MILFORD HAVEN : ENERGY KINGDOM – SYSTEM ARCHITECTURE REPORT

A PROSPERING FROM THE ENERGY REVOLUTION PROJECT

WEDNESDAY 24 NOVEMBER 2021

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1 ABOUT US

ENERGY SYSTEMS CATAPULT (ESC)

Part of a world-leading network of innovation centres, Energy Systems Catapult was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth.

We are an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia, and research – with around 200 staff based in Birmingham and Derby with a variety of technical, commercial and policy backgrounds.

We take a whole system view of the energy sector – from power, heat and transport to industry, infrastructure, and consumers – helping us to identify and address innovation priorities and market barriers to decarbonise the energy system at the lowest cost.

To overcome the systemic barriers of the current energy market, we work to unleash the potential of innovative companies of all sizes. Helping them to develop, test and scale the products, services and value chains required to achieve the UK's clean growth ambitions as set out in the Industrial Strategy.

MILFORD HAVEN: ENERGY KINGDOM (MH:EK)

Milford Haven: Energy Kingdom is a two-year project, exploring what a decarbonised smart local energy system could look like for Milford Haven, Pembroke and Pembroke Dock. The project will explore the potential of hydrogen as part of a multi-vector approach to decarbonisation. Central to the project, and to achieving Net Zero, is a commitment to engage with the community and local industry, providing insight and opportunities for growth.

Our ambition is to gather detailed insight into the whole energy system around Milford Haven, to identify and design a future smart local energy system based on a truly multi-vector approach and comprehensive energy systems architecture.

The project is multi-faceted and will see the team investigate local renewable energy, including solar, onshore wind, future offshore wind and biomass for decarbonised gas transition; diversified seed markets for hydrogen across buildings, transport and industry; consumer trials of fuel cell vehicles and hydrogen-ready heating systems.

We believe the project holds promise in showcasing the far-reaching benefits of low carbon energy. If successful, it has the potential to lead the way and become the first of many Smart Local Energy Systems supporting the U.K and our local communities in reaching the Government's target of net zero greenhouse gas emissions by 2050.

2 EXECUTIVE SUMMARY

The transition to Net Zero requires action across the economy. As the UK's largest energy port, Milford Haven is an area which could be at the front of this transition. Milford Haven can support this proposal as:

- According to a 2011 report the port of Milford Haven, the UK's largest energy port, activities around the waterway inject £324m to the Pembrokeshire economy and supports 5,000 jobs[1].
- The port itself is capable of handling 30% of all the United Kingdom's gas demands[2].
- Pembroke B power station is the largest gas power station in Europe[3] generating enough power for 3.5 million homes and businesses.
- The nearby Pembrokeshire Demonstration Zone seeks to demonstrate the feasibility of 90MW of floating offshore wind[4] with Prime minister, Boris Johnson famously stating that the UK could be the Saudi Arabia of wind energy[5].

Transitioning could include electrifying demand, converting assets to hydrogen or fitting CCS to assets. Government policy is developing to drive the deployment and integration technologies that support this transition including:

- four low carbon clusters by 2030
- 40GWs of offshore wind by 2030
- two CCUS clusters by 2025
- fossil fuel car sales phased out by 2032
- 25TWh of low carbon heat networks by 2030
- 900,000 heat pumps installations/year by 2028

The facts above also support the government's commitment to developing a multi-vector energy system for the UK that is hydrogen enabled and position Milford Haven as a unique location to demonstrate a commercially viable, technically feasible, scalable, replicable, and investable working energy economy incorporating all energy vectors.

A hydrogen enabled economy is one where a significant range of energy and services are delivered through hydrogen. All of this is underpinned by an architecture, or structure, of policy, regulation, markets technologies and interoperability with other energy vectors e.g. natural gas and electricity.

Acting as part of a multi vector energy system, the hydrogen economy plays an important role in the UK future energy system as stated by the UK Hydrogen Strategy[6], "With the potential to overcome some of the trickiest decarbonisation challenges facing our economy – including our vital industrial sectors – and secure economic opportunities across the UK, low carbon hydrogen has a critical role to play in our transition to net zero".

This work describes the outcomes of the effort to define designs of future energy system architectures, combining; technology, the interconnectivity between them and data; with markets,

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[1] https://www.mhpa.co.uk/economic-impact/

[2] https://www.mhpa.co.uk/the-port/

[3] https://www.group.rwe/-/media/RWE/documents/03-unser-portfolio-und-loesungen/betriebsstandorte/pemb-power-station-a4-20pp-brochure.pdf

[4] https://www.marineenergywales.co.uk/marine-energy-in-wales/demonstration-zones/pembrokeshire-demonstration-zone/

[5] https://www.bbc.co.uk/news/science-environment-54285497

[6] https://www.gov.uk/government/publications/uk-hydrogen-strategy

trading platforms and policies; with business models and defined organisational governance. The aim of these designs is to provide:

- The basis for a roadmap for the next phases of development and implementation,
- Confidence to innovators and investors in the future longevity of investments in hydrogen and,
- A common basis of understanding for all stakeholders wishing to contribute to the Milford Haven: Energy Kingdom.

The report is structured to provide context, then to set the structures for possible system arrangements which could emerge in the future, detail about technical, governance and market considerations and finally a set of trading platform requirements to underpin the delivery of such arrangements.

The core findings of this large piece of work are difficult to summarise however the following points aim to capture them.

1. **Smart Local Energy Systems (SLES') are dominated by a huge number of complex inter-relationships.**

- People to technology to business models to markets to regulations to policies
- Local areas to adjacent locales, regions and national systems
- Vector to vector interfaces (between electricity, natural gas, hydrogen, water, liquid fuels)
- Production and usage (supply and demand) including storage
- Actor to actor in the value chain (people, organisations and businesses)
- Capital investment and operational revenue

A whole systems approach is critical to ensure that development in one area isn't at the expense of another. This is difficult, but the complexity is there whether it is managed or not. The approach we've demonstrated here, to consider the depth and breadth and the interplay between all entities while managing the complexity could act as a template for other places and initiatives to benefit from.

2. **That, although, Net Zero might be driven locally there are key enablers which are currently in the hands of central government and include**

- Effective carbon pricing regulation
- Production support initiatives to support asset construction
- Regulating emergent monopolies as hydrogen producers emerge in small numbers
- An agreed approach to network and infrastructure cost recovery
- Supplier obligations (if appropriate) to encourage uptake of low-carbon gases
- Publication of standards, particularly on purity and quality so that innovators have confidence as to the operation of their equipment

Without many of these there is only so far local authority, industry and other stakeholders can currently go before hitting major regulatory or legal barriers (especially with hydrogen given its early maturity).

3. **This report identifies a number of actions at varying levels (central government, future discussions, immediate actions and local decisions) which form the basis of required next steps. They are collated and summarised in section 11 (given the number of them they are not reprinted here).**

In summary there is still a lot to do to create a hydrogen economy and a smart local energy system, but this is the most comprehensive picture to date of the underlying structures required to make future innovation and investment as effective as possible.

This work has been achieved with the support of a huge range of stakeholders from around the port of Milford Haven, (see section 19), without whom this work could not have been completed, thank you.

Finally, it should be noted that the vast majority of the work for this report was completed before release of the UK Hydrogen Strategy. Suitable reference has been included in some areas however some in-depth thinking such as hydrogen business model proposals and a low carbon hydrogen standard have not been considered at this time.

3 INTRODUCTION

Milford Haven: Energy Kingdom is a two-year project, exploring what a decarbonised smart local energy system could look like for Milford Haven, Pembroke and Pembroke Dock. The project will explore the potential of hydrogen as part of a multi-vector approach to decarbonisation. Central to the project, and to achieving Net Zero, is a commitment to engage with the community and local industry, providing insight and opportunities for growth.

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MH:EK is one of the chosen “Detailed Design” projects within the Prospering from the Energy Revolution (PfER) programme of works funded by Innovate UK as part of their Industrial Strategy Challenge Fund (ISCF). The project is centred around South-West of Wales, encompassing both Milford Haven, Haverfordwest and surrounding towns and villages. The project includes partners and sub-contractors including Pembrokeshire Country Council (PCC), Port of Milford Haven, ARUP, ESC, OWRC, Riversimple and Wales & West Utilities.

Energy Systems Catapult was tasked to deliver a set of systems architecture options. This aims to enable the development of a local hydrogen system that can manage the supply, transport and demand for the immediate and future scenarios, further it enables flexibility for new entrants into the system as technology changes and policy and regulation matures over time.

The need for a transition from natural gas to hydrogen is increasingly being seen as an important step to achieve the UK’s 2050 net zero ambitions. This is because large-scale hydrogen production may provide key inter-seasonal energy storage for an energy system sustained by the UK’s abundant renewables such as wind power and marine resources. Additionally, hydrogen can be used for heating, high grade heat, as a feedstock in chemical processes, for transportation directly, for creating synthetic fuels and other uses all of which displace traditionally carbon intensive fuels.

The key Systems Architecture objectives of this work are:

- To provide a common understanding of the range of possibilities of a future local energy system in Milford Haven and surrounding areas and to drive for choices and/or decisions to be made which affect the interfaces between businesses, technologies, and commercial arrangements and which form a high-level local energy system design.
- To provide innovators and investors with a greater understanding of the scale of opportunities and risks in a future hydrogen economy, and key decisions which can impact on outcomes.
- To Highlight gaps in existing businesses roles and responsibilities to inform on future growth opportunities and set new requirements for new activities.

- To Illustrate challenges in the integration of a local energy system and the key interfaces with regional / national entities and to further identify the negotiations for change that may be required.

These objectives support MH:EK project developed objectives, of which the relevant ones are:

- To develop a conceptual proposal for what a 2050 decarbonised MH energy system could look like and the short-term investments.
- To understand and map market mechanisms that would create a sustainable demand for a hydrogen energy economy.
- To establish a roadmap from the MHEK perspective of policy change necessary to support an energy system that incorporates hydrogen.
- To establish the potential role of and likely support mechanisms needed to see replicable roll out of a hydrogen energy system.
- To develop a detailed concept design of an energy system for MH in 2030 that is in transition towards being fully decarbonised.

Though the MH:EK systems architecture is primarily hydrogen focused the future implementation is intended to be an integrated multi-vector smart energy system and so the interfaces with natural gas, water and electricity are also considered below, particularly with electricity since the relationship between the two are so fundamental and given the opportunities to provide flexibility between the two vectors and deliver cost savings to consumers.

The work presented here has the benefit of looking 5-10 years ahead to prepare for the complex changes that will be required to make such a significant transition. As such, not everything can be implemented straightaway but, it is hoped that this systematic approach to considering the future will provide investors and innovators with more confidence of the market potential for their involvement as well as understanding of key remaining areas of uncertainty to be addressed.

Note that a comprehensive glossary of terms is included in section 18.

3.1 WHAT IS A SYSTEMS ARCHITECTURE?

A systems architecture is a high-level design. It is normally drafted by a systems architect / solutions architect who has worked with lots of stakeholders to understand their needs and requirements who then creates a picture of the intended structure for the specific solution. This high-level structure is used to facilitate the next level of detailed design but provides a common view and direction for all parties to share a vision around.

In the energy space, systems architecting (at a whole systems level) is a relatively new process, but it has an established track record of developing integrated solutions to complex problems in industries such as aerospace, defence, automotive, IT and telecoms.

For the MH:EK project we are using the architecting process slightly differently. Often an architecture presents an answer, a single blueprint for implementation but we have used architecting to present sets of high-level options. This is essential because of the number of stakeholders involved who have different motivations and requirements means that a single solution is unlikely to completely satisfy everyone's requirements. There is also a high degree of uncertainty as many differing factors outside of stakeholder control will influence the end result, adding complexity or directly changing potential solutions. The point of the architectures is to support the discussions around the integration of a collection of those businesses together yet leaving as many options open to future changes as possible.

There are still developments of first of a kind (FOAK) demonstrators, which will demonstrate the viability of certain approaches and of national decisions and strategies which might influence the chosen outcome. Furthermore, we recognise that the development of a hydrogen economy is unlikely to be a single big bang implementation, but rather will start small and build on successive successes. Therefore, some decisions on the overall structure of the hydrogen system are valid in early development but may get replaced (or supplemented) by other approaches which come along later, therefore a future hydrogen economy must be flexible enough to accommodate evolutionary development.

Note this document is supported by a systems architecture design captured using a model-based systems engineering (MBSE) tool called "Enterprise Architect". Section 12 provides the details on how to download both the free Enterprise Architect (EA) viewer and the MH:EK model. Note that the key diagrams and findings have been included in this report for the convenience of readers.

3.2 WHO SHOULD THIS DOCUMENT HELP AND HOW?

The initial needs identified from the PFER submission, monitoring slides and early project quarterly reviews are highlighted in Figure 1. Note that not all of these needs can be satisfied by the architecture work or this document but are included because they have helped to shape the thinking and set context for the work presented here. For legibility and to highlight the interconnections between the needs, all the needs are presented in a single diagram below. The needs names and descriptions are included in full text in appendix in section 13.

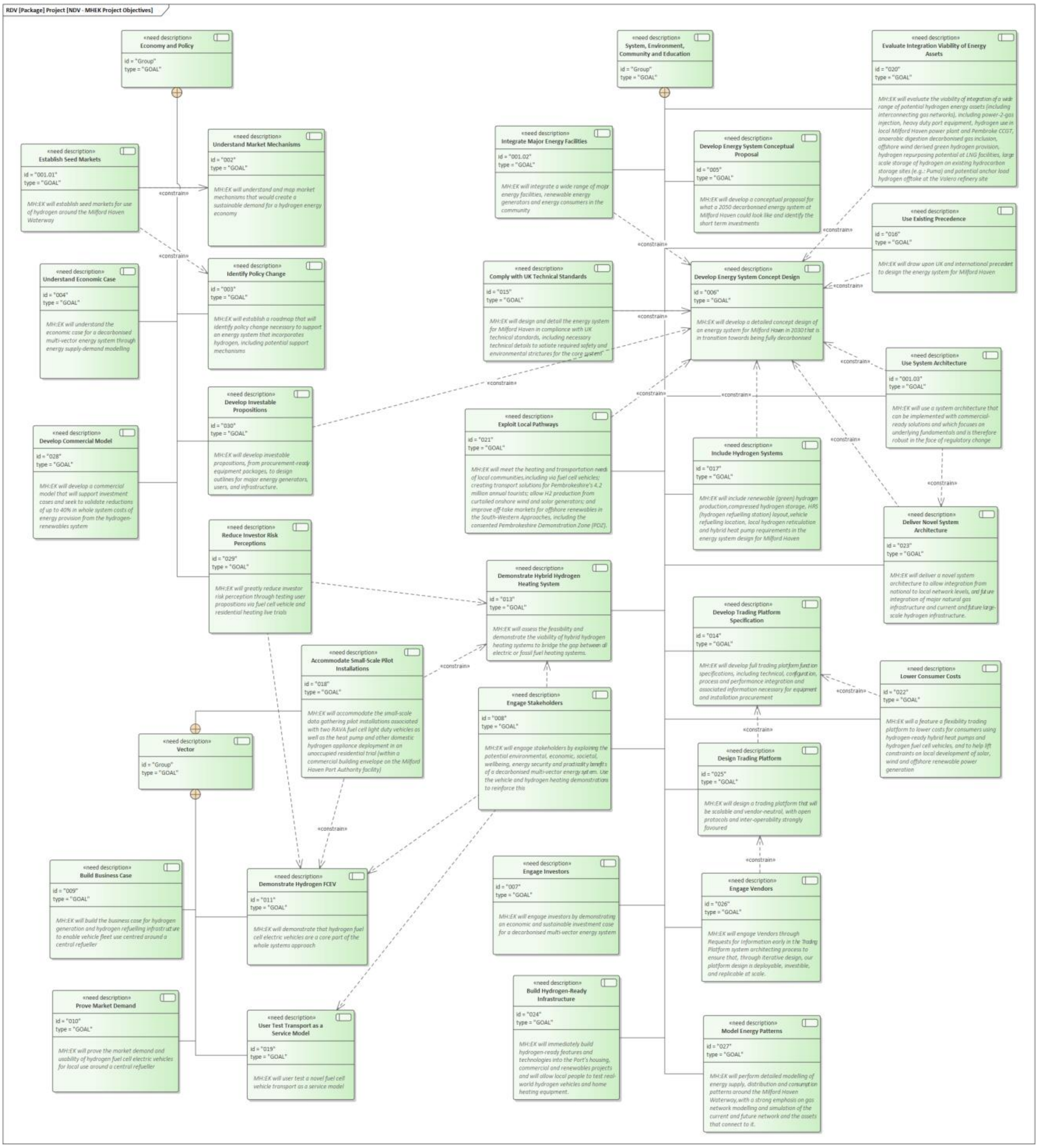

Figure 1 – MH:EK Project Needs captured from stakeholders

Stakeholders and actors working in the hydrogen sector, or which may transition as part of the move to Net Zero energy systems, particularly in the Milford Haven area might use this document and associated systems design diagrams to explore possible futures. Specifically, many developments in the hydrogen sector will require multiple parties to build consensus and agree on a way forward. The intention is that these architectures clarify interfaces, relationships, and dependencies and, furthermore, allow for interested parties to explore possibilities. The architecture should also help decision makers make choices, particularly where a consensus has not been reached. To that end, key decision points or choices to be made are highlighted in boxes (as described in section 3.3), to draw attention to key developments which could enable, or otherwise impact, specific outcomes. The intention is that these decisions / choices are ones that stakeholders within Milford Haven should spend some time on deciding to be able to choose a path to a future smart local energy system which works for the majority of the stakeholders.

This work could not have been completed without the generous support of the partners and contributors to the Milford Haven: Energy Kingdom project. It reflects the requirements and concerns which many of the contributors raised in a number of workshops. Furthermore, those views have been supplemented through engagement with other areas of industry, a review of national strategy & policy and selected international legal documents and operational performance.

The needs captured through those stakeholder engagement sessions are organised and captured in the appendix in section 14. Rather than link every item through the EA tool, we have kept them in the excel format to be viewable by more stakeholders and have manually checked they are covered throughout the design work, though adding full traceability at a later stage might be valuable to keep track of future choices and design decisions.

As for what happens next, this document should help existing stakeholders to be able to make decisions in light of the needs of other stakeholders and to understand what position they might take on regional and national issues. Furthermore, as these decisions are made, options can be closed down in the EA model effort can be focused on designing the detail for chosen areas.

3.3 DOCUMENT STRUCTURE

This document is logically organised to walk through the physical, organisational, regulatory, and commercial relationships between actors, technologies, and functions in a future hydrogen system.

This work is being presented in three distinct sections.

- Overall considerations and background information on system elements which are relevant across any possible hydrogen economy futures. Sections 5, 6 and 7 cover physical, organisational and market considerations respectively.
- Potential system arrangements, which lay out the approaches to how different hydrogen economies might be designed and the specific business links, technical interfaces, market requirements for facilitation to deliver each of those. Section 8 and 9 cover the local trading platform opportunity and design for the systems architecture.
- An accompanying Sparx Systems™ Enterprise Architect™ download for exploring the project components.

Additionally, the appendices contain a wealth of supporting information including the justifications for many of the points raised, or the background information to bring stakeholders to a common understanding.

Finally the conclusion (section 10) and Annex A (section 11) contain summary insights and the collation of the action points defining next steps, respectively.

Key decision points or design choices to be made are highlighted in boxes, to draw attention to key developments which could enable, or otherwise impact, specific outcomes.

These points have been divided into four categories:

- National action point: Not something for the Milford Haven stakeholders but more advice to be shared with government, regulators, code bodies etc. on changes required to enable future local energy and hydrogen systems.
- Action point: A task or activity to perform which should unlock a piece of information or insight to support discussions or decisions.
- Discussion point: A subject which requires agreement, compromise (or at least insight prior to escalation) to understand what multiple stakeholders need.
- Decision point: A decision to be taken which will then allow innovators and investors to have sufficient clarity to be able to proceed.

4 INTRODUCTION TO HYDROGEN SYSTEMS

The MH:EK project is looking to create a whole energy system which shines the light on the potential of hydrogen as a way of unlocking renewable energy sources and the considerations for Milford Heaven Waterway.

This section outlines the possible ways a hydrogen system could develop. It starts by looking at studies which have considered the potential size of the hydrogen market, it's production methods and uses. It then looks at the different stages a hydrogen system may go through. These stages have been termed 'potential system arrangements' and will be used as framework for considering the requirements for a UK hydrogen system to develop and evolve.

4.1 INTRODUCTION TO HYDROGEN AS AN ENERGY VECTOR

Hydrogen is set to be a key energy vector in the UK's 2050 Net Zero energy system. The increased decarbonisation ambition in the UK has increased projections for its use and its importance in the transition.[7] It can be particularly useful for a low carbon energy system as (based on 'Hydrogen in a low carbon economy, CCC, 2018'):

- It can be produced in multiple ways meaning it is flexible and not resource constrained.
- It produces no emissions at the point of combustion.
- It can combust to generate high temperatures.
- It can be stored in large volumes for a long time and if compressed can be more energy dense than batteries
- It can potentially be distributed through existing polyethylene natural gas pipes.

These characteristics mean it could be used to decarbonise hard to abate sectors and to manage demand and supply variations in an increasingly electrified energy system.

Hydrogen's key relationships with other systems are illustrated in Figure 2 while some of the different production technologies and uses are expanded upon in the figures which follow. This is largely appropriate for both national and local scale hydrogen systems but was the first step taken to understand what component parts exist and can be categorised.

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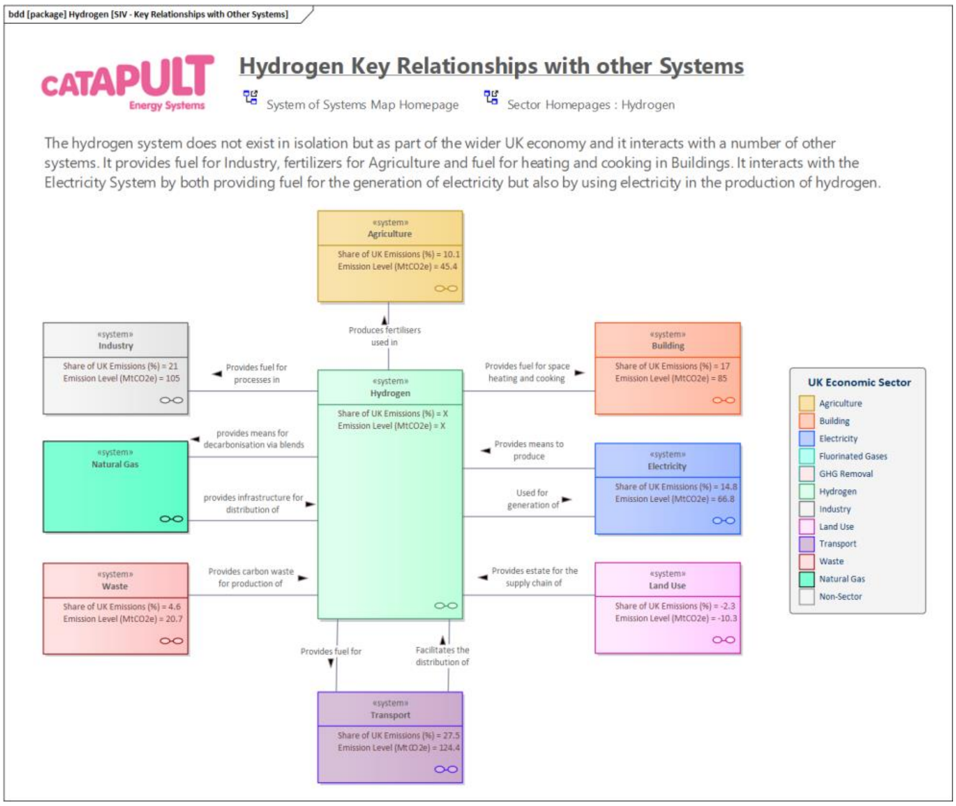
[7] https://es.catapult.org.uk/reports/innovating-to-net-zero/



The hydrogen system does not exist in isolation but as part of the wider UK economy and it interacts with a number of other systems. It provides fuel for Industry, fertilizers for Agriculture and fuel for heating and cooking in Buildings. It interacts with the Electricity System by both providing fuel for the generation of electricity but also by using electricity in the production of hydrogen.

Figure 2- Hydrogen key relationships with other systems

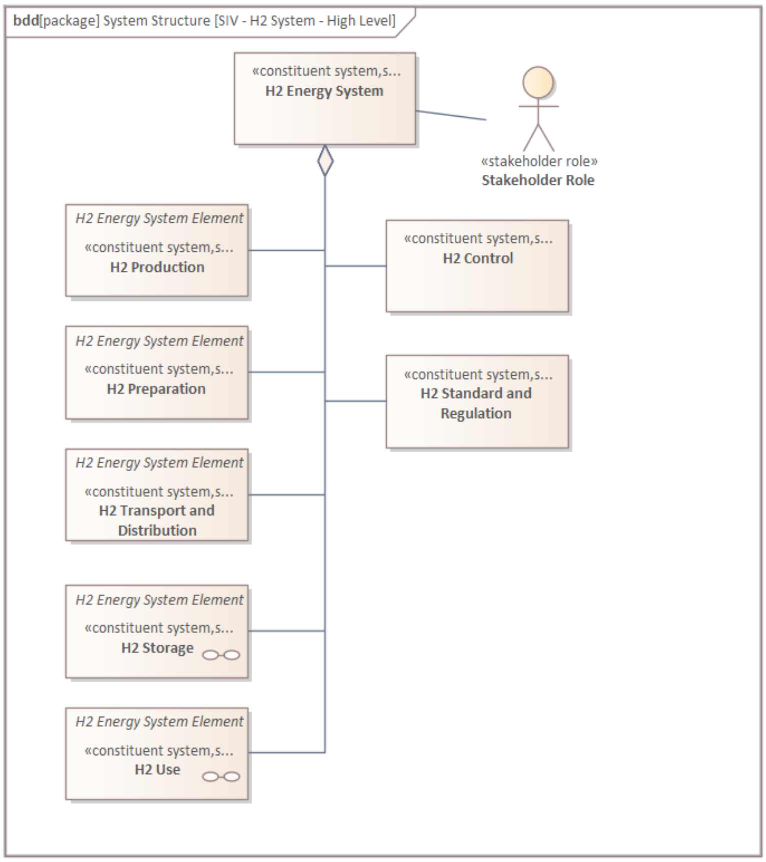


Figure 3 - General overview of hydrogen system relationships

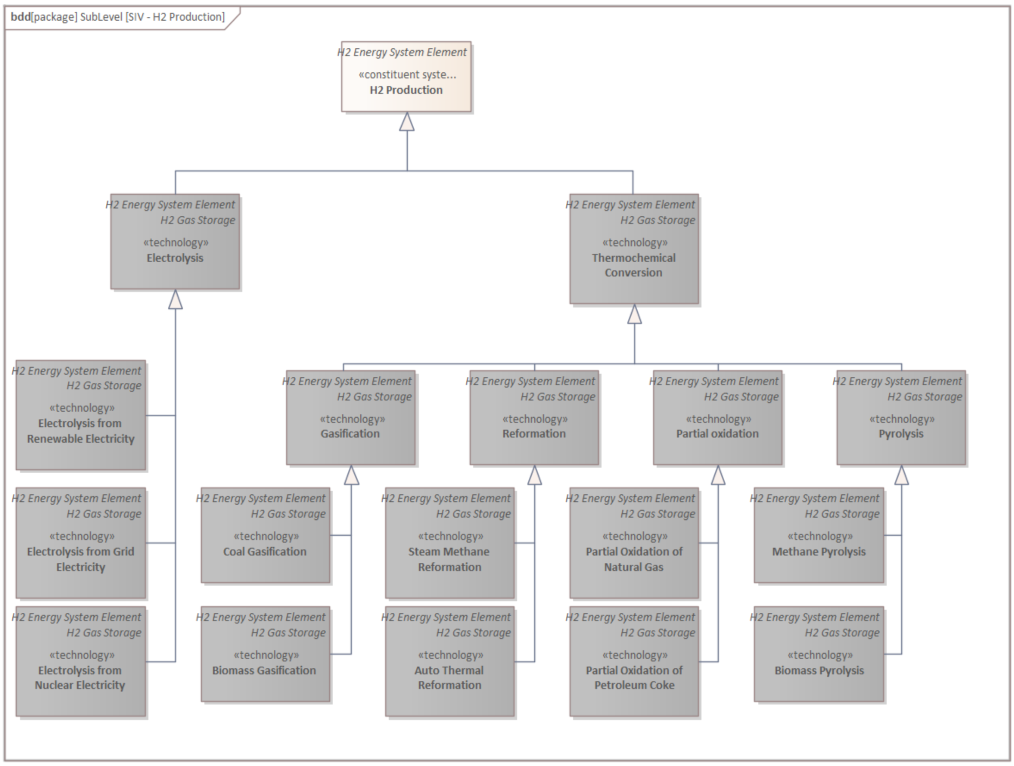


Figure 4 – Examples of hydrogen production technologies

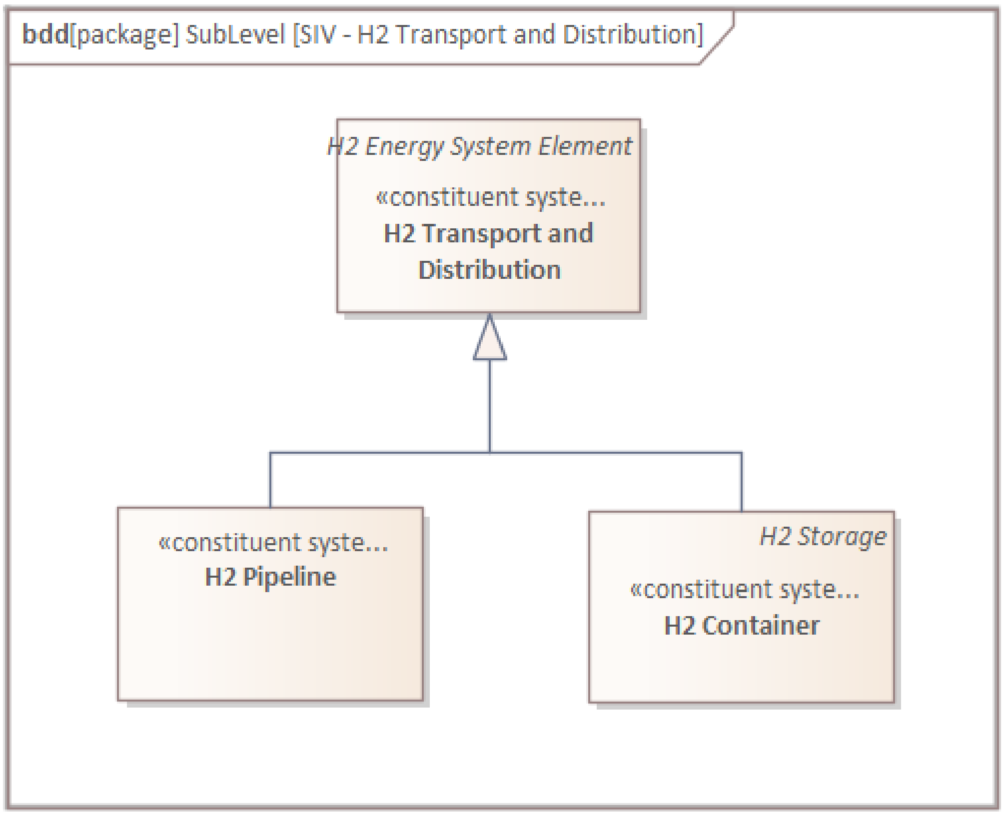


Figure 5 – Examples of hydrogen transport and distribution technologies

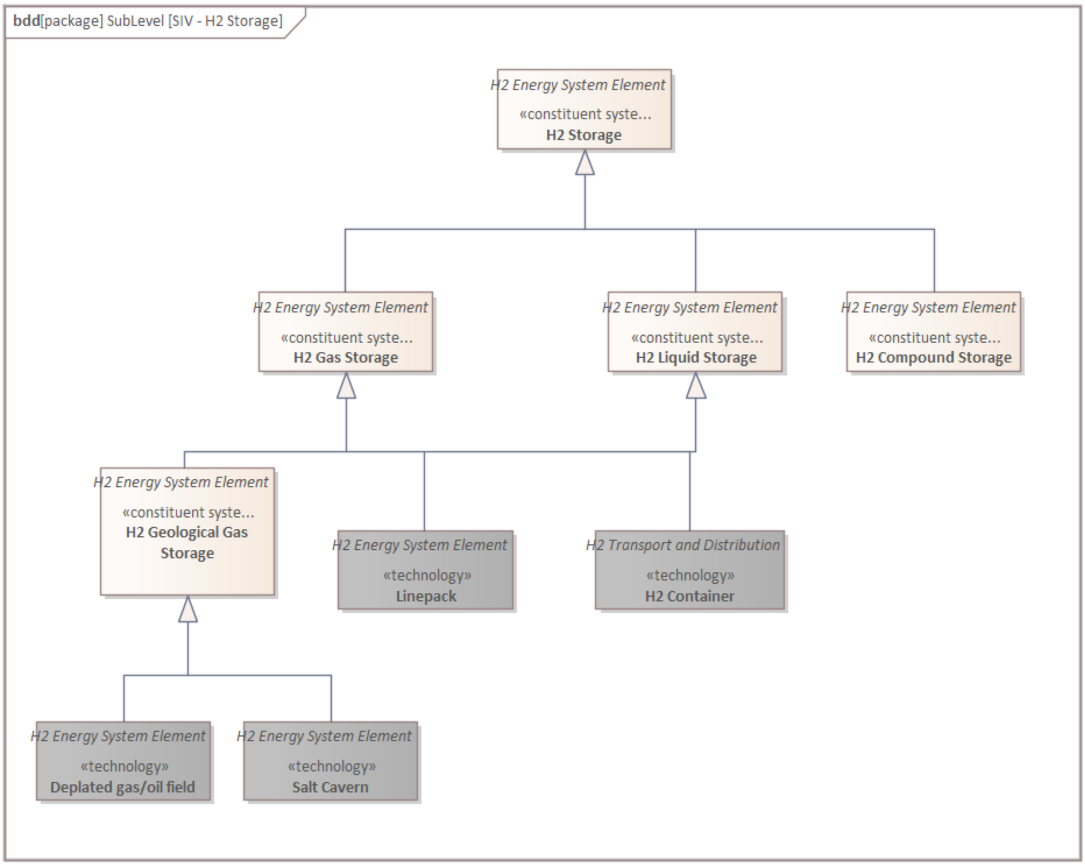


Figure 6 – Examples of hydrogen storage technologies

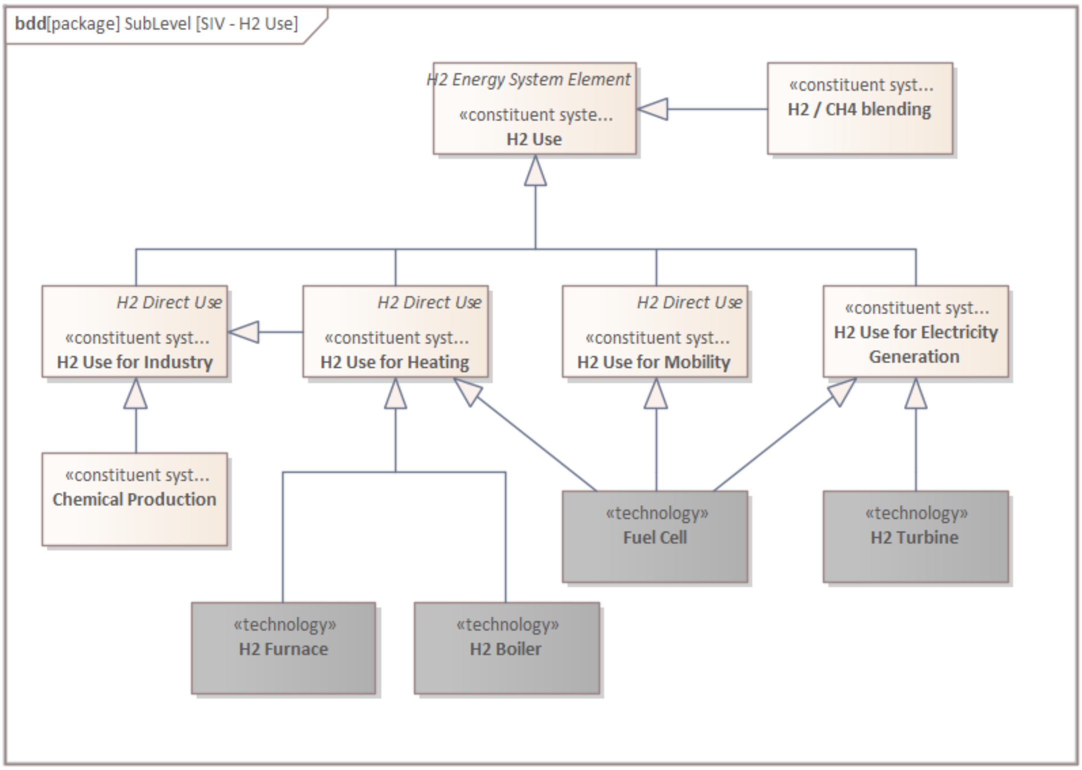


Figure 7 – Examples of hydrogen use sectors and technologies

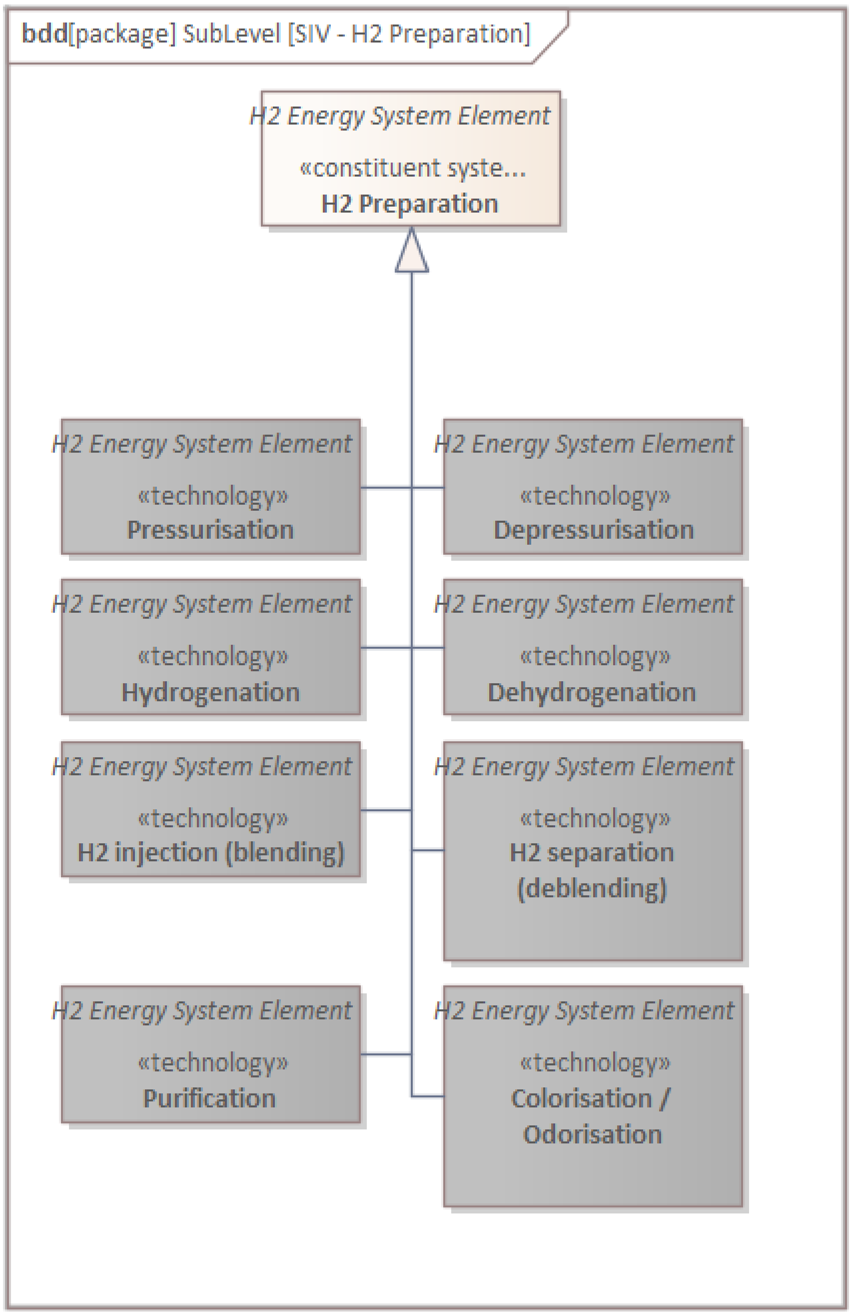


Figure 8 – Examples of hydrogen preparation technologies

4.2 NATIONAL SCENARIOS FOR HYDROGEN PRODUCTION AND USE IN THE UK

There is considerable uncertainty surrounding the future hydrogen system. Hydrogen could be used in many sectors and could be produced in several ways all of which have very different characteristics. Some certainty is brought by the current government policy aim to have 5GW of hydrogen production capacity by 2030[8] however, the policy framework to drive this is not yet in place. Longer term, there are no specific policies for the use of hydrogen, however, to reach net zero it will be a key energy vector in several sectors.

National Grid's Future Energy Scenarios show the important role hydrogen could play in the future energy system, as well as the large uncertainty. The potential supply of hydrogen across the different scenarios is shown in Figure 10 with the scenarios used outlined in Figure 9.

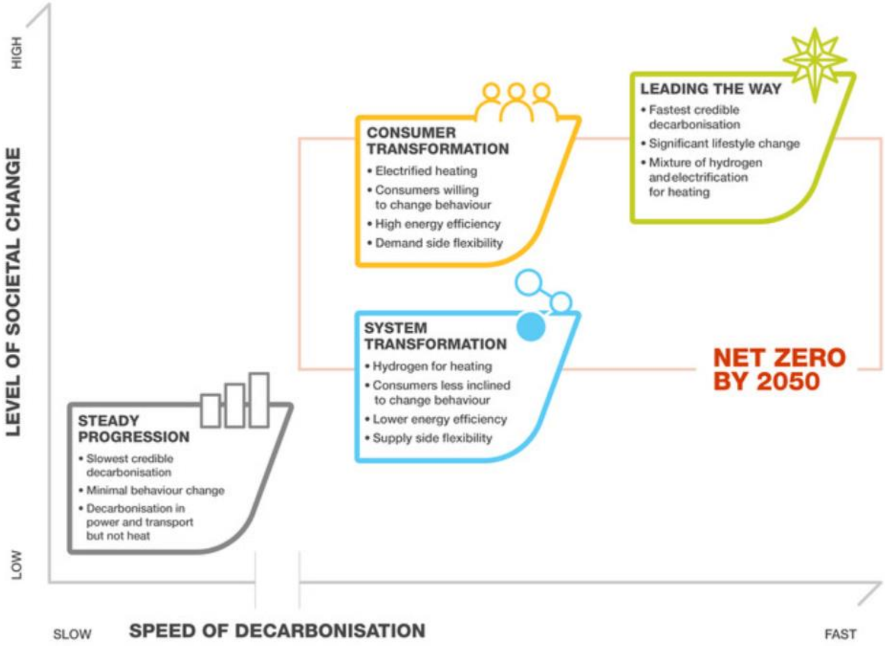


Figure 9 – The scenario framework, (National Grid, Future Energy Scenarios, 2021[9])

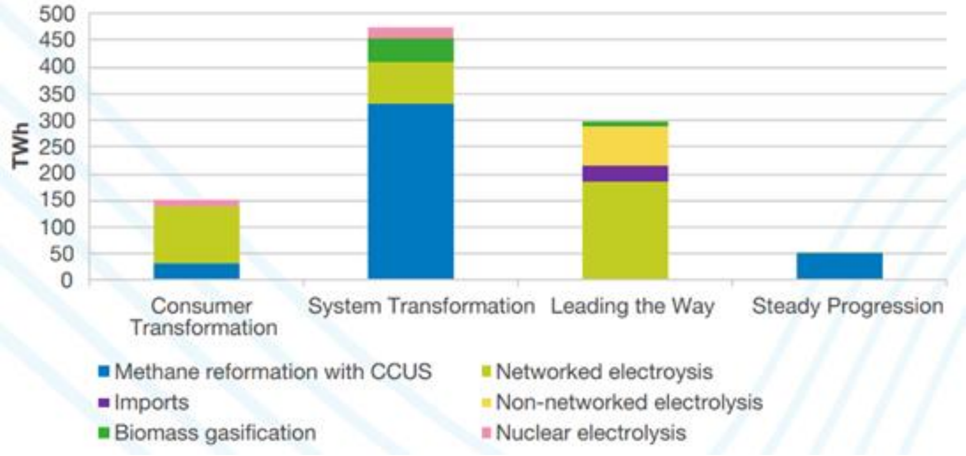


Figure 10 – Hydrogen supply in 2050 (National Grid, Future Energy Scenarios, 2021[9],[10])

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[8] https://www.gov.uk/government/publications/uk-hydrogen-strategy

[9] https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021

[10] https://committees.parliament.uk/writtenevidence/7164/pdf/

The hydrogen supplied varies from roughly 50TWh-475TWh; a considerable variation across scenarios with the lower bound from a scenario which does not reach net zero. For context the current natural gas system supplies 900TWhs per year.

The scenarios also highlight the high uncertainty around the technology which could supply this hydrogen with notably, System Transformation seeing a high capacity of Methane Reformation with Carbon Capture, Utilisation and Storage (CCUS) supported by electrolysers and Leading the Way favouring electrolysis and imports.

Figure 11 shows the applications using hydrogen across the scenarios as detailed in Figure 9.

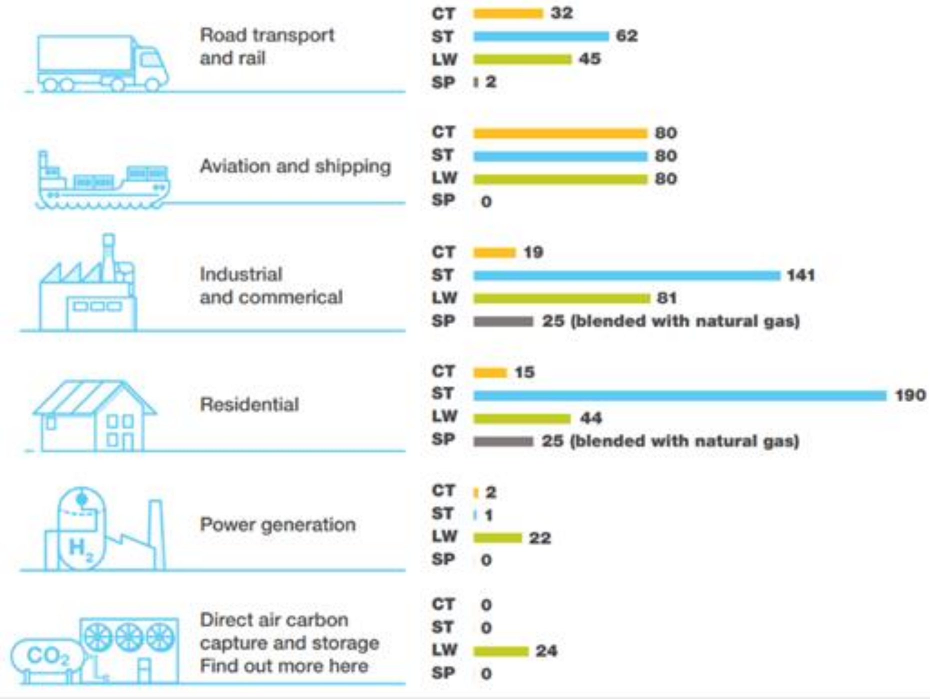

Figure 11 – 2050 Hydrogen demand (National Grid, Future Energy Scenario[9]*)*

This again shows considerable uncertainty moving forwards, particularly in industry and residential heating.

This uncertainty across the future supply and use of hydrogen is driven by several factors (explanation of each of these is provided in section 17):

- Cost projections and comparison to alternatives
- Suitability for applications
- Interaction across hydrogen uses
- International production
- Carbon emissions headroom nationally and CCUS capture rate
- Impact from the development of other systems
- Government policy (UK and international)

This high level of uncertainty and interaction between multiple different sectors may make it difficult for strategic decisions to be made, which will be needed, to enable the future hydrogen system. To help manage this complexity, this report looks to outline the different ways hydrogen systems could develop. It then uses this framework to systemically looks at the requirements which need to be met for this to occur.

4.3 THE RELEVANCE OF THE HYDROGEN TRANSITION FOR PEMBROKESHIRE

The transition to net zero will require a substantial change to how energy is produced, distributed, and consumed in Wales and Pembrokeshire. Illustratively, over 10 megatons of carbon emissions were generated by business and industry in Wales in 2020 alone[11] and the Welsh Government has committed to reaching net zero emissions in 2050 with ambition to get there sooner[12]. Figure 12 shows the relative size of emissions from different sectors today and how this needs to change across the UK to 2050 under different scenarios.

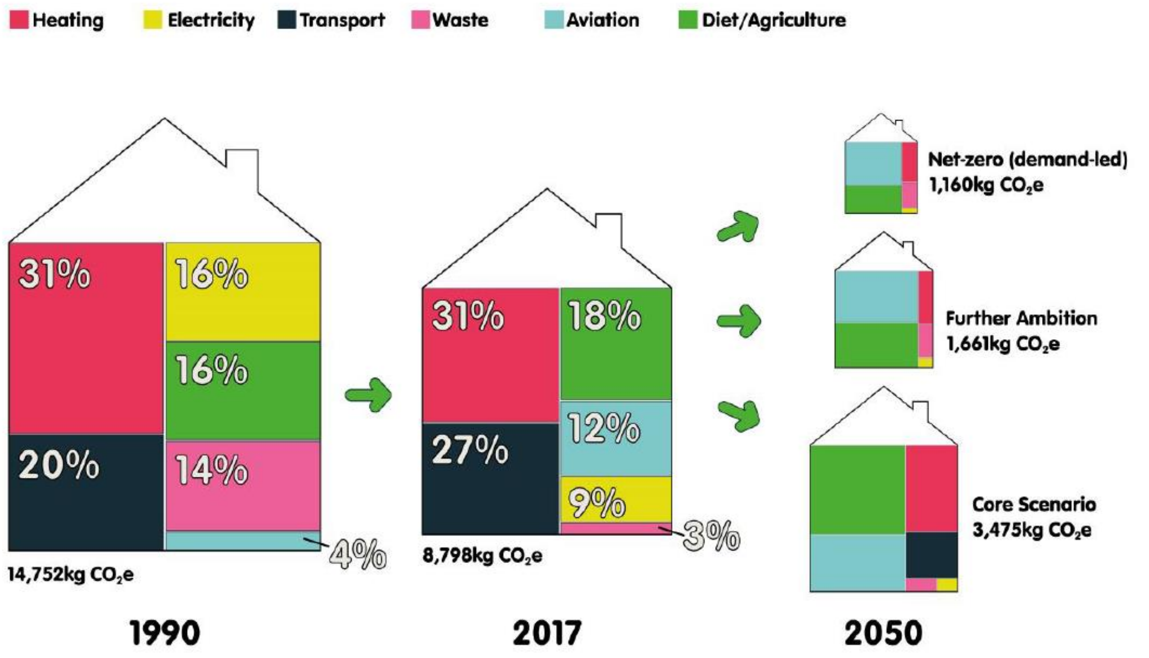

Figure 12 – Infographic of UK average household emissions (with historical shares)[13]

This transition will open up opportunities while affecting how energy is consumed in both residential, commercial, and industrial settings.

The Pembrokeshire population was 123,300 in 2013 where 28,178 resided in either Milford Haven or Haverfordwest[14], the rest being in smaller towns, villages, or rural locations. The region's main industries are agriculture, tourism, and marine energy (including oil and gas).

The potential changes to life to reach net zero were discussed by ESC in Living Carbon Free (2019)[15]. The ones relevant to the use of hydrogen in the region are shown below:

- Heat- improving home energy efficiency and decarbonising the fuel source either through connecting to a heat network or using electricity or hydrogen for heating. Smart controls could also reduce usage.
- Transport- reducing distances travelled (possible through flexible working or carpooling), shifting to walking, cycling, buses, trains, electric vehicles, or hydrogen vehicles.

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[11] The UK Government's Plan for Wales, May 2021

[12] https://gov.wales/wales-commits-net-zero-2050-sets-out-ambitions-get-there-sooner

[13] ESC, Living Carbon Free, 2019, https://www.theccc.org.uk/publication/living-carbon-free-energy-systems-catapult/

[14] Public and Corporate Economic Consultants, Economic Profile of Pembrokeshire, June 2015

[15] https://www.theccc.org.uk/publication/living-carbon-free-energy-systems-catapult/

As such, the development of hydrogen in the area could support people decarbonising their use of heat and/or transport. That said, it is also clear that there are other options for decarbonising these sectors. Section 4.2 showed the high level of uncertainty around where hydrogen will be used and how much, therefore it is currently unclear if hydrogen will be the right solution for these applications in the region. The MH:EK project aims to push forwards understanding in this space to enable informed decisions to be made. Initiatives being undertaken and championed by MH:EK, such as the Riversimple Rasa cars, electrolyser refuelling on the Milford Haven port key and the Port Authority hybrid heating system, if properly showcased to the public, aim to build end user support for hydrogen. However, there are many other factors such as consumer confidence in hydrogen products or the disruption caused by a change that much more study in this area is required.

The transition will also have a large impact on the industrial assets in the region. The organisations involved that require a net zero solution include:

- South Hook Liquefied Natural Gas (LNG) Terminal[16], has the capacity to provide up to 20% of the UK's natural gas and primarily imports from Qatar.
- Dragon LNG[17], has the capacity to provide up to 10% of the UK's energy needs through natural gas imports and has two shareholders, Shell, and Ancala LNG Ltd.
- RWE Combined Cycle Gas Turbine (CCGT)[18] has a 2.2 GW net capacity, enough to power around 4M homes, over two times the number of households in Wales.
- Valero Pembrokeshire Oil Terminal[19], has a throughput capacity of 270,000 barrels a day and accounts for 15% of total Welsh exports.

These are all strategically important sites both locally and nationally. In the transition to net zero these assets will need to have clear plans to manage their exposure to risk and capitalise on the clean growth opportunity. Natural gas is key to the first three industrial sites in the list above and to the economy of the region. Figure 13 shows the potential reduction in natural gas usage to net zero (the relevant scenarios were shown in Figure 9, note Steady Progression does not meet net zero).

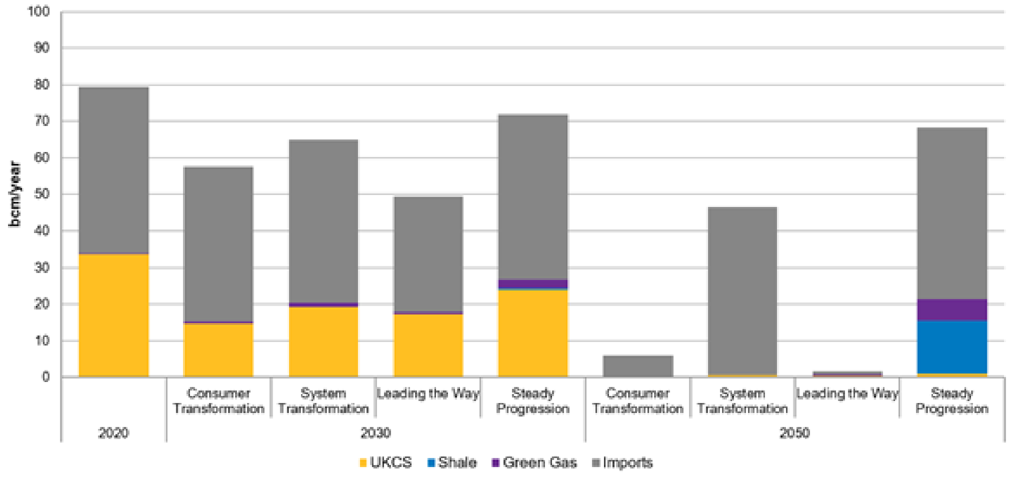

Figure 13 – FES Gas demand profile for the whole of the UK[9]

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[16] https://www.southhooklng.com/

[17] https://www.dragonlng.co.uk/

[18] https://uk-ireland.rwe.com/locations/pembroke-ccgt-power-plant

[19] https://www.valero.com/about/locations/pembroke-refinery

It can be seen that there is high uncertainty around natural gas future use but that it could dramatically reduce in the coming decades. For each of the industrial sites highlighted hydrogen could be a key energy vector as shown in Table 1 below.

Industrial site	Potential link to hydrogen
South Hook LNG Terminal	Could be converted to import/export hydrogen. Natural gas imports could still be used in a net zero world. A lot of the natural gas use in the scenario 'System Transformation' is driven by Steam Methane Reforming (SMR)/ Autothermal Reforming (ATR) with CCUS.
Dragon LNG	
RWE Combined Cycle Gas Turbine (CCGT)[20]	Could be converted to using hydrogen or possibly a blend of natural gas and hydrogen at first.
Valero Pembrokeshire Oil Terminal	Valero produces and uses hydrogen on site for their own processes however consultation would be required to understand what further infrastructure benefits could be realised.

Table 1- key industrial sites in Milford Haven and potential links with low carbon hydrogen

As such, hydrogen could play a key role in the region moving forwards, as a promising way to decarbonise homes, transition infrastructure and drive investment in the region.

The businesses discussed above and others in the sector provide a hugely significant part of the national and local economy, and many are actively engaged in the drive towards net zero including the transition to hydrogen, this boosts the economy and should support job retention in the area. Evidence includes the multiple government funds being made available[11] such as:

- £1M to kickstart the clean industry transition along the Milford Haven waterway
- £28M for the Pembrokeshire Dock Marine project (£2.45M from UK Govt and £25.55 from Welsh Gov to deliver a £60.4M project)
- £20M funding to support the development of the South Wales Industrial Cluster[21] (SWIC). Creating a sustainable plan for the region through the production and distribution of hydrogen power, cleaner electricity production that uses carbon capture technologies, hydrogen rich natural gas and large industry decarbonisation through fuel switching and the production of cleaner transportation fuels, see Figure 14.

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[20] https://uk-ireland.rwe.com/locations/pembroke-ccgt-power-plant

[21] https://www.swic.cymru/news

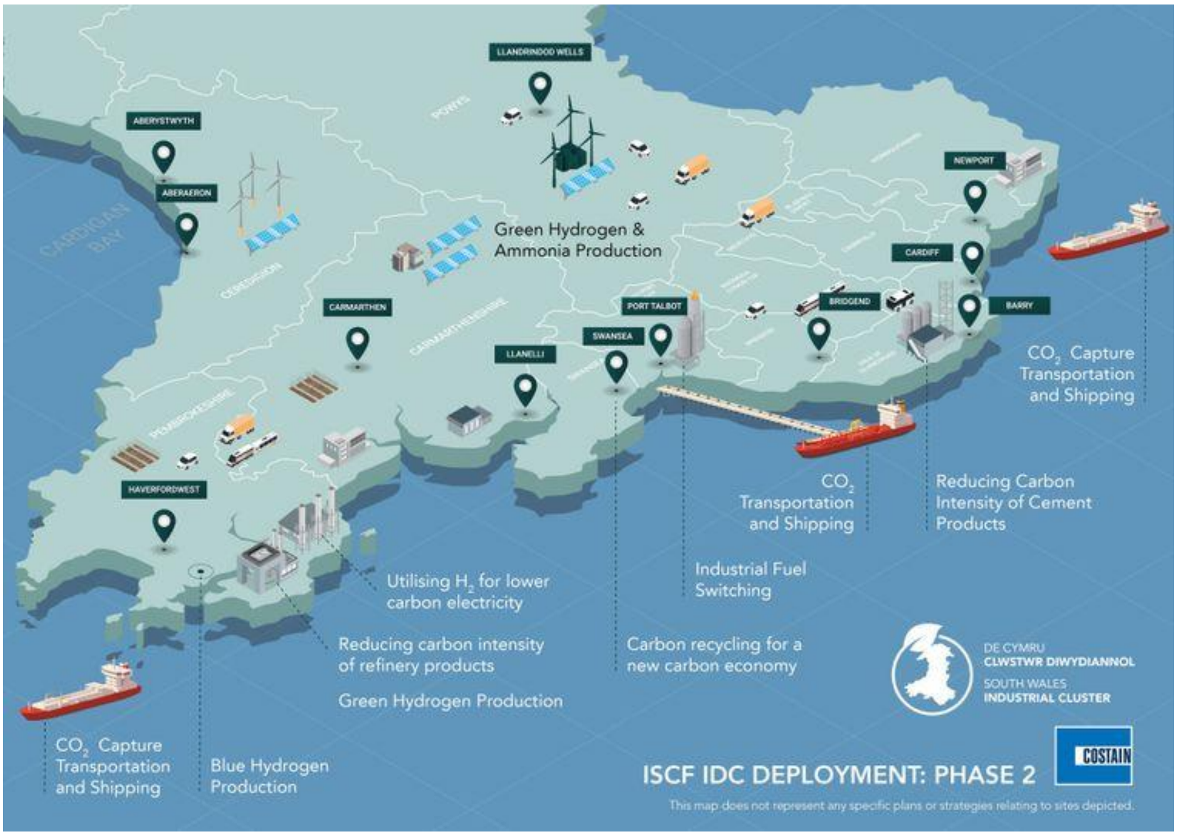

Figure 14 – SWIC Deployment: Phase 2[21] carries out engineering studies for route to decarbonisation

Hydrogen is one clear approach for decarbonising the MH:EK region however should not be considered a lone solution and the integration of hydrogen with other systems and energy vectors is critical, this is critical if hydrogen uptake is at the lower end of projections at around the 50TWh level and the area is left with more hydrogen than there is demand, see Figure 11. The MH:EK consortia are particularly interested in expanding the current knowledge base in this space. If the area can position itself as a leader in hydrogen, it should support further investment, providing more momentum to accelerate the UK's transition to a net zero economy. Pembrokeshire is well positioned to do this due to the existing infrastructure and high levels of expertise.

A Local Energy Asset Representation (LEAR) for the project has been completed for the area around Milford Haven, Neyland and Pembroke Dock. It gives an understanding of the buildings in the local area; their annual and peak energy demands and the energy networks that serve them. It also provides some information on the levels of employment and deprivation in the area. It is not expected that the information contained in this document exactly matches the items it reports on but, rather, provides a reasonable representation of them.

Action point: The project stakeholders including those in future phases should aim to remain central to the developments of the decarbonisation debate in the region, providing links, insights, and coordination. Search for more net zero proposals, both hydrogen and other solutions and assess whether the MH:EK project could link in with these plans in the future. Discuss with WWU their plans for transitioning to net zero. Assess whether the MH:EK project could in the future link in with these plans.

4.4 POTENTIAL SYSTEM ARRANGEMENTS

From the workshops and other stakeholder engagement we identified a number of possible system arrangements for how a hydrogen physical system and associated commercial arrangements could play out. These potential system arrangements (PSAs) have been used to systematically consider the potential needs of hydrogen systems from a technical and commercial perspective.

The arrangements, as described below, focus on describing hydrogen market arrangements as they are the new features, though it is important to note that other vectors can also transition, either at the same time or at a later stage.

It is important to note that, throughout, we have tried to be careful to not assume that everything has to transition concurrently and that multiple arrangements could co-exist. Additionally, some arrangements may be steppingstones in transitions to later ones, rather than having to make a single choice of the future arrangement. However, we present them here as each arrangement has both similarities and differences in terms of solutions to make them work.

PSA1 Self Consumption: A site owner, owns and/or operates both the hydrogen production facility and the demand facility. The transfer of hydrogen can all be considered internal sales but there is an additional opportunity to sell any excess.

PSA2 Private contracts: Hydrogen production is either co-located with demand centres, one-to-one in a cluster or hydrogen producers sell directly to customers who are more geographically remote. Hydrogen is moved between premises in either local, dedicated pipelines or in containerised transport (e.g. pressurised bottles, tanks on trucks). Commercial arrangements are expected to be contracts between both parties rather than a trading platform but with an opportunity to sell any excess.

For customers in potential systems arrangements 3 to 7 it is important to note that those end-users will need their assets or appliances to be blend / hydrogen ready or have alternative arrangements in place (e.g. a local dedicated natural gas supply, local alternative production or electrification etc.) else this could slow / block the transition.

PSA3 Local blended hydrogen (single producer): A single producer of hydrogen blends hydrogen into the natural gas system such that every customer (commercial and domestic) downstream of the injection location receives a blend of hydrogen and methane molecules. This scenario occurs before an approach for managing blend levels have been established (as proposed by Frontier Economics in 'Hydrogen Blending and the Gas Commercial Framework' (2020)[22]). Commercial transactions occur between parties injecting at the local node and customers downstream (possibly via suppliers).

PSA4 Local blended hydrogen (multiple producers): A system where-by hydrogen is injected, into the natural gas network, at local points (likely a local distribution zone (LDZ)) such that every customer (commercial and domestic) downstream of the injection location receives a blend of hydrogen and methane molecules. A process has been agreed for coordinating the injections of multiple generators to ensure the blend limit stays within the allowed region. Commercial transactions occur between parties injecting at the local node and suppliers who transact with customers. The range and limit may vary with location based on the assets in the region.

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[22] https://www.frontier-economics.com/media/4201/hydrogen-blending-commercial-framework.pdf

PSA5 Local dedicated hydrogen: An area of natural gas network converts to hydrogen fully or else a bespoke dedicated hydrogen network is developed. Trading is similar to today's trading with natural gas (notwithstanding that retail offers can change to end customers). One consideration is that there is likely to be insufficient competition between generators on the network to maintain reflective price signals and a price regulation for producers may be required.

Care is required to ensure that retailers can choose to trade natural gas in some locations and hydrogen in others. Alternatively, it might be appropriate to bundle hydrogen retail and networks (i.e. if a customer is receiving hydrogen in a local place, then you need to have a specific retailer). Lack of competition in a small geographical area may require a regulated producer (natural monopoly). Supply and demand in a local area needs to be matched (either via the supplier buying and selling and/or a third party with residual balancing rights).

PSA6 National blended hydrogen: A national system of moving a blend of natural gas and hydrogen around the existing natural gas network. There is a process established for managing the blend limit to ensure it stays within the allowable range. The range and limit may vary with location based on the assets in the region.

PSA7 Regional / National dedicated hydrogen: A national/regional (where a regional system simply means more than one interconnected local systems) system of hydrogen pipelines run throughout GB (either as new construction or where previous natural gas pipelines have been upgraded). A well-developed hydrogen market exists so market participants contract through a mixture of long-term contracts and the markets over different time periods.

These arrangements are intended to provide context for the next few report sections, which explain in fairly broad terms, design aspects and changes required to support the emergence of a hydrogen economy. In many places there are options and alternative ways of making a future hydrogen local energy system work. In section 9 each of the potential system arrangements are explored in more detail. Where there are specific options or combinations of choices which are needed to support a specific, potential system arrangements they are called out, effectively providing multiple system architectures to support a transition from business as usual to an integrated, multi-vector, hydrogen-based smart local energy system. It should be noted that this work does not consider the financial viability or cost of different approaches, simply the pathways down which a hydrogen system could develop.

5 HYDROGEN PHYSICAL SYSTEM ARCHITECTURE

The physical aspect of a hydrogen system must include the elements to generate, move, store, and use hydrogen. This section provides an overview for a future operationally functioning system incorporating such system elements and the interfaces required when moving from one element to the next. Furthermore, in each section there is commentary on what the project could do next to develop each element or interface. This chapter's focus is on the hydrogen system but does consider the interactions with other energy vectors.

The hydrogen system can be seen at a high-level view in Figure 15. This highlights the five main elements which are discussed in greater detail later in section 5 and numbered in yellow in the diagram.

1. **Production**: ① The process of isolating or extracting hydrogen.
2. **Transport and Distribution**: ② The process of moving hydrogen physically from one place to another either in a container or through pipelines.
3. **Storage**: ③ Methods for keeping hydrogen in one location for later use.
4. **Use**: ④ Stage where hydrogen is used to produce energy or a chemical reaction.
5. **Preparation**: ⑤ Process that changes one or more properties of hydrogen (form, pressure, blend...).

The appendix in section 15 further includes the interfaces (numbered in pink in the diagram below) required between the elements and the items external to the systems that also have an influence such as:

- **Natural Gas System**: the natural gas energy system used to produce hydrogen ①.
- **Heat**: the heat energy system which is required for some production methods ① and is a by-product ⑧ of all exothermic reactions through the system (production, use, depressurisation etc.).
- **Electricity System**: The electrical transmission and distribution system which provides the source of some hydrogen production methods ① (e.g. electrolysis). Electricity can also be produced from hydrogen ⑦.
- **By products**: Any product made during each process which is not the output energy carrier ⑧ . Heat, water, and emissions are different types of by-products.
- **Emissions**: Emissions include all the emitted gasses not used at the end of each process. CCUS reduces emissions.
- **Other resources**: Coal, oil, biomass, and other energy sources that can be used to produce hydrogen ①.

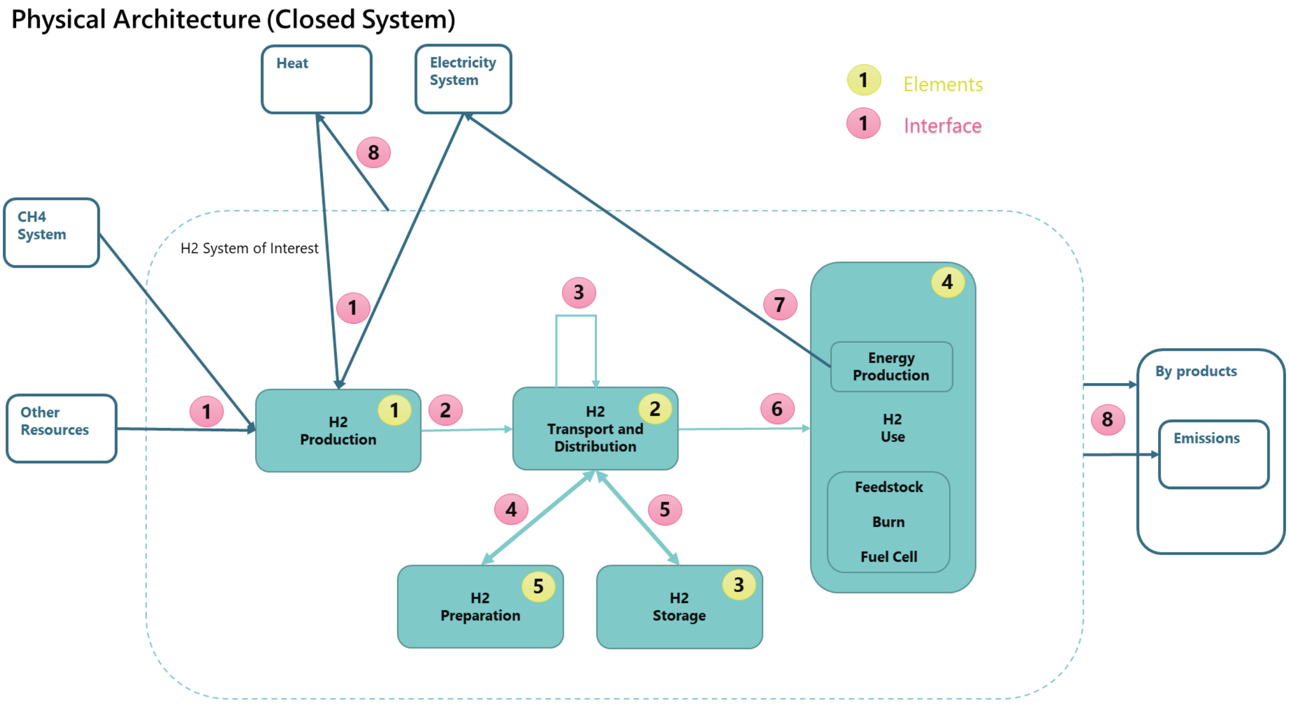

Figure 15 – High level hydrogen energy system elements and interfaces

Other items that have been identified as important to the MH:EK system are as follows and will also be discussed in more detail.

- Blended Hydrogen network
- Import / Export
- Hydrogen System Interoperability
- Hydrogen System Control
- Hydrogen Standards

The roles of the different stakeholders such as suppliers, system operators, regulators and consumers are also discussed throughout the sections in their ability to develop and operate different physical arrangements.

More detailed definition of terms, background information and examples using use cases are available in the appendix in section 15.

5.1 PRODUCTION

Hydrogen is a component of water, fossil fuels, biomass and can be extracted from its compound using different technology and energy sources. Currently, hydrogen is mainly used for industrial purposes, such as producing fertiliser and refining oil. Almost all the hydrogen produced today is produced from fossil fuels through steam methane reformation, high temperature and pressure releasing carbon dioxide into the atmosphere. For hydrogen to be part of the transition away from fossil fuels, the main objectives relative to production are:

- Transitioning to lower emission hydrogen production for existing demand.
  - By reducing the emission of the production process. For example, using electrolysis with low carbon electricity source.
  - By capturing the emissions (e.g. CCUS) emitted during the production process from carbon dioxide emitting processes (SMR, ATR, biomass gasification…). Hydrogen can also play a

part in enabling CCUS by using the captured carbon, for example in the production of green methanol from hydrogen and carbon dioxide.

- Scaling up production for novel applications in an efficient, controllable, and environmentally friendly way.

5.1.1 PRODUCTION TECHNOLOGIES

Depending on the production process the cost and environmental impact of production will vary significantly. The quality of the hydrogen produced also depends on the process and is linked to efficiency for each process.

In order to install hydrogen production, the location must provide access to the necessary resource. Access to reliable source of renewable electricity with sufficient supply of water and energy is necessary for electrolysis for example or the proximity to the transmission or distribution gas network for methanisation.

Through these processes, by-products will be generated (oxygen from electrolysis, carbon monoxide/dioxide from methane reformation, carbon black from pyrolysis and heat output) which can have an environmental and commercial impact.

Hydrogen production scale and technology is developing at a growing pace. New technology is likely to be available in the coming years potentially using different feedstock, energy, or conversion processes. The source of hydrogen can be defined by the production process used and its:

- **Feedstock**: Energy source and other resources used to generate hydrogen (electricity, water, biomass, natural gas, heat…)
- **By-products**: Secondary products generated during the hydrogen production process.
- **Physical properties**: The characteristics of the hydrogen plant from location, size, capacity, start/stop times etc…
- **Environmental properties**: emissions, emissions intensity and embodied emissions can characterise a production process.

The properties of hydrogen as an energy output (such as cost and quality) are not considered in this section but in the commercial and hydrogen properties sections. The description of elements characteristics and environmental properties are developed in the appendix in section 15.

5.1.2 PRODUCTION INTEROPERABILITY

Hydrogen can be produced from any primary energy source. To focus on the net zero incentive in the MH:EK area, the options presented here are:

- Hydrogen produced through electrolysis using renewable electricity and water.
- Natural gas or derivative conversion through reforming or pyrolysis including carbon capture where required.
- Gasification or pyrolysis of biomass.

The availability of feedstock varies by location. For electrolysers the electricity, water intake and connection to the distribution infrastructure needs to be considered. The carbon content of the electricity and the purity of the water (or the possibility of purification) need to be considered as well as the availability.

For natural gas feedstock, access to the gas network (transmission or distribution depending on amount required) is essential. For carbon dioxide emitting processes, the development of CCUS will drive the scale of net zero emitting production capacity. Therefore, transport to the location of storage and usage of carbon dioxide will affect the likelihood of the implementation of a production plant.

Production plants must fulfil the needs of the end use. Hydrogen needs to be transported to its destination and meet the quantity and quality requirements for end use.

The location of production plants and the share of each technology should be coordinated with a long-term vision for the ability of the system to:

- Match supply and demand, including purity requirements
- Connect to the end user
- Connect to other networks (clusters for local energy systems and import/export for national system)
- Compete & co-ordinate with other production sites (coordinated planning)
- Compete with other energy vectors for that location (e.g. heat pump or district heat planning and incentives)
- Become carbon neutral by 2050

In the next ten years, electrical and hydrogen demands are likely to significantly increase (the values for hydrogen were outlined in Section 4.2). Production opportunities should be investigated for their short- and long-term potential. A strong cooperation between the developments can speed up the implementation. The impact of each development will depend on its ability to subsist economically and integrate with the hydrogen economy of the future. Some important points to consider:

- The end use of any hydrogen being produced will dictate the quantity of production and quality of its purification.
- The location will be crucial as large volume transport is still challenging.

5.1.3 PRODUCTION CONTROL

The hydrogen production process is controlled by the plant operator. The operator can request the plant to start, stop or level production depending on the hydrogen demand and dispatch signals. The variety of feedstock and technologies should provide hydrogen baseload demand as well as forecast peak demand and real time variations. The different gasification and reformation plant size and efficiency should allow this flexibility. However, with the intermittence and uncontrollable nature of renewable energies such as solar and wind, the production from electrolysers may need to vary to better match the availability of low-cost electricity. Connecting electrolysers to the grid, mixing productions sources (electrolyser, SMR, biomass, multifuel gasification plant…) and developing storage can provide greater control to match the hydrogen demand.

For a co-located system arrangement, the plant operator controls production, dispatch, and use. Once multiple producers operate on the same network, flexibility increases, competition appears and information exchange between the different stakeholders need to be defined. Different dispatch approaches are detailed in section 5.9.3 and potential systems arrangements in section 9.

5.1.4 LOCAL PRODUCTION CONSIDERATIONS

The MH:EK project covers an extensive range of energy assets in Pembrokeshire, including many resources and infrastructure. However, with the range of choices comes the integration of multiple systems.

Due to its coastal location and low density population, MH:EK is perfectly placed for renewable electricity production from onshore and offshore wind as well as solar and the potential of tidal technology. As for other energy sources, MH:EK is one of the main import/export hubs of natural gas to the UK and the main LNG import terminal which can be linked to other hydrogen production facilities. As such, MH:EK is an entry point to the transmission network and the local distribution network. For example, offshore hydrogen production (e.g. Dolphyn & Deep Purple projects) in the Celtic, Irish, and North Seas, could be linked to the MH port LNG infrastructure, which could provide a hub for offshore hydrogen production and subsequently transported and/or stored. The large offshore projects are planned with long lead times of many years; therefore early engagement and integration with onshore hydrogen infrastructure plans would be critical.

The integration of the electrical and natural gas systems to produce hydrogen will be crucial for the energy transition. This includes physical, commercial and data compatibility between and within the systems. Gathering the short- and long-term needs from the different parties will support the creation of a pathway at local level and ambitions towards national and international partners.

Decision point: Each Milford Haven project design should emphasise the need to plan when and where to produce hydrogen and include the import potential and evolution. Short and mid-term planning for hydrogen production should focus on reaching cost targets and emissions (including CCUS scale) and cost for fossil fuels thermochemical conversion. The medium to long term should be flexible to accommodate innovative approaches including biomass conversion.

MH:EK can pave the way to best hydrogen production methodology before private investments (within and from outside of the region) and global interactions will drive the production growth.

Stepwise low carbon production in combination with secure supply to meet demand can support a smooth transition for growing hydrogen demand. Continuous upgrade with low carbon production options can support the decarbonisation objectives.

5.2 TRANSPORT AND DISTRIBUTION

Transport and distribution are the link between all the different elements whenever hydrogen is not solely used onsite. It can be integrated within each element through private pipes. Also, processes such as refuelling trucks and off grid portable hydrogen generator can be considered as a combination of transport, storage, and end use. In the architecture, it is important to consider the boundaries and the properties characterising each element. One actor can have several roles and bring together the elements.

Transport of hydrogen is fairly similar, at a high level, to transport of natural gas. It can be transported and distributed through pipelines or containers (by road, rail, or waterways). They have the main characteristics for control: quantity, quality, and pressure. These characteristics obviously depend on the end use of the gas.

However, the physical properties of hydrogen make it more challenging to transport than natural gas. Higher pressure or liquefaction is required to transport hydrogen because of its lower energy density. Hydrogen can embrittle some metals (such as pipelines, valves, pumps, welds…), weakening them, potentially causing leaks. Hydrogen's very high flammability and explosive properties make the need to prevent leaks a critical and novel challenge. High volume compressors for hydrogen are still novel technology under development. It can also be transported, stored, and used as a compound such as ammonia or methanol. Each preparation step (liquefaction, compression, hydrogenisation) is an energy intensive process in itself and has associated asset and operational costs. If the preparation is solely for transport feasibility, the opposite operation will be required before end use.

As development continues in the large volume transport of hydrogen through pipelines and by containers, the hydrogen transport and distribution element will focus on the importance of:

- In the short term, the colocation of production and demand to demonstrate the reality of hydrogen production and applications. However, this will limit the scale of use for heating and road transport for example.
- Material development for safe transport and distribution.
- The preparation allowing easier, safer, and cost-effective handling.
- The connection of centralised and distributed production.

Transport and distribution, if not integrated in the other elements (private pipes within production, storage, or end use) is carried out by the network operator of pipelines or freight operator of containerised hydrogen.

5.2.1 TRANSPORT AND DISTRIBUTION BY CONTAINER

Containers are more suitable for smaller volumes and to reach off grid areas. Like for storage, hydrogen needs to be prepared before transport. Hydrogen is most commonly transported under high pressure or in liquid form. Hydrogen can also be transported as a compound such as ammonia, methanol, or liquid organic hydrogen carrier (LOHC). One of the benefits to transport hydrogen compounds is that it can be stored at atmospheric pressure and ambient temperature. However, each conversion requires energy and causes losses and emissions.

Containers can allow hydrogen and hydrogen carriers to be transported by:

- Road tankers
- Waterways - coastal tankers can be used to carry LOHC between ports.
- Rail

Containers are suited for remote location and temporary usage. By default, containers serve as integrated storage. They can also be integrated with storage and end use from small dispenser to mobile refuelling vans and trucks.[23]

Containerised hydrogen distribution is currently the favoured method of transport due to the relatively low volume of hydrogen used. This is likely to remain when the hydrogen grid develops, working in parallel similarly to natural gas (low volumes, off grid distribution, speciality gas…). The main operating cost and associated emissions being the distance between production and end use. It operates in a fairly similar manner to the distribution of liquid natural gas and oil derivative products used for the industry, refuelling stations and off grid power generation.

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[23] https://www.fuelcellsystems.co.uk/

5.2.2 TRANSPORT AND DISTRIBUTION THROUGH PIPELINES

Pipelines used to transport hydrogen range from small, private pipelines, to distribution and the development of a national transmission network.

The current gas network infrastructure could be the backbone of the future of hydrogen transmission. The existing network could be repurposed section by section to reduce emissions where hydrogen (or blended hydrogen) demand is sufficient, and devices are compliant. The end user profiles, and the security of supply will impact the pipeline design specifications.

By default, gas pipelines offer linepack flexibility similar to operational short live storage. When demand exceeds supply, the outlet pressure drops, and additional gas is available in the pipeline. Linepack doesn't offer a storage solution but offers a margin for control and reinforcement.

As a steppingstone, up to 20% hydrogen can be mixed in the natural gas transmission and distribution network with minimal alteration to the network. However, this is only an option if the end use devices are compliant. This can provide a secure base demand without major infrastructure disruption and decommissioning need and stranded assets. Blended hydrogen physical systems are described in more details in section 5.6 providing insight on interoperability, control, and transition considerations.

The main role of the system operator is to link the supply to the demand by managing transport and distribution of hydrogen throughout each level of the network. It has to control the movement of hydrogen, either liquid or gas using pressure valves or pumps throughout the network. In essence, this could end up being similar to the natural gas (including LNG) and oil products architecture. However, the complexity of transitioning from the existing architecture will lead to hybrid systems requiring more complex and novel control. Because of the different physical properties of natural gas, hydrogen, and blend, it is crucial for the controller to compensate for different gas speeds to avoid oscillations and instability as detailed in section 5.9.

The parameters that the system operator needs to manage comprise:

- Quantity and form for suitability of pipeline and containerised transport and distribution.
- Capacity and availability.
- Distance and time required between supply and demand.
- Compression stages and required energy. This includes pressure compatibility within the gas network. For blended distribution, hydrogen injection quantity also needs to maintain the blend levels within limits ..
- Time and distance to end use request.

Hydrogen price and uptake is highly dependent on its quantity and availability. The development of the infrastructure for hydrogen to be mass produced or imported then reach a wide range of consumers will be lengthy and take place in stages.

5.2.3 LOCAL TRANSPORT AND DISTRIBUTION CONSIDERATIONS

As a major hub for natural gas and LNG, MH:EK contains many assets to import, transport and distribute gas and is ideally placed to repurpose and develop the hydrogen network through trials and regulation support by:

- Careful and flexible consideration of a gradual approach considering market, regulations, and technological developments.
- Plan how and when the transport and distribution infrastructure can evolve from local energy system to a national and international one.
- Depending on the outcome of blending projects and the ensuing regulatory changes, the possibility to inject as much hydrogen as permitted could really boost the production upscale and flexibility. This could significantly reduce emissions in the short term with minimum disruption. The impact on all assets down the line must be carefully planned to avoid backlash and disruption on other developments. For example, if the natural gas supply to a blending station starts supplying hydrogen, the mixing plant will have to adapt its mixing control and measurements. This could make the local hydrogen supply redundant if not carefully managed.

Decision point: MH:EK project in collaboration with WWU should actively lead planning and preparation for regional and national hydrogen transport and distribution transition with other Gas Distribution Networks Operator (GDNO) and ESO.

The consequence of this will be the role of MH:EK as leader in the development of the national hydrogen network that will define hydrogen availability across the UK and potential uptake. This role can also lead to policy influence and the share of hydrogen in the energy mix. This will have a direct impact on retaining existing assets, skills, and employment in the region.

5.3 STORAGE

Storage holds a double role to support supply and demand. Storage includes large scale geological stores (salt caverns, oil, and gas fields…), linepack in the pipelines (relative to the size of the network) to containers, mobile and stationary. The storage operator controls the injection and discharge rate to balance the system and minimise costs. The granularity of control will depend on the physical characteristics, the response time required for the consumer and the ability of hydrogen equipment to respond and the system controller approach.

Storage capacity and control have multiple roles to support the upscale of the energy network:

- The main role is to balance the system and support fluctuation in supply (e.g. from renewable) and demand (within day or interseasonal).
- A storage operator can use price signal to minimise cost for both electrical and hydrogen system stakeholders.
- Support the electricity system by providing interseasonal storage. Again, the same connected hydrogen storage can act as a flexible service to support planned supply of both electrical and hydrogen demand as well as to support the electricity system as a reserve for exceptional event.

Increasing storage and smart control can support the development of the hydrogen market but careful attention is needed to the related cost and cost recovery as well as the risk of redundancy if supply becomes more secure either from steadier production or secured import.

5.3.1 LOCAL STORAGE CONSIDERATIONS

Despite its geological landscape not being suitable for large scale gaseous storage (no salt cavern, depleting oil, and gas fields in the region), development to support hydrogen storage from MH:EK may take different directions and it will be essential to be flexible regarding the long term future:

- Maintain existing natural gas import, transmission, and storage assets to support hydrogen production. With the development of CCUS and other methane reformation techniques, the existing gas network can support the production of hydrogen in a different location, close to end use or storage facilities.
- Upgrade the network to support gaseous hydrogen to be transported to storage facilities and final use. This is supporting the transition from natural gas to hydrogen. As described above, many physical, safety and regulatory barriers still exist and are likely to remain for some time.
- Development of other forms of hydrogen storage such as liquid hydrogen, ammonia, methanol among other that can be beneficial in terms of cost, safety, and storage density. MH:EK existing assets, experience, and skills with LNG for example may prove an advantage for the development of these new storage mediums.

Discussion point: MH:EK project in collaboration with WWU, Dragon LNG, the port terminals and all storage stakeholders should define a pathway for hydrogen storage for the short, medium, and long term including its role, the form, quantity, and operation of storage using MH:EK existing assets and expertise where possible while considering national storage options as well.

Consideration with national policy is vital to understand the future possibilities for ownership of storage assets, which may struggle to find a feasible commercial business model to fund the asset development. See section 7.1 on production support strategies.

Storage offers flexibility that can reduce the overall power generation investments. It should always be considered (inclusion potential and exclusion reasons) in planning applications.

The consequence of this decision could put MH:EK at the heart of the future hydrogen and energy flexibility locally and nationally. Alternative storage also needs consideration to avoid future stranded assets.

5.4 USE

Hydrogen is not only an energy vector but also an essential feedstock to many chemical processes.

In theory, hydrogen could be used wherever methane is currently used throughout industry, heating, and electricity generation. However, it is not a straight switch just because green hydrogen is environmentally friendly at end use even once it can be produced economically at scale. There will be some asset upgrade needed due to the physical difference and the competition with other energy vectors. Investment, policy, and consumer acceptance will also play a major role. Hydrogen also has the potential to replace some of the current use of oil-based fossil fuels for the industry, mobility, and heat sectors.

From the energy usage perspective, the benefits and efficiency of using hydrogen from converting electricity into hydrogen for an application that can use electricity directly such as domestic heating or electric vehicles can be difficult to prove. Hydrogen is more likely to decarbonise coal, natural gas, and oil usage alongside electrification in parts of the energy system that electricity cannot accomplish due to the end use profile requirements.

Hydrogen and hydrogen carriers are used as three main different ways for the different end users:

- as a chemical feedstock (e.g. for ammonia, fertiliser…).
- as an energy source for fuel cells to produce electricity (e.g. mobility, backup power…).
- burning to generate heat or power (e.g. heating, industry, electricity generation…).

New findings are emerging through tests and innovative trials. A shared learning environment and collaborative work can accelerate knowledge development and support the development of interoperability standards. The potential connection of multiple end use to a common network could support scaling up, uptake, minimise transport costs but may require a preparation stage prior to end use. Accurate comparison for end use between sectors and energy vectors can support uptake, acceptance, and price comparison. More information and examples are presented in the appendix in section 15.

Historical practice, market structure and protocols for oil or gas, automotive, industry and building sectors will impact the prospects for an efficient integrated system. Where fuel is delivered to petrol stations by tankers, hydrogen refuelling stations should assess the options of similar method or connection to the hydrogen pipeline network or collocating production. Different fuel cell tanks pressure requirements are being developed independently for mobility and stationary applications. Integration of third-party applications can also lead to initial development time and effort such as developing interface for hydrogen in building management systems. It is crucial to determine hydrogen compatible standards to allow optimal control to avoid having multiple independent systems. The integration and the control of multiple and varied end uses requires good understanding of flexibility parameters and a clear definition of delivery priorities. An early role of the system operator could be supporting stakeholders in agreeing connection, communication, and control arrangements. This can apply at microgrid, and local levels then progress to transmission operations. The different potential systems arrangements are detailed in section 9.

5.4.1 LOCAL USE CONSIDERATIONS

In terms of energy use, MH:EK has many energy intensive sectors (agriculture, marine, food including fisheries, mobility, oil, and gas industries) that will face the different options in the decarbonisation pathway whether for their gas or oil derivatives consumption. This includes use from industries and agriculture, the whole range of mobility from marine vessels (from tugs across the port to growing maritime import/export of energy and goods), road (car, freight, agricultural vehicles), rail (diesel engines phase out) and power generation. Urban areas are interlinked with the industrial activities of the port and so could benefit from coordinated industrial, commercial, and domestic energy use including heating by increasing cogeneration and maximising renewable use. The coordination during the decarbonisation transition between all these assets and the development of smart local energy system should benefit all actors in the local area.

Action point: MH:EK project could push for future designs to include multiple end users' connections requirements.

Different options include connecting end users to the same network by either using one standard for all or include preparation (purification, pressurisation...) close to end use. Working closely with WWU, integrate and coordinate requirements for hydrogen injection (including blend and compression) for the potential end users such as Pembroke power station, Valero refinery, domestic and commercial heating.

Connecting end uses on the same network increase efficiency and reliability. Preparation requirements for different applications should be addressed. Integrating end use connections has the potential to increase existing demand and unleash new technology.

For the purpose of this report, the end uses are categorised by sectors to highlight the different needs, usage behaviour, alternative energy vectors and challenges:

- Industry (as a chemical feedstock or for high heat processes)
- Mobility (road, rail, marine, aerospace...).
- Heating (including space heating, water heating and connected appliances)
- Stationary fuel cell applications (as backup or for off grid applications)

Furthermore, once these sectors have established a secure supply chain, the use of hydrogen could supplement electrified sectors.

5.4.2 INDUSTRY

Currently, the chemical industry is the largest producer and consumer of hydrogen. Most of the hydrogen produced for the industry comes from natural gas. More than 50% of hydrogen consumption around the world goes to **ammonia production** and **oil refining.**

Other industries deemed difficult to electrify also rely on hydrogen as a chemical feedstock or to produce high heat. They include **methanol production, steel, and other metalwork production** (e.g. tungsten, copper, nickel extraction), **food processing, glass and cement production** and **welding.**

Hydrogen is also used in **electronics components manufacturing**, for **medical applications** and **water treatment** or as a **coolant** for different industry applications.

For applications where hydrogen is used as a feedstock, it is unlikely to be replaced by another element. The ambition in this field, is to keep the same process using green hydrogen to reduce embodied emissions. This will affect the whole supply chain including production to distribution.

Where hydrogen is used as a heat source for high grade heat (>650°C), heat electrification may offer an option if advancement is realised in the coming years. If industrial heat pumps can increase their operating temperatures, they could, in theory, serve well over a third of industrial heat demand. However, many industries – including non-ferrous metals, ceramics, chemicals, and food –

use batch processes requiring large amounts of energy in short bursts. These can cause voltage or frequency problems, necessitating upgrading of the power grid.[24]

As the main hydrogen consumer, the industry sector can be targeted as a worthwhile user for the continued research and development of large scale electrolysers and develop CCUS. Large scale green hydrogen production is expected to prove the feasibility of a hydrogen economy and enable further applications. Valero already produce hydrogen as part of its refinery plant for desulphurisation. Two steam methane reformer units were retrofitted to capture the carbon dioxide produced in the process of making hydrogen.[25]

Where hydrogen and hydrogen-based chemicals are already used, the interoperability will lie in the smooth transition in low carbon production and distribution to the end use. Also, if the same standards of quality can be used for hydrogen as a chemical feedstock, for combustion or fuel cell, the need for preparation can be reduced and the scale of production, transport and distribution and storage increased making a significant impact on overall costs.

Decision point: Early assessment of current hydrogen use, by MH:EK stakeholders in collaboration with other partner projects (such as SWIC), for refinery and agriculture to plan decarbonisation of production to existing demand.

This can put MH:EK at the forefront of low carbon hydrogen production without having to follow demand development timescale. In the event of regulatory requirements to decarbonise production, the decision may become reactive and costly.

5.4.3 MOBILITY

Mobility applications encompass into road, railway, waterways, aerospace, and space transport. Fuel cells for mobility are an alternative for electrical batteries. The obvious advantage of batteries is the efficiency of using electricity directly. However, the benefits of fuel cells, compared to electric batteries are range, vehicle size and refuelling capability (time and location).

One of the characteristics of electrolysers is that they can directly produce the high purity hydrogen required for fuel cell mobility applications. The fuel cell process is the opposite process of electrolysis. A fuel cell is a device that generates electricity through an electrochemical reaction, not combustion. In a fuel cell, hydrogen and oxygen are combined to generate electricity, heat, and water.[26]

This section focuses on the use of mobile fuel cell for transportation as opposed to stationary applications for power generation covered in section 5.4.5.

Hydrogen and hydrogen based fuels (such as synfuel, ammonia…) are an option for the decarbonisation of mobility. For aviation, road, marine and rail transport, the replacement of internal combustion engines has started with mainly battery powered and hybrid engine vehicles especially for smaller engines. Fuel cell electric engines are also a technologically viable alternative especially when batteries are too heavy, too slow to recharge for long continuous use, not powerful enough and where battery performance is affected by the environment (e.g. wet). Identical fuel cell

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[24] https://about.newenergyfinance.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/
[25] https://www.valero.com/responsibility/environmental-stewardship/recycling-process
[26] https://www.fchea.org/fuelcells

stacks and tanks can be used and produced by the same manufacturer for multi mobility sector applications (road, rail, water…). They range for tank sizes and volume of production. The next step in the transition is the coverage of all types of vehicles and the supporting infrastructure (supply chain, refuelling, maintenance, servicing etc.) to become economically competitive.

It is important for the development of fuel cell technology; tank features; and refuelling protocols, between mobility sectors, to line up. For example, developing common refuelling practices would allow a cross mobility sector refuelling strategy and the development of strategic refuelling hubs for multiple mobility end uses (road/rail/marine/aerospace). This could prevent regulatory hurdles, increase volumes, uptake and reduce industry costs.

MH:EK is particularly well placed for the development of hydrogen based systems for maritime applications such as:

- Interoperability of refuelling standards could put MH:EK at the forefront of the development of local marine applications such as local ferries, tugboats etc. using their experience and existing development on the sea front of a refuelling station. In the longer term, this could scale up to international marine transportation.
- Skills and experience in best practice for natural gas can be exploited to support the development of hydrogen on the coast:
    - For international hydrogen marine transport by being involved in the definition of hydrogen tank types, ship arrangement, risk assessment etc.
    - For interconnection at the port with the definition of interoperability of port terminals for import and export.
    - Cyber security in line with the oil and gas industry to protect vulnerable and automated systems.

As an emergent option for mobility and the multitude of prototypes and demonstrators, designers, manufacturers, and the whole supply chain will need to work globally across all mobility applications. However, as fuel cell vehicles are an adaption of the power systems, tests and regulations can be adapted and integrated with existing vehicles regulations. For example, crash test can be adapted to the integrity of the hydrogen system for components testing and installation.

One critical point is the interoperability between the fuel cell electric vehicles (FCEV) and the charging infrastructure. This includes:

- The compatibility for end use mobility applications (pressure, standards…)
- The hydrogen source for refuelling station
- The number and location of Hydrogen Refuelling Stations (HRS)

Action point: The MH:EK project is running three scenarios (across high-electric to high-hydrogen) that consider different transport demands of both the PCC and PoMH fleets. The project should analyse the results and, along with the experience of the Riversimple RASA cars, assess the transition of the council fleet of vehicles (buses van, bin lorries, cars) as part of the whole region energy plan.

The MH:EK refuelling station is ideally based on the Milford Haven Marina for the project’s immediate needs however part of a whole region energy plan should consider optimised refuelling station locations that account for marine and other applications. The scale of new mobility developments and integration with potential public access should also be integrated into planning.

5.4.4 HEATING

The main use of natural gas in the UK is space heating but also includes water heating (stored or direct), gas appliances such as gas cookers and ovens, fireplaces, fire pits, outdoor lighting etc… The end use of these applications cannot be differentiated behind the current metering settings.

It is estimated than 90% of households are connected to the gas grid. The UK is therefore in a predisposed position regarding the proportion of houses connected to the grid. Where decarbonisation of heat can be driven by the use of heat pumps, the change from gas to electricity can be costly and disruptive in terms of decommissioning, installation, and use.

For domestic heating applications, the main objective of the development of hydrogen heating are to:

- Replace natural gas with green hydrogen to reduce emissions with an optional blended hydrogen phase.
- Support hybrid heat pumps (local network with long term storage).
- Develop a decarbonisation of heat strategy using the most suited energy vector across the UK.

The development of hydrogen may be similar to the development of natural gas in the 20th century. Specific area is switched to hydrogen (residential area, port, industrial estate). If large scale production and transport becomes safe and economically viable, networks can be connected to increase resilience and flexibility.

Blended hydrogen is a steppingstone towards heat decarbonisation by potentially:

- Reducing emissions in the short term across a large number of properties.
- Supporting gas pipeline research and development towards conversion to pure hydrogen.
- Increase flexibility of the system where variable blend is supporting by varying the proportion of hydrogen to natural gas within a predefined range to help with matching supply to demand.

Note that the use of hydrogen to replace oil, methane, and coal for industrial heating rather than space heating in discussed in detail in section 5.4.2.

Section 5.6 details hydrogen blend considerations for the whole energy system. The different options between natural gas and pure hydrogen, the control and interoperability within the gas network and other energy vector.

5.4.5 ELECTRICITY GENERATION

Electricity generation from hydrogen falls into two categories:

- Stationary fuel cells used as power supply at different scale for direct hydrogen use (final use).
- Hydrogen powered internal combustion engines can generate electricity to the grid for indirect use where the energy carrier is still part of the energy system.

Direct Use – Stationary Fuel Cells

Stationary fuel cells can provide electrical power for off grid applications or backup for uninterruptible supply. Stationary fuel cells can replace diesel generators to cut emissions as well as reducing noise and smell. Hydrogen can also offer one source for electricity as well as refrigerant for dual temperature control.

Technology and solutions for off grid or portable energy storage is already available. Fuel cell applications range from personal fuel cell generators, CCTV towers, wildlife filming to industrial applications or the supply of off-grid power in isolated regions or islands. Stationary backup power generators are used during grid outage for critical infrastructure such as hospitals, telecom towers and data centres.

The benefits of hydrogen storage compared to batteries include that fuel cells do not self-discharge, are lighter hence bigger capacity for the same weight, longer lifetime and more tolerant to extreme weather (damp, cold, hot). In some applications, the heat generated by the fuel cell can be used or stored to combine heat and power (CHP).

The main integration barrier will be the supply of hydrogen, the safety of the tank and the connection to the electrical output.

Indirect Use – Hydrogen Gas Turbine

Converting hydrogen or a blend of hydrogen and natural gas into electricity can provide flexibility to the whole energy system. In an integrated energy system, hydrogen can provide flexibility between an increasing intermittent renewable electricity production and the seasonal peak demand.

More details on blended hydrogen powered gas turbines can be found in section5.4.5.

Electricity and hydrogen can support each other. Hydrogen is one of the key options for storing renewable electricity at time of peak production (summer) and be a source of electricity generation for peak demand (winter). Hydrogen power stations can provide grid balancing to assist with high demand during low renewable supply. Hydrogen and ammonia can be used in gas turbine as a blend or be retrofitted together with the inlet pipework to use hydrogen. Ammonia can also be burnt in coal-fired power plants to produce electricity. This process turns the ammonia back into nitrogen and water and do not emit any carbon dioxide.

More details on multi vector control can be found in section 5.9.4

Pembroke Power Station successfully transitioned from oil to natural gas between 2008 and 2012 thanks to the development of the construction of the two LNG terminals. In 2015, the turbines were upgraded to offer different operating modes to optimise efficiency, maximise power output and lower maintenance cost. Based on this experience, Pembroke Power Station could be at the forefront on research into both CCUS and hydrogen conversion to reduce emissions while keeping the electricity supply stable and affordable. CCUS and hydrogen source introduction can be concomitant.

The ability of the region to adapt and repurpose skills and assets could generate substantial environmental and economic benefits.

Discussion point: Consult with RWE's plan for the long-term future of Pembroke Power Station. Ensure the plan to fits with the local and national hydrogen architecture plan and decarbonisation pathway. Options to inject hydrogen, combine biomass, add CCUS or a combination of these options need to be analysed depending on available resources and the growing demand.

The influence of the power station on the gas and electricity network is immense from production, to end use and can be a major actor in reducing emissions in the region.

5.5 PREPARATION

Because of the volatile properties and low volumetric energy density of hydrogen at ambient temperature, hydrogen must often undergo some preparation before it can be transported, distributed, or used. However, the properties of hydrogen and its ability to be modified through the different stages of its lifecycle can also be a benefit for its application.

Preparation of hydrogen includes all the processes that change one or more properties of hydrogen to be suitable for the subsequent stages of operation. Some processes are linked and can be combined (e.g. pressure, temperature, and form). The energy demand, the emissions and the cost associated with the conversion and possible reconversion must be balanced with the savings in transport and distribution and storage. This will become a major factor if green hydrogen can be produced at large scale and imported.

The following list of preparation processes is not exhaustive and research to increase capacity, efficiency and production scale will play a major role in development and cost reduction. More details about each type of preparation are detailed in the appendix in section 15:

- Change in **Form** (hydrogenation / dehydrogenation) including **State** (Liquid / Gas)
- Change in **Pressure** (pressurise / depressurise)
- Change in **Quality** (Purification)
- Change in **Hydrogen content** (Blend / De-blend)
- Inject **Additives** (e.g. Colourise / Odourise)

The preparation of hydrogen can be part of each element (pressurisation during production, conversion to LOHC as part of the transport and distribution element). The importance of hydrogen preparation lies in its energy and environmental properties: the characteristics of each element (capacity, efficiency, energy used, emissions…) and the properties of the output flow.

As the hydrogen economy develops around the MH:EK region, for each development, the importance of relating the quality requirements of each production sites with the potential uses to allow expansion and connectivity. The research into transport and distribution contamination as well as new purification technologies will mitigate the risks to create isolated systems.

Discussion point: Planning applications should include hydrogen characteristics and preparation requirements early in project design. As contamination happens through pipeline distribution, local purification by end users may be needed. In the longer term, a common specification must be defined for hydrogen transport and distribution to allow interoperability. This will allow more low cost, generic purification technology to be available for fuel cells for example.

Hydrogen is much more versatile than electricity, gas, and oil. Planning and understanding preparation needs can support interoperability, control efficiency, connection of networks. This is particularly important for the transition between successive system arrangements.

5.6 BLENDED HYDROGEN NETWORK

Hydrogen can be blended with natural gas and potentially replace natural gas for the current gas applications linked to domestic, commercial, and industrial heating system and associated appliances. Most pipes and appliances can already use a blend of up to 20% hydrogen without major changes. Blended hydrogen can bring rapid benefits on the road to decarbonisation and be an expanding transition towards full hydrogen heating. The flexibility and the variability of blended hydrogen can also help the balancing in the early days of the hydrogen transition. It also allows the production of cheaper hydrogen as it doesn’t need the purity of fuel cell applications.

5.6.1 PHYSICAL DESCRIPTION

A section of the existing gas network can be isolated, and hydrogen injected at a mixing station to supply downstream consumers with a blend. Hydrogen can also be injected onto a private gas network. Depending on the application, the blend can be constant or variable. A variable blend indicates the scenario where the percentage of each gas is allowed to vary, up to a maximum quantity throughout minutes, days, and hours. The advantage is that means there is flexibility in the specific quantities of hydrogen produced (which makes it easier for electrically produced hydrogen to follow renewable generation). The disadvantage is that variable blends can be unacceptable to some industrial consumers. The hydrogen blend can then be distributed throughout the network using the current gas grid.

Storage of natural gas has been declining with the increase and security of import. Storage of blended hydrogen is therefore not deemed as an economical solution. It is assumed that hydrogen is part of its dedicated infrastructure then blended on demand with a secure supply of natural gas grid.

The main applications for blended hydrogen are heating (domestic and industrial) and power generation since they are the main natural gas uses and emission contributors. Blended hydrogen is an intermediate option on the pathway to a fully decarbonised heating system.

None of the gas network and associated devices are currently physically ready for pure hydrogen flow. Furthermore, as hydrogen is classified as an extremely flammable gas, current regulations constrain the transport and use of hydrogen (0.1% permitted in the current gas network). The blend limit may be a set point for the UK or could vary by region. The allowable variation in the blend could also vary across the UK; in some regions the blend could be permitted to vary significantly whereas in others only to sit within a tight range. The deciding factor on the allowable blend proportion and range depends on the assets in the region and current regulations. However, with the new considerations for hydrogen use, legal barriers need to be assessed specifically for the risk and feasibility associated with large scale blended hydrogen.

On the consumer side, metering arrangements need to be clarified to offer competitive and fair tariffs for variable blend and additional services. The energy density of hydrogen is less than natural gas. This means that for two meters registering the same volume of gas used in a home, the energy delivered will differ if part of the delivered natural gas was hydrogen. Therefore, for consumers to be accurately billed for the gas they use, with hydrogen being blended in the network, new arrangements will be needed.

The roles of government, gas network companies and hydrogen producers need to be clear and coordinated. Market arrangements must be established to ensure the hydrogen blend sits within the permitted range while the market can still operate efficiently as detailed in section 9.

5.6.2 INTEROPERABILITY

HyDeploy[27] aims to prove that blending up to 20% volume of hydrogen with natural gas is a safe and greener alternative to the gas we use now.

Hy4Heat[28] project's mission is to establish if it is technically possible, safe, and convenient to replace natural gas with pure hydrogen in residential and commercial buildings and gas appliances.

Both projects have proven that it was safe and there was no impact on the way consumers use their gas boilers and cookers. The next steps are:

- To increase the mix of users (domestic, commercial, and industrial) and applications (heating, power generation) on the same network.
- To interconnect networks and upscale the blended network.
- To transition to a pure hydrogen network.

Element's interoperability

The transition from a natural gas network to a hydrogen one (with or without a blending phase) will happen in stages. The gas network will have to accommodate different levels of hydrogen throughout the network with sections of natural gas, sections with different levels of blend, sections with variable blend and sections with pure hydrogen.

The table below shows the limitation and compatibility of blend share by hydrogen system elements and measurement (from 2018)[29]. The table doesn't show the ability of each application to cope with blend variability without modifications or performance reduction which is critical for system integration.

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[27] https://hydeploy.co.uk/

[28] https://www.hy4heat.info/

[29] https://www.pge.com/pge_global/common/pdfs/for-our-business-partners/interconnection-renewables/interconnections-renewables/Whitepaper_PipelineHydrogen.pdf

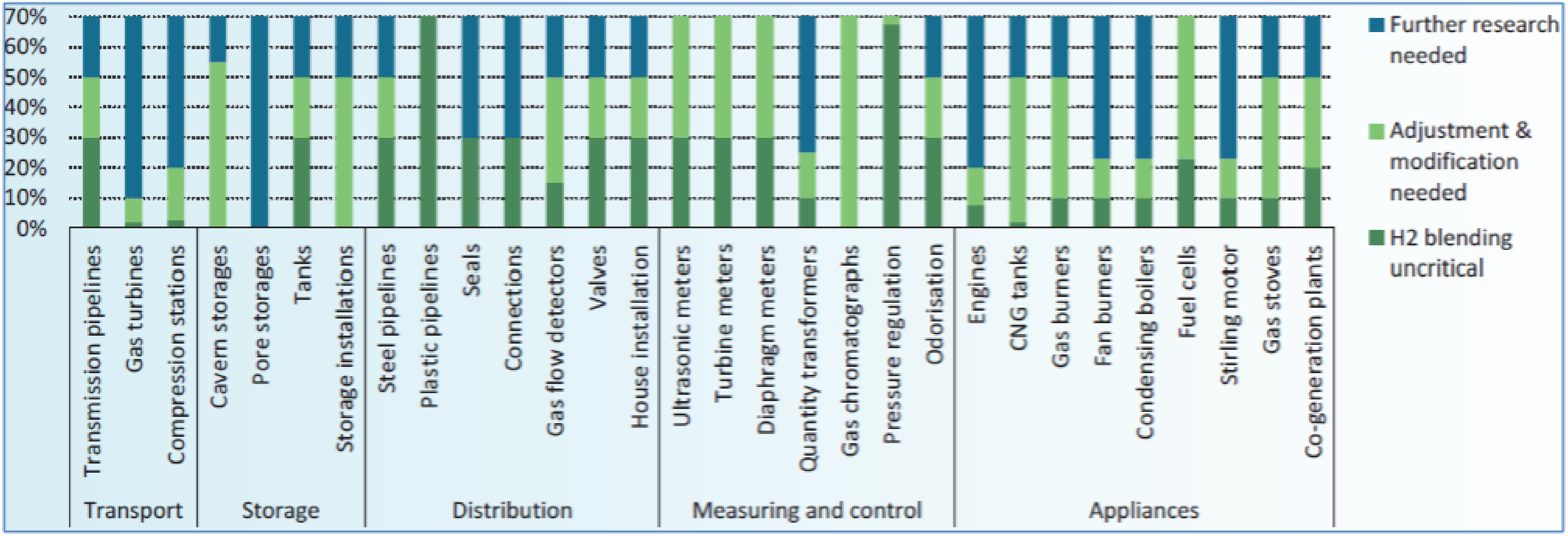

Figure 5 Limitations on the blend share of hydrogen by application – the most important applications to the blend share are gas turbines, compressing stations and CNG tanks. (PG&E R&D and Innovation, 2018)

Figure 16 – Limitations on the blend share of hydrogen by application[29]

The transition to a blended or pure hydrogen grid is not limited to hydrogen ready pipelines. As well as pipes, seals, connections, compressors, and valves have to be able to contain hydrogen at the desired pressure for a similar lifespan. Associated instrumentation to measure quantity, pressure, flow, quality to control the system must also be compatible.

Gasses interoperability

Pipelines could allow hydrogen to be transported safely and efficiently to potentially millions of consumers. A very vast transmission and distribution network already exists. The existing natural gas infrastructure could provide the backbone for hydrogen transportation if it is compatible or can be repurposed and developed. The transformation of the natural gas network into a hydrogen gas network can be performed in stages repurposing and building sections of the network to full hydrogen with an optional step of injecting fixed or variable levels of hydrogen into the system.

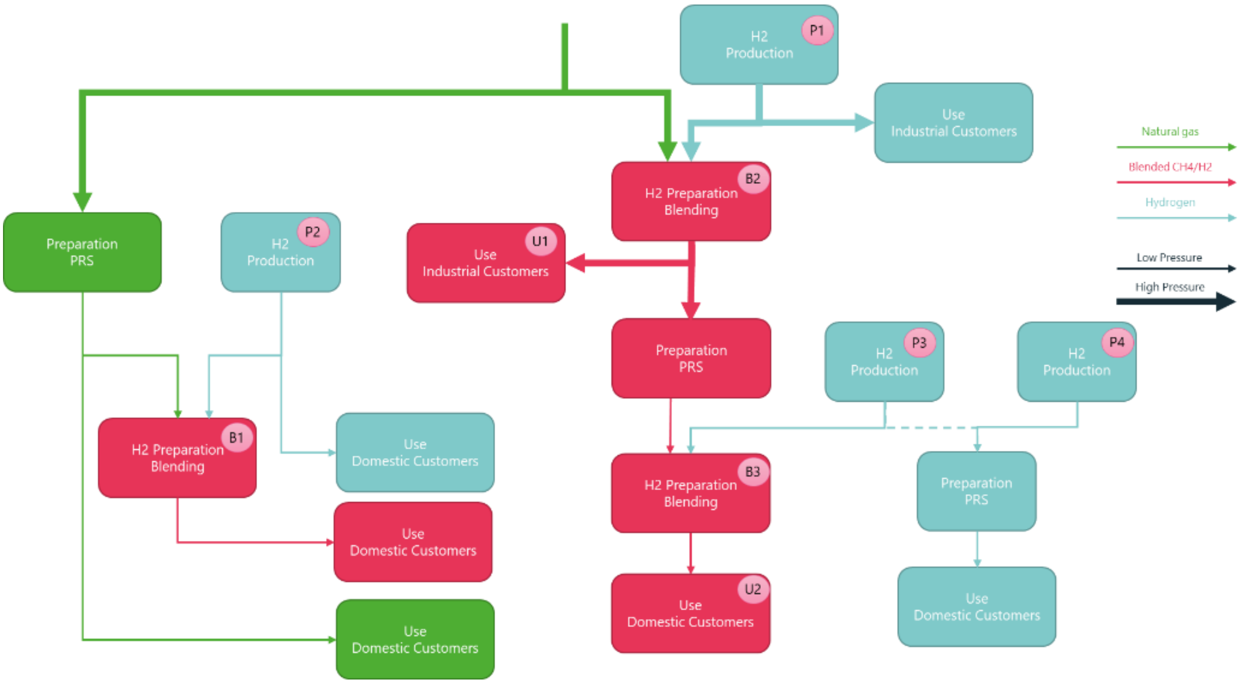

Figure 17 – Example of multiple gas forms coexisting in one gas network

The figure 17 above shows an example of the stage transition of the gas grid. Sections of the grid are upgraded from natural gas to blended hydrogen or pure hydrogen. Considerations and implications of each stage of the transition are detailed below.

The figure 17 above doesn’t represent graphically gas storage for clarity. The option of deblending gas is not represented on this figure as the principal identified case is at end use to keep a constant blend, therefore can be embedded within the end use block. The diagram also only represents two levels of pressure (high pressure and low pressure).

A gas network is able to accommodate concomitantly natural gas, blended and hydrogen networks and connect them to each other. However, each modification will affect all the branches of the network downstream and possibly the demand upstream.

Any change in the blending or form of hydrogen will affect all the actors downstream. Therefore, planning and communication must be managed between all parties.

For example:

- When a blending station (B1 or B3) is introduced, all physical parts from pipelines, compressors to domestic users' appliances must be ready and compatible with the level of blend offered.
- Similarly, when a hydrogen production plant (P2) is introduced and connected to a network of users from either natural gas or a blend, the distribution system (pipeline, seals, connections, valves), the appliances (boilers, cookers) and associated devices (meters, colouration, odourisation) must be ready to be converted quickly and efficiently to minimise disruption. Some assets can be hydrogen ready (e.g. pipelines) while some others have to be changed over (e.g. burners).
- When Production P3 is added to an existing blended network, the added blend needs to keep between blend limits. Injection levels at B3 must either be coordinated between hydrogen producers (P1 and P3), or measurement can be added to B3 to inform additional level acceptable from the secondary producer P3.
- If hydrogen production P1 increases and can produce sufficient supply to maximise the blend (fixed or variable up to 20%) for mixing station B2, hydrogen production P3 may become obsolete or only used for backup. The location of Production P2 may have been designed to provision for the development of a new pipeline to reinforce production plant P4 as other hydrogen demand increases.
- A network can comprise multiple end users with different constraints on blend content and variability. Users U1 (industrial) may need fixed hydrogen content while U2 (domestic) can accept a variable blend. Existing and additional metering may vary for different consumers. The system operator needs to reconcile data to offer fair prices for each type of consumer as well as being competitive with energy alternatives. Several options can be assessed and agreed with the network operator:
    - Add a preparation stage at the industrial plant to measure, add and control the blend prior to end use. The added hydrogen can come from local storage, production, or connection to a pure hydrogen network.
    - Disconnect the two networks:
        - The variable blend is injected onto the local distribution zone with a variable hydrogen blend.
        - The industrial site can be disconnected from the grid. The required natural gas can be provided by container, or the plant can potentially be connected to another network. This can also bring the opportunity to develop co-located hydrogen production to decarbonise the plant with both developments happening in parallel.

Also, the following challenges are not represented on the diagram but need attention:

- The connection of different quality of gas (different blends or different quality of hydrogen) will not offer the benefits of the highest quality gas and limit the range and applications at end use. The quality throughout the system needs careful management to offer maximum efficiency and adequate quality for the consumer using appropriate measurement and control.

As the hydrogen network develops, the transition from a natural gas grid to a hydrogen grid will require the transition of control and regulation. This multi gas network can become three independent control entities or become a combined gas national grid.

5.6.3 CONTROL

Blend control

Depending on the network area and the connected users, the blend can be fixed, controlled or variable. The controllability and variability of hydrogen concentration in a domestic heating network for example, can offer a great flexibility in the specific quantities of hydrogen produced. With intermittent production and demand on a network, variable hydrogen blend can provide added decarbonisation using excess hydrogen. During a transition phase, if the readiness of new supply and demand are not synchronised, variable blend can be controlled to support the newly connected assets.

This flexibility can also support a secure demand base for hydrogen, which can be an enabler to kick off large scale low carbon hydrogen production.

However, variable blends can be unacceptable to some industrial consumers such as power station. The mixing station leading to such users' needs to control the blend level. The user can be disconnected from the network or another mixing station including accurate measurement and control is required to maintain a fixed blend supply to the end user.

Multi gas control

If multiple gas forms (natural gas, blend, and pure hydrogen) are present on the same network, it is crucial to ensure that at any point in time, adjacent pipe networks are compatible for:

- Flow and pressure control within each gas form as well as production and mixing.
- Quantity and quality control to match supply and demand. This includes quantity and quality monitoring.
- Blend management at mixing stations (intake telemetry and control of blend variation and limits)
- Rules for exceptional events

It is important to note than natural gas and pure hydrogen require different models and control parameters due to the physical differences of gasses. For domestic heating, the level of blend is usually too low (up to 20%) to significantly affect the user experience. However, the burners and the inlet flow controls for heating and gas turbines are affected.

5.6.4 TRANSITION

Gas networks are already trialling and planning for the future use of the network. A list of gas network hydrogen pathway projects is available in the Energy Network Association (ENA) "Gas Goes Green" report[30].
Blended hydrogen could be used as a hydrogen carrier and be deblended for end use. This technology is currently expensive but remains an option if the characteristics of the process and the need become favourable.

However, pipelines can only go where they are laid. New network needs to be carefully planned, considering the development of competitive solutions and applications (development of the electricity and heat network, industrial development). The coordination and integration at national

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[30] https://www.energynetworks.org/industry-hub/resource-library/britains-hydrogen-network-plan.pdf

and international level of the transformation efforts are crucial for efficiency and long-term viability and benefits.

The development of pilot standalone hydrogen projects to hydrogen clusters should be developed with a coordinated national vision allowing flexibility for technical and commercial developments, variations in supply and demand, and integration within the whole energy system. Defining the required data followed by opening and sharing data of hydrogen assets and projects will help:

- Improve forecasting supply and demand of hydrogen
- Allow integration with other energy vectors (natural gas, electricity, oil…)
- Analyse physical and commercial impact of projects
- Support planning
- Help secure investment.

Despite the important initial investment, pipeline transmission and distribution is the cheapest way to move large volume of gas for multiple end-users to a wide range of users from industry to domestic heating. Large volume transmission is also key to connect the hydrogen and electrical networks. The evolution of the gas grid from natural gas, through areas of blended gas to pure hydrogen will maintain the continuous supply of gas-powered stations to produce electricity and industry and connect to the distribution network to supply gas for heating and potentially refuelling stations.

Operators bring the sector expertise not only for the most suited location for blended hydrogen conversion but also for the long-term options. However, well informed and engaged consumers can lead to greater uptake and participation. The cooperation between the different stakeholders is crucial for hydrogen to become an integral part of smart local energy systems.

5.6.5 LOCAL BLENDING CONSIDERATIONS

Blending up to 20% of hydrogen in the natural gas network is the quickest solution to reduce emissions without affecting public safety and network integrity.

Now that trials are proving the safety and feasibility of blended hydrogen in network, increasing the blend, and expanding the network can create a step change in demand and set hydrogen production to upscale considerably. However, the appropriate hydrogen concentration (level and variability) may vary between networks and applications.

Action point: MH:EK should define a clear roadmap for the whole transmission and distribution network including blended hydrogen.

WWU are best placed to advise on entry points and sections of the network where hydrogen blend will be beneficial. The roadmap should be based on strong coordination and engagement between producers and end users. The adaptability to offtake the blend will come from multiple end users including potential large-scale demand from Pembroke Power station and Valero Pembroke refinery to industrial, commercial, and domestic heat and mobility (e.g. Pembroke Docks). PCC will have an important role in engaging and informing consumers. If public acceptance is low, regardless of the benefits, intake will be low. For the longer term, the roadmap should include the future potential for connection of pure hydrogen.

All the different strategies, including upgrading costs (production, pipeline modification), preparation (blending, deblending) must be weighed against alternative means delivering sustainable energy to consumers while limiting increase to energy bills. A clear roadmap will both enable early hydrogen production take-off, standardise transport and distribution and device conversion in a timely and efficient manner where hydrogen introduction is suitable in the energy transition.

5.7 IMPORT / EXPORT

Import and export will play a major role in the development of hydrogen. Currently, most hydrogen development projects are closed systems following co-located arrangements. A closed hydrogen system is a system where all the hydrogen produced is consumed within its boundary. They are, however, connected to other energy vector systems such as electricity, natural gas, or heat. Currently, most hydrogen systems are closed mainly because of their scale and the challenges of hydrogen transport. Closed systems will play an important part in the development of a hydrogen economy by trialling different physical and economic solutions to prove feasibility and bring confidence to investors.

When two such systems merge, the hydrogen outside of their boundaries is either imported or exported before the two systems can be combined into one larger, more complex closed system. If two systems remain independent but exchange hydrogen, trading between the systems must be considered. Finally, for national and international hydrogen systems to emerge, import and export will play a major role in the prospects of hydrogen in the energy mix. Physical and commercial benefits and constraints will impact each system level. For example, for independent local systems to be reliable, storage will be sized for the peak demand depending on the production capacity. If cost effective and reliable high-volume transmission becomes available to local systems, storage may become obsolete.

In contrast, an open hydrogen energy system will have hydrogen exchanges outside its boundaries with other energy systems through import and export. More details on closed and open systems and architecture diagrams are developed in the appendix in section 15.

The proposed projects shortlisted for further techno-economic modelling within the MH:EK are focusing on multi vector SLES. From a hydrogen point of view, it is crucial to consider the impact of connecting the systems together and, in the long term, the possibility of importing and exporting hydrogen out of the SLES boundaries.

Next sections describe control and interoperability of each element and their place in the evolution of the system arrangement to support discussion and decision points for MH:EK.

Discussion point: Unlike natural gas, MH:EK, in future, could have the ability to produce hydrogen, offering the potential to reduce import dependency and opportunities for export. As a major energy import port, long term considerations will impact the whole region economy. The hydrogen economy will probably consist of multiple forms of hydrogen such as gaseous, liquid hydrogen and ammonia... MH:EK owns extended capacity for import and export and associated storage, preparation, transport, and distribution for both gaseous and liquid products. Repurposing and expanding assets will be key in retaining skills and employment in the region. Identifying gaps in the supply chain will offer diversification opportunities for companies (electrolysers, integrated storage, hydrogenisation…).

As production and the international market grow, MH:EK should monitor closely export opportunities.

Japan has shown the aspiration to develop rapidly the supply chain for hydrogen import and export with projects (HySTRA[31] and AHEAD[32]) focusing solely on the topic. These projects rely on strong collaboration and investment from government, academia, private and public companies.

Leading the way in hydrogen export can support the role of MH:EK in exporting hydrogen products, technology, and skills.

5.8 HYDROGEN SYSTEM INTEROPERABILITY

Interoperability is the ability of a product or system to cooperate with other products or systems to share resources.[33]

Operational, technical, communications and business-wise interoperability needs to be developed for a future integrated hydrogen market. The physical connections and interoperability of each element is described within each previous section of this chapter (sections 0 to 0). Further description and examples are available in the appendix in section 15. The interoperability between systems (clusters), information and other energy vectors are described in more details in this section.

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[31] http://www.hystra.or.jp/en/

[32] https://www.ahead.or.jp/en/

[33] https://es.catapult.org.uk/brochures/an-introduction-to-interoperability-in-the-energy-sector/

5.8.1 HYDROGEN CLUSTERS INTEROPERABILITY

Many hydrogen projects under development are closed systems (e.g. co-located renewable site, electrolyser, and industrial end use) and hybrid systems (local hydrogen generation and storage for hybrid heating systems) or analytics based. As the multitude of projects can prove the feasibility of technology and end use, the prospect of replicating, expanding, or connecting multiple systems should be considered.

Interoperability within hydrogen clusters will support the creation of a national hydrogen network and again at international level.

In order to connect two separate hydrogen systems to make an overall system better than the sum of its parts, the following features have to be considered:

- Capacity planning and allocation.
- Compatibility of the 2 systems – pressure, quality, data exchange, control requirements…
- Connection compatibility – location, pressure, assets
- Actors' roles and responsibilities – governance, owner/operator
- Units, services, tariff calculation, rules

If two systems cannot be directly connected, the differences and barriers can be assessed for them to converge towards an interoperable model. Sharing the findings and growing compatibility can lead towards new regulations and standards rather than isolated independent systems. This could be more beneficial than imposing standards during the demonstrator phase which could stifle innovation.

5.8.2 ENERGY INFORMATION INTEROPERABILITY

As multiple projects develop, in the absence of existing standards, the ability of the different assets to exchange information can be limited to the sole purpose of each project. As the hydrogen economy is still in its infancy, current standards are still sparse in terms of data generation, data format, sharing (availability and transparency), access, units, exchange procedure for hydrogen. As systems expand, replicate and interconnect, it will become crucial to converge towards a more harmonised data system for the different assets and services to work together. For example, the creation of a data catalogue including metadata definition and access rules can help users identify and understand current operations. The access to the relevant data will allow more efficient control and resilience.

As the number of actors within the hydrogen system grow at different levels (from microgrid to national grid), data exchange and interoperability will allow smart control and optimisation. Predictive and automated control can help manage storage, system integration, reduce peak demand and reinforcement needs.

In the same way as in the development of smart grids or district heating or many novel systems, data exchange and interoperability standards will follow the successful outcomes of the first demonstrators. But as the number of actors grows, it is a fitting time to define high level needs and a data framework to integrate existing data communication and format and the specific requirements of hydrogen.

For the whole hydrogen energy system, interoperability between the different elements in the system (production, transport, preparation, storage, and use) during the transition will play a significant role in acceptance and allow the growth of the system. Data use and availability are crucial to provide better visibility of system usage, spare capacity, and constraints, to inform investment needs, and to facilitate opportunities for strategic coordination. Opening and sharing data between projects can improve future designs and convergence towards a more connected and interoperable system. This will also serve as the basis of future standards and regulations.

5.8.3 LOCAL SYSTEM INTEROPERABILITY CONSIDERATIONS

As a major importer/exporter of natural gas and the surrounding storage and connection capacity, MH ports holds the skills and expertise to develop and support rules to transition to the different forms of hydrogen. MH:EK location gives the potential to connect information exchange and interoperability from microgrid to international level.

MH:EK encompass all the actors who will have to integrate different levels of volume and stages for trading and physical data. Industry experts, local authorities, academia, consumers, and consumer groups should get involved to share findings from projects leading to common approaches to hydrogen projects. Accurate information and cost of deployment can accelerate learning pace and decision making. Both public and private sectors reporting mechanism can be put in place for the benefit of all.:

- The port will have to exchange data from international import to land usage. This will support control to import request, dispatch, and storage levels.
- Electrolyser will use data from gas and electricity networks. In the short term, this will essentially be at local level. However, it will be at the forefront when scaling up to an integrated national electrical and gas transmission systems develops.

- Local energy systems are already defining their communication systems to control electricity and may use these standards to integrate hydrogen in the system.
- Asset registration strategy for all hydrogen-based assets, connections and services should be visible. Asset registration and visibility of overall supply and demand can drive the optimisation of the new production needs and repurposing opportunities.

For each project within MH:EK, digitalisation and data must be an integral part of the scope. A coordinated asset register can increase development coordination, encourage interoperability, and help identify gaps and opportunities for future developments. Another important aspect is the openness of data to promote the definition of a hydrogen energy system data architecture that is compatible with the other energy vectors and fits within the whole energy system. This will avoid the sectors working in siloes, developing multiple disparate platforms and standards. The governance of such platform must be clearly defined from the onset to identify the objectives, roles, and responsibilities from all parties.

Discussion point: At a local level, PCC could include data openness and energy data requirements as part of the planning applications process. Sharing information publicly and between energy stakeholders about assets, data and software, control framework could increase system interoperability and encourage innovation.

The consequences of this decision could enable MH:EK to be a key player in supporting the government and Ofgem to create an open data system from the onset and avoid future rework and data development seen in the electrical system.

5.8.4 VECTOR INTEROPERABILITY

Vector interoperability means linking the different energy vectors (gas, electricity, heat…) with each other from production to the different end use (heat, mobility, another energy vector generation….).

From the hydrogen point of view, hydrogen can be produced using surplus electricity generated from low-carbon sources. This requires sufficient renewable capacity and availability. Both systems need to be able to communicate when there is a surplus. Renewable hydrogen can also help balance the supply and demand of electricity in isolated regions such as islands.

Electricity generation is increasingly dominated by intermittent renewable power. Long term and large-scale hydrogen storage can add flexibility to the whole energy system.

On the end use side, a hybrid heating system is a combination of a heat pump working in tandem with a gas boiler (natural gas, blend, or pure hydrogen) and can be separate units or integrated. The hybrid system typically uses electricity to maintain a consistent temperature most of the time. When the outside temperature drops below a certain temperature, the system switches to the gas boiler. The system can also allow electricity flexibility to the grid especially in constrained systems. The system can also come with gas storage for off gas grid properties for colder months.

For industry, heat pumps can help decarbonise the low temperature supply, hydrogen can supply high heat process supply, both coupled with waste heat recovery.

These options require careful consideration in terms of their contribution to the decarbonisation of the energy system as well as economic and technical implications. Linking sectors will allow the optimisation of the energy system as a whole, rather than decarbonising and making separate efficiency gains in each sector independently. For smart local energy systems, hydrogen can be integrated to existing and emerging technologies. Connectivity, smart metering, digitalisation, and flexibility markets can make local areas more resilient and efficient.

However, several barriers still persist:

- **Operational rules** between heat, gas, electricity, and transport needs. As the different systems currently operate independently, digitalisation and data exchange infrastructure between sectors can improve integration and asset use optimisation.
- **Infrastructure integration**. Infrastructure planning should make the most of existing infrastructure but also consider the physical links between energy carriers for the short and long term.
- **Regulatory barriers**. For example, taxes and incentive can push the development of one vector disproportionally and make decarbonisation less effective. Uncoordinated and changing regulations form a complex framework discouraging interoperability.
- **Cost effective decarbonisation**. Cost comparison and investment types are very different for heat pumps, hybrid systems, hydrogen boilers, district heat. Decarbonisation of heat, for example may involve more flexible, localised and multi vector approach.
- **Public acceptance** and lack of knowledge and information. The lack of experience in integrated systems can create scepticism among policy makers, financial institutions, local authorities… There is a lack of skilled multi vector auditors, designers, and installer. Consumers are not always aware of their options and the value of the different vectors in terms of cost, comfort, and the impact of their behaviour.

5.9 HYDROGEN SYSTEM CONTROL

The main objective of a hydrogen energy control system is to supply enough energy to meet the demand at any moment in time. In other words, successful control is delivering:

- **The right product**: An extensive network delivering high volume of hydrogen may not help fuel cell vehicle refuelling stations if the minimum quality requirements are not met. Different forms of hydrogens (compound, blend, liquid and gaseous of different qualities) can be controlled independently or collectively.
- **At the right place**: High volume, high purity production in Wales will not necessarily support industrial adoption of hydrogen in the North East of England.
- **At the right time**: Whether transport and distribution are achieved by container or pipeline, the time taken in transport needs addressing.
- **At the right cost**: This remains a major barrier to the development of hydrogen affecting all the preceding points. For example, the cost of purifying can defeat the benefits of high-quality production contaminated during pipeline transport.

For each system, the total supply (import, production, storage reduction) is equal to the total demand (export, use, storage increase). To achieve this, the controller needs to collect and interpret data feeds from multiple sources, i.e. the different elements and the environment. The controller then sends commands (dispatch, level, start, stop, etc…) before receiving feedback.

The hydrogen system can consist of one or several operators that must coordinate the following activities:

- Analyse forecast and current demand.
- Determine the available energy resources.
    - Hydrogen production characteristics such as quantity/quality/schedule/profile etc.
    - Import availability and price.
    - Storage levels.
- Procure hydrogen for the consumer needs.
- Request dispatch and dispatch hydrogen.
- Request demand side response.
- Receive feedback.

The control of the hydrogen system consists of different layers of control. Each element needs to be controlled, i.e. hydrogen plant operator, freight operator, industrial plant, and heating system operators… Produced hydrogen needs to be dispatched, storage facilities need to have hydrogen injected and discharged, transport and distribution must allow the hydrogen to reach the consumer etc. Each element will hold some constraints and flexibility to keep the system safe and stable at all times. These elements are characterised through measurements such as pressure sensors, flow controllers, smart meters… They can communicate with each other and exchange information with a system control layer. The system controller is responsible for ensuring the effective operation of the interconnected devices.

This section describes the different requirements and parameters used to control a hydrogen energy system. The development of different types of control systems from a co-located system to a local energy system to a national system is discussed with the challenges and recommendation for the transition from each stage to the next. The constraints and flexibility of each element will also be assessed.

5.9.1 CONTROL SYSTEM ARCHITECTURE

The goal of the controller is to supply hydrogen safely and reliably to the consumers. Forecasting is used to define a set of assumptions on supply and demand patterns. Forecasting of hydrogen supply and demand is a combination of static/dynamic, short/long term analysis depending on the application. This is used to develop the necessary generation and storage capacity and the network capability to meet the consumption needs. The system operator is responsible to keep the system within safe operating limits at all times.

A hydrogen only system, covering hydrogen in gaseous or liquid form, considering blend and compounds outside of the remit of the controller, could be very similar to the current natural gas system in terms of control. LOHC technology could offer similar handling and operation as the current oil system using existing control and infrastructure. The operator controls dispatch from production or storage then controls flow and pressure throughout the network system to match demand.

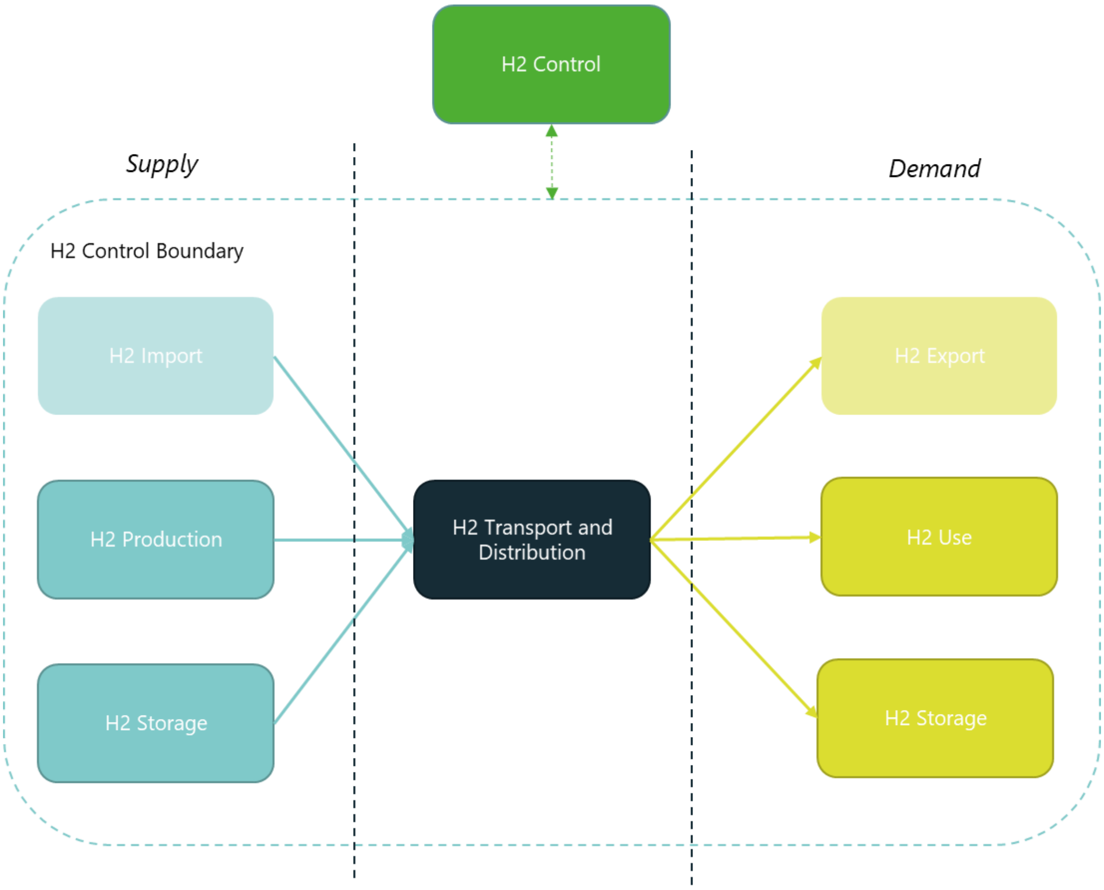

Figure 18 – High Level Control System Architecture

This section describes the controller in terms of needs, architecture, and the transition between a co-located system, to a local hydrogen system to a national system.

Different aspects of controllers are important to take into consideration. They will impact the different options to control the system and transition from one system arrangement to the next.

- Physical and commercial interconnection: Assets will dispatch based on the contracts they hold with other market participants. Trading and contracts are discussed in Section 7.
- Single / Multiple producers: Once multiple producers connect to the same network, the compatibility (pressure, form, quality) must be maintained and controlled.
- Closed system / Open system: The difference lies in the defined boundaries of the controller. In a closed system, all hydrogen is produced and consumed within the boundaries of system. In an open system, whatever its size, hydrogen can be imported and exported outside of the controller boundaries.
- Centralised / Distributed control: Within the boundary of a system, the control system can be centralised or distributed. Again, this can apply to any scale of systems from co-located system to international.
  A centralised system for a specific area of the hydrogen network monitors and controls the different elements. A centralised system takes overall control of the whole system. One of the benefits of a centralised system is that it provides more visibility and control of the different assets and can influence the definition of current and future goals.
  A distributed hydrogen control system consists of many individual controllers throughout the system. A central operator can supervise the overall system where the distributed systems are connected or rely on import and export. The operator can be in charge of the regulation and the coordination between the different operators. Distributed control systems provide more

autonomy and flexibility for local initiatives for the specific demands of consumers within the boundaries. The benefits can be driven by increased digitalisation, specific local needs, and increased customer control.

- Forecast / Real time: Supply and demand forecasts are used to plan the development of the hydrogen infrastructure using ever more complex models to face the uncertainties in the short, medium, and long term. The position of hydrogen as a clean energy solution is still unclear. However, future energy scenarios from the National Grid ESO[34] predicts that hydrogen will provide between 21% and 59% of 2050 net zero end-user energy needs.

Decision point: As the number of local hydrogen projects grows, there is a development opportunity for the region to plan their integration into a regional cluster. Understanding the control architecture, the communications protocols, and the level of interoperability between the different controllers will support the definition of the network control strategy.

By analysing the needs of the different systems, where connecting or centralising control could be beneficial, the different controllers could converge to support an adequate interface between systems and operators.

Short-, medium- and long-term planning and forecast should be coordinated within MH:EK and include progress of national and international developments. All forecasts should include some flexibility and be able to adapt to new standards.

The consequences of early decision on connections opportunities and storage capacity can allow new opportunities to be viable and avoid stranded assets in the future.

With a system sized for forecast supply and demand, real time control needs to adjust for real time fluctuating supply and demand. Intermittent production especially from electrolysers relying on renewable energy and variable demand from consumer drives the need for a controller to step in to keep the system balanced at all times. Gaseous control is slower and simpler than electrical control mainly due to the speed of the energy flow and the inherent variable gas storage within pipeline (linepack). However, the slower distribution and transportation requires increased anticipation for delivery in a predictable and reliable way. As previously described, each element provides different levels of flexibility and constraints. The controller should also adapt during each transition to rising supply and demand and to the interconnection of multiple systems and controllers.

The roles and responsibility of the system operator will vary depending on the different types of controllers. Some roles will be similar to those existing for the natural gas network, however, it is important to start defining the future roles and responsibilities for hydrogen suppliers, distributors, operators.

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[34] https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents

5.9.2 REQUIREMENTS AND CONSTRAINTS

An operator's role, at any network level, in charge of controlling a hydrogen energy system is to deliver hydrogen safely to the consumers. However, depending on the size and scope of the role, operators can have a much wider range of responsibilities that can benefit the whole system during the development of the hydrogen market. The control system functionalities can include:

- **Safe operation:** Safe operation is common to all systems. Gas pressure must be maintained within safety range. Under and over pressurisation can result in fire and explosion. Leak detection and maintenance also needs considering to be prepared during these events. Keeping the hydrogen safe and secure is complex due to the versatility and novelty associated with hydrogen as well as the integration with other energy vectors.
- **Security of supply:** The security of supply is defined for this report as the availability of hydrogen at affordable price. For the long term, security of supply covers changes during upscaling and stepwise transition supported by timely investment in agreement with environmental constraints. For the short term, security of supply focuses of the ability of the system to react promptly to sudden changes and exceptional events.
- **Commercial operation:** The operator must manage the system in a way which minimises prices for consumers while meeting the other requirements. This should include structuring operations to have competition for different services it procures, if possible, from all assets that could provide the service.
- **Emission reduction:** The main reason the role of hydrogen has taken off in recent year is its role to achieve net zero by 2050. It is a combination of decarbonising its current production and replacing fossil fuels. System operators are in a privileged position to play a critical role in achieving each step towards net zero. The role of operators is at the crossroad of policies, technology, and societal changes. They have the potential to be the quickest and most efficient to respond to shift signals. For example, at local level, targeted production can benefit from low-cost renewable electricity production. They can support and coordinate asset owners and operators to plan the transition safely, efficiently and at the lowest cost to consumers.
- **Data Management:** Data management is an intrinsic part of the controller. The controller needs to collect and interpret data feeds from multiple sources, analyse the data using a set of rules and send operational order for hydrogen to be produced, dispatched, stored, released, or curtailed. Flow, pressure, quality, and blend levels have to be maintained at all times. The decision and standards for instrumentation and communication technology associated with each element is a fundamental part of the design of the system design.
- **Efficiency:** System operators, especially at local level, can also design the controller to maximise system efficiency to minimise the energy used, the emissions levels, the cost to consumers, the maintenance of assets, the capacity reinforcement. The ability of the operator to make the hydrogen system more efficient will depend on the assigned role and responsibility as well at its capability to measure, monitor, analyse and control the defined performance of the hydrogen network. For example, allowing the operator to provide flexibility services depending on the time of use can be reduce the need to reinforce the system. By offering local storage (heat or hydrogen) or price band can shave the peak demand during high demand at the end of the day.
  However, the need for efficiency must not counteract against the benefits of simplicity of the system. Simplicity makes it easier for stakeholders to engage. It can also make the system more predictable and performance more transparent.
- **Integration and coordination**: The regulatory, technical, and commercial integration and the coordination within projects will support and speed up the development and the adaptability of the developing hydrogen system.

- **Standards:** Operators are best placed to adapt to new regulations and government advice such as the take up of low carbon solutions, powered by a major expansion of low carbon electricity and hydrogen supply (new cars and vans and all boiler replacements by early 2030 and HGV by 2040)[35]. However, existing standards and regulations in place are not always effective and can constrain the development of novel hydrogen applications such as blended hydrogen. Operators are also in a prime position to provide advice for the whole system and relay barriers and concerns from the different elements.
- **Between hydrogen forms and quality:** One of the differences between natural gas and hydrogen is that the hydrogen energy system is much more versatile in terms of forms (ammonia, methanol, LOHC…) and quality (purity levels and blend levels…). The operators need to be responsive to the development of the different forms of hydrogen. If demand for ammonia increases, is the distribution network adequate for the increased volume? Is this increase going to trigger a drop in gaseous hydrogen demand? What would the impact be on the gaseous hydrogen distribution network?
- **Between operators**: If operators control systems independently, local successes will struggle to replicate and expand into an interconnected national system. Due to the uncertainty of the role of hydrogen and natural gas in the decarbonisation pathway, collaboration and coordination between operators can contribute to better plan needs and secure investment. Each operator will develop their own “control room” operations, market development and network planning. Sharing information, technical knowledge, expertise, and skills are essential to coordinate the effort of performing an integrated stable and efficient control system.
- **With other energy vectors:** Finally, if hydrogen production is connected to a shared electricity or gas network, the operator needs to integrate other vectors demand and pricing into production control. For example, the minimum and maximum electrical power needed when the electrolyser and the compressor are active will impact the electrical grid control. Similarly, if hydrogen is used to generate electricity, optimisation of the control loop of both the hydrogen and electrical systems are impacted.

The strategic decision of each controller and operator should be defined in terms of consumers’ needs rather than solution. The potential to integrate with parallel systems or to be controlled externally should be included in the design from the onset.

Further functionalities to optimise and secure the operation of the assets can include but is not limited to leak detection and location, predictive modelling, digital twin, forecasting, planned maintenance etc.

5.9.3 DISPATCH APPROACHES

Hydrogen dispatch for a production plant refers to the action of releasing hydrogen to the network. Dispatch operations coordinate the flow of hydrogen safely through the network. Uninterrupted gas flows are essential for the safe and reliable operation of the pipeline network. Stored hydrogen is another source of dispatchable energy reducing the risk of intermittent renewable electricity or the need to rely on grid electricity. The dispatch approach adopted by the operators will control the flow of hydrogen through the network.

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[35] https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

The dispatch approach must always guarantee safe and secure operation of the system.

For a co-located system arrangement, the plant operator controls production, dispatch, and use. Once multiple producers operate on the same network, dispatch can be planned by the plant operator and managed by the system operator for short term changes. The number and variety of generators and the distance to the consumers will make the control operations more complex but also provide flexibility opportunities and control options.

If a central operator controls all or parts of the system, the balance between the different factors lies within the central operator within regulations. The main feature of a central dispatch operator is that balancing is performed in one integrated process.

However, competition can incentivise system operators to maximise the benefits of evolving market demand, monitoring, forecasting, communication, and interoperability. In a distributed system, close cooperation between operators to increase flexibility. For example, a group of producers can combine their generating facilities for more effective delivery management and share revenue between members.

Dispatch is based on contracts between market participants. These contracts mainly follow market and trading activities (80 to 85% of electricity dispatch today). Self-dispatch based on trading is also called economic dispatch. This method selects the lowest cost available generation or storage available. The purpose is to produce the most cost-effective result. Long term agreements, such as Power Purchase Agreements (PPA) for electricity generators provide essential payment guarantee and security for investors. They can specify dispatchability options for a predefined generation of volume and price for the length of the contract.

Priority dispatch for renewable energy has been a major factor in the development of renewable energy. Now that a renewable market is established, priority dispatch has been phased out. Today, electricity dispatch follows merit order stack, price derating… Priority dispatch of low emission hydrogen would allow production to meet demand without competing commercially with other generators. For example, hydrogen production can be prioritised to curtailment or electricity export. These arrangements need to be bound in time and long-term arrangements need to be fulfilled to preserve investors' confidence. They can also be changed on a voluntary or agreed basis once the market develops.

The rest of the dispatch (15 to 20% for electricity) follows direct control signals which balance the hydrogen flows to ensure real time network safety and integrity. These signals can also respond to emergency events such as peak load, fault on the system…

Storage and flexibility of supply (generation feedstock options) and demand (variable blend) will impact dispatchability and add to the efficiency of the hydrogen. Storage should be valued as a service to ensure flexibility and reduce production reinforcement.

Hydrogen and electricity dispatch are interlinked and can support each other. The growth of renewable energy has been intensifying fluctuation in electricity supply and affecting new dispatch rules. The use of renewable energy to produce hydrogen may influence the dispatch and curtailment of wind and solar energy. Stored hydrogen can subsequently be used to produce electricity. An integrated system could optimally dispatch hydrogen for storage and direct consumption. The electricity production forecast from renewable is well advanced whereas hydrogen demand forecast, and storage solutions are still in their infancy and changing rapidly.

Other factors can influence pricing or control signals such as:

- **Local**. Prioritise local energy production and usage through innovative approaches and business models. For example, hydrogen storage can be prioritised over export.
- **System efficiency**. The choice between production and storage dispatch can be designed for production or storage injection/discharge efficiency ahead of cost. This is likely to be prioritised for research and development.
- **Emission reduction**. Optimising dispatch to maximise use of renewable sources. This can be part of the of the local, regional, national energy strategy.
- **Demand Side Response**. Signals can also be sent to the end users to adjust their consumption (e.g. time of use tariffs, real time pricing for industrial consumers). This can contribute to the balancing of the network on a voluntary basis. By providing a more efficient use of hydrogen supply and financial benefits. This can only be enforced in emergency situations

National action point: Priority dispatch definition could prove to be an important factor for green hydrogen growth in the region. Government should publish how it intends to derate hydrogen produced through different methods with different carbon intensities and/or efficiencies.

There is a need to develop dispatch predictive models for the region as a cost saving opportunity in the interaction between the electricity generation and hydrogen delivery cost, especially where electricity price fluctuates.

Long term capacity models will support investment and help identify when and where capacity increase in needed. This can give more certainty regarding price expectations and influence the dispatch options (short- and long- term).

5.9.4 MULTI VECTOR CONTROL

At present, gas, oil, and electricity are operated separately. Hydrogen has the capacity to join up the different energy vectors. Natural gas and electricity are both feedstock for hydrogen and hydrogen can play a role as an ancillary service for electricity production.

In order to control simultaneously a gas and electricity system, the characteristics and requirements differences need addressing. Electricity balancing is complex and sub second whereas gaseous control is much simpler and slower.

Hydrogen storage can support energy peak production and peak demand. Large scale hydrogen storage can be used for excess hydrogen and electricity demand. This adds a level of complexity to define the capacity required and the rules to operate injection and discharge. Storage control can also limit renewable curtailment.

As hydrogen burns at different temperature and requires different oxygen intake to get efficient combustion, upgrading a power station from natural gas to blended hydrogen or pure hydrogen will take substantial testing and refining. Once these challenges are overcome, the following step will be to supply the right amount of hydrogen to keep the electricity grid stable and balanced. The communication and rules between hydrogen and electricity networks also have to be defined. Introducing hydrogen for electrical power generation is adding further variety to the electrical system operation and complexity for the operator to keep the system stable. Hydrogen could add flexible generation to existing power source and storage. Electricity can be produced from multiple sources such as wind, solar, hydro, nuclear and fossil fuels. The capacity to connect and control the sources to the electricity grid while limiting the emissions will define the electricity supply flexibility criteria for each part of the network. Security of supply (such as intermittence and storage) will play a major role in the source mix.

The details of how quickly and reliably hydrogen power station can balance the system at scale to integrate with the electrical supply system will define its role as an ancillary service. The controllability of the different sources and stores will increase efficiency. This will only be possible if the different network can communicate and share information efficiently.

The cooperation of the different operators (local and national gas, electricity, heating) will be crucial in the development of multi vector energy systems.

Decision point: Decide the role and responsibilities of operator at micro grid and local level from the onset.

Defining the information requirements and the efficiency criteria in an open and transparent manner could increase transparent reporting of successes and reuse of efficiency criteria to develop similar systems.

5.10 HYDROGEN STANDARDS

Hydrogen related standard and regulations are evolving rapidly as the place as hydrogen an energy vector is growing. Standards are developing at different paces depending on the sector and applications. For example, many new standards relative to fuel cell for mobility and refuelling stations are now widely accepted by the industry. However, this mainly apply to light road fuel cell electric vehicles. For other applications, such as blended hydrogen, the pace of standards development is much slower. Demonstrators and private networks must apply for regulation exemptions to quantify the risk before live trial. Current legislations permit 0.1% hydrogen in the current natural gas network. The development of a large-scale blended hydrogen network and the maximum level of hydrogen will rely new legislation. Any new use or form of hydrogen and the integration of multiple supply and use is likely to be impeded by the gap in standards as long as hydrogen is solely considered as a dangerous gas.

There is a strong need for hydrogen standards to be developed to ensure appropriate safety of technology from design, specifications, construction, installation, commissioning, operation, maintenance to decommissioning… As the number of projects increases rapidly, standards will be essential to build a safe hydrogen system and asset compatibility to enable widespread deployment. Safety and consumer perception will be key in the development and any safety issue or incident could cause irreparable damage to the current fast development.

Regulations and common standards cross usage (industry, mobility, heating), cross transport (rail, road, marine) and cross countries are developing rapidly. This is a key priority of the hydrogen council[36], a global CEO-led initiative of leading companies with a united vision and long-term ambition: for hydrogen to foster the clean energy transition for a better, more resilient future.

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[36] https://hydrogencouncil.com/en/

Many current standards are based on natural gas or explosives due to the nature of hydrogen. However, these standards and regulations are not always adapted to the novel uses of hydrogen in fuel cells or as a fuel for heating. Following innovative technologies and the varied applications for hydrogen and their fast development, guidance needs to be developed and coordinated specifically for hydrogen for all aspects of the system.

The development of standards can support the development of a hydrogen economy by performing actions in an agreed and repeatable way. The criteria defined in standards can make the stakeholders' life simpler, increase reliability and effectiveness, support compliance to regulation for the benefit of consumers.

At the British Standards Institution (BSI), the hydrogen technology committee is responsible for 20 published standards and 30 in progress. PVE/3/8 Gas containers - Hydrogen technologies are responsible for the UK input into ISO/TC 197 and CEN-CLC/JTC 6 for standards related to systems and devices for the production, storage, transport, measurement and use of hydrogen. It excludes cryogenic vessels and aerosols.[37]

This includes the physical installation and operation, for example, of electrolysers, storage location, materials selection, quality requirements for the different applications, different fuel cell applications, blending levels, detection and measurement, data exchange and the integration of these elements.

Best practice guidelines are quicker to develop than standards and are common practice in novel systems development. A shared, published guideline such as a Code of Practice can improve quality and safety across the different elements (and sub-elements) design, installation, and operation. Some guidelines are specifically designed to improve integration between elements across the energy sector. This can increase confidence in the system to improve user satisfaction, to boost uptake and to de-risk investment in the market.
It is crucial to get involved in such standardisation working groups from the onset not only to propose ideas to the group and influence the outcome but also understand the needs and propositions from the wider group.

At an element level, the "BCGA CODE OF PRACTICE CP 33: The Bulk Storage of Gaseous Hydrogen at Users' Premises" provides recommendations for the design, commissioning, handover and operation, examination, and maintenance of hydrogen storage at users' premises. This document can support easier and faster design, implementation, approval, accreditation for projects.

Another example, at an integration level, the heat and grid connection Code of Practice for heat networks have supported the creation of standards policy as well as securing larger investment. This was led by a consortium including consumers, government, local authorities supported by CIBSE (Chartered Institution of Building Services Engineers). A hydrogen economy is still in its infancy and would benefit from a similar approach. The development of multiple projects, without collaboration, may not be able to expand and thrive beyond the subsidised phase. The right to time to develop standards is crucial to avoid silos without stifling innovation.

Investors, regulators, national energy partners, local authorities and consumers in the public and private sectors will have to form an effective partnership with a vision to scale up the hydrogen economy and expand the infrastructure.

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[37] https://standardsdevelopment.bsigroup.com/committees/50184404

While developing standard and regulation, it is crucial to investigate both physical and economic impact on the system and its interaction. Developing open standards and protocol can support interoperability of elements, data, control, and services with an end vision to benefit consumers by supporting competition, choice, protection, and safety.

Hydrogen is the ultimate example of utility integrator. Hydrogen is tightly linked to most energy vectors (electricity, gas, oil, heat…) and utilities (water, waste, information…) for production and can have a significant role in the broadest range of end uses (chemical feedstock, industry, heating, all mobility sectors). It will both compete and support each one of them in the path to net zero.

As a maritime port, Milford Haven: Energy Kingdom is a unique and privileged part of the UK to be at the forefront of the energy transition and the development of the hydrogen economy. From its history and relationship with energy, MH:EK is both exposed and best placed to explore the role of hydrogen in decarbonisation. The area can be exposed to the environmental impact of climate change on the land, air, and sea. The economic impact of the energy transition will depend on the development choices and the adoption of new technology.

MH:EK is an energy hub having within its boundary high import, transit, production, and use. This combination will allow to integrate in parallel renewable energy production, energy efficiency and industrial and heat decarbonisation. Part of the decarbonisation pathway could use the cooperation between urban areas and the industrial activities by benefiting from local production and the integration between hydrogen, electricity, and heat vectors.

6 ROLES AND RESPONSIBILITIES FOR LOCAL ENERGY SYSTEMS (ORGANISATIONAL ARCHITECTURE)

The following section describes functions which might need to be done in order to support the emergence of integrated local energy systems. When these functions are adopted by an organisation these become roles and responsibilities of that business. Note that emergence of these functions is sometimes to manage local issues (like the optimisation of local assets) and sometimes as a result of "smart" (like managing a data rich, highly flexible system) and sometimes both. The root causes have not been distinguished here.

It's been assumed that existing businesses continue with the same functions they already have and that the functions listed below could be spread around those businesses or create the need for new organisations.

Finally, it should be noted that the work in sections 6 and 7 was completed before release of the UK Hydrogen Strategy. Suitable reference has been included in some areas however some in-depth thinking such as hydrogen business model proposals and a low carbon hydrogen standard have not been considered at this time.

6.1 NEW SYSTEM OPERATION FUNCTIONS

A managed local energy system, which means a defined area where the flow of energy vectors, within the zone and input/output from the zone are monitored and controlled, could have multiple benefits. The size of the area and the roles and responsibilities of the actors involved are to be defined, but this section describes the required functions to allow for debate and agreement on how to divide up the activities.

1. Local opinion and governance structures giving more say on what happens
2. Community ownership bringing revenue back to local places
3. Local energy is prioritised reducing losses on the system and providing additional value
4. Better integration of multi-vector resources
5. An acceleration of delivery through optimised local choices and deployment

The questions remain about whether it is possible to realise these benefits with the current commercial, technical and governance arrangements and furthermore, what the consequences and drawbacks of such an approach might be.

One or more organisations might be responsible for a range of functions as shown in Figure 19. Within this report the functions that are required for local systems operation are discussed, independently of any decision on institutional arrangements or specific roles and responsibilities of any given business.

Traditionally these activities have largely been managed centrally by either a network company or a system operator, in the case of natural gas and electricity. A locally managed energy system has new opportunities to bring together multiple assets and multi-vector equipment for the optimal performance for those asset owners or a local community.

This section looks at what local energy system functions might be needed and how to go about delivering those functions. Note that no point is made about the energy vector, be it electricity, natural gas, or hydrogen. The same functions apply in each case (albeit with differences in timings and geographies).

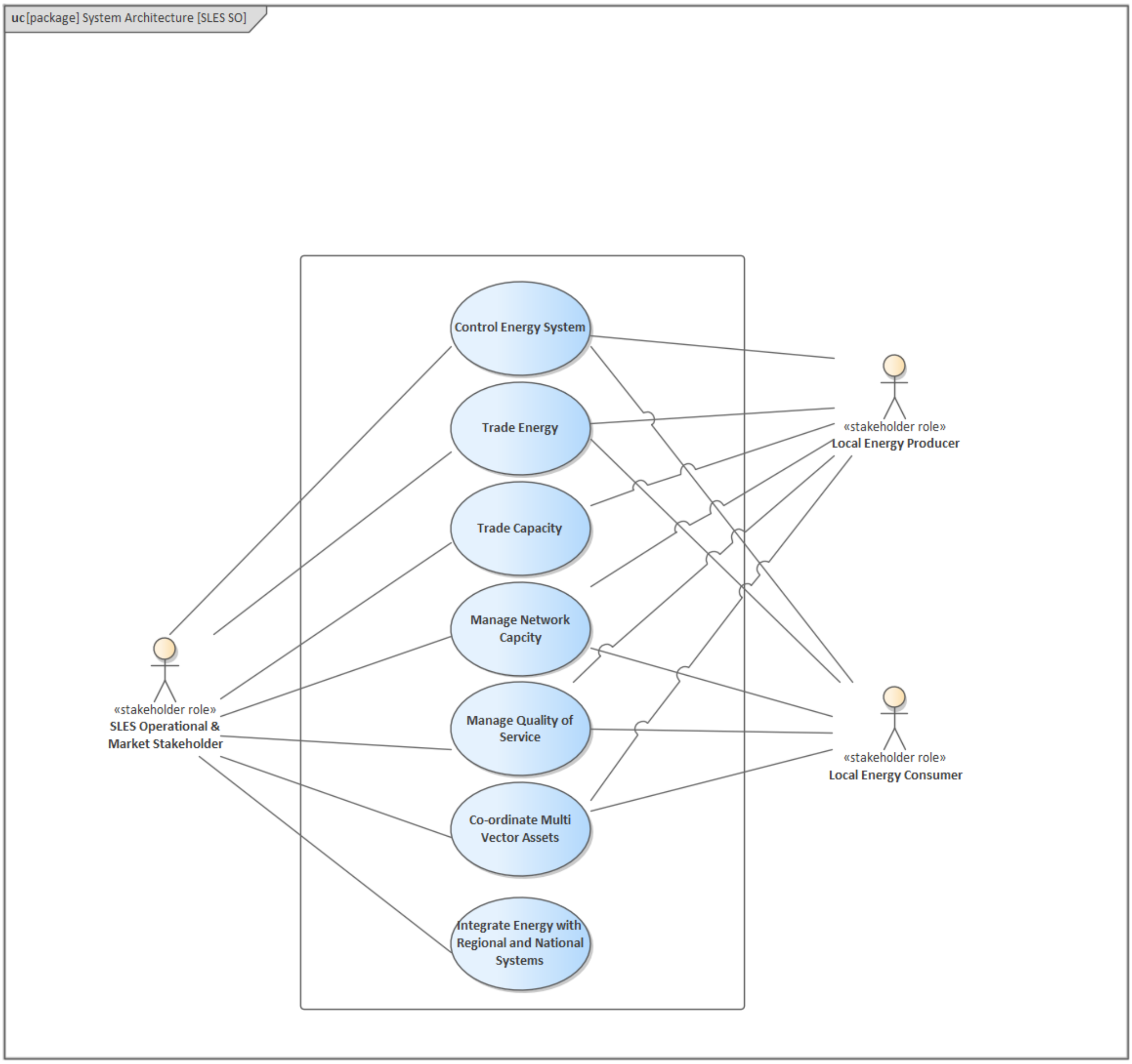

Figure 19 – system operation and market functions use-cases (note each use-case function in the diagram is explored in the sections below) illustrated with relationships to production and consumption

6.1.1 MATCH PRODUCTION WITH CONSUMPTION

Within a defined area consumption and production needs to be balanced. For electricity, this needs to be done continuously and at microsecond intervals. For natural gas, today, this is usually done daily at a national level. Future operation may be different to how balancing happens today with the emergence of more flexibility services, demand side response and multi-vector operation.

For hydrogen, the extent of monitoring will likely depend on whether the scope is for a dedicated hydrogen system or a blended one. In a blended system the challenge is to inject sufficient hydrogen to maintain an overall average blend percentage at all points in time. Where there is a single injection point, the key challenge is varying injection with seasonal variation (when more natural gas is used then more hydrogen can be injected), but in a system with multiple injection points there is a need to co-ordinate the contribution at each point. In a dedicated hydrogen system balancing is required to maintain pressures over the course of a day, which, just like in the gas system today, is aided with line-pack.

Three approaches to controlling the level of blend are suggested below through the use of sequence diagrams, which indicate which actors, perform what actions, in which order.

Note that while this section is discussing the process for blending these approaches support 0-100% blend percentages.

A note on reading sequence diagrams:

Sequence diagrams provide a visual representation of the actions which each actor (or system) perform and the handovers between them. It is a graphical way of explaining the flow of a story rather than trying to write it all in a description and becomes very useful for very complex activities which require back and forth communication or transactions between multiple parties.

Each vertical line represents a timeline for a given element (those elements could be actors i.e. people or organisations and are represented by stick figures. They could also be systems like a computer program which would be represented by a simple rectangle, but we haven't gone into those here). The yellow/beige vertical rectangles represent a contiguous block of actions being performed by an actor, such as internal data processing, or producing something. The arrows between these rectangles represent messages, data, or other transactions, which need to go between actors, such as in our examples where trading actions take place. They are read top to bottom and then by following the messages to see what transactions take place. A message loop (an arrow which leaves and returns to the same actor) is used to express a key action, that the reader should be aware of, that is wholly contained within a single actor (basically highlighted actions for clarity and understanding).

There are additional nomenclature subtleties and nuances that are useful for the SysML specialists, but these will not be covered here and can be safely ignored by those readers wanting a general overview.

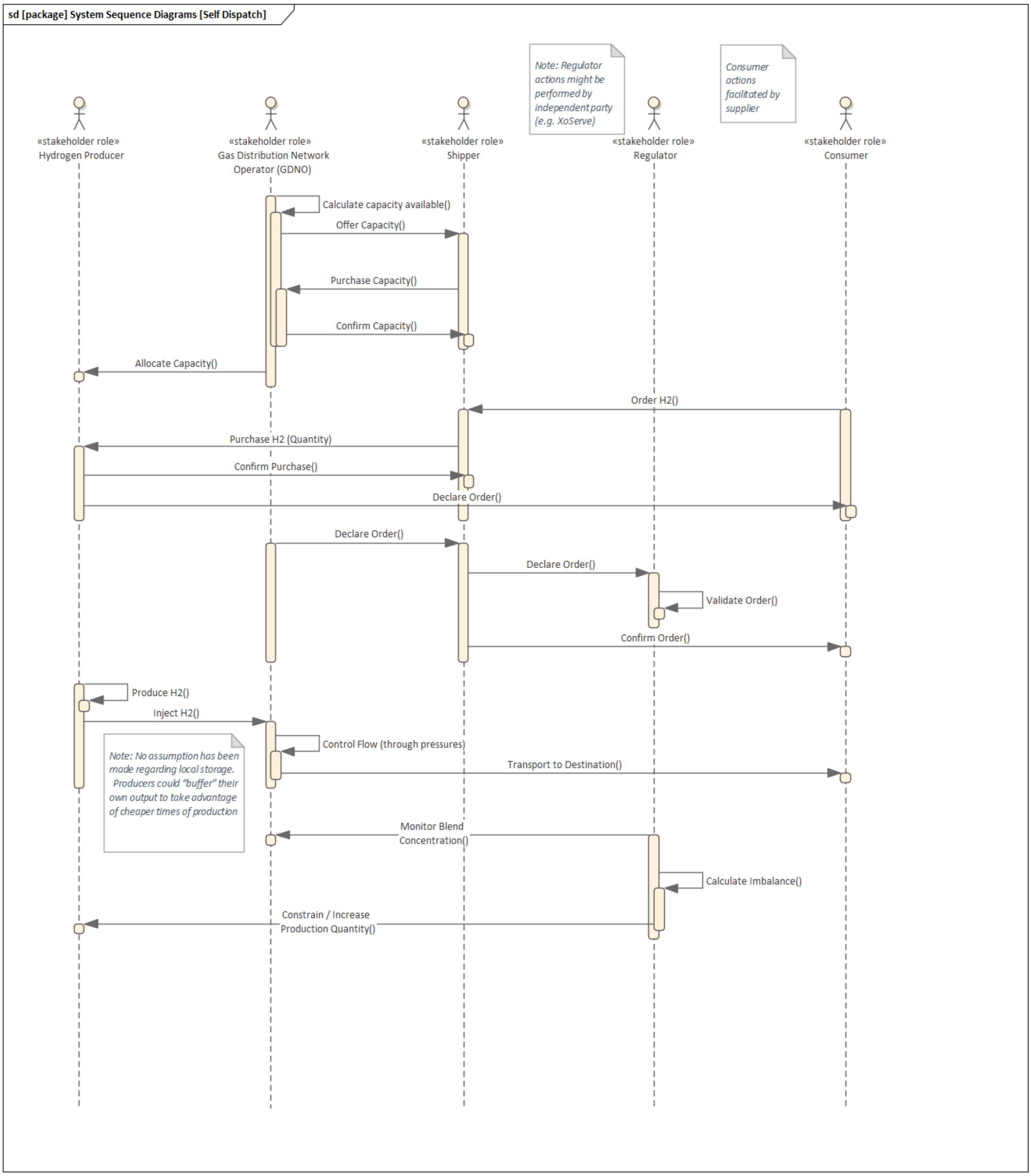

Figure 20 - Sequence diagram for self-dispatch of hydrogen based on trading alone

In the example in Figure 20 each producer of hydrogen is responsible for dispatching exactly the right amount of hydrogen, based on what they traded with a shipper. In theory this works fine but there might be a time when what is delivered is different to what was planned, say due to a plant fault. In this case there would likely need to be a financial redress (hence XoServe for balancing and management) and possibly (not shown) a reserves operator to provide real-time, physical back-up (as shown in Figure 21 below).

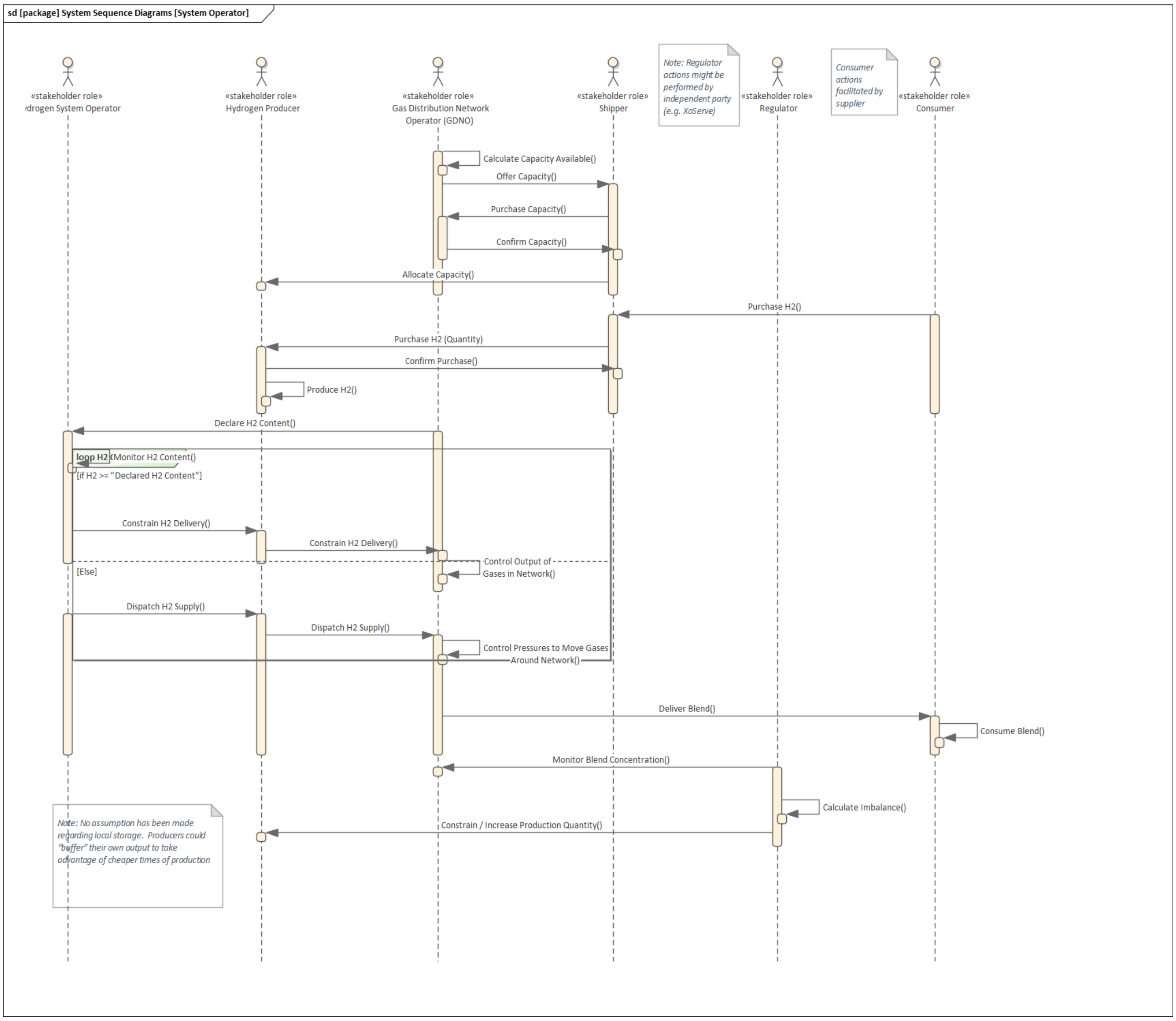

Figure 21 – Sequence diagram for a systems operator driven blending control scheme

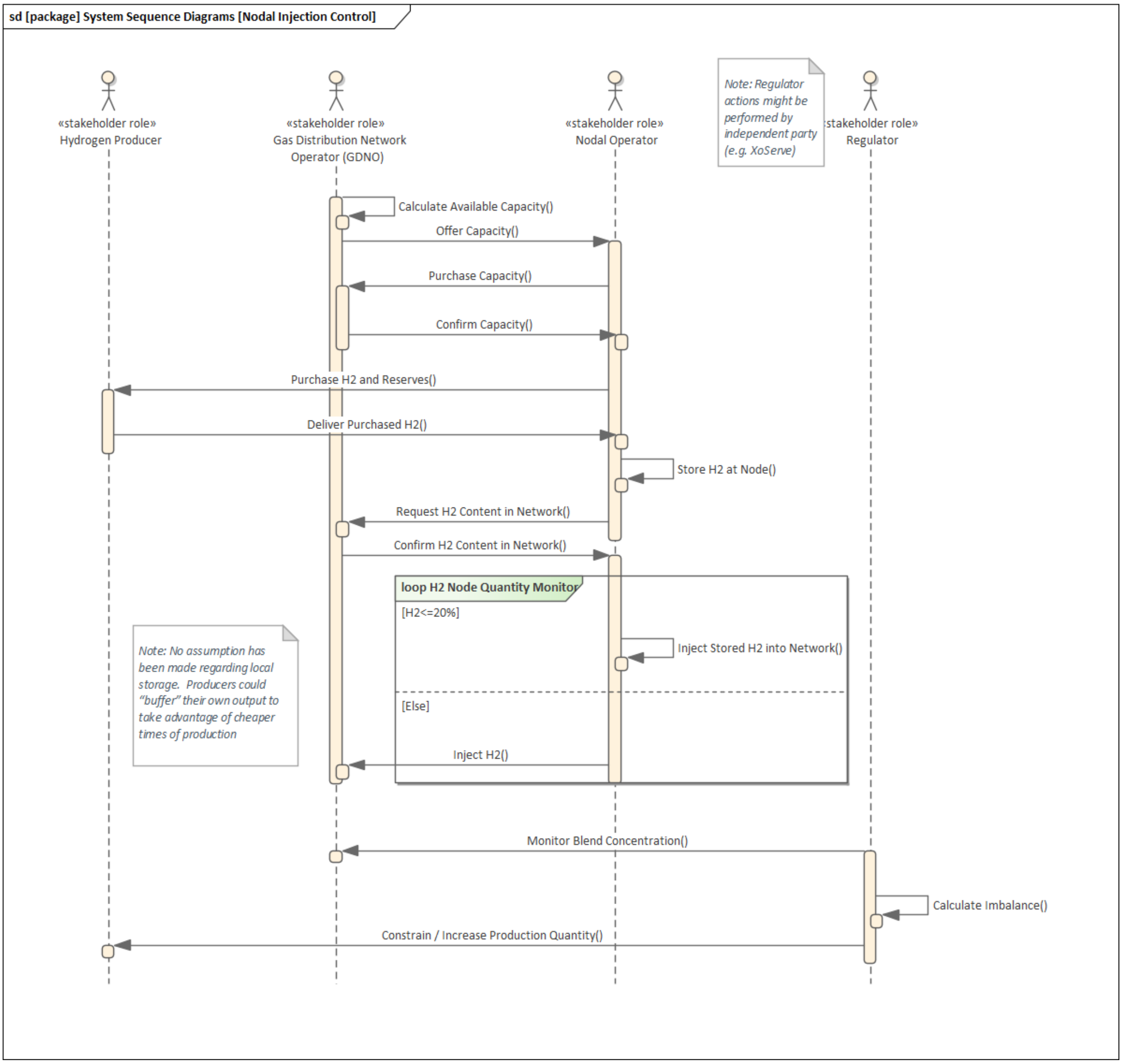

Figure 22 - Sequence diagram for a single nodal control approach to hydrogen blending

In the approach shown in Figure 22 a 'central' injection node buys hydrogen and then controls the injection at a single injection point on the gas network, thereby controlling a consistent blend. This prevents each H2 producer having to coordinate exactly how much to contribute to the overall blend. The single node operator then also becomes the reserves operator in the event that a single plant goes down by utilising H2 from one of the other producers.

Decision point: Decide which of these blending control models better serves the local energy system's needs and stakeholders.

The consequences of this decision are that different business models would be more / less viable. For example, the single injection node actor doesn't currently exists, this could be the system operator, gas transporter (i.e. the GDNO) or another entity not yet conceived. Also, this requires production assets to be located close to the single injection point.

For electricity, what this means is asking demand to follow production or vice versa. There are a number of ways of doing that, either directly, with sending control signals to increase or decrease production or consumption or through indirect methods such as through dynamic time and location pricing signals which provide an indication of value for a specific action. It is important to note that incentive-based direct load control is basically a firm resource that bids into markets or enters into contracts with SOs (but this still involves incentives/prices), whereas the indirect approach is response to prices with no commitment.

The advantage of direct control is that it is often more deterministic, and the operator is more or less sure of what outcome is going to occur from a given action. Direct local control and market participation also directly contributes to price formation, therefore there is much greater downward pressure on prices, resulting in greater efficiency and better outcomes for consumers. The indirect method, however, is likely to be more adaptable to changing technologies and to the changes in value that are placed on a given outcome (e.g. are greenhouse gas emissions valued higher or lower than system stability at different times of the day, week, month, and year). Another advantage of indirect price response is no admin hurdles for market participation. Finally, indirect control (e.g. via pricing signals) means that other aspects of the system, such as the level of constraint on the network, are also able to indicate a price. In that case, any individual user might make decisions which are most optimal to them, some people might accept a higher price for charging an EV at any time in the day (depending on both network and energy costs) whereas others might accept heating the home earlier / later given a suitable price incentive. This approach must consider price protection and the safeguarding of more vulnerable customers against high costs at specific times of the day.

Decision point: Decide which aspects of systems in Milford Haven would be better as indirect or directly controlled early on and communicate to stakeholders.

The consequences of this decision are that different business models would be more / less viable. For example, a directly controlled architecture would require that an organisation is responsible for making a control decision and that might adversely affect other partners (e.g. an energy supplier offering a time of use tariff to incentivise use while a network operator can turn equipment on or off).

In an indirectly controlled approach then equipment manufacturers might need to be able to take in multiple price signals and make different optimisation choices. In direct control circumstances, network companies are likely to have more confidence in outcomes.

6.1.2 TRADE RESOURCES AND CAPACITY

A function of a local energy system may be to manage the trade of resources e.g. a quantity of electricity or hydrogen. Even if the majority of trading is actually performed by a trading platform, the system operator is still likely to have a "reserves operator" function, to iron out any issues (e.g. by controlling pressures / voltages, by storing or releasing previously stored commodities or by constraining or encouraging other actors' actions) thereby performing final system balancing.

In addition, a local energy system could also trade network capacities, such as the power carrying capacity in a cable or the maximum flow of a gaseous commodity. Presently the approaches for this are handled very differently and mostly through national schemes. However, the emergence of locally based energy systems may bring opportunities to do it differently.

Decision point: Decide whether MH:EK trading platforms should trade in commodities alone (see section 8 for more details on the trading platform) or also trade access to network capacity and infrastructure resources (i.e. payments which get more infrastructure built).

The consequences of this decision are that roles and responsibilities of new and existing system actors could be very different, affecting their business models. Existing regulated assets may also need to be managed differently.

Network capacity is more likely a real concern for control by a systems operator who needs to ensure that the energy flows are reaching intended destinations without adversely straining the infrastructure that delivers them and for users who want reliable performance.

In the case of electricity this is about ensuring power limits are not exceeded to cause thermal issues and that power quality limits are met to ensure harmonic, voltage and phase angle statutory thresholds. For gas systems capacity management means making sure that gas is in the right place when it is needed, and that pressures and flows are controlled to make the system operate efficiently and safely. This is discussed more fully in 6.1.4

In a local system it is possible that local assets (such as generation and storage equipment or pipes and wires of the network) might belong to the local community, to an independent owner, or be part of the existing regulated asset base of pipes and wires. For a local energy system operator to work efficiently a decision is required as to how control can be optimised across assets owned by different parties or if a local system operator would need to purchase them, or rights to sole use, directly. It will also be critical to understand the relationships with the broader regional and national energy systems. There may be times when it is financially beneficial to trade with, say national flexibility markets, however local constraints need to be fixed (in terms of the physics) first and so this must always be considered when making optimisation choices.

Decision point: Decide how much choice, in relation to providing geographic services, an individual asset owner can have if trading in the local energy markets. What back-stops are absolutely required to ensure physical limits are not exceeded and how are these communicated, contractually at the time of connection.

The consequences of this decision are that business models around access to markets, revenue stacking etc. are affected

6.1.3 MANAGE NETWORK CAPACITIES

Managing network capacities means making sure that the infrastructure which brings a given energy vector to customers is controlled and protected from over-stress or damage. Note that this is all about making the best of the installed capacity, rather than predicting future needs and planning and installing capacity (e.g. more generation, storage, or network assets) which is not covered here. Even if some of the management of networks is through trading additional oversight and control is required to ensure that unforeseen circumstances (like a plant outage) or resolving locational challenges not addressed by trading, are rectified. This is required independently (in that different parties are responsible for different actions) and jointly (in that both need to happen to achieve the end objectives) with the matching of supply and demand, which is to ensure that generation or production quantities are properly balanced. You can have managed network capacity and still have a mismatch of generation/production to demand.

For gaseous products there is a natural buffer of capacity through line-pack, the product which is contained within pipes. Today’s natural gas system is balanced on a day-to-day basis and the pressure fluctuates in different parts of the network throughout the day. The other network management activity means making sure that resources are in the right place at the right time. The biggest consideration for hydrogen is that, in a blended system, there needs to be consideration for the location of concentration of different molecules.

In electricity there are requirements to manage both the power quality (See section 6.1.4) and to ensure that no part of the network is overstressed, which results in a thermal issue and possible permanent damage. One significant challenge to managing local thermal electricity network constraints is that, at low voltages, there are a small number of customers and devices which can respond to requests for mitigating actions. While this, itself isn’t too onerous, there is a conflict between physics and commercial concerns. Figure 23, shows the physical hierarchy of needs for resolving network issues. Fundamentally, only local customers can contribute to alleviating local issues, but anyone can assist in resolving national issues. However, the owner of a given asset, might choose to wait to deliver to a regional or national buyer of flexibility or services if the commercial terms are more favourable.

As an example, consider an EV owner who arrives home after collecting their children from school. Maybe their area has a high concentration of families with school age children which creates a local peak demand for EV charging. Perhaps the organisation that is responsible for local network management offers an incentive to reduce charging now or for other EV drivers to deliver energy from their cars via vehicle to grid charging (V2G). Perhaps the national peak occurs in an hour and energy will be more expensive at that point. The asset owner, or their automated equipment, if operating completely for the financial benefit of that asset owner, would either cause a local power issue, or result in inflating local service charges to the point of being as lucrative as all other daily services.

National Action Point: Government to determine new approaches to drive cost-reflective, temporally, and geographically granular network charges to avoid market distortions.

At the moment distribution network operators (DNOs) are using active network management (ANM) to begin this process of procuring flex services. The open networks future worlds project is also looking at the interactions between local and national controls which could inform the approach at Milford Haven.

Discussion point: There is a need to resolve, likely at a national level, what physical actions will be mandated for “keeping the lights on” and which actions will be left open for market forces to incentivise and drive.

Milford Haven has the advantage of being able to demonstrate multi-vector, local energy system management before other areas given the work going on now but it requires decisions on commercial responsibilities and agreement from multiple parties on how to operate. For example, this could include a statement on who is responsible for managing the blend of H_2 into natural gas pipes or who is responsible as a residual balancer to ensure there was always enough reserve of H_2.

The consequences of this decision are that business models flexibility services, the roles, and responsibilities of distribution system operators (DSOs) vs GDNO (would you still need both, for example) etc. and the role for a residual balancer i.e. a backstop to step in under extreme conditions are potentially quite different to today’s approach (and whether you need national and regional actors for this role).

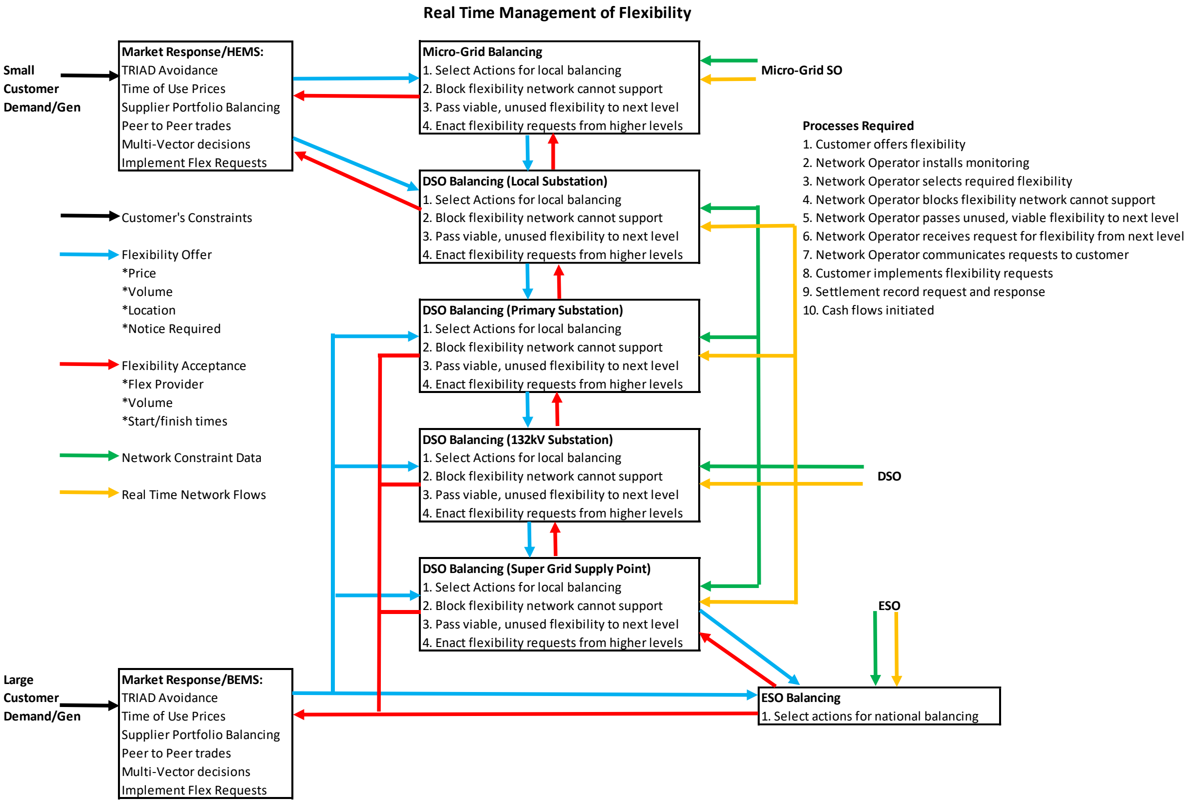

Figure 23 - Physical hierarchy for flexibility

Given that different parties are responsible for different aspects of managing capacity and resources, coordination is required to ensure that responsibilities are not missed, and that duplication is avoided. For electricity, there is work currently underway, with the ENA (Open Networks project) looking at the interface between the ESO and DSO as market facilitators. There may be additional work for microgrid operation and to understand the role of retailers and service providers which is currently outside the remit of the Open Networks project.

Some new functions might be required for hydrogen, however, and there are links with the Gas Goes Green initiative, also run by ENA, which is looking at some of the complexities of blending. Milford Haven could prove a valuable early testbed for some of these ideas as well.

Decision point: It is critical for government, regulators, and businesses to agree on the roles and responsibilities for network management to provide the levels of confidence for innovators and investors to operate in this space. For example, an agreement on what a DSO will be responsible for (could include the system operation, market operations and/or multi-vector operations. This might also include the roles for microgrid operators and community systems operators. For Milford Haven it might be possible to be an early demonstrator being an integrated multi-vector operator using the combination of assets in the area.

6.1.4 MANAGE QUALITY OF SERVICE

The sections above describe how energy produced is provided to consumers in a safe way, across a variety of network connections. There are additional considerations for the quality of the energy product which arrives.

For hydrogen this is primarily about the quality / purity of hydrogen delivered to the end user but might also include,

- Embedded carbon content
- Percentage blending (in a blended system).
- Moisture content
- Pressure

This is likely to be a collaborative effort between producer and network operation. Hydrogen moving through pipes has to be cleaned, have moisture removed, have particulate matter filtered out. Importantly, this starts with the production quality and is then supported through network activities.

Action point: There is currently no standard for the purity of hydrogen for domestic use, but one is likely to be required soon. Milford Haven and stakeholders should ensure that they understand the requirements for local quality. Particularly for fuel cells, where this is currently more likely to have a firm requirement for purity and cleanliness to maintain performance. In the short term, different areas can work with different requirements, so it is okay to explore these locally and then later agree on a national standard if required.

The implications of this decision are that it includes or excludes certain sets of options as a trade off against cost and complexity. For example, current fuel cells need the highest level of purity to reduce degradation, but that purity requirement comes at a significant cost and complexity.

Note that not all hydrogen needs to share the same purity. For Milford Haven, the decision could be that all FCEVs are fuelled from hydrogen created in electrolysers co-located with refuelling stations while hydrogen for blending for delivery to domestic boilers can have different standards. Ultimately, for commercially viable businesses, producers may want a single standard to produce to or to only produce for certain applications. Single standards, with the broadest applicability, may be much more attractive in the longer term.

Quality of service relies on having accurate monitoring and reliable data, particularly if trading is predicated on certain measures of performance. Information to capture and convey includes:

- Production location (for locational pricing and incentivisation to use local energy)
- Injection location (where this is different to production location) and is used by the system operator to manage pressures and blending levels.
- Carbon content or manufacturing method (here there is a real challenge of proving the origin of different molecules of hydrogen vs trading in certificates)
- Quantity delivered (includes properties of quantity such as form, pressure, purity and more)

For electricity the parameters key for managing power quality include:

- Voltage levels (e.g. for LV 230V +10%, - 6%)
- Harmonic content
- Phase imbalance
- Power factor / phase angle

Thermal issues (note that these are primarily managed as described in section 6.1.3)

The power of flexibility to address many of these challenges are well documented but there is subtlety required in the data transferred and the parameters traded to be able to adequately address these challenges. For example, constant resistive loads, such as kettles, oil heaters, 5-bar heaters, fan heaters, oven and hob elements respond to actions from DNOs, such as reducing the voltage, which is done often in order to manage thermal constraints, by also reducing the current they draw. However, constant power devices, like the power supplies in modern electronics such as TVs, computers, gaming consoles, battery electric vehicle chargers, draw more current when the voltage is reduced. This means that trading or controlling, solely on the parameter of kWh will not allow for controlling more nuance and often leads to deploying multiple solutions to solve individual problems, rather than maximising the cross-benefits from existing assets.

6.1.5 INTEGRATE WITH REGIONAL AND NATIONAL SYSTEMS

Any local system will need to integrate with broader systems, whether that is regional or national systems. The use of the word "system" here is taken to include policy, legal, commercial aspects as well as purely technical considerations. There are actions which can be taken purely locally in the first instance, like selling hydrogen locally using dedicated pipes or containerised transport, but most things will need to integrate with the national schemes eventually to ensure optimal outcomes for consumers and interoperability between adjacent systems. Examples are given in Table 2.

Aspects of energy system which could be made "local"	**Example**	**Interface considerations with regional / national systems**
Trading	Trading some resources locally (asset owners choose what to sell on a local market, local users decided what to buy)	Making sure not to trade twice (across different platforms) or to ensure that any revenue stacking is allowed
Physical standards	A local network may decide on different limits for hydrogen purity or voltage tolerances	Equipment manufacturers will still likely only manufacture equipment for a bigger market. Customers move areas and take equipment with them too
Control approaches	Some areas may adopt a different approach to control, for example some flexibility schemes put final control in the customer's hands (i.e. they can always reject a request for flexibility) whereas other operators are putting a final decision with the network company	Still need to interface with national schemes to manage larger issues such as total hydrogen content in a blend or frequency management for electricity
Control responsibilities	Choosing to locally dispatch resources through innovative approaches and business models	Needs to be co-ordinated with adjacent areas and national systems to prevent oscillations and network performance issues

Table 2 – Aspects of Energy System which could be made Local

Even if one aspect of a Smart Local Energy System is "local" others may not be and there will still be national laws which must be obeyed and worked within, however local energy systems have the advantage of motivating and coordinating local stakeholders to drive more immediate results and this impact should not be diminished.

Decision point: What is the ambition for the level of independence from national and regional systems within the MH:EK boundary? The implications of that decision drive a lot of different possibilities of business models and ways of working, plus mitigating actions for the risks and interfaces to wider systems.

The implications revolve around what to formally devolve from national institutions and such decisions have a long lead times and wide-ranging implications for consumers. Take something relatively simple like selling energy as a service, today that would be impossible to do since the billing regulations require transactions against specific billed quantities of kWh/m^3. Outside of trials there needs to be an understanding of what current regulations are blockers to local systems.

6.1.6 CO-ORDINATE MULTI-VECTOR ASSETS

Some actors might simply operate on one vector (e.g. a local hydrogen system operator) but the more likely outcome, with a hydrogen system is uniting multiple energy vectors performing actions such as optimising hydrogen production over electricity for storage or switching between gaseous vectors and electricity in hybrid heating systems dependent on current system performance.

Decision point: Decide whether MH:EK should push for multi-vector co-ordination and services from its markets and trading platforms or to continue with multiple parties being responsible for each entity.

The consequences of this decision are that roles and responsibilities of new and existing system actors could be very different, affecting their business models.

One clear example of multi-vector co-ordination is to produce hydrogen when there is an abundance of electricity generation, rather than curtailment off generation. A significant challenge here is that much new generation, particularly for renewables is connected using "flexible connection contracts", which means that those "new-generation" asset owners get connected for a lower price but can be disconnected in the event of over-supply and therefore they receive no commercial payment for curtailment. Their costs were reduced at connection time and have been factored into their business models. Local, bilateral contracts could be set up to take advantage of periods where such assets are constrained to provide additional revenue but that also need coordination with local network operators who will need to be convinced that their export limits won't be breached. For example, in an actively managed network zone a DNO requires that a generator is constrained to prevent over generation in a specific area. Additional bilateral contracts might provide flexibility if, instead of constraining the generator off, the ANM triggered the flexible demand "on", so for example an electrolyser would ramp up to take the additional generation available and still protect the network. This works in theory but requires the careful citing of flexibility in appropriate constraint locales.

In Milford Haven a new set of operations are likely to be required for managing the blending of hydrogen from multiple producers of hydrogen. There is an opportunity to build a local systems operator who can manage multiple control vectors.

Discussion point: Convene the DNO and GDNO stakeholders to explore the opportunities that multi-vector control can bring in systems operation and how to convey requirements to equipment manufacturers who can bring about multi-vector control advantages.

6.2 RETAIL FUNCTIONS

There are a huge range of options for future retailers when it comes to selling hydrogen (and by extension multi-vector transactions where desired). Listed below are three key ones. While any decision on how to deliver retail is down to individual innovators there are policy and regulatory issues which prevent some of these models from happening. For example, retailers are legally required to charge for kWh which make Energy as a Service (EaaS) approaches difficult to deliver as things stand.

Selling hydrogen:

In this retail scenario, hydrogen is transported to the consumer in its dedicated form (i.e. with a high level of purity) for use in hydrogen boilers (including hybrid boilers) for domestic use. For hydrogen to be used domestically, the residence will require a retrofit of heat generation (boilers) to support this new fuel. The retail model for this is predicted to be like that of current natural gas retail provision. Hydrogen will be delivered to residence with a metering system to measure the volume of hydrogen delivered and used. Additional safety systems to detect leakages will be required to be installed at the residence. The carbon and emissions savings are a product of the source of production of hydrogen. Customer acceptance for this retail method is to be explored but advantages are the approach is similar to natural gas boilers and are low carbon. The disadvantages are the impacts needed to include hydrogen (currently concerns over ventilation). In a hybrid system there are additional questions around who chooses when to run on electricity versus gaseous products and what that does to the energy bill.

Selling hydrogen as a blend with natural gas:

In this retail scenario blended natural gas-hydrogen is transported to the consumer. Here, traditional domestic heating systems may continue to be used (depending on the percentage quantity of the hydrogen) with little to no retrofit required. The retail model for this is predicted to be like that of current natural gas retail provision i.e. blended hydrogen is delivered to the residence in the traditional delivery methods of natural gas with a metering system to measure the volume of hydrogen delivered and used. Current safety systems might be inadequate to detect leaks of the blended gas, therefore retrofit might be required to be implemented at the residence. This method will have some carbon impact on the environment caused by the natural gas content of the gas. This is likely to have minimal impact on end customers who will see little change in performance.

Selling domestic Energy as a Service (EaaS):

This retail model consists of offering end-to-end management of a customer's energy assets and services[38]. Different energy vectors could be used in delivering energy to the required residences. For instance, heat pumps could be used, as well as electrification of heat/domestic cooking. In this retail model, the consumer only cares about having their needs and desires met. Similarly with how mobile telephone contracts moved from "minutes and MB" to a monthly service charge (with fair usage limits), EaaS proposes to deliver on consumer's expectations for a regular (i.e. monthly) fee and promises servicing, asset management (e.g. managing flexibility services as described above) and installation packages for material upgrades (including new heating technologies, insulation etc.) This retail model could potentially be relatively cheap, in terms of capital costs, compared to the other retail models discussed. The energy delivered to the residence will be charged at the point of use without specifically paying for the metered quantities. Safety components of this model are borne by the retailer as part of this energy service while the carbon impact is varied depending on the energy vector used and the source of production of the energy delivered. Customer acceptance for this method is likely to be relatively high because there is no capital cost to retrofit the domestic energy delivery and distribution systems of the residence. This method also rewards retailers who can provided better, differentiated services to customers rather than just the lowest "per unit" cost of energy. In other words, there are potentially services, such as Energy as a Service, maintenance contracts, flexibility offers, technologies for better controlling in home devices, selling enhanced assets (such as better radiators) which could come out of retailers which could stand them apart from other retailers, selling on price alone. As highlighted earlier in the section, Energy as a Service (EaaS) approaches are difficult to deliver as retailers are legally required to charge for kWh.

Action point: Milford Haven stakeholders can help by adding their voice to future changes required (for example on the ENA's open networks future worlds project) to allow new business models and by working with retailers to ensure that the right data is available to allow them to run commercially viable businesses.

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[38] Energy-as-a-Service. The new smart: clean, connected and community-based energy https://www2.deloitte.com/uk/en/pages/energy-and-resources/articles/energy-as-a-service.html

6.2.1 BILLING

Domestic billing for various blends of fuels will require a change in the current billing system. The future billing methodology[39] is currently researching ways in which new zones could be developed to facilitate correct billing based on the composition of the blend such that the calorific value is appropriately accounted for. Billing for a blend will be more complicated than billing for a dedicated hydrogen supply and would be an interim solution due to not being compliant with net zero.

More sophisticated business models involving electricity, such as anywhere domestic half-hourly consumption, the sales of services back to operators, or one vector providing alleviation for another, will require different billing methodologies. Some of these are being explored in P379[40] (Multiple Suppliers through Meter Splitting), P375 (Settlement of Secondary BM Units using metering behind the site Boundary Point), P376 (Utilising a Baselining Methodology to set Physical Notifications) and P415 (Facilitating access to wholesale markets for flexibility dispatched by Virtual Lead Parties). The future arrangements will impact the sort of multi-vector, multi-service business models that could be offered in Milford Haven. All of these codes aim to change the way that balancing and settling are done and how that can engage different participants in flexibility services.

Action point: for some of the initial MH:EK projects to be more successful, different business models for interfacing will be more or less feasible. For example, to allow heat as a service companies to deliver heating to homes (which might make hydrogen / hybrid uptake more attractive, then P379 and P415) might be especially useful. Future retailer partners might need to be chosen which have decided to implement systems to take advantage of these code changes.

In the shorter term, Milford Haven could be a proving ground to demonstrate the effectiveness of such codes.

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[39] Future Billing Methodology
https://futurebillingmethodology.co.uk/

[40] note that P379 has just been withdrawn but many of its needs and learnings could still be implemented in future work so it is included here for completeness.

6.3 OTHER ACTORS

6.3.1 HYDROGEN STORAGE OPERATORS

Storage is a key consideration for a hydrogen system to ensure that variable production rates do not mean erratic delivery to end customers whether that is by private connections or through blended or dedicated pipelines.

Storage can also help in accessing market prices at the best time by producing hydrogen when production costs are lowest (for example when electricity is cheap in electrolysis systems) and then selling when it is most valuable.

There are different operating models with the main ones being:

- 3rd Party buying and selling:
    - Here an independent company owns a storage asset and buys hydrogen at one price and sells at another in a similar way to a battery owner. This relies on price volatility to make the business case worthwhile which might be disadvantageous to other parts of a hydrogen economy.
- Lease storage capacity
    - In this model an independent organisation operates a storage facility and sells space in it to a producer or consumer for them to store their hydrogen. Those organisations are responsible for future trade.
- Reserves operation
    - In this model the storage operator also acts as a floating reserve, monitoring the hydrogen content in blend, or the pressure in a dedicated system and injecting more hydrogen as required. It is likely that this is more of a function than an independent system operator, or regulated body, acting in the wider public interest.

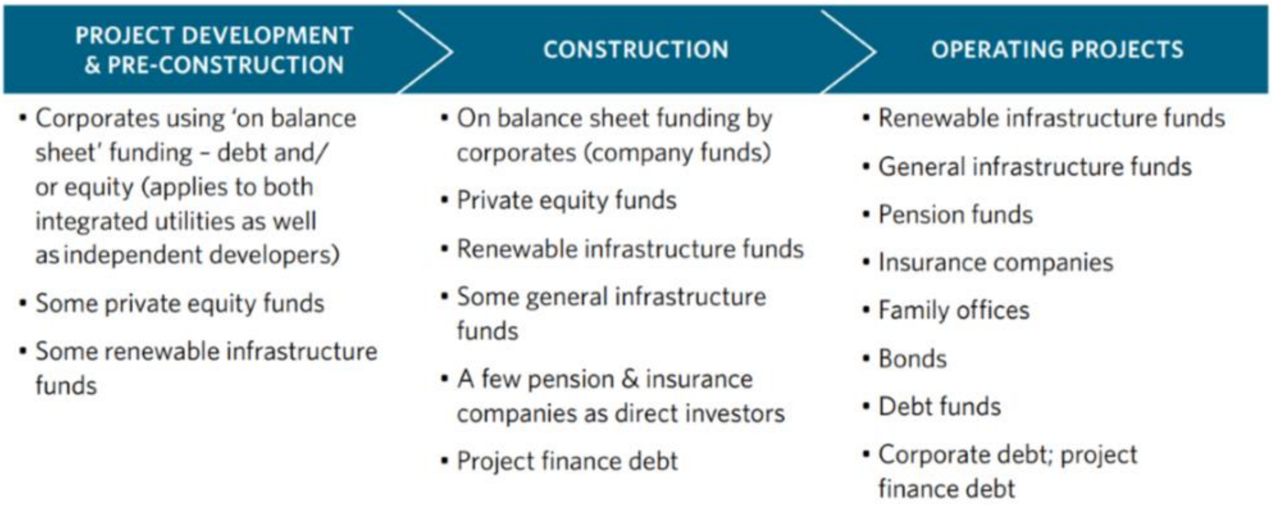
7 HYDROGEN INVESTMENT AND TRADING

7.1 WHAT COULD DRIVE INVESTMENT IN HYDROGEN

7.1.1 WHO WOULD INVEST?

Investment in hydrogen system elements will be driven by the returns that investors think they can achieve on the assets weighed against the risk of the investment. In the short term, gaining expertise in this new sector will also be a consideration. For the hydrogen system to develop it requires investment in hydrogen production, storage, use and distribution/transmission assets.

Different types of investors will engage at different stages of an investment, bringing different types or sources of funds. For example, Figure 24 lists the range of investor types and funds that are typically involved at different stages of a renewable energy project (from 'Finance Guide for Policy-makers: renewables energy, green infrastructure', Kirsty Hamilton and Ethan Zindler, 2016[41]).



PROJECT DEVELOPMENT & PRE-CONSTRUCTION	CONSTRUCTION	OPERATING PROJECTS
• Corporates using 'on balance sheet' funding - debt and/ or equity (applies to both integrated utilities as well as independent developers) • Some private equity funds • Some renewable infrastructure funds	• On balance sheet funding by corporates (company funds) • Private equity funds • Renewable infrastructure funds • Some general infrastructure funds • A few pension & insurance companies as direct investors • Project finance debt	• Renewable infrastructure funds • General infrastructure funds • Pension funds • Insurance companies • Family offices • Bonds • Debt funds • Corporate debt; project finance debt

Figure 24- Renewable energy project stages and investor ecosystem, 'Finance Guide for Policy-makers: renewables energy, green infrastructure', Kirsty Hamilton and Ethan Zindler, 2016, Credit to HgCapital for the Ecosystem of Finance approach used as the basis for this table.

Different investor types have different risk appetites, which is reflected in the rate of return they expect to achieve from an investment and the types of technologies and projects they invest in, as illustrated in Figure 25 'Finance Guide for Policy-makers: renewables energy, green infrastructure', Kirsty Hamilton and Ethan Zindler, 2016[42]).

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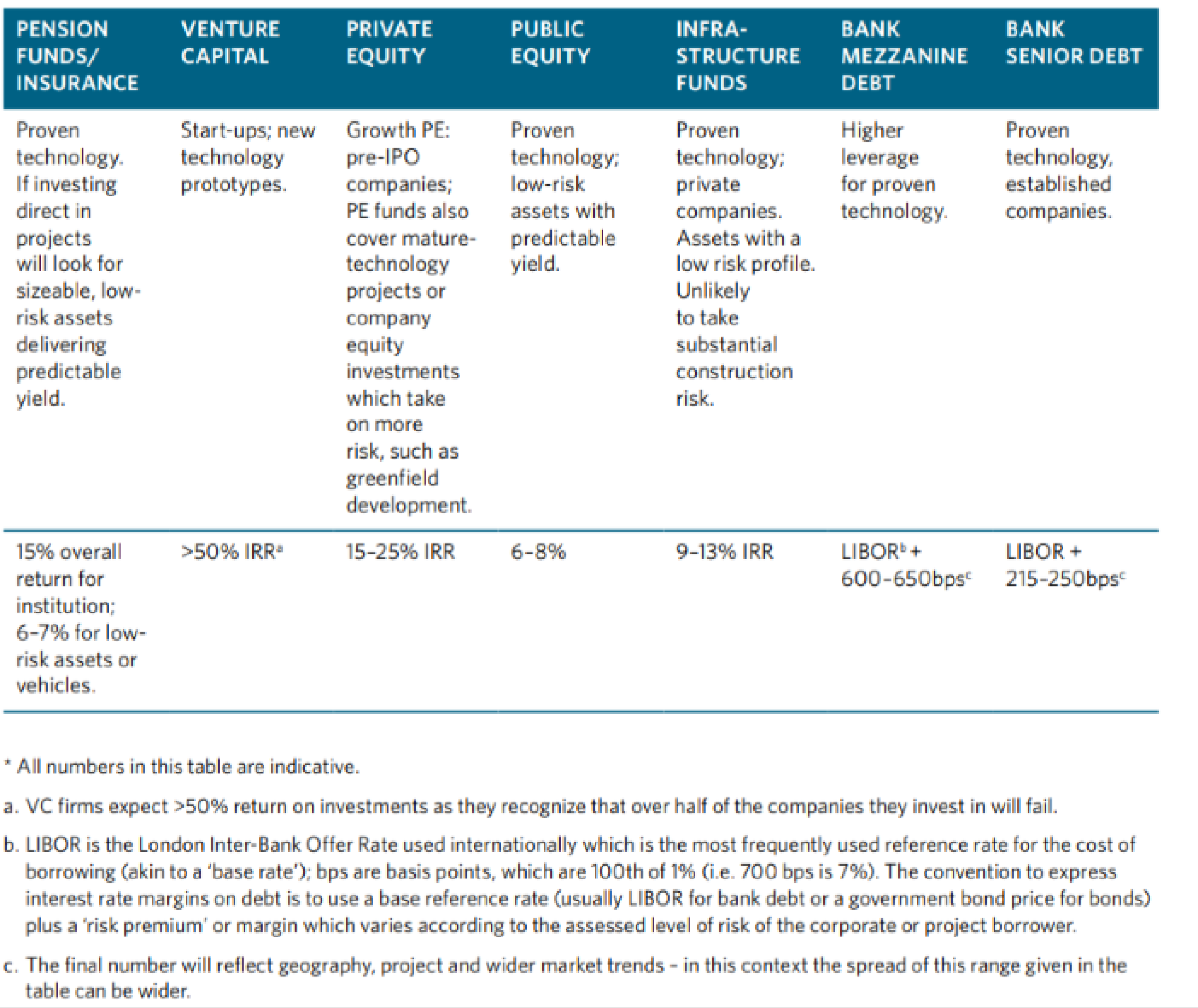
[41] https://www.bbhub.io/bnef/sites/4/2016/08/Finance-Guide-for-Policymakers-RE-GreenInfra-August-2016.pdf

[42] https://www.bbhub.io/bnef/sites/4/2016/08/Finance-Guide-for-Policymakers-RE-GreenInfra-August-2016.pdf



PENSION FUNDS/ INSURANCE	VENTURE CAPITAL	PRIVATE EQUITY	PUBLIC EQUITY	INFRA-STRUCTURE FUNDS	BANK MEZZANINE DEBT	BANK SENIOR DEBT
Proven technology. If investing direct in projects will look for sizeable, low-risk assets delivering predictable yield.	Start-ups; new technology prototypes.	Growth PE: pre-IPO companies; PE funds also cover mature-technology projects or company equity investments which take on more risk, such as greenfield development.	Proven technology; low-risk assets with predictable yield.	Proven technology; private companies. Assets with a low risk profile. Unlikely to take substantial construction risk.	Higher leverage for proven technology.	Proven technology, established companies.
15% overall return for institution; 6-7% for low-risk assets or vehicles.	>50% IRR[a]	15-25% IRR	6-8%	9-13% IRR	LIBOR[b] + 600-650bps[c]	LIBOR + 215-250bps[c]

* All numbers in this table are indicative.

a. VC firms expect >50% return on investments as they recognize that over half of the companies they invest in will fail.

b. LIBOR is the London Inter-Bank Offer Rate used internationally which is the most frequently used reference rate for the cost of borrowing (akin to a 'base rate'); bps are basis points, which are 100th of 1% (i.e. 700 bps is 7%). The convention to express interest rate margins on debt is to use a base reference rate (usually LIBOR for bank debt or a government bond price for bonds) plus a 'risk premium' or margin which varies according to the assessed level of risk of the corporate or project borrower.

c. The final number will reflect geography, project and wider market trends – in this context the spread of this range given in the table can be wider.

Figure 25- Summary of different sources of project finance, 'Finance Guide for Policymakers: renewables energy, green infrastructure', Kirsty Hamilton and Ethan Zindler, 2016).

Energy projects can also be funded by communities, with people owning a share and gaining some type of benefit as a result. Community shareholders can be rewarded through sharing a portion of the profits that a local project makes, and examples exist across the UK today[43]. Community energy projects are often set up with wider aims and initiatives as well such as reducing fuel poverty or taking climate action. Under current market and policy arrangements, however, it is difficult for domestic users to choose to buy energy locally, due to factors such as system value of consuming energy closer to the source of production not being accurately reflected in prices and consumers being unable to contract with more than one supplier.

There is increasing investor interest in hydrogen globally. Figure 26 below shows the current projects which are at different stages of gaining investment globally. The total project pipeline capacity increased 60% in the year since the last analysis. In this analysis the Hydrogen Council estimated that to 2030 there will be USD 130 billion investment in announced projects, USD 120 billion for projects which will be needed to reach government targets and USD 250 billion of 'implied' investment from OEMs and suppliers to support projects.[44]

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[43] See https://communityenergyengland.org/pages/state-of-the-sector

[44] https://hydrogencouncil.com/wp-content/uploads/2021/07/Hydrogen-Insights-July-2021-Executive-summary.pdf

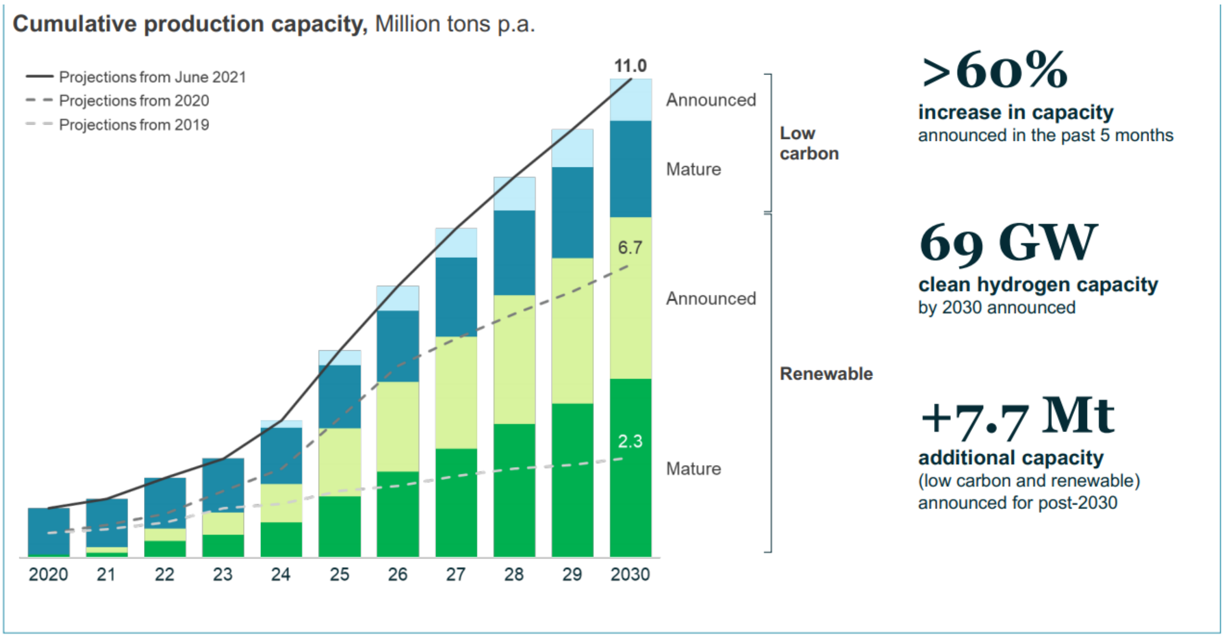

Figure 26 - Announced clean hydrogen capacity through 2030('Hydrogen Insights', Hydrogen Council, 2021)[45]

Action point: Schedule and carry-out regular horizon-scanning on investment trends and cost reductions for hydrogen - UK, EU and international – using credible sources e.g. IEA, IRENA, specialised consultancies to improve awareness of the investment landscape.

7.2 DRIVERS AND FACTORS INFLUENCING INVESTMENT IN HYDROGEN

Multiple factors drive or strongly influence hydrogen investment, including:

- Carbon policy
- Costs of hydrogen production, storage, distribution, and supply chain costs
- Power system development and market prices
- Design of Government support policy for hydrogen production
- Requirements of end users and strength of demand
- Development and availability of supporting infrastructure
- Natural gas network conversion
- Technology/investment risk profiles
- Regulatory barriers

Each of these is discussed below.

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[45] https://hydrogencouncil.com/wp-content/uploads/2021/07/Hydrogen-Insights-July-2021-Executive-summary.pdf

Carbon policy

The UK Government’s commitment to achieving net zero by 2050, enshrined in law, is a key long-term driver of investment in hydrogen. Previous modelling for achieving 80% reductions in greenhouse gas emissions for the UK economy were unclear as to whether hydrogen would play a role. Following the adoption of net zero modelling from various sources[46] now more strongly suggests that hydrogen will play a role in achieving net zero, though the future shape and scale of this role is unclear as shown in Section 4.2.

Carbon pricing, through the UK Emissions Trading Scheme (UK ETS), is a key pillar of carbon policy for the energy sector. However, many other policies layer together to create different ‘effective carbon prices’ for different energy vectors and uses. Effective carbon prices are the incentive or reward for a firm or individual to reduce emissions (in £/tCO2e) resulting from direct (e.g. explicit carbon pricing instruments, energy, and fuel taxation, etc.) and indirect (e.g. reduced VAT on energy, subsidies for low and zero carbon options, etc.) carbon policies. The work conducted under Rethinking Decarbonisation Incentives project quantified the uneven effective carbon prices across different UK energy uses and vectors (see Figure 27).

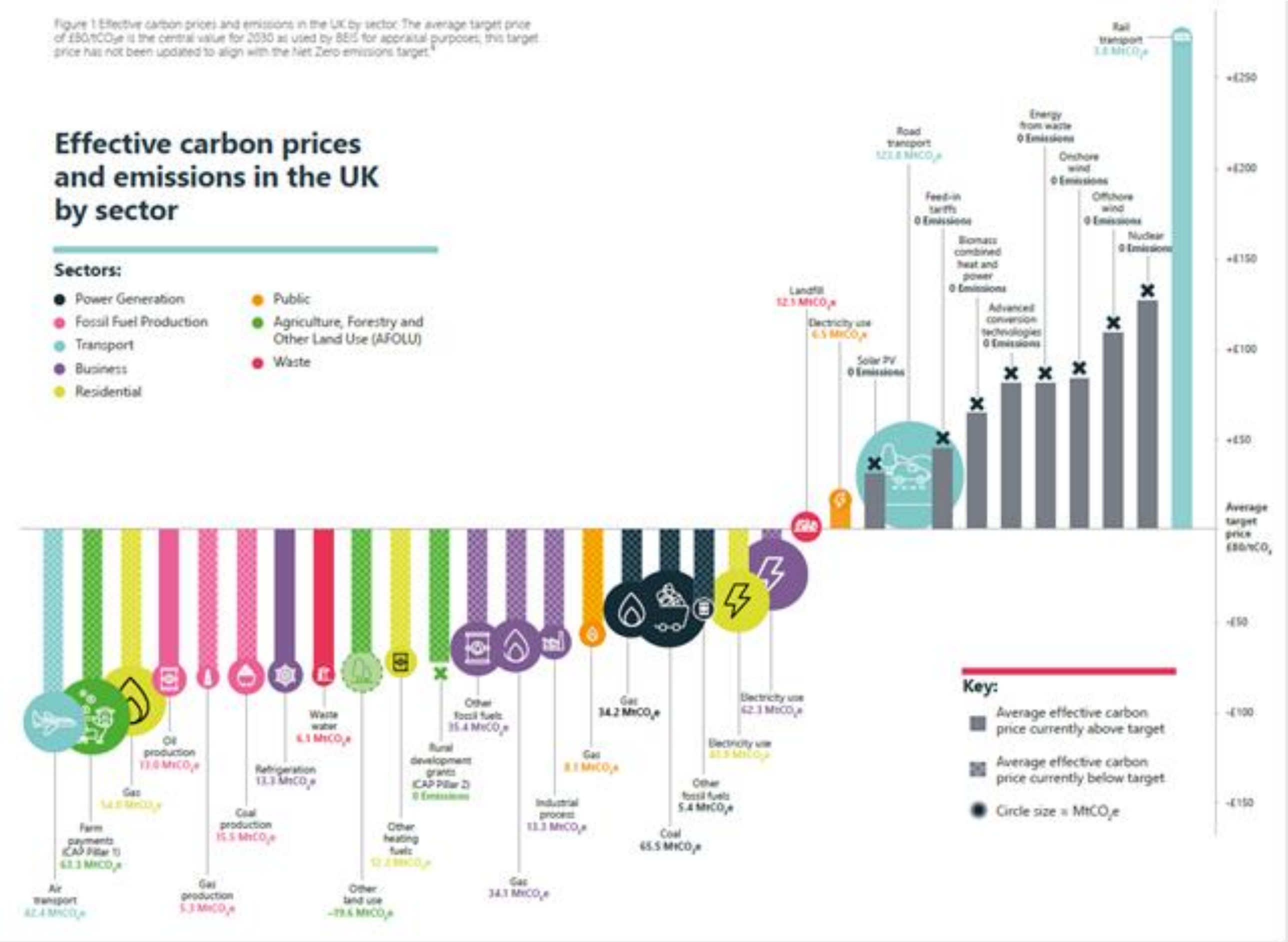

Figure 27- Effective carbon prices and emissions in the UK by sector. The average targets price of £80/tCO2e is the central value for 2030 as used by BEIS for appraisal purposes, this target price has not been updated to align with the net zero target.

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[46] See: https://es.catapult.org.uk/reports/innovating-to-net-zero/; https://www.theccc.org.uk/publication/sixth-carbon-budget/

The ‘effective carbon prices’, as illustrated in the Figure 27 above, reveal the incentive or disincentive for different users to convert to or use a low carbon energy vector. It also affects the relative costs of low carbon technologies or solutions and is therefore highly relevant in relation to the economics of hydrogen production methods and their carbon intensity. For example, levelising effective carbon prices between residential electricity and residential gas would significantly improve the competitiveness of all forms of low carbon heating including heating based on hydrogen.

Ensuring coherent ‘effective carbon prices’ across energy vectors and sectors will be critical for the development of low carbon hydrogen and to enable efficient vector switching involving low carbon hydrogen. IMechE et al. (2020) highlighted the uneven vat rates across hydrogen sectors and different vectors as a key barrier to the development of the hydrogen sector[47]. Carbon policy will need to develop in a way that guarantees the needed outcome of net zero and so it can be expected that standards will be necessary to complement carbon prices in the form of, for example, fuel content obligations, product standards or procurement eligibility requirements. In its 6th carbon budget report, the CCC called for application of emissions performance standards to be applied to unabated natural gas in the power sector, with full phase out by 2035[48]. In order to implement such policy, it will be necessary to track carbon through the energy system and robust monitoring, reporting and verification will be required as well as certification of the carbon intensity of products.

National Action point: UK government to ensure alignment of effective carbon prices across energy vectors, removing distortions across energy vectors and sectors; this will help achieve optimum investment in and use of hydrogen.

As was developed for renewables, it is likely that the hydrogen production sector will need to develop a Guarantee of Origin (GoO) certification scheme and the possibility for producers and users to trade certificates. This is key to optimising investment in the different ‘colours’ of hydrogen, determined by the carbon intensity of production methods, in alignment with the CCC’s carbon budget cycle. This is discussed further in section 7.3.

Costs of hydrogen production, storage, distribution, and supply chain costs

The characteristics of the supply chains for different production, storage and distribution technologies and their interactions with a changing policy and market framework over the next two decades will strongly influence investment outcomes. The cost of hydrogen relative to alternative energy technologies and the relative costs of different hydrogen production and storage technologies will drive how the market develops.

The cost difference between electrolysed hydrogen and hydrogen from SMR/ATRs with CCUS will greatly impact how the market develops. ESC’s modelling shows that biomass gasification with CCUS could also play a key role in producing hydrogen but that this is more limited, due the availability of biomass, compared to electrolysers and SMRs/ATRs with CCUS.

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[47] https://www.imeche.org/docs/default-source/1-oscar/reports-policy-statements-and-documents/hydrogen---policy-anomalies-document-final-2020.pdf?sfvrsn=2

[48] The 6th Carbon Budget: Electricity Generation, 2020, https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Electricity-generation.pdf

Figure 28 shows how green (electrolysed) and blue (SMR/ATR with CCUS) hydrogen production costs could evolve with time.

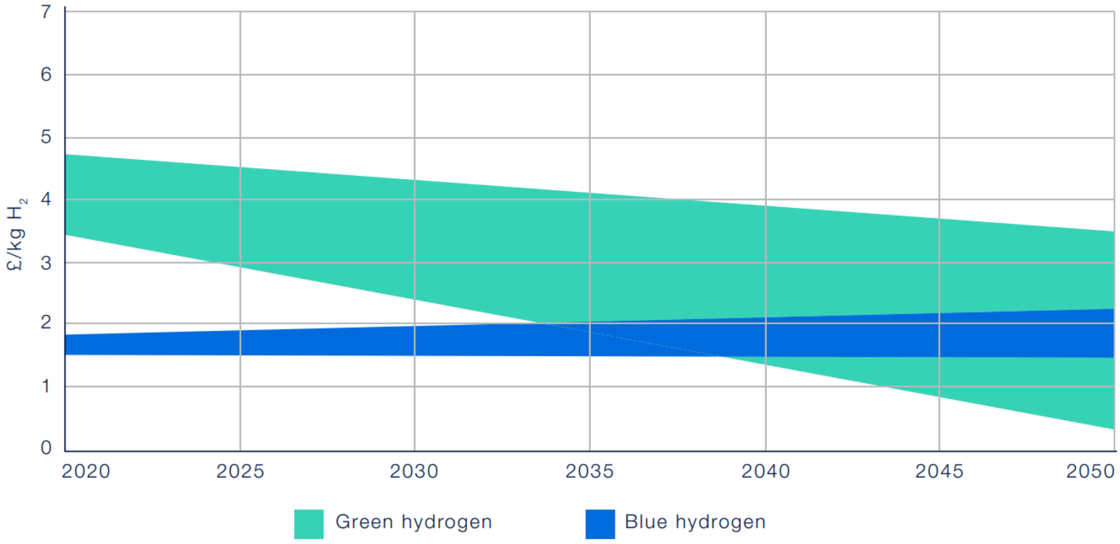

Figure 28- cost estimates of blue and green hydrogen prodction costs to 2020 compiled from vaious sources by Scottish Government[49].

At present the total costs of green hydrogen are much higher compared to blue hydrogen but the potential for cost reduction for both electrolysis from renewables is significant though highly uncertain. Analysis by Scottish Government (Figure 28) is based on a much wider range of cost estimates for green hydrogen compared with blue hydrogen, though generally the costs for green hydrogen are expected to reduce while for blue hydrogen they are expected to increase. Hydrogen production support policy will potentially play a key role in driving down capex costs for electrolysers, as it has done so for offshore wind.

How wholesale gas prices evolve in coming years will be important for how blue hydrogen's variable costs vary relative to green hydrogen. With global gas prices depending on supply and demand, key factors on the supply-side are discovery of new economically exploitable gas fields and availability of economic transport or pipelines to transport gas from these fields to places of demand. On the demand-side, factors include upturns or downturns in economic activity but will also include switching from oil to gas or from gas to electricity, which will be driven by jurisdictions' carbon policies.

Development of the power system and power prices will be extremely important factors impacting the economics of green hydrogen production and this is covered in more detail in the next section.

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[49] Scottish Hydrogen Assessment, Scottish Government, 2020- https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2020/12/scottish-hydrogen-assessment-report/documents/scottish-hydrogen-assessment/scottish-hydrogen-assessment/govscot%3Adocument/scottish-hydrogen-assessment.pdf

	Blue hydrogen	**Green hydrogen**
Infrastructure	Significant advantages from re-using existing gas network infrastructure to transport feed energy & sequester carbon dioxide. SMR infrastructure is conventional technology & carbon capture relatively simple (e.g. versus post combustion power plant CCUS).	Requires renewable generation (RES) &/or distribution and transmission network infrastructure as well as electrolysers – this is effectively incremental infrastructure to support the incremental power demand required to produce hydrogen
Total costs	Currently significantly lower than green hydrogen (helped by lower infrastructure footprint), but with less potential for cost declines and a residual carbon footprint that needs to be cleaned e.g. via purchasing carbon EUAs.	Currently high, but with large potential for cost declines as electrolyser capex falls with scaling. Access to low-cost power is also a key cost driver.
Variable costs	Directly linked to market price for natural gas + processing costs for SMR and CCUS. Likely to be significantly lower than average green hydrogen variable costs across at least a 10-15 year horizon.	Directly linked to power market prices in most cases, given strong advantages of connecting electrolysers to the grid (e.g. to access top up power & additional revenue streams).
Key issues	Limited potential to reduce costs over time. Cost effective access to sequestration infrastructure e.g. depleted gas fields. Dealing with residual carbon footprint.	Renewable resource constraints. Power network constraints. Electrolyser capex decline rates. Prevalence of low market power prices to support utilisation rates high enough to earn a return on capital.

Table 3- Comparison of supply chain features for producing green and blue hydrogen, TIMERA Energy https://timera-energy.com/5-factors-driving-hydrogen-investment/

Power system development and market prices

As summarised in Table 3 above, the economics of green hydrogen production will be strongly influenced by power prices. The CCC in 2018[50] estimated that electricity prices could make up around 85% of the levelised cost of hydrogen produced by electrolysers. Figure 29 shows the resulting impact that changes in power prices could have on the cost of electrolysed hydrogen.

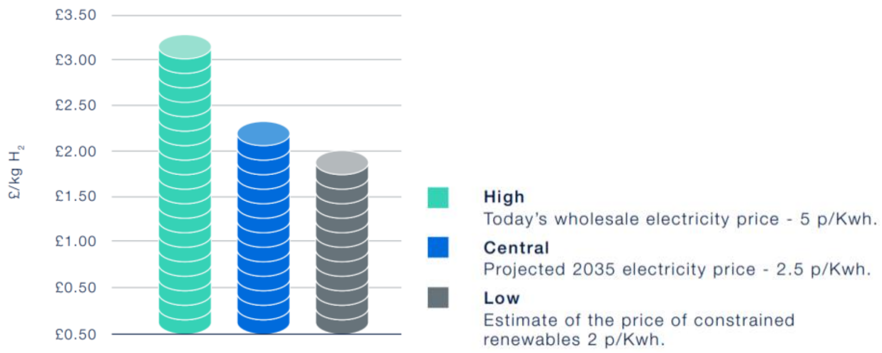

Figure 29- Impacts of electricity price (average) on hydrogen production costs in 2035)[51]

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[50] Hydrogen in a low carbon economy, CCC, 2018

[51] Scottish Hydrogen Assessment, Scottish Government, 2020- https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2020/12/scottish-hydrogen-assessment-report/documents/scottish-hydrogen-assessment/scottish-hydrogen-assessment/govscot%3Adocument/scottish-hydrogen-assessment.pdf

Electrolysers will not only be affected by the average electricity price, but also be affected by the frequency of time periods where hydrogen is low cost. Figure 30 shows how the levelised cost of electrolysed hydrogen production varies with the load factor of the asset.

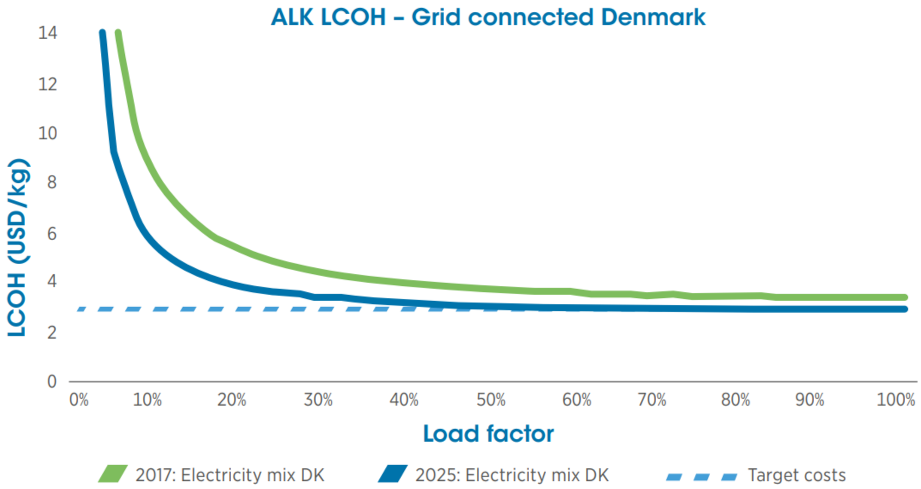

Figure 30- Hydrogen supply costs as a function of electrolyser load, 'Hydrogen: a renewable energy perspective', IRENA, 2019 based on 'Hydrogen from Renewable Power, IRENA, 2018.

As such, electrolyser business models will be dependent on the availability of low-cost power based on renewable generation, largely offshore wind. By contrast, the business models of hydrogen-fuelled turbines will depend on prices being able to reflect conditions of resource scarcity and the system's need for flexibility or other system services.

The power system is currently undergoing a major transformation as it is being adapted to cope with very large shares of variable renewables, involving extensive change to market design, policies, and regulations. Increasing the flexibility of the GB power system is a priority for the UK Government, which released an updated Smart Systems and Flexibility Plan in July 2021[52].

The UK Government is currently considering wider changes to the GB power market[53] and in its 6th carbon budget report, the CCC urged the Government to come forward with proposals for long-term market design by 2025[54]. Of the various considerations, the following will be particularly important for hydrogen:

- How to develop more granular locational signals, to optimise assets across the network and incentivise consumers to use technology to manage their energy demand, and whether to seek these signals through further changes to the network charging regime and the continued development of local flexibility markets, or a more fundamental shift to regional or locational pricing[55]. This could strongly influence where electrolysers, hydrogen turbines and new renewable generation plant are built and how they operate. Network congestion could restrict the scaling of hydrogen and so efficient siting of energy resources is crucially important.
- How to harness the benefits of closer to real-time signals in the wholesale market, including shorter gate closure and settlement periods, so that a broader range of actions can be taken

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[52] Smart Systems and Flexibility Plan
[53] Call for Evidence, Smart Systems and Flexibility Plan
[54] The 6th Carbon Budget: Electricity Generation, 2020, https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Electricity-generation.pdf
[55] Smart Systems and Flexibility Plan 2021, page 18

to help manage the system.[56] National Grid is also opening up the markets for which it is responsible (i.e. ancillary services, balancing mechanism, capacity market) to a much wider range of resources. This could provide additional revenue opportunities for hydrogen but will also mean strong competition between all energy resources, including demand versus supply.

- How to ensure long-term investment signals are provided to build the infrastructure we need to meet our low-carbon objectives and maintain security of supply, and whether existing schemes and market signals are sufficient or need to be adapted.[57] Hydrogen storage and hydrogen turbines are expected to play an important role in providing reliability to the power system, particularly in times when the availability of generation from variable renewables is limited for an extended period of time. How the design of the short-term electricity markets and capacity market are evolved will be particularly important for hydrogen.

Modelling of the GB power system – for example, by ESC, Baringa, CCC, National Grid - sees a major role for variable renewables in all scenarios. The exact share of variable renewables depends on cost reductions that can be achieved for the competing technologies such as advanced nuclear or gas combined with CCUS. The share of variable renewables will also impact how much system flexibility is required and cost reductions for flexible nuclear or gas combined with CCUS as well as extent of activation of demand-side flexibility will also impact the competitiveness of hydrogen in providing flexibility to the power system.

Electricity prices in the spot markets (i.e. day-ahead and intraday) will be impacted by a number of factors including:

- supply and demand, which will be influenced by policies (e.g. demand reduction and energy efficiency; electrification of demand; procurement of low carbon generation).
- the extent of interconnection and trading arrangements in place with neighbouring countries and how power markets in neighbouring countries develop.
- whether/how network constraints are incorporated in energy prices.
- internalising externalities, particularly for carbon.
- the existence of price distortions (e.g. through schemes that provide compensation outside of the wholesale markets, such as CfDs or the Capacity Market).
- the amount of flexibility in the system.

National Action point: Ensure system value is more accurately reflected in energy price signals that are granular by time and location.

Local Action point: build the business model for projects to be resilient to potential future changes in electricity market design and policy.

While spot prices might be expected to become more granular and volatile with growth in variable renewables and improvements in market design, increasing flexibility will respond to this, driving towards new price equilibria and reducing volatility.

At present, spot market prices are distorted by the presence of out-of-market compensation, particularly through the CfD and Capacity Market schemes[58]. This, alongside other factors, impacts investor confidence in long term price signals. Reforms to market design are therefore necessary to improve the quality of price signals in parallel with reforms to the overarching policy framework to

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[56] Smart Systems and Flexibility Plan 2021, page 18

[57] Smart Systems and Flexibility Plan 2021, page 18

[58] For further information see : https://es.catapult.org.uk/reports/rethinking-electricity-markets-the-case-for-emr-2/

minimise distortions and to align with the objective of achieving better performing markets (as outlined in 'Rethinking Electricity Markets- EMR2.0')[59]. The July 2021 update of the Smart Systems Flexibility Plan[60] indicates such reforms are currently under consideration.

Design of Government support policy for hydrogen production

The development of support policy for hydrogen can benefit from the experience and learning that has resulted from developing and implementing renewables support policy. The latter evolved over the last decade, in response to the different stages of technologies' development and evolving market conditions as well as some trial and error. Best practice design principles have consequently emerged, in the UK and globally, such as incentivising competition (e.g. auctions) to drive down costs, procuring volumes of low carbon generation at the scale required to align with carbon reduction commitments, and reducing risk and the cost of capital through revenue stabilisation and long-term contracts with Government as the credible counterparty.

While the UK's CfD scheme has been extremely successful in driving down the costs of generation for renewable electricity generation technologies and scaling up investment, the supported technologies are starting to mature and distorting impacts (i.e. price cannibalisation) on the functioning of the electricity spot markets are increasingly noticeable. For example, in its recent Call for Evidence on Enabling a High Renewable Net Zero Electricity System, the Government sought evidence on how the CfD scheme could be adapted in order to minimise whole system costs as at present generators are shielded from price signals through the design of the contracts, consequently resulting in inefficient location of generation and distorted bidding behaviour in the electricity spot markets. It is clear, based on questions raised in the CFE, that Government is considering alternative designs.

Support policy for hydrogen will be evolved as the technologies mature and as market conditions change. Government will design support with the objective of commercialising and scaling up investment in hydrogen-based technologies at least-cost to consumers and taxpayers, and whole system impacts, and interactions are more likely to be given closer attention in policymaking in future. The Government's commissioned analysis[61] exploring potential business models for hydrogen and possible support mechanisms, indicates the objectives that the Government considers important in establishing hydrogen support (see Table 4). The final objective in Table 4 below, relating to compatibility with a path to a subsidy free world, indicates the intention that support will be temporary and may evolve over time. Details of the current state of play on developing support mechanisms are set out in the next section.

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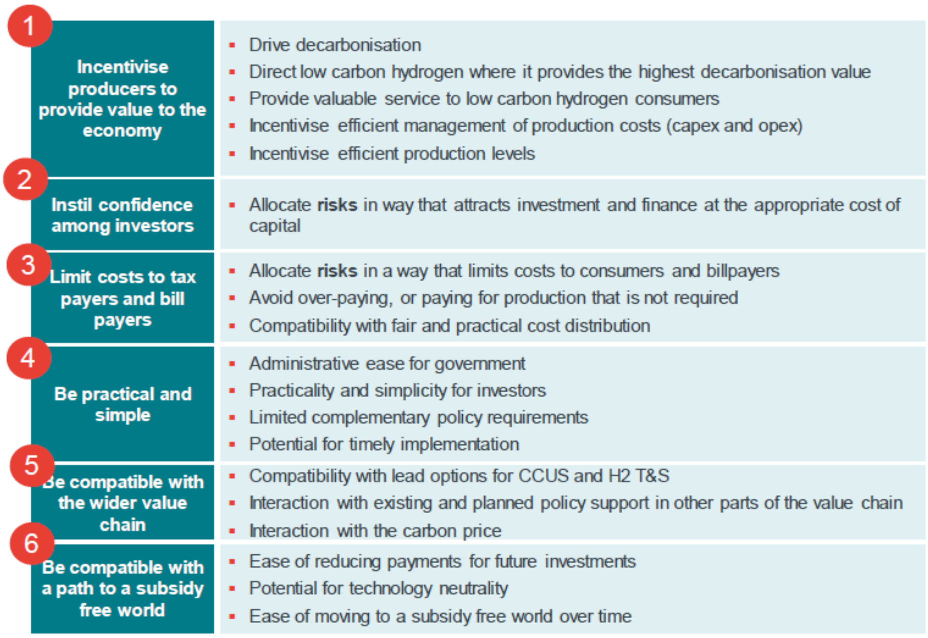
[59] https://es.catapult.org.uk/reports/rethinking-electricity-markets-the-case-for-emr-2/

[60] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1003778/smart-systems-and-flexibility-plan-2021.pdf

[61] https://www.gov.uk/government/publications/business-models-for-low-carbon-hydrogen-production



1	**Incentivise producers to provide value to the economy**	▪ Drive decarbonisation ▪ Direct low carbon hydrogen where it provides the highest decarbonisation value ▪ Provide valuable service to low carbon hydrogen consumers ▪ Incentivise efficient management of production costs (capex and opex) ▪ Incentivise efficient production levels
2	**Instil confidence among investors**	▪ Allocate **risks** in way that attracts investment and finance at the appropriate cost of capital
3	**Limit costs to tax payers and bill payers**	▪ Allocate **risks** in a way that limits costs to consumers and billpayers ▪ Avoid over-paying, or paying for production that is not required ▪ Compatibility with fair and practical cost distribution
4	**Be practical and simple**	▪ Administrative ease for government ▪ Practicality and simplicity for investors ▪ Limited complementary policy requirements ▪ Potential for timely implementation
5	**Be compatible with the wider value chain**	▪ Compatibility with lead options for CCUS and H2 T&S ▪ Interaction with existing and planned policy support in other parts of the value chain ▪ Interaction with the carbon price
6	**Be compatible with a path to a subsidy free world**	▪ Ease of reducing payments for future investments ▪ Potential for technology neutrality ▪ Ease of moving to a subsidy free world over time

Table 4 - Objectives for Government while establishing hydrogen support ('Business Models for Low Carbon Hydrogen Production', Frontier Economics, 2020)[62]

Requirements of end users and strength of demand

Given currently unfavourable economics, the demand for low carbon hydrogen in Milford Haven will need to be driven by policies. The development of policies to support hydrogen production and use are in the early stages and a national strategy for hydrogen has yet to be released. While hydrogen is not yet competitive in many areas, much is expected to change over time for different applications. Figure 31 shows the current competitiveness of hydrogen applications compared to low carbon and traditional alternatives and Figure 32 shows projections for when hydrogen could potentially become competitive in different applications.

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[62] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910382/Business_models_for_low_carbon_hydrogen_production.pdf

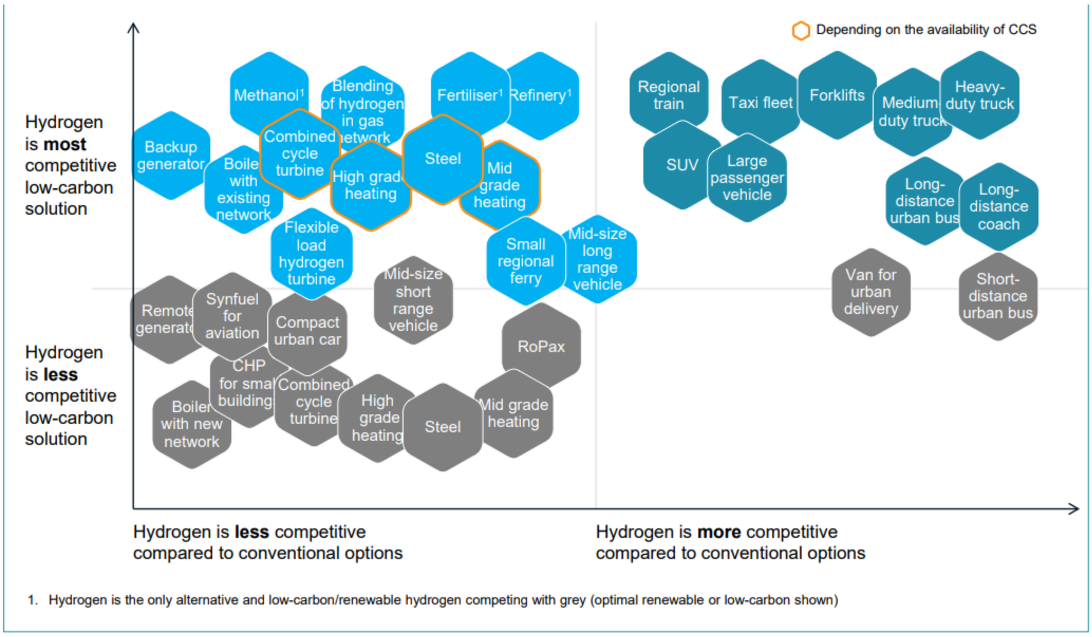

Figure 31 - Competitiveness of hydrogen applications versus low-carbon and conventional alternatives ('Path to hydrogen competitiveness', Hydrogen Council, 2020)[63]

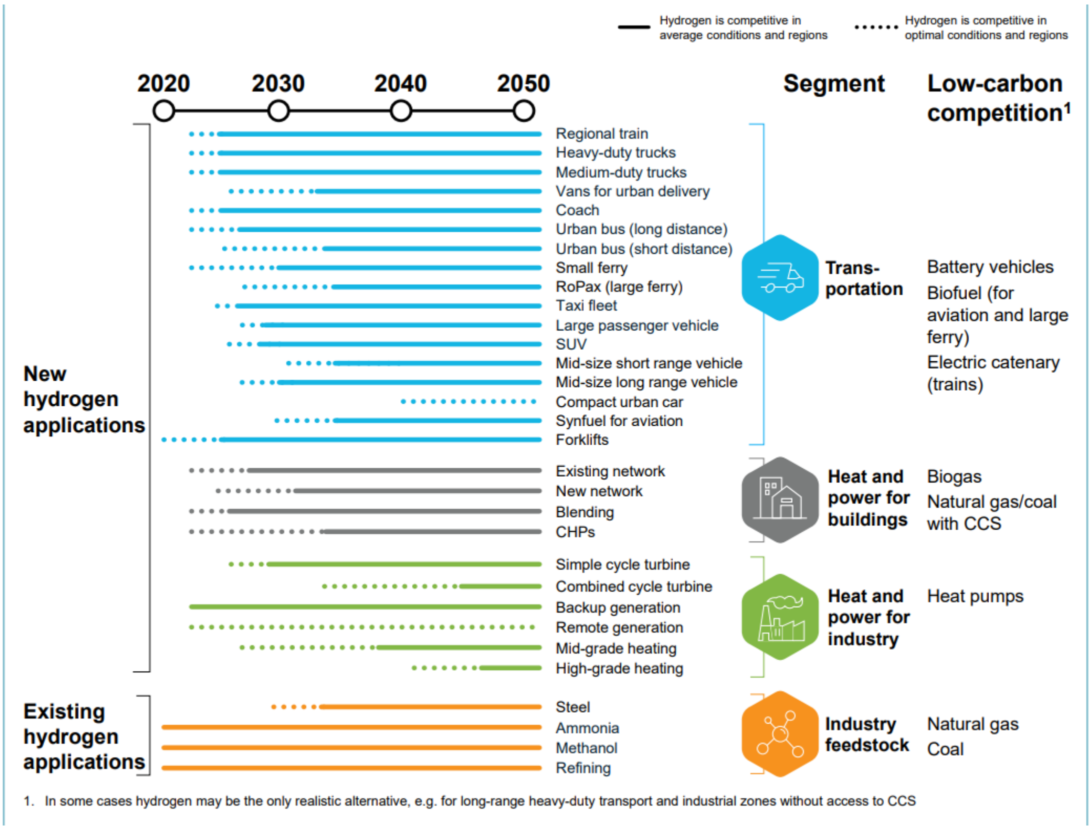

Figure 32 - cost competitiveness trajectories of hydrogen appliations ('Path to hydrogen competitiveness', Hydrogen Council, 2020)64

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[63] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

[64] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

In the early stages of developing the hydrogen system, end user requirements will strongly shape hydrogen deployment and supply chains. Initially, support policy will focus on where decarbonisation value is highest, such as high value industrial processes, heavy transport, power peaking services and long-term storage for the power system and will likely need to be technology specific. Particularly important to such high value processes will be the verification of purity and lifecycle carbon content through metering and certification.

The design of contracts between producers and users will define the risk sharing relationships and contract structures will be tailored to user's requirements in terms of price, volume, and other criteria. In the absence of spot markets, longer term contracting is likely to be important to limit risks to investors in production facilities. Government-led contracting is an option to transfer some risk away from investors, particularly demand risk,

As mentioned above, carbon policy will be crucial in driving the longer-term demand for low-carbon hydrogen across the energy system. For uses such as heating and transport, however, electric alternatives have a head-start thanks to the existence of technology-specific support policy for electric vehicles, heat pumps and associated infrastructure.

As demand policy is relatively nascent for hydrogen, this creates considerable demand risk for hydrogen producers. Indeed, transferring demand risk away from investors is one of nine priority considerations in developing hydrogen production business models, identified by Frontier Economics and strongly influences Government's preference for options based on contractual payments to producers or regulated returns instead of obligations on suppliers or end user subsidies[65].

Technology specific policies might therefore be pursued both upstream (e.g. electrolysers) and downstream (e.g. hydrogen boilers) in the early stages in order to reduce technology costs. Following cost reduction and as the technologies mature, however, it would be efficient to promote competition between low carbon alternatives by redesigning policy to target market outcomes (e.g. decarbonised fuel, decarbonised buildings). Societal preferences and consumer attitudes will also strongly influence technology adoption rates.

Development and availability of supporting infrastructure

The early development of hydrogen markets is likely to be strongly shaped around and by existing infrastructure due to strong interdependency, will be strongly affected by how network infrastructure – gas, electricity, CCUS - develops. Supporting infrastructure is not just about building dedicated hydrogen networks, it includes re-purposing the existing gas network and infrastructure to move, store, distribute and integrate hydrogen into the wider energy system. In a recent survey by DNV[66] of 1100 senior international professionals involved in the emerging hydrogen economy, respondents selected a lack of investment in hydrogen infrastructure (38%) as the joint-highest risk their organizations face in relation to hydrogen. For those currently not invested or involved in hydrogen, a lack of hydrogen infrastructure was the top reason why they focused elsewhere.

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[65] ('Business Models for Low Carbon Hydrogen Production', Frontier Economics, 2020) https://www.gov.uk/government/publications/business-models-for-low-carbon-hydrogen-production

[66] https://www.dnv.com/focus-areas/hydrogen/rising-to-the-challenge-of-a-hydrogen-economy.html

Different production methods for hydrogen have different infrastructure requirements and opportunities. Hydrogen produced by electrolysis requires connection to an electricity network or to be co-located with an electricity production facility. Energy prices and/or network charges should influence where electrolysers choose to locate and may encourage colocation with renewable generators and hydrogen storage facilities. Electrolysers' impact on electricity transmission investment is incremental.

For blue hydrogen, the existing gas network infrastructure can be re-used to transport and feed energy and sequester carbon dioxide – although it is also likely that new carbon dioxide transport and storage infrastructure will be needed to support CCUS. CCUS applied to SMR/ATR of biomass gasification is simpler compared with CCUS for post-combustion power generation based on coal or gas.

For distribution of hydrogen to users, containerised transport will be required for a considerable time until the scale of demand justifies developing dedicated hydrogen networks. In the nearer term, blending hydrogen with natural gas in the existing gas network can help drive demand for hydrogen without requiring additional investment or adaptation of gas consuming assets. This will require processes to be established to determine which areas can have hydrogen blending and to manage the blend level (see Section 5.6).

If a decision is taken to fully convert a natural gas network (that may already be carrying blended gas) to carry hydrogen, hydrogen demand in the region could potentially increase considerably. Hydrogen supply and demand would need to be ramped up and matched. New sources of hydrogen supply would be needed and gas-using assets in the region would need to be converted to or replaced with assets that can carry or use hydrogen. Possible approaches for dramatically increasingly the supply of hydrogen to facilitate a conversion process are set out in Table 5 below. If a decision is taken to fully convert a natural gas network (that may already be carrying blended gas) to carry hydrogen, hydrogen demand in the region could potentially increase considerably. Hydrogen supply and demand would need to be ramped up and matched. New sources of hydrogen supply would be needed and gas-using assets in the region would need to be converted to or replaced with assets that can carry or use hydrogen.

Possible approaches for securing hydrogen supply when a network area is converted to hydrogen	**Implications/ risks**
Have clear plans and forewarning that an area is going to be converted to hydrogen and allow the market to deliver investment in production and storage capacity.	Possibly high risk depending on economic incentives. A region could top up hydrogen supply with containerised transport or separating blended hydrogen from a national pipeline, but this would likely be very expensive.
A specific support mechanism to bring forwards investment.	This would be a large intervention in the market but would guarantee the required investment.
Ownership and investment by an independent system operator.	If concerns relating to market competition or resilience (e.g. ability to cope with demand shocks) exist, there may be a justifiable case for an independent system operator to own and operate the system.
Have generators and storage in the region which are exporting hydrogen to other regions, via container, private pipe or blending into a national pipeline, switch to supplying to the local network.	This could only work in specific locations but may work well. It is possible that a small amount of this will happen in most network areas when they are converted. Whether this will naturally occur within the market should be considered when assessing if there is a need for intervention in the region.
International imports	This is only possible for areas connected to a port which have the import facilities in place.
National/regional imports	Via a national transmission pipeline that connects to another market/network, which can export to the new network.
Networks are built which can take a variable blend of hydrogen (i.e. from 20%-100%).	This approach would enable hydrogen generation capacity to be steadily built up, with natural gas being supplied when there is a shortage of hydrogen. Assets would need to be able to take a variable blend. Some users may have limited tolerance for blend variability.

Table 5 - approaches for securing hydrogen supply to network areas converted to carry hydrogen

Technology/investment risk profiles

At the beginning of this section it was explained that different types of investor have different risk appetites. Investors and lenders conduct risk assessments of technologies and projects before going ahead with an investment. This is a challenging process for new innovative technologies as they are not familiar to lenders and because investments may involve integration of several technologies and network enablers. New assessment methods and tools are required. For example, HSBC and Imperial College have developed a two-stage method[67]:

1. Assessment of Technology Readiness Level (TRL) to determine the suitability of debt financing.
2. Assessment of the technology against six risk dimensions (POMLET) that shape lending decisions (see Table 6).

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[67] https://www.sustainablefinance.hsbc.com/carbon-transition/lending-to-low-carbon-technologies

Risk dimension	**Examples**
Policy risk	Change in government policies (fiscal, trade, monetary…); Change in price support/stabilisation; lack of regulation track record; lack of policy transparency or stability; lack of supporting infrastructure support; change in supranational support
Operational risk	Force majeure events; Loss from inadequate internal processes; internal or external fraud; employment practices, safety; Market manipulation, antitrust; Damage to assets due to national disasters/vandalism/terrorism; software failures
Market risk	Output price; Output volume; Business model risk; Lack of practicability of cashflows; Input prices; currency risk; Counterparty credit quality (construction/O&M/offtake); Change in revenue stacking options; Correlation to other assets; Shocks to expected life
Legal & Regulatory risk	Regulatory requirements; Obtaining permits and licenses; Compliance with new laws; Legal/litigation costs; Reputational risk; Litigation risk; Change in law; Land/property rights; Inadequate management of non-contractual rights; Failure to meet non-contractual obligations; Patents; Contract unenforceability
ESG risk	Community impact; Environmental damage; After-life environmental risk; Air/water/land pollution; Greenhouse gas emissions; Lack of management track record
Technical risk	Construction risk; Project complexity; Stability of technology; Efficiency of technology; Supporting infrastructure requirements; Lack of contractors track record; Lack of technology track record; Technology supply chain; Technology guarantee availability

Table 6 - Examples of POMLET risk dimensions (Source: HSBC and Imperial College)

The POMLET risk analysis was applied to CCUS in the UK, represented in Figure 33. Based on the evidence at the time (i.e. October 2019), the analysis indicated that mitigations to the current policy and market risk would be key to enabling commercial deployment of CCUS.

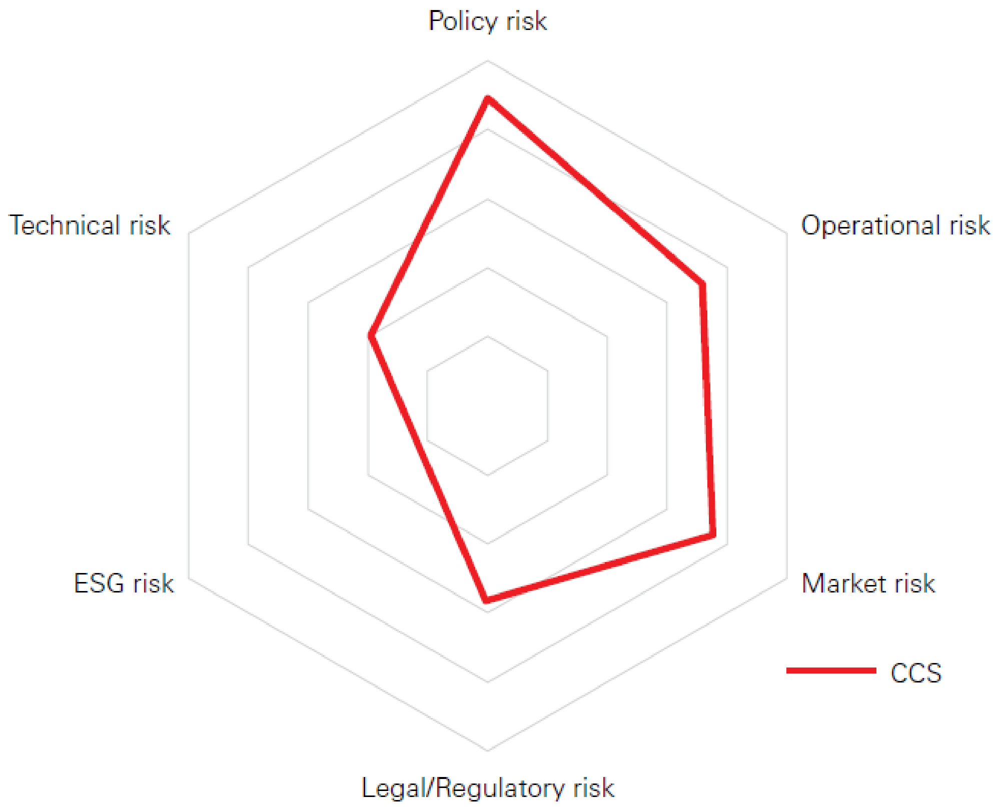

Figure 33 - CCUS risk spider (Source HSBC and Imperial college)

Investors and stakeholders in Milford Haven will need to be highly aware of the various investment-related risks associated with developing different hydrogen-based technologies that could be developed in the area. Deep assessment of the risks for individual technologies or integrated solutions using an appropriate methodology could help identify helpful interventions that could be taken at local level to complement national policy and help mitigate risks for investors. The risks should be monitored closely as they will change in time as conditions change and innovation can be fast-moving. Risk mitigation is crucial to reducing the cost of capital and attracting investment.

Action Point: Assess the TRL and conduct a detailed risk assessment (e.g. POMLET) for hydrogen-based technologies or solutions that could be developed in the Milford Haven area. Identify how risks could be mitigated, and actions that could be taken and by who. This could identify ways that local authorities could help mitigate risks and attract investment.

Regulatory Barriers

The system elements and markets discussed in the previous sections will require changes to current regulation to operate. The current regulations that cover the natural gas and electricity markets have evolved over time from those originally created for the publicly owned utilities of the 1960s[68]. They were written with just electricity and natural gas in mind, to regulate large generators supplying energy one way to consumers through networks. As such across the UK and Europe there are regulatory barriers to the use of hydrogen, ambiguity as to how it fits into arrangements and very little standardisation.

A lot of work has been done in recent years to alter these regulations to fit with the new more distributed and decentralised electricity system. However, less has been done to evolve the gas network regulations.

The project Hylaw "Hydrogen Law and removal of legal barriers to the deployment of fuel cells and hydrogen applications", 2018, completed a systematic review of the regulatory and legal barriers to the use and production of hydrogen in the UK and across Europe.[51] The findings are well presented with an interactive map to explore which system elements these barriers apply to.

These barriers need to be removed to enable timely investment in hydrogen assets and to reduce uncertainty in the markets.

National Action point: UK Government to systematically identify and remove regulatory barriers, as described above, to the development of low carbon hydrogen.

7.2.1 CURRENT STATE OF POLICY SUPPORT FOR HYDROGEN INVESTMENT

National Policy

The second point of the recently published 10 Point Plan introduced a raft of measures to drive the growth of low carbon hydrogen, including:

- A target of 5GW of hydrogen production capacity by 2030, with 1GW of this to be achieved by 2025.
- A £240 million net zero Hydrogen Fund.
- Commitment to publish Hydrogen Strategy and set out a revenue mechanism and hydrogen business models for driving private investment.
- Proposed network demonstration in Levenmouth area of Fife, to provide hydrogen to 300 homes over 4 years.
- Facilitating the scaling of hydrogen by establishing industrial 'superplaces' that will pull together offshore wind, CCUS, electrolysers, industrial processes, industrial heat, power, shipping, and trucking.
- By 2023 complete testing required to enable 20% blending of hydrogen into gas system.
- Hydrogen heating trials in local neighbourhood by 2023, for a large village by 2025 and potentially for a town by 2030.

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[68] http://www.dcode.org.uk/assets/images/P2%20Security%20of%20Supplies%20Open%20Letter.pdf

Other points of the 10 Point Plan will help drive investment and innovation for hydrogen, include:

- Point 4 – Accelerating the Shift to Zero Emission Vehicles: Investment of £20 million in 2021 for freight trials to pioneer hydrogen and other zero emission lorries; consult on a date for phasing out the sale of new diesel heavy goods vehicles (HGVs) that would be an important investment driver for hydrogen-based HGVs.
- Point 6 - Jet Zero and Green Ships: continued commitment to R&D such as £15m FlyZero 12-month study to develop zero emission aircraft that could enter into service by 2030, and R&D relating to infrastructure upgrades to airports for hydrogen aircrafts; consultation on Aviation Decarbonisation Strategy in 2021; a £15m Sustainable Aviation Fuels competition and establishment of a clearing house and certification scheme for new fuels, with possible fuels mandate starting in 2025.
- Point 7 – Greener Buildings: launch of a Heat and Buildings Strategy in 2021, which will include creating a market led incentive framework to drive growth in decarbonised heating with Government retaining optionality on hydrogen heating, an electrified heating system, or a mixture of both as it conducts pilots.
- Point 8 - Investing in CCUS: a commitment to establish CCUS in two industrial clusters by mid 2020s, and aim for four of these sites by 2030, capturing up to 10 Mt of carbon dioxide per year. These clusters or superplaces are to involve CCUS and hydrogen, with Wales being one of the areas identified alongside the North East, the Humber, the North West, and Scotland; £1 billion CCUS Infrastructure Fund; business models and revenue mechanisms for CCUS and hydrogen.
- Point 10 – Green Finance and Innovation: by 2022, start vessel trials in Orkney, work towards a hydrogen port in Tees Valley (£3m), and launch feasibility studies for several clean maritime clusters across the UK; £1bn net zero Innovation Portfolio for technologies' commercialisation to include hydrogen; £100m for Energy Storage and Flexibility innovation challenges, including long-term storage

Support for low-carbon hydrogen production expected shortly

The UK Government is set to launch a support mechanism for hydrogen producers in 2022[29] to help meet the target of 5GWs of hydrogen production capacity by 2030. A consultation on 'preferred' hydrogen business models is set to be released during 2021. This support policy could potentially be an extremely important driver of investment in Milford Haven, and it would be highly recommended to engage with the consultation process.

BEIS commissioned Frontier Economics to explore potential business models for low carbon hydrogen. The findings recommended supporting investment with either a contractual model with agreed terms for returns for investors, a regulatory model where returns are set by a regulating body or hybrid approach which takes elements of the two (see Figure 34 below).[69] For these models, key design features are recommended to be explored further:

1. Using a split structure in order to manage downside demand risk:
   - Under the split structure, separate support payments would be given to cover fixed and capital costs regardless of demand, but variable costs would only be covered where low

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[69] https://www.gov.uk/government/publications/business-models-for-low-carbon-hydrogen-production

    carbon hydrogen is being produced. This approach is less likely to over incentivise production and to lead to higher than necessary subsidy costs for taxpayers/billpayers.
    - Under an alternative backstop approach, the Government would act as counterparty to be a 'buyer of last resort' for low carbon hydrogen, to provide demand certainty for producers, as the market develops.

2. Choosing between a revenue stabilisation model (e.g. CfDs) or a premium to sales revenue:
    - Under a premium model, producers receive a subsidy on top of market revenue from the sale of low carbon hydrogen.
    - A revenue stabilisation model aims to provide a guaranteed return to producers by topping up the revenue received through sales in the market (valued at an agreed reference price) to an agreed level (the strike price).

3. Indexing support payments to the input fuel price, which places input price risk on consumers and may reduce cost of capital, to avoid placing excessive input cost risk on investors

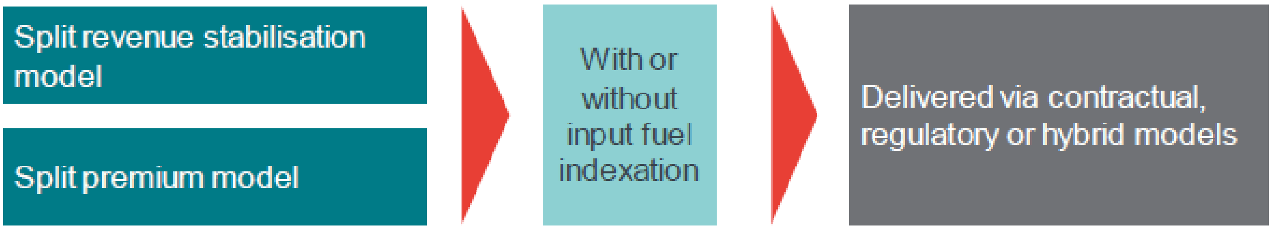

Figure 34 - Summary of business models for hydrogen to be explored further[70]

Business models to support CCUS have also been explored, including for application to hydrogen generation infusing SMR/ATR and biomass gasification. This workstream for CCUS started before the specific workstream for hydrogen production support, with a consultation having been released in July 2019 with emerging findings[71], a response issued in August 2020[72] and updated thinking having been released in December 2020[73] (which considered the work done by Frontier and the now established workstream on hydrogen support models). This states that CCUS business models will be consulted on in 2021.

The work conducted so far on the support mechanism has mainly outlined the high-level principles that will underpin its design and identifies the key challenges that the support mechanism needs to address. The recent update states that the Government currently prefers the contractual approach over the regulatory option for large scale hydrogen production using CCUS. It also states that 'different production technologies, project scales, and end uses have different technical and economic characteristics, and business model policy design needs to reflect these, i.e. there is

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[70] ('Business Models for Low Carbon Hydrogen Production', Frontier Economics, 2020) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910382/Business_models_for_low_carbon_hydrogen_production.pdf

[71] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/819648/ccus-business-models-consultation.pdf

[72] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/909706/CCUS-government-response-business-models.pdf

[73] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/946561/ccus-business-models-commercial-update.pdf

unlikely to be a 'one size fits all' approach'. The work moving forwards is also considering providing support for the distribution and storage of low carbon hydrogen in case this is needed for early projects.

During the early stages of developing hydrogen markets, R&D funding and pilots will continue to be important for increasing understanding of aspects relating to system development and network conversion. Some R&D projects are currently underway in the UK[74] but more will be needed.

Action Point: Consortium Members to engage with national policymaking and register with information processes (e.g. LCCC information portal; BEIS; DfT; Innovate UK) relating to support for hydrogen-related investment and activities. Collaborate and coordinate to identify potential projects and early investments that could be strategic for developing hydrogen in the region. Consider how to assess and describe the potential strategic benefits in making the case for investment support. Also consider options to involve communities in investment opportunities.

Fuel obligation

The Renewable Transport Fuel Obligation (RTFO) is currently the only established funding stream in the UK for low carbon hydrogen. Very little hydrogen is currently used under the scheme; 306litres in Q1-Q3 of 2021[75], but this could grow with time. The RTFO requires transport fuel suppliers' sales to include 9.6% low emission fuels and 0.5% development fuels (rising to 2.8% by 2032), one of which is hydrogen, or suppliers must buy certificates signifying someone else has sold these fuels. Development fuels receive double the Renewable Transport Fuel Certificates to other fuels meaning they count twice towards meeting a supplier's obligation. The obligation applies to fuel supply for ': (i) road vehicles, and (ii) non-road mobile machinery (including inland waterway vessels which do not normally operate at sea), tractors, and recreational craft that do not normally operate at sea ' and since 2018 renewable aviation fuel is eligible for subsidy though there is no obligation on this sector. There are strong sustainability criteria for the low carbon hydrogen to be eligible.

Regional/local policy

Wales has released a draft hydrogen strategy for Wales[26]. This work was consulted on in early 2021 and is now being refined in line with the feedback, ahead of the agreed actions being taken by the Welsh Government. The strategy highlights several priorities for the use of H2 in Wales, which are shown in Figure 35 below. The Welsh Government has powers to create policy across a range of areas including planning, agriculture, land use, housing regulations, and local government[27]. The wider policy for reaching net zero in Wales is laid out in 'Prosperity for All: A low carbon Wales'[28].

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[74] Gas Goes Green, Britain's Hydrogen Network Plan, https://www.energynetworks.org/newsroom/what-you-need-to-know-about-britains-hydrogen-network-plan

[75] https://www.gov.uk/government/statistics/renewable-fuel-statistics-2020-fourth-provisional-report/renewable-fuel-statistics-2020-fourth-provisional-report

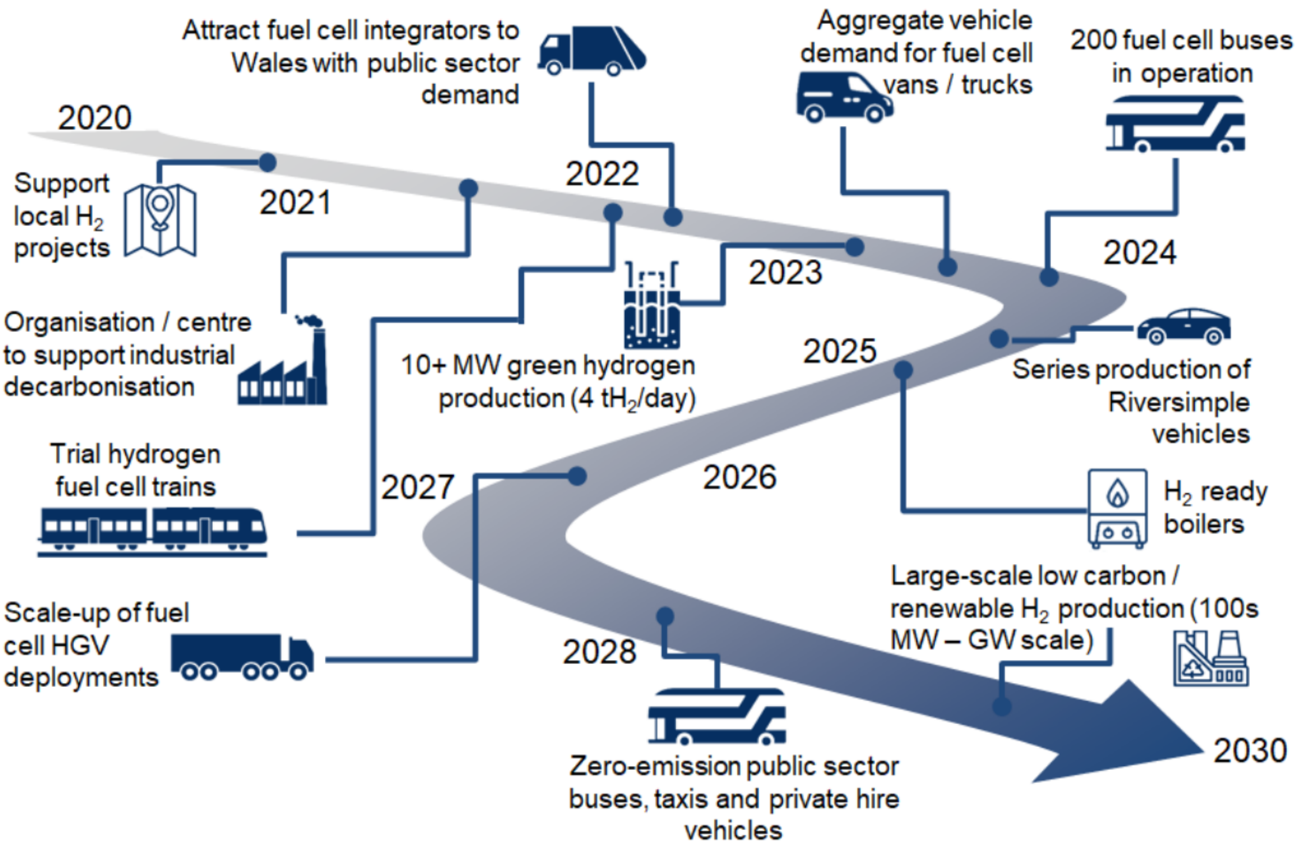

Figure 35 – Welsh Hydrogen Strategy high level Image[76]

Action Point: The consortia should follow and engage with the development of the Wales Hydrogen Strategy and track progress. Engage with the debate on devolution of powers to local level to develop local energy resources/systems for Net Zero[77].

Action Point: Milford Haven stakeholders should map and track the changing policy and regulatory landscape (local, regional, national, international) for hydrogen in order to effectively manage regulatory risk and to identify new opportunities.[78]

7.2.2 NETWORK INVESTMENT AND REGULATION

For the market to evolve to a small local market or to a large liquid market, networks must evolve, either in tandem with or leading investment. In parallel, to reach net zero, decisions must be made about the future of the natural gas grid. It must either be progressively decommissioned over a period of time or converted to carry low carbon gas. A regulatory process is not yet established for undertaking decisions on either building new hydrogen networks or converting natural gas networks to carry hydrogen, to deliver the associated investment and to recover these costs. For optimal choices to be made about hydrogen infrastructure, a process must be established which can undertake the following (based on 'Network Regulation for Net Zero, Frontier Economics, 2021):

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[76] See https://gov.wales/sites/default/files/consultations/2021-01/hydrogen-in-wales-consultation.pdf
[77] See https://es.catapult.org.uk/news/smart-local-energy-systems-finance-and-investment/
[78] See https://es.catapult.org.uk/news/the-policy-and-regulatory-context-for-new-local-energy-markets/

- Cost benefit analyses- the process should be able to assess the costs of different approaches and their relative benefits. This will require information on what is possible in different areas and the level of disruption each would cause. This should consider future costs for a region and the distortions within the assessment caused by short term Government policy.
- Consider local preferences- the specific interests of a local area must be included so that a resulting plan is deliverable as considered in ESC's work on Local Area Energy Planning (LAEP).
- Look across vectors- this process must holistically consider the different options for a region looking at both the cost of gas/hydrogen networks and electricity system infrastructure.
- Consider uncertainty- this process may need to invest ahead of need and make decisions in the face of considerable uncertainty. This process must enable this uncertainty to be understood and have an approach for managing it so that a net zero energy system can be delivered.
- Coordinate network investment locally and nationally- local network choices need to consider regional and national decisions so that a coherent system is developed. For example, a national transmission pipeline to a region may change the approach of a local area.

National Action Point: A process must be established for assessing whether and how to adapt or build networks for hydrogen. This process should have a local and national component and should link to wider whole systems strategic planning processes (e.g. National Grid system planning; Local Area Energy Planning (LAEP)).

Action Point: The MH:EK consortia to conduct the process discussed above in the region. This could build on the work done in the LEAR (Local Energy Asset Representation) delivered for the MH:EK consortia.

If the decision is made to convert an area to hydrogen or for a new hydrogen network to be built, there must be a process for recovering the costs of this investment. In the UK, Ofgem[79] recently reformed electricity network charges such that tariffs are now based on two components: 1) forward looking charges and 2) recovering sunk costs. The forward-looking component looks to drive efficiency, by exposing a user to the costs that they impose on the network through their behaviour. Tariffs are typically designed to target the capacity used by time and location. The second part looks to recover the remaining costs that have already been spent on the network and therefore would not be recovered by the forward-looking charge alone. This component is therefore spread across consumers. The final design of the charging framework is shaped by a set of principles that typically involve multiple trade-offs.

In 'Gas Network Regulation for the Net Zero Transition', Frontier Economics considered how network costs for hydrogen networks could be recovered. They proposed that:

- While there is a small hydrogen customer base all costs i.e. conversion costs, should be recovered across a wide customer base such as all taxpayers or all energy users.
- Once the customer base has considerably grown, forward looking charges should apply to network users with residual costs still being spread across a large customer base.

The consultants also noted, that to avoid cross-subsidisation and distortions between tariffs for natural gas and hydrogen networks, there must be a robust process for assessing the value of

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[79] https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/network-charging-and-access-reform

natural gas assets at the time of conversion and transferring the value to the hydrogen Regulated Asset Bases (RAB).

There are challenges with recovering the costs of decommissioning existing natural gas assets as the consumer base using these assets declines. A framework for recovering these costs may need to be created that carefully considers cost allocation to strike the correct balance between fairness and efficiency.

National Action Point: Government should develop a process for recovering the costs of hydrogen network infrastructure and, if required, decommissioning of natural gas network infrastructure.

Frontier Economics[80] explored the need for regulation of private pipes, which are funded through Government support schemes. They found there is little regulation needed for this type of investment, other than in the following ways:

- Third party access - as the market develops, there may be other users who wish to connect to these pipelines. The owners of the infrastructure may deny access due to their own interests in the region (possibly as vertically integrated companies). Allowing access is likely to be beneficial overall, rather than another pipeline being built. To enable this efficient use of infrastructure and considering that these pipelines will likely be built with the help of Government subsidies, a provision that projects must provide non-discriminatory access to third parties could be worked into the projects’ support contracts. It is arguable that general competition law would already require owners to provide non-discriminatory access, but experience in a number of infrastructure contexts suggests that some form of ex ante regulation / contractual obligation may provide helpful clarity.
- Revenue sharing - to avoid windfall profits for these projects, when/if other users wish to connect to their pipelines, contracts could also include mechanisms for sharing third party access revenues. These may be needed because there is such high uncertainty about these future revenues that investors are unlikely to count them within their initial business models.
- Whole system coordination - there may be a need for a process, for Government supported projects, to assess how network investments could be built to support future system development. The process could recommend that pipes are built in strategic locations or at a large capacity.

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[80] Gas Network Regulation for the Net Zero Transition, 2020’ (this report was commissioned by ESC and is not yet published).

7.2.3 SHORT-TERM POLICY SUPPORT OPPORTUNITIES FOR MILFORD HAVEN

Considering the above-mentioned Government targets and revenue support, we have populated the table below to indicate the system elements that may be investable in the next 5 years and whether this funding would be better suited for Pembrokeshire than other regions.

Opportunity for investment in the next 5 years (UK)	Suitability for Pembrokeshire
Green- likely	Green- better for Pembrokeshire than other regions
Orange- unclear	Orange- same chance as other regions
Red- unlikely	Red- Pembrokeshire has less chance than other regions
Grey – Unclear	

Table 7- key for Table 8 and Table 9

System Element		Opportunity for investment in the next 5 years (UK)	Suitability for Pembrokeshire	Key targets or policies
Production	Electrolysis	🟩	🟩 Likely to be H2 demand in the region which won't be met by SMR/ATR with CCUS.	Production support mechanism to be introduced.
	Biomass gasification with CCUS	🟧	🟧 Interest in locating with offshore wind generators.	Production support mechanism to be introduced.
	Nuclear	🟧	🟥	£385 million in an Advanced Nuclear Fund
	SMR/ATR with CCUS	🟩	🟧 See biomass gasification with CCUS.	Production support mechanism to be introduced.
	Pyrolysis	🟥	🟧	£1 billion to 2025 on operational CCUS in four industrial clusters.
Imports/exports	National (inter-regional)	🟥 5+ years for development other than containerised transport.	🟩	
		🟥 5+ years for development	🟩	
	International			

Table 8- opportunity for investment in system production and import/export elements in the next 5 years and the suitability for Pembrokeshire

		Opportunity for investment in the next 5 years (UK)	Suitability for Pembrokeshire	Key targets or policies
Use:		🟩	Unclear	£250 million clean steel fund Climate Change Levy (CCL)- applied to large industrial emitters, reduced through climate change agreements (CCA). The Welsh hydrogen strategy- establish industrial decarbonisation organisation/centre in 2021.
Use: Mobility	Cars and Vans	🟧	🟧	2030 end sale of petrol and diesel cars EV chargepoint support schemes Bursary for EVs and H2 vehicles. EU carbon portfolio emission standards for vehicle manufacturers.
	HGVs	🟩 Innovation trial funding	🟧	Target- reduce HGV emissions by 15%, 2025 (2015 baseline). £20 million in zero emission freight trials Gov to consult on phase out of new high carbon HGVs.
	Buses	🟩	🟧	Aim for 4000 more zero emission buses. Funding stream for low emission buses. The Welsh H2 strategy aims for 200 fuel cell buses by 2024.
	Trains	🟩 Innovation funding	Unclear	Target- no diesel passenger trains by 2040. Trials for hydrogen powered trains. The Welsh H2 strategy- trial hydrogen fuel cell trains by 2022.
	Planes	🟥	🟧	Government to consult on a Sustainable Aviation Fuel mandate possibly (2025). Aviation decarbonisation strategy (2021) £15M on low carbon 'FlyZero' program and sustainable aviation fuels.
	Shipping	🟩	🟩	Clean Maritime Plan details the UK approach for decarbonising shipping.[37] £20 million investment into Clean Maritime Demonstration Programme for feasibility studies including £3 million for development of a hydrogen port in Teesside.
	Forklifts	🟩	🟧	The Hydrogen Council found, under the right circumstances, hydrogen may already be viable.[38]
	Off-road machinery	🟩 Innovation funding	🟧	£40 million for R&D in low carbon construction, mining, and other off-road heavy vehicles.
Use: Buildings	Hydrogen boilers	🟧	🟧	Heat and Buildings Strategy (2021). 10-point plan trial targets.
	Hydrogen fuel cells	Unclear	🟧	
	Hybrid heat pumps	🟧	🟧	
	Heat networks (using hydrogen fuel cells)	🟧 Funding for heat networks, little incentive to use H2.	🟧	£122 million for Heat Network Transformation Programme. Existing Heat Networks Investment Project- £320million (ends in 2022 but with plans to be replaced).
Use:	CCGT retrofitted to use H2	🟥	🟧	CCC 6th carbon budget sees zero carbon electricity production by 2035. Policy will likely be drafted to drive this.
Use: storage	Local storage	🟩	🟧	£100 million for Energy Storage and Flexibility innovation.
	National storage	🟥 Potential for hydrogen storage to support the electricity system.	🟥	

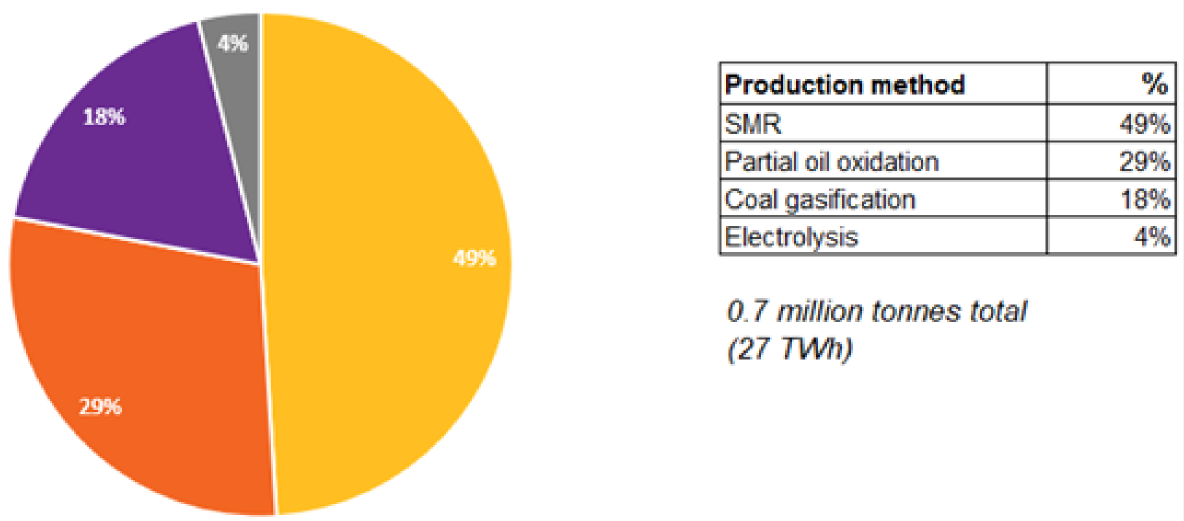
Table 9- opportunity for investment in hydrogen use system elements in the next 5 years and the suitability for Pembrokeshire

7.3 POTENTIAL EVOLUTION OF HYDROGEN MARKETS AND TRADING

This section considers how today's hydrogen markets might evolve over time and how trading of hydrogen products and services could develop at local/regional and national levels. The section includes references to steps that could be taken in the short-term before a dedicated hydrogen network would be created. It also covers the options of establishing a local hydrogen market based on a dedicated, isolated hydrogen network and at the other end of the spectrum, the set up a national trading exchange for hydrogen based on a national gas network fully converted to hydrogen. The final sub-section considers the potential role and evolution of network regulation.

7.3.1 CURRENT HYDROGEN MARKETS

The UK's current hydrogen markets are limited and largely serve industrial production and consumption of hydrogen. Two companies - Ari Liquide and Air Products - control over 90% of the merchant hydrogen market². In 2020, 0.7 million tonnes (~27 TWh) of hydrogen were produced in the UK with around half of hydrogen production being produced by SMR while electrolysis accounted for just 4% of production.



Production method	%
SMR	49%
Partial oil oxidation	29%
Coal gasification	18%
Electrolysis	4%

0.7 million tonnes total (27 TWh)

Figure 36- Current UK hydrogen production methods, National Grid, Future Energy Scenarios, 2020[81]

7.3.2 EARLY STAGE OF A HYDROGEN MARKET

While the hydrogen market is expected to grow in coming years, it will likely remain relatively small for much of the next decade. During this initial stage of development, it can be expected the market will have a high level of asset specificity, where an asset is specifically useful to a limited number of parties. This means that to invest in a production asset, producers need some assurance that the limited number of potential clients will buy hydrogen. On the other side the buyer needs some assurance that if they convert to using hydrogen, there will be someone to sell it at a

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[81] https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents

reasonable price. As such, asset specificity often leads to long term contracts between participants to enable investment and operation.

In the early stages of developing the low carbon hydrogen market, given the latter is considerably more costly compared to carbon-intense hydrogen, government support is needed, and details of a support mechanism are expected to be released shortly. For low carbon hydrogen, this could mean that long term contracts with Government as counterparty are established, reducing risk and cost of capital for investors (see Section 7.2.1).

During the first decade or so of the market's development, it is unlikely that a dedicated hydrogen network would be developed at national scale. Hydrogen will likely be transported via containerised transport and private pipes. The location of the assets, length of the contract and whose responsibility it is to provide the distribution will drive whether a private pipe or containerised transport is chosen. It is more likely to be a private pipe for a long-life well-used connection supported by a long-term contract (or even vertical integration) and the option of containerised transport for small volumes and if assets cannot be located near each other. Within the transitioning phase there may be opportunities for containerised transport to support network security and arbitrage between hydrogen in different areas.

7.3.3 INITIAL STEPS TO ENCOURAGE AND ENABLE TRADING

Trading is valuable as it enables parties to exchange surpluses and shortages, allowing them to serve more customers and market segments while reducing the need for storage and additional capacity for the market as a whole. From a participant's perspective the reasons for trading are:

- Physical purchase/sale- simply buying or selling natural gas linked to your projected production or use.
- Financial Hedge- these are used to 'lock-in' a projected profit margin.
- Risk management of portfolio- stakeholders spread out the procurement of their contracts across different time periods. They manage their portfolio to ensure they are not caught out by high prices in the future but also that they have not secured much higher contract prices than they would pay have had they waited.
- Portfolio optimisation- intelligently managing a portfolio to try and minimise risk and maximise financial returns.
- Speculation and profit- attempting to make money through trading contracts ahead of delivery based on their changing value.

The value of trading increases when there are more market participants and greater diversity in their specific production and demand profiles. Experience of market design and operation from around the world shows that short-term markets (i.e. spot markets) often help to achieve more efficient outcomes. Compared to bilateral contracting, trading in spot markets is more transparent, promotes competition and enables efficient price discovery. Trading in such markets is also anonymous, which reduces risk for participants, particularly small players. Due to the greater transparency and availability of trading data, market monitoring is also possible and plays an important role to prevent anti-competitive or sub-optimal market behaviour. It will take time for such an exchange to be established for hydrogen trading since it will only make sense when there are a wider range of buyers and sellers. Initially it is expected that trading will involve bilateral long-term contracting.

In 2020 for the Dutch Ministry, Ouden[82] conducted an initial exploration of the advantages of creating a hydrogen exchange and how this could be developed for the Netherlands (see Figure 37). This work found that hydrogen trading could be a catalyst to accelerate the physical development of the system. Establishment of a trading hub would take time given hydrogen markets are very immature at present and trading hydrogen products will only become worthwhile for participants once there are sufficient surpluses and shortages.

Ouden (2020) proposes that to help a low carbon hydrogen market develop, the following initial steps could be taken:

- Establish a Guarantee of Origin (GoO) certification system – this would provide transparency and value to consumers regarding the carbon intensity of the hydrogen they are purchasing.
- Create a market for hydrogen blending, potentially through a blending obligation - hydrogen blending could build a market for hydrogen within a shared network, where gas suppliers could trade hydrogen even if it is not delivered directly to their customers (similar to how suppliers can claim to supply renewable electricity). This is dependent on the right processes being in place to enable blending in a region (discussed in Section 5.6 and 6.1).
- Create a price index – a published price index could be established as part of the preparatory process leading up to the launch of a trading exchange, as was implemented for the natural gas markets previously. The price index would be based on quotes from companies active in purchasing and selling hydrogen. The quotes would be regularly produced and then, in accordance with rules, the exchange would convert the quotes into a price index that gets published. It would be necessary to differentiate between the price of high and low carbon hydrogen and Guarantees of Origin could be helpful to achieve this. In addition, separate markets may be needed for different purities.

The Netherlands is now considering in detail how to take forward some of Ouden's recommendations. Other economies are showing strong interest in hydrogen. Nine countries plus the European Union published hydrogen strategies or roadmaps in 2020 and early 2021 for hydrogen, with nearly twice this total currently under development (as of June 2021)[83]. Also, EEX, the well-established trading company, have set up a Hydrogen Working Group to 'reflect on designing a sustainable wholesale trading market for hydrogen.'[84]

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[82] https://www.government.nl/binaries/government/documents/reports/2020/09/24/a-hydrogen-exchange-for-the-climate/A+Hydrogen+exchange+for+the+Climate.pdf

[83] https://iea.blob.core.windows.net/assets/5e6b3821-bb8f-4df4-a88b-e891cd8251e3/WorldEnergyInvestment2021.pdf

[84] https://www.eex.com/en/services/hydrogen

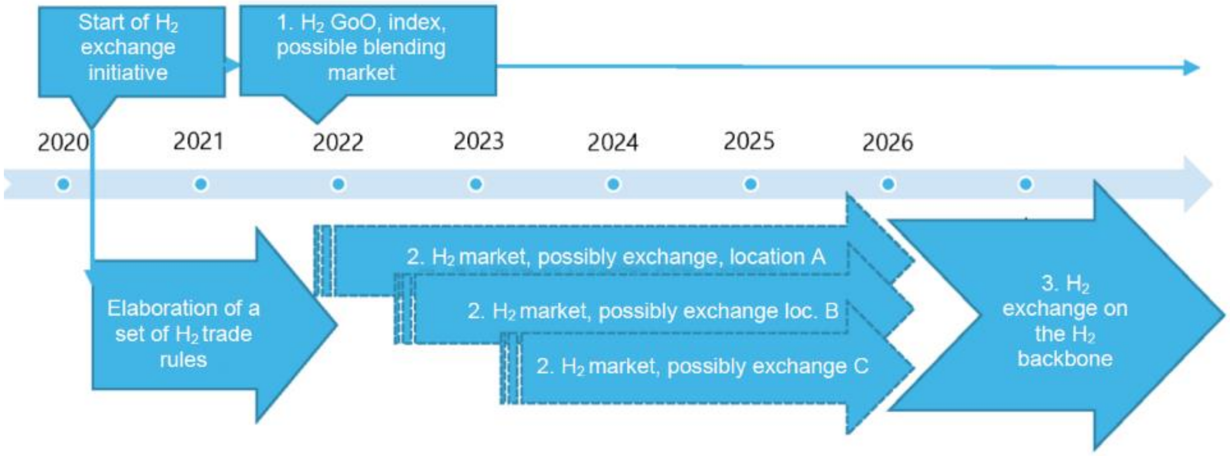

Figure 37- Proposed evolution of hydrogen markets for the Netherlands, Source: Ouden, 2020.

A GoO scheme for hydrogen could be similar to the EU's GoO[85] and UK's REGO[86] schemes used for renewables. While the GoO scheme for renewables was developed to provide transparency for consumers and support corporate social responsibility (CSR) reporting and claims, such schemes can also be used to support policy compliance and standardisation of trading products. Increasingly stringent regulation of carbon can be expected in coming years and robust monitoring, reporting and verification will be necessary with consistent application across sectors and energy vectors[87]. The CertifHy project[88] has reviewed existing GoO schemes with regards to extracting lessons learned that could be relevant in establishing an EU GoO scheme for hydrogen.

Contract terms on purity can be standardised to increase liquidity and the ease of transactions.[89] The prices in the different purity markets will be linked as:

- some users could buy hydrogen of any purity.
- participants could arbitrage between the markets with the differential in prices between the markets being the cost of purifying the hydrogen.

There will be different level of liquidity for different purities. Therefore, the different purity markets may evolve at different rates.

National Action Point: UK Government to develop a UK scheme to certify the carbon intensity of H2, such as a GoO scheme, or adopt EU or international approaches. Enable trading of certificates.

National Action Point: UK Government to strengthen robustness of carbon accounting and tracking across the UK's energy system as well as monitoring, reporting and verification (MRV) for carbon.

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[85] https://lexparency.org/eu/32009L0028/ART_15/

[86] https://www.ofgem.gov.uk/environmental-and-social-schemes/renewables-energy-guarantees-origin-rego

[87] as proposed in *'The case for an Economy-Wide Carbon Regulator, Danial Sturge, 2021'*[87]

[88] https://www.certifhy.eu/images/project/reports/D3.1_Review_of_GoO_systems-final.pdf

[89] https://www.government.nl/binaries/government/documents/reports/2020/09/24/a-hydrogen-exchange-for-the-climate/A+Hydrogen+exchange+for+the+Climate.pdf

Action Point: The consortia, Milford Haven stakeholders and the UK government should monitor international developments in the development of initial steps to facilitate hydrogen trading and actively engage in knowledge exchange.

7.3.4 ESTABLISHING A LOCAL HYDROGEN MARKET AND TRADING IN MILFORD HAVEN

Specific areas, such as those that host industrial clusters like Milford Haven, may develop a density of hydrogen producers and users and variety in demand and supply profiles ahead of the rest of the country. Once a region has sufficient producers and users to make a liquid market, then a local hydrogen market could be established in this region and the price in this area could be used as a price index for other areas. In these regions, participants would buy and sell hydrogen using a combination of long-term contracts and the market.

Hydrogen infrastructure development in Milford Haven could be the starting point for the development of a local/regional market that could in time join up with other markets and eventually create a virtual national hub. Once a virtual national hub is created, this would likely impact the local/regional hub at Milford Haven with migration of trading products and associated volumes to the national hub. The need for local trading, however, would remain in order to meet local energy needs.

The potential sources of hydrogen supply and demand in the region are being considered by Arup as part of the MH:EK project.

The project should consider in more detail whether and when a critical mass would likely be reached, how this could be accelerated (see previous section on investment) and how a local trading platform could develop to facilitate the local market. This platform could also link vector-switching actions and support the trading of other energy vector products and services. The specifics of a potential multi-vector local trading platform are set out and discussed in Section 8.1.

If areas of the natural gas network are converted to a pure H2 network, then suppliers will need to supply hydrogen to customers in these regions. As this will not be one large, connected network, suppliers will not be able to buy H2 for consumers on natural gas networks and vice versa or for consumers on a separate network with the same energy vector. This means retailers will need to balance their portfolios (supply and demand) within the different networks/areas. This essentially creates a form of locational pricing for hydrogen. In parallel, suppliers will likely need to adapt to optimise their portfolios locally for electricity depending on how market design and the design of network tariffs evolve. Such developments would significantly influence the development of business models and create new opportunities.

At this early stage of the market, the abuse of market power is potentially a high risk if small areas of natural gas networks are converted to carry hydrogen and the options to import hydrogen from competitive sources is limited. To mitigate this, prices can be regulated. Another approach, as recommended by Frontier Economics[90], would be to enable a single integrated monopoly gas provider to cover all elements of supply other than retail, bringing together all of the

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[90] http://www.frontier-economics.com/uk/en/news-and-articles/articles/article-i4332-market-and-regulatory-frameworks-for-a-low-carbon-gas-system/

uncompetitive elements of the system in a single organisation. This proposal is based on the reasoning that shocks to supply and demand are likely to be larger in relative terms on a smaller network and the security of supply risks to consumers likely to be significantly larger.

Various factors or options can help increase activity and liquidity. For example, the locating of production of hydrogen carriers, such as ammonia, within a region could add to the liquidity in the market and support market development. Blending is unlikely to be a high value activity but would facilitate scale-up of the market and increasing liquidity.

National Action Point: Establish arrangements to monitor competition on small hydrogen networks.

National Action Point: Create the regulatory framework for establishing a single integrated monopoly gas provider for early development of small networks where insufficient competition exists. Create a process for removing arrangements if competition increases sufficiently in region.

Action Point: Support the development of price indices- the consortia could raise this nationally as an action that needs to take place. More proactively, participants of the Milford Haven local market could actively publish their own cost estimates to support the establishment of price indices that are based on the needs of the local market but could be used in other areas.

Action Point: Support the establishment and trading of Guarantees of Origin (GoO). To take place, a method for measurement, recording and verification of hydrogen carbon intensity needs to be established. The consortia could advocate for the establishment or piloting of a national scheme.

Action Point: Engage with national policy-making process to establish blending in the region and advocate for a national place to trade blended hydrogen- this would require processes to be established to manage blending. This is discussed in Section 6.

Action Point: Develop local multi-vector trading platform based on current and future local needs.

Action Point: Consortia members and MH hydrogen stakeholders should monitor developments in other ports/regions and nationally so that local trading developments are compatible, adding value and align if appropriate though without unnecessarily curbing local ambition.

7.3.5 ESTABLISHING A NATIONAL TRADING EXCHANGE

If local hydrogen markets become more numerous and continue to grow, it could at some point be economically justifiable to join these local markets with a backbone pipeline. Trading would increase with the expansion of infrastructure and a national trading exchange could emerge, similar to the natural gas market today.[91] The trades would occur at a hypothetical point (in the same way natural gas in GB is traded at the National Balancing Point) such as a local hydrogen system or on a national hydrogen network (the potential development of a hydrogen network is discussed below).

A well-developed market would include trading of different products over different time periods enabling market participants to manage risk and optimise their portfolios. With shared hydrogen networks, the spot market would be accompanied with balancing markets as the system operator would need to procure resources for its balancing actions. To complement the spot markets, various forwards and futures markets could develop, so that participants can effectively manage risk. Table 10 illustrates that a wide range of products are sold in gas markets across Europe.

2019 Product evaluation based on absolute volumes*	OTC	CLEARING	WD DA	BOW W/E WDNW BOM	MA MONTHS	QUARTERS	SEASONS	YEARS (CAL + GAS)	EXCHANGE	(% SHARE)	BALANCING TRADES	SPOT PROMPT	FUTURES MONTHS	FUTURES QUARTERS	FUTURES SEASONS	FUTURES YEARS	OPTIONS MONTHS
TTF	Y	Y	Y	Y	Y	Y	Y	Y	ICE PGS CME	90 9 1	N	Y	Y	Y	Y	Y	Y
NBP	Y	Y	Y	Y	Y	Y	Y	Y	ICE PGS CME	99 0 1	Y	Y	Y	Y	Y	Y	Y
NCG	Y	Y	Y	Y	Y	Y	Y	Y	PGS ICE	98 2	N	Y	Y	Y	Y	Y	Y
GASPOOL	Y	Y	Y	Y	Y	Y	Y	Y	PGS ICE	99 1	N	Y	Y	Y	Y	Y	N
PSV	Y	Y	Y	Y	Y	Y	Y	Y	GME PGS ICE	78 14 8	Y	Y	Y	Y	Y	Y	N
TRF	Y	Y	Y	Y	Y	Y	Y	Y	PGS	100	N	Y	Y	Y	Y	Y	N
VTP	Y	Y	Y	Y	Y	Y	Y	Y	PGS	100	N	Y	Y	Y	Y	Y	N
ZEE	Y	Y	Y	Y	Y	Y	Y	Y	PGS	100	Y	Y	Y	Y	Y	Y	N
ZTP	Y	Y	Y	Y	Y	Y	Y	Y	PGS	100	N	Y	Y	Y	Y	Y	N
PVB	Y	Y	Y	Y	Y	Y	Y	Y	MIB PGS	96 4	N	Y	Y	Y	Y	Y	N
VOB	Y	Y	Y	Y	Y	Y	Y	Y	PGS	100	N	Y	Y	Y	Y	Y	N

*KEY: GREEN: =/>600TWh AMBER: <600tTWh BLUE: <250TWh RED: <50TWh GREEN: =/>500TWh AMBER: <500TWh BLUE= <100TWh RED: <30TWh

GREY: No volumes

Hubs column based on OTC + Exchange 'score'/56; OTC column based on 'score'/28; Exchange column based on 'score'/28

ICE=ICE/Endex PGS=PEGAS CME=CME Europe MIB=MIBGAS Y=AVAILABLE N=NOT AVAILABLE

Table 10 - Traded products at gas hubs in Europe (OIES, 2019)[92]

Illustratively, in the natural gas market today trading generally starts from 5 years in advance up until the spot market that covers the day-ahead and intraday time periods, with the majority of trading taking place in the period 6 months ahead of the spot market.

The dynamics of hydrogen markets, however, are expected to be different to gas markets. Given that decarbonisation will drive greater weather-dependency for hydrogen, the dynamics of

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[91] For a high-level description of the UK gas market see: https://es.catapult.org.uk/brochures/an-introductory-guide-to-the-gb-energy-industry-chapter-3-gas-market-structure-and-statistics/

[92] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/05/European-Traded-gas-hubs-the-supremacy-of-TTF.pdf

hydrogen markets can be expected to lie somewhere between electricity and gas. For electricity, which must be balanced in real-time, prices are relatively volatile, reflecting continuously varying consumption and production. Electricity prices also reflect today's reality of limited storage and demand response though this is set to change with improved market design and regulation. By comparison, the natural gas markets are much slower, largely because of the availability of relatively cheap storage in the system (e.g. linepack).

In a low-carbon future, when hydrogen production becomes more weather dependent (i.e. electrolysis) and if uses are more wide-ranging and potentially weather driven (i.e. heating either directly using boilers, or indirectly by using hydrogen to generate electricity to power electric heat pumps), then shortages and surpluses will become much more volatile and the need for storage and system services will grow. This will strengthen the need for markets and trading platforms. This may also strengthen the business case for different – less weather dependent - production technologies such as gasification or SMR with CCUS. International markets for hydrogen will have additional requirements to function effectively. The EU has started considering regulatory implications for cross-border trading of hydrogen. While the UK has left the EU, its trading relationship with the EU remains important and new arrangements have been agreed for energy.

A report commissioned by the EU Agency for the Cooperation of Regulators (ACER) identifies some key regulatory aspects that EU institutions would potentially drive forwards to facilitate establishment of a signal hydrogen market, such as[93]:

- Clear definitions for renewable and low carbon gases, and gas-based energy storage
- Certificate schemes (e.g. 'guarantees of origin') for renewable and low carbon gases, including pure hydrogen
- Establishment of international standardisation bodies and global technical regulations
- Harmonised regulation and guidelines for gas quality (e.g. H2 concentration levels)
- Hydrogen market and infrastructure regulation e.g. Tariffs Network Code (to avoid issues arising from tariff levels affecting cross-border trade); unbundling; third party non-discriminatory access; hydrogen market design in line with the EU's electricity and gas markets.

National Action Point: The UK could position itself as a leader to influence or drive forward international developments for hydrogen trading.

Action Point: MH:EK consortium to assess development of wider EU hydrogen markets and whether this is a material consideration for early-stage investment in the MH region.

To exploit international trading opportunities, the UK will be dependent on developments at EU and international level that facilitate trade, though the UK could position itself as a leader to influence or drive forward international developments.

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[93] https://documents.acer.europa.eu/Official_documents/Position_Papers/Position%20papers/ACER_CEER_WhitePaper_on_the_regulation_of_hydrogen_networks_2020-02-09_FINAL.pdf

8 THE LOCAL TRADING PLATFORM OPPORTUNITY FOR MILFORD HAVEN

This chapter discusses the potential benefits for the Milord Haven: Energy Kingdom project in creating a trading platform for the region. Potential functions of a local multi-vector trading platform are discussed as well as the potential markets which could be hosted on such a platform. This section also pays attention to when a trading platform and different products would be useful in the Milford Haven region.

8.1 POTENTIAL BENEFITS OF A LOCAL MULTI-VECTOR TRADING PLATFORM

Across the UK, trading platforms and local energy solutions are being explored to improve the operation and development of the energy system, which can ultimately unlock multiple benefits for energy consumers and society. A trading platform can enable more granular price signals in a specific location and enable greater competition between energy resources and market actors, potentially unlocking new and/or greater revenue streams for assets. Trading platforms enabling trade in local energy resources and services could provide consumers with greater choice (i.e. low carbon, local) and greater rewards for providing services to the grid.

The potential value of local energy systems, which a local trading platform could help unlock, can be categorised as follows (ESC, 2018[94]):

- Network benefits: network energy losses reduction, managing network constraints and operational needs (congestion, thermal, voltage), and deferring or delaying investment.
- Supporting small-scale renewable integration: both through active grid management and stimulating investment.
- Improving hedging opportunities for small scale users.
- Unlocking local demand side flexibility.
- Supporting local social objectives, potentially reducing local energy bills, and empowering the community/ individuals.

To add value to a national trading hub, a local trading platform would need to be designed to meet local needs and exploit the benefits that local energy offers, as outlined above. This depends on whether GB policy and market design can be evolved so that market prices more accurately reflect system physics in time and by location in relation to the value of carbon, capability (flexibility), capacity, congestion, and commodity[95]. Market structure and governance arrangements are also critically important and will directly impact the role and functions of the trading platform.

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[94] https://es.catapult.org.uk/news/the-policy-and-regulatory-context-for-new-local-energy-markets/

[95] https://esc-non-prod.s3.eu-west-2.amazonaws.com/2019/11/ESC_TowardsNewFrameworkForElectricityMarkets_FN.pdf

The key strategic choices of relevance – to be decided by Ofgem and BEIS - include:

- the role of system operators:
    - at the national level, with the potential transformation of NG ESO to the status of an Independent System Operator and potentially overseeing multiple energy vectors, as recently proposed by Ofgem[96];
    - at the distribution level, whether: asset ownership and system operation will be unbundled; the system operator will be allowed to own and/or operate energy trading platforms as combined system/market operator or if trading platforms should be operated by a neutral third party, whether the system operator will manage multiple energy vectors.
    - how system operators will be coordinated between national and regional/local levels.

- better quality price signals varying by location, and more dynamically, to reflect system value more accurately in the short-term, including:
    - future role of network charges
    - future role of local energy markets to assist with network cost recovery and providing price signals
    - options for locationally differentiated energy pricing e.g. zonal, nodal

- the extent to which better quality price signals are complemented with strategic planning (e.g. Local Area Energy Planning)
- the extent to which market coordination is centralised, decentralised, or mix of both
- how carbon is regulated and/or priced

Several research and demonstration projects have been supported by the Government to explore the benefits and practical aspects of trading platforms and to inform decision-making relating to the strategic choices set out above. There are further projects proceeding internationally. Nearly all of these trading projects - see Table 11 below - are focussed on electricity and flexibility trading. LMEX is one of the few projects that incorporates trading of gas/hydrogen within its scope.

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[96] https://www.ofgem.gov.uk/sites/default/files/docs/2021/01/ofgem_-_review_of_gb_energy_system_operation_0.pdf

Project	Project Partners	Description and Comments
Project Fusion	SPEN, DNV GL, Origami Energy, PassivSystems, Imperial College London, SAC Consulting, Fife Council, The University of St Andrews	• Funded under the Network Innovation Competition • Trial to commoditise local demand-side flexibility through a competitive market based on the Universal Smart Energy Framework (USEF) • Enables DNOs and market actors to utilise local network flexibility in competitive, transparent manner • Standardisation of flexibility products and services for both local and national network balancing
Cornwall Local Energy Market	Centrica plc, WPD, National Grid, Exeter University	• Funded by ERDF, Centrica, and the British Gas Energy for Tomorrow Fund • Virtual marketplace for both I&C and domestic consumers • Intended to enable whole system coordination, access to network data and price discovery • Considers how to ensure that ESO and DSO activities do not conflict
Project Transition	SSEN, ENWL, Northern Powergrid, Atkins, CGI, Origami Energy, British Gas, Elexon	• Funded under the Network Innovation Competition • Transition develops and demonstrates a 'Neutral Market Facilitator' platform, to be used by DSOs. • The project builds on the model produced by the Open Networks Project (world B) • The project will consider coordination between DSOs and the ESO • Project Transition has published detailed requirements for how whole system coordination would work.
Project Leo[97]	SSEN, University of Oxford, EDF Energy R&D, Oxford Brookes University, Oxford City Council, Oxfordshire County Council, Low Carbon Hub CIC, Piclo	• Funded under PFER (Innovate UK) • Aims to create a local energy marketplace which will allow for the aggregation of electricity loads, their flexible dispatch, and peer-to-peer energy trading.
TraDER	Electron, EDF, ESC, CGI, Community Energy Scotland (SSEN, Elexon)	• Funded by BEIS Flex competition grant • Neutral market facilitator • Price-driven collaborative trading for an energy resource on multiple markets in same time period, with notification of commitments and trader self-dispatch to relevant parties.
Piclo Exchange	Piclo	• Funded by BEIS Flex competition grant • Demonstration of open, transparent, and neutral flexibility marketplace. Participants can trade in primary and secondary flexibility markets at both local and national level.
LMEX Liverpool Multi-Vector Energy Exchange	New Resource Partners, Smart Power Networks, Regent Capital, SP Energy Networks, Decentralised Energy Solutions, University of Essex, Sp Manweb, ESC	• Funded under PFER (Innovate UK) • Multi-vector trading platform with peer-to-peer trading • Testing hardware and software • To include all resources e.g. heat pumps, heat networks, solar-powered hydrogen production to replace gas supply and power fuel cells, battery, and REDOX based energy storage.

Table 11 Energy trading platforms - research and demonstration projects

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[97] https://www.energy.ox.ac.uk/wordpress/project-leo-local-energy-oxfordshire/

For the UK, the added value of the MH:EK developing a trading platform relates to exploration of the potential of a multi-vector trading platform that can facilitate trading in markets for *both* hydrogen and electricity with coordinated system operation tailored to the needs of the Milford Haven area and coordinated with the evolving national infrastructure and markets for hydrogen.

A local multi-vector trading platform can complete a wide range of functions for each of the markets it operates and for the market participants which use the platform. These are set out in Table 12. Some functions, such as procurement and trading, transaction settlement, market services, analytics, and feedback, would be common to any trading platform. It is coordination, optimisation, aggregation, dispatch and control, and carbon monitoring and verification that will be highly valuable with respect to efficiently bringing together supply and demand, and integrating distributed energy resources (DER), variable renewable generation and different energy vectors. Given their importance, they are set out in more detail below.

FUNCTION CATEGORY	EXAMPLES of potential functions
Coordination	• Coordinating platform tasks • Facilitating and coordinating data flows • Harmonisation of standards and principles • Alignment with external platforms and markets • Enabling participants to coordinate their participation in markets • Coordinating local and national markets, and system operator actions e.g. facilitating rules-based and/or price-based collaborative trading across markets
Optimisation	• Optimising across markets for participants • Optimising across energy vectors for participants
Aggregation	• Aggregation of local energy resources (including via aggregators) for bidding into markets
Dispatch and control	• Sending signals to dispatch assets • Notification of asset dispatch • Verification of asset dispatch • Sending signals to switch energy vectors • Notification of energy vector switch • Verification of energy vector switch • Dispatch of assets
Carbon monitoring and verification	• Provide monitoring and verification needed to prove the carbon intensity of hydrogen, electricity, or other energy vectors
Procurement and trading of products and services (e.g. physical, financial)	• Attracting buyers and sellers to the market, or relying on aggregators bidding on to the platform • Communicating requirements and availability • Matching providers and purchasers
Platform transaction settlement	• Verification of service against transaction • Settlement of transactions
Platform market services	• Credit checking • Asset pre-qualification
Analytics and feedback	• Network analytics, response times etc. • Counterparty scoring and review • Identification of market faults • Provision of data to market monitor for assessment of a) market manipulation/behaviour and b) market design performance • Provision of data to all participants, this could be enabled through blockchain.

Sources: ESC research; Ofgem - Future Insights Series: Flexibility Platforms in Electricity Markets.

Table 12 Potential functions of a local multi-vector trading platform for Milford Haven

Coordination

A local trading platform could have a crucial role to play in; coordinating markets, participants, aggregators, and system operators' actions as well as potentially in relation to handling data, harmonising rules or standards and coordinating with other trading platforms. Some market stakeholders have suggested this could be done using blockchain for trading so that trades are faster and visible to all[98,99].

As previously mentioned, particularly relevant to trading platform set up and operation, is the future role of system operators. For system operators, it is necessary to ensure that the action of one system operator (e.g. DSO) is not inefficiently counteracted by the actions of another system operator (e.g. ESO). In the absence of coordination, for example, assets might be paid twice, or assets might be paid by both system operators to complete opposite actions. Due to this risk and given the current lack of coordination on data sharing and control of assets, almost all ESO ancillary services for electricity have contractual clauses that prevent distribution level assets with flexible connections (e.g. in ANM zones) from participating in those ancillary services to the ESO.

Coordination between system operators and market participants can be rules-based or price-driven:

- Rules-based: the platform holds rules for the actions, which can happen at different times and/or need to be taken under different scenarios. These rules will ensure that actions taken by one participant consider the needs of different market participants and coordinate actions by different market participants. For example, ENA is developing *WS1A: P5 - Primacy Rules for Service Conflicts* through *Open Networks*.[100]
- Price-based: participants bid for products. The prices represent the value to different participants of different actions, and as such the process theoretically ensures the most mutually beneficial action for all stakeholders is taken. Projects such as BEIS FleX: TraDER[101] have been exploring how to integrate trading platforms with DNOs' ANM systems through price-based and rules-based approaches.

Local trading platforms will likely need to coordinate with other trading platforms, and there could be trading between them if a trading platform is responsible for optimising its own area. The trading platform in Milford Haven could allow users from other areas to buy or sell hydrogen on the platform (possibly provided one of the assets is in the region). This would require the stakeholder not in the region to register on the platform. They could then buy H_2 in the region or sell H_2 to the region.

Optimisation

Trading platforms also help optimise market participation for participants as the platform can award them the best combination of contracts within the markets, they are eligible for, so

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[98] https://theswitch.co.uk/energy/guides/technology/blockchain-energy

[99] https://www2.deloitte.com/uk/en/pages/energy-and-resources/articles/blockchain-applications-in-energy-trading.html

[100] https://www.energynetworks.org/assets/images/ON21-PRJ-PID%20Project%20Initiation%20Document%20(post-consultation)-v4.0%20FINAL.pdf

[101] https://www.gov.uk/government/publications/flexibility-exchange-demonstration-competition-flex-winning-projects/flex-competition-winning-projects

facilitating revenue stacking. In addition to this, the platform can facilitate energy vector switching by coordinating dispatch signals and price signals, enabling assets to exploit and optimise opportunities across vectors.

The GB power market could potentially switch to locational energy pricing (probably at the 132kV level or higher, initially) and if the nodal pricing approach was adopted then nodal markets would form behind the node, essentially forming a local energy market. The energy spot price would be uniform in this nodal market, but prices would vary between nodal markets. The local trading platform would adopt the role of optimising the system behind the node and would aggregate resources to bid into the national markets.

Aggregation

The platform could aggregate assets together and bid them into markets. This can enable:

- Assets to access markets where individually they would not meet the minimum characteristics.
- Assets to bid into markets they otherwise would not be able to access. The trading platform could do this by being registered as a Virtual Lead Party (VLP) and bid into the balancing mechanism on behalf of participants, including aggregators, who are not registered as suppliers. This would reduce market administration challenges and transaction costs for DER. Recent rule change means that VLPs can participate in ESO's ancillary services markets and the proposal for BSC Code P415[102], if adopted, would mean that VLPs could participate in wholesale electricity markets.
- The trading platform could potentially act as an aggregator or a supplier, operating consumers assets to reduce the cost of the electricity they use by shifting demand and/or makes money for them by selling services to the ESO and DSO. Certain suppliers already have proprietary flexibility platforms, such as EDF's Powershift platform, which optimise, control and trade third party owned assets to keep the grid balanced and enable customers to earn revenues from flexibility services.[103]

Dispatch and control

For detail on the potential options for dispatch and control and considerations surrounding it see Section 5.9.3

Carbon monitoring and verification

The demand for hydrogen is primarily being driven by the demand for zero carbon energy. The trading platform will therefore need to have the capability of verifying the carbon content and origin of the hydrogen as this will directly link to the value of the hydrogen. This requirement is necessary for all PSAs. Carbon tracking will be necessary for other energy vectors too and this will need to be granular by time and possibly location. A consistent approach to monitoring, reporting and verification (MRV) of greenhouse gas emissions will be needed across the UK, and the GB hydrogen market more specifically[104]. Government support mechanisms will likely be linked to carbon intensity of hydrogen and may require specific ways of tracking the true carbon intensity of

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[102] https://www.elexon.co.uk/mod-proposal/p415/

[103] https://www.edfenergy.com/large-business/energy-solutions/powering-flexibility

[104] https://es.catapult.org.uk/news/the-case-for-a-carbon-regulator/

a fuel (such as in those proposed for the Renewable Transport Fuel Obligation[105]). This is an area where Milford Haven could take initiative if developments have not sufficiently progressed in other parts of the UK or at national level. See Section 7.2 for further details on potential GoO schemes.

8.2 POTENTIAL HYDROGEN PRODUCTS AND SERVICES TO BE TRADED

8.2.1 TRADING HYDROGEN

Hydrogen trading could start in local areas with a sufficient density of hydrogen producers and users. The trading platform could also be used to help suppliers balance their portfolio locally or regionally if networks are isolated for blending or full conversion to hydrogen. The potential evolution of hydrogen trading was discussed more in Section 7.3.

Users could trade hydrogen at different times ahead of the delivery period. The trading platform could host these markets, with the times for trading and standardised contracts for trading developed based on the needs of participants. As discussed in Section 7.2, standardisation of contracts, for example in relation to purity, will facilitate trading and building a liquid market, while enabling participants to procure their specific requirements. The trading platform could have a function that links the different purity markets for participants, enabling them to state the type of hydrogen purity they require, and which platform can procure the lowest cost hydrogen that meets those criteria.

Due to the variability of intermittent renewable energy sources which electrolysers may procure electricity from; real time trading may be valuable. As such, based on market participant requirements, the local trading platform could host a real-time trading market, particularly if prices in the short-term wholesale electricity markets vary by location as would be the case with zonal or nodal pricing.

The platform could have the potential for secondary trading of contracts between participants.

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[105] https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-guidance-2021

8.2.2 SELLING RESERVES AND ENERGY SYSTEM SERVICES TO THE SYSTEM OPERATOR (SO)

If hydrogen networks develop there will need to be a party who manages these networks. This party will need to procure services to balance and manage the network as discussed in Section 6. The local trading platform could be the platform through which the party does this, or the local trading platform could place bids on the party's own platform. Through the latter approach, single assets could bid into this market and others through the same portal and potentially use the local trading platform to optimise between them depending on its functionality. Also, the local trading platform could aggregate local resources together and bid them into the market even if individually they would not have met the required capacity thresholds.

8.2.3 TRADING TRANSPORT SERVICES AND NETWORK ACCESS RIGHTS

A condition for trading is that there be a fixed location or network (with third party access rules) where trading takes place. The transport infrastructure and extent of connection between production and consumption is a key defining feature of the PSAs set out in Section 4.4. The transport infrastructure/options will change over time with important implications for trading opportunities and development of any trading platform(s). Options that facilitate connection include building terminals for import and export as well as storage facilities near places of production and consumption. Particularly important will be how the gas networks develop.

The sale of services for transporting the hydrogen from where it generated or stored to where it will be used or stored, could be managed through the platform, which would promote competition between companies that transport hydrogen. The visibility of transport costs would bring a locational dimension to hydrogen prices, advantaging local hydrogen.

Once hydrogen blending or hydrogen networks are present, participants will need to buy rights to access and use the network capacity just as for gas today. Today, network capacity can be acquired at an entry (for gas delivery) or exit (for gas offtake) point through bids in auctions or applications via the Gemini system and in the case of interconnections to other countries, via the PRISMA system. Participants can book either form or interruptible entry capacity, and peak or off-peak exit capacity.

In the early stages of hydrogen network development, it may be that local or regional networks develop ahead of the national backbone that connects them up and so the auctions or processes for booking pipeline capacity could be managed via the local trading platform and/or directly with the network owner.

8.2.4 GUARANTEES OF ORIGIN

The need for GoOs, tracking the carbon intensity of hydrogen, was discussed in Section 7.2. The local trading platform could enable the trading of GoO certificates or link with a national market trading them.

8.3 POTENTIAL ELECTRICITY PRODUCTS AND SERVICES TO BE TRADED

8.3.1 BUYING AND SELLING ELECTRICITY THROUGH NATIONAL WHOLESALE MARKETS

The GB electricity markets are well-established with trading in day-ahead and intraday timeframes through the European Power Exchange (EPEX SPOT) and Nordpool. The trading platform could link with national wholesale markets to enable assets to procure electricity through the local trading platform or enable them to sell electricity on the national wholesale markets through the local trading platform.

As outlined in Section 7.2, electricity trading is likely to place at local level as well as national level in future though the Government and regulator have yet to clarify the target model and how the current system will evolve to achieve it.

Locational price signals are needed to ensure network users internalise the impacts of their behaviour/decisions on the costs of the total system. This will then ensure users:

- invest in the right places; and
- consume or produce at the right times.

For energy (i.e. kWh), the spot prices are uniform across the whole of GB and network constraints are not reflected in these prices. Under the current arrangements all parties pay upfront for the network capacity required for them to participate in the national energy market; having done this they are then free to trade as they wish. Network charges, based on long-run marginal costs (LRMC), vary by location, and are used to influence point a) above while the spot prices of the wholesale energy market are based on short-run marginal costs (SRMC) and are used to influence point b) above. In effect our current system is designed to send investment and dispatch signals separately.

Energy prices in the spot markets, however, could potentially vary geographically through either zonal pricing (as envisaged by the EU target model, with defined boundaries that reflect congestion) or through locational marginal pricing (LMP), also known as nodal pricing (applied to nodes on the transmission system, down to for example 132kV), to simultaneously send short-run and long-run signals to influence both a) and b). If such locationally varying prices are introduced, then the forward-looking part (Use of System) of the network tariff must be removed to avoid double-counting, leaving just the residual of the network charge.

The price at each node reflects the locational value of energy, which includes the cost of the energy and the full cost of delivering it including energy losses in networks and network congestion. Nodal prices are determined in real-time using an algorithm to calculate the incremental cost of serving one additional MW of load at each respective location subject to system constraints (e.g. transmission limits, maximal generation capacity). In principle, there should be no or minimal out-of-market actions by NG ESO in nodal markets since the nodal pricing algorithm accounts for security constraints on the system and so energy and reserves are co-optimised.

Under nodal pricing, a supplier would be able to optimise its portfolio *behind* a node in the local nodal market, but not *between* nodes across the electricity system. Retail suppliers and generators would need to hedge their exposure to pricing differences between nodes. The most commonly used form of hedging in nodal markets is financial transmission rights (FTRs). Such products would be traded via the national power exchanges but could also be traded on local platforms.

From the national system operator's perspective, the LMP algorithm treats aggregated generation behind a node (net of aggregated demand behind the same node) the same way it would treat a single generator or load of the same capacity if it were located at the same node. From a supplier's perspective (or a DNO/DSO's perspective), it can minimise its exposure to the nodal price by reflecting it in charges to consumers to drive consumption / distributed generation behaviour. Effectively, the supplier (or DNO/DSO) is incentivised to optimise their portfolio of local DER behind the node. Following optimisation, resources could then be aggregated – facilitated through a local trading platform - and offered into the wholesale markets in addition to being used to manage the distribution network.

At the lower voltage levels behind the node, LMP is not practical yet due to inadequate data availability, monitoring capability and low volume of DER. In time this might change, but in the meantime, locational pricing signals could come from either the forward-looking part of network charges (i.e. DSUoS), which could give rise to the need for hedging products available through the local trading platform, or from local flexibility markets e.g.:

- network tariffs being set at a level that reflects peak conditions, with the marketplace offering payments for flexibility actions, thus reducing the effective tariff for participants; or
- the marketplace applying mandatory charges for non-participation.

8.3.2 SELLING ANCILLARY SERVICES TO THE ESO/FSO

Trading platforms can facilitate participation of assets/resources, including through aggregation, in ESO's national ancillary services markets. As discussed earlier, they could provide a route for assets which may otherwise be unable to bid into these markets (by acting as a VLP or aggregating assets together to meet a minimum bid size).

At present, the ESO tends not to procure ancillary services from assets in ANM zones, which are managed by DNOs, as the ESO cannot be certain that the assets will be able to deliver and may be prevented from doing so by the ANM system. It is possible that a local trading platform could enable the ESO to procure ancillary services from assets in ANM zones by coordinating between the ESO, the DNO and ANM system as trialled in Project TraDER. There are other ways this problem could be overcome, as explored in WPD's project 'Optimal Coordination of Active Network Management Schemes and Balancing Services Market'.[106]

ESO is currently making improvements to how it procures ancillary services, including set up of a Single Market Platform (SMP) that should facilitate revenue stacking and interaction with other trading platforms. If, nodal pricing would be implemented then, as explained above, the role of ESO would be much smaller and the ancillary services would be predominately non-frequency related. For balancing at the distribution level, for most scenarios or possible future directions, it could be expected that DSOs would play a larger role. When ancillary services would be location specific then it could be expected that in future, they would be procured via the DSO rather than the ESO.

At present, the GB power market has a Capacity Market; NG as the EMR Delivery Body procures the needed volume of capacity through auctions to achieve a pre-defined reliability standard. While eligibility criteria are defined for the assets participating in auctions, there are as yet no requirements in relation to the capacity's capability (e.g. flexibility; ability offer particular services,

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[106] https://www.westernpower.co.uk/downloads-view-reciteme/336778

such as inertia) or location of capacity. This could change in future (as discussed in the recent call for evidence 'Capacity Market: Improving delivery assurance and early action to align with net zero'[107]) and may mean a role for the local trading platform. It is also possible that the Capacity Market might be phased out or replaced with a different design of capacity renumeration mechanism e.g. strategic reserves, decentralised mechanism, options.

8.3.3 SELLING BALANCING AND CONSTRAINT MANAGEMENT SERVICES TO THE DNO/DSO

As mentioned above, the transition to DSO would involve DNOs or DSOs procuring services to, for example, address local network constraints and balance the local area, reduce energy losses, manage voltage quality, and respect thermal limits. This will likely involve defining new products and establishing new markets. The DNO/DSO may procure the services directly or via the trading platform, and in some future scenarios the DSO is envisaged to operate the platform as a combined system operator and market operator. The trading platform established by the project could be set up to be this DSO-led trading platform. Alternatively, an independent local trading platform could bid into the DSO platform. Through this second option participants could access and optimise across several markets through one portal.

DSOs could choose to procure flexibility services as investing in network upgrades is expensive. Network upgrades can be avoided through better management of the electricity flows on the network, maximising the use of existing capacity and controlling flows to stay within network capacity limits. Such an approach may not always be able to prevent upgrades, but it can delay the need for investment until a later date. This can be very valuable if it is unclear whether the upgrade will be needed long-term if the necessary capacity of the upgraded network is still unclear or if the network upgrade will take time to deliver in areas of growing demand.

Through a local trading platform, DNOs/DSOs can procure flexibility services to either defer or avoid investment. The platform would receive revenue from DNOs/DSOs using the platform. Platforms such as Piclo Flex have already been in commercial operation since 2019.[108]

These DSO flexibility services are highly locational, and assets/resources that do not fall within the Constraint Management Zone (CMZ) for the relevant service the DSO is requesting will not be able to participate. As shown on WPD's Flexible Power platform, Milford Haven is not currently in a CMZ where WPD is looking to procure flexibility, nor is it listed in the "Signposting" information as a potential future Constraint Managed Zone between now and 2025.[109] However, this could be expected to change over time with increase in generation connections or if demand increases, particularly with take up of heat pumps or electric vehicles.

Ofgem's RIIO-ED2 Methodology Decision from December 2020[110] is enhancing the potential ability for trading platforms to allow for the selling of flexibility services to the DSOs. As part of their baseline expectations, when developing and amending flexibility services products, contracts, and qualification criteria, Ofgem have stated that there should be clear processes in place that are

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[107] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005672/capacity-market-cfe.pdf

[108] https://piclo.energy/about

[109] https://www.flexiblepower.co.uk/locations/western-power-distribution/map-application

[110] https://www.ofgem.gov.uk/system/files/docs/2020/12/ed2_ssmd_overview.pdf

transparent and participatory to involve other DNOs, the ESO, and current and potential distribution flexibility service providers. Ofgem has also stated that DNOs should "coordinate and engage with third party platform providers, who can offer system value by providing new routes to market and driving whole system outcomes. DNOs should not prevent the emergence of this sector and should enable third party platforms to 'plug-in' to DNOs' flexibility procurement processes."[111]

Further developments in secondary trading could be opening up, especially given Ofgem's statement in their RIIO-ED2 Methodology Decision that under *Activity 2.2: Facilitate efficient dispatch of distribution flexibility services*, one of their baseline expectations is that "DNOs shall facilitate secondary trading of distribution flexibility services and curtailment obligations."[112]

Historically, each DNO has had its own methods of procuring needed flexibility, leading to a variety of different services and contracts between DNOs. The ENA Open Networks project has been attempting to standardise the services and contracts, including better alignment with ESO services and contracts, through a variety of workstreams and products. These include: WS1A P1: Enhancements to the Common Evaluation Methodology and Tool; WS1A P2: Procurement Processes; WS1A P4: Common Contract; WS1A P5: Primacy Rules for service conflicts.[113] The standardised services being developed are: *Dynamic, Restore, Secure* and *Sustain*. Such standardisation of products and services would be valuable for hydrogen as the markets develop.

8.3.4 SELLING FLEXIBILITY TO CURTAILED GENERATORS

Generators which connect to a distribution network can agree to a flexible connection in order to accelerate being connected to the network and/or potentially reduce costs. These assets can then be curtailed if a section of the distribution network would otherwise be overloaded. There may be flexible demand or generation behind this constraint which could turn up or down and enable the generator to continue generating. Enabling this is complex, as it requires specific contracts between the curtailed generators in the region and the other assets which could reduce the generators level of curtailment. A trading platform can solve this problem by allowing the generator to procure this service through the trading platform. The generator or ANM system alerts the trading platform that the generator is curtailed, and the trading platform allows assets to bid in to the market to alleviate the curtailed generator.

The BEIS Flex project, TraDER, trialled this type of market in Orkney in 2021 and gathered learnings on how to make this market function effectively. One of the findings was that for this type of market to operate, it requires data from the ANM system regarding the curtailment queue stack.

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[111] https://www.ofgem.gov.uk/system/files/docs/2020/12/ed2_ssmd_overview.pdf pp. 87.
[112] https://www.ofgem.gov.uk/system/files/docs/2020/12/ed2_ssmd_overview.pdf pp. 84
[113] https://www.energynetworks.org/assets/images/ON21-PRJ-PID%20Project%20Initiation%20Document%20(post-consultation)-v4.0%20FINAL.pdf

8.3.5 SELLING CURTAILMENT QUEUE POSITIONS

Projects such as UKPN's *Energy Exchange* are exploring the potential financial incentives for curtailment queue trading to better incentivise participation of low cost and optimally sited generators, allowing constraints to be relieved in the most efficient manner.[114] It will do this by through the auctioning and trading of capacity rights, creating a new local 'host' energy market, and distribution flexible connection customers trading their place in the queue.

Revision of existing contracts will likely be necessary to enable such trading of capacity rights or queue positions, and future standardised contracts with DSOs could better enable this as standard. The ENA's Open Networks currently has a number of products looking at this, including *WS1A Flexibility Services – P3: Principles to review legacy Flexible Connection (ANM enable) Contracts.*[115] A "Legacy Contract Curtailment Review" Principles Consultation is expected by October 2021, with the aim of agreeing with Ofgem the approach to cost recovery resulting from the provision of improved curtailment options by December 2021.

8.3.6 DIRECT TRADING BETWEEN LOCAL CONSUMERS AND LOCAL ASSETS

Within a local energy market - depending on how it is structured and operated, as discussed above – the market participants could engage in peer-to-peer trading where a consumer can contract directly with another consumers or producer. Through this, community energy projects could have new business models and consumers could choose to buy local energy. This P2P trading could be facilitated by the trading platform. At present, the current market arrangements (i.e. Supplier Hub Model) prevent this this as it is not possible for a prosumer to sell any excess generation to someone else and not possible for a customer to buy electricity from anyone other than their sole contracted supplier. Even through Ofgem's regulatory sandbox, the trialling of P2P requires a licensed supplier to be involved. BEIS and Ofgem have acknowledged that the supplier hub model needs reform, but no proposals have been announced yet. In the meantime, industry has been trying to progress incremental improvements through reforms to the industry codes (e.g. P375 accepted, P379 rejected, P415 in progress).

8.3.7 TRADING CAPACITY/ CONNECTION/ ACCESS RIGHTS

Network access rights define the nature of users' access to the networks which includes how much they can import or export, when and for how long, where to / from, and how likely their access is to be curtailed and what happens if it is. Ofgem is currently reviewing access rights. Transmission and distribution are currently treated differently; transmission have a range of access right options while the trading of access rights is outside the scope of the review for because Ofgem concluded such options could not be implemented in time for 2023. In the longer-term future, however, with for example improved data exchange and network monitoring at lower voltage levels, trading of access rights through local trading platforms may be possible.

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[114] https://innovation.ukpowernetworks.co.uk/projects/energy-exchange/

[115] https://www.energynetworks.org/assets/images/ON21-PRJ-PID%20Project%20Initiation%20Document%20(post-consultation)-v4.0%20FINAL.pdf

8.3.8 GUARANTEES OF ORIGIN

In the GB power market, a Guarantees of Origin (GoOs) scheme is established for electricity (i.e. REGOs) with platforms for trading these certificates such as the ePOWER platform[116]. A local trading platform could enable the trading of GoO certificates for hydrogen as well as for electricity or any other energy vectors (as discussed in Section 7.2).

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[116] http://www.epowerauctions.co.uk/eroc.htm

8.4 SUMMARY OF POTENTIAL TRADING PLATFORM MARKETS

Table 13 summarises the detail above on the potential trading platform markets.

	Market	**Buyer**	**Sellers**	**Features and considerations**
Hydrogen	Trading hydrogen energy	Hydrogen producers Hydrogen storage owners/operators Hydrogen consumers H2 suppliers	Hydrogen producers Hydrogen storage owners/operators H2 demand side response H2 aggregators H2 suppliers	Markets of different timeframes leading up to delivery – spot and futures/forward markets, if sufficient liquidity, buyers/sellers, and volumes Over the Counter (OTC) contracts – some contract standardisation and brokerage services Markets for different purities/qualities Automated way of linking markets for purities Balancing products/services Locational info with links to transport market. Ability to input own transport costs over different distances.
	Selling reserves and system services to the SO (local, regional, or national)	ESO/ISO DNO/DSO	Hydrogen producers Hydrogen storage owners/operators H2 suppliers/consumers H2 aggregators	Platform could aggregate resources to access markets. The local trading platform could be the SO's platform for procuring flexibility (particularly in PSA 5), or the local trading platform could place bids on the SO's own platform.
	Containerised transport	Large hydrogen users, hydrogen suppliers, hydrogen producers, hydrogen storage owners/operators.	Containerised transport operators Participants hold contracts with containerised transport operators	Bilateral contracts between containerised transport operators and transport users. Encourages competition in the containerised transport market. The trading platform could allow market participants to automatically include these costs in wholesale market prices. This would encourage local consumption of H2.

	Market	Buyer	Sellers	Features and considerations
	Network capacity rights	Network users and the network owner.	Network users and the network owner.	Access arrangements (entry/exit; firm, interruptible, off-peak) for blended networks or dedicated networks. More likely to be managed through local platform if no national core network established and depending on who network owner is.
	Guarantees of Origin - hydrogen	Hydrogen producers Hydrogen storage owners/operators H2 demand side response H2 aggregators H2 suppliers	Hydrogen producers Hydrogen storage owners/operators H2 demand side response H2 aggregators H2 suppliers	Requires the establishment of a GoO scheme for hydrogen and a process for monitoring, reporting, and verifying carbon intensity. Could link with a national market or possibly include a shadow price to show the potential value of the carbon intensity of the hydrogen being traded.
Electricity	Buying and selling electricity through national wholesale markets	Aggregators Suppliers Storage owners/operators Electrolysers Electricity generators Other local energy markets	Aggregators Suppliers Storage owners/operators Electrolysers Electricity generators Other local energy markets	The local trading platform could link with national wholesale markets to enable assets to procure electricity through the local trading platform or enable them to sell electricity on the national wholesale markets through the local trading platform.
	Selling ancillary services to the ESO/(ISO)	ESO(ISO)		Could aggregate assets together to bid into national services markets, operate as a VLP and/or enable assets in ANM zones to bid.
	Selling balancing and constraint management services to the DNO/DSO	DNO/DSO		Balancing requirements at distribution level expected to increase with need for local balancing. DNO/DSO could use this trading platform to procure flexibility, alternatively, the trading platform could bid onto the DNO/DSO platform.
	Selling flexibility to curtailed generators	Electricity generators with flexible connections		Enables access and increased consumption of renewables in a region if there is curtailment.

	Market	Buyer	Sellers	Features and considerations
				Requires data from the ANM system.
	Selling curtailment queue positions	Electricity generators with flexible connections	Electricity generators with flexible connections	May require revision of existing contracts.
	Direct trading between local consumers and local assets	Local consumers	Local assets	Enables buyers to choose to just trade with local assets, possibly paying a premium for this. The current market arrangements (i.e. Supplier Hub Model) prevent this currently.
	Trading capacity/ connection/ access rights	Network users and network operator	Network users and network operator	Currently not being looked at for distribution level. In the longer term, potentially various options (e.g. buy access, trade connection agreements, auctions for access rights, share access between users).
	Guarantees of Origin - electricity	Aggregators Suppliers Storage owners/operators Electrolysers Electricity generators Other local energy markets	Aggregators Suppliers Storage owners/operators Electrolysers Electricity generators Other local energy markets	Already established for electricity (i.e. REGO). Could trade, link with a national market, or include a shadow price.

Table 13 Electricity and hydrogen products/services that could potentially be traded on a multi-vector trading platform

As discussed in Section 8.2, the platform could enable participants to optimise across multiple markets. It could do this by enabling access to various markets through one portal and potentially facilitated by aggregation. This facilitates assessment of multiple options or could provide functionality to optimise for assets across different markets, choosing the best purchase or selling prices for the assets.

This could encourage energy vector switching and effective operation across vectors as well as improving business models for low carbon and flexible assets in the region.

8.5 POTENTIAL NEED FOR THE TRADING PLATFORM MARKETS AND DIFFERENT CAPABILITIES

The section below explores under which circumstances the different trading platform markets above would be useful in the market broadly in Pembrokeshire/MH. For some markets this will be driven by when the market is developed enough to warrant hosting of a market on the trading platform. For others it could be affected by wider market developments which may render the need for the trading platform obsolete. These are detailed in Table 14.

Key:

- Green- clear benefits in the next 5 years
- Orange- potential benefits in the next 5 years
- Red- no discernible benefits in the next 5 years

	Trading platform market	**When would this be needed?**	**What wider developments could reduce the need for this market?**	**Potential short-term benefits in MH**
Hydrogen	Trading hydrogen energy	When there are sufficient shortages and surplus of hydrogen in a region (or nationally). It's hard to know at what point this will occur. It's possible that without the platform there'll be little visibility of this.	A national hydrogen market could be created if national hydrogen network established, which may reduce the scope of the local trading platform but the need to trade local energy services will continue.	🟧
	Selling reserves and energy system services to the SO	This will not occur until it is necessary to manage hydrogen in networks.	The SO could manage these services through its own portal.	🟥
	Containerised transport	This should be included if there is a hydrogen market on the platform as this could increase the efficiency of the market.	Same as 'Trading hydrogen'.	🟧
	Trading network capacity rights	This could not occur until there is a hydrogen network. It is one way that blending could be managed.	Different approaches are possible.	🟥

	Trading platform market	**When would this be needed?**	**What wider developments could reduce the need for this market?**	**Potential short-term benefits in MH**
	Guarantees of Origin for hydrogen	As soon as hydrogen can be traded there should be a mechanism for verifying carbon intensity. GoO certificates can be traded and CSR/ESG or consumer preferences for low carbon H2 could drive demand. Using GoOs to ensure compliance with policy obligations would more strongly drive their value.	The need to track and account for carbon will only increase but alternatives to a GoO scheme may be possible.	🟩
Electricity	Buying and selling electricity through national wholesale markets	Aggregators, suppliers, and multi-vector assets are operating in the region. The trading platform adds value by enabling access to multiple revenue streams and/or optimising.		🟧
	Selling ancillary services to the ESO/(ISO)	There are aggregators/assets in a region that wish to operate in the BM (the platform could become a VLP) or other markets. The trading platform adds value by enabling access to multiple revenue streams and/or optimising. MH is an ANM region – therefore assets in these regions cannot currently supply ancillary services to the ESO but a trading platform may be able to enable this in future.	Accessing the BM and ancillary services could become easier through a local trading platform. Existing arrangements could be changed to enable assets in an ANM region to provide services to the ESO (possibly via the DNO/DSO).	🟩
	Selling balancing and constraint management services to the DNO/DSO	If the DNO/DSO is procuring flexibility to manage constraints – this is currently not happening in the MH region but will likely develop in the future.	Location marginal pricing (i.e. nodal pricing) applied at the distribution level would reduce/remove the need for these	🟧

	Trading platform market	**When would this be needed?**	**What wider developments could reduce the need for this market?**	**Potential short-term benefits in MH**
		If the DNO/DSO procures flexibility to help balance the network - this currently does not happen in the MH region but could do so in future.	services. Today. LMP can only practically be applied at transmission level but in time this might change.	🟧
	Selling flexibility to curtailed generators restricted by network constraints	Such curtailed generators do not currently exist in the region but could do so in future.	DSOs may introduce a method for enabling this. Greater granularity of price signals at distribution level by time/space.	🟧
	Selling curtailment queue positions	Curtailed generators do not currently exist in the region but could do so in future.	DSOs may introduce a method for enabling this.	🟧
	Direct trading between local consumers and local assets	If there is a demand for buying energy generated locally. For this market to operate, it requires the wider retail market arrangements to have been adapted to enable customers to buy electricity without having to go through their supplier.		🟧
	Trading capacity/ connection/ access rights	This is dependent on whether network capacity rights evolve to support this.		🟥
	Guarantees of Origin- electricity	This could be worthwhile if linked with other markets on the platform.		

Table 14 – Trading Platform Market options for Pembrokeshire/MH

Table 14 shows that most elements of a trading platform would not be useful immediately. The real benefit of the trading platform appears to come when it hosts multiple markets, enabling assets to optimise across markets, multiple energy vectors and access new revenue streams. The trading platform could potentially initiate trading through, for example, enabling assets in the ANM zone to provide ancillary services to the ESO and facilitating the trade of Guarantees of Origin certificates for hydrogen. As with most other examples set out in the table, both of these examples, however, require regulatory change.

8.6 TRADING PLATFORM REQUIREMENTS' SPECIFICATION

Section 16 is a requirements specification for the trading platform. This details the functionality the trading platform 'shall', 'should' or 'could' have. It also considers the specific functionality which would be required to deliver each of the possible markets discussed above.

It is included as an appendix for purely practical reasons, the size format required for readability would make this core part of the document unwieldy.

9 DESIGNS FOR SYSTEM ARCHITECTURES

Earlier (in section 4.4) we introduced the idea of potential system arrangements (PSA). These are sets of physical architectures, organisational architectures, and market architectures which together, describe how a system is delivered and operated. In this section we take a look at each one in turn, armed with the information from the document above but observing the key, most relevant points for each arrangement. Each PSA is expressed as a use-case diagram which describes the roles required and the high-level functions through which different roles interact. The arrangements are focused on the nuance of hydrogen networks as those are the new aspects considered, but it is expected that each arrangement is multi-vector with the same thinking applied to hydrogen, applied to natural gas and electricity as well as described in the sections above.

A note on reading use-case diagrams:

Use-case diagrams are a visual representation of the actions which one or more actors (business or organisations) perform. They specify a "what" and not a "how" and are intended to convey, to designers and implementers things which they need to consider in realising a system.

The ovals are "use-cases" and describe a single thing which should be done. The stick figures are called actors and indicate roles which interact with a given action so that use-cases act as actions which involve one or more "actors" (meaning people, businesses, or organisations). Note that roles are just that a responsibility to do something, it doesn't indicate which real business or organisation does that role and that remains flexible for any given implementation. Use-cases can be further defined into types (denoted by a line with an arrowhead) for example, a use-case to "produce H2" might have types of "electrolysis", "Autothermal reformation" and so on, listing the different options to "produce H2". Furthermore, expected actions as part of the use-case can also be represented (using a dashed line with the word "include" on it). For example, "store H2" has an "include" of "prepare H2" which would describe the steps of cleaning, pressurising and any conversion required to make H2. They are sub-steps which must be completed but don't always need to be shown on a diagram, for clarity.

The icon which looks like a few links of chain is an indication that there is more design material, hierarchically below that use-case in the software tool.

The numbers by the head of the stick figure (the actor) in each diagram is called "multiplicity" and indicates the number of instances of an actor. For example, when a producer has a "1" next to it, it indicates that 1 and only 1 producer exists, when a producer has "1…" next to it, it means a minimum of 1 and a maximum of 'any number'.*

Use-case diagrams have a format and convention which is useful to engineers in system and software roles but are often a helpful graphical aide to generalists to save on large amounts of written description and have been used here to highlight the key approaches to the different potential system arrangements.

9.1 PSA1: SELF CONSUMPTION ARRANGEMENT

This scenario assumes that there is a single site, with a single owner/operator (which itself could be a special purpose vehicle or a joint venture, comprising of multiple different businesses) who operates both the hydrogen production facility and the demand facility. The transfer of hydrogen, between source and destination, can all be considered internal sales noting that there is an additional opportunity to sell any excess, through any of the other potential system arrangements detailed below.

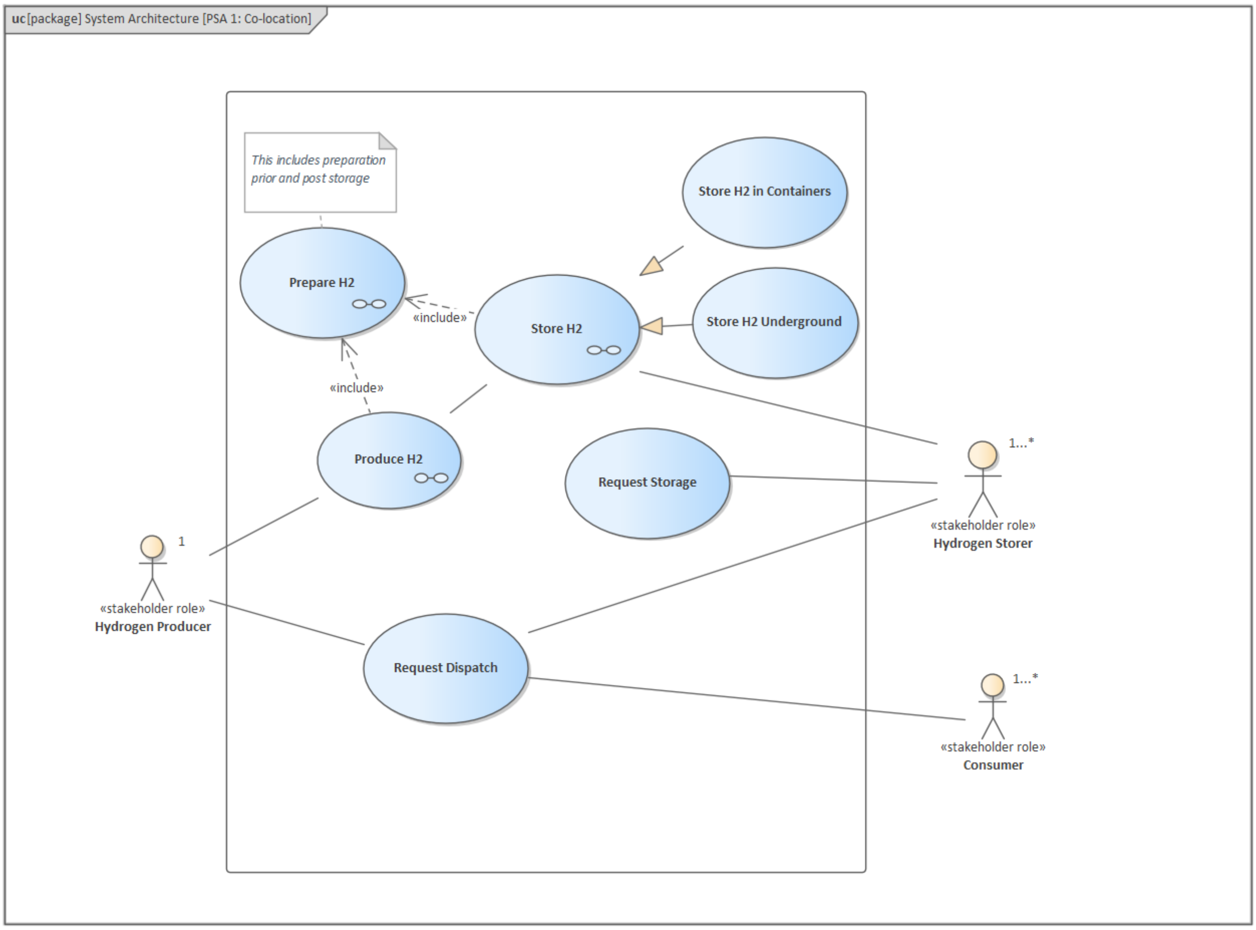

Figure 38: Use-case diagram for PSA 1

9.1.1 PHYSICAL CONSIDERATIONS

In current setups, most projects under development are self-consumption arrangements. The system is therefore designed and sized for supply to meet the demand. The price, volume and purity of the produced hydrogen are designed to meet the demand. Storage, preparation, transport, and distribution are most of the time very limited or integrated within the production or use. The control development can thus be more targeted at demonstrating the benefits and possibilities of hydrogen or the feasibility of a chosen technology with the following aims:

- to prove the reality of hydrogen as an energy vector.
- to make hydrogen accepted by consumers.
- to provide practical applications for standardisation and support regulators.
- to give confidence and encourage investment.
- to provide a benchmark to forecast cost and technology requirements before upscaling.
- to provide practical applications for comparison with other energy sources.
- to learn lesson highlighting benefits and barriers to hydrogen market development – what is working, needs developing, needs abandoning.
- to support the development of a roadmap for market deployment.

9.1.2 ORGANISATIONAL CONSIDERATIONS

Organisational considerations for PSA1 are quite straightforward as all the commercial interactions are solely between the hydrogen producer and consumer, along with any logistics elements which move the hydrogen around. For PSA1 we have assumed a single owner or consortium owners who are completing internal sales, rather than anything complicated.

For setups which include purchasing and invoicing then this is covered in PSA2.

There are no required organisational changes or currently unfulfilled functions which need to be addressed from today’s business as usual arrangements and as such PSA1 could be a commercial reality today.

9.1.3 MARKET AND TRADING CONSIDERATIONS

Self-consumption arrangements can exist at any stage of market and trading developments. At present, the production and consumption of hydrogen is largely carbon intensive and based on the needs of heavy industry. With growth and greater weather dependency in the production and consumption of hydrogen, there will be more volatility in surpluses and shortages and therefore greater need or opportunity for storage and trading. As the market matures, self-consumers may be presented with more supply and demand alternatives at better prices in the market compared to self-consumption, as well as opportunities to be rewarded for their flexibility in consuming or producing at certain times.

With high levels of self-consumption, there may be little need for trading.

9.2 PSA2: PRIVATE CONTRACTS ARRANGEMENT

In PSA2 it is assumed that hydrogen production can be anywhere (geographically) in relation to users. Hydrogen is moved between premises in either local, dedicated pipelines or in containerised transport (e.g. pressurised bottles, tanks on trucks). Commercial arrangements are expected to be purchase order / invoice arrangements between the parties rather through an organised market hosted by a trading platform. A single producer can meet the needs of multiple users. Operating models for storage assets include either buying hydrogen and sell it later or can rent out storage space for a producer to utilise.

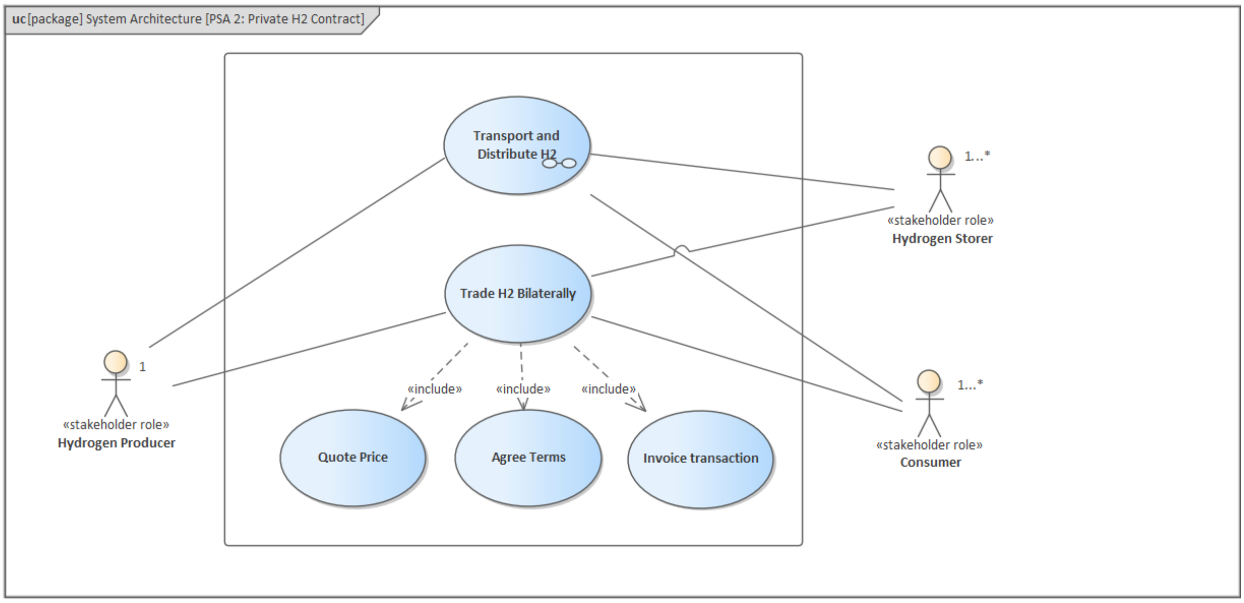

Figure 39 – Use-case diagram for PSA 2

9.2.1 PHYSICAL CONSIDERATIONS

In this arrangement, as for self-consumption, the system is designed for supply to meet demand and also include transport. The control remains straightforward even if communication between multiple stakeholders needs to be established. Distance, the quantity, the form of hydrogen (gas, liquid, compound) and future planning are likely to influence the choice of transport between pipeline and containerised transport.

9.2.2 ORGANISATIONAL CONSIDERATIONS

Organisational considerations for PSA2 are quite straightforward as all the commercial interactions are solely between a hydrogen producer and consumers, along with any logistics elements which move the hydrogen around.

There are no required organisational changes or currently unfulfilled functions which need to be addressed from today's business as usual arrangements and as such PSA2 could be a commercial reality today.

9.2.3 MARKET AND TRADING CONSIDERATIONS

In this PSA, producer(s) and user(s) agree a private bilateral contract, the structure of which dictates the terms and conditions of trade, such as purity, volume, price, and risk allocation. This contract may be accompanied with a GoO certificate to verify carbon-intensity. Bilateral contracting can be present at any stage of system and market development and is compatible with existence of a voluntary trading exchange. Contracts are likely to be long term in nature, to help manage risks over investment timeframes.

In the early stages of developing hydrogen markets, it is expected that considerable Government support will be needed to kickstart the market, help reduce costs and reduce risks for investors. Long-term contracting for low carbon hydrogen might involve Government as counterparty, as is currently the case under the CfD scheme. Such Government-led contracts would likely include conditions to minimise costs and safeguard consumers. For example, as discussed in the networks section, Government support contracts for projects that build private pipes may need to include provisions for third party access, revenue sharing to avoid windfall profits and whole systems coordination. Bilateral private contracts can be brokered and are often referred to as ‘over-the-counter’ (OTC) transactions. With the development of a spot market enabling trading in shorter timeframes through an exchange, the duration of long-term contracts might reduce as more opportunities to manage risk materialise. Unless participation in a trading pool is mandatory, considerable private bilateral contracting can be expected to continue. At local scale, this may result in insufficient liquidity; whether or not a local hydrogen market is a mandatory pool is therefore an important design consideration.

9.3 PSA3: LOCAL H2 BLENDED (SINGLE PRODUCER) ARRANGEMENT

A single producer of hydrogen blends hydrogen into the natural gas system. An area for the blended network must be defined and isolated from the rest of the gas network (see section 5.6).

There is no concern over managing complicated arrangements for sharing the blend limit as there is only a single producer. Note that it is possible for a single producer to own multiple injection sites. For example, one hydrogen producer could own multiple electrolysers in an area and choose when to operate which. It is also feasible that a single producer also imports hydrogen from another area as a backup or to complement the amount they can produce and injects. The key point is that there is only one entity responsible for managing the blend content.

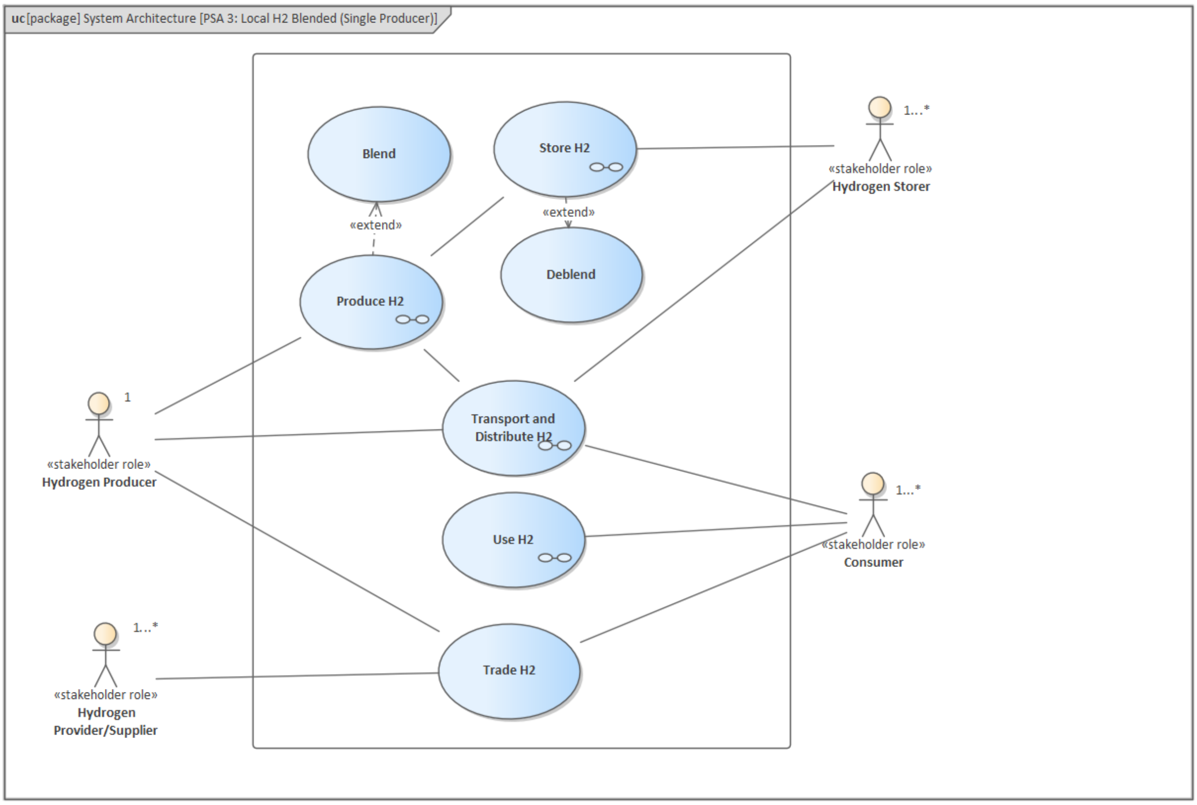

Figure 40 - Use-case diagram for PSA 3

9.3.1 PHYSICAL CONSIDERATIONS

This arrangement can be newly developed or a blending capability addition to PSA1 and PSA2. As blending hydrogen is not allowed under current regulations, an exemption for the area must be sought.

As assets will need to supply a set profile of hydrogen (a set proportion of the natural gas profile throughout the day), there may be an interest in using storage to buffer the demand for hydrogen with the availability of low-cost input fuels.

Depending on the end use, the level and the variability of blend have to be controlled. In this scenario, this is likely to be defined as part of the terms of the producer's connection agreement. The needs of users in a hydrogen blended area must be assessed before a hydrogen producer can blend hydrogen into the network. If a downstream user cannot take a hydrogen blend level or variability, it may be decided that a hydrogen generator it not allowed to connect to the network. Alternatively, the asset can:

- Upgrade to be compatible.
- Find an alternative natural gas procurement.
- Find an alternative energy source (e.g. electrification)

If the level of blend is constant, metering arrangement should consider the level of blend. However, it is up to the operator to control the metering arrangements for variable blend and define billing accordingly. Variable blend could increase load factor for generators as a way of flexibly selling excess hydrogen production.

It should be noted that many stakeholders have raised it would be inefficient to store a blend (as the main component, natural gas supply is secure) and the aim should be to store hydrogen. As such, Figure 40 shows the storage asset either deblending hydrogen from the gas network or being connected to the producer with a private pipe. Deblending is likely to be prohibitively expensive and as such, in this system arrangement, storage is likely to be located close to producers, connected by private pipes.

There must be a process for keeping track of where hydrogen producers have connected to the network and therefore where producers can still connect before approaches are put in place to manage hydrogen blending.

9.3.2 ORGANISATIONAL CONSIDERATIONS

Organisational considerations for PSA3 are quite straightforward and any of the models for blending described in section 6.1.1 are feasible. Complication arises if more than one retailer is able to supply customers. All retailers will contract with the only hydrogen producer but there is a need that the total consumption from all retailers to equal the amount of hydrogen injected into the network. In early implementations a single retailer in a trial would alleviate the challenge but would result in no competing offers to tempt consumers with.

Each retailer could balance their own customers but if the one retailer mis-orders then it is harder to identify who is responsible for the mismatch without a residual balancing actor. Potential system arrangement 4 introduces the system operator who would be able to alleviate this issue. In the meantime, responsibility for managing the overall blend can remain with the hydrogen producer who is best placed to deliver a consistent blend to the network, however something would need to be done about managing the costs to provide this residual balancing.

Discussion point: Are there individual customers in early conversion areas for whom alternative arrangements (i.e. a dedicated supply and storage of natural gas) who can be provided with what they need and allow the rest of the area to convert

There are no required organisational changes or currently unfulfilled functions which need to be addressed from today’s business as usual arrangements, provided a variable level of blend is acceptable, and if so PSA3 could be a commercial reality today. If a steady blend amount is mandatory, then it is likely that balancing / reserves businesses will be required to intervene and provide a back-up in the event of failure to meet the requirements.

9.3.3 MARKET AND TRADING CONSIDERATIONS

Blended hydrogen could be sold through the wholesale gas market (or local market if only part of the network is blended) and suppliers could attribute the low carbon hydrogen to their portfolio (so long as verified e.g. through GoOs) even if it was not directly being supplied to their customers.

Blending will need to be driven by policy. The way hydrogen blending fits into asset business models will be driven by the structure of this policy (see section 7.2.1) and the allowable hydrogen blend range in the region (i.e. whether the blend needs to stay consistent throughout the year).

As hydrogen blending is a short term solution it is likely the blending level will be set at that which all assets in the blended hydrogen area can operate. In this scenario little/no additional investment will be needed to convert assets to using hydrogen or in the network to be able to carry the H2 blend. There would, however, need to be investment in low carbon hydrogen producers. If an alternative route is taken, where the blend limit is set at a level which requires assets to be upgraded to take a blend, then investment will be needed. This will be driven by the principles discussed in the last section. It may be hard to gain investment for these upgrades as blending will not continue for a long time before the area must be converted to a net zero solution. Assets could convert to electricity or maintain a natural gas supply.

Sufficient pipeline capacity would need to be reserved for the hydrogen, initially on a non-competitive basis as this PSA is based on a single hydrogen producer. Prices would also need to be regulated for this PSA due to lack of competition.

Blending arrangements will likely be made to fit with existing arrangements for gas trading, through the National Balancing Point (NBP), as far as possible. Shippers would continue to trade energy and have imbalances settled on a national basis. If isolated parts of the network would be blended, however, then local trading could develop if sufficient buyers and sellers would exist, as described below for PSA4.

9.4 PSA4: LOCAL H2 BLENDED (MULTIPLE PRODUCER) ARRANGEMENT

Figure 41 shows a use-case where hydrogen is produced by multiple producers (as indicated by the 1…* notation). The biggest complication this brings is that (as described in section 6.1.1) multiple producers are each trying to inject hydrogen into the natural gas supply, but the upper limit is a maximum hydrogen content. There is a need to co-ordinate each producers' actions to manage to that content. Section 6.2 describes different approaches to solve this challenge. The hydrogen system operator is included (which isn't a role as it exists today) for completeness with those approaches described above. Note that the roles are not the same as companies – there is no intention to describe which organisation(s) perform which roles. The assumption is that there isn't a variable blend at this point since there are sufficient producers to make up short falls of any other producer. Note that this isn't to say the blend can't change over time. For example, for the first few years it could be agreed that the blend is 10% hydrogen and then it increases to 20% as more production facilities are commissioned. In other words, the blend rate changes over years but not minutes.

Commercial transactions occur between parties injecting at the local node and suppliers (presumably national as today) who transact with customers downstream. Similarly storage models are flexible as discussed in 6.3.1.

Every customer in the area will be affected by the blending and would either need to be comfortable with the blend or make alternative arrangements (such as electrifying or securing a different source of natural gas).

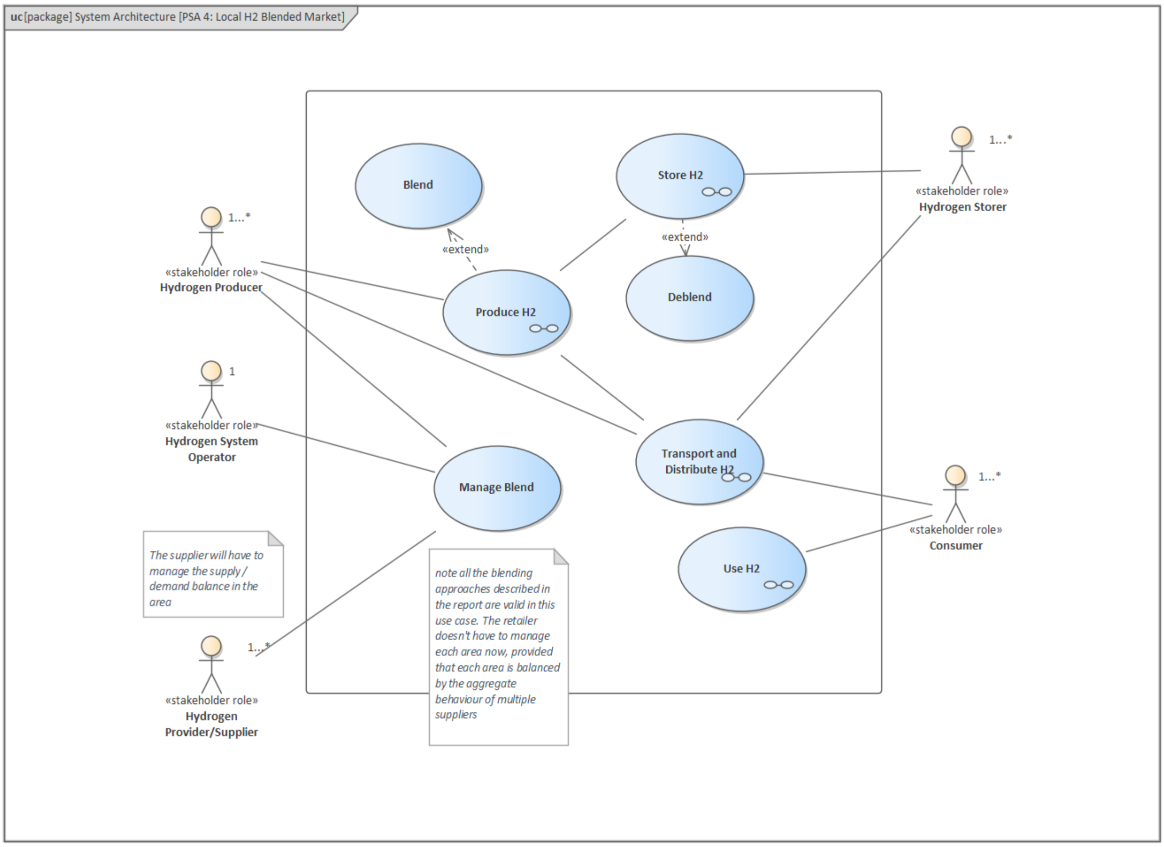

Figure 41 - Use-case diagram for PSA 4

9.4.1 PHYSICAL CONSIDERATIONS

The main concerns from PSA3 are the coordination between multiple hydrogen producer to maintain the blend limit in all sections of the network. An example of multistage blending on a network is described in section 5.6.2.

The different methods discussed to maintain the blend level and variability in each downstream section of the network are:

- Traded network capacity- this would work by a set capacity of network in the blended areas being reserved for hydrogen. This capacity would vary based on the estimated volume of hydrogen that will be flowing through the network in different time periods.
- Single injection point- this would work by all of the producers sending hydrogen to a single injection point at which hydrogen is added to the system.
- Multiple injection points - The assets need to be coordinated so that they collectively keep the blend within the allowed range and variability. The coordination can be centralised to allow each producer to inject a defined level of hydrogen. It can also be the responsibility of each producer to measure the current blend and keep the output blend level and variability within range. Consideration will need to be given to ensure fairness and compliance.

Another option would be allowing some parts of the network to raise hydrogen level above the blend limit adding a further deblending stage. As deblending is still not seen as a viable option, both energy incentive and commercially complex, this is not developed in as much detail as the controlled blending options.

The considerations for a local dedicated hydrogen arrangement (PSA5) also apply.

- A process for deblending- Some stakeholders may wish to supply hydrogen to an end user through blended pipes, with the end user deblending at the other end. Enabling this would be complex. Network charges, shipping capacity rights and licenses may need to change to include deblending. For this process to work the user would likely need to enter into a bilateral contract with an upstream producer. What the end user buys off the market must be considered as well as what is done with the natural gas they separate from the hydrogen, the network tariff applied to the user and the information they should provide to the network operator.

9.4.2 ORGANISATIONAL CONSIDERATIONS

Assuming the need for a constant blend level, the core organisational responsibility here is for the system operator, they either take a primary role or have an action of residual balancing and strategic reserve dependent on the approach to balancing as described in section 6.1.1.

In addition, hydrogen producers need to be able to moderate their production (could be increase or decrease) to be able to respond to the hydrogen system operator’s request for constraint, or to boost delivery in the event that another producer falls short. Effectively a balancing mechanism needs to exist for multiple producers injecting into a natural gas network and producers will need to support that.

Of course, both of these complications can be reduced, or avoided altogether, if a variable blend is allowed onto a network or if the storage operator acts to deliver balancing (see section 6.3.1).

9.4.3 MARKET AND TRADING CONSIDERATIONS

Under this PSA, the existence of multiple producers brings with it the benefits of competition and trading. The investment considerations are the same as in PSA3 other than with the addition of the process to coordinate blending. In Section 6.1.1, two methods were discussed for maintaining the blend limit. With greater competition, there may be less of a need to regulate prices and more opportunity to drive down costs through competition.

If isolated parts of the network are blended and there are multiple producers injecting in the isolated area, there may be a need for local balancing. The procurement of balancing services could be managed through a local trading platform. Blended energy in the isolated area could also be traded through a local trading platform (OTC brokerage).

9.5 PSA5: LOCAL DEDICATED H2 ARRANGEMENT

In PSA 5 an area of natural gas network converts to hydrogen fully or else a bespoke dedicated hydrogen network is developed.

As such all assets connected to the network have been converted to use hydrogen. A separate supply of natural gas may have been installed for users that still require it or an area of the natural gas network may not be decommissioned (though it likely would be by 2050 if not converted to H2).

Trading is similar to today's trading with natural gas, notwithstanding that retail offers can change to end customers (i.e. as Energy as Service etc.).

Care is required to ensure that retailers can choose to trade natural gas in some locations and hydrogen in others (i.e. in areas which have not yet got hydrogen available).

Lack of competition in a small geographical area may result in insufficient competition leading to the requirement of a regulated producer (natural monopoly) and supply and demand in a local area needs to be matched (either via the supplier buying and selling and/or a third party with residual balancing rights)

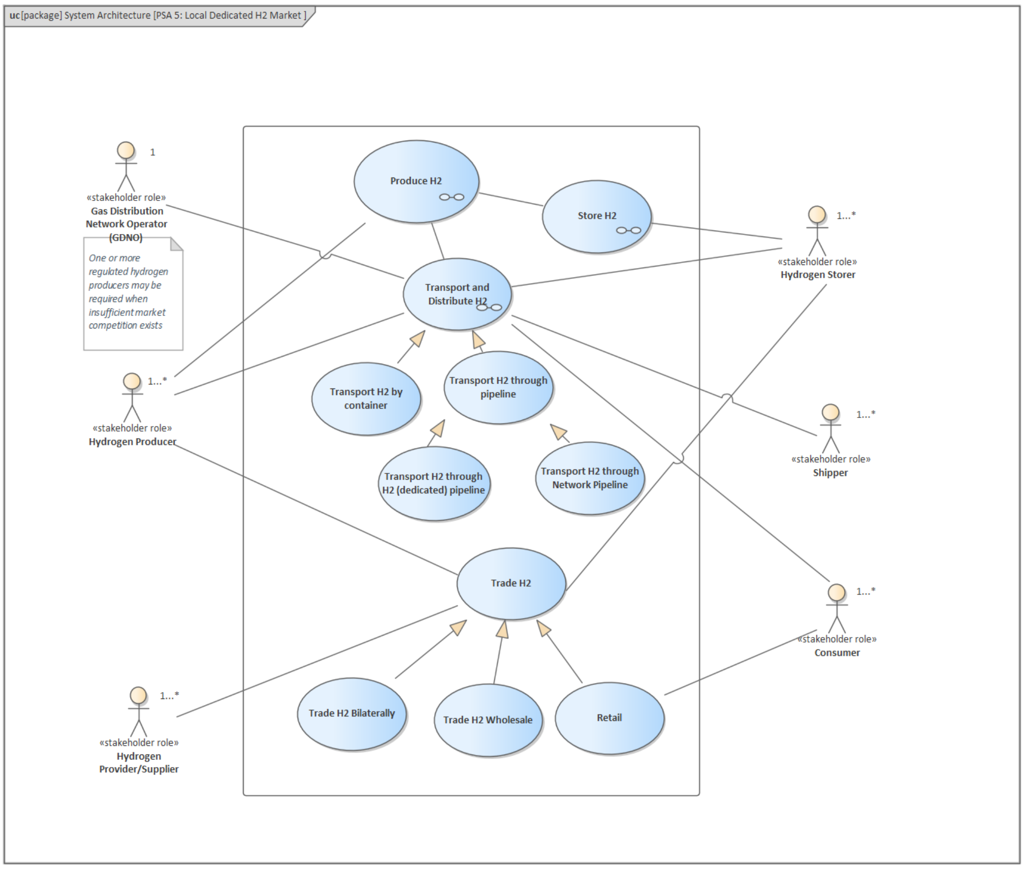

Figure 42 - Use-case diagram for PSA 5

9.5.1 PHYSICAL CONSIDERATIONS

In this setup, multiple producers can produce hydrogen for multiple consumers and potentially import and export outside of the local area.

For example, a way MH:EK could develop, multiple sources using renewable energy connected to electrolysers, auto thermal reformation and biomass gasification supplying heating, industry, and mobility in the region. Such local energy systems can be centrally controlled by one energy system controller which aims can focus on:

- Optimise energy use, energy efficiency.
- Minimise price for consumers. This can be done by optimising time of use for consumers or increase competition. This really depends on the scale of the market and the development of regulations.

- Prioritise use of local energy. This can minimise transport and promote local production. This can help retain skills and local employment.
- Prioritise decarbonisation to meet targets.

These different needs can be combined and adjusted throughout the development of the local area assets. This will require coordination and control between the different vectors.

Once multiple instances of elements and energy vectors are present, information needs to be compatible to be accessed and sent by the controller. For example, electricity supply for direct use and hydrogen production must be managed to follow electrical load, sufficient hydrogen production, price signals and optimal storage solution such as electrical storage to smooth electricity supply, hydrogen storage for interseasonal demand variations etc. In another example, hydrogen used for mobility, industry and heating have to be compatible and can include quality, interoperable units as well as current and forecast use. The purity in the network may be decided by the largest consumer, the highest purity requirements to fit all end users, the ease and cost of adding purification at end use for example.

The local area controller should be able to read metering data either from the energy supplier or directly from the consumer, potentially installing additional metering. This could be included at design phase. The status, availability, capacity of supply from different sources (whether from production or storage) has to be visible to the controller.

9.5.2 ORGANISATIONAL CONSIDERATIONS

At this point all of section 6.1 applies except references to controlling blending. In many ways the operation of a dedicated hydrogen system is much simpler than any level of blended system. The key point is now how to match production with consumption. In the early days' hydrogen production is likely to be limited whereas demand may greatly peak in the coldest winters (whether hydrogen is used either for heating or as seasonal storage to support electrification) therefore storage and demand flexibility are critical to managing the availability of hydrogen. As are back-up sources of containerised hydrogen (possibly from overseas) for emergency operation.

If this is the role of a reserves operator or residual balancer such as how National Grid Gas operate to the residual balancing incentive on today's natural gas system. While alternative approaches could be developed this current way of working is a natural first step for this activity, albeit in a local network, rather than national.

9.5.3 MARKET AND TRADING CONSIDERATIONS

If a decision is taken to convert a natural gas network to carry hydrogen, based on an independent whole system assessment, which considers costs and uncertainty across different energy vectors (as discussed in section 7.2.2) then hydrogen supply must be secured for the region. As discussed in section 7.2, this may be challenging given the step change required to ramp up supply and convert or replace gas-consuming assets. Significant interventions are likely required.

The existence of a local network dedicated to transporting hydrogen assumes a critical mass of producers and users. Import and/or export arrangements are necessary to ensure the market's efficiency and competitivity. Where insufficient liquidity exists, prices will need to be regulated. This PSA also requires suppliers to balance their portfolios (supply and demand) within the network, which creates a form of locational pricing for hydrogen.

Depending on progress in coordinating systems and markets, switching between energy vectors can reduce carbon emissions as well as prices for consumers. Such energy vector switching could be realised through a local energy trading platform and could provide small networks or systems with valuable flexibility. As small networks will be more vulnerable to shocks compared to national or large regional networks, the backstop role of the system operator will be important and potentially involve considerable out-of-market procurement of resources (e.g. storage).

With isolated networks dedicated to transporting hydrogen, while other parts of the main network continue transporting natural gas or blended gas, the opportunity to establish a trading hub or platform at local level is possible ahead of establishing a national trading hub. The local market could create price indices that could be used in other areas and a highly successful local hub may go onto become the national hub if a national pipeline later joins up local markets.

9.6 PSA6: NATIONAL / REGIONAL H2 BLENDED ARRANGEMENT

In this arrangement there is a regional or national network carrying a blend of hydrogen and natural gas. We define the difference between a local and a regional system as being that a local system is self-contained, all balancing activities need to occur inside that local area, as a responsibility of all retailer/suppliers operating in that area. In a regional or national system blending is done on aggregate across that "region" with balancing needing a residual balancing action.

Conceivably such an arrangement could occur if many "local" blended systems are integrated together although it is important to consider whether some local areas will transition to fully dedicated hydrogen before areas are connected together. If local areas which have transitioned to dedicated hydrogen are connected together then refer to section 9.7.

The location of blend sites is critical. For example, if all hydrogen production is in one area of the country (say the South East of England) and is injected, say to 20%, then by the time the concentration is measured, in Scotland, there won't be many molecules of hydrogen (as a percentage of the total volume) left. Assuming all the other locations in between the south east and Scotland have only injected more natural gas, yet off-take is occurring, then, by definition there can't be much left. See section 6.1.1 for details on the approaches to blending.

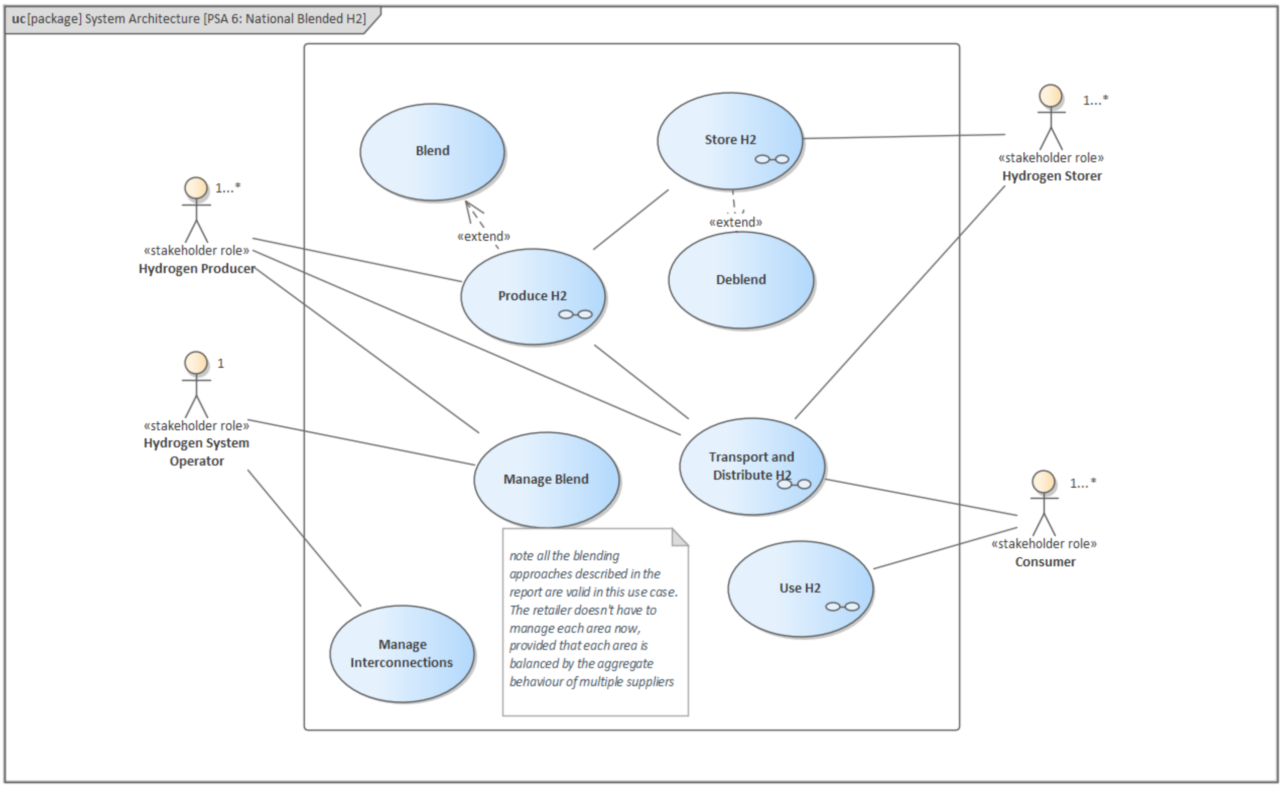

Figure 43 - Use-case diagram for PSA 6

9.6.1 PHYSICAL CONSIDERATIONS

This arrangement combines the considerations described for a local blended network (PSA4) and a national hydrogen network (PSA7). The additional consideration comes with :

- The location and level of hydrogen from multiple injections points. Single injection point is not considered for a regional level. The number and diversity of injection points is likely to be greater than for a local system adding to the complexity of the blend options (predefined, centrally controlled, injection point control or a combination of these).
- The stepwise transitions from natural gas to blend and blend to pure hydrogen. The impact of each transition on the supply demand control and the blend levels needs to be coordinated. For example, if a hydrogen storage asset is used for multiple injection points, transitioning one of them to pure hydrogen will affect the capacity requirements and impact the multi gas control of both systems.

9.6.2 ORGANISATIONAL CONSIDERATIONS

With a national blended hydrogen system a set of systems operation functions are required, as with PSA4, to perform national blend balancing across many retailers and producers, and also, likely to perform a residual balancing role (See section 6.1 for details on the approaches for blending).

Retailers in a national system will either purchase a blended product OR specific quantities of natural gas and hydrogen and the relative calorific values could then be managed as they are today in each natural gas region

9.6.3 MARKET AND TRADING CONSIDERATIONS

The market and trading consideration for this PSA are the same for PSA4, except at regional scale. In developing the hydrogen network, local networks could be joined up to create a regional network and hydrogen markets would develop alongside the infrastructure. Markets over larger geographic areas are typically more liquid and enable greater system efficiencies (e.g. balancing) but other system services remain highly specific to particular locations. Local markets may be hosted on a regional trading platform or local trading platforms may co-exist alongside regional trading platforms. Equally, regional, or local markets could be hosted on a national trading platform.

9.7 PSA7: NATIONAL / REGIONAL DEDICATED H2 ARRANGEMENT

PSA 7 is a relatively simple extension of PSA 5 in that a set of local dedicated hydrogen networks are integrated together or else a bespoke dedicated hydrogen network is developed.

Trading is similar to today's trading with natural gas, notwithstanding that retail offers can change to end customers (i.e. as Energy as Service etc.).

With these regional or national arrangements national retailers can trade natural gas in some locations and hydrogen in others (as regions transition).

Lack of competition should now not be an issue as with PSA 5 but where local areas have integrated together then consideration is needed for how different systems for dispatch and control integrate together (assuming they're not the same)

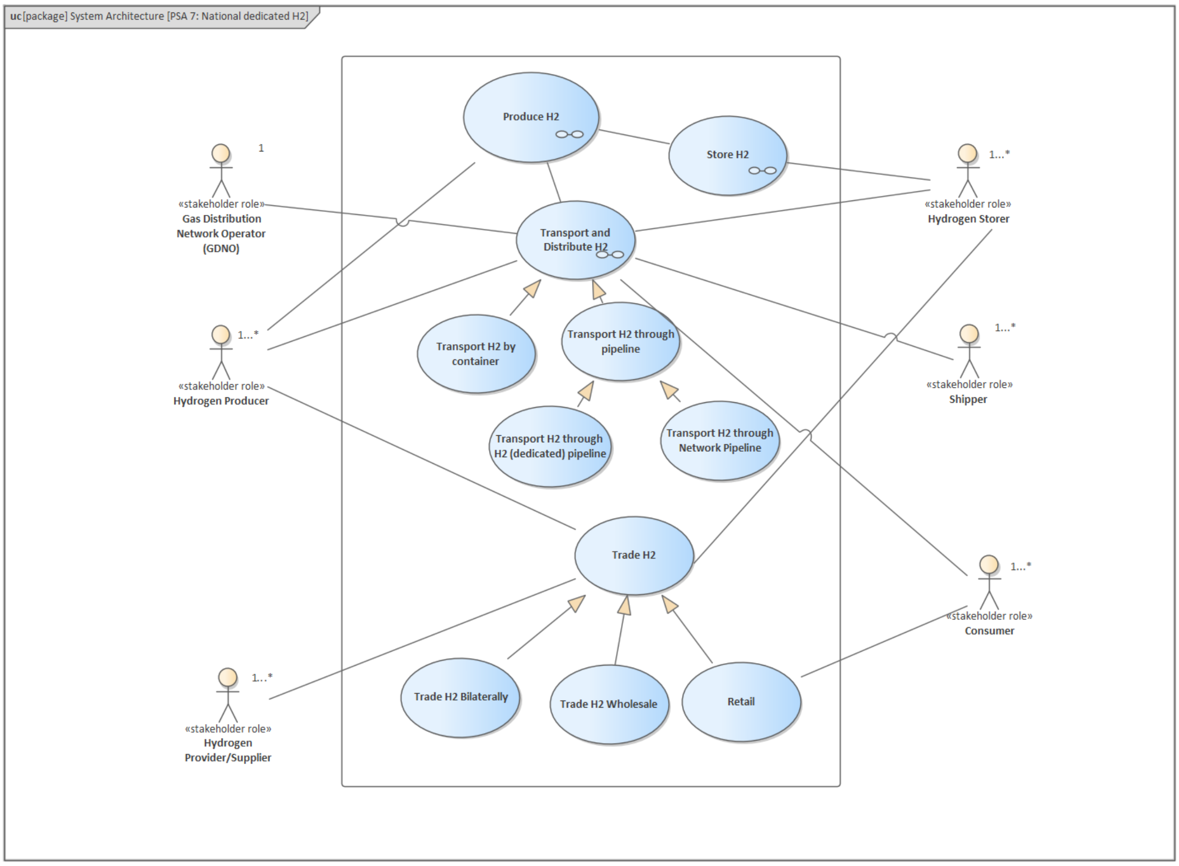

Figure 44 - Use-case diagram for PSA 7

9.7.1 PHYSICAL CONSIDERATIONS

As the hydrogen system develops and levels of control build up, each system inevitably becomes open. For each system, the total supply (import, production, storage reduction) needs to match the total demand (export, use, storage increase).

As for the development of the natural gas network in the UK in the 60s and 70s, if import becomes reliable and cheaper than domestic production combined with the development of a safe and comprehensive transmission system, the value of small scale production and storage will diminish, and the system operation will have to adapt. However, in a scenario like electricity development, if local production and flexibility can support efficiency and reliability, the needs from centralised generation will change over time.

Hydrogen supply within the boundary of a system is the sum of import, production, and available storage. This represents the total capacity of the system. The balance between these three elements can ensure security of supply.

The role of the controller on the supply side is to coordinate dispatch requests following rules and regulations and market signals (see section 5.9.3). The operator needs control the connected supply inlets to the network. This requires multi vector control of production feedstock and flexibility. Storage facilities, compressors and other preparation assets are usually co-located at these points.

The supply control has to coordinate from one side the capacity from production, import and storage to dispatch hydrogen in a prescribed form to the required location in time.

The parameters that the system operator needs to manage comprise:

- Capacity and availability
- Efficiency
- Ramping up and down capability
- Time and distance to end use request

Action Point: MH:EK stakeholders should make an active effort to work with other hydrogen projects to develop a consistent understanding to controlling dispatch and monitoring hydrogen networks with the intent of having a common approach to make integration simpler and quicker.

National Action Point: BEIS/OfGEM to consider unifying an approach and publishing a standard.

9.7.2 ORGANISATIONAL CONSIDERATIONS

In each case we have concentrated on the operational considerations of different roles. In national systems there is a need to consider the planning aspects too. In a system with scale and with visibility across multiple vectors it is important to understand how costs for the asset base are recovered. As a simple example, should a hydrogen turbine, which can provide electricity using seasonally stored hydrogen, be able to be funded through a mechanism such as the electricity capacity market? Under existing rules, it should be able to. Well what about a hydrogen electrolyser which can turn excess electricity into hydrogen for use by that turbine later? Under current rules it wouldn't be allowed but might this change in the future to encourage development. See section 7.1 for comprehensive detail on investment strategies.

A combination of the GDNO and Storage Operator (as described in section 6.3.1) would also be able balance the dispatch of hydrogen and take the role of a residual balancer rather than needing a specific additional systems operator.

9.7.3 MARKET AND TRADING CONSIDERATIONS

Under this PSA, a national core or transmission level pipeline connects up the regional and/or local markets to form a larger regional or national network. With establishment of a national hydrogen network, it becomes possible to set up a national exchange for trading hydrogen hosting organised short-term markets (see section 7.3*)*. The hydrogen trades through the national trading exchange would occur at a hypothetical point such as a local hydrogen system or on a point on the national hydrogen network. The national spot markets for hydrogen and electricity would likely become linked, enabling exploitation of the flexibility opportunities that come with market integration across energy vectors and larger geographic areas

Local or regional hubs trading hydrogen and/or electricity may continue to operate in parallel to a national trading hub, as locally specific products and services would still be needed, but their scope would change and likely reduce with the onset of a national trading exchange. Where regional networks exist, suppliers would need to balance their portfolio within the regional network.

As for PSA5, step change investment would be needed in hydrogen production, networks, and low carbon hydrogen-using assets in the region to be converted. By this stage, investment may be increasingly market-led though interventions would be needed to manage the step change transition.

9.8 TRANSITIONING BETWEEN AND SCALING POTENTIAL SYSTEM ARRANGEMENTS

The state transition diagram, in Figure 45, below illustrates how to transition between each of the potential system arrangements

Critically, what isn't shown on the diagram is that parts of a business could operate under different PSAs (i.e. as a producer you could self-consume some hydrogen on a co-located site and sell some more on a national hydrogen network if one were available. While this is achievable and possibly desirable in the early days of a transition it would create significant challenges for organisations such as system operators and regulators who would need to be able to support multiple approaches simultaneously. See Table 15 for more information on considerations of how a business could operate in multiple configurations as the same time.

A note on reading state transition diagrams:

A state transition diagram graphically illustrates each stable "state", in this case the potential system arrangements, represented as a box. Alongside the states are the "transitions", represented as arrows between the boxes. The notes on the lines are the simplest set of actions that need to be completed to transition between the two states.

Each start point, labelled "BaU" (business as usual) highlights a starting point, from today, and reflects that you could jump into the states in the middle of the diagram if desired (i.e. it is technically possible, though practically unlikely, to transition to a completely national blended hydrogen system with multiple producers and all customers using a blend in one step). Each "End" condition indicates that a business could stop at that point and not have to transition to another arrangement and set of markets, until that organisation felt it was advantageous to do so.

Note that it is possible to show the reverse arrows to illustrate how businesses could back out of a state and transition back up the diagram, but it makes the diagram much more complicated, and it seems very unlikely so for clarity these are not shown on the diagram.

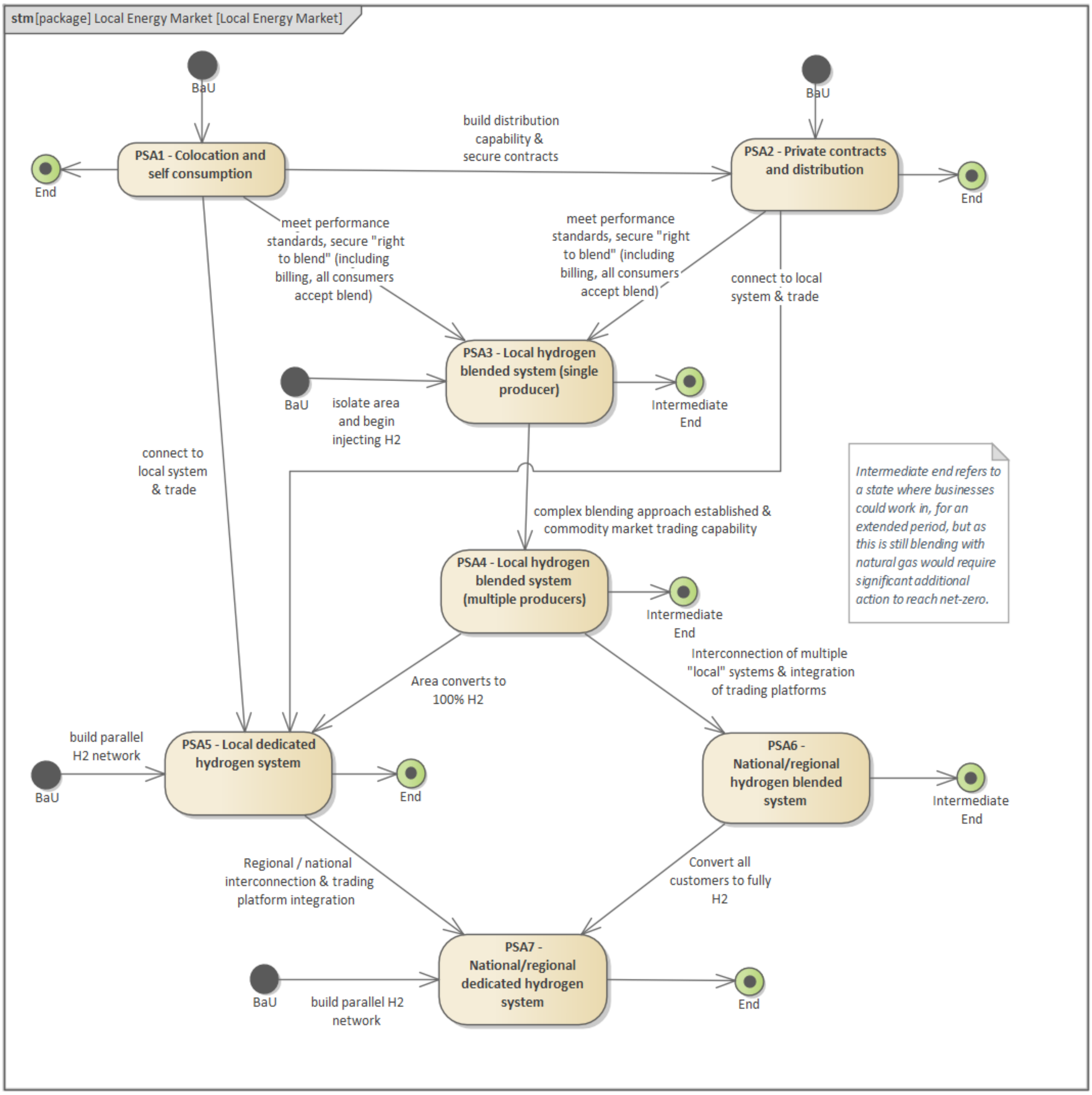

Figure 45 - State transition diagram to show how to move between potential system arrangements

9.8.1 PHYSICAL CONSIDERATIONS

As the system develops and interconnects, production has to be kept aligned with the use. The transition towards net zero will take time and the place of hydrogen in the energy mix will have to face simultaneously the following three challenges:

- The increase of hydrogen demand for heating, mobility, industry, and electricity generation in the UK and worldwide. The increase over the next 30 years will probably be stepwise depending on adopted technology and acceptance allowing mass applications.
- The supply of hydrogen locally, nationally, and worldwide. Where and when hydrogen production will be able to meet the need to replace fossil fuel and can compete with electricity or other energy vectors.
- How the balance between supply and demand can be achieve during each stage of development. Any oversupply or overdemand can be a setback to acceptance and future investment and development.

To transition from multiple co-located systems and assets to interconnected systems, independent controllers need connecting.

Independent controllers need connecting when multiple co-located systems and assets become interconnected. The transition requires interoperability of control including interoperability of information and communication. Model interoperability also supports the impact analysis within the hydrogen system and with other energy vectors. The new control system can become either a:

- Centralised controller replacing the individual controllers.
- A set of distributed controllers communicating with each other.
- A set of distributed controllers supervised by a high-level controller

9.8.2 MARKET CONSIDERATIONS

Table 15 below describes how a part of a business acting under one PSA can also be configured to operate part of its business in another arrangement. This gives maximum opportunity to be able to transition between the different arrangements. Note that the table is written from the perspective of a hydrogen producer. For consumers / end-users it is assumed that they are connected to one pipe, and/or have containerised hydrogen delivered as appropriate, and they can operate in any of the arrangements simultaneously as well. As for the other actors, most notably system operators it is assumed that each PSA will have its own actors (whether that it is whole organisations or departments who are purely focused on keeping their arrangement working effectively. In effect the system operator in PSA4 and the system operator in PSA6 are independent (even if, in reality it is one organisation performing both roles).

		One part of a hydrogen producer's business						
		PSA1	PSA2	PSA3 (1 supplier)	PSA4 (n suppliers)	PSA5 (local H2)	PSA6 (Nat blend)	PSA7 (Nat H2)
One part of a hydrogen producer's business	PSA1	x	self-consume some H2, trade the rest and transport to users	private sales for some H2 and local market for other	private sales for some H2 and local market for other	private sales for some H2 and local market for other	private sales for some H2 and local market for other	private sales for some H2 and local market for other
	PSA2	x	X	private sales for some H2 and local market for other	private sales for some H2 and local market for other	private sales for some H2 and local market for other	private sales for some H2 and local market for other	private sales for some H2 and local market for other
	PSA3	x	x	X	though unlikely, a producer could inject into one network as the sole producer and contribute in another	though unlikely, a producer could deliver H2 into a local blended network and into a local dedicated H2 network	local sales for some H2 and national market trading for other H2 production	local sales for some H2 and national market trading for other H2 production (though unlikely to have local blend and national dedicated H2)
	PSA4	x	x	X	X			

	One part of a hydrogen producer's business						
	PSA1	PSA2	PSA3 (1 supplier)	PSA4 (n suppliers)	PSA5 (local H2)	PSA6 (Nat blend)	PSA7 (Nat H2)
PSA5	x	x	X	X	X	local sales for some H2 and national market trading for other H2 production	local sales for some H2 and national market trading for other H2 production
PSA6	x	x	X	X	X	x	highly unlikely to have a national blended and dedicated H2 system
PSA7	x	x	x	X	X	x	x

Table 15 - Co-existence of multiple arrangements (from a hydrogen producers' point of view

9.9 INITIAL PROJECTS AND CONSIDERATIONS FOR TRANSITION:

In this section we cover the two shortlisted projects for early demonstration and the three core project areas being considered by the MH:EK team namely:

Ref	Title	Description	Presumed initial PSA category
1	MH Heat network and microgrid	Electrolyser generates hydrogen from renewable electricity sources to avoid constraints.	PSA2
2	Pembroke food park		PSA2
3	Pembroke schools and leisure		PSA2
4	FCEV charging	Electrolyser or tanker deposits hydrogen into refueller (in this case considered the user, despite onward delivery to driver)	PSA1 (electrolyser) PSA2 (tanker delivery)
5	Hydrogen heating trial	For a future project phase hydrogen delivered to hybrid heating systems	PSA3 (Assuming one supplier of hydrogen into blend)

Table 16 - Initial Milford Haven Projects

Table 15 contains the generic considerations of how different potential system arrangements can work together (i.e. be compatible at the same time) while Figure 45 describes what needs to be satisfied to enable another transition to be open to a given actor. Table 17 describes the considerations that each of the early projects listed in Table 16 should be aware of to future proof their implementations for future potential system architecture roll-out. The aim is that by doing a bit more at design and deployment now, there is more opportunity with later changes.

Transition	**Design considerations**
PSA1 to PSA2	Ensure there is more production capacity than required for initial sales, ensure that contracts are flexible enough to support organic growth of either supply or demand.
PSA1 to PSA3	Location of generation site could be critical to be at a network injection point which works for all customers downstream – e.g. avoiding critical C&I users who can't take a blend or variable blend therefore: Create a process to assess the allowable hydrogen blend in a region. Identify optimal generation location to create an injection point. Introduce metering arrangements which work with variable hydrogen blending. Create a process to monitor where hydrogen producers have connected to the network.
PSA1 to PSA5	Flexible contracts to move from direct trading to market transactions and technical capability of moving from direct pipes or containers to pipe connections. Hydrogen purity sufficiently high to be allowed to connect.

Transition	**Design considerations**
PSA2 to PSA3	As per PSA1 to PSA3
PSA2 to PSA5	As per PSA1 to PSA5
PSA3 to PSA4	Need sufficient controls to be able to respond to balancing blend requirements, organisational systems to manage retailer interface.
PSA4 to PSA5	Hydrogen purity sufficiently high to be allowed to connect
PSA4 to PSA6	Ability to trade on multiple markets (national/regional and local) and to ensure that sales can't be duplicated.
PSA5 to PSA7	Flexibility to move between trading platforms, understand data requirements in an open format to be able to move between different systems.
PSA6 to PSA7	Hydrogen purity sufficiently high to be allowed to connect. Flexibility to move between trading platforms, understand data requirements in an open format to be able to move between different systems.

Table 17 - Considerations for initial projects to support future transitions

10 CONCLUSION

What is a SLES? A question which many people have tried and are still trying to address. Throughout this work have found that a significant recurring theme which defines a truly Smart Local Energy System is the integration between different related areas, to a far tighter degree than in our existing energy systems. Solutions to these interface challenges are presented throughout this document as either options (see section 9), or considerations requiring further exploration and development (Section 11).

Fundamentally in Milford Haven: Energy Kingdom there are relationships between:

- Organisations, technologies, markets, and policies
  - For example, decisions on blending approaches, impacts control technologies and similarly on the roles and responsibilities for who ensures the blending quantities are controlled which would, likely, be defined through licence conditions. That requires different approaches for asset ownership and different methods of trading.
- Local and adjacent locales, regions, and national systems
  - Possible conflicts arise at the interfaces between local and regional, especially where commercial and physical imperatives aren't necessarily aligned for example a local asset might alleviate a local challenge but might be more commercially attractive to trade nationally.
- Inter-related vectors
  - Electricity can be used to create hydrogen, hydrogen can be injected in proportional quantities to the flow of natural gas, multi-vector, or hybrid demand (say a hybrid heating system) can switch between supply sources, thereby providing system flexibility.
- Production and demand
  - For markets to build organically both supply and demand need to grow in lockstep.
  - Storage can provide a buffer to smooth out variable supply and demand profiles although supply business models (both ownership and operating models) are the least mature.
  - For hydrogen, industrial and chemical feedstock applications seem to be first to market but heating and transport opportunities aren't far behind but require more sophisticated market, retail, and control approaches (particularly in blended systems)
- Actors / businesses within the value chain
  - Roles and responsibilities change in future SLES' and new ones are created, making opportunities for existing businesses or new ones to emerge with interfaces between multiple parties needed to be coordinated.
- Capital and operational income
  - Outside of private investment, production support mechanisms are likely to be the best source of funding for early construction. In the long term, these should be phased out in favour for a long-term decarbonisation driver e.g. through carbon pricing or supplier incentives.

All of these reinforce the need to design with a whole systems approach as we have here. Considering a single component for a solution without considering the effect on the complex interdependencies is likely to miss key features.

For this reason we think the approach that this project has pursued has demonstrated a template process for what could happen in other Smart Local Energy Systems, where knowledge of specific solutions and techniques is important, but where a comprehensive process such as the one followed here captures local opportunities and challenges and best frames a set of comprehensive needs and solutions for a more sophisticated approach to energy systems.

Over the course of the work several themes re-occurred which require a centralised government response. These are collected together in (Section 11) as "National Action Points". **These are the pieces of advice to government and regulators for supporting the hydrogen transition arising from this work.** In the table are links to the detail in the rest of the document but in summary the core ideas which could be blockers to a hydrogen heavy SLES are:

- Making hydrogen valued appropriately against other vectors or carriers such as natural gas could require a more comprehensive approach to carbon pricing. This could also be helpful to appropriately value the different forms of hydrogen production (e.g. blue or green)
- Early movement on regulating production until there is sufficient competition to send appropriate pricing signals
- An agreed approach to network and infrastructure cost recovery
- An approach to supplier obligations (if appropriate) to encourage uptake of low-carbon gases.
- Publication of standards, particularly on purity and quality so that innovators have confidence as to the operation of their equipment.
- An approach to production support (similar to CfDs) of hydrogen assets to establish and build an early set of production (and storage) assets until the industry is self-sufficient.

Finally, we have identified the initial potential system arrangements (PSAs) which can be started immediately and with roadmaps for the other arrangements to emerge.

- PSAs 1 and 2 to a certain extent, already exist now with private organisations producing and trading hydrogen privately.
- PSA 3 is the first stage in developing a blended hydrogen system requiring market development at the retail end, progressing to PSA 4 with the establishment of a proper trading market to facilitate end-to-end trading.
- PSA 5 is the first stage in a dedicated hydrogen system

On those, during the design process it became obvious that a blended system is much more complicated than a dedicated one in terms of implementation and that a blended system with a fixed blend limit, i.e. must be 20% constantly rather than a varying limit is more complicated still, despite the prevailing direction in industry seeking to pursue this in terms of a low initial capital cost. Perhaps further, whole system cost and complication analysis would be helpful to decide whether or not this should be the first port of call.

This report identifies a number of actions at varying levels which form the basis of required next steps. They are collated and summarised in (Section 11) and form the set of recommendations from this work.

11 ANNEX A – ACTION, DISCUSSION AND DECISION POINTS COLLATED

This annex can be found in a separate document titled: "MHEK full report - Annex and Appendix (except C and E)"

12 APPENDIX A – DOWNLOADING THE ENTERPRISE ARCHITECT SYSML MODEL

This appendix can be found in a separate document titled "MHEK full report - Annex and Appendix (except C and E)"

13 APPENDIX B – NEEDS CAPTURE PROCESS

This appendix can be found in a separate document titled "MHEK full report - Annex and Appendix (except C and E)"

14 APPENDIX C – NEEDS CAPTURED DURING STAKEHOLDER WORKSHOPS

This appendix can be found in a separate document titled "MHEK full report - Appendix C, Needs captured during stakeholder workshops"

15 APPENDIX D – PHYSICAL SYSTEM SUPPORTING DETAIL

This appendix can be found in a separate document titled "MHEK full report - Annex and Appendix (except C and E)"

16 APPENDIX E – TRADING PLATFORM

This appendix can be found in a separate document titled "MHEK full report – Appendix E, Trading Platform Requirements Specification"

17 APPENDIX F – UNCERTAINTY IN THE FUTURE USE AND PRODUCTION OF HYDROGEN

This appendix can be found in a separate document titled "MHEK full report - Annex and Appendix (except C and E)"

18 APPENDIX G – GLOSSARY

This appendix can be found in a separated document titled "MHEK full report - Annex and Appendix (except C and E)"

19 APPENDIX H – ACKNOWLEDGMENTS

This appendix can be found in a separated document titled "MHEK full report - Annex and Appendix (except C and E)"

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