Department for Energy Security & Net Zero

HYDROGEN TRANSPORT AND STORAGE NETWORKS PATHWAY

December 2023

© Crown copyright 2023

This publication is licensed under the terms of the Open Government Licence v3.0 except where otherwise stated. To view this licence, visit nationalarchives.gov.uk/doc/open-government-licence/version/3 or write to the Information Policy Team, The National Archives, Kew, London TW9 4DU, or email: psi@nationalarchives.gsi.gov.uk.

Where we have identified any third-party copyright information you will need to obtain permission from the copyright holders concerned.

Any enquiries regarding this publication should be sent to us at:
hydrogentransportandstorage@energysecurity.gov.uk.

Contents

Introduction

Hydrogen transport and storage (T&S) infrastructure will be critical in supporting our low carbon hydrogen production ambitions by 2030. T&S connects producers with consumers and balances misalignment in supply and demand. In line with our British Energy Security Strategy (BESS) commitments, the Department for Energy Security and Net Zero (DESNZ) is developing business models at pace to provide the support necessary to bring forward T&S infrastructure. Alongside that work we are assessing the growing evidence of emerging hydrogen T&S network needs to determine what infrastructure is needed, where, and when.

As part of a wide-ranging consultation on T&S, government consulted on whether T&S infrastructure required strategic planning[1]. In August 2023 we published our government response in which we set out our minded to position that there is a need for a degree of strategic planning, led by DESNZ in the interim with the Future System Operator (FSO)[2] taking on strategic planning activities for hydrogen in due course. As part of that, we committed to publishing a 'hydrogen networks pathway' to set out the next steps in our vision for the strategic development of hydrogen T&S in the UK and the role of the FSO. Strategic planning can provide greater certainty on network requirements both in the short and longer term. It can give clarity and confidence to potential consumers, producers and infrastructure projects, fuelling the growth of the hydrogen economy. It is also intended to inform the allocation of the hydrogen storage and transport business models.

The production of a hydrogen T&S networks pathway is also in line with the recommendations in the "Mission Zero" Independent Review of Net Zero, led by Chris Skidmore[3]. Those recommendations included ensuring that the FSO takes forward a role in system planning for hydrogen and that government takes decisive leadership on identifying minimum viable pipeline and storage network needs, both of which this publication advances.

Chapter 1 sets out DESNZ's approach to conducting interim strategic planning and the strategic objectives that will guide this process. Our three overarching objectives for T&S infrastructure build-out are: to promote net zero by supporting decarbonisation at pace, to bring whole energy system benefits, including security of supply and helping mitigate impacts on the environment, and to unlock the development of an economic and efficient hydrogen market that supports wider growth. Chapter 1 explores how different types of transport and storage infrastructure can help meet these objectives, including the strategic role of a core network and the role of storage in supporting security of supply and demand. The final part of Chapter 1 explores how some of the key variables in the development of the hydrogen economy will shape T&S needs.

[1] https://www.gov.uk/government/consultations/proposals-for-hydrogen-transport-and-storage-business-models
[2] The FSO is referred to as the Independent System Operator and Planner (ISOP) in the Energy Act 2023, which confers upon it its statutory powers and duties. In practice we expect it to have a different operational name once established.
[3] https://www.gov.uk/government/publications/review-of-net-zero

Chapter 2 provides a comprehensive update on the emerging evidence that will help inform the size, shape and timing needs of hydrogen T&S network infrastructure. Updated internal analysis of hydrogen demand indicates that a near term strategic priority for hydrogen network development at scale is to enable the decarbonisation of early industrial and power users by the early 2030s. This will require significant pipeline infrastructure to connect this early demand to suitable production and geological storage facilities. The location of production plants currently planned in the UK to 2030 provides a clear indication of where early infrastructure could hold strategic value in the near term, and the opportunities to develop hydrogen storage at scale to these timescales are limited to onshore locations with suitable geology for salt caverns.

Considering this evidence, Chapter 3 sets out the T&S network needs case. To enable the growth of hydrogen demand necessary to meet our decarbonisation goals in the short term, the hydrogen economy needs onshore salt cavern storage, and the associated pipeline infrastructure, connected to hydrogen production plants and clusters of industrial and power demand. This needs case supports an ambition for the first hydrogen storage and hydrogen transport business models **to support up to two hydrogen storage projects and associated regional pipeline infrastructure to be in operation or construction by 2030**.

Chapter 4 provides further details on the institutional and regulatory arrangements for hydrogen T&S. It includes details on the timeline of activities by which we expect the FSO to take on responsibilities for strategic planning for hydrogen T&S infrastructure. **We are setting an ambition for the FSO to formally take on these responsibilities from 2026.** This ambition is subject to making progress on determining the scope of the FSO's activities for strategic planning for hydrogen T&S, making any necessary legislative and/or regulatory changes (such as amendments to licence conditions) to permit the FSO to conduct these activities, and finalising the funding arrangements to enable the FSO to be sufficiently resourced to carry out these activities. It also provides an update on the regulatory framework necessary to support and enable the deployment of T&S infrastructure.

The conclusion sets out some key next steps, including a forward look to planned updates in 2024 on the first T&S business models allocation rounds, proposals to consult on the FSO's hydrogen strategic planning activities, and updates on emerging evidence of T&S network needs.

This Pathway is published alongside and complemented by multiple sister publications. The Hydrogen Transport Business Model and Hydrogen Storage Business Model Market Engagement documents provide an initial look at the proposed high-level timelines and processes for allocation, including initial high-level proposals for the eligibility and assessment criteria for determining which projects receive support, and how T&S can be coordinated. The Hydrogen Production Delivery Roadmap sets out how we expect the hydrogen production landscape to evolve towards 2035. The Hydrogen to Power (H2P) consultation looks to gain views on the need for and design of market intervention to support deployment of hydrogen to power. Government believes that market intervention is currently necessary to mitigate identified barriers and to support the accelerated deployment of H2P to support power sector decarbonisation and security of supply. The fourth Hydrogen Strategy update to the market provides a comprehensive overview of developments across the hydrogen value chain since the publication of the UK Hydrogen Strategy in 2021, and a forward look of delivery over the coming decade.

Chapter 1: Strategic Planning

Strategic Planning Methodology

In the Hydrogen Transport and Storage Infrastructure: Minded to Positions (T&S Minded to Positions) published in August 2023, we set out our minded to position that there is a need for a degree of strategic planning, combined with elements of a market-led development, to enable the efficient, cost-effective and timely roll-out of hydrogen transport and storage (T&S) infrastructure[1]. The build-out of hydrogen T&S infrastructure, and in particular larger scale or systemically important assets, should be guided by centrally coordinated, locally sensitive, strategic planning that is integrated across energy and other relevant systems.

We set out our view that strategic planning can:

- Provide greater certainty on network requirements both in the short and longer term,
- Provide clarity and confidence to offtakers for whom hydrogen is a viable decarbonisation pathway,
- Support a coordinated drive to net zero and offer opportunities to align construction and identify efficiencies in infrastructure build-out,
- Provide a wide, whole system view, and a route to identify and make use of opportunities where they exist,
- Provide the best opportunity to maximise decarbonisation, provide enduring system resilience and ensure value for money for energy consumers,
- Provide more efficient infrastructure build-out, at the right pace, location and scale, resulting in greater investor confidence and ensuring decarbonisation goals are met.

Combining this with efficient market mechanisms that utilise competition and promote innovation can minimise overall system costs and deliver value-for-money decarbonisation. Likewise, large scale central planning needs to be balanced with an understanding of local and regional needs, as recognised in Ofgem's recent consultation on the Future of local energy institutions and governance.[4]

We said that DESNZ would take on the role of strategic network planner on an interim basis, working closely with industry and the regulators. In the future we intend for the majority of strategic planning activity for hydrogen to be done by the Future System Operator (FSO).

This document is the first step towards developing a strategic planning process that can inform the growth of a hydrogen T&S network. We anticipate it to be the first of a series of publications that build on the current evidence of network needs and what infrastructure should be considered a priority as a result. Early iterations will be informed by assessments of emerging demand and production profiles, as well as technological developments. Our focus is

[4] https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance

on defining strategic objectives that can be used to give a clear sense of direction and help inform near term-assessments of the necessary infrastructure build-out. The scope of what network needs can be identified with confidence will increase over time as the direction of the hydrogen economy becomes clearer.

Current Strategic Planning on Energy Networks

Strategic network planning for gas and electricity transmission is currently undertaken by National Gas Transmission and the Electricity System Operator (ESO) respectively as the transmission system operators and planners. Distribution network operators also plan their networks in accordance with anticipated customer connection needs.

While the approach to strategic planning is slightly different across gas and electricity, there are key stages across both that at a high level, provide a clear methodology to follow for hydrogen strategic planning. These include four core activities: forecasting the future for energy supply and demand, translating the forecasts into what the network needs to meet these future requirements, scoping options to develop the network and selecting specific actions/projects to achieve those developments.

Electricity Strategic Network Planning

On the electricity network, the ESO conducts a variety of strategic network planning activities:

Future Energy Scenarios (FES): these present different ways in which the energy system could be decarbonised by 2050, covering key variables across changing customer behaviour and whole system changes, such as the use of hydrogen for heating.

The Network Options Assessment (NOA): which provides the ESO's recommendations for which electricity network reinforcement projects should receive investment and when.

More recently, the NOA has been supported by network designs set out in the Holistic Network Design (HND), to ensure transmission connections for offshore wind are delivered to meet our net zero targets in the most appropriate way.

The ESO provides its recommendation on the best options to develop the network, but the final decision on what infrastructure gets built lies with the project managers and Ofgem, who approve their proposed expenditure through the network price control.

The ESO are building on the approach taken for the HND to deliver a transitional Centralised Strategic Network Plan (tCSNP), which will take a whole system approach to designing the transmission network. Once established, the FSO will take on responsibility for the CSNP.

Gas Strategic Network Planning

Gas transmission and distribution planning is currently carried out independently by gas transporter licence holders. Gas storage facilities are owned and operated on a commercial basis by private entities, and planning is driven by a mixture of physical and economic factors.

National Gas Transmission (NGT) conducts network planning for the National Transmission System (NTS). Currently, the Transmission Planning Code (TPC) outlines the regulatory, safety and resilience standards which this planning process must consider. Long-term planning is informed by analysis conducted by the ESO in the annual FES publication.

NGT's high level strategic planning is conducted largely through the annual Gas Ten Year Statement (GTYS). This is split into four key sections, covering:

- Drivers of change on the gas network: details factors which can trigger network development, such as legislative change, customer requests, asset health or decarbonisation targets.

- Network capability: analysis of the required network capability of the NTS to manage drivers for change. This considers short, medium, and long-term requirements.

- Options: assessment and development of solutions to address drivers of change.

- Development: further refinement and development of the options selected in the previous section. This section covers project development, sanctioning, execution, review, and closure.

NGT also produce the Annual Network Capability Assessment Report (ANCAR), which provides a snapshot of the physical capability of the NTS and how that capability compares to present and future system requirements.

Each of the four Gas Distribution Networks (GDNs) produce Long Term Development Statements (LTDS), based on their own forecasting data. These cover the process for gas distribution system planning, supply and demand forecasts, system reinforcement projects and associated investment.

NGT and the GDNs provide their business cases for network capability development to Ofgem. Development is funded through the network price control.

The Energy Act 2023 (the "Energy Act") contains powers to establish the Future System Operator (FSO) and to enable it to conduct system planning for both gas and electricity transmission (although National Gas will continue to assess its network capability in parallel). The Energy Act makes amendments to the Electricity Act 1989 and Gas Act 1986 (the "Gas Act") to create two new licensable activities for electricity system operator activity and gas system planning activity. The energy regulator Ofgem, will monitor and regulate against these licences, which include provisions for electricity and gas network planning for Day 1 of the operation of the FSO as system planner. Ofgem has recently conducted a non-statutory consultation on some elements of FSO's Day 1 licences[5], alongside the joint DESNZ and Ofgem 'FSO Second policy consultation and update' consultations[6]. Ofgem and DESNZ will undertake a statutory consultation of the FSO's Day 1 licences in 2024, ahead of the FSO's launch.

As discussed in the T&S Minded to Positions, hydrogen is a gas within the Gas Act, and the next steps in ensuring the FSO can effectively and efficiently take on strategic planning activities for hydrogen are discussed in Chapter 4 below.

Hydrogen Strategic Network Planning

Early strategic planning activities for hydrogen will focus on identifying the T&S infrastructure for which there is the clearest needs case as the hydrogen economy develops. This Pathway presents the first conclusions from this process, and we will continue to build and expand strategic planning in line with the growth of hydrogen supply and demand. During this time we intend to draw on the expertise and capabilities of the FSO in electricity and gas networks, and increasingly hydrogen as it relates to those networks, to support our hydrogen strategic planning activities. In turn this will help ensure a smooth transition of strategic planning activities from DESNZ to the FSO, as discussed in Chapter 4 below.

In the interim, we are approaching strategic planning by setting out overarching objectives for T&S infrastructure, reviewing the range and variation in forecasts of future hydrogen supply and demand, analysing current evidence of near-term T&S needs based on demand estimates and using this to set an ambition that will guide the first allocation rounds of the T&S business models.

While our initial focus for strategic planning for hydrogen T&S will be on the development of onshore T&S assets and will be informed by our strategic objectives and evidence of T&S needs as set out above, as well as work across government and Ofgem, we are also considering offshore T&S infrastructure needs. In part, this will be informed by spatial planning work such as the Marine Spatial Prioritisation (MSPri) programme[7].

Setting overarching objectives: The gas and electricity system planners have clear objectives they must plan to as set out by their licence conditions. In the T&S Minded to Positions[1] we suggested that strategic priorities for the early development of T&S infrastructure would need to be identified based on whole system considerations. We have taken this as a first step in our strategic planning process. These strategic priorities are set out in the following section.

[5] https://www.ofgem.gov.uk/publications/future-system-operator-fso-draft-licences-consultation
[6] https://www.gov.uk/government/consultations/future-system-operator-second-policy-consultation-and-project-update
[7] The MSPri programme aims to deliver cross-government agreement on how to optimise the future use of English waters up to 2050, driving decision making across Government and delivery partners including seabed managers and regulators.

Forecasts of hydrogen supply and demand: We have looked ahead to understand the variables between the ways in which the hydrogen economy could develop and what implications these variables have for T&S requirements. We have been guided by existing external forecasts of future energy needs, such as the ESO's Future Energy Scenarios (FES), and we have drawn on external analysis and recommendations from the Committee on Climate Change (CCC) and National Infrastructure Commission (NIC). An overview of these variables is set out later in this chapter.

Analysing current evidence: The next stage of the process was to assess the current state of the evidence across these variables and what that evidence suggests about near-term T&S network requirements. The results of this process are set out in Chapter 2.

Identifying early needs: Consideration of the strategic objectives, the possible futures for the hydrogen economy and the current state of evidence across demand and the technical characteristics of T&S infrastructure, has informed our assessment of priority T&S network needs, set out in Chapter 3. These have been used to set the ambition for the first allocation rounds of the transport and storage business models (HTBM, HSBM).

Options to deliver network needs: The final step of strategic planning, the selection of options for fulfilling network needs, will in the near term be taken on predominantly by the allocation process of the HTBM and HSBM for transport and storage infrastructure respectively. Initial high-level proposals for this process are set out in Hydrogen Transport and Storage Market Engagement Documents, published alongside this Pathway. Alongside this, we are working to ensure that suitable market and regulatory frameworks are in place to support the development of T&S infrastructure, with an update on this work provided in Chapter 4.

The strategic planning process is an iterative one, just as it is for existing energy networks. We intend to produce further analysis on of T&S requirements in 2024, as evidence on the growth of hydrogen production and demand improves.

Overarching Strategic Objectives for T&S

As set out above, strategic planning will be guided by a set of objectives, and these should fit with the broader objectives of both DESNZ and the FSO, to ensure a smooth transition of strategic planning activities. The FSO will have statutory objectives to carry out its functions in a way that promotes net zero, the security of supply of electricity and gas and an efficient, coordinated, and economical electricity and gas system.

Building on the strategic considerations set out in the T&S Minded To Position, T&S infrastructure build-out should aim to fulfil the following three overarching objectives:

- To **promote net zero** by supporting decarbonisation at pace.
- To enable **whole energy system** benefits, including security of supply and helping mitigate environmental impacts.

- To unlock the development of an economic and efficient hydrogen market that **supports wider growth**.

These objectives will guide the strategic planning process and shape the resulting infrastructure needs identified. In turn, these will inform government T&S policy priorities, and the ambition for the T&S business model allocation rounds. The T&S business models and allocation process will also be designed with a view to furthering these objectives, through a combination of design elements, timing, scope and eligibility and assessment criteria as appropriate.

Net Zero Objective

To support decarbonisation, strategic planning should, to the extent it is safe, economical, efficient and in the interests of consumers, ensure that:

- T&S enables decarbonisation at pace, by being available in the right place at the right time to connect low carbon hydrogen production to demand.
- T&S infrastructure enables demand for low carbon hydrogen to be met through diverse, secure and resilient long-term supplies for consumers.

The need for hydrogen T&S is driven by our net zero ambitions and the utility of low carbon hydrogen as an alternative to fossil fuels for a wide range of end use sectors. Our first strategic objectives should be to ensure that the infrastructure is in place to allow end users to decarbonise using low carbon hydrogen where it is a credible and efficient option. Projects that can demonstrate that their proposed infrastructure helps connect and support known credible low carbon hydrogen demand, such as in industrial sectors or electricity generation, could be judged as fulfilling these objectives.

T&S infrastructure will enable demand for hydrogen from consumers to be met reliably and securely and is a key objective for the development of this infrastructure. Delivering secure and resilient hydrogen supplies will be critical not only to meeting consumer needs for a safe and reliable energy supply, but as a key enabler of wider fuel switching. Integrated pipeline networks and large-scale storage are likely to have a particularly important role by providing access to multiple supply points and balancing differences in supply and demand, including mitigating short- and long-term supply disruption.

Whole System Objective

To unlock whole system benefits, strategic planning should, to the extent it is safe, economical, efficient and in the interests of consumers, ensure that:

- T&S infrastructure increases overall energy security of supply in a low carbon energy system, for example by providing long term energy storage solutions to support electrification and enabling low carbon flexible power in the form of H2P.
- T&S unlocks wider system benefits, such as by reducing impacts on the water system, helping to manage the costs of electricity system constraints, or reducing decommissioning costs of natural gas infrastructure through repurposing.

The transport and storage of hydrogen will be critical parts of the much wider energy and environmental systems of the UK, offering not only resilient energy supplies to consumers but opportunities to develop a fully integrated low carbon energy system. Hydrogen is a key technology for the decarbonisation of the power sector and security of electricity supply, alongside providing decarbonisation pathways for unabated gas generation. Hydrogen could have a key part to play in delivering security of supply in such a system and the right T&S infrastructure will be critical in enabling that role. Developing hydrogen T&S infrastructure in a way that is coordinated with electricity and natural gas infrastructure can help ensure a smooth and resilient transition to net zero. T&S can also provide opportunities to reduce the environmental impact of the energy sector, not only through supporting emissions reductions but by increasing locational flexibility in siting energy assets and mitigating environmental impacts such as on water availability. Infrastructure assets could help meet these objectives by, for example, offering a wider choice of locations for future production.

Market Growth and Economic Objective

To enable hydrogen market and economic growth, strategic planning should, to the extent it is safe, economical, efficient and in the interests of consumers, ensure that:

- T&S infrastructure development enables the necessary and anticipated growth of the hydrogen economy, including through expanding access to hydrogen to new users, providing security of demand for producers and building in scalability and future-proofing assets where appropriate.
- T&S infrastructure development supports the growth of a competitive and increasingly integrated hydrogen market to deliver value for money and reduce costs for consumers.
- T&S infrastructure development supports the development of the hydrogen sector and related supply chains, with attendant economic benefits of increasing jobs and investment across the UK regions, and furthering UK net zero and environmental ambitions.
- T&S enables the UK to take a leading position at the forefront of the growing international hydrogen market, promoting trade opportunities, supporting UK innovation, developing international energy supply chains, and increasing energy security.

Infrastructure scaled to meet only near-term confirmed demand could limit growth and risk future hydrogen network constraints. T&S infrastructure should be developed to anticipate and support the growth of the hydrogen economy. Assets with built-in scalability, or that demonstrate flexibility of future use could be judged as fulfilling this objective. Where there is high potential for hydrogen use, T&S can be the critical facilitator for growth, by opening up new areas or sectors to hydrogen supplies and supporting the growth of a large, integrated market that provides good value for money for hydrogen consumers. DESNZ analysis suggests that the UK hydrogen sector could potentially unlock up to £11 billion in private investment and support over 12,000 jobs by 2030[8]. The growing supply chain has the double economic benefit of both supplying UK projects, and potentially supplying overseas projects

[8] https://www.gov.uk/government/publications/hydrogen-net-zero-investment-roadmap

through exports. While the UK domestic market should be the early focus, T&S can also enable the UK to play a leading role in the development of an international hydrogen market, by connecting the UK to import and export opportunities.

Strategic Roles of Transport Infrastructure

Regional Pipeline Networks

Transport infrastructure that creates regional networks to connect centres of production, demand and geological storage is an early step to meeting many of these objectives in the near term. The transport requirements for close concentrations of production and demand present credible early opportunities to support decarbonisation at pace among clustered industrial sites. The development of regional networks can be phased to retain the flexibility required to support future network expansion and market growth. This growth in turn can provide greater resilience, market liquidity and security of supply for network users through connections to multiple sources of production and to geological storage, as well as reducing volume risk for production projects connected to multiple off-takers. We consider this archetype of pipeline network to be critical to supporting the hydrogen economy both in the near term and as it develops in the future.

Core Network

Transport infrastructure that contributes towards the realisation of a core network for the transmission of hydrogen could also be a significant step to meeting our strategic objectives. A core network refers to an integrated system of high-pressure pipelines connecting multiple supply, demand, and storage points. Such a network would provide transmission of hydrogen both within and between regional networks, connecting these to additional production and storage sites, and serve more dispersed users directly.

In October 2023, the NIC published their Second National Infrastructure Assessment which included a key recommendation to government to pursue the creation of a core network[9]. The Assessment proposed that a core network should focus on providing access to likely sites of both electrolytic and CCUS enabled hydrogen production for the most likely large users, such as chemicals and steel, which are mostly in the industrial hubs. It recommended ensuring that networks pass through areas where storage is most feasible to locate, particularly those sites that look most promising to develop first.

We agree with these strategic objectives of a core network. We believe there are significant benefits to the hydrogen economy that could be delivered through a core network, but that determining the most suitable routing and timeline for such a network requires further evidence.

A core network could:

- Enable more competition in the market and hence support market development and price discovery, lowering risk and costs. By connecting multiple producers and stores to

[9] https://nic.org.uk/studies-reports/national-infrastructure-assessment/second-nia/#tab-netzero

a single integrated network, monopoly power would be limited, and users would gain the benefit of a single competitive price for hydrogen and access to the network.

- Provide greater network resilience against supply outages.
- Reduce the impact of local imbalances in production/demand.
- Act as a strategic enabler for future production and demand through connection to geographically constrained storage, unlocking the ability of hydrogen to play a key role in delivering a decarbonised power sector and increasing energy security of supply.
- Increase optionality for production location. This could unlock greater potential for electrolytic hydrogen production to locate close to abundant renewable electricity generation and behind network constraints to help alleviate electricity network constraint costs. It could also allow access to hydrogen and geological storage for more hydrogen to power (H2P) plants and dispersed sites with proximity to the route. For example, a core network that connects the north of Scotland with hydrogen demand centres further south could exploit the huge potential for electrolysis from offshore wind in the north of Scotland.
- Mitigate environmental impacts of siting decisions, such as water availability, by reducing the need for hydrogen production to be located close to concentrations of demand and geological storage.

The alternative to an early core network would be to allow regional networks to develop and grow independently. These may still ultimately connect, but not necessarily via a single transmission system analogous to the National Transmission System, or, in a future where hydrogen use is more limited, these may not connect at all. Isolated regional networks do not allow the sharing of geographically constrained geological storage infrastructure and they would reduce the diversity of sources of hydrogen supply to end users. It is also less likely that a single market price for hydrogen would emerge, which could result in higher costs for consumers in some parts of the UK.

Any development of a core network for hydrogen is likely to have significant interdependencies with the existing natural gas transmission system. Repurposing existing natural gas pipelines could prove a cost-effective means of creating a core network for hydrogen, but only when and where this proves feasible while maintaining resilient supply for natural gas users. Repurposing must also be demonstrated to be safe and reliable. The FutureGrid project is currently testing and demonstrating for the Health and Safety Executive (HSE) the extent to which different elements of existing network infrastructure are hydrogen ready[10]. Those that are not may require additional work or replacement before they can safely carry hydrogen.

We welcome the NIC's recommendation and agree in principle with the strategic case for a core network. We intend to produce further analysis on T&S requirements in 2024.

[10] https://www.nationalgas.com/document/141506/download

International Networks

Transport infrastructure can also connect UK markets with European and international markets through connections to ports, interconnectors, offshore networks and storage facilities. The trade of hydrogen, and related goods and services, can help support the UK's hydrogen economy, developing hydrogen energy supply chains, delivering employment opportunities and increasing labour force skills across the UK.

Based on industry intelligence, the UK could have up to 20GW of low carbon hydrogen production capacity by the early 2030s, and exports of hydrogen could help bring some of this potential pipeline of projects forward.[11] High demand in continental Europe, the UK's renewable energy capacity and its geographical proximity offer the potential for UK exports via interconnectors to be part of a wider hydrogen network in Europe. Pipeline connections to Europe could increase both the UK and Europe's long-term energy security. Shipping as a transport pathway could also play a role in building supply chain resilience, providing low-carbon hydrogen from distances beyond pipeline capabilities.

The location of international transport infrastructure will need to be strategically considered alongside the UK's domestic hydrogen production, transport and storage networks and locations. T&S infrastructure will be a critical enabler of the UK's hydrogen trade ambitions, and the pace and scale of network needs driven by this use case will be kept under review.

Local Transport Infrastructure

In addition to regional networks, there may also be a role for pipelines which connect a single producer with a single or a few offtakers located nearby, either as a precursor to connecting to a wider regional or core network, or as self-contained units of producer and local user(s). This could be especially useful for early electrolytic hydrogen projects, which could prove the viability of new technologies and enable the early growth of the hydrogen economy. These small-scale pipelines would essentially allow for the early co-location of electrolysers with primary offtakers, such as dispersed industrial sites located outside the main industrial clusters. Dispersed sites account for around half of industrial emissions.[12]

Early local pipeline projects may or may not have credible potential to eventually connect to the wider pipeline network providing access to the geological storage that is likely to be required for security of supply. When, where and how to support such pipelines requires further consideration on a project-by-project basis, acknowledging the early enabling role they can play, but balancing this against the risk of future stranded assets. Such consideration would take several factors into account, including necessity, affordability, and value for money.

There could also be a role for the transporting of hydrogen by tube trailer to certain types of offtakers for whom a pipeline would be unnecessary or impractical, for example supplying temporary construction sites, or those requiring particularly small volumes of hydrogen. These

---

[11] The UK's 'Hydrogen net zero investment roadmap' identified a pipeline of up to 20GW of potential low carbon hydrogen projects (through to 2037): https://www.gov.uk/government/publications/hydrogen-net-zero-investment-roadmap

[12] https://www.gov.uk/government/publications/net-zero-strategy/3-reducing-emissions-across-the-economy

limited transport options could be complemented by above ground storage options. Examples of these types of T&S plans can be seen in the early pipeline of hydrogen projects, for instance from those supported through the first Hydrogen Allocation Round serving users far from potential regional networks.

Strategic Roles of Storage Infrastructure[13]

Geological storage technologies (e.g. salt caverns and depleted hydrocarbon fields) have the potential to provide long-term, large-scale hydrogen storage that can support our strategic objectives for T&S infrastructure. Above ground storage technologies, (e.g. tanks) may also have a role to play, particularly in areas where geological storage is unavailable (e.g. due to geology or an absence of transport connections.) The locational factors affecting hydrogen growth map, published with this pathway includes information on prospective geological storage sites). However, due to its limited hydrogen storage capacity, the extent to which above ground storage may meet our strategic objectives will largely depend on the scale and location of its deployment.

Geological storage will likely play a key role in making significant steps towards achieving our strategic objectives that cannot be achieved economically or efficiently solely through above ground storage. By its technological characteristics alone, geological storage can provide a resilient, long-term supply of hydrogen. This aligns with the hydrogen storage business model (HSBM) minded to position to prioritise support for geological storage in the first allocation round (see the HSBM Market Engagement document).

We can also categorise hydrogen storage by its ability to play a role in system operation or provide a strategic reserve for hydrogen. Both types of storage are likely to be necessary as the hydrogen economy evolves and will, to some extent, support our strategic objectives. It will be important for government's approach to strategic planning and the allocation of HSBM support, to consider the need for and build-out pathway of storage for these two use cases.

Network Balancing and Security of Supply and Demand

Geological storage will be necessary to manage intra-day, inter-day and inter-seasonal imbalances in hydrogen entry and exit volumes in the hydrogen network (i.e. where the extent of an imbalance in the hydrogen network cannot be managed by simply flexing pipeline pressure). Intra-day imbalances on the natural gas networks are currently addressed by both residual balancing, where the Gas System Operator undertakes trades within the gas market to resolve imbalances in the network, and by allowing pipeline pressures to flex up and down within acceptable tolerances ("line-pack"). The lower energy density of hydrogen, coupled with the immaturity of network infrastructure, means that line-pack opportunities for hydrogen networks will be much more limited. Storage infrastructure could fill this gap - supporting

[13] We recognise that the range of hydrogen storage technologies is not limited to geological and above-ground storage (e.g. chemical storage is another emerging hydrogen storage technology). Chemical storage technologies are in earlier phases of development (i.e. proof-of-concept for some) and are not considered to be as technologically mature as geological or above ground storage. We therefore cannot yet comment on how these technologies might support our strategic objectives and have focussed this section on geological and above ground storage.

security of supply and demand for offtakers and producers of hydrogen respectively. We expect that hydrogen network balancing will need to occur on an intra-day basis, so fast-cycle storage will be required as well as storage that can operate over longer periods, for example to meet seasonal imbalances, both of which can be supplied by salt cavern storage.

Geological storage will likely be necessary to enable network balancing at the scale that will potentially be required as the hydrogen economy develops (see Section 2 Current Evidence of T&S Needs: Demand). This role is expected to be of particular importance while the hydrogen economy is in its infancy, when a shortage of hydrogen producers and offtakers could expose both counterparts to hydrogen shortages and excesses respectively. Imbalances may also arise as a result of short and long-term hydrogen supply disruptions (e.g. dunkelflaute periods[14]) where the need for stored hydrogen to provide security of supply could be critical, particularly for electricity generation where there is expected to be a great reliance on hydrogen storage availability to support this industry. The risk or perceived risk of these occurrences could act as a barrier to the emergence of hydrogen producers and offtakers (including fuel switchers), which may delay industrial decarbonisation.

In its Second National Infrastructure Assessment, the NIC indicates a need for a strategic energy reserve by 2040 that can generate 25TWh of electricity that, if supplied entirely by hydrogen, would be equivalent to 40TWh of hydrogen storage**Error! Bookmark not defined.**. Our priority at such an early stage in the development of a hydrogen economy is to ensure there is sufficient storage capacity for the effective system operation for early network users. However, we will also consider whether building sufficient storage capacity to build strategic reserves of hydrogen will be necessary in the future to support broader energy security and minimise the impact of such occurrences as described above, on the hydrogen and wider energy system.

Above ground storage may be a more economical and efficient option to provide security of supply for smaller offtakers or hydrogen demand that is temporary or transient (e.g. NRMM on large construction projects.) It can also enable the use of electrolysers for dispersed sites by helping to balance intermittent supply with demand on a smaller scale where cost-effective, making up for the lack of network connection.

Supporting Decarbonisation of the Power System and the Net Zero Target

Storage at scale will be important in a future energy system where renewable generation – wind and solar power in particular – play an increasingly dominant role. Excess renewable generation that might otherwise be curtailed during periods of high generation and low demand, or due to localised network constraints, could instead be used to power electrolytic hydrogen production, which could be coupled with hydrogen storage.

Stored hydrogen could subsequently be put to a variety of uses across the hydrogen economy, including rapid operating hydrogen-fuelled power generation. This could provide a flexible source of low carbon electricity for when demand is greater than the supply from variable

[14] Dunkelflaute periods are periods of low wind/solar energy supply (due to low winds/sunlight) and high energy demand.

renewable generators. The availability of hydrogen storage is critical to enabling hydrogen-fuelled power generation to operate flexibly to provide low carbon capacity to complement intermittent renewable generation.

Geological hydrogen storage could provide low-carbon hydrogen for power generation which could displace more carbon intensive alternatives and therefore contribute to the delivery of the government's commitment for a fully decarbonised power sector by 2035, subject to security of supply. Government analysis shows that having hydrogen available in the power sector could achieve lower emissions at a lower cost than corresponding scenarios without hydrogen.[15] DESNZ have published a consultation alongside this Pathway, seeking stakeholder views on the need for and design of a hydrogen to power business (H2P) model. In part, the proposed business model looks to help overcome some of the barriers to deployment of H2P, one of which being the dependencies on nascent critical enabling infrastructure including hydrogen T&S.

Reducing Hydrogen Production Capacity Requirements and Supporting International Hydrogen Trade

Hydrogen storage may help efficiently plan overall hydrogen production capacity requirements if sufficient hydrogen storage capacity is developed. Once storage is available, production facilities will be able to optimise their output, producing hydrogen when it is most efficient and cost effective rather than in direct response to demand. Any hydrogen produced which is not immediately required by an offtaker can be stored and sold later – this could also support security of supply.

Although in the earlier phases of the hydrogen economy, our priority will be to make hydrogen storage available to support domestic hydrogen production and demand. We want to play a key role in exporting hydrogen to other countries. As international markets continue to develop, there will be opportunities for the UK to play an increasing role in the trade of hydrogen. During long-term periods of low hydrogen demand but high production, stored hydrogen could be exported to support the UK's position in European and international markets. Likewise, during long-term period of high-demand and low production, storage sites could be replenished with imports of hydrogen. Enabling the trade of hydrogen could help support the UK's hydrogen economy, the development of international energy supply chains and energy security.

Drivers of Network Needs

Illustrative Scenarios for Future Hydrogen Supply and Demand

Variables in how the scale, location and type of hydrogen production and demand might develop result in a wide range of estimates for what T&S infrastructure will be necessary to support that development. Likewise, when and where T&S infrastructure will be available influences the growth of production and demand. The interdependencies between demand, supply, storage and transport can be managed through a flexible approach to strategic

[15] https://www.gov.uk/government/publications/benefits-of-long-duration-electricity-storage

planning that responds to the best available evidence of opportunities for hydrogen growth. Such an approach can identify minimum infrastructure requirements that are likely to be needed across multiple possible future scenarios and can form the basis for a future T&S network that can grow flexibly according to emerging need.

Estimates of the necessary T&S infrastructure required by 2035 vary widely depending on the assumptions made about the variables in hydrogen production and especially in hydrogen demand. Assumptions made about the costs and technical characteristics of future hydrogen infrastructure also impact growth estimates. Illustrative scenarios can show the range of ways in which the hydrogen economy could develop.

One illustrative scenario is where hydrogen use is more limited and, end-use is more likely to centre around industrial clusters with proximity to hydrogen storage. Demand could predominantly come from industrial feedstock processes, the production of hydrogen-derived transport fuels, some industrial fuel switching, and hydrogen to power (H2P). There could be limited hydrogen use outside of the clusters, for example to fuel switch certain dispersed industrial sites which are able to co-locate with an electrolyser. To meet high electricity demand, the demand for hydrogen to power in such a world could be extensive. The assumed prevalence of renewable electricity generation could favour a higher proportion of electrolytic production.

The demand profile in this illustrative scenario would drive the development of regional networks centred around connecting geological storage to clusters of industrial demand. The demand for hydrogen in power generation in more dispersed locations could drive the need for a core network, made up of a combination of new build pipelines and repurposed natural gas infrastructure, connecting power sites to multiple geological storage sites. Such a network would increase options for locating green production and hydrogen demand in a wider range of locations. There could be a limited role for small-scale pipelines, tube trailers and above ground storage serving electrolysers located close to offtakers, for example certain dispersed industrial sites looking to fuel switch to hydrogen or supplying temporary or mobile demand.

In an alternative illustrative scenario, more evenly split between electrification and hydrogen, where hydrogen demand materialises in a wider range of industrial sectors and some road transport applications, we could likely see greater growth in both CCUS enabled and electrolytic production to meet this demand. CCUS enabled production would likely be centred around industrial clusters with access to CCUS infrastructure. Electrolytic, and potentially other types of production could be more widespread around the country. Taken together this mix of production technologies could drive the case for a more extensive core hydrogen pipeline network, including some repurposing of natural gas pipeline, potentially at both transmission and distribution level. Such a network could connect geological storage to more areas, enabling the development of more regional networks with otherwise limited local access to geological storage.

In a third illustrative scenario, where hydrogen use is widespread and includes heat in buildings, hydrogen would need to be widely available via distribution networks in most industrial clusters, built up areas and across a wide range of more dispersed sites. Hydrogen production would also be widespread across all technology types and locations. Alongside new hydrogen network build, significant portions of the existing natural gas network at both transmission and distribution level would likely need to be repurposed to carry hydrogen, while maintaining security of supply on a reduced natural gas network.

These illustrative scenarios demonstrate the scale of variables that will impact on the growth of hydrogen transport and storage infrastructure. In setting out these variables below, we also recognise these impacts are not one way; that the scale, location, and pace at which transport and storage infrastructure develop will themselves drive and shape the growth of demand and production.

Variables:

- **The scale, location and type of demand**

These include both the scale of hydrogen demand that comes forward across a range of sectors, including industry, power, transport and potentially heat, and the concentration of demand across the UK. These variables will be determined by technology and supply chain readiness, as well as the cost-effectiveness and availability of hydrogen relative to other decarbonisation options, which will vary depending on sector. Specific government policy will also play a role, for example, the strategic decisions on hydrogen heating, potential financial measures (such as carbon pricing and potential market intervention to support deployment of hydrogen to power), targets/commitments (e.g. within the sustainable aviation fuels mandate), as well as enabling standards and regulation. Demand is the single largest variable driving the location and scale of transport infrastructure and while geology plays the largest role determining storage location, scale is driven by demand variables, especially heat and power.

- **The scale and location of production**

The location and scale of production required to meet the evolving demand for hydrogen out to 2035 will be critical in shaping T&S network needs. We need to plan our hydrogen production capacity to meet the needs of the hydrogen economy. Cost, demand and availability of low carbon electricity for both CCUS enabled and electrolytic hydrogen production are key determinants for production location and scale but are also closely interconnected with the development of T&S itself, especially for large-scale electrolytic production. Government support programmes through Cluster Sequencing and the Hydrogen Allocation Rounds are also important determinants. The Hydrogen Production Roadmap sets out how we expect the hydrogen production landscape to evolve towards 2035. Storage is especially important for the intermittent production associated with electrolysis and to deliver economic supplies of CCUS enabled hydrogen able to match changing demands at short notice, while location of production will drive transport network needs.

- **Wider system developments**

These include the future of natural gas demand, the location and scale of electricity network constraints, water availability, the need for long-term energy storage and the decarbonisation of power generation will all impact on T&S needs. The deployment pathway of CCUS infrastructure will also affect the decarbonisation options available to some industry and power sector users in those locations, and hence on the relative attractiveness of hydrogen and need for hydrogen T&S. These variables will be determined by a wide range of factors, including emerging evidence on the comparative costs of options to mitigate electricity system constraints and provide long term energy storage, and developments in storage technology. Government is currently considering the future role that natural gas and potential hydrogen storage, as well as other sources of flexibility, can play in the long-term, as well as options to mitigate electricity network constraints. The need and shape of a core network for hydrogen will likely be driven by wider energy system needs, as will the scale and type of storage.

- **The growth of international trade**

The development of international regulation, international cooperation and standards and certifications will be important variables, as will the role imports of hydrogen could play in increasing our energy resilience by diversifying our supply mix. Key determinants of these variables include the growth of global demand, especially in continental Europe, the pace in the reduction of levelized cost of hydrogen to drive the development of international trade for hydrogen and its derivatives, and the progress of early international hydrogen interconnectors. While government is targeting support at domestic hydrogen production for domestic use, it is facilitating the future trade of hydrogen through bilateral and multilateral collaboration and seeking to align standards, where appropriate. Government will seek to work with neighbouring countries, including relevant gas operators, to better understand transport, storage and network options in the North Sea. Participating in the trade of hydrogen will require a diversified mix of international transport infrastructure, potentially including offshore pipelines and interconnectors, as well as the domestic infrastructure required to support export/import terminals. This will also need to be strategically considered alongside the UK's domestic hydrogen production, transport and storage networks and locations.

- **The technological features of T&S infrastructure**

In particular the geological conditions most suited to hydrogen storage, emerging storage technologies and the extent to which the natural gas network can be safely repurposed for hydrogen. These will largely be determined by ongoing research and the outcome of relevant safety studies, such as industry led projects that are exploring the feasibility of repurposing the natural gas pipelines to accommodate hydrogen. If emerging T&S technologies become commercially viable, this could change the T&S requirements for producers and users. For example, if lined rock caverns could be used as storage in areas that do not have salt strata, dispersed sites may not need transport to link them to salt cavern storage[16]. The results of research and development in T&S infrastructure will shape, drive and constrain the growth of T&S, and could have significant impacts on cost and competitiveness of varying technologies.

Next Steps

In this section we have set out our methodology and strategic objectives, and the first steps we have taken to assess the key drivers of T&S network needs to inform DESNZ's role as interim

[16] Please refer to the accompanying Hydrogen Transport and Storage Costs Report for more detail on the technical and cost characteristics of T&S infrastructure.

strategic planner. This approach has been designed with a view to enabling a smooth transition of strategic planning activities to the FSO, the process for which is discussed in Chapter 4 below. As the FSO is established, we will work with them to expand their role in interim strategic planning in support of DESNZ, ahead of the transition of responsibilities.

It is not possible to pinpoint the specific infrastructure that will fulfil all our strategic objectives, nor do we believe it would be right to attempt to take such a prescriptive approach at this early stage in the growth of the hydrogen economy. As Chapters 2 and 3 set out below, sufficient evidence is available now to identify early network needs that can help meet emerging demand for low carbon hydrogen in the near term. This early infrastructure can provide a basis for further network build-out that can evolve in accordance with increased certainty of future hydrogen supply and demand.

Comprehensive evidence is not currently available for all the variables identified in this chapter. The growth of international trade will undoubtedly drive future transport and storage development, but current evidence is too nascent to determine near term network requirements. Wider energy system needs, such as the potential for electrolytic hydrogen production to play a role in managing electricity system constraints, are expected to drive network needs, but more work is required to quantify how, when and where hydrogen T&S infrastructure can best provide these wider system benefits. The following chapter sets out the evidence that is available now across production and demand and an accompanying Hydrogen Transport and Storage Costs report summarises the technical and cost characteristics of different T&S infrastructure.

Chapter 2: Current Evidence of T&S Needs

Introduction

Notwithstanding the uncertainty set out above, evidence is already emerging of where and when early supply and demand is likely to come forward. Reviewing this early evidence can help us determine where early T&S infrastructure can be of most strategic value and enable the growth of the future hydrogen economy.

By connecting producers with consumers and balancing mismatches in supply and demand, T&S infrastructure will be critical in enabling hydrogen to play its full role in decarbonising the UK economy. Determining where and when hydrogen supply and demand is likely to come forward will therefore be essential in ensuring that the right infrastructure is available in the right place, at the right time. Since the publication of the Hydrogen Strategy in 2021, our understanding of where supply and demand is likely to locate has improved. This will help enable early strategic decision making across the hydrogen value chain.

Production

Alongside this document we have also published a Hydrogen Production Delivery Roadmap setting out how we expect the hydrogen production landscape to evolve towards 2035, and the key opportunities and challenges that we will face. This section sets out our current understanding of the likely locations, operating profile and infrastructure requirements for CCUS enabled and electrolytic hydrogen production. As set out in the roadmap, we also recognise the important role that technologies other than water electrolysis and CCUS enabled natural gas reformation could have in allowing us to scale up our hydrogen production capabilities. We will continue to take account of the specific infrastructure requirements of such technologies as the evidence base grows, but these are not discussed below.

CCUS enabled (blue) hydrogen production

CCUS enabled hydrogen plants currently offer the largest individual production capacities of any projects in the current UK pipeline, with the ability to produce hydrogen at consistent baseload close to large points of demand in industrial clusters from the mid-2020s onwards. CCUS enabled hydrogen could also have an important role in power sector decarbonisation. To support this technology, we are taking forward the development of four CCUS clusters, HyNet (North West England and North Wales), East Coast Cluster (Teesside and Humber), Acorn (North East Scotland) and Viking CCS (Humber).

CCUS enabled hydrogen plants are anticipated to run at fairly constant outputs throughout the year, for which pipeline infrastructure is optimal. This operating profile is unlikely to require significant volumes of storage to smooth supply. However, storage will likely still be required where offtakers do not have a constant profile of demand and to provide security of supply and broader resilience, for instance against maintenance shutdowns.

Electrolytic (green) hydrogen

Due to its potential electricity system, energy security and decarbonisation benefits, electrolysis is likely to be a core hydrogen production technology in the long run. It is able to operate flexibly, responding to the availability of electricity inputs, and when paired with renewable electricity can deliver zero carbon hydrogen.

Electrolytic hydrogen provides a way of utilising otherwise wasted ‘curtailed’ electricity, which is caused when we have more low carbon generation than we can use at that point in time. As we scale up deployment of renewables and nuclear, we expect that increasing levels of excess electricity generation can be used to produce hydrogen.

Compared to CCUS enabled hydrogen plants, electrolytic hydrogen production could be more dispersed across the UK, locating close to abundant renewable generation or away from regional challenges in water supply. However, in the early years of the hydrogen economy, location of demand is likely to be a key determinant of project location.

Electrolytic hydrogen plants are also assumed to operate more flexibly than CCUS enabled producers, driven by electricity prices, low carbon electricity availability and Low Carbon Hydrogen Standard (LCHS) requirements. This means, unless the plant is servicing a fully flexible offtaker, storage is likely to be needed to balance supply. Electrolyser capacity will also be a key determining factor of the scale of storage required.

Production: Transport & Storage Key Message

The fixed location of production plants in the UK project pipeline provides a clear indication of where early infrastructure could hold strategic value in the near term. The Hydrogen Strategy Delivery Update published alongside this Pathway document provides a visualisation of successful projects through Strands 1 and 2 of the Net Zero Hydrogen Fund (NZHF) and the first Hydrogen Allocation Round (HAR1).

In the longer term, T&S could be a critical enabler to allow electrolytic producers to locate electrolysers to maximise whole energy system and environmental benefits, for example behind grid constraints and away from areas of water stress.

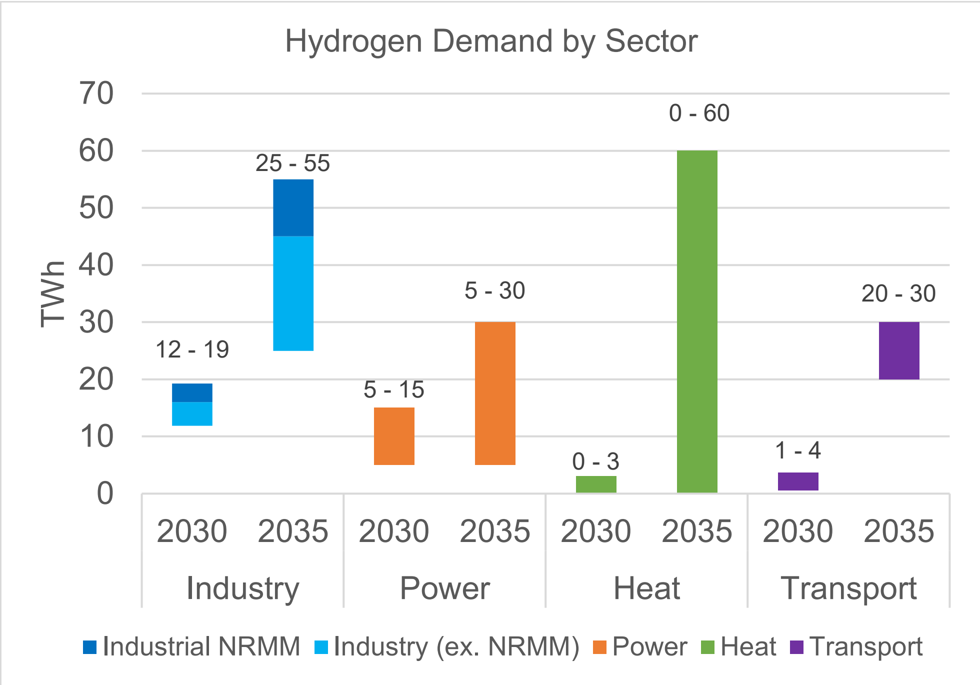
Demand

Low carbon hydrogen is a leading option to decarbonise industrial processes that are harder or more expensive to electrify, and can provide cleaner, homegrown energy for power, transport, and potentially home heating. It can play a vital role in enabling these sectors to contribute to our aim to have slashed emissions by 78% by 2035 in line with Carbon Budget Six, decarbonise the UK power system by 2035, subject to security of supply, and keep us on track towards delivering our legally binding target of net zero greenhouse gas emissions by 2050.[17]

The Hydrogen Strategy Delivery Update provides a comprehensive overview of the steps government is taking to promote hydrogen demand in the UK.

This section sets out our current understanding of where, when, and for what purposes early demand for hydrogen is likely to materialise and provides potential ranges for hydrogen demand across key sectors in 2030, 2035 and 2050. These ranges are an update to those provided in the UK Hydrogen Strategy and are intended to illustrate the potential scale of demand in each sector, but do not represent specific sectoral demand targets or policy positions. Figure 1 shows demand estimates for 2030 and 2035 for industry, power, heat and transport. The sectors included within the scope of the demand ranges are not exhaustive. Further detail on evidence sources and methodology is available in the analytical annex to this document.

Figure 1 - Hydrogen Demand by Sector



Industry

The Industrial Decarbonisation Strategy[18], published in 2021, set out how industry can reduce its emissions in line with net zero, including by replacing the use of fossil fuels with low carbon alternatives such as low carbon hydrogen, electricity, and bioenergy. One of its core principles is that government has a 'technology neutral' approach to industry's decarbonisation decision making, allowing industrial sites to choose the most suitable decarbonisation route for their context. For many industrial sites, electricity, hydrogen, and bioenergy are all possible options for replacing existing fossil fuel use. Carbon Capture Utilisation and Storage (CCUS) will also

[17] https://www.gov.uk/government/publications/net-zero-strategy
[18] https://www.gov.uk/government/publications/industrial-decarbonisation-strategy

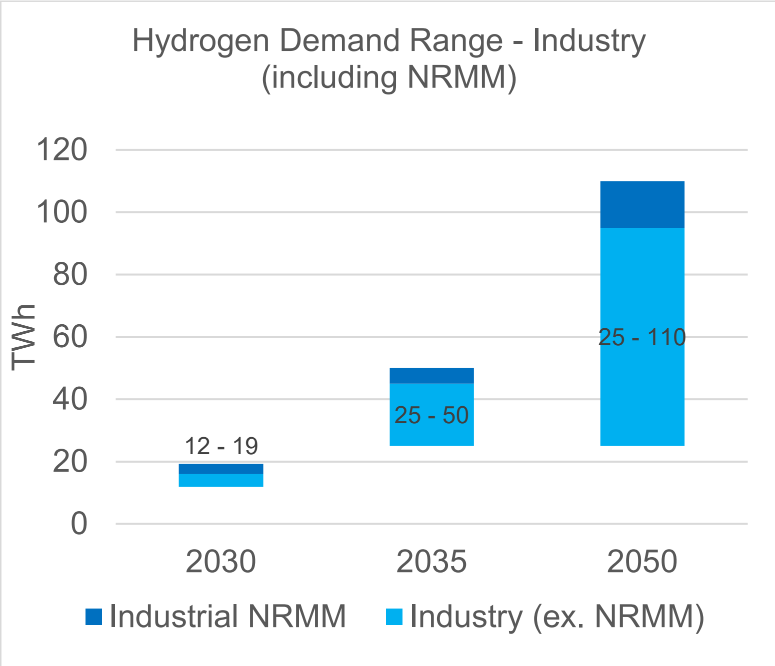
play an important role in the decarbonisation of industry, particularly for sectors with high process emissions such as cement. The optimal fuel switching technology will depend on several factors such as: (1) the specific technical requirements or limitations of the industrial process, (2) the commercial readiness of a suitable low carbon technology, (3) site access to low carbon fuels, (4) the relative cost of each technology, (5) the physical space requirements and implications of introducing different technologies (e.g. larger plot space requiring larger units, hazards), and (6) the wider policy landscape.[19]

Industrial sites in the UK have been producing and using hydrogen for years. This hydrogen is generally produced by steam methane reformation without carbon capture, which is not low carbon, or else as a by-product of another carbon intensive industrial process. We estimate that hydrogen is currently produced at around 30 sites in the UK, spanning various energy intensive sectors and production methods. This hydrogen is either used as a chemical feedstock, such as for the production of ammonia to manufacture fertilisers or can be combusted on site to be used as a fuel. Low carbon hydrogen will need to displace the carbon-intensive hydrogen used in industry as a chemical feedstock, where there are limited alternatives.

Low carbon hydrogen is also likely to be a leading option to decarbonise industrial processes that are harder or more expensive to electrify. Near-term opportunities for hydrogen conversion include high temperature steam boilers and combined heat and power (CHP) processes in sectors such as chemicals and refineries, especially in clusters with early access to hydrogen. In the future, we anticipate demand for hydrogen to emerge for new low carbon processes as well. For example, hydrogen is expected to be important for the reduction of iron ore in green steel production, and for the manufacture of low carbon fuels such as for aviation and shipping[20]. Alongside hydrogen's role as a chemical feedstock, we expect additional uptake via fuel switching of energy intensive sites, as well as those engaging in high temperature, direct fired processes. This is because in some cases hydrogen has several advantages over electrification, such as the ability to more easily convert existing combustion equipment and its capacity to achieve high temperatures owing to its similarities with natural gas.

[19] https://www.gov.uk/government/calls-for-evidence/enabling-industrial-electrification-a-call-for-evidence
[20] Note that hydrogen demand for the production of transport fuels is included in the demand ranges for transport, not industry.

Figure 2 - Illustrative hydrogen demand range in Industry including industrial Non-Road Mobile Machinery (NRMM)



Government analysis shows that industry is likely to be one of the main users of hydrogen, and an important early adopter. This is supported by evidence of real-world projects which are in development, including those in the first Hydrogen Allocation Round. Demand is anticipated to rise rapidly in the late 2020s and 2030s.

The ranges presented in Figure 2 for industry (ex. NRMM) are based on two scenarios for hydrogen used as an industrial fuel. The scenarios are based on analysis by DESNZ using the Net Zero Industrial Pathways (NZIP) model.[21] The ranges presented for industrial NRMM are based on recent research by ERM on the techno-economic feasibility for decarbonisation of NRMM and analysis by the CCC[22], with the upper bound based on a theoretical technical potential deployment pathway. Note that the demand estimates cover demand for industrial NRMM only. Other sectors that use NRMM may contribute further demand. Further detail on the methodology can be found in the analytical annex.

Industry is well positioned to utilise hydrogen T&S infrastructure, given there is a high concentration of likely demand within industrial clusters, where sites can share infrastructure, speeding up rollout and lowering costs. For these reasons, in the early years of the hydrogen economy it is likely that most industrial demand for hydrogen will be located within these industrial clusters.

However, roughly half of UK industrial emissions are produced by dispersed sites[23], outside of industrial clusters. Such sites will also need to decarbonise. We do not expect electrification to deliver the entirety of this decarbonisation. Current evidence suggests that for some industrial

[21] See Annex 4 of the Industrial Decarbonisation Strategy for details on the NZIP model and scenario framework
[22] See methodology description in box 4.3 of the CCC's CB6 methodology report
[23] https://www.gov.uk/government/publications/net-zero-strategy/3-reducing-emissions-across-the-economy

sites outside of clusters, hydrogen use could represent the least-cost decarbonisation pathway, subject to affordable hydrogen being available.

The government is committed to understanding the implications of repurposing the gas grid for transporting hydrogen, which could make hydrogen accessible to dispersed sites which are currently on the gas grid. As part of this, we will continue to explore the impact of different strategic decisions on the role of hydrogen for heat, given that these are likely to impact the potential cost and timing of any grid conversion undertaken to supply dispersed sites. In a scenario where there is limited repurposing of the existing gas infrastructure or build out of new network infrastructure, dispersed sites that opt to use hydrogen would likely require nearby production and storage infrastructure. This could be on-site, nearby, or as part of a local hydrogen network. In areas of limited grid connectivity, dedicated low carbon electricity generation to power electrolysers may also be required. Delivery of hydrogen by truck could also be suitable, particularly where demand for hydrogen is lower, and/or to industrial sites which are too remote for pipelines.

The operational profile of hydrogen demand is likely to vary by industrial sector and size of plant. However, compared to other potential end use sectors such as power and domestic heating, the demand from industry is likely to be relatively consistent across seasons. Many sites will also operate processes continuously throughout the day and night. Some hydrogen storage will be required to enable load balancing and ensure security of supply. This could be via large scale storage, or in limited circumstances, via smaller scale onsite storage.

Industry: Transport & Storage Key Message

The development of hydrogen T&S infrastructure within industrial clusters should be a priority in the 2020s. Developing pipelines to connect leading clusters could also facilitate greater security of supply for industrial users. There is the potential for widespread uptake of hydrogen in industry outside of clusters, but this is heavily dependent on the ability to access affordable hydrogen. T&S could serve as a critical enabler of this access.

Non-Road Mobile Machinery

Non-Road Mobile Machinery (NRMM) can be broadly defined as any mobile machine, transportable industrial equipment, or vehicle that is not intended for carrying passengers or goods on the road. This includes most construction vehicles, as well as generators, tractors, port cranes, and a wide range of other machinery. Equipment is used in a range of sectors such as construction, mining and quarrying, manufacturing, agriculture, forestry, logistics and transport.

NRMM can be powered by hydrogen either through use of a fuel cell or an internal combustion engine. There could also be opportunities to retrofit hydrogen powertrains onto some existing NRMM. Hydrogen has the potential to be an important decarbonisation option for NRMM, particularly for applications which require high mobility and high-power outputs and are operated in settings without access to a sufficient electricity grid connection. Hydrogen could also be useful as a low carbon fuel for generators, allowing equipment to be refuelled on site.

Fuel demand from NRMM is likely to be highly dispersed across the UK, with demand sources potentially incorporating both temporary and permanent locations and ranging from sites using a single piece of NRMM to larger sites where multiple and varied types of equipment are in use. Supplying hydrogen to NRMM therefore presents different challenges compared with supplying fixed industrial sites, where demand profiles are more predictable.

A range of hydrogen delivery options could be used for sites using NRMM, depending mainly on the size of demand and on the duration of the site. This includes trucked delivery (either to onsite refuelling bowsers or to refuel the NRMM directly), delivery and swap-out of hydrogen cylinders or container-based mobile refuelling bowsers, or onsite electrolysis (subject to site grid connectivity or onsite renewable power generation). Pipeline delivery may also be viable for large, fixed sites such as an airport or seaport.

NRMM: Transport & Storage Key Message

The T&S needs of NRMM sites will vary depending on the size of demand and on the duration of the site. Whilst there may be a role for pipelines in supplying larger fixed sites or hydrogen distribution hubs, the majority of hydrogen NRMM end users will likely be supplied by trucked hydrogen.

Power

Hydrogen to Power (H2P) – the conversion of low carbon hydrogen to produce low carbon electricity – is seen as a key technology in supporting our commitment for a decarbonised and secure power system. H2P plants can provide flexible low carbon generation capacity and can contribute to long-duration energy storage. It can be deployed at a range of scales to provide new low carbon flexible electricity generating capacity to complement variable renewable generation and provide a decarbonisation pathway for existing unabated gas generation.

Government analysis shows that having hydrogen available in the power sector could achieve emission reductions at lower cost than scenarios without hydrogen, by reducing the need for renewable build out and reducing curtailment.[24] In addition, in a world with high levels of electrification for decarbonisation across the economy, and hence more limited hydrogen use, greater H2P capacity could be required to meet the increased electricity demand.[25]

The power sector could require significant quantities of hydrogen to meet decarbonisation targets. H2P is therefore likely to be a key offtaker for low carbon hydrogen, creating demand across the hydrogen value chain. The early ramp-up of demand will in part be driven by the government's commitment to decarbonise the power sector by 2035, whilst ensuring security of supply. Beyond that, H2P capacity will likely continue to increase but load factors will decrease with time, reflecting the expected overall reduction in flexible technology running

[24] https://www.gov.uk/government/publications/modelling-2050-electricity-system-analysis
[25] https://www.gov.uk/government/publications/energy-and-emissions-projections-2021-to-2040

hours as renewable generation provides increasing volumes of electricity supply – as outlined in the case for change within the first REMA consultation.[26]

H2P will be heavily reliant on T&S infrastructure. The peak rate of hydrogen consumption will require hydrogen to be delivered via pipeline. The consumption rate, as well as the highly variable load profile (due to its role as flexible source of low carbon generation) means that large scale geological storage will be critical to enabling large scale H2P capacities. Internal modelling shows that the lower the load factor for H2P plants (more peaking) the greater the hydrogen storage capacity required.

Figure 3 - Illustrative hydrogen demand range in power

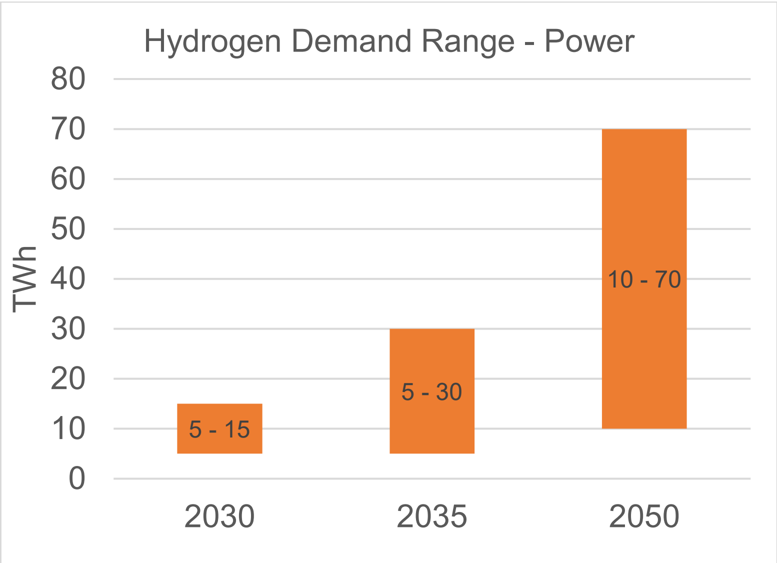


Figure 4 - Illustrative hydrogen to power capacity range

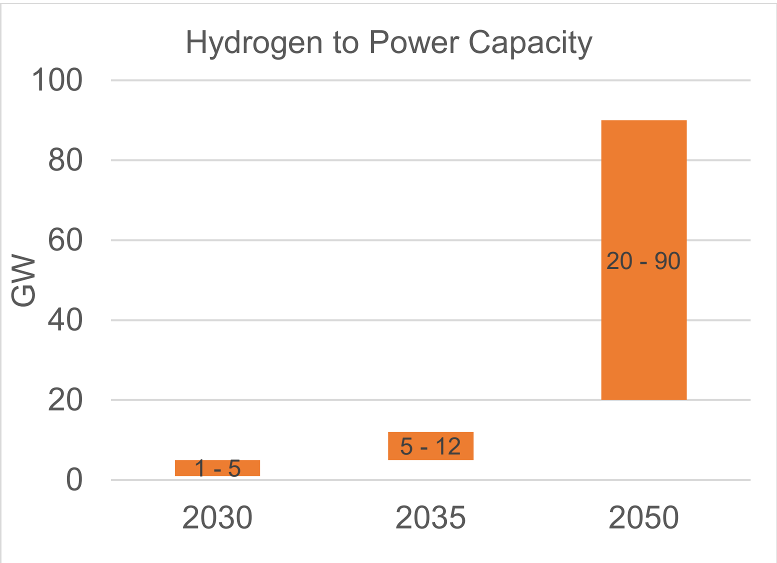


Figure 3 shows illustrative demand ranges for H2P, and Figure 4 shows illustrative ranges for hydrogen to power capacity. The ranges reflect uncertainty in the role of hydrogen in the power sector, driven by uncertainty in overall and peak electricity demand levels, the mix of electricity

[26] https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements

generation technologies, and the relative costs and advantages of hydrogen relative to other forms of low carbon flexible capacity. Further detail on the methodology used to estimate demand and capacity can be found in the analytical annex.

The mapping of larger power plants captured by the Digest of UK Energy Statistics (DUKES)[27] shows that whilst plants are located across England and South Wales, many are in potential hydrogen or CCUS industrial clusters. Power plants closer to hydrogen or CCUS clusters are more likely to decarbonise earlier due to the availability of infrastructure.

Power plants could potentially initially utilise a blend of hydrogen with natural gas. Blending hydrogen for these purposes is more likely to happen onsite, rather than upstream. Some industry stakeholders report that power plants linked to clusters could act as flexible offtakers due to their ability to take a variable volume of hydrogen to then blend onsite with natural gas prior to combustion. We are intending to further assess the value of onsite blending in potentially supporting development towards 100% hydrogen firing.

Power: Transport & Storage Key Message

Hydrogen pipelines and large-scale geological storage are critical to enabling 100% H2P. In the 2020s, alongside the deployment of 100% firing plants, some plants could start coming forward to fire a blend of hydrogen. We expect the majority of plants to initially locate near to industrial clusters, although not exclusively.

Heat

Decarbonising heating is a central challenge to achieving net zero, with heat in buildings accounting for 23% of all UK carbon emissions. Government has committed to take strategic decisions on the role of low carbon hydrogen heating in 2026. To ensure we meet our emissions reduction targets, these decisions will also need to determine our wider strategy on clean heat technologies, including the extent of electrification of heat through heat pumps.

Heat pumps and heat networks are established technologies that will be the primary means for decarbonising heating over the next decade and play a key role in all 2050 scenarios. Annual deployment of heat pumps will potentially need to reach up to 1.6 million installations by 2035.[28]

Whilst heat pumps and heat networks will be the primary means of decarbonising heating for the foreseeable future, there is the potential for hydrogen to play a role in future in some locations. The government will therefore continue its programme of research to assess feasibility.

Decisions on hydrogen heating will be taken in 2026 but we will accelerate work to analyse the costs and benefits of heat pathways. Once established, we will request the Future System

27 https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes
28 Deployment is assumed to be required to meet the turnover of fossil boilers outside of areas covered by heat networks as well as demand from new build homes.

Operator to advise government on the energy system impacts of heat decarbonisation pathways, including how best to manage a highly electrified system.

Figure 5 - Illustrative hydrogen demand range in heat

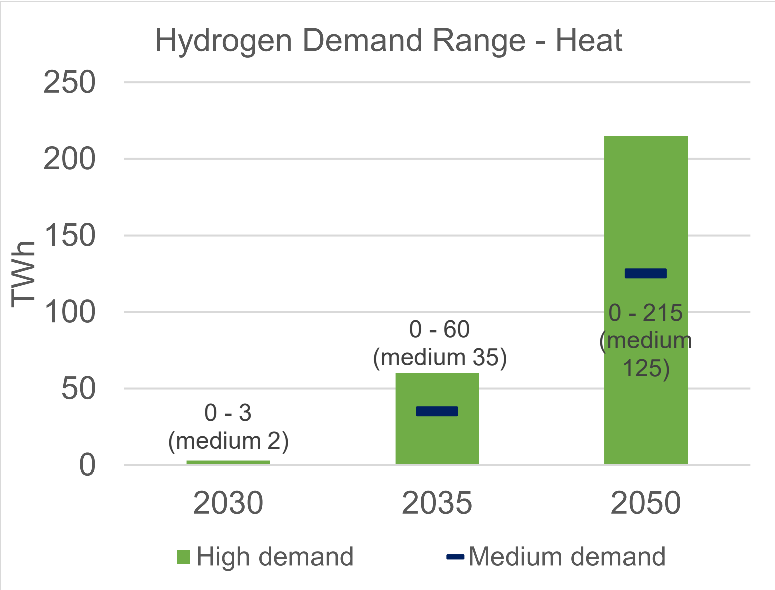


Figure 5 shows illustrative demand ranges for hydrogen in heat, including an indicative medium heat demand scenario. Estimates of hydrogen demand in heat are consistent with the scenarios used in the Net Zero Strategy[29] and the latest Carbon Budget Delivery Plan[30]. The low end of the range assumes there is no significant use of hydrogen for heating in buildings, with roll out of heat pumps ramping up from our 2028 target of 600,000 installations a year to up to 1.6 million a year by 2035. The high end of the range assumes relatively widespread use of hydrogen in heating for existing buildings on the gas grid, alongside a continued rollout of heat pumps at the rate of 600,000 a year. The medium demand scenario illustrates a more moderate adoption of hydrogen heating, for example where hydrogen is only deployed in specific regions or local areas or where hybrid heating systems are used. This does not represent a central estimate of hydrogen demand in heat.

Heat: Transport & Storage Key Message

Given the current wide range of uncertainty around hydrogen heat deployment, we do not anticipate this sector being a driver of infrastructure requirements prior to the 2026 strategic decisions on the role of hydrogen for heat.

Transport

Hydrogen has an important role to play in decarbonising heavier transport applications such as aviation and shipping, and potentially some buses and heavy goods vehicles (HGVs).

---

29 https://www.gov.uk/government/publications/net-zero-strategy
30 https://www.gov.uk/government/publications/carbon-budget-delivery-plan

Government expects battery electrification to remain the dominant zero emission technology for passenger cars and vans.

Figure 6 - Illustrative hydrogen demand per transport mode

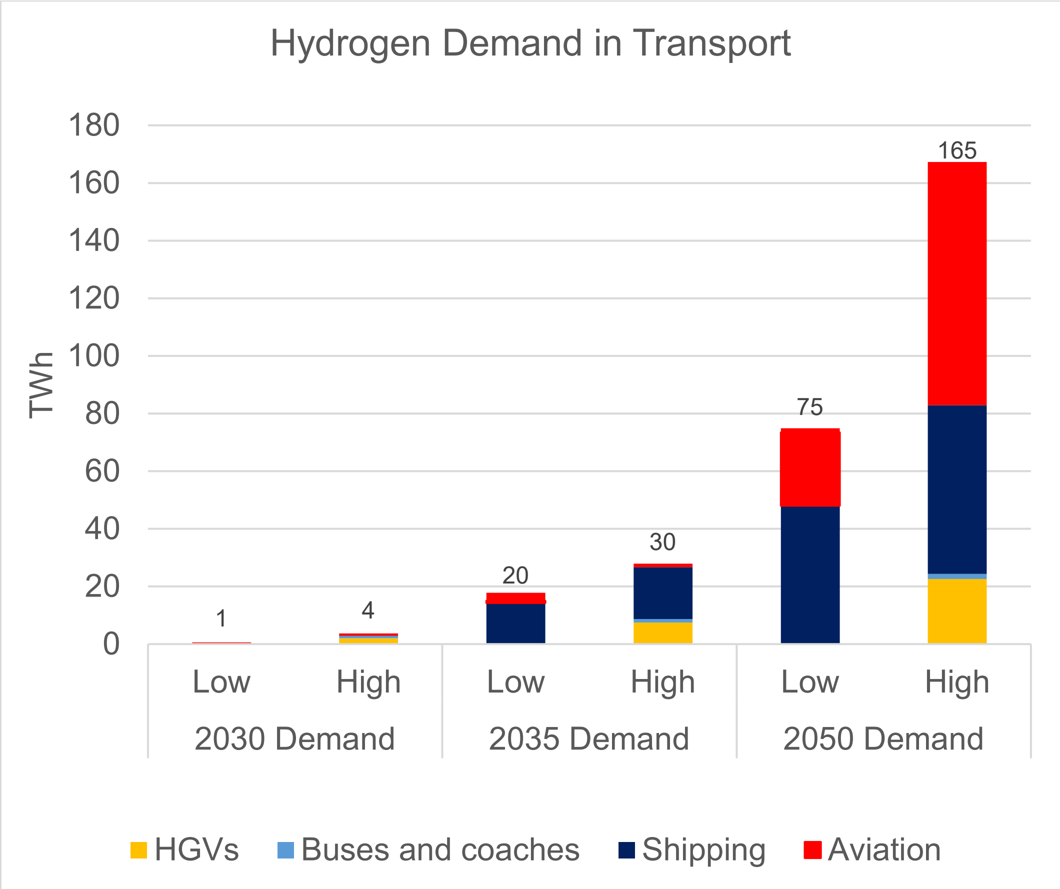


Figure 6 shows illustrative estimates of hydrogen demand in transport broken down by transport mode. Transport is currently expected to make up only a small proportion of hydrogen demand in 2030, led by potential use in buses and HGVs. Demand is expected to grow rapidly through the 2030s, predominantly driven by uptake in the maritime and aviation sectors. By 2050, transport could be one of the largest end-use sectors for hydrogen. Government analysis indicates that hydrogen demand in maritime (including derivative fuels) remains high in all scenarios and we recognise that there have been significant recent developments in the maritime sector that could result in demand coming forward sooner than current modelling suggests The Government will publish updated estimates for domestic maritime in the next update of the Clean Maritime Plan. Demand for aviation is more uncertain. It will depend partly on the availability of biomass and waste fossil feedstocks to produce Sustainable Aviation Fuel (SAF), and the development of zero emissions flight (ZEF) technologies. Further detail on the methodology used to estimate hydrogen demand in transport can be found in the analytical annex.

Road Transport

The transition to zero emission commercial vehicles is well underway in the smaller weight vehicle categories. Here, battery electric is becoming the early dominant technology for lighter

HGVs operating in the urban distribution market and for operations which have a duty cycle that brings them back to base every day.

Many manufacturers are also putting this technology to use in the largest trucks. However, batteries may not be the answer for all cases, especially in the larger weight classes. Manufacturers are bringing hydrogen fuel cell HGVs to the market which could offer a longer range between refuelling than most battery electric HGVs today and an experience most similar to that of diesel. The preferred technology for specific use cases will vary on factors such as vehicle operating weight, drive cycle diversity and maximum journey lengths.

The road freight sector is diverse, with a range of HGV use-cases and refuelling patterns. UK government policy on the transition to zero emissions is technology neutral, allowing the markets to dictate the best solutions for zero emission road freight. Both battery electric and hydrogen fuel cell, as zero exhaust emission technologies, will have a role in decarbonising the HGV sector.

Given current trajectories for development of both technologies, and feedback from across the sector, we expect that battery electric HGVs will be capable of meeting the needs of most use-cases by the 2035 and 2040 phase out dates, and likely much sooner. We expect that hydrogen fuel cell HGVs will likely play a role in decarbonising harder-to-decarbonise applications, for example where vehicles need longer ranges or rapid refuelling capabilities.

Hydrogen demand for HGVs is therefore dependent on the rollout rate of zero emission HGVs along with their associated infrastructure, and the relative costs and benefits of hydrogen compared to electrification. Similarly, hydrogen demand for buses and coaches is dependent on the rollout rate of zero emission vehicles and the relative costs and benefits of hydrogen compared to electrification. Overall energy demand for buses and coaches is low compared to other transport modes, so hydrogen demand volumes will be relatively small even at the high end of the range.

The Department for Transport intends to develop a zero emission HGV and coach infrastructure strategy for publication in 2024. The strategy will set a strategic direction and outline the respective roles and responsibilities of both government and industry towards the delivery of the refuelling and recharging infrastructure needed to meet the 2035 (for HGVs 26 tonne and under) and 2040 end of sales dates for new non-zero emission HGVs.

Maritime

The estimates of the demand for hydrogen from maritime presented in this document draw on the evidence that informed the Government’s Carbon Budget Delivery Plan, including a major external research project that was commissioned to inform the 2019 Clean Maritime Plan. We recognise that there have been significant developments since then that will influence the demand for hydrogen from maritime, including the successful agreement at the International Maritime Organisation (IMO) in July on an ambitious new strategy on the reduction of greenhouse gas (GHG) emissions from international shipping. The Government has developed a new maritime emissions model to provide more up-to-date insights into the demand for hydrogen from maritime. A first use of this model will be in the next update of the

Government's Clean Maritime Plan which will include updated decarbonisation scenarios for domestic maritime.

Hydrogen carriers like ammonia and methanol (produced from low carbon hydrogen) are expected to play a significant role in maritime decarbonisation. Based on the cost assumptions used in the external research project commissioned to inform the 2019 Clean Maritime Plan[31], it was estimated that ammonia would be the most prevalent fuel in shipping by around 2050. However, there is uncertainty regarding which hydrogen carrier will be the most cost effective and further analytical work may reach different conclusions on this. In addition, there are several characteristics of ammonia, such as its toxicity, which are a concern for some sectors. These characteristics may influence the choice of future fuel and therefore decarbonisation pathways may not be purely based on cost. In the nearer term, certain sectors operating primarily in UK territorial waters or solely between UK ports could be early adopters of low carbon hydrogen via combustion engines and fuel cells.

The demand range assumes the proportion of fuel purchased in the UK stays constant over time: this is highly uncertain, and if refuelling patterns change in the future, this could mean hydrogen demand for shipping is higher or lower than the range presented. If some fuel is imported, then the demand for domestically produced hydrogen for shipping would be lower than shown.

The location of hydrogen demand to produce derivative fuels used in maritime and aviation is uncertain. However, it is possible that they will be produced in similar locations to existing fuels, where the industrial infrastructure and knowledge is most available and there is proximity to existing major ports and airports.

Aviation

The Jet Zero Strategy[32] sets out the government's approach to delivering net zero UK aviation by 2050. The strategy recognises the role which hydrogen can play both in zero emission flight, through combustion or the use of fuel-cells, as well as a potential process input and direct feedstock for Sustainable Aviation Fuels (SAF). SAF is expected to play a significant role in aviation decarbonisation, but the majority of SAF is likely to come from biomass and waste fossil feedstocks in the short term, which use smaller amounts of hydrogen as a feedstock.[33]

The use of hydrogen as a feedstock in aviation is likely to increase in the future, as more novel technologies, like power to liquid, begin to scale. Hydrogen demand estimates are based on analysis by the Department for Transport (DfT). The range in demand for hydrogen in Figure 6 is driven by different levels of ambition and resource availability. Demand for liquid hydrogen in aviation is dependent on the rollout rate of zero emission aircraft. Demand for hydrogen to

[31] UMAS, E4Tech, Frontier Economics, CE Delft (2019), 'Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution. Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs. A report for the Department for Transport'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816018/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf
[32] https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050
[33] https://www.gov.uk/government/consultations/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate

make SAF is dependent on the level of ambition for SAF, achieved through the SAF mandate targets, and the availability of alternatives to power to liquid, particularly SAF made from biomass.[34] In high scenarios, hydrogen demand for SAF production could be very large, reaching around 85 TWh of demand.

For direct hydrogen use in aviation, the nature of demand and associated infrastructure requirements will depend on the size of airport. The Zero Emission Flight Infrastructure (ZEFI) report[35] categorises UK airports into several archetypes. For the smallest airports, trucked hydrogen with on-site storage may be the most viable option. For airports servicing regional and short-haul flights, trucked hydrogen could be viable in 2030, but pipeline delivery will likely be required by 2050 along with onsite liquefiers and storage. The same applies for large airports as no long-haul hydrogen flights are expected in 2030. However, large airports may eventually opt for dedicated off-site production to secure supply. The scale of future hydrogen demand for medium to large airports in the future may drive the formation of hydrogen hubs in their respective areas.

Transport: Transport & Storage Key Message

Hydrogen demand for transport is likely to increase rapidly in the 2030s, driven mainly by derivative fuels for maritime and aviation. In the 2020s, we expect some early demand to be driven by potential bus and HGV applications, which would require new hydrogen refuelling capability but would otherwise be deliverable without large scale hydrogen infrastructure. Current demand estimates indicate that the transport sector is therefore unlikely to be a driver of infrastructure requirements in the near-term, but deployment should continue to consider future anticipated locations, volumes of hydrogen required to meet decarbonisation ambitions across different transport modes, and access to different types of transport. The Government will keep the transport sector’s infrastructure requirements under review as better evidence becomes available on the hydrogen demand from different transport sectors, including in the refresh of the Clean Maritime Plan.

Costs of T&S infrastructure

Alongside production and demand drivers, the development of T&S infrastructure will be shaped by the technical and cost characteristics of the infrastructure itself. We have therefore published a separate report on the technoeconomic characteristics of T&S infrastructure, which describes T&S technologies and can inform strategic planning.

[34] SAF can be derived from a wide range of sources, which can achieve carbon savings relative to fossil fuel in different ways. The production technology employed is dependent on the feedstock used and therefore the chemical conversion process required to synthesise kerosene. Power-to-liquid (PtL) combines hydrogen and CO2 derived from a point source or captured from the air using non-biomass or fossil derived electricity.

[35] https://cp.catapult.org.uk/programme/preparing-uk-airports-for-zero-emission-aircraft/

Technoeconomic characteristics: Transport & Storage Key Message

Geological hydrogen storage represents the most cost-effective[36] and mature technology option to develop storage at the potential scale required by 2030, based on our current analysis as discussed in the Demand section in this chapter.

While road transport offers flexible transport for small quantities of hydrogen, pipelines are needed to transport large volumes of hydrogen to industrial and power users. Subject to the ongoing safety assessments, these could be either new build or repurposed, but the gas system impacts of any repurposing programme would need careful consideration to maintain resilience.

Locational factors affecting hydrogen economy growth map

DESNZ and Ofgem collaborated to produce an interactive map on the locational factors that may affect hydrogen economy growth. The purpose of this map is to collate publicly available location data on factors that might impact the growth the hydrogen economy, for example the location of existing gas infrastructure. The information presented in this map falls into the following categories: data on existing energy infrastructure and consumption; planning data on renewable energy projects and market intelligence data for potential hydrogen projects. In addition, the map includes layers produced by Edinburgh University for their UK Hydrogen Storage Database[37] highlighting prospective areas for hydrogen storage offshore.

One of the many market barriers to T&S deployment is a lack of information on hydrogen economy growth. Collating known information and publishing this is a small step to reducing this barrier, noting that uncertainty around supply and demand growth still presents challenges.

Unless otherwise stated within the map, the data is the latest and best available at the time of publishing. This version of the map is the first iteration, and the plan is to update the map in the future to sync with the latest data available.

We welcome feedback on this map, including suggestions for additional layers that could be included in future iterations which can be sent to hydrogenevidencebase@energysecurity.gov.uk. In this first version of the map, there are a variety of different visual representations for the layers. For example, different colour palettes and different methods of representing scale, such as colour and/or size gradients. This has been done with the expectation we will receive feedback on the preferred technique to consider in future iterations.

[36] Here we consider 'cost-effectiveness' as storage that can provide the greatest capacity at the lowest cost.
[37] https://www.ed.ac.uk/geosciences/research/institutes-centres/institutes/earth-planetary-science/edinburgh-earth-resources/research-activities/geoenergy/uk-hydrogen-storage-database

Next Steps

The evidence presented here provides a clear indication of where early infrastructure could hold strategic value in the near term.

We intend to continue updating our understanding of the emerging evidence of future hydrogen supply and demand, and the technoeconomic and locational factors that could shape T&S deployment. We also intend to produce further analysis on T&S requirements in 2024.

Alongside this document we have also published a Hydrogen Production Delivery Roadmap setting out how we expect the hydrogen production landscape to evolve towards 2035, and the key opportunities and challenges that we will face.

The Hydrogen Strategy Delivery Update provides a comprehensive overview of the steps government is taking to promote hydrogen demand in the UK. DESNZ have also published a consultation alongside this Pathway, seeking stakeholder views on the need for and design of a hydrogen to power business model.

Chapter 3: Near Term Needs Case

Building Emerging Regional Networks in Areas of Highest Potential

T&S infrastructure will be necessary to support the development of early hydrogen demand, particularly for industrial demand and power generation. Pipeline transport offers the most cost-effective and efficient mode of transporting the volumes of hydrogen expected to be required to support hydrogen demand in the early 2030s. Geological storage at scale can also provide a cost-effective option for deployment of hydrogen storage, which the decarbonisation of power generation is particularly reliant on.

As set out in Chapter 2, our demand analysis indicates that a near term strategic priority for hydrogen T&S network development should be to enable the decarbonisation of industrial and power users by the early 2030s as these are the sectors where we expect demand at scale by this time, and therefore a substantial need for hydrogen T&S infrastructure to first materialise. To enable this decarbonisation in the near term, which will support our CB6 and net zero goals, the hydrogen economy will need regional scale networks by the early 2030s to connect onshore salt cavern storage, which is geographically constrained, to production and industrial and power demand in those areas it is most likely to come forward within these timescales.

It is also important that early T&S infrastructure is located where it has potential to provide significant strategic value beyond the early 2030's, for instance through further connections to new production, demand or storage, for instance by linking to a core network. In collaboration with Ofgem we have produced an interactive map to collate publicly available locational data on factors that might impact the growth of the hydrogen economy. For example this includes, the location of existing gas infrastructure, which can give an indication of where early T&S infrastructure could be developed to provide the most strategic value both in the near term and beyond. This strategic value includes supporting security of supply for industrial and power demand through the timely development of sufficient capacities of T&S infrastructure.

We therefore consider that a necessary first step to support hydrogen demand growth is through supporting the development of emerging regional networks to connect early production and demand to suitable storage projects that can be developed by the early 2030's. As discussed in the HSBM Market Engagement document, there are limited locations in the UK with suitable geology for salt cavern storage. However, salt caverns offer the best opportunity to develop storage at scale that could be operational within the timeframe necessary to support such networks and hence our decarbonisation goals.

To support the development of the emerging regional networks, decisions on the suitable regional pipelines to take through the HTBM will need to be coordinated with the HSBM decisions on storage. In line with the conclusions set out in Chapter 2, building regional networks to connect early production and demand to storage at scale offers the best opportunity to support early industrial decarbonisation and hydrogen power generation. Such networks can be expanded in future as certainty grows on the exact shape and size of the hydrogen economy across locational aspects of electrolytic production, power generation and demand growth. For instance, the network may need to develop to support hydrogen demand that will likely scale up in the 2030s and beyond, such as aviation and maritime demand. This objective-based approach is intended to allow government to retain flexibility on how this ambition will be realised, subject to changes in infrastructure requirements that are specific to transport infrastructure (e.g. pipeline length/location).

The early support for regional pipeline networks could extend to the development of a core network connecting regions and sources of hydrogen production, storage and more dispersed demand. As outlined in Chapter 1, we agree in principle with the case set out by the NIC for a core network in their Second National Infrastructure Assessment[9] and the benefits it could provide. We intend to continue to review this position, and investigate where, when and how such a network might develop, and what the possible implications for the allocation of the T&S business models may be.

Ahead of HTBM support being available, we have created several measures to support the development of T&S assets through existing government programmes. For example, the Net Zero Hydrogen Fund and Low Carbon Hydrogen Agreement can provide limited funding for costs of associated T&S infrastructure for hydrogen production projects.

Further work is also required to assess the extent to which the HTBM may need to support local transport infrastructure to connect production and demand outside of the emerging regional networks in the future and how this would interact with the support available through the HPBM. The HPBM can support the development of limited hydrogen T&S infrastructure associated with production facilities, agreed on a project-by-project basis by taking several factors into account, including necessity, affordability and value for money. Whereas for the HTBM, we propose that it supports the development of shared transport infrastructure. Whilst not proposed to be in scope for the first allocation round, in future this may include local shared transport infrastructure.

Timing of T&S Requirements

Supporting the development of emerging regional networks in areas of highest potential is aligned with external analysis of T&S requirements. It is consistent across external sources of evidence and analysis that significant capacities of T&S will be required by 2030 to support a substantial ramp-up of T&S infrastructure required after this time, to deliver the network needed by 2035 and beyond, particularly to enable hydrogen to power.[38]

For instance, the CCC and NIC's analysis both indicate a need for a hydrogen T&S network by 2035. The CCC[39] expect non-power hydrogen demand in 2035 to be 65TWh due to

[38] External publications each use differing assumptions regarding the volume of demand, and how much demand is met by different offtakers. While there are differences in assumptions, similar conclusions are drawn regarding the need for a hydrogen T&S network, and this is also supported by our internal analysis.
[39] https://www.theccc.org.uk/publication/delivering-a-reliable-decarbonised-power-system/

manufacturing, construction and shipping but their central scenario predicts 85TWh of hydrogen demand for power by 2035. Based on this, the CCC estimates a need for 2,800 km pipelines by 2030 and 3,800 km by 2035. The CCC analysis also indicates a significant ramp up in storage requirements by 2035, from 2.1 - 2.8 TWh in 2030 to 3.3 - 5.2 TWh by 2035.

The NIC[9] recommend a core pipeline network by 2035 connecting a series of industrial clusters across England, Scotland and Wales to geological storage. The NIC estimates a minimum of 8 TWh of storage required by 2035, driven by the need to decarbonise the power sector.

We recognise the long lead times for large-scale infrastructure of this type. For example, conversion of existing geological storage facilities for hydrogen can take 3 - 5 years and new build storage can take 5 - 10 years to construct. Pipelines can take an estimated 6 - 12 months of pre-construction and around 3 years for construction or repurposing. It is therefore necessary for early T&S projects to progress with development to enable the T&S network we will likely need by the early 2030s to materialise.

To support our decarbonisation goals, while allowing some flexibility for project developers to align with the development of production and demand projects, we consider it necessary for early T&S projects to be in construction or operation by 2030.

Conclusion

We have set out that our demand analysis strongly indicates a reliance on T&S infrastructure to enable hydrogen demand, particularly industrial and power generation decarbonisation in the early 2030s. It is important that early T&S infrastructure is located in regions with both suitable geology to develop storage at scale within these timescales and with high potential for hydrogen production and demand to connect to. Building such infrastructure will create emerging regional networks with potential to grow and evolve in the future to meet broader strategic objectives.

This needs case supports an ambition to enable the early build-out of emerging regional hydrogen networks connecting production and demand to suitable storage at scale by the early 2030s, with potential to scale up beyond those early regions as the hydrogen economy grows. Suitable geology for storage at scale within these timescales is limited to a few regions, and we anticipate that developing emerging regional networks in two regions initially is a deliverable objective in practice. Our ambition for the first hydrogen storage and hydrogen transport business models is therefore to support **up to two hydrogen storage projects and associated regional pipeline infrastructure to be in operation or construction by 2030.** Specific projects will be assessed against our strategic objectives and other business model criteria, for which initial high-level proposals are set out in the Market Engagement documents for the HSBM and HTBM.

This ambition is consistent with the external analysis presented above, which clearly indicates a need for significant T&S infrastructure by 2030 and a ramp up of T&S capacity by 2035 to support anticipated hydrogen demand. Supporting up to two geological storage facilities and the associated regional pipeline infrastructure in areas with high demand potential will only provide part of the overall T&S likely to be needed by 2035, meaning there is a low risk of these assets becoming stranded.

Our strategic planning process is an iterative one, just as it is for existing energy networks, and we intend to produce further analysis on the location and timing of T&S requirements in 2024. In Chapter 1, we set out our agreement with the NIC in principle that there are benefits a core network could deliver to the hydrogen economy. In the future, we intend to do further analysis to assess the potential scale, pace and geography of developing such a network, as well as on how, where and when further storage at scale might be needed and be deliverable. This will be reflected in outputs of our strategic planning work, including setting ambitions for future allocation rounds of the HTBM and HSBM.

Next Steps

To support the ambition presented in this chapter, we intend to open the first allocation rounds for T&S business models in 2024 following engagement with the sector. Projects will be assessed against a range of clear and transparent criteria and our initial high-level timelines set out to name successful projects in Q4 2025. More detail on the initial high-level proposals for the allocation approaches is being published alongside this Pathway in the T&S business models Market Engagement documents.

Further work is needed to determine how hydrogen T&S infrastructure requirements in the early 2030s may develop as more evidence on hydrogen production and demand becomes available. We intend to conduct further analysis into the potential scale and scope of a core T&S network, as well as the need case for local transport infrastructure, and aim to relay this in future outputs of our strategic planning work, including setting ambitions for future allocation rounds of the HTBM and HSBM.

We have set out government's assessment of the use cases and required timing for early hydrogen infrastructure. As the hydrogen market develops, we expect suitable commercial conditions to materialise for assets to operate profitably. Support offered through the T&S business models will be made on a case-by-case basis as and when projects with a clear economic case can demonstrate that support from government can offer value for money and unlock crucial investment.

Chapter 4: Policy & Institutional Framework

The Future System Operator

In the Hydrogen Transport and Storage infrastructure: minded to positions[1], we set out our minded to position that in the short to medium term, the UK government, working closely with Ofgem and industry, should take a leading role in providing early strategic direction for the build out of hydrogen T&S infrastructure.[40] For the longer term, we set out our minded to position that the FSO takes on a central strategic planning role, within the statutory framework provided for by the Energy Act 2023.

We are now providing further details for the timeline of activities by which we expect the FSO to take on responsibilities for strategic planning for hydrogen T&S. We are setting an ambition for the FSO to formally take on these responsibilities from 2026. This ambition is subject to making progress on determining the scope of the FSO's strategic planning functions in relation to hydrogen T&S, progress on any necessary adjustments to the FSO's funding arrangements and making any regulatory changes (whether to legislation, licence conditions or industry codes) required to confer those functions on it.

To help us deliver on this ambition, we aim to launch a consultation by summer 2024 on the activities which the FSO should conduct for strategic planning of hydrogen T&S infrastructure. By determining what the FSO should be responsible for, this can in turn inform the funding and other regulatory arrangements needed. It will be important to ensure that the activities the FSO takes on are aligned with its responsibilities for the other parts of the energy system, including strategic planning for the electricity and natural gas systems.

The FSO's responsibilities for hydrogen from Day 1

Government has introduced legislation, as part of the Energy Act, to establish the FSO as a new, publicly owned organisation (described in the Act as the Independent System Operator and Planner or ISOP). The FSO will hold key roles for electricity and gas networks and will take a whole energy system approach when operating, planning, and developing these networks. The FSO will be independent – not only of other commercial energy interests, but also from the day-to-day operational control of government. Depending on a number of factors, including discussing timelines with key parties, the aim is for the FSO to be operational in 2024.

The government's minded to position is that strategic planning for hydrogen T&S will not be a Day 1 activity for the FSO. Instead, its focus will be on electricity and natural gas system planning. However, from Day 1 the FSO will need to account for hydrogen production, transport, storage and use in power to the extent that it impacts the electricity and natural gas networks. For instance, the FSO will need to consider where hydrogen can add system value by overcoming electricity network constraints and will need to account for the grid implications

[40] UK Government, Hydrogen Transport and Storage infrastructure: minded to positions, August 2023

of planned or potential hydrogen electrolysers or power plants. Similarly, when conducting system planning for natural gas infrastructure the FSO will need, for instance, to consider what opportunities there may be to repurpose natural gas infrastructure, which could help achieve substantial cost savings compared to new build hydrogen pipelines.

Centralised Strategic Network Planning (CSNP) is the activity through which the FSO will conduct energy system planning. It will cover electricity transmission network planning along with gas strategic network planning, to enable it to undertake whole system planning and a holistic view of the energy system. Ofgem have consulted on the CSNP[41] and have recently published their Decision on the framework for the Future System Operator's Centralised Strategic Network Plan[42], setting out the broad process and regulatory framework that will be introduced for the FSO to deliver it.

In line with the FSO's Day 1 activities, initially CSNP will need to take account of hydrogen in so far as it impacts electricity and gas networks, but would not directly conduct strategic planning for hydrogen T&S. Our expectation is that when the FSO takes on responsibility for strategic planning for hydrogen T&S, CSNP will also account for hydrogen T&S infrastructure specifically. This would support efficient decision making for what hydrogen T&S is required, thereby unlocking investment, ensuring build out costs are minimised and providing greater certainty for hydrogen producers and users seeking to connect to network infrastructure. Including hydrogen in CSNP would also help ensure that strategic planning for hydrogen T&S takes a whole system approach, taking accounting of existing and planned electricity and natural gas infrastructure.

Prior to the FSO taking on responsibilities for strategic planning for hydrogen T&S directly, the government will be responsible for this and will follow the strategic objectives set out in Chapter 1 of this publication. Government will provide support through its T&S business models to incentivise the development of T&S infrastructure. Whilst government is responsible for the strategic planning of hydrogen T&S infrastructure, we will work closely with the FSO to best support this, drawing on its expertise as the electricity and gas system planner. Similarly, during this time we will support the FSO to help ensure it is well positioned to take account of the production, transport, storage and use of hydrogen when meeting its responsibilities to conduct CSNP and other activities as the electricity and gas system planner.

The FSO's responsibilities for hydrogen longer term

We are setting an ambition that from 2026, the FSO will formally take on responsibility for strategic network planning for hydrogen T&S. The purpose of this is to provide the market with a realistic timeline by which the FSO as a public body, with operational independence from government, can take on strategic planning for hydrogen T&S, working to integrate this into its whole system approach to energy infrastructure planning in Great Britain.

---

[41] Centralised Strategic Network Plan: Consultation on framework for identifying and assessing transmission investment options

[42] Decision on the framework for the Future System Operator's Centralised Strategic Network Plan | Ofgem

We recognise that 2026 is a stretching ambition for the FSO to expand its capabilities to conduct activities for strategic planning for hydrogen T&S. We will work with the FSO and with Ofgem to ensure a smooth transition. We also expect that the extent of the activities the FSO conducts for this will evolve over time as hydrogen T&S markets grow and its capabilities develop.

Details of the activities the FSO should take on for strategic planning for hydrogen T&S have not yet been determined. The 2026 ambition is therefore subject to progress being made on determining the scope of these activities, which will guide funding arrangements and any legislative and/or regulatory changes needed to enable this. We will work closely with Ofgem and the FSO to define these activities and to help ensure the FSO has the capabilities to conduct them. We are therefore aiming to launch a consultation by summer 2024 on the FSO's scope of activities for strategic planning for hydrogen T&S.

This is intended to build on the series of consultations that the government and Ofgem have launched to determine FSO activities for electricity and gas system planning. We anticipate there may be similarities between the FSO as the gas system planner for natural gas and its responsibilities for hydrogen. Key activities which the FSO will take on as the system planner for natural gas include providing an advisory role to the government and to Ofgem, conducting gas network capability assessments, developing innovation and market strategies, and promoting system resilience and security of supply. Further information of the agreed and potential roles for the FSO, including as the gas system planner are provided in the Future System Operator - Second Policy Consultation and Update (August 2023).[43]

The FSO will also be commissioned in early 2024 to produce an initial Strategic Spatial Energy Plan as recommended by Nick Winser, the UK's Electricity Networks Commissioner, in his review of electricity transmission network deployment. The first iteration of the SSEP will cover associated infrastructure for power generation, including offshore generation in GB waters, as well as hydrogen assets, to enable a more efficient electricity network and reduce waiting times for generation projects to connect to the grid. Further detail on the government's approach to the Strategic Spatial Energy Plan is provided in the Transmission Acceleration Action Plan.[44]

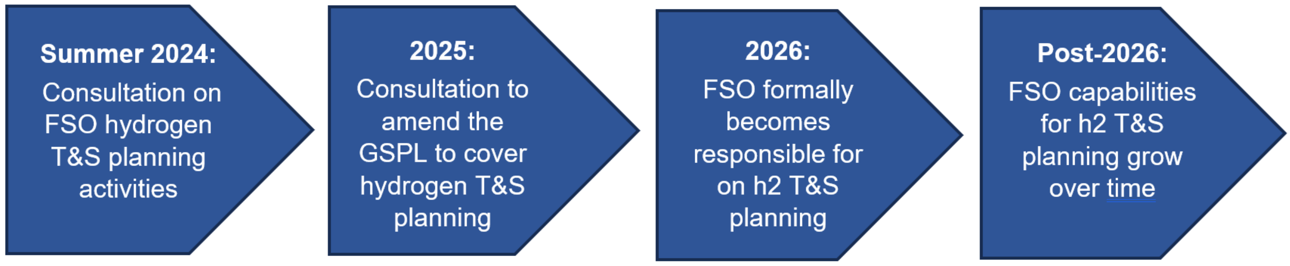
The regulatory changes required for the FSO to formally take on functions relating to strategic hydrogen T&S planning will depend on the final scope of activities it will be carrying out. In line with our minded to position that strategic planning for hydrogen T&S will not be an FSO Day 1 activity, we anticipate that initially the FSO's responsibilities under the Gas System Planning Licence (GSPL) would not include hydrogen planning. For the FSO to become responsible for strategic planning for hydrogen T&S our expectation at this stage is that this will fall under its responsibilities as the holder of the Gas System Planner Licence, and the GSPL will therefore need to be amended to set new obligations on the FSO.

Ofgem recently consulted on draft conditions for the GSPL which cover the FSO Day 1 activities for natural gas, with a statutory consultation on the FSO's Day 1 licence to be

[43] UK Government, Future System Operator - Second Policy Consultation and Update
[44] https://www.gov.uk/government/publications/electricity-networks-transmission-acceleration-action-plan#:~:text=The%20Transmission%20Acceleration%20Action%20Plan,design%20standards

published in 2024, prior to the FSO's launch.[45] If any changes are required to the GSPL to enable the FSO to take on a strategic hydrogen T&S planning role, the aim would be to consult on those in 2025. We think this broad timeline will help us deliver on our ambition for the FSO to take on strategic hydrogen planning for T&S from 2026. Below is an illustrative timeline to set out these steps:

Figure 7 - Illustrative timeline for FSO to take on responsibility for strategic planning for hydrogen T&S:



Next Steps:

Government is responsible for strategic hydrogen T&S planning until FSO takes on this role in line with the strategic objectives set out in Chapter 1. During this time, government and the FSO will work together to help ensure that in its strategic planning for hydrogen T&S, government is able to draw on the FSO's expertise as the electricity and gas system planner, and that the FSO is supported to best account for hydrogen in so far as is required to in meeting its obligations for electricity and natural gas.

DESNZ aim to consult by summer 2024 on the scope of strategic hydrogen T&S planning activities for the FSO. If any changes are required to the GSPL to enable the FSO to take on a strategic hydrogen T&S planning role, the aim would be to consult on those in 2025.

Government will work with the FSO to help ensure it develops the necessary expertise and capabilities for a smooth transition when it takes over responsibilities for strategic hydrogen T&S planning.

Our ambition is for the FSO to formally take on strategic planning for hydrogen T&S from 2026. This is subject to making progress on determining the scope of the FSO's strategic planning functions in relation to hydrogen T&S, making any regulatory changes (whether to legislation, licence conditions or industry codes) required in connection with conferring those functions on it and making any related adjustments to the FSO's funding arrangements.

[45] Ofgem, Future System Operator (FSO) draft licences consultation

Regulatory Frameworks

Government is exploring a wide range of policy and regulatory levers to support the development of the hydrogen economy.

As set out in the hydrogen transport and storage infrastructure: minded to positions, hydrogen is a “gas” for the purposes of the Gas Act 1986, and therefore regulatory requirements and prohibitions that apply to the transportation, shipping, supply and storage of natural gas may also apply to hydrogen. In responses to the T&S infrastructure consultation, it was clear that stakeholders are engaged with the subject matter and that many are concerned that the existing market framework and industry commercial arrangements could present barriers to the emergence of the hydrogen economy.

It is government’s intention to keep the market framework and industry commercial arrangements under review with a view to introducing timely amendments where they are warranted. This review will include ongoing work taking place through the Hydrogen Delivery Council’s Transport and Storage Working Group in the first instance but is likely to encompass further engagement with stakeholders, for example via a call for evidence and/or consultation on more specific proposals at a later date.

Alongside economic regulation, establishing a non-economic regulatory framework that is suitable for hydrogen projects will be important for ensuring the UK meets its ambitions for the hydrogen economy and net zero. We have been assessing the applicability of the current regulatory framework, and working to implement timely changes where needed to ensure projects can be enabled in a timely manner.

In 2022/2023, we assessed regulatory barriers facing hydrogen projects in our Regulatory Frameworks chapter, within the Hydrogen Transport and Storage Infrastructure consultation. In the government response we set out areas of action, such as:

- On planning regulations, the government recognises the need for clear and robust processes and guidance. The government has committed to improving the process for Nationally Significant Infrastructure Projects (NSIPs) to make it better, faster, and greener. The NSIP Action Plan sets out 18 actions to achieve this, working to make the system more optimal, while keeping communities and the environment at the heart of decision-making. One of the reform areas in the NSIP Action Plan is to improve system-wide capacity and capability, which includes developing skills and training, and extending proportionate cost recovery by the Planning Inspectorate and key statutory consultees to support effective preparation and examination of NSIPs and build resilience into the system.
- New drafts of National Policy Statement documents were published for consultation, which included references to hydrogen to provide greater clarity and guidance on hydrogen planning and development. These changes aim to help projects navigate the planning process and highlight the urgent need for all types of low carbon hydrogen infrastructure.

- Wider planning reforms, being led by the Department for Levelling Up, Housing and Communities. Planning reforms are being partly delivered through the Levelling Up and Regeneration Act and partly through reviews of national planning policy.
- On environmental regulations, UK regulators worked together, with industry and other stakeholders to produce guidance on Emerging Techniques for Hydrogen Production with Carbon Capture. Further guidance is planned on emerging techniques of hydrogen production via electrolysis. These documents will help industry navigate these complex areas to bring new projects to fruition.
- Establishing the Hydrogen Regulators Forum in January 2022 to determine current and future non-economic regulatory responsibilities across the value chain. The Regulators Forum formalises engagement with other regulators by holding meetings to identify, prioritise, and coordinate policy action on regulatory challenges, address gaps, and implement any changes required to the existing non-economic regulatory framework. These meetings work to establish a collective understanding of the non-economic regulatory challenges faced by different use cases, including strategic considerations of resource prioritisation to maximise impact, and to ensure that risks are identified and appropriately managed. The Regulators Forum has also established subgroups to structure bespoke sessions on different topics and regulatory areas, including offshore, the environment, and standards.
- Publishing the Offshore Hydrogen Regulation Consultation, as an initial approach to regulate offshore hydrogen pipelines and storage infrastructure.

In September 2023, the UK Government addressed critical barriers impacting the deployment of first-of-a-kind offshore hydrogen projects. The UK Government made three changes through secondary legislation, to extend existing offshore gas pipeline and storage regulatory frameworks, to cover offshore hydrogen pipelines and storage. These changes ensure the environmental and decommissioning aspects of offshore hydrogen projects are duly considered and also form part of an initial framework to facilitate hydrogen exports via pipelines, enabling cross-border pipeline trade. Government regards this as an initial approach to regulatory design which is operable for early offshore hydrogen projects and may be subject to further evolution. This position is set out further in the Offshore Hydrogen Regulation Consultation and government response.

We have also published a research project conducted by Verian (formally Kantar Public) alongside this publication, that explored barriers hydrogen projects may experience with relevant planning regulations, as well as potential solutions that could reduce these barriers. The Government recognises that local authorities, as well as the wider planning sector, face serious capacity and capability challenges which have resulted in delays, including in the processing of planning applications, impacting on homeowners and developers alike. To address this, the Department for Levelling Up, Housing and Communities has developed a comprehensive Planning Capability and Capacity programme which provides the direct support that is needed now, delivers funding to local government, providing upskilling opportunities for existing planners, and further developing the future pipeline into the profession. Alongside this, DESNZ will further consider the recommendations contained in the Verian report and continue to work with relevant bodies to mitigate the impact of these barriers where possible.

Government has been engaging closely with industry, regulators, other countries, and international bodies to identify regulatory barriers through coordinated work on a range of regulatory issues. These discussions help develop a stronger understanding of different regulatory areas and informs the necessary work required on both policy and technical fronts to address these challenges. An example of action here is producing the aforementioned offshore hydrogen legislation changes and guidance on Emerging Techniques for Hydrogen Production with Carbon Capture.

Next Steps

The regulatory framework as it relates to hydrogen is broad and complex, including rules and regulations relating to the environment, safety, markets, competition, planning and specific end uses. As the hydrogen economy develops, new regulations and timely amendments may be required.

DESNZ recognises the vital role of early hydrogen projects for the growth of the hydrogen economy. Given the emergence of first-of-a-kind offshore hydrogen projects in UK waters, DESNZ are leading regulatory coordination for offshore hydrogen projects to ensure relevant and timely project approvals/consents are obtained through close engagement with project developers, regulatory bodies and devolved administrations. This will enable the identification of regulatory issues experienced by early UK hydrogen projects and inform ongoing work on future regulatory design. Regulatory guidance from DESNZ to UK industry and regulators is not currently planned but is being kept under review.

DESNZ is also working with relevant regulators to explore the value of hydrogen pipeline gas quality standards and to prioritise assessing the environmental regulatory regime for hydrogen - to ensure it is adequate for UK hydrogen projects. DESNZ will consider the views raised in the Hydrogen Transport and Storage Infrastructure Consultation and Offshore Hydrogen Regulation Consultation when further policy/regulation is being designed.

Government will continue working with regulators and industry to help ensure regulatory coordination and to develop a common understanding on how current regulation supports hydrogen networks and storage. Government will work to ensure that regulatory frameworks evolve in a manner that supports scaling up the hydrogen economy for our 2030 ambitions and to help meet Carbon Budget 6 and net zero objectives.

Conclusion & Next Steps

This Pathway is an early output of the strategic planning activities DESNZ is undertaking prior to these becoming a responsibility of the FSO. As strategic planning will continue to assess new evidence of network needs, the needs case for T&S infrastructure will evolve and grow. The strategic planning process is an iterative one, just as it is for existing energy networks. We intend to produce further analysis on the location of T&S requirements in 2024, as evidence on the growth of hydrogen production and demand improves. This will be reflected in outputs of our strategic planning work, including setting ambitions for future allocation rounds of the HTBM and HSBM.

The Pathway sets out the high-level strategic ambitions for T&S infrastructure based on an assessment of the available evidence across the critical variables driving T&S network needs. The conclusions of this process, as set out in Chapter 3, are that our near-term ambition for transport and storage infrastructure is to support up to two hydrogen storage projects and associated regional pipeline infrastructure be in operation or construction by 2030.

As set out in Chapter 1, T&S infrastructure beyond emerging regional networks could be critical in fulfilling our strategic objectives. In 2024 we intend to provide further analysis on T&S requirements. We agree in principle with the benefits that a core network could deliver to the hydrogen economy, and in future intend to conduct more analysis to assess the potential scale, pace and geography of developing such a network. Limited local transport infrastructure is already supported through the HPBM, and we intend to keep the needs case for this infrastructure under review to help ensure that sufficient support is available as needed, taking account of the respective scopes and interactions between the HPBM and the HTBM.

The high-level strategic ambitions for T&S set out in the Pathway are intended to guide the allocation of the first round of the transport and storage business models, which are being designed for 2025. Our initial high-level proposals for the business models' allocation processes, including eligibility and assessment criteria can be found in our Market Engagement documents, published alongside this Pathway. We aim to provide further detail on the application guidance for the first allocation rounds of the business models in Q2 2024. Our aim is for the first allocation round application windows to open in Q3 2024, with a view to announcing successful projects in Q4 2025.

To provide the enduring institutional framework to enable the roll out of T&S infrastructure, we have also set an ambition for the FSO to formally take on responsibility for strategic hydrogen T&S planning from 2026. DESNZ aim to consult by Summer 2024 on the scope of strategic hydrogen T&S planning activities for the FSO.

Ensuring there is a regulatory framework that is suitable for hydrogen projects will be important for helping the UK meets its goals for the hydrogen economy and broader net zero ambitions. To help ensure there is a regulatory framework that enables and supports the T&S network, the Government will continue working with regulators and industry to help ensure regulatory coordination and to develop a common understanding on how current regulation supports the production, use, transport and storage of low carbon hydrogen.

Hydrogen Demand Analytical Annex

This analytical annex provides more detail on the hydrogen demand estimates set out in Chapter 2 of this document. It explains the methodology and assumptions used to estimate demand in each sector. It also highlights some key uncertainties affecting demand.

We have estimated hydrogen demand from a range of end use sectors in the UK: industry, power, heat and transport (HGVs, buses & coaches, maritime and aviation). Further demand could come from uses that are not modelled here, including blending into the gas grid or export to other countries.

The methodology, assumptions and sources we have used vary by sector. For each sector, the approach we have chosen aims to show an illustrative demand range based on the best currently available evidence and reflecting the key uncertainties driving demand. Using a tailored approach for each sector allows us to model sectors in more detail, explore specific considerations affecting certain sectors more than others, and understand a wider range of outcomes for the role of hydrogen. However, this means the demand ranges for different sectors are not necessarily based on consistent scenarios, so caution should be used when comparing demand ranges between sectors. For example, it may not be appropriate to combine the low scenarios of every sector to estimate a lower bound for hydrogen demand, as this may not be consistent with carbon budget targets when considered at a whole system level. This analysis should therefore be viewed alongside whole system analysis[46] when considering the role of hydrogen in reaching carbon budgets and net zero.

Hydrogen demand is highly uncertain. The ranges presented illustrate the scale of hydrogen demand in a range of sectors, but in most cases do not show a full range of potential outcomes for hydrogen. Changes in technologies and markets over the next decades could mean there are net zero-consistent scenarios where demand for hydrogen is higher or lower than the ranges presented. To reflect the uncertainty in the analysis, the demand estimates for 2035 and 2050 have been rounded to the nearest 5 TWh except where demand is small (<5 TWh).

The ranges illustrate what demand could look like in different sectors, but do not represent demand targets or policy positions.

[46] For example, analysis for the Net Zero Strategy and Carbon Budget Delivery Plan

Industry

Figure 1 - Illustrative hydrogen demand range in industry (including NRMM)

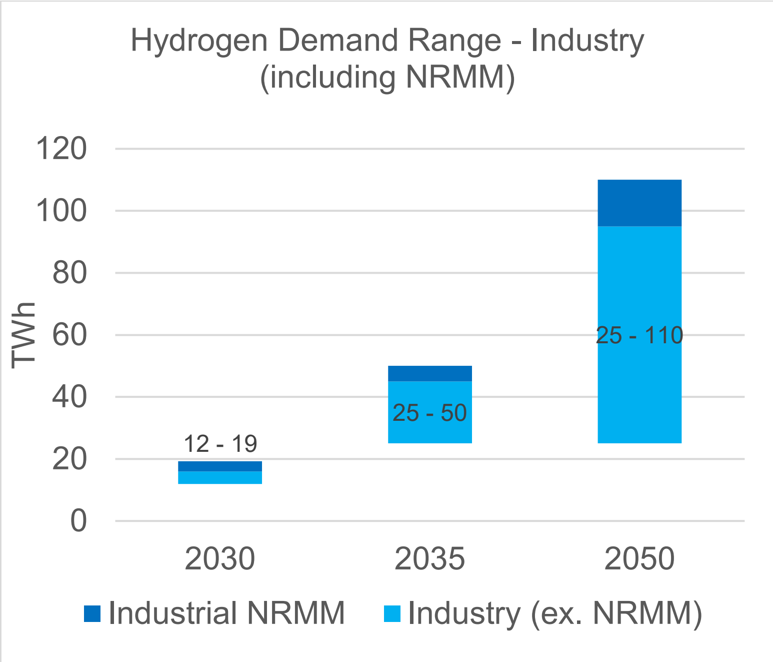


Figure 1 shows the potential demand for hydrogen in industry, including industrial non-road mobile machinery (NRMM). The definition of industry used here is in line with the definition used in the Net Zero Strategy[47].

Industrial demand excluding NRMM

The demand estimates for all industrial sectors except NRMM are based on DESNZ analysis using the Net Zero Industrial Pathways (NZIP) model[48]. The model calculates the most cost-effective decarbonisation route for industry for a given set of assumptions, including fuel and equipment costs and availability of CCUS and hydrogen. Key assumptions relevant to hydrogen demand are as follows:

- DESNZ estimates of hydrogen production costs for electrolytic and CCUS enabled hydrogen are an input to NZIP. Hydrogen production is assumed to take place in industrial clusters.
- NZIP calculates hydrogen transport and storage costs for a given site based on the distance an end-user is from an industrial cluster point where the hydrogen is assumed to be produced. The model therefore does not account for situations where hydrogen is produced at or near to an industrial site outside of the clusters, though this is a possibility being explored by some real-world electrolytic hydrogen projects.

[47] Under this definition, industry includes manufacturing, construction and industrial non-road mobile machinery; it does not include industrial buildings, oil & gas or mining.
[48] See Annex 4 of the Industrial Decarbonisation Strategy for details on the NZIP model and scenario framework

- NZIP models the demand for hydrogen for industrial fuel switching but does not model demand for hydrogen used as a chemical feedstock.

The low end of the demand range shown here is based on the ‘cluster networks’ scenario described in the Industrial Decarbonisation Strategy, where hydrogen is only available within 25km of industrial clusters. The high end of the range is based on the ‘national networks’ scenario, where hydrogen is available to all sites and the least-cost option of hydrogen transport is selected from direct pipeline to a production point, trucking, or grid hydrogen (if available). Grid hydrogen accessibility begins at the clusters and expands geographically in small increments up to 2050. Having hydrogen available at dispersed sites significantly increases the potential hydrogen demand in industry. The range shows a set of plausible pathways for industrial decarbonisation, but demand for hydrogen in industry could be outside of this range. As well as the uncertainty around hydrogen availability outside of clusters, there is additional uncertainty around technology readiness and the cost-effectiveness of hydrogen relative to other decarbonisation options. There could also be additional demand for low carbon hydrogen as a chemical feedstock.

Industrial NRMM

Demand estimates for industrial NRMM are based on recent research by ERM on the techno-economic feasibility for decarbonisation of NRMM and analysis by the CCC[49]. The lower end of the range assumes no hydrogen is used to decarbonise NRMM, with other decarbonisation options proving more appropriate. The higher end of the range in 2050 explores the maximum technical potential for hydrogen uptake. It assumes that all industrial NRMM switches to a hydrogen internal combustion engine or a fuel cell system. The upper values for 2030 and 2035 reflect a technical potential deployment pathway for hydrogen among industrial NRMM, identified by the CCC.

The ranges only include hydrogen demand for industrial NRMM. Demand for hydrogen in NRMM in other sectors, such as agriculture, could add further demand beyond the ranges shown.

[49] See methodology description in box 4.3 of the CCC’s CB6 methodology report

Power

Figure 7 - Illustrative hydrogen demand range in power

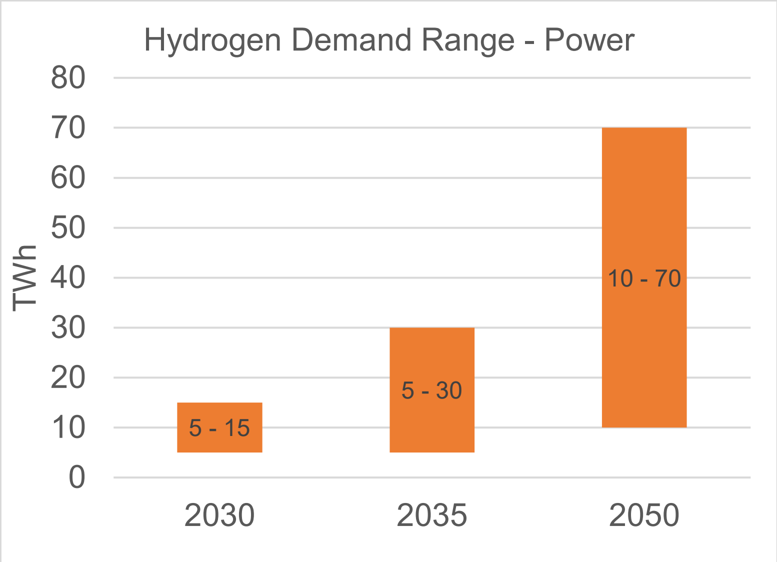


Figure 8 - Illustrative hydrogen to power capacity range

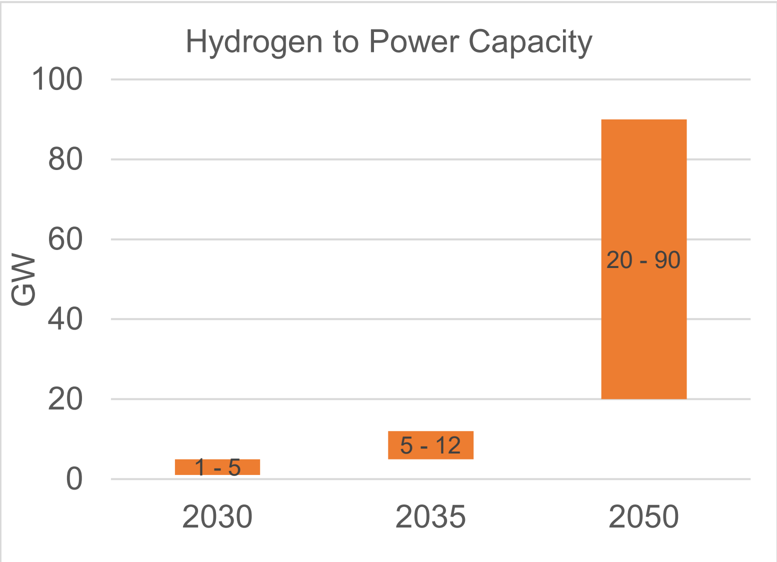


Figure 2 and Figure 3 illustrate demand and capacity ranges for hydrogen-to-power (H2P). These ranges are illustrative scenarios meant to highlight what demand and capacity government expect could be needed in 2030, 2035 and 2050. They are based on evidence sources (see methodology section below) which consider the different roles that H2P could play in the power system. For example, some sources point to H2P as a key peaking solution which could also be used for security of supply while others think it could have more of a midmerit role at higher load factor[50]. We think there is value in considering various scenarios and assumptions when thinking about how much H2P could be needed, as this allows us to understand the uncertainty in hydrogen demand for power.

The ranges reflect the high levels of uncertainty associated with the H2P sector, especially in 2050.

Key enablers such as fuel availability and hydrogen transport and storage infrastructure coming forward can affect how much H2P is deployed onto the system and therefore impact the suggested ranges. Overall and peak electricity demand levels as well as H2P costs and benefits compared to other forms of low carbon flexible technologies are also factors which could impact H2P deployment.

We expect to update these figures in 2024 as we improve our internal analysis on the role of H2P in the energy system.

Methodology

The ranges draw on recent literature from various external and internal sources, including DESNZ's analysis on net zero and the power sector[51]; LCP's analysis on the need for government intervention to support hydrogen to power[52]; National Grid's Future Energy Scenarios (FES)[53]; Afry's analysis on the benefits of long duration electricity storage[54]; and CCC's analysis on delivering a reliable decarbonised power system[55]. The ranges also consider market intelligence on hydrogen-to-power rollout. The figures for all years are drawn from the studies listed above, but with some adjustments:

- 2030: figures from the CCC analysis are excluded as market intelligence suggests the hydrogen capacity and demand modelled in 2030 could be too high based on available market intelligence. Figures from the Afry analysis and some of the FES scenarios are also excluded as market intelligence suggests these estimates are too low compared to the pipeline of projects we are aware of. All of the DESNZ scenarios are included.
- 2035: Only the lowest figures of the CCC scenarios were included. This is because we think assumptions used for H2P could be too optimistic and levels of gas CCS deployed appear too low. All of the DESNZ, Afry and Net-Zero consistent FES scenarios are included.
- 2050: the CCC analysis does not include numbers for 2050. We only included the high resource and high innovation scenarios from the Net-Zero Strategy as the high

[50] This is why the highest/lowest capacity figures may not correspond to the highest/lowest demand figures. For example, in 2050, the LCP analysis suggests that about 90GW of H2P capacity could be needed, while their demand range is comparatively quite low (i.e. between ~ 10 to 35Twh)
[51] See Annex O of the Energy and Emissions Projections, https://www.gov.uk/government/publications/energy-and-emissions-projections-2021-to-2040
[52] https://www.lcp.com/energy/publications/the-investment-case-for-green-hydrogen
[53] https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[54] https://afry.com/en/newsroom/news/benefits-long-duration-electricity-storage
[55] https://www.theccc.org.uk/publication/delivering-a-reliable-decarbonised-power-system/

electrification scenario did not look at H2P. The Net-Zero Strategy only includes figures for 2050. All of the DESNZ, Afry and Net-Zero consistent FES scenarios are included.

- We have removed LCP's high price scenarios for 2030, 2035 and 2050 as well as the medium price scenarios for 2030 and 2035. This is because, under these scenarios, a Combined-Cycle Hydrogen Turbine (CCHT) would dispatch after a Combined-Cycle Gas Turbine (CCGT); since LCP have not looked into emissions intensity in their report to government, we think there is a high risk that these scenarios will be inconsistent with the government's commitment to decarbonise the power system by 2035, subject to security of supply.

Heat

Figure 9 - Illustrative hydrogen demand range in heat

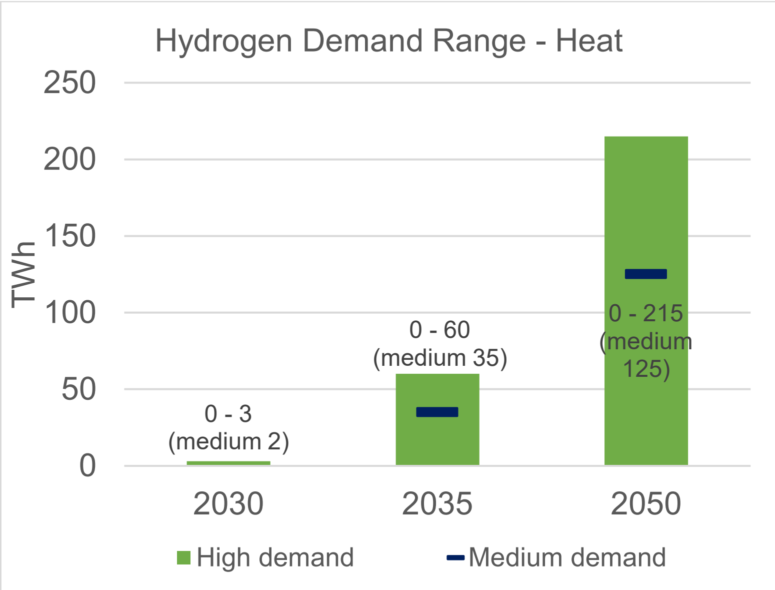


Figure 4 shows ranges for hydrogen demand in heat. The figures include heat in domestic and non-domestic buildings. The demand estimates are based on DESNZ analysis consistent with the scenarios used in the Net Zero Strategy and the latest Carbon Budget Delivery Plan[56]. Hydrogen demand in heat is highly uncertain and dependent on strategic decisions on the role of hydrogen relative to electrification in heat. The low end of the range assumes there is no significant use of hydrogen for heat in buildings, with rollout of heat pumps ramping up from our 2028 target of 600,000 installations a year to up to 1.6 million a year by 2035. The high end of the range assumes relatively widespread use of hydrogen in heating for existing buildings on the gas grid, alongside a continued rollout of heat pumps at the rate of 600,000 a year. Even in the high scenario, there is still a significant role for heat pumps and heat networks.

Figure 4 also includes an indicative medium heat demand scenario, which is intended to illustrate a more moderate adoption of hydrogen heating. For example, this could occur if hydrogen heating is limited to specific regions of the country; if hydrogen is available across

[56] https://www.gov.uk/government/publications/carbon-budget-delivery-plan

the country but the proportion of buildings using it is lower than in the high scenario; or if hybrid hydrogen heat pumps are deployed. This scenario does not represent a central estimate of hydrogen demand in heat.

Transport

Figure 10 - Illustrative hydrogen demand range in transport

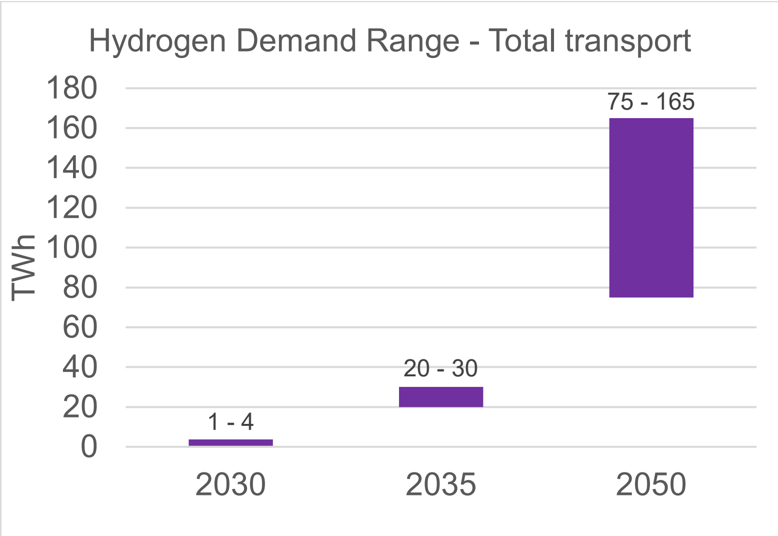


Figure 5 shows ranges for hydrogen demand in transport. This includes demand in HGVs, buses & coaches, maritime and aviation; we assume no hydrogen is used in cars & vans. We have not quantified hydrogen demand in rail, as the impact on total hydrogen demand would be small, but hydrogen trains remain part of our rail decarbonisation plans. The following sections explain the methodology used to estimate demand for each transport mode.

HGVs

Figure 11 - Illustrative hydrogen demand range in HGVs

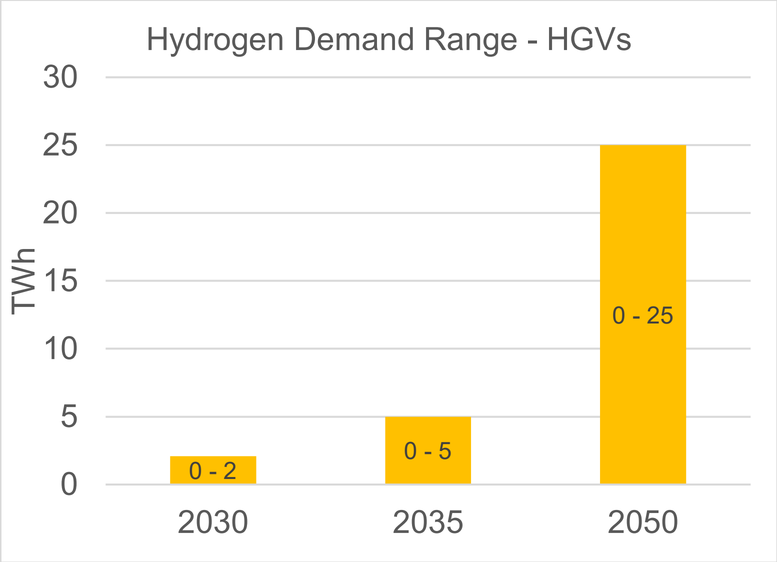


Figure 6 shows ranges for hydrogen demand in HGVs. The demand estimates for HGVs are based on Department for Transport (DfT) analysis. The rollout rate of zero emission vehicles is consistent with assumptions used in the Carbon Budget Delivery Plan[57], calibrated to the latest forecasts of fleet sizes. Lighter-weight HGVs are expected to electrify under all scenarios. There is uncertainty around how heavier HGVs will decarbonise. The HGV high demand range assumes that 50% of articulated HGVs will use hydrogen and the remainder will electrify, while the low range assumes all articulated HGVs will electrify.

[57] https://www.gov.uk/government/publications/carbon-budget-delivery-plan

Buses & coaches

Figure 12 - Illustrative hydrogen demand range in buses & coaches

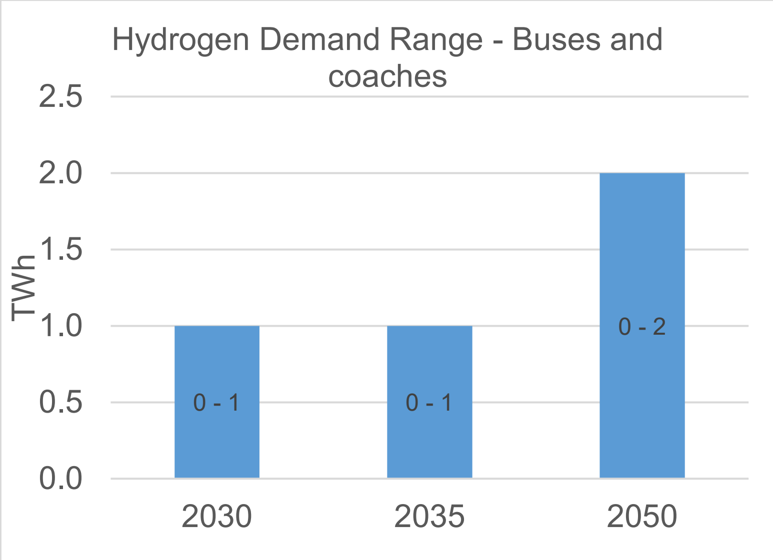


Figure 7 shows ranges for hydrogen demand in buses and coaches. Hydrogen demand estimates for buses and coaches are based on DfT analysis, which uses a similar approach to HGV analysis. The rollout rate of zero emission buses is consistent with the Carbon Budget Delivery Plan. The low scenario assumes all buses are electrified, while the high scenario assumes hydrogen is used in 30% of zero emission buses. In all scenarios, a significant proportion of buses are expected to electrify; hydrogen could play a role in specific circumstances, for example on particularly intensive duty cycles and long-range routes, but this is uncertain.

Maritime

Figure 13 - Illustrative hydrogen demand range in maritime

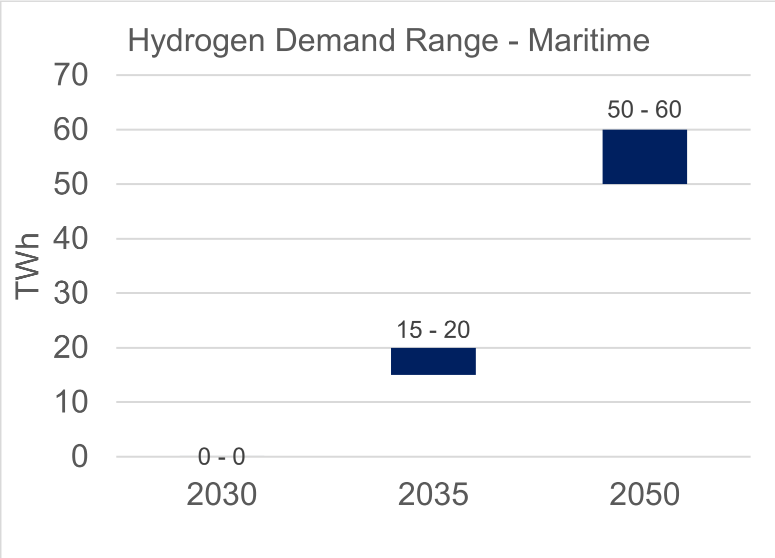


Figure 8 shows ranges for hydrogen demand in maritime. The figures include demand for hydrogen and hydrogen-based fuels for decarbonising both domestic and international shipping[58]. The demand estimates for maritime are based on an external research project commissioned by DfT to inform the 2019 Clean Maritime Plan. Both the high and low scenarios are consistent with the ambition level in the Carbon Budget Delivery Plan. The range is driven by different levels of electrification for non-modelled domestic ships and different requirements for pilot fuels. In the demand ranges presented, ammonia and methanol demand has been converted to hydrogen demand using assumptions on the amount of hydrogen input required to produce a unit of ammonia or methanol.

The analysis assumes the proportion of shipping fuel purchased in the UK stays constant over time: this is highly uncertain, and if refuelling patterns change in the future, this could mean hydrogen demand for shipping is higher or lower than the range presented. The figures represent the total demand for hydrogen and hydrogen-based fuels in the UK and have not been adjusted to reflect the potential for imports of some of these fuels. If some of the fuel was imported, then the demand for domestically produced hydrogen for shipping would be lower than shown.

In the next update of the Clean Maritime Plan, DfT will be utilising their newly developed maritime emissions model to produce updated decarbonisation scenarios for UK domestic maritime. This will provide a more up to date picture of the likely hydrogen demand from domestic maritime and the Government will review any implications for infrastructure requirements.

[58] The UK share of greenhouse gas emissions from international shipping is defined as the emissions from the fuel sold in the UK for use in international shipping. This definition is consistent with the definition used in the Net Zero Strategy.

Aviation

Figure 14 - Illustrative hydrogen demand range in aviation

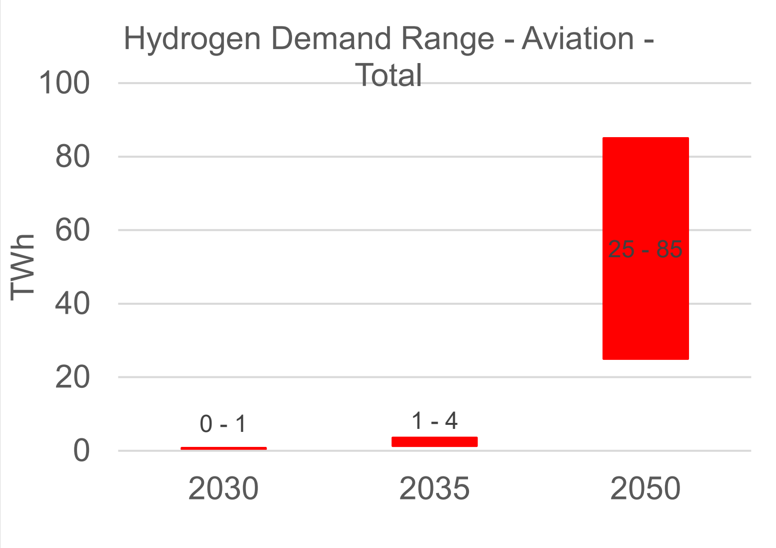


Figure 9 shows ranges for hydrogen demand in aviation. Liquid hydrogen can be used directly to power zero emissions aircraft. Hydrogen can also be used as a feedstock for some types of sustainable aviation fuel (SAF), particularly power to liquid (PtL) which combines hydrogen with carbon dioxide to make synthetic kerosene which can be used in existing aircraft. The demand estimates include both liquid hydrogen and hydrogen used as a feedstock for SAF. Demand estimates are based on DfT analysis.

The range of hydrogen demand in 2030 and 2035 is drawn from the scenarios developed for the SAF Mandate consultation CBA.[59] The scenarios in the CBA vary the trajectory for the SAF Mandate, as a percentage of UK aviation fuel demand. They also vary the biomass availability and the level of the sub-mandate for power-to-liquid (PtL) fuels. For 2030 and 2035 the maximum and minimum amount of hydrogen from the CBA are provided in each year. This analysis was undertaken in March 2023 as part of the SAF Mandate Consultation but will be subject to ongoing review.

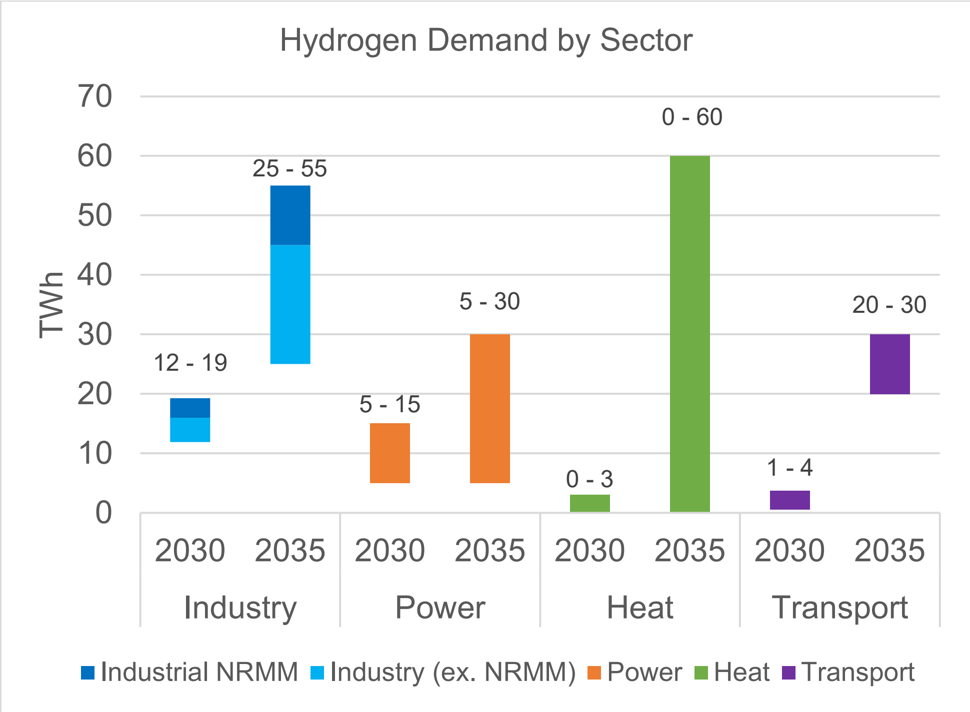
The modelling for 2050 uses scenarios generated for the Jet Zero Strategy to produce a range of hydrogen demand. They are built around the ‘High Ambition’ scenario, and assume 50% of aviation fuel is SAF in 2050. The lower hydrogen scenario assumes high availability of biomass for SAF, so very little PtL is needed to meet the mandate, and hence there is low demand for hydrogen as a feedstock for SAF. It also assumes zero emission aircraft are in operation in 2050, and fuel efficiency improvements of 2% per annum. The higher hydrogen scenario assumes low availability of biomass for SAF, so a high volume of PtL SAF is required to meet the mandate, hence there is a high demand for hydrogen as a feedstock for SAF. It also assumes higher air traffic movements (based on ‘Continuation of Current Trends’), lower efficiency improvements, and no zero-emission aircraft.

[59] https://www.gov.uk/government/consultations/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate

Summary

Figure 10 shows our estimates of demand for all sectors in 2030 and 2035. These figures reflect our current understanding of hydrogen demand across a range of sectors. We will keep these figures under review as new evidence on hydrogen demand emerges.

Figure 10 - Illustrative hydrogen demand by sector



This publication is available from: www.gov.uk/government/publications/hydrogen-transport-and-storage-networks-pathway

If you need a version of this document in a more accessible format, please email alt.formats@energysecurity.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.