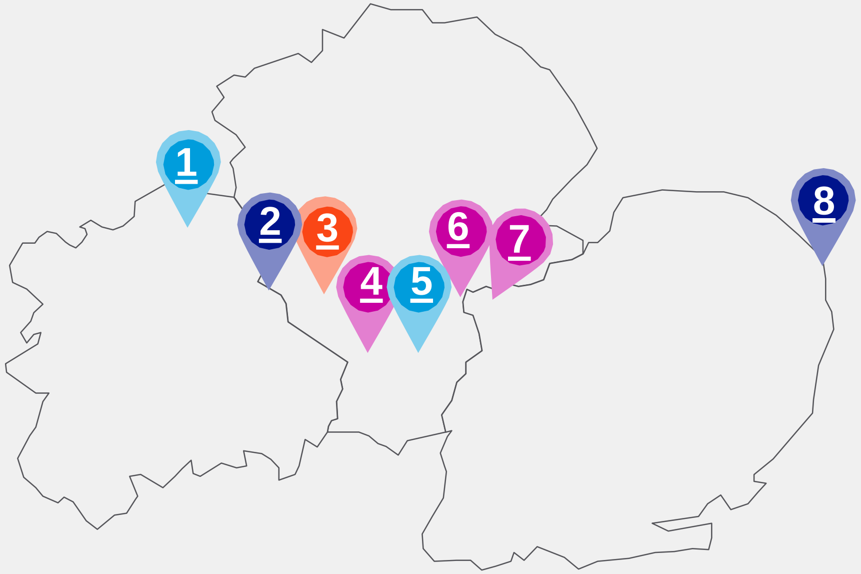
Click the pins on the map to find out more information on the hydrogen projects.

North West key

1. Breeze hydrogen train
2. HyNet North West
3. Net Zero North West
4. North West Hydrogen Alliance
5. HySecure

Hydrogen in the Midlands and East Anglia

As seen in the figure, the Midlands and East Anglia have a diverse range of hydrogen projects. As the Midlands don't have access to coastal carbon storage facilities to enable large scale blue hydrogen supply or immediate access to offshore wind to generate large scale green hydrogen, the Midlands are faced with unique challenges and opportunities when considering a clean hydrogen transition. On the other hand, in East Anglia through the Hydrogen East program gas industry participants are exploring opportunities to take advantage of existing gas infrastructure to develop coastal blue hydrogen supplies, as well the opportunity to develop large scale green hydrogen from one of Great Britain's largest offshore wind fleets (Norfolk).



From a market perspective, there is clearly growing innovative hydrogen activity across the value chain in the Midlands and East Anglia. For example, the Tyseley Energy Park (Birmingham) hydrogen hub feasibility study is exploring the potential for an in-land blue hydrogen production facility, which will require innovation solutions for CCUS.

In addition, there is increasing markets focused work being driven in this region. For example, the Hydrogen Gas Market Plan project (based in Warwick) is collaborating with industry to drive market focused hydrogen work forwards to explore how hydrogen can be integrated within Great Britain's energy mix at minimum disruption to gas industry participants.

*Please note this figure is not exhaustive.

Key to the following hydrogen projects:

- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

Click the pins on the map to find out more information on the hydrogen projects.

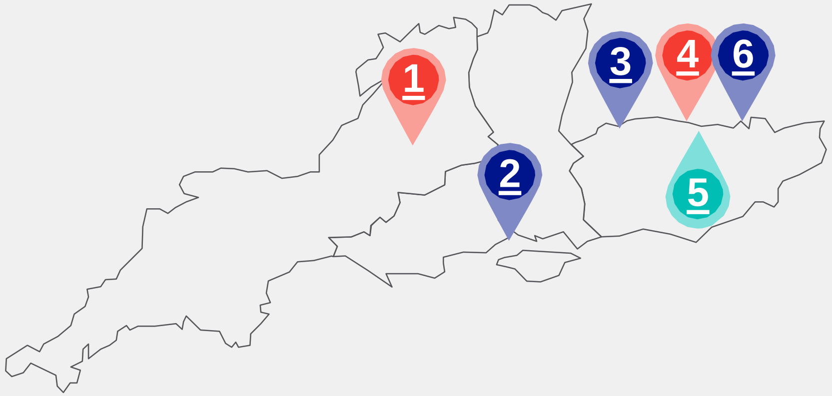
Midlands and East Anglia key

1. **Hydeploy Keele University**
2. **Tyseley Energy Park hydrogen hub**
3. **Clean air hydrogen bus**
4. **Hydrogen Gas Markets Plan**
5. **Hydrogen in the NTS**
6. **Future Billing Methodology**
7. **Hydrogen blending and the gas commercial framework**
8. **Hydrogen East**

Hydrogen in the South of England

The South of England has a range of hydrogen projects aiming to decarbonise an energy intensive region across all demand sectors (i.e. heat, industry, power generation and transport). For example, Project Cavendish aims to decarbonise a power generation cluster located at the Isle of Grain in Kent with blue hydrogen, with the ambition to provide a low carbon energy source to benefit London and the South East of England. It is important to recognise that some of the most ambitious hydrogen projects in the region, such as the Southampton hydrogen super hub, have only emerged recently (Q4 2020). This clearly illustrates how rapidly the hydrogen agenda is developing.

Most significantly from a markets perspective, hydrogen is gaining momentum from policy makers as seen in the first published work on business models for low carbon hydrogen production, as well as the pivotal role hydrogen plays in the Prime Minister's 10 Point Plan and subsequent 2020 Energy White Paper. The Prime Minister Boris Johnson has pledged to make a "big bet" on the role hydrogen technology could play to drive down carbon emissions for the UK.



*Please note this figure is not exhaustive.

Key to the following hydrogen projects:

- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

Click the pins on the map to find out more information on the hydrogen projects.

Hydrogen in the South key

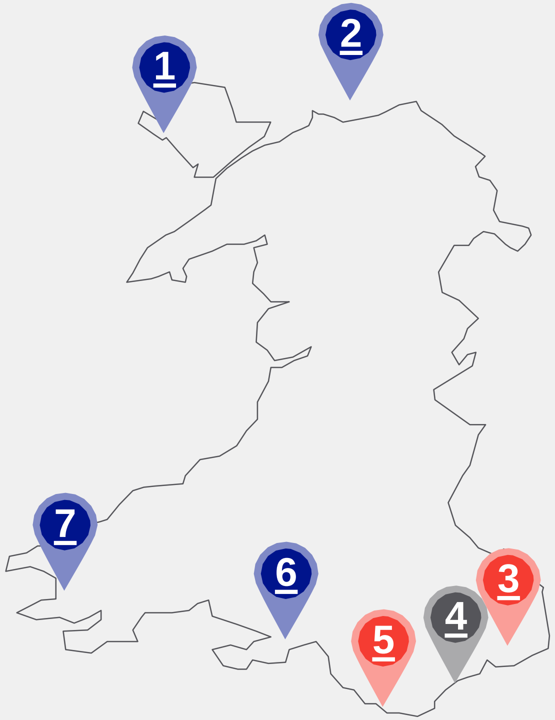
1. **Swindon hydrogen hub**
2. **Southampton hydrogen super hub**
3. **ITM Motive**
4. **Hy4Heat**
5. **Business models for low carbon hydrogen production**
6. **Project Cavendish**

Hydrogen in Wales

There is growing hydrogen ambition within Wales. A consultation (January 2021) on Developing the hydrogen energy sector in Wales, commissioned by Welsh Government includes a pathway and next steps for driving hydrogen development in Wales. This latest hydrogen report focuses on short-term hydrogen projects in Wales, specifically considering the deployment of commercially developed hydrogen opportunities such as hydrogen for transport.

As seen in the figure, Wales has a diverse range of hydrogen projects. From a market perspective, there are clear synergies between the potential to take advantage of existing energy infrastructure in the region to produce clean hydrogen (both blue and green), and also the potential to decarbonise energy intensive demand sectors with hydrogen. The hydrogen market focus is largely centred within Wales, with clear ambitions to use locally generated hydrogen to decarbonise local emissions.

*Please note this figure is not exhaustive.



Key to the following hydrogen projects:

- Hydrogen supply
- Hydrogen transportation
- Hydrogen demand
- Hydrogen market framework
- Hydrogen commercial model
- Hydrogen research and development

Click the pins on the map to find out more information on the hydrogen projects.

Project key

1. **Hydrogen Holyhead**
2. **Port of Mostyn Tidal Lagoon**
3. **South Wales Industrial Cluster**
4. **H2 Wales**
5. **Hy Hy**
6. **Net Zero South Wales**
7. **Milford Haven Energy Kingdom**

To find our more information or to get involved in the Hydrogen Gas Markets Plan, please view our websites or email us at: **box.FOGForum@nationalgrid.com**

Hydrogen GMaP website

Future of gas website