Milford Haven : Energy Kingdom – System Architecture Report – Annex and Appendix (except C and E)

Milford Haven : Energy Kingdom, A Prospering from the Energy Revolution project

Energy Systems Catapult

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29th July 2021	Draft	First draft for review
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Contents

11. Annex A – Action, discussion and decision points collated

The table in this annex is a collection of the points that are relevant to the project and the ESC would recommend for further exploration, for more detail see section 3.3 of the main report

Ref	Chapter	Page No	Type	Action Point
1	4.3 The relevance of the hydrogen transition for Pembrokeshire	24	Action Point	The project stakeholders including those in future phases should aim to remain central to the developments of the hydrogen debate in the region, providing links, insights, and coordination
2	5.1.4 Local production considerations	31	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.
3	5.2.3 Local Transport and Distribution Considerations	35	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 GDNO and ESO.
4	5.3.1 Local Storage Considerations	37	Discussion Point	MH:EK project should define a pathway for hydrogen storage using MH:EK existing assets and expertise where possible while considering national storage options.
5	5.4.1 Local Use Considerations	39	Action Point	MH:EK project could push for future designs to include multiple end users' connections requirements
6	5.4.2 Industry	40	Decision point	Early assessment of current hydrogen use in the MH:EK for refinery and agriculture to plan decarbonisation of production to existing demand.
7	5.4.3 Mobility	42	Action Point	Analyse the transition of council fleet of vehicles (busses, van, bin lorries, cars) and compare to their electric alternative as part of the whole region energy plan.
8	5.4.5 Electricity Generation	45	Discussion Point	Plan the long-term future of Pembroke Power Station. The plan needs to fit with the local and national hydrogen architecture plan and decarbonisation pathway.
9	5.5 Preparation	46	Discussion Point	Planning applications should include hydrogen characteristics and preparation requirements early in project design.
10	5.6 Blended Hydrogen network	53	Action Point	MH:EK should define a clear roadmap for the whole transmission and distribution network including blended hydrogen.

Ref	Chapter	Page No	Type	Action Point
11	5.7 Import / Export	55	Discussion Point	As production and the international market grow, MH:EK should monitor closely export opportunities.
12	5.8 Hydrogen System Interoperability	59	Discussion Point	At a local level, PCC could include data openness and energy data requirements as part of the planning applications process.
13	5.9 Hydrogen System Control	63	Decision point	Understanding the control architecture, the communications protocols, and the level of interoperability between the different regional controllers will support the definition of the network control strategy.
14	5.9.3 Dispatch approaches	68	National Action Point	Government should publish how it intends to derate hydrogen produced through different methods with different carbon intensities and/or efficiencies.
15	5.9.4 Multi vector Control	69	Decision point	Decide the role and responsibilities of operator at micro grid and local level from the onset.
16	6.1.1 Match Production with Consumption	78	Decision point	Decide which of the blending control models better serves the local energy system's needs and stakeholders.
17	6.1.1 Match Production with Consumption	78	Decision point	Decide which aspects of systems in Milford Haven would be better as indirect or directly controlled early on and communicate to stakeholders.
18	6.1.2 Trade Resources and Capacity	79	Decision point	Decide whether MH:EK trading platforms should trade in commodities alone or also trade access to network capacity and infrastructure resources.
19	6.1.2 Trade Resources and Capacity	79	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.
20	6.1.3 Manage network capacities	81	National Action Point	Government to determine new approaches to drive cost-reflective, temporally, and geographically granular network charges to avoid market distortions.
21	6.1.3 Manage network capacities	81	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.
22	6.1.3 Manage network capacities	82	Decision Point	It is critical for government, regulators, and businesses to agree on the roles and responsibilities for network management.
23	6.1.4 Manage quality of service	83	Action Point	Milford Haven and stakeholders should ensure that they understand the requirements for local hydrogen quality.
24	6.1.5 Integrate with regional and national systems	85	Decision point	What is the ambition for the level of independence from national and regional systems within the Haven and surrounding areas.

Ref	Chapter	Page No	Type	Action Point
25	6.1.6 Co-ordinate multi-vector assets	86	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.
26	6.1.6 Co-ordinate multi-vector assets	86	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.
27	6.2 Retail functions	88	Action Point	Milford Haven add their voice to future changes required to allow new business models and by working with retailers to allow them to run commercially viable businesses.
28	6.2.1 Billing	89	Action Point	Milford Haven could be a proving ground to demonstrate the effectiveness of standards.
29	7.1.1 Who would invest	93	Action Point	Schedule and carry-out regular horizon-scanning on investment trends and cost reductions for hydrogen
30	7.1.2 Drivers and factors influencing investment in hydrogen	95	National Action Point	UK government to ensure alignment of effective carbon prices across energy vectors, removing distortions across energy vectors and sectors
31	7.1.2 Drivers and factors influencing investment in hydrogen	100	National Action Point	Ensure system value is more accurately reflected in energy price signals that are granular by time and location.
32	7.1.2 Drivers and factors influencing investment in hydrogen	108	Action Point	Assess the Technology Readiness Level (TRL) and conduct a detailed risk assessment for hydrogen-based technologies or solutions that could be developed in the Milford Haven area.
33	7.1.2 Drivers and factors influencing investment in hydrogen	109	National Action Point	UK Government to systematically identify and remove regulatory barriers to the development of low carbon hydrogen.
34	7.1.3 Current state of policy support for hydrogen investment	112	Action Point	Consortium Members to engage with national policymaking and register with information processes relating to support for hydrogen-related investment and activities.

Ref	Chapter	Page No	Type	Action Point
35	7.1.3 Current state of policy support for hydrogen investment	113	Action Point	The consortia should follow and engage with the development of the Wales Hydrogen Strategy and track progress.
36	7.1.3 Current state of policy support for hydrogen investment	113	Action Point	Milford Haven stakeholders should map and track the changing policy and regulatory landscape (local, regional, national, international) for hydrogen.
37	7.1.4 Network Investment and regulation	114	National Action Point	A process must be established for assessing whether and how to adapt or build networks for hydrogen.
38	7.1.4 Network Investment and regulation	114	Action Point	The MH:EK consortia to conduct the process discussed above in the region
39	7.1.4 Network Investment and regulation	115	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.
40	7.2.3 Initial steps to encourage and enable trading	122	National Action Point	UK Government to develop a UK scheme to certify the carbon intensity of hydrogen or adopt EU or international approaches. Enable trading of certificates.
41	7.2.3 Initial steps to encourage and enable trading	123	National Action Point	UK Government strengthen the robustness of carbon accounting and tracking across the UK's energy system as well as monitoring, reporting and verification (MRV) for carbon.
42	7.2.3 Initial steps to encourage and enable trading	123	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.
43	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	124	National Action Point	Establish arrangements to monitor competition on small hydrogen networks.

Ref	Chapter	Page No	Type	Action Point
44	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	124	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 these arrangements if competition increases sufficiently in the region.
45	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	124	Action Point	Support the development of price indices
46	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	124	Action Point	Support the establishment and trading of Guarantees of Origin (GoO)
47	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	124	Action Point	Engage with national policy
48	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	124	Action Point	Develop a local multi-vector trading platform based on current and future local needs.
49	7.2.4 Establishing a local hydrogen market and trading in Milford Haven	125	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.
50	7.2.5 Establishing a national trading exchange	127	National Action Point	The UK could position itself as a leader to influence or drive forward international developments for hydrogen trading.
51	7.2.5 Establishing a national trading exchange	127	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.

Ref	Chapter	Page No	Type	Action Point
52	9.3.2 Organisational considerations	156	Discussion Point	Identify individual customers in early conversion areas for whom alternative arrangements can be provided
53	9.7.1 Physical considerations	167	Action Point	MH:EK stakeholders to work with other hydrogen projects to develop a consistent understanding to controlling dispatch and monitoring hydrogen networks.
54	9.7.1 Physical considerations	167	National Action Point	BEIS/OfGEM to consider unifying an approach and publishing a standard.

12. Appendix A – Downloading the Enterprise Architect SysML model

<MH:EK Model Viewer Guide> 0.3MB Word Doc

(https://catapultore.sharepoint.com/:f:/r/sites/MilfordHavenEnergyKingdom/Shared%20Documents/WP01%20System%20Architecture/5.%20Draft%20Report?csf=1&web=1&e=mCZfax)

<MH:EK Project Model> 9.3MB Zip File

(https://catapultore.sharepoint.com/:f:/r/sites/MilfordHavenEnergyKingdom/Shared%20Documents/WP01%20System%20Architecture/5.%20Draft%20Report?csf=1&web=1&e=mCZfax)

13. Appendix B – Needs capture process

13.1. First Stage

MH:EK project objectives were extracted from the PFER submission, followed by a first review to split them into groups (Economy & Policy, Environment and Vectors). The quarter 1 review meeting (30/06/2020) allowed ESC to express these objectives as goals as shown in the diagram presented in the main document and listed below:

Need Group: System, Environment, Community and Education

Need Group: Vector

Need Group: Economy and Policy

Need: Develop Investable Propositions

Needs description: MH:EK will develop investable propositions, from procurement-ready equipment packages, to design outlines for major energy generators, users, and infrastructure.

Need: Reduce Investor Risk Perceptions

Needs description: MH:EK will greatly reduce investor risk perception through testing user propositions via fuel cell vehicle and residential heating live trials

Need: Develop Commercial Model

Needs description: MH:EK will develop a commercial model that will support investment cases and seek to validate reductions of up to 40% in whole system costs of energy provision from the hydrogen-renewables system

Need: Model Energy Patterns

Needs description: MH:EK will perform detailed modelling of energy supply, distribution and consumption patterns around the Milford Haven Waterway, with a strong emphasis on gas network modelling and simulation of the current and future network and the assets that connect to it.

Need: Engage Vendors

Needs description: MH:EK will engage Vendors through Requests for Information early in the Trading Platform system architecting process to ensure that, through iterative design, our platform design is deployable, investible, and replicable at scale.

Need: Design Trading Platform

Needs description: MH:EK will design a trading platform that will be scalable and vendor-neutral, with open protocols and inter-operability strongly favoured

Need: Build Hydrogen-Ready Infrastructure

Needs description: MH:EK will immediately build hydrogen-ready features and technologies into the Port's housing, commercial and renewables projects and will allow local people to test real-world hydrogen vehicles and home heating equipment.

Need: Deliver Novel System Architecture

Needs description: MH:EK will deliver a novel system architecture to allow integration from national to local network levels, and future integration of major natural gas infrastructure and current and future large-scale hydrogen infrastructure.

Need: Lower Consumer Costs

Needs description: MH:EK will a feature a flexibility trading platform to lower costs for consumers using hydrogen-ready hybrid heat pumps and hydrogen fuel cell vehicles, and to help lift constraints on local development of solar, wind and offshore renewable power generation

Need: Exploit Local Pathways

Needs description: MH:EK will meet the heating and transportation needs of local communities, including via fuel cell vehicles; creating transport solutions for Pembrokeshire's 4.2 million annual tourists; allow H2 production from curtailed onshore wind and solar generators; and improve off-take markets for offshore renewables in the South-Western Approaches, including the consented Pembrokeshire Demonstration Zone (PDZ).

Need: Evaluate Integration Viability of Energy Assets

Needs description: MH:EK will evaluate the viability of integration of a wide range of potential hydrogen energy assets (including interconnecting gas networks), including power-2-gas injection, heavy duty port equipment, hydrogen use in local Milford Haven power plant and Pembroke CCGT, anaerobic digestion decarbonised gas inclusion, offshore wind derived green hydrogen provision, hydrogen repurposing potential at LNG facilities, large scale storage of hydrogen on existing hydrocarbon storage sites (e.g.: Puma) and potential anchor load hydrogen offtake at the Valero refinery site

<u>Need</u>: User Test Transport as a Service Model

<u>Needs description:</u> MH:EK will user test a novel fuel cell vehicle transport as a service model

<u>Need</u>: Accommodate Small-Scale Pilot Installations

<u>Needs description:</u> MH:EK will accommodate the small-scale data gathering pilot installations associated with two RAVA fuel cell light duty vehicles as well as the heat pump and other domestic hydrogen appliance deployment in an unoccupied residential trial (within a commercial building envelope on the Milford Haven Port Authority facility)

<u>Need</u>: Include Hydrogen Systems

<u>Needs description:</u> MH:EK will include renewable (green) hydrogen production, compressed hydrogen storage, HRS (hydrogen refuelling station) layout, vehicle refuelling location, local hydrogen reticulation and hybrid heat pump requirements in the energy system design for Milford Haven

<u>Need</u>: Use Existing Precedence

<u>Needs description:</u> MH:EK will draw upon UK and international precedent to design the energy system for Milford Haven

<u>Need</u>: Comply with UK Technical Standards

<u>Needs description:</u> MH:EK will design and detail the energy system for Milford Haven in compliance with UK technical standards, including necessary technical details to satiate required safety and environmental strictures for the core system

<u>Need</u>: Develop Trading Platform Specification

<u>Needs description:</u> MH:EK will develop full trading platform function specifications, including technical, configuration, process and performance integration and associated information necessary for equipment and installation procurement

<u>Need</u>: Demonstrate Hybrid Hydrogen Heating System

<u>Needs description:</u> MH:EK will assess the feasibility and demonstrate the viability of hybrid hydrogen heating systems to bridge the gap between all electric or fossil fuel heating systems.

<u>Need</u>: Demonstrate Hydrogen FCEV

<u>Needs description:</u> MH:EK will demonstrate that hydrogen fuel cell electric vehicles are a core part of the whole systems approach

Need: Prove Market Demand

Needs description: MH:EK will prove the market demand and usability of hydrogen fuel cell electric vehicles for local use around a central refueller

Need: Build Business Case

Needs description: MH:EK will build the business case for hydrogen generation and hydrogen refuelling infrastructure to enable vehicle fleet use centred around a central refueller

Need: Engage Stakeholders

Needs description: MH:EK will engage stakeholders by explaining the potential environmental, economic, societal, wellbeing, energy security and practicality benefits of a decarbonised multi-vector energy system. Use the vehicle and hydrogen heating demonstrations to reinforce this

Need: Engage Investors

Needs description: MH:EK will engage investors by demonstrating an economic and sustainable investment case for a decarbonised multi-vector energy system

Need: Develop Energy System Concept Design

Needs description: MH:EK will develop a detailed concept design of an energy system for Milford Haven in 2030 that is in transition towards being fully decarbonised

Need: Develop Energy System Conceptual Proposal

Needs description: MH:EK will develop a conceptual proposal for what a 2050 decarbonised energy system at Milford Haven could look like and identify the short term investments

Need: Understand Economic Case

Needs description: MH:EK will understand the economic case for a decarbonised multi-vector energy system through energy supply-demand modelling

Need: Identify Policy Change

Needs description: MH:EK will establish a roadmap that will identify policy change necessary to support an energy system that incorporates hydrogen, including potential support mechanisms

Need: Understand Market Mechanisms

Needs description: MH:EK will understand and map market mechanisms that would create a sustainable demand for a hydrogen energy economy

Need: Use System Architecture

Needs description: MH:EK will use a system architecture that can be implemented with commercial-ready solutions and which focuses on underlying fundamentals and is therefore robust in the face of regulatory change

Need: Integrate Major Energy Facilities

Needs description: MH:EK will integrate a wide range of major energy facilities, renewable energy generators and energy consumers in the community

Need: Establish Seed Markets

Needs description: MH:EK will establish seed markets for use of hydrogen around the Milford Haven Waterway

13.2. Second Stage

The information captured during the project has been assessed using a systems approach called Needs Analysis. This is where the opinions and concerns of a set of stakeholders is gathered (such as in the Focus Groups and workshops), reviewed and categorised. This process is graphically represented in Figure 1 and the data is provided in section 14. This data is then incorporated into the Systems Architecture, when applicable, and a few examples are given below.

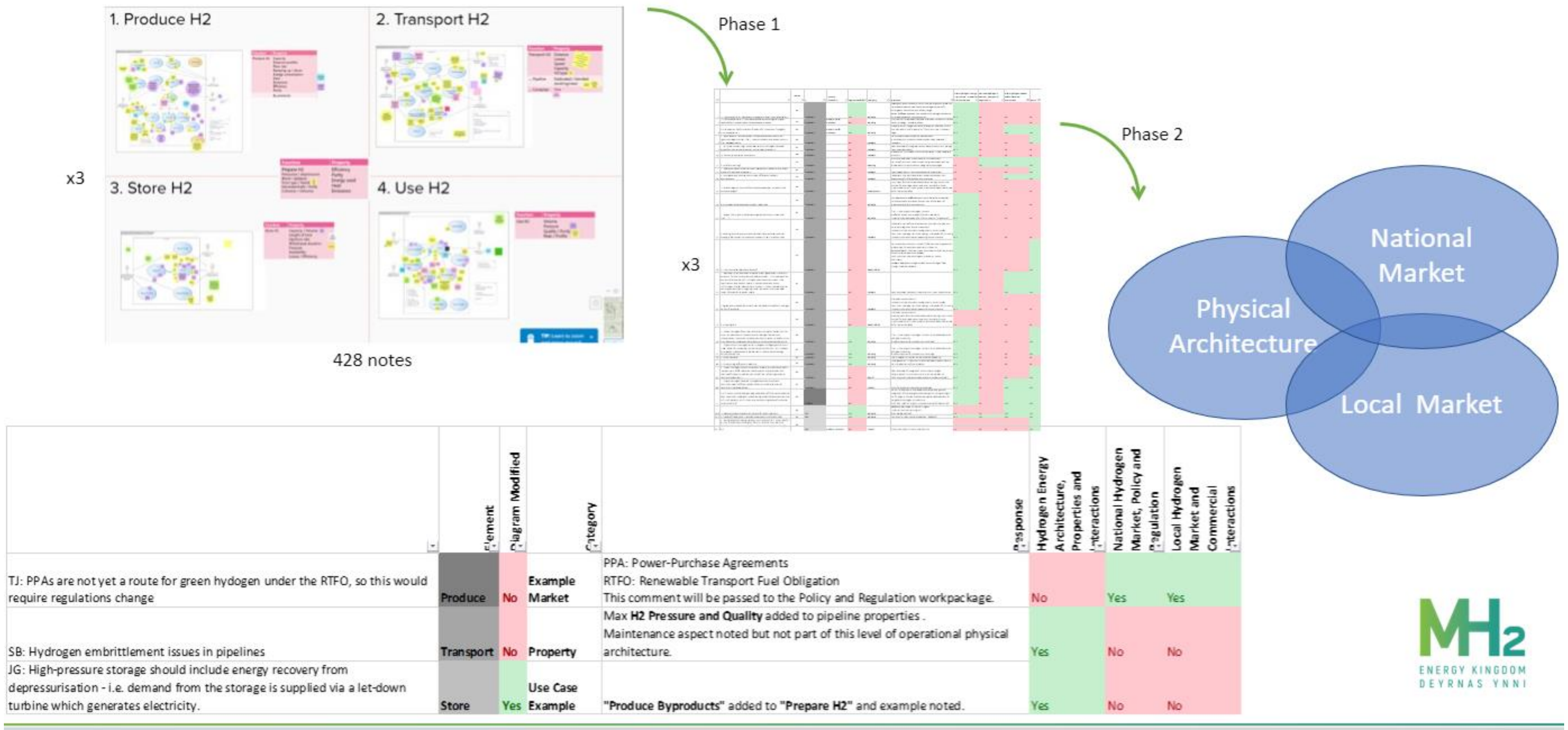

Figure 1 – Outline Process for Needs Analysis Assessment

14. Appendix C – Needs captured during stakeholder workshops

Data is in word doc, separate appendix, link below

https://catapultore.sharepoint.com/:f:/r/sites/MilfordHavenEnergyKingdom/Shared%20Documents/WP01%20System%20Architecture/5.%20Draft%20Report?csf=1&web=1&e=89i7OF

15. Appendix D – Physical system supporting detail

In the interest of clarity and conciseness, some background information, definitions and examples are located in this appendix for readers seeking further details on some of the topics developed in the main body of the document.

15.1. Physical Architecture

The top level hydrogen energy system architecture is presented in section 5. It is also of interest to identify the structure differences between local and national systems as well as comparing with other energy vectors.

The high level structure and the main interface for a local hydrogen energy system is shown below for both national and local context:

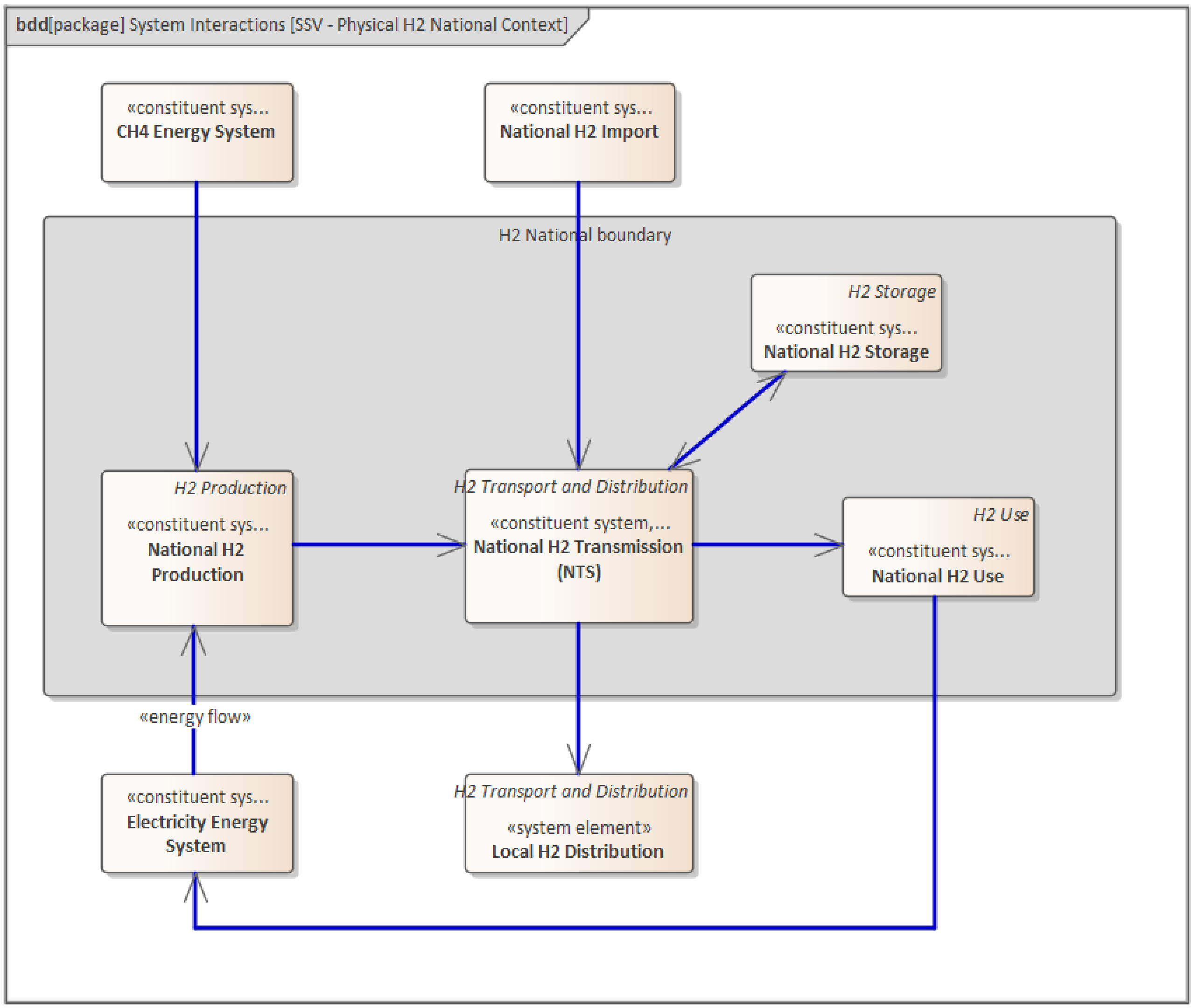

*Figure 2: High Level **National** Hydrogen Energy System Energy Flows*

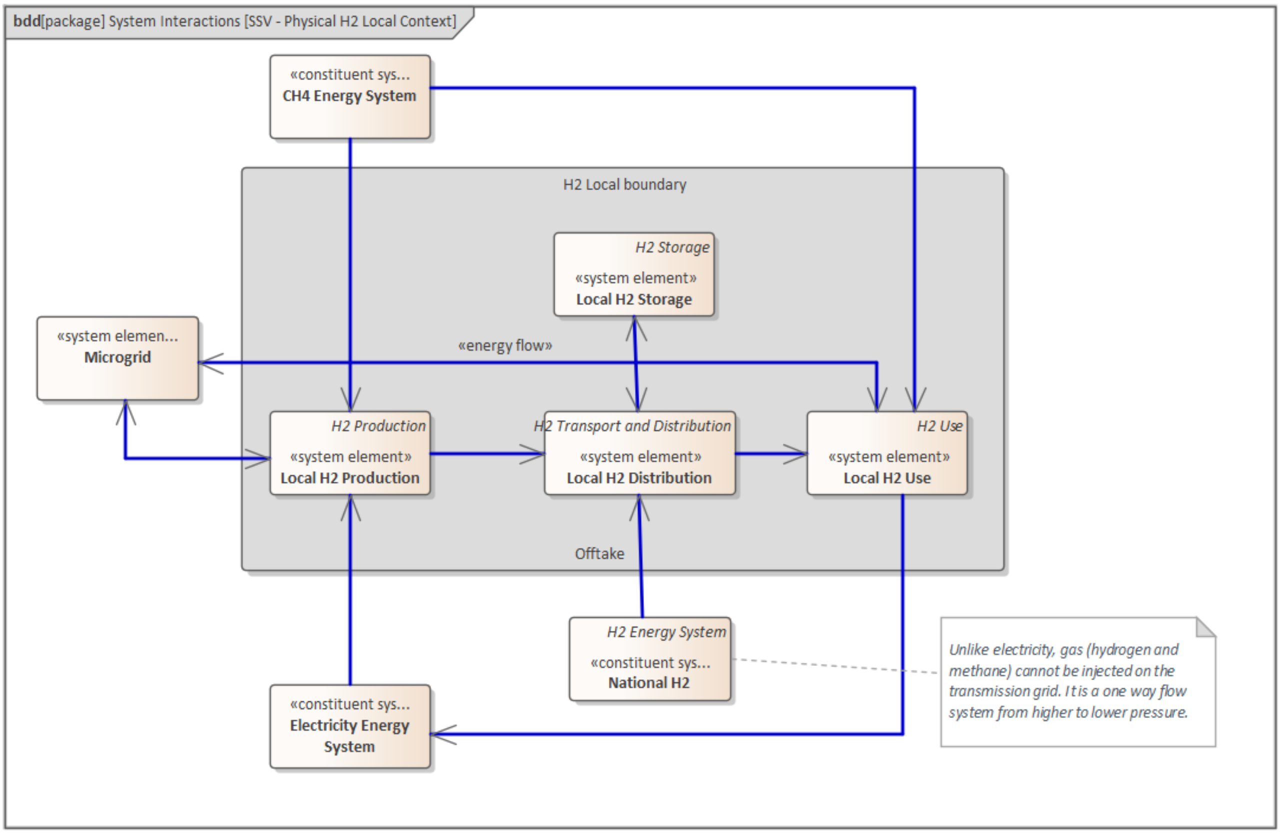

*Figure 3: High Level **Local** Hydrogen Energy System Energy Flows*

National and local architectures are essentially composed of the same elements with similar energy flows and interactions with other energy systems. The main difference is scale involved in terms of volume, pressure and flows from production to users.

The development of a local and national energy system will grow from small local project then scale up and integrate. The Gas Goes Green report[1] envisages a first phase of preparing for the transition in the coming five years, followed by solution pilots by 2030 then scaling up to a full transition by 2050.

Analogy and Interaction with the natural gas system:

Hydrogen is seen as a closest replacement for natural gas in a net zero world as, when burned, it releases water vapour rather than carbon dioxide. This has led to an increased and renewed interest in hydrogen in the past year. However, while decarbonising the end use, hydrogen needs to be produced without generating emissions or with capturing these emissions.

In terms of properties, hydrogen and natural gas are both in the gas form at ambient temperature and afford many similarities in terms of expertise and regulations. Existing infrastructures and supply chain can be used as a transition to hydrogen especially within the Milford Haven region using both national and local levels. Both have the same potential for storage and end use. However, hydrogen is not available in its natural form so must be produced from other energy

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

sources. Its volatile properties require further preparation and, as a new vector, will need acceptance from both industry and individual consumers.

	Similarities	**Differences**
Properties	Both are gas at ambient temperature. They both can be converted to liquid form and back to gas.	Physical properties are different: • The energy content per volume is over 3 times lower for hydrogen. • The lightweight of hydrogen makes it difficult to contain and transport. • More explosive and flammable properties.
Production	x	• Natural gas is an energy source. • Hydrogen is an energy vector. It is rarely found in its natural form thus requires energy source to be produced. • Natural gas is imported and schedules throughout the year to fulfil peak demand.
Storage	Both provide a reliable source of supply for intermittent production or high demand times. Gas storage reduces production reinforcement for seasonal peak demand (e.g. heating) Some assets can be shared, repurposed, replaced or upgraded	See physical properties
Transport and Distribution	They can be transported through pipelines and containers. Some assets can be shared, repurposed, replaced or upgraded.	See physical properties. • Hydrogen embrittlement of metal • Multiple forms of hydrogen (blend/liquid…)
Use	Similar end use: • Heating (industrial and domestic) • Electricity production	• Burning natural gas produces carbon dioxide. • Burning hydrogen produces water vapour. • Fuel cells allow production of electricity.
Control	Control of flow and pressure throughout the system.	See physical properties.

Interoperability	Hydrogen can be used for most natural gas applications (with or without modifications)	• Natural gas regulation (quality, pressure, flow, operation) and data exchange rules are well developed.
Link		Natural gas is a resource to produce clean hydrogen using CCUS.
Development		To tackle climate change, natural gas use is set to decrease and hydrogen to increase.

Analogy and Interaction with the electricity system:

Electricity and hydrogen produced using renewable energy are currently the two main energy vectors presented in the future net zero world. Other actors include bioenergy and heat network to support the two main energy vectors.

This section covers the physical comparison between the electricity and hydrogen energy systems. It is obvious that the associated cost will play a major role in future adoption. However, existing assets, skills, supply chain, flexibility, availability and integration will be crucial in the future architecture of the whole energy system. using the electricity source directly for a similar application. However, green hydrogen production can facilitate the integration of high level of intermittent renewable energy such as wind and solar int

Hydrogen storage is key in making renewable energy achievable. Hydrogen storage can be achieved at a larger scale than electrical batteries and doesn't suffer from time discharge and are less susceptible to atmospheric conditions such as cold and damp weather.

The electricity transmission infrastructure is well developed even if it will need to undergo major reinforcement and regulation changes with decentralisation and increased electrification. It has been extensively used as a centralised system. On the other hand, the hydrogen transmission network is still in the first phase of development in the UK (HyNTS[2]) and Europe (EHB[3]). The plan is to reuse, upgrade and add to the existing natural gas network. However, at distribution level, hydrogen can also be transported by container.

Another difference due to the physical properties, hydrogen flows from high to low pressures where electricity can flow upstream making it easier to connect multiple systems.

[2] https://www.nationalgrid.com/uk/gas-transmission/document/133841/download
[3] https://ec.europa.eu/info/sites/info/files/energy_climate_change_environment/events/presentations/05.04_mf34_presentation-european_hydrogen_backbone-muthmann.pdf

	Similarities	Differences
Properties	x	Electricity and hydrogen are complementary energy carriers.
Production	They are both energy vectors produced from energy source (either renewable or not).	Different resources required. Different suitable locations. Different processes.
Storage	Both have proven track record for short term storage and fast release.	Interseasonal hydrogen storage is more efficient than electrical storage. Hydrogen storage can rely on geological features (caves) as well as manmade containers.
Transport and Distribution	Both can use national transmission and regional or local distribution network.	• Infrastructure • Flow • Containerised hydrogen.
Use	• Industry • Mobility • Heating	Depending on applications, hydrogen and electricity can compete or support each other.
Control	Balancing Dispatching	Electrical frequency control is much faster than hydrogen pressure control.
Interoperability	Hydrogen can provide a balancing support mechanism to the electrical grid by either using or generating electricity.	The electricity elements interoperability is mature even if it is evolving fast to a more decentralised system. The hydrogen elements interoperability is novel.
Link	Hydrogen is a resource to produce electricity. Electricity is a resource to produce green hydrogen.	Fuel cells convert hydrogen to electrical energy. Electrolysers extract hydrogen from water using electricity.
Development	The development of the hydrogen system will impact	

Analogy and Interaction with the oil system:

Hydrogen has an important role to play in the reduction on reliance on crude oil based products on the path to net zero. Crude oil is a finite natural resource that needs preparing into fuel such as petrol, diesel, kerosene… The oil transport and distribution network (pipeline and containers) can potentially be used to transport hydrogen based product in liquid form. Oil products in the UK are mainly used for mobility. Combusting oil products for mobility has been the largest emitting sector of GHG emissions for several years. Electric and hydrogen powered vehicles are the main two alternatives.

	Similarities	Differences
Properties	Both needs energy intensive preparation to be used. They are both highly flammable. Both have high energy density.	Physical properties are different: • Hydrogen is a gas at ambient temperature. • Crude oil resources are finite. • Oil derivatives have been handled safely for decades.
Production	Crude oil and hydrogen need preparing before being used as fuels.	• Crude oil is naturally occurring and extractable. • The oil products supply chain is very mature.
Storage	Both can be stored in tanks for heating and mobility. Storage can be used for flexibility. Some oil products assets can be shared, repurposed, replaced or upgraded.	See physical properties • Oil based storage regulations are very mature.
Transport and Distribution	Both can be transported through pipelines and containers. Some assets can be shared, repurposed, replaced or upgraded.	See physical properties. • Oil product infrastructure and supply chain are mature • Hydrogen needs to be prepared to be transported as a liquid.
Use	Similar end use: • Fuel for mobility • Heating (industrial and domestic) • Chemical feedstock • Electricity production	• Oil combustion produces a multitude of GHG. • Burning hydrogen produces water vapour.
Control	x	Mature oil products infrastructure and control system with fluctuating prices based on supply demand.
Interoperability	Hydrogen can be used for most oil products applications.	Current oil based products reliance will take time to be replaced by alternatives.
Link	Oil companies have good access to large scale refineries than can be converted for hydrogen production and preparation.	The main current use for hydrogen is for oil refining. Hydrogen can be extracted from oil based products.
Development	x	To tackle climate change, oil products use is set to decrease and hydrogen to increase.

The differences between energy vectors, either positive or negatives are discussed in the following sections for each element of the hydrogen energy system.

15.2. Production

The use case diagram below shows the needs identified to produce hydrogen and the links with stakeholders involved in the process.

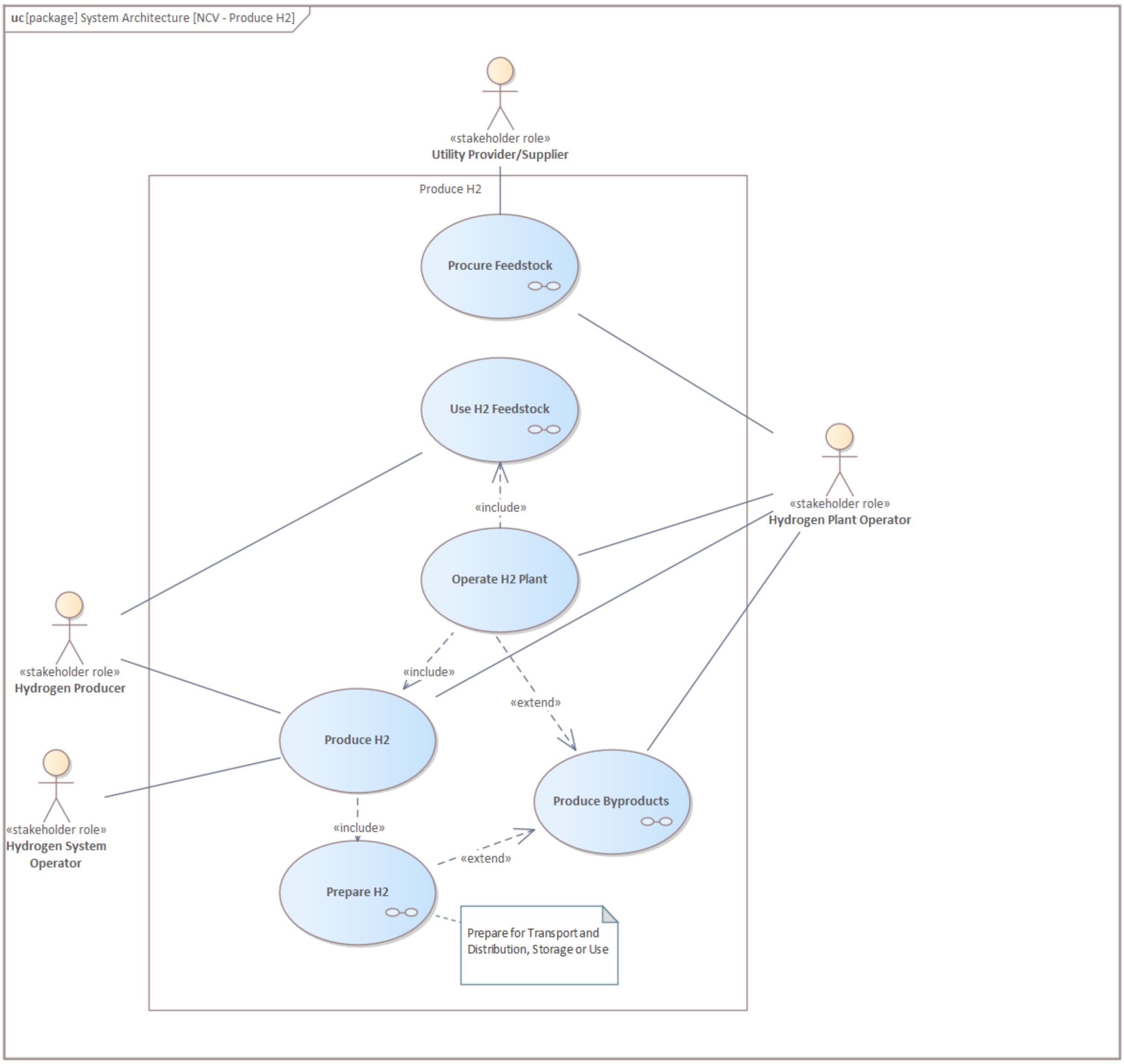

Figure 4: Produce Hydrogen Use Case Diagram

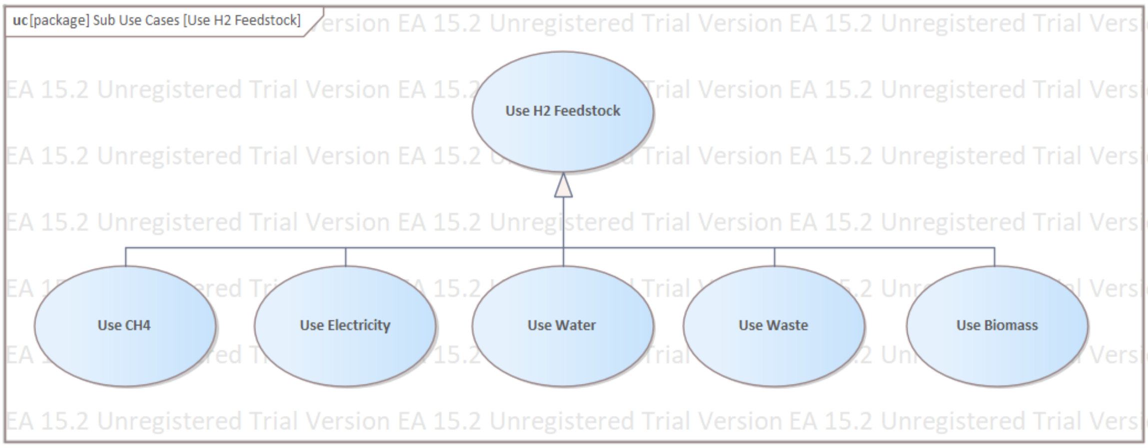

Figure 5: Example of feedstock for hydrogen production Use Case Diagram

The production asset must have access to the feedstock, for example, water and electricity requirements at scale for large electrolysers. Water can be sea water (treated), wastewater (cleaned up) or grid water will impact the required procurement scale, the cost associated with water treatment, and the embodied carbon.

Hydrogen production scale and technology is developing at a growing pace. New technology is very likely to be available in the coming years potentially using different feedstock, energy or conversion process. Produced hydrogen type is often defined by a colour but there is no international naming convention. So rather than defining hydrogen with a colour, for the purpose of architecture design, instead of describing a technology, the production process will be defined by its feedstock, by-product and the process physical and environmental properties. A summary table is shown below in Table 1. Additional characteristics can be defined to assess the production and how the whole system can be controlled.

One form of low emission hydrogen production is the hydrogen produced by splitting water molecules using renewable electricity via electrolysis. Electrolysis is the opposite process of fuel cell. Green hydrogen is currently the only zero emission gas but only represented 4% of the UK hydrogen production in 2009 according to the CCC[4]. Electrolysis is also the preferred method of hydrogen production for the investible propositions for the Milford Haven : Energy Kingdom project. The main assets around the haven are existing and potential locations for solar farms, onshore and offshore wind farms that have the potential to be connected to electrolysers.

Hydrogen can be produced from methane (or other hydrocarbon) in large volumes, by using one of two primary methods. Steam methane reformation is the most common method for producing bulk hydrogen and accounts for most of the world's production. This method uses a reformer, which reacts steam at a high temperature and pressure with methane and a nickel catalyst to form hydrogen and carbon monoxide. Alternatively, autothermal reforming uses oxygen and carbon dioxide or steam to react with methane to form hydrogen. The downside of these two methods is that they produce carbon as a by-product, so we would need to explore carbon capture solutions to trap and store this carbon. Whether carbon dioxide in large scale operations can be used in an environmentally way or remain underground is still under review. However, steam and autothermal reforming can play an important role in the transition to fill the gap when demand increases.

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[4] https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf

An alternative between these first two processes is methane pyrolysis, sometimes referred as turquoise hydrogen. Instead of burning the fossil fuels to generate heat to reform natural gas, heat is delivered by electricity. The main difference lies in the production of carbon in solid form rather than gaseous carbon dioxide requiring CCUS.

Another option is biomass gasification. This is a mature technology that converts biomass using high temperature, without combustion, heat and steam, into gasses from which hydrogen can be separated. Combined with CCUS, this technology can be a low emitting hydrogen production solution.

Hydrogen can also be a by-product of the oil refining process. However, refineries tend to use more hydrogen than they produce but this will account for the hydrogen demand of the industry.

However, with the objective of reducing the emission of hydrogen production towards a decarbonised energy vector, the diversity of production will provide flexibility of meeting increasing demand and transitioning from fossil fuels.

Another important element within the production process is the production of by-products. These by-products can be beneficial or detrimental in the physical, environmental and commercial domains. For example, during each process, heat can be generated and either:

- Wasted in the surrounding environment
- Used within the process
    - Heat used for plant space heating or recycled through the process
    - Oxygen produced through electrolysis can be used for combustion applications to improve energy efficiency
- Captured and traded (e.g. heat network, CCUS, carbon black, oxygen)

Note that private pipes, preparation and storage taking place within the production plant is part of the characteristics of the plant and affects the output flows.

Multiple resources can be used to produce hydrogen. Each technology (electrolysis, thermochemical conversion, pyrolysis, gasification) has different control characteristics, feedstock, emissions, cost etc. The different technologies can support each other in the hydrogen transition and allow more flexible control. The growing number of electrolysers connected to renewable energy sources may not be sufficient to follow potential demand expansion and stifle growth. Maintaining SMR and ATR during the development of CCUS and developing different technologies can provide larger scale steady production, which will be a major asset to support demand growth.

Most hydrogen used today is produced onsite or closed to where it is used, mainly for industrial purpose. For short haul distribution, private pipelines or container transportation is used. These types of distribution are self-contained and controlled on demand. The local production of hydrogen reduces transport and distribution but requires the local construction of hydrogen production either:

- From a dedicated electrolyser. This needs to be scaled for the current and forecast demand. It can either be connected to the electricity grid for on demand production or dedicated renewable energy source. The intermittence of renewable electricity source must be compensated by capacity and storage solutions.

- From methane, biomass or other fossil fuel reformation. As the most mature technology to produce hydrogen, it offers the flexibility of feedstock source (natural gas, naphtha…) to suit the production site and offer different degrees of modularisation. However, it still suffers from high energy source demand especially when dealing with emission capture.

Some of the risks associated with collocated hydrogen production, with an industrial site for example, is the increased asset value and the energy management. The production demand, therefore, revenue, profit and potentially viability is highly dependent on the results of the site. If the collocated production is the main source of hydrogen to the site, excess and under production must be accounted for.

However, for large volume and multiple end use (industry, heating, power generation and refuelling stations for example), a pipeline network will have to be developed.

The main benefit of a centralised large volume production system is the reduction in production costs. I can also support flexibility, resilience and efficiency of the whole system for uninterrupted supply. However, some major barriers remain for large scale production :

- First electrolysers must be connected to a large scale source of renewable electricity. Once hydrogen is produced, the produced hydrogen needs to be transmitted and distributed. The possibility to be connected to the existing gas grid or the possibility to develop pipelines to connect to a hydrogen network needs to be carefully planned and costed. This is developed in the next section (Transport and Distribution).
- Large natural interconnectors and gas import ports, such as MH:EK, already have the scale of natural gas feedstock to produce hydrogen at scale and the connection to the national transmission grid. However, the development of CCUS including the ability to use or store carbon emissions will be vital in developing low emission hydrogen from natural gas. It will also need to identify the technical gaps in injecting hydrogen in the grid.

Colour	Technology	Description	Feedstock	By-products	Physical Properties	Capacity	Quality	Efficiency (process)	Feedstoack availability	Established industrial process	Environmental Properties	GHG emission (operational)	Cost	Current cost	Cost prediction - 2050
	Electrolysis														
Green	Electrolysis	Small scale electroclyser (excess renewable wind/solar)	Electricity Water	Oxygen											
Green	Electrolysis	Medium scale electrolyser (dedicated renewable wind/solar)	Electricity Water	Oxygen											
Yellow	Electrolysis	Large scale electrolyser (grid electricity)	Electricity Water	Oxygen											
Pink	Electrolysis	Nuclear electricity	Electricity Water												
	Thermochemical Conversion														
Blue	Steam/Autothermal Reforming	SMR / ATR with CCUS	Methane / Naphta / LPG Oxygen												
Grey	Autothermal reforming	ATR	Methane / Naphta / LPG Oxygen												
Grey	Steam Reforming	SMR	Methane / Naphta / LPG Oxygen	CO / CO2 Heat											
Grey	Partial Oxidation of natural gas	-	Methane Oxygen from air	CO / NOx											
Grey	Partial Oxidation of petroleum coke	-	Petroleum coke Oxygen from air	Heavy oil, soot											
Turquoise	Pyrolysis	Thermal decomposition without oxygen	Biomass (No O2)	Solid products including Tar											
Turquoise	Pyrolysis	Thermal splitting of methane	Methane (No O2)	Solid products including Carbon black / Graphene											
Black or Brown	Gasification	Coal and oil gasification	Coal	Tar											
White? Brown?	Gasification	Other gasification	Biomass / Waste / Petcoke / Lignite	Tar											
	Other														
Purple	Combined thermalchemical and electrolysis splitting of water.	-	Water Nuclear Power and Heat												
Red or Orange	High temperature catalytic splitting of water	-	Water Concentrated solar power or nuclear waste heat												
White	Naturally occurring Hydrogen	-	x												

Capacity	Low capacity	High capacity
Quality	Low quality	High quality
Efficiency (process)	Low efficiency	High efficiency
Feedstoack availability	Low availablilty	High availabilty
Established industrial process	Developing	Established
GHG emission	High emissions	Low emissions
Cost	High cost	Low cost

Table 1 - Hydrogen production technology comparison

Notes: This table is a visual representation of the different hydrogen production methods. The purpose of this table is to provide a high level comparison between the main characteristics of the different types of hydrogen production. It does not intend to give absolute values. Each technology parameters can also vary greatly depending on the quality of feedstock, operational conditions, location.

15.3. Transport and distribution

The use case diagram below shows the needs identified to transport and distribute hydrogen and the links with stakeholders involved in the process.

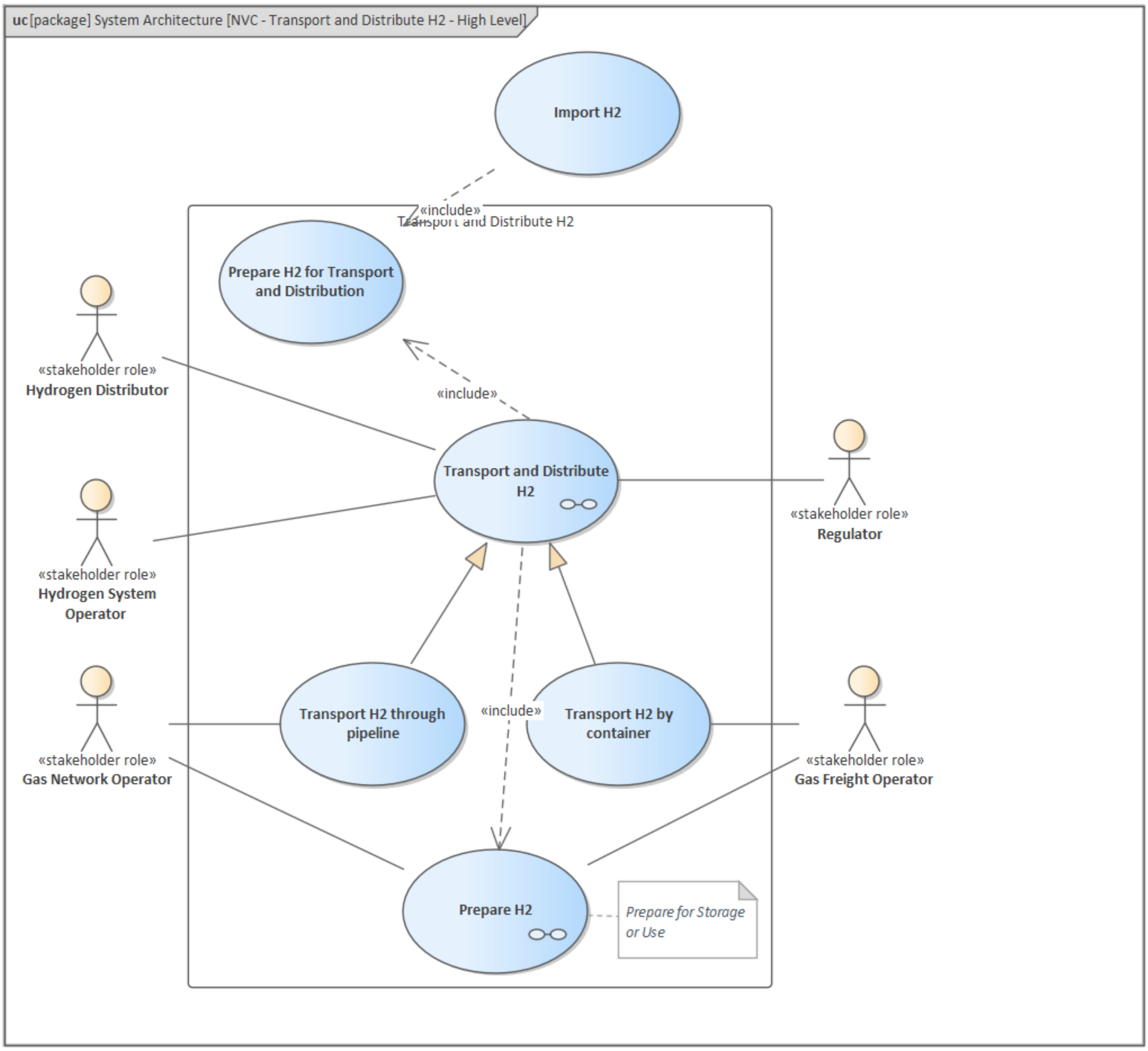

Figure 6: Transport and Distribute Hydrogen Use Case Diagram

Some examples and considerations for transport and distribution by container and pipeline are detailed below:

Transport and Distribution by Container

Containers are designed to withstand the pressure and temperature of the hydrogen or hydrogen compound transported. Some of the containers are expensive and specifically designed to accommodate the safety requirements of compressed or liquid hydrogen. This affects the material used, the lining, valves and fitting and requires specific telemetry systems. However, some hydrogen compounds can be containerised in more standard liquid or gas containers. The development of the fleet of purpose build could be deterred by the development of large volume pipeline transport and the risk of becoming obsolete.

Freight operators provide the transport of hydrogen by rail, road and waterways often including loading and unloading from a supply point to the consumer. This allows meeting specific demands for lower volume of hydrogen compared to pipeline transport. For pipeline control, the hydrogen network operator needs to control hydrogen flows and pressures throughout the network keeping the whole system under safe operation conditions.

Transport and Distribution through Pipelines

H100 Fife project[5] is developing a world-first hydrogen network in Levenmouth that will bring 100% renewable hydrogen into homes in 2022, providing zero-carbon fuel for heating and cooking. In the project's first phase, the network will heat around 300 local homes using clean gas produced by a dedicated electrolysis plant, powered by a nearby offshore wind turbine. Such projects will future proof the development of the hydrogen network by looking at potential end users' needs and ensure correct pressure specification and control. Planning in design will bring many benefits and avoid future upgrades and reinforcement. However, this project installed an independent hydrogen network (including pipes) to offer customer choice throughout the project and beyond. This should provide great insight on pure hydrogen system development and control and consumer acceptance but not for infrastructure transition. Parallel networks are however not a commercially viable option for the future.

Due to the difficulty of transporting hydrogen, small scale local demonstrators tend to adopt colocation of assets where the production is established at the point of use. This is particularly appropriate for local fleet refuelling stations where renewable electricity feeding an electrolyser can produce and store the hydrogen. Small scale network can allow green hydrogen to be imported and distributed to different applications (industry, refuelling station, blended hydrogen) via a buffer store. The downside of this approach is that the system cannot easily share extra production with other systems nor rely on other production sites to support high demand during low production periods. However, storage and containerised transport can help support balancing a system of this scale.

Upgrading the natural gas network to hydrogen by treating, relining, replacing and adding pipelines to protect them from embrittlement and high pressure makes them expensive up front. But once built, they are the cheapest and most efficient way to deliver high volumes of hydrogen.

An important difference from the electrical system is that hydrogen flows from high pressure to low pressure whereas electricity is more bidirectional. The significance of this physical fact is that, in an electrical system, excess production can be reinjected to the grid. For the gas network, excess production would be difficult to reinject on the network. It would have to have extra compressors to "push back" the gas and the connected network would have to be designed to allow this. However, hydrogen can be more easily stored either stationary or transported by container to other consumers.

For hydrogen to become a major energy vector to tackle climate change, especially decarbonised heating, the need for a high volume, distributed pipeline transport network is essential. Compared to containerised transport, pipelines allow transport of large quantity of hydrogen over long distances. As for current natural gas arrangements, pipeline and containerised transport and distribution can be mainly independent systems in terms of control and end use.

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[5] https://www.sgn.co.uk/H100Fife

The interoperability and transition between the natural gas, blended hydrogen and pure hydrogen is described in detail in section 5.6

It is worth noting that there are over 4,000 km of oil pipelines in the UK transporting liquid petroleum products including onshore and offshore crude oil. Some multiproduct pipeline systems have already the control in place to connect a refinery to several depots for different types of consumers. They can control large volume batches of gasoline, diesel, LPG or aviation fuel to the correct depot depending on demand through one pipeline network. If hydrogen based liquid products (LOHC) could be transported under similar operating conditions (temperature, density…), adding batches of hydrogen could help transitioning liquid fuels towards net zero.

As shown in the figure below, the port of Milford Haven is well connected from the oil terminal, the refinery including local storage towards the centre of the UK. The use and the evolution of this high capacity assets will be critical for both gas and liquid.

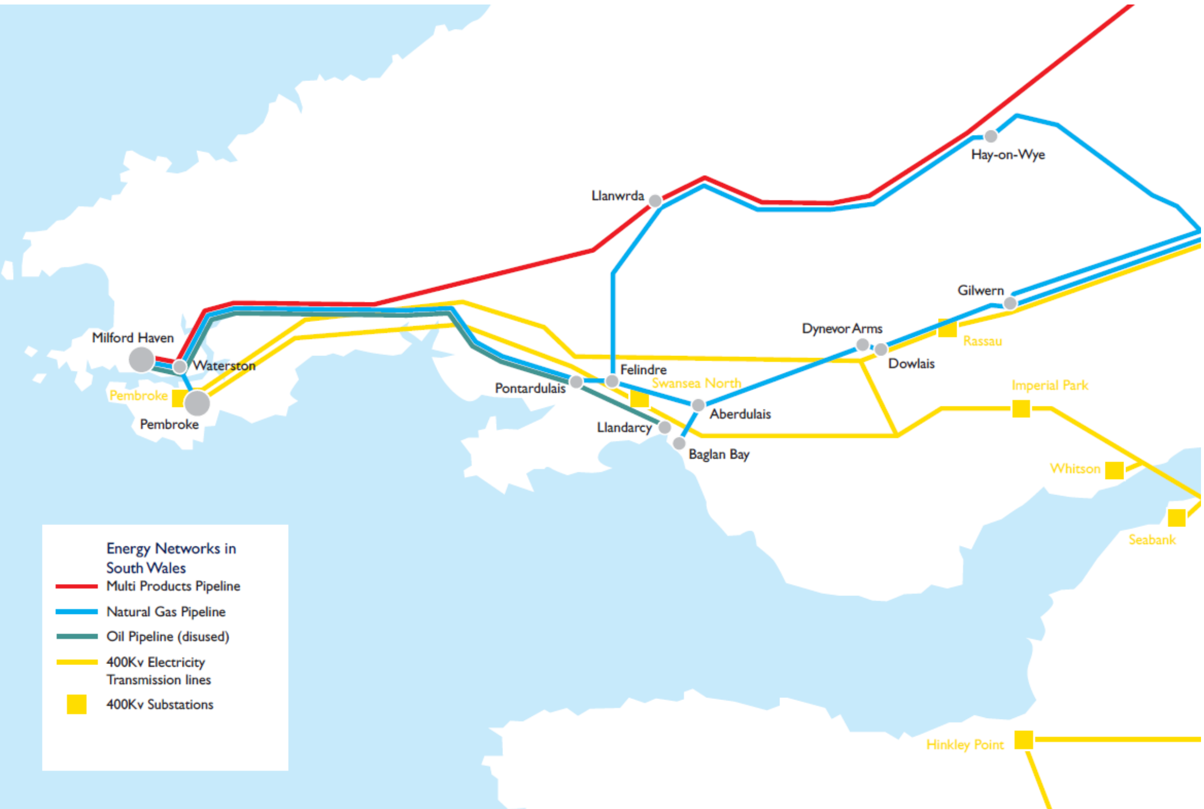

Figure 7: The South Wales Energy Network[6]

Hydrogen transport and distribution scale and technology will mature as technology develops. It will have to adapt to the characteristics of the production and usage and preparation process. Therefore, for the architecture design, instead of describing the existing ways of transport, the process is described by its characteristics. Additional characteristics may have to be defined in the future as the hydrogen system develops.

[6] https://www.mhpa.co.uk/oil-and-gas/

Note that transportation within another element will modify the characteristics of that element. To the same extend, preparation (in particular pressurisation) and storage (e.g. linepack) are part of the element characteristics (e.g. energy used, efficiency).

15.4. Storage

Storage can sometimes be a grey area as it can be difficult to qualify somewhere in between production and end use and is sometimes integrated within other elements. Storage competes with and supports the diversity of supply connected to each system. Connecting multiple local hydrogen systems, developing a national hydrogen grid and import/export will provide greater resilience to the hydrogen system. The level and location of storage required throughout this development will depend on the price and security of supply of the different options. Local storage (from production to end user) will provide the operator the capacity to adjust their supply or output depending on hydrogen demand and price and be less subject to price volatility.

Storage faces the same hurdles as transport and distribution (section 5.2) due to the physical properties of hydrogen. For mobility applications, it must be safe, compact and light. For long term storage, it must be reliable, support high pressure or high volume. There is also the cost associated to storage which needs to be shared between the production and end user stakeholders.

The purpose of hydrogen storage is to:

- Help match supply and demand profiles (volume and time)
- Provide grid balancing and flexibility (availability and control) for the gas and electricity network.
- As a fuel reserve in tanks for mobility (volume and weight)

The versatility of hydrogen offers many storage options such as liquid or compressed gas, chemical compound and within or on the surface of solids. With increasing integration of energy vectors, hydrogen storage also competes with electricity, heat and mechanical storage depending on the application. (see example in appendix section 14.4)

For example, storage is an inherent part of production. Produced gas is rarely used instantly and is usually stored locally before being transported for usage or to another storage asset. The level of storage can smooth out the delivery and reduce the overall capacity of intermittent resources. Another example, when a hydrogen tank is filled for a fuel cell backup generator or fuel cell electric vehicle, this is considered in the end use element of the system.

Importantly, linepack within the pipeline transmission and distribution network is a type of storage embedded into the transport element that can be controlled during operation.

Storage at large scale or national level will be typically connected to the transmission system. For smaller scale, local and integrated systems, storage can also be directly connected to production and delivered to the end user with the distribution being integrated within these elements.

Hydrogen storage can play a major role in the interoperability with the electrical and heat systems. An integrated circular electrical, heat and hydrogen energy system can support:

- Foundation of renewable wind and solar electricity generation which is weather dependant.

- Strategic hydrogen and heat storage for flexible capacity and resilience which also reduces the need to curtail production.

The best storage solution will depend on the application and the connection availability to the applicable energy vector (up and downstream of storage). Efficiency and cost are likely to improve for many storage solutions due to the current technology advancements and investment.

For hydrogen storage, interoperability and safety between the different hydrogen forms (gas, liquid and compound) as well as the connection to distribution are critical.

Like for transport and distribution, hydrogen needs to be prepared to be stored in either liquid form or as a compressed gas or as a hydrogen energy carrier.

Hydrogen can be stored as a compressed gas, as liquid gas (at -253 degC) or chemically in a solid-state storage medium. Since these methods are constantly developing, the hydrogen storage will be represented by its characteristics rather than its technology and the energy stored and dispatched will be represented by its properties. Improving size, weight, efficiency and safety while increasing scale and lowering cost remain the main challenges.

Hydrogen storage is one solution amongst many energy storage options fulfilling different purposes as shown in Figure 8. However, hydrogen is more readily storable than electricity at large scale. This means that hydrogen has a great value as a low emission replacement for natural gas or oil products for direct and integrated storage where electrification would require large scale or long term storage or under-utilised infrastructure. For example, interseasonal storage would support high heating winter demand. Some high capital infrastructure along the natural network already exists and could be utilised or converted for hydrogen or hydrogen carrier storage. However, this would imply for the upstream and downstream network to be suitable for the stored form of hydrogen or additional preparation would be required. For example, blended hydrogen would need to be performed downstream of storage as it is not currently economical to store natural gas.

Compared to other energy storage in terms of capacity and discharge, hydrogen and hydrogen carriers can provide very large quantity of stored energy as shown below[7]:

[7] https://electrificationstrategy.eu/faq/costs-benefits-and-distributional-impacts/hydrogen-is-the-better-technology-for-energy-storage

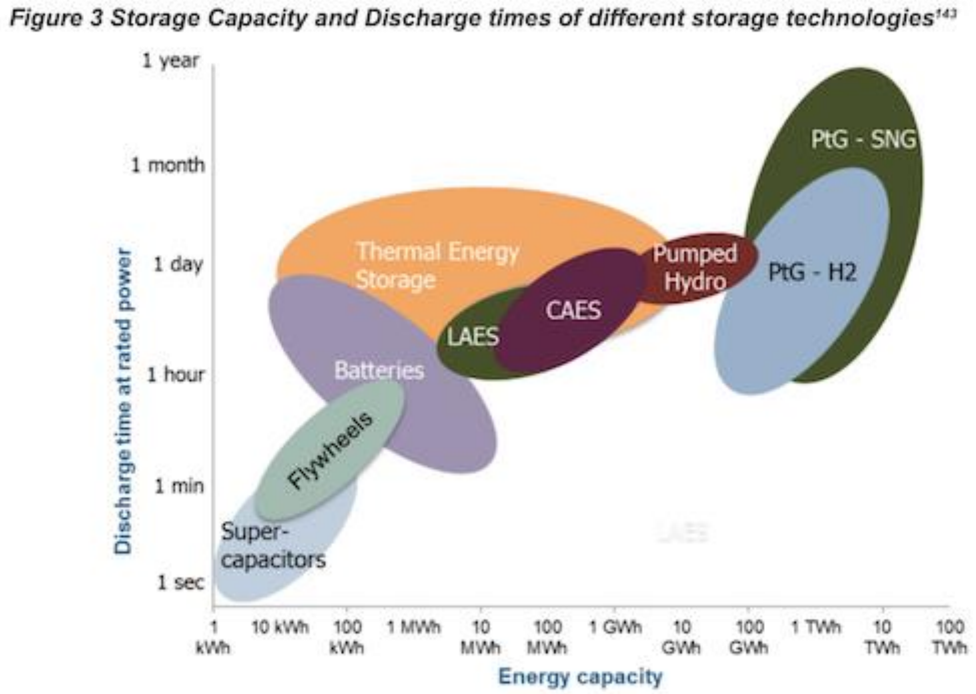

Figure 8: Storage Capacity and Discharge Times of Different Storage Technologies

PtG – Power to Gas

SNG – Synthetic Natural Gas

LAES – Liquid Air Energy Storage

CAES – Compressed Air Energy Storage

This figure doesn't undermine the importance of small scale readily available hydrogen within the elements of the hydrogen energy system.

The preparation process is fundamental in the different types of storage. Reuse and repurposing of existing hydrocarbon storage assets such as LNG terminal and geological storage will influence the development of storage. Storing Hydrogen includes developing and maintaining the storage infrastructure which consists of two main types:

- Hydrogen can be stored in large quantities underground in existing caverns, salt domes and depleted oil and gas fields. Due to their sizes, geological stores offer the benefit of inter seasonal, large volume storage. Salt caverns seem to offer the most promises. Despite not being present in the MH:EK area, salt caverns in the other part of the UK could be linked through the developing national network. Salt caverns are already used for storing oil and natural gas. Storage of hydrogen is similar to that of natural gas in terms of design and operation making knowledge and skills available and well-practiced. However, pipelines for access and transport properties requirements are more challenging.
- The more versatile and expandable technology for local areas is the use of containers (tanks and cylinders) that can take all the forms of hydrogen carrying energy presented above depending on the end use. The MH:EK region already features many natural gas and oil

storage facility at the port LNG terminals, the Valero's oil terminal and Puma storage facility. These existing assets will not only provide a physical lead to the transition to hydrogen but also the expertise, workforce and supply chain.

Peak production of renewable energy doesn't match peak consumption. Different storage technologies can help reduce the peak load during day variations. Increase of intermittent renewable electricity sources and the electrification of heat combined with the increasing number of electric vehicles makes the electrical system more difficult to control and peakier than ever. The whole energy system cannot rely only on electrical batteries to provide seasonal peak demand which usually occurs on cold still days when electrical generation is low. There are many ways to store energy as some examples are shown below in Figure 8. The most suitable technology depends not only on the capacity and discharge time but also on the efficiency, the available feedstock, the location, the end use applications, the associated capital and operational costs. The best solution for a particular system can be a combination of energy storage determined by a technical and economical assessment. One very strong aspect of hydrogen compared to electricity is the possibility of storage at scale over a long period. This complementarity of electricity is an opportunity for hydrogen to support and integrate these two vectors towards a decarbonise energy system. Electricity and hydrogen can also both be used as heating source individually or combined.

Import and export, once regulated and established could complement and reduce the need of storage. Natural gas storage has been decreasing significantly due to the security and cost of import.

Storage also includes hydrogen tanks for mobility applications. Heavy goods vehicles (HGVs), busses and trains require to store and carry large volume of energy for long range journeys and quick refuelling for continuous operation.

Storage is a key enabler to develop a hydrogen economy and a net zero energy system. The main objectives of hydrogen storage are:

- The development of technology to prepare hydrogen for storage.
- The development of storing materials for containers.
- Integration and control of the hydrogen system.
- Integration with the electrical system and the natural gas system.

The use case diagram below shows the needs identified to operate hydrogen storage and the links with stakeholders involved in the process.

15.5. Use

With the latest government target to reduce emissions by 78% by 2035 compared to 1990 levels, emissions will be a decisive point when fossil fuel powered assets come to be replaced or upgraded at the end of their lives. This applies to assets from gas central heating systems for on and off grid households, road vehicles of all sizes, industrial furnaces to aircraft fleet. Consumers may face a wide range of devices and contracts options. They should be able to change technology and services on a regular basis and understand the compatibility with other existing solutions or as part of future solutions. For several applications such as heavy transport (road, marine and aerospace), high-temperature processes in industry, an adequate electrical solution is still lacking and there is still a need for a sustainable gas.

For consumer to make informed decisions, it is essential to be able to compare the different vectors parameters and outcomes. This will be expanded in the different subsections below and illustrated with examples.

For example, it is important to use common units and terms to describe the forma and quantity of hydrogen. The quantity of hydrogen or hydrogen carrier can be measured and reported in weight, volume, energy density or energy content in kWh. For usage, net output power and cost can be defined against these different quantities. Similarly, GHG comparison per volume, weight or kWh produce can be misrepresentative.

For mobility, where storage size and weight are important hydrogen weight is often used. This is relevant for car models' comparison as pressure standards are well developed and accepted. However, for heating, the calorific value is an important factor to compare different gas sources.

The development of common standards for the different ways hydrogen is used and within the various chemical, combustion and fuel cell applications will support each other's development and facilitate interoperability at end use for consumers. This will increase flexibility and allow scaling up to support the progression towards a hydrogen economy. Developing the different end use of hydrogen independently for each application could end up creating a multitude of low volume speciality hydrogen. More details on existing standards are available in section 5.10.However, existing legislations related to the current use of hydrogen may hinder the development of innovative solutions. Exceptions and ongoing best practice should allow the introduction of new technology and their integration.

The table below summarise the different categories of hydrogen end use as presented in this document. It highlights what energy vector hydrogen can replace and compete as well as the potential usage characteristics. This table does not intend to cover all applications but aims at supporting discussion and vector comparisons.

Hydrogen Use	Replace	Compete with	Notes	Baseload	Daily Peak	Seaonal Peak	Flexibility
Industry				High	Burst	Low	Medium
Ammonia production	Grey hydrogen						
Oil refining	Grey hydrogen						
Methanol production	Methane (SMR/ATR) Coal gasification	SMR with CCUS Biomass gasification	Use of CO2				
Steel	Coking coal for furnace	Electric arc furnace					
Glass Processing Cement production	Fossil fuel source of heat		Industrial heat				
Hydrogen Use	Replace	Compete with	Notes (volume/potential)				
Mobility				Low then upscale	None	Low	
Road Mobility			**Refuelling range** Refuelling time Use refuelling supply chain and infrastructure				
Personal vehicles	ICE	Electric batteries	Electric vehicles are a long way ahead Refuelling stations infrastructure needs developing				
Vehicle fleet Council, rental, industry Busses, bin lorries	ICE	Electric batteries	Return to same location for refuelling				
HGV	ICE	Electric batteries	Hubs for refuelling				
Marine Applications							
Short routes / small vessels		Electric batteries	Frequent charging possibilities				
Long routes / large vessels			Engine space constraints Refuelling time				
Hydrogen Use	Replace	Compete with	Notes (volume/potential)				
Heating / Appliances							
Off grid heating	Oil	Electric batteries	Road supply Seasonal peak	Low	None	High	Low
Grid connected boilers	Methane	Heat pumps Hybrid heat pumps	Grid connected: like for like from a consumer point of view Heat pump would require major upgrade and potentially keep backup gas boiler	Medium	High	High	Low
Hydrogen Use	Replace	Compete with	Notes (volume/potential)				
Electricity generation							On demand
Small scale Portable devices	Gas cyclinders	Battery powered					
Medium scale Backup generators	Diesel generator Oil tanks						
Large scale Power plants	Methane / Coal	Electrical storage					

Figure 9: Hydrogen end use categories characterisitcs summary

More background information and examples for the specific categories end use (industry, mobility, heating) are detailed below.

15.5.1. 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:** Hydrogen is the main component needed to produce ammonia (NH_3) by fixated nitrogen from the air. Ammonia is mainly used as a fertiliser for the agricultural industry. The sector is under great pressure to decarbonise and be overall environmentally friendly. However, as population grows, fertiliser demand is likely to

increase. This will not only require decarbonising of ammonia production but also increase production.
Ammonia also possesses very versatile properties. Ammonia is also used in cleaning products and as a refrigerant. There is a potential for green ammonia to be used as a chemical energy carrier and fuel. Ammonia also has the potential to be used as shipping fuel (see Mobility in section 5.4.3) or converted back into electricity (see Electricity Generation section 5.4.5). The potential multiuse of ammonia could boost up the scale of production and transportation and affect the whole supply chain.

- **Oil refining.** Hydrogen is also widely used in the oil refining industry to transform crude oil into useful products and remove contaminants (fuel for transport, lubricants and petrochemical feedstock for manufacturing plastics, solvents etc). During the oil refining process, hydrogen is often produced as a by-product, but larger amount as required onsite for further applications.
  As transport fuels decline with decarbonisation, the need for hydrogen for fuel hydrotreating in refineries such as Valero will reduce. However, the existing hydrogen production capacity will provide opportunities for road fuel switching to hydrogen and other applications or export.

Other industries use hydrogen and are, at present, deemed more difficult to electrify than other sectors. A non-exhaustive list of some of the industries where hydrogen could be used as a chemical feedstock or to produce high heat is shown below:

- **Methanol production.** Methanol (CH_3OH) is commonly used as a solvent, fuel and antifreeze. It is also a feedstock to other chemicals or a hydrogen carrier.
  Methanol can be produced by the direct combination of hydrogen and carbon dioxide. This process allows industrial plants to reduce their carbon dioxide emissions to produce a fossil fuel substitute.
- **Steel production and other metalwork**.(e.g. tungsten, copper, nickel extraction)
  In the steel industry, hydrogen is used to extract iron from its ore through a furnace using coke produce from coal. Decarbonising steel production will combine both replacing coking coal for the furnace and capturing carbon dioxide emission at scale.
- **Food processing**. Hydrogen is used to turn unsaturated fats to saturated oils and fats to keep them solid at room temperature and increase shelf life (e.g. margarine)
- **Glass production** needs temperature high enough to melt sand and prevent oxidation. Similarly, **cement production** requires high heat. Research to decarbonise these sectors involve hydrogen.
- **Welding.** Replacing natural gas with hydrogen to produce high heat.

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

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 – everything required in pulp, paper, food processing and tobacco, plus pre-heating for higher-temperature processes like glass manufacturing, cement and chemicals. 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.[8]

15.5.2. Mobility

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.

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.[9]

Fuel cells for mobility are an alternative for electrical batteries in replacing fossil fuels. For 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. The obvious advantage of batteries is the efficiency of using electricity directly. Fuel cell electric engines are a technologically viable alternative 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). 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. The benefits of fuel cells, compared to electric batteries are:

- **Range** – electric vehicles sales still suffer from range anxiety where FCEVs are like ICE. The range is limited by the battery/tank size and the vehicle weight.
- **Vehicle size**. As hydrogen tanks are lighter than batteries for the same energy storage, FCEV may be more appropriate for heavier vehicles and long range applications such as HGV.
- **Refuelling time/location**. Again, recharging BEV takes much longer than FCEV; therefore, requires longer periods in the same location. Local installation of recharging facilities is required for personal BEV at home, workplaces, shopping centre which is not always feasible or practical. However, the refuelling network for FCEV could be like ICE by adding hydrogen storage in petrol stations. For large vehicles (HGV, ferries, trains), strategic locations of refuelling stations can fulfil the needs of fast refuelling and long distance travel.

Reducing fuel tank/battery size and refuelling/recharging times and infrastructure are the source of many research projects and advancements which will play a contribution in the future of mobility alongside policy, regulation and investment.

[8] https://about.newenergyfinance.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/
[9] https://www.fchea.org/fuelcells

If the development of fuel cell technology, tanks features and refuelling protocols between mobility sectors lines up, this could prevent regulatory hurdles, increase volumes and uptake and reduce industry costs. For example, hydrogen fuel cell tanks for mobility applications typically use 350 or 700 bar depending on the size of the vehicle – lightweight vehicles use 700 bar while larger vehicles (lorries, busses, marine vehicles…) tend to use 350 bar in a larger tank. For road, rail and water applications, identical fuel cell stacks and tanks can be used and produced by the same manufacturer. They range for tank sizes and volume of production. 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).

The key to provide the right amount of hydrogen and storage is to model and analyse the consumption characteristics to differentiate between the different application. The usage characteristics include:

- Capacity
- Pressure
- Security of supply
- Location

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. As fuel cell road vehicles are entering an existing fleet and following most of the same standards, tests and regulations can be adapted for the specificity of hydrogen 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. Hydrogen fuel cell tanks typically use 350 or 700 bar depending on the size of the vehicle – lightweight vehicles use 700 bar while larger vehicles (lorries, busses, marine vehicles…) tend to use 350 bar in a larger tank. Developing cross mobility standards could support the multi-use and viability refuelling stations.

One critical point is the interoperability between the FCEV and the charging infrastructure. This includes:

- The compatibility for end use mobility applications
- The hydrogen source for refuelling station
- The number and location of HRS

There are currently many choices and options for different infrastructures for mobility, often individual and bespoke. Different alternatives are in use across the world for road, rail and water fuel cell mobility, particularly for very specific use such as city busses, bin lorries, small ferries, forklifts… The development of hydrogen carrier fuel cell could add further alternative for refuelling. Standardising the refuelling requirements for road vehicles, marine applications and train would support the creation of hydrogen hubs facilitating the expansion and integration of fuel cell use for mobility. For example, the development and the strategic location of hydrogen refuelling hubs could allow long distance connections for HGV for example, connecting ports to main distribution centres. Road is also the vastest network of transport in the UK. If these HRS are compatible with personal vehicles, the intake of FCEV could encourage investment in building more HRS making FCEV a real option for drivers.

Refuelling stations are a specific type of hydrogen storage. This can be achieved from multiple sources. For example, if the hydrogen network supplies a residential area, would the best solution for a local hydrogen refuelling station be purifying the gas from the network or have the gas delivered by road tankers or be connected to electricity grid to supply pure hydrogen from an onsite electrolyser or a hybrid solution?

The considerations include the forecast demand, the existing assets, the capital and operating costs, the HRS tank location and access, the energy supply (electricity and gas) capacity, the risks associated with each solution from design to retirement. Once a solution is adopted, the possibility to upgrade, integrate or discard any of the future options needs to be considered. Similarly, when a new technology that could impact hydrogen refuelling stations develops, it is essential to assess its acceptance and its ability to integrate or replace existing technology.

For aviation, hydrogen and hydrogen based synthetic fuels are currently the only option for decarbonisation the industry.

15.5.3. Heating

Heating is the largest volume and most peaky demand for natural gas. If hydrogen is to become the main solution for heating in a net zero future, this will imply the development of a national hydrogen grid and offer a great opportunity to interconnect multiple uses. However, the quality required at end use could create multiple networks if preparation cannot be integrated.

Figure 10 below shows an example of grid use for both mobility and heating.

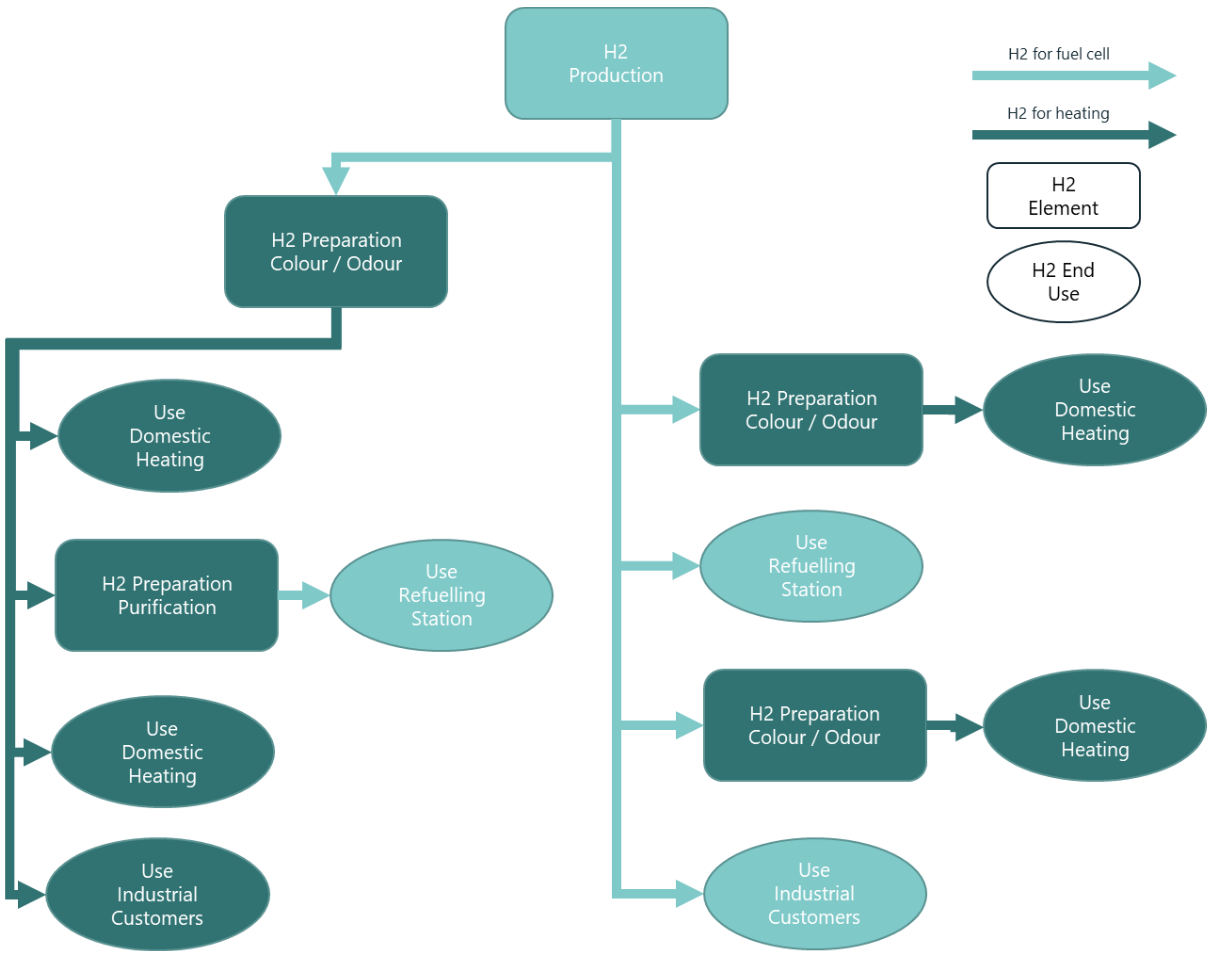

Figure 10: Example of network architecture to supply hydrogen for mobility and heat

Higher quality hydrogen is required for fuel cells applications than for heating or blending. Colourant and odorant must be added when hydrogen is used for domestic heating. It is also worth noting that different industrial applications may require different quality standards (e.g. electronic industry requires higher purity than hydrogen fuelled industrial heat). Preparation, either purification or coloration/odorisation in this example) will therefore be an essential element in creating an interconnected hydrogen grid. This will require careful measurement of quality and an assessment of the different types of impurities and their effects especially if they do very during transport or storage. A similar strategy can be used for different pressures and forms for a variety of consumers.

15.6. Preparation

As shown in the example above, preparation will be crucial in creating an integrated hydrogen energy system. The different types of preparation presented in section 5.5 are detailed below:

Change in Form (hydrogenation / dehydrogenation)

The form of hydrogen is of paramount for each element of the hydrogen system. Some forms provide feasible and commercially sensible ways to transport and store hydrogen. The final form needs to fulfil the end use requirements.

Hydrogen can be :

- in gas or liquid state, pure or blended with natural gas
- an element of a chemical compound or absorbed by metal hydrides.

Hydrogen can be produced and used in its natural form. However, it may be safer and more practical to convert to a hydrogen carrier such as ammonia, LOHC or methanol especially for long distance containerised transport. Pressurised or liquid hydrogen require advanced pressurised or cryogenic containers whereas hydrogen carriers can be kept under atmospherics conditions in simple containers. The hydrogen compound can be used in its form as a chemical feedstock or as fuel or hydrogen can be extracted from its compound for end use. All these variants are part of the hydrogen energy system where the different options are defined by the end user's needs and the characteristics of each process (capacity, efficiency, supply chain…) and the associated cost.
More recent research show that certain compounds, called metal hydride, can trap hydrogen molecules at room temperature and pressure, then release them upon demand. Solid or paste state storage in metal hydride could provide an alternative to hydrogen pressure tank for fuel cells applications.

For example, what impact could the progress of hydrogen carriers such as green ammonia as fuel cells energy source or for heat and power generation as well as its main current use as fertiliser. This could open up some new markets, transform long term, large scale storage and distribution, import/export solutions and modify the pathway to integrate multiple applications that are currently reliant on fossil fuels. The impact will encompass the whole life cycle of hydrogen based energy. While preparation will always carry a cost and energy penalty, most elements can involve a combined solution; for storage requirements due to renewable intermittency and seasonal demand variations, hydrogen could compensate short term, rapid fluctuations while ammonia could support the longer term, larger scale storage.

The interoperability between natural gas, blend and pure hydrogen is detailed in section 5.6. Depending on the evolution and the quantity of hydrogen and hydrogen carriers, the different

forms of hydrogen may create separate markets. However, flexibility especially with transport and storage may give producers and users the choice of different hydrogen forms depending on the market needs.
For example, a large electrolyser can produce hydrogen for a gas grid as well as storing ammonia or LOHC for long term storage depending on the demand. The stored hydrogen carrier can then be sold as such or converted back into hydrogen when production slows, or demand rises.

Change in Pressure (pressurise / depressurise) – for gas form

The most common way to reduce the volume of a gas is to increase its pressure by compressing it at constant temperature. Like natural gas, hydrogen is pressurised and depressurised to allow moving from one element to the next from production until final use.

In a gas network, pressure is the main control parameter. Transport and distribution through pipelines is controlled by a series of compressors to allow the hydrogen to flow from high pressure to the lower pressure required at the end of the transport process. The location of these stations is defined by the topography of the terrain, the type of product being transported, or operational conditions of the network. Compression technology is also available for storing hydrogen, transporting via containers, refuelling stations and other applications. However, large volume compressors are still under development and may become a bottleneck for large scale applications or national transmission.

Pressurisation and depressurisation require energy, produce some emissions and produce by-products (such as heat) that need to be included in the related element characteristics. The properties of hydrogen also bring some challenges compared to other gases. The highly explosive and lightweight properties require different regulations and safety measures compared to natural gas.

For example, high-pressure storage can include energy recovery from depressurisation: if demand from the storage is supplied via a let-down turbine, electricity can be generated. Depending on the technology, the efficiency of the process will vary, and the hydrogen can be contaminated by impurities through that process.

Typical pressures for each element of a gaseous hydrogen system are shown below:

- Production output: 10 to 40 bar
    - Electrolyser: 20 to 30 bar (increasing to 80 bar)
    - SMR ~20 bar
- Preparation
    - Post-production: up to 100 bar
- Transmission >85 bar (typical 100 bar)
- Distribution: >7 bar
- Storage
    - Salt caverns 105 and 270 bar depending on depth
    - Transmission outlet 50 to 80 bar
    - High pressure cylinders 430 to 500 bar
- Use
    - Refuelling station – 350 and 700 bar
    - Domestic boiler – 20mbar (like natural gas)
- Import (high pressure compressed) – 350 bar

Change of State (Liquid / Gas)

Change of state (liquid to/from gas) always involves change in temperature and/or pressure.

Changing the form of hydrogen from gas to liquid is an energy intensive and expensive process. The technology of liquefaction by chilling hydrogen to near absolute zero is well proven and has been used by NASA for decades as rocket fuel. Once in its liquid state, hydrogen becomes non-corrosive. Liquid hydrogen is usually stored in containers varying in size depending on the usage profile and pressure and end use.

Liquid hydrogen containers are bulky, heavy and expensive but the storage regulations are similar to those of natural gas. Existing LNG facilities already have access to large quantities of gas, storage space and expertise to handle large quantities of hazardous materials.

Change in Quality (Purification)

The quality of hydrogen encompasses the purity, i.e. the concentration of hydrogen and the different contaminants such as water vapour, dust and debris. The production process can produce different level of quality and contaminants can be picked up during transport, storage or preparation.

Different production methods will produce different hydrogen quality. The quality can also deteriorate during transport, distribution and storage. Finally, the level of purity and quality requirements vary across end use applications and different standards apply. Also, the specifications for the different contaminants such as water, oxygen, carbon monoxide may differ.

Unless the production is dedicated for a single end use, the interoperability between end use will depend very much on quality. The quality from production to end use may also vary throughout the life of the assets and the different stages offering variable quality at end use. Impurity detection and measurement has therefore a prominent role to play.
As the local systems expand and connect, the requirements for hydrogen quality may require some adjustments to each one of the elements. High purity production may be lowered if the system becomes connected to a lower quality network. Purification stages may be required at different stages such as post storage or just prior to end use.

Different purification techniques exist depending on the type of contaminant, the purity required and the scale of use. Each technique has limitation as well as advantages; this report will focus on the physical, environmental and commercial characteristics of the technique rather than the technique as long as it is suitable for the end use.

For example, high purity hydrogen is needed for some fuel cell applications. However, when used as blended hydrogen for boilers or power generation, lower purity can be used. The production method and transport need to consider the end use of the hydrogen quality required as the production efficiency and cost will be affected. Variable quality can affect the efficiency of burners for example or increase emissions.

Quality standards are well developed for fuel cell applications (see section 5.10). However, recommendation for a UK hydrogen quality standard for heat applications are still being drafted[10] (Hy4Heat). Over stringent standards could also refrain interoperability of end use and system connections.

Note that connecting different network with different quality can lead to significant changes upstream and downstream of the connection. The impact can be positive: increase quality and efficiency in one branch, possibility to lower quality of production incurring saving. It can also be negative and costly to adapt the end use application such as burner or controller or add a purification stage prior to end use.

Change in Hydrogen content (Blend / Deblend)

The change in the ratio of hydrogen to methane blend content is a specific type of hydrogen quality. Blending hydrogen with natural gas is seen as a preparation to the transition from natural gas to full hydrogen. Blending and deblending and their associated control and interoperability are described in section 5.6.

Colourise / Odourise

As hydrogen is odourless and colourless, odorisation and colourisation can be performed prior to usage. Recognisable odorants can help detect leaks at any stage. Colourants can be used in domestic boilers and cookers to ensure safe burning and increase user acceptance by mimicking natural gas colour. Odorants are also being trialled on blended hydrogen and need to meet the minimum requirements for odorants already used in natural gas. However, colorants and odorants affect the quality of the hydrogen carrier and might not be allowed for certain applications such as fuel cells.

An example of connected industrial, mobility and heating end users using preparation stages is shown in section 14.5.3.

15.7. Closed and open systems

An introduction to the concept of closed and open system is developed here. The influence of the decision to close or open a system will be highlighted and the impact on

The difference in terms of control, compatibility and flexibility will be highlighted as well as role this can have in the development of hydrogen economy.

A closed hydrogen system is a system where all the hydrogen produced is consumed within its boundary. They are however connected 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.

A high level architecture is shown below:

10 https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/5e58ebfc9df53f4eb31f7cf8/1582885917781/WP2+Report+final.pdf

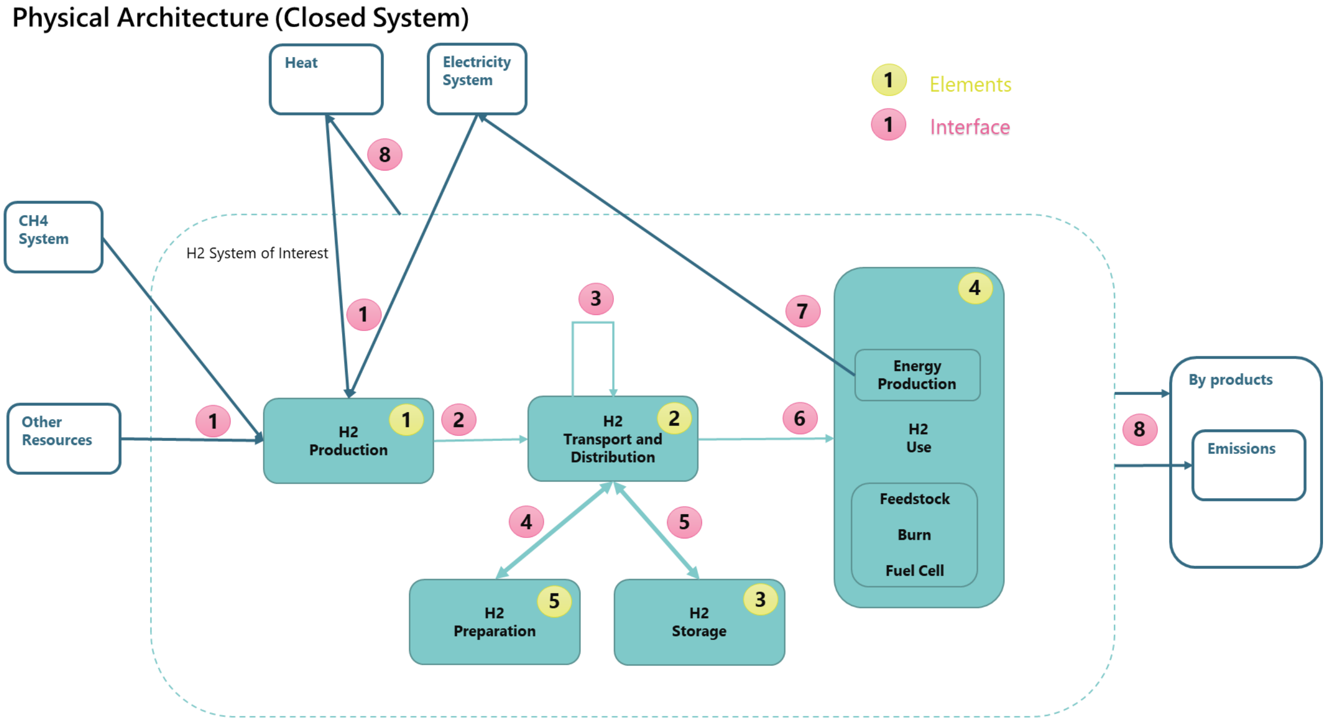

Figure 11: Closed hydrogen energy system architecture

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.

A closed loop system can benefit from regulation exemption to address specific problems and such as industry, building or grid demonstrators, colocation of HRS and petrol facilities. However, regulation exemptions need to have a pre-defined purpose bound in time. They must not impede the connection between systems nor be detrimental to competition.

A centrally controlled closed loop system is usually simpler to control as the production can be sized to fit the demand. However, production and storage capacity must match peak demand which can lead to diminished productivity or wasted hydrogen if supply exceed demand. The system is also at risk in case of under capacity.

In contrast, an open hydrogen energy system will have hydrogen exchanges outside its boundaries with other energy systems through import and export as shown below.

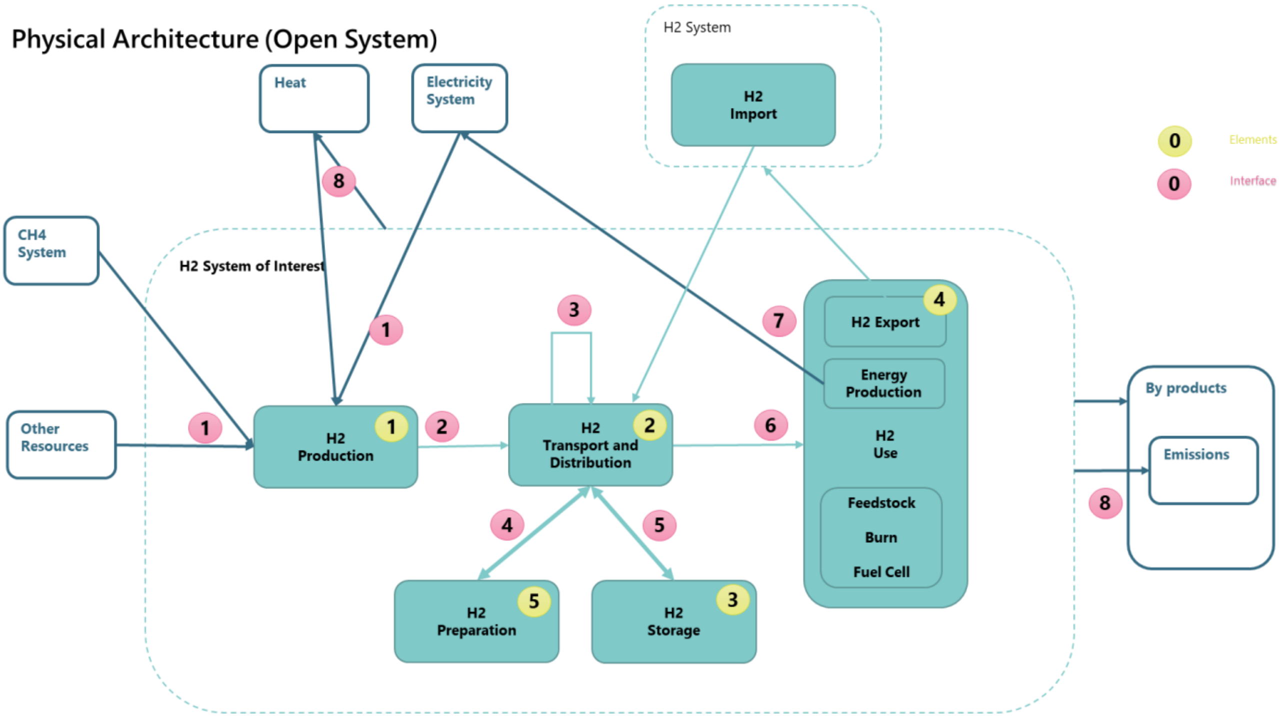

Figure 12: Open hydrogen energy system architecture

For a collocated system, this means exchanging hydrogen flows with other systems and transitioning to a local energy system.

For a local system, export will appear where large scale hydrogen can be produced and transported to multiple systems. These systems will be able to import and share hydrogen as well as produce their own in combination with storage facility.

When a national system develops, it is most likely than international import, export and interconnections will take place in a similar way it currently happens for the physical natural gas and oil systems.

International hydrogen based products import will play a major role in the future of MH:EK and is discussed in the pipeline transport and distribution section 5.2.2.

The proposed projects shortlisted for further techno-economic modelling within the MH:EK are focusing on multi vector Smart Local Energy Systems (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.

15.8. Elements characteristics and flow properties

To make the architecture robust and future proof in a fast changing environment, it is important to focus on the properties of the elements and the behaviour capabilities rather than the technology solution. A robust architecture will allow the system to grow, new technology to emerge and elements to still work together efficiently.

It is also important to recognise that what we think is valued today is not necessarily what will be valued tomorrow. Therefore, a solid architecture foundation supported recognised characteristics to define the system arrangements will provide evolvability and adaptability

The architecture options and the behaviour of the actors will quantify the value of the properties. It is important to note the interactions between properties: both within each domain (production capacity and demand), and between domains (cost and quality)

15.8.1. Element characteristics

The element characteristics are used to design and control the system.

Capacity

Capacity is the overall energy flow property which allows to size the system from small scale demonstrators to a national system.

The production capacity, without storage, need to meet the peak demand of the system. The storage capacity allows the production capacity for a whole system to be sized on the overall average demand.

The transport and distribution capacity needs to support the connection between production, storage and end use.

A property of storage is its modularity. The modularity represents how the storage capacity can be modified (increased, decrease or relocated)

Efficiency

Each element will have its own efficiency, but it is essential to quantify the overall efficiency of the life cycle of the hydrogen from production to final use. Life cycle efficiency over a whole year (to include seasonal variations) will allow comparison between different energy vectors. Efficiency is also one of the parameters of the control method. The total efficiency of an element can also consider the use of by-products such as heat or oxygen. Heat can be used by the plant for its operation or be connected to an external heat network, therefore reducing the local heat demand from other vectors.

The efficiency of each element is the ratio between the energy input at the start of the process and the energy available at the end of the process.

The efficiency of the **production process** is the ratio between the energy output and the energy source input. This can be defined for example in kWh used per tonnes of Hydrogen (tH_2) produced

The efficiency of the **transport and distribution process** itself is the ratio between the energy at the destination and the energy available before transportation.

The efficiency of the **storage process** is the ratio between the injected energy and the discharged energy.

The efficiency of the **consumption process** will depend on the end use. For example, for heating the efficiency represent how effectively energy is converted into heat. This allows to compare different energy sources for heating (electricity, natural gas, hydrogen, oil, geothermal…). To the same extend, fuel cell efficiency can be compared with electric batteries or internal combustion engines (ICE) to convert into kinetic energy for mobility.

Ramping Up / Down (Production)

The characteristics of the production process to accommodate variation (increase / decrease) of input, their impact on the plant and the output.

Distance/Length (Transport and Distribution)

The distance between the source of hydrogen to its destination.

Time (Transport and Distribution)

The time it takes for the product to go from its origin to its final destination. The temporal aspect of transport and distribution is important as gas travels relatively slow through pipelines and containers.

Injection and Discharge Rate (Storage)

Injection and discharge rates are the amount of gas that can be injected or withdrawn into/from a storage facility daily. Discharge can also be referred as withdrawal or delivery.

Availability (Storage)

The volume of gas available to the marketplace at a particular time, also called working gas.

Security of Supply (Use)

The level of security of supply will depend on the application and will impact the other elements. Lower level of security of supply will allow greater flexibility. Security of supply must be ensured with clear legislation and planned to minimise cost for reinforcement.

15.8.2. Flow properties

The physical properties of hydrogen flow between elements considered in this architecture are shown below. The properties should be common to all system whatever the scale and complexity and flexible enough to adapt for new technology. Properties can also be added, removed or replaced if the system or elements evolve with time.

The flow properties used for design and control for the presented architecture and system arrangements are:

- The form of hydrogen (gas, liquid, compound)
- The quality of hydrogen (including concentration, purity, and blend levels)
- The pressure (main control parameter)
- The quantity (forecast profile and current measured values)
- The duration of storage (active control, day reserve to interseasonal)

15.8.3. Environmental properties

Environmental properties are parameters that are chosen to define the effect of each element on the environment. *It is usually quantified as the negative impact on the environment.*

Emissions

The term "emission" is used across the document to allow flexibility and development of the definition depending on the application.

For example, the CCC define the four most common greenhouse gases (GHG) used for their comparisons as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NOx) and Fluorinated-gases (F-gases). For local authority application, the emissions of particulate materials (PM2.5 and PM10) can be included in the model.

Burning hydrogen does not produce carbon dioxide emissions and it is often reported that the only by-products are water vapour and heat. This is true for fuel cells or where the oxygen intake is controlled. However, due to the higher flame speed, using a natural gas burner with atmospheric air with hydrogen could generate higher NOx emissions.

GHG emissions can be measured in metric tons of carbon dioxide equivalent (MTCO2e) based on the warming potential of the gas. However, each gas or particle type can be accounted for individually or simplified, for ease of reading, as "equivalent of taking 1000 cars off the road" for approximately 5000 MTCO2e/year.

Emission intensity

It is appropriate to differentiate between emission and emission intensity as they have different roles in decarbonisation.

Emission intensity is the emission rate of a given pollutant (see emission above) relative to the intensity of a process. Carbon intensity of hydrogen production, for example, can be expressed in terms of carbon dioxide emission (or equivalent) per energy produced in kilowatt-hours (kWh). It allows comparison between different processes using median values in kg of carbon dioxide equivalent emitted per kg of hydrogen produced (kg CO2e / kg of H2) from coal gasification (20), to SMR (15), methane pyrolysis (6) and electrolysis (1).

Emission intensity can be used by the controller to meet decarbonisation target. It can also be used by governing bodies for tax purposes.

However, the emission intensity of the source of hydrogen production must be accounted for in the embodied emissions calculation.

Embodied emission

A lot of work is being done to decarbonise the source of energy – many companies from oil, to automotive have now included their supply chain in their roadmap to net zero.

Like electricity, guaranteeing the source of energy is a challenge. Renewable electricity can now be tracked. Consumers can buy certified renewable or low carbon electricity and support green electricity generation. Policy and regulation have also been supportive.

For hydrogen, the main challenge is the definition of the emission system boundary. As the attraction of hydrogen is the very low end use emissions, the boundary can be defined around the production process or also include the origin of the feedstock. The inclusion of feedstock transport and hydrogen transport and distribution could also be integrated. A clear definition for the calculation or estimation of embodied emissions from each production process is also required. An agreement on acceptable levels could support the development of policy and standards.

15.9. Introduction to interoperability

Interoperability is the ability of a product or system to cooperate with other products or systems to share resources.[11]

The six types of interoperability presented for the energy sector apply for the hydrogen energy sector. This section will emphasise the challenges hydrogen brings to interoperability for each element in the system and the role of interoperability in the transition from fossil fuels to a hydrogen and electricity economy. The six interoperability types are:

1. **Consumer Interoperability**: ensuring that provisions exist for consumers to switch between both different commercial offers and technology choices.
2. **Commercial Interoperability**: to ensure that incentives are aligned across the energy system to ensure that value can flow where it needs to, driven by market forces.
3. **Data Interoperability**: to ease the sharing and portability of data between different systems.
4. **Device Interoperability**: to ensure that devices are swappable, replaceable and exchangeable as needs change and technologies develop and to allow consumers to make informed choices between open and closed eco-systems.
5. **Physical Interoperability**: to ensure that end-to-end systems function as changes happen to parts of the system.
6. **Vector Interoperability**: to ensure that energy provision across gas, electricity, heat, transport fuels etc. are compatible with one-another and that coordination occurs in a timely fashion.

Operational, technical, communications and business-wise interoperability needs to be developed for a future integrated hydrogen market. The physical connection and compatibility within and between each element of the system is detailed in the next section after the description and challenges of each element. Some other aspects of physical interoperability for the hydrogen energy system are detailed below.

15.9.1. Demand interoperability

Hydrogen demand within the boundary of the system is the sum of end use (direct or indirect), storage availability and export.

From an operator perspective, scaling up hydrogen demand and high volume transport can come from standardising end use needs. As discussed in previous sections, the form, pressure and purity at end use differ from high purity for fuel cell and some industrial applications to lower purity for burning for heat as an example. However, multiple avenues can be assessed.
For gas blending, standards can support upscale and compatibility between high pressure power turbines inputs and domestic heating. Downstream hydrogen addition can be managed downstream if variable or higher blend can be supported at domestic level.
For mobility, refuelling stations can support multiple road, rail, marine applications and allow new opportunities to spawn from existing infrastructure.
However, the development of different options for similar end use (i.e. fuel cell tank pressures, ammonia/ammonia fuel blend/gaseous/liquid hydrogen…), by diversifying the infrastructure and

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

divide the investment and progress of certain technologies.

15.9.2. Energy information interoperability

Some examples of information interoperability for both the production side connecting the energy source and hydrogen networks and the end user side are detailed below.

From a hydrogen production viewpoint, an electrolyser can be combined with an existing wind or solar park connected to an electricity grid. The energy management system will aim to optimise the use of the intermittent and uncertain produced electricity (avoiding curtailment) and the flexibility of the electrolyser. To do so, the hybrid controller requires data from both the electrical and hydrogen systems. The response time of the electrolyser will have to accommodate the electrical load (depending on end use) and the hydrogen output requirements. Again, the hydrogen can be stored and used for multiple applications including refuelling stations and fuel cell to reinject electricity on the grid would demand surpass supply. The integration could generate more benefits than the sum of each technology working independently.

On the consumer side, safe and precise measurement of hydrogen flow for billing purpose and potentially smart functionalities. Due to the differences between natural gas and hydrogen, lower calorific value and higher explosive risks, current meters may need adjusting or not be suitable for blended or pure hydrogen. Hydrogen gas meters may be bigger to allow extra flow for the same heat produced and safety parts. The meters also need to meet current metering regulations such as SMETS 2 for domestic meters.

15.10. Standards, regulation and code examples

A desktop research was performed to find the main regulations which govern hydrogen either directly or indirectly by its interaction with other related systems.

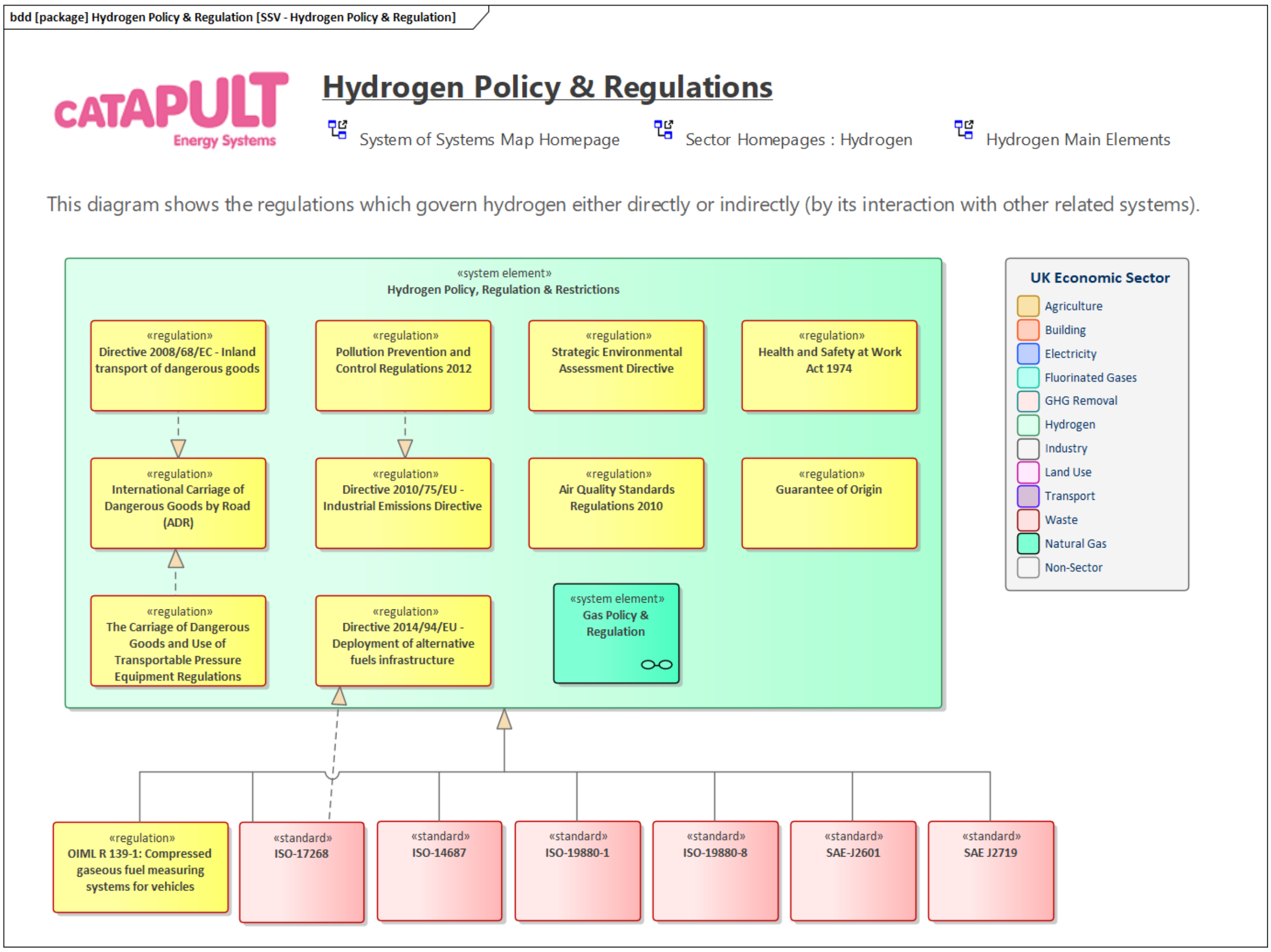

Figure 13: Hydrogen policy and regulation

The extracted regulations, standards, codes have been categorised to follow the structure of this document and can be used for further analysis:

- Physical aspects for each element described in this document
  - Electrolysers - Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications (ISO 22734)
  - Transport and Distribution of hydrogen – Gas supply committee (GSE/33) at BSI looks specifically into it from compressor stations to quality. Transportable cryogenic and gas containers.
  - Storage – gas containers, safety test for different volumes and pressures, location of storage in residential zones.
  - Fuel cell applications – many standards already exist and are under development for all mobility applications and power units.
    - Hydrogen vehicles and refuelling stations from installation, pressure, quality to nozzles etc. already have an extensive set of standards.
  - Hydrogen use for Aerospace / Healthcare use / Water treatment
  - Heating – blending proposal (CEN/TC 109 N 1353)
  - Materials – testing and impact of hydrogen (embrittlement, permeation…)
- Health and Safety
  - Prevent and mitigate the effects of major accidents

    - Safe handling of hydrogen
    - Emissions of Hydrogen
- Measurement and Data
    - Measurement method for the evaluation of hydrogen embrittlement resistance of high strength steels (ISO 16573-1)
    - Gas analysis (determination of hydrogen content in natural gas)
    - Support data interoperability
    - Support testing and terminology
    - Support definition, identification and tests of hazards
    - Data exchange to support control
    - Energy consumption definition and measurement
    - Hydrogen detection for stationary applications
- Operability and Interoperability
    - Keeping the system working during and after extraordinary events
    - Pressure levels across the system
    - Environment protection – Marine and coastal access
    - Embrittlement risks and understanding
- Commercial aspects
    - Fuel price information and availability

16. Appendix E – Trading Platform

Data is in word doc, separate appendix, link below

https://catapultore.sharepoint.com/:f:/r/sites/MilfordHavenEnergyKingdom/Shared%20Documents/WP01%20System%20Architecture/5.%20Draft%20Report?csf=1&web=1&e=89i7OF

17. Appendix F – Uncertainty in the Future use and production of hydrogen

This section provides more background information for the future use of Hydrogen and supports details given in section 4 of the main report.

- Cost projections and comparison to alternatives- due to the nascent technology, it is unclear how hydrogen production costs will change over the next 10 years and how the costs of hydrogen applications will change. What is also unclear for some applications is how hydrogen costs will alter compared to other low carbon solutions. The Hydrogen Council explored this in 'Path to hydrogen competitiveness- A cost perspective' (2020), assessing potential cost trajectories for different hydrogen uses compared to alternative energy vectors. They highlighted that the cost reductions for hydrogen production and use will be linked to the level of investment placed in these technologies. The level of investment internationally that will come forwards is unclear, as even though lots of countries have developed ambitious hydrogen strategies in the last year, many of them have not yet been followed up with policy instruments. This uncertainty makes it difficult for some sectors to make strategic enabling decisions (such as install hydrogen refuelling infrastructure or install a hydrogen transmission line to a region) without which it may be difficult for some applications to convert.
- Suitability for application- For some applications it is still unclear how well-suited hydrogen is to the application. Considerations such as ease of conversion and safety could affect uptake.
- Interaction across uses- considering the multiple uses for hydrogen, investment decisions for key infrastructure may be based on the needs of several sectors. Therefore, the use of hydrogen for one application can have an impact on the potential to use it in other applications.
- International production- there are discussions underway about both the ability of hydrogen to be introduced internationally and imported to the UK as well as produced in the UK and exported. Figure 14 below shows cost projections for hydrogen from different areas of the world if produced from solar and/or onshore wind. This shows the potential for areas of the world with natural renewable resources to generate low cost hydrogen.

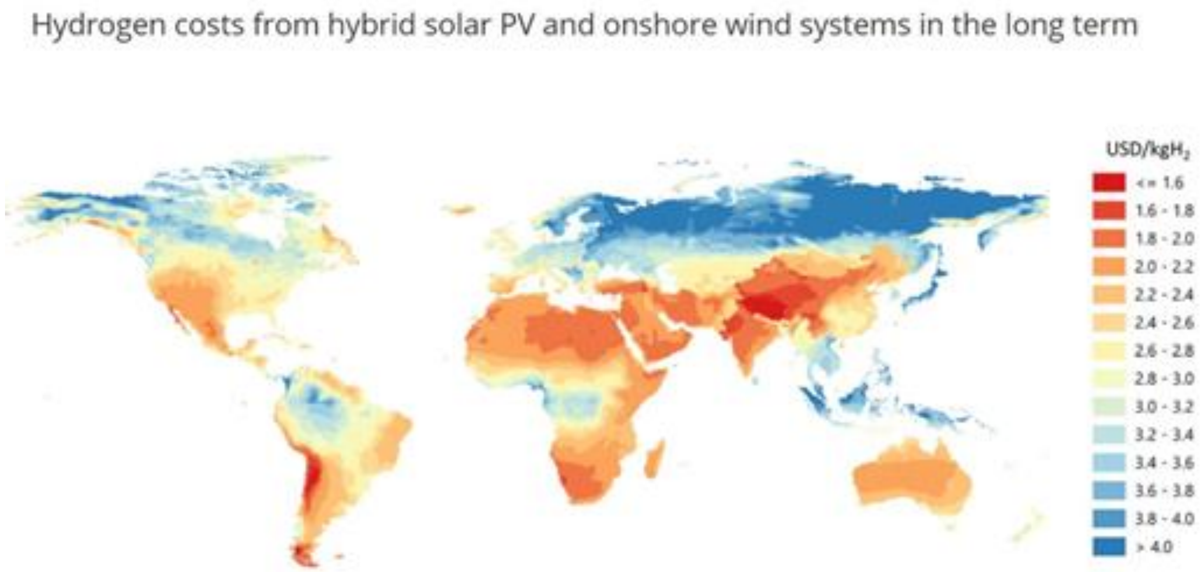

Figure 14 – IEA, 2019 - https://www.iea.org/reports/the-future-of-hydrogen

It is unlikely this import infrastructure will materialise in the short term. However, this adds risk to investors building hydrogen production capacity as their prices may be undercut by international imports. It also adds uncertainty for governments introducing policy. It should be noted that in 2018 the CCC estimated that the extra costs of transportation would mean there would be a lasting role for domestic generation.

- Emissions headroom- Hydrogen produced via SMR/ATR with CCUS has residual emissions as capture rates are not 100%. Therefore, if there is little capacity for residual emissions then hydrogen production through SMR/ATR with CCUS may not be net zero compatible.
- Impact from the development of other systems- hydrogen system development and the overall need for hydrogen will be heavily influenced by the development of other systems:
    - SMR/ATRs require CCUS infrastructure to produce low carbon hydrogen.
    - The need for hydrogen to help balance the electricity system will be driven by the flexibility needs of the electricity system.
- Government policy (UK and international)- in the absence of a carbon price driving action to net zero, government policy will have a large impact on system development. Additionally, the processes used to determine network investment decisions will shape where and how hydrogen is used. The UK Hydrogen Strategy is yet to be released.

18. Appendix G – Glossary

Term	Acronym	Definition / Description	Link	Source
Architecture	-	The designed and emergent structure of a system, and the manner in which the physical, informational, operational and economic components of a system are organised and integrated.		
Active Network Management	ANM	In electricity distribution circuits, Active Network Management (ANM) describes control systems that manage generation and load for specific purposes.		Wikipedia
Autothermal Reforming	ATR	Autothermal Reforming (ATR) is a process for producing syngas, composed of hydrogen and carbon monoxide, by partially oxidizing a hydrocarbon feed with oxygen and steam and subsequent catalytic reforming.		Air Liquide
Battery Electric Vehicles	BEV			
Biomass		Plant based substance used to generate heat or electricity		
Blended System	-	Gas system where hydrogen (usually low concentration <20% volume) is injected into a natural gas supply.		
Business, Energy & Industrial Strategy (Department for)	BEIS	A ministerial department supported by 41 agencies and public bodies. Their focus is on building an economy that works for everyone, so that there are great places in every part of the UK for people to work and for business to invest, innovate and grow.		ERIS Starter Guide Glossary
CAPital Expenditure	CAPEX			ESC SSH Acronyms and Glossary
Carbon Capture, Utilisation and Storage	CCUS	Capture and usage or long term storage of carbon dioxide as it is released into the atmosphere from fossil fuels		ESC SSH Acronyms and Glossary
Climate Change Committee	CCC	The UK's independent adviser on tackling climate change	https://www.theccc.org.uk/	
Climate Change Levy	CCL		-	
Coal Gasification			-	
Cogeneration	-	See CHP	-	
Combined Cycle Gas Turbine	CCGT			ESC SSH Acronyms and Glossary
Combined Heat and Power	CHP	Process that captures and utilises the heat that is a by-product of the power generation process.		
Compressed Air Energy Storage	CAES			
Contracts for Difference	CfD	The scheme is the government's main mechanism for supporting low-carbon electricity generation.	https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference	
Constraint Management Zone	CMZ			
Corporate Social Responsibility	CSR			
DiMethyl Ether	DME	Biofuel		

Term	Acronym	Definition / Description	Link	Source
Direct / Indirect Use	-	In the context of hydrogen: Direct usage means that the application is the final use of hydrogen, e.g. mobility, industry, building. Indirect use means that the hydrogen is converted into another energy vector that can potentially have a similar end use as hydrogen or be converted back into hydrogen.		
Distributed Energy Resources	DER			
Distribution Network Operator	DNO			
Distribution System Operator	DSO			
Enterprise Architect	EA	Model based system engineering tool developed by Sparx Systems	https://www.sparxsystems.eu/	
Energy Network Association	ENA	Energy Networks Association (ENA) represents the energy networks in the UK & Ireland.	https://www.energynetworks.org/	
Electricity System Operator	ESO			
Electrolysis		Process where electric current is passed through a substance to bring about a chemical change. An electrolyser uses water and electricity to generate oxygen and hydrogen.		
Energy from Waste	EfW			ESC SSH Acronyms and Glossary
Energy Network Association	ENA	Industry body for the companies which run the UK & Ireland's energy networks.	https://www.energynetworks.org/	
Energy Revolution Integration Services	ERIS	ERIS exists to respond to the integration challenge and to break down the siloed thinking which stands in the way of sustainable new smart local energy markets.		ERIS Starter Guide Glossary
Energy Systems Catapult	ESC	Set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth.	https://es.catapult.org.uk/	
Enterprise Architect	EA	A model based systems engineering software tool	-	
Export	-	In the context of hydrogen, export represents the hydrogen sent outside of the system boundary. The total hydrogen output of a system is the combination of use and export.		
Future Energy Scenarios	FES			
First of a Kind	FOAK			
Front End Engineering Design	FEED	This activity aims to robustly set out a project's technical requirements at the start and focus on an estimated investment cost		
Fuel Cell	FC	A device that produces electricity through an electrochemical process, usually from hydrogen and oxygen although other fuel cells are available (e.g. methane fuel cells)	https://h2tools.org/hyarc/hydrogen-glossary-and-acronyms	H2Tools
Fuel Cell Electric Vehicles	FCEV	Electric vehicle using hydrogen gas for generating electric power.		

Term	Acronym	Definition / Description	Link	Source
Gas		Used to denote the state of matter. Care should be taken to not use gas to mean LNG/Methane/Natural gas as (for example) hydrogen might also be used in gas form		
Gas Distribution Networks Operator	GDNO			
Greenhouse Gas	GHG			
Heavy Good Vehicle	HGV			
Hydrogen	H2			
Hydrogen Fuel Cell Vehicle	HFVC			
Hydrogen Refuelling Station	HRS	Infrastructure designed for filling a vehicle with hydrogen fuel. It can be part of a station for fossil fuel refuelling or an independent infrastructure.	https://hydrogeneurope.eu/	Hydrogen Europe
Hydrogen Use	-	This represents the various ways hydrogen can be used. The multiple used are described below: - Mobility (road transport / aviation / shipping / rail) - Industry (refineries, chemicals, iron and steel, construction, cement and lime, food and drink etc...) - Heating (including space heating, cooling, hot water, cooking) - Power generation (power generators for direct and indirect use)		
Import	-	In the context of hydrogen, import represent the source of hydrogen which is produced outside of the system of interest boundary. (e.g. international import for the nation system; national and regional transmission import for the local system). The total source of hydrogen is the combination of production and import.		
Indirect Use	-	See Direct / Indirect use definition		
Industrial Strategy Challenge Fund	ISCF			
Internal Combustion Engine	ICE			
Interoperability	-	Interoperability is the ability of a product or system to cooperate with other products or systems to share resources.	https://es.catapult.org.uk/brochures/an-introduction-to-interoperability-in-the-energy-sector/	
Linepack	-	The total volume of gas contained within the system at any time. This is measured in millions of cubic meters at atmospheric pressure.	https://www.nationalgrid.com/uk/gas-transmission/glossary-terms	National Grid
Liquid Air Energy Storage	LAES		https://energystorage.org/why-energy-storage/technologies/liquid-air-energy-storage-laes/	
Local Energy Asset Representation	LEAR	This document provides a representation of a local energy system and is created by collating and processing data from a variety of sources and using in ESC in house modelling techniques.		ESC Acronym List
Locational Marginal Pricing	LMP			

Term	Acronym	Definition / Description	Link	Source
Liquefied Natural Gas	LNG			ESC Acronym List
Liquid Organic Hydrogen Carriers	LOHC	Organic compounds that can absorb and release hydrogen through chemical reactions (used for storage / transport)	https://en.wikipedia.org/wiki/Liquid_organic_hydrogen_carriers	
Methane	CH_4	Chemical formula of methane, a chemical compound such as natural gas or biomethane. Methane is the main component of "Natural Gas", the term used throughout this document.		
Methylcyclohexane	MCH	Example of LOHC		
Milford Haven : Energy Kingdom	MH:EK	The MH:EK project aims to accelerate the transition to an integrated hydrogen and renewable energy system by creating diverse, local, community-based markets that integrate with, and benefit from, the cluster of major energy infrastructure along the Milford Haven Waterway.	https://ore.catapult.org.uk/stories/milford-haven-energy-kingdom/	
Model Based Systems Engineering	MBSE	A software tool such as Enterprise Architect to map	-	
Mobility		In the context of hydrogen, mobility represents all the different modes of transport by land, water and air powered by hydrogen. The terms transport and transportation should be avoided to avoid confusion with the distribution of hydrogen.	-	
National Grid	NG	In the electricity sector in the United Kingdom the National Grid is the high-voltage electric power transmission network covering Great Britain, connecting power stations and major substations and ensuring that electricity generated anywhere on it can be used to satisfy demand elsewhere.		ESC SSH Acronyms and Glossary ERIS Starter Guide Glossary
Natural Gas	CH_4 (plus traces)	A term often used interchangeably with Methane to indicate the product which gets to homes and businesses to be combusted		
Open Cycle Gas Turbine	OCGT			ESC SSH Acronyms and Glossary
Operational Expenditure	OPEX			ESC SSH Acronyms and Glossary
Pembrokeshire County Council	PCC			
Potential System Arrangement	PSA			
Power-Purchase Agreements	PPA	Long term contract for generating and selling energy for generation capacity of more than 250kW.		
Potential System Arrangement	PSA			
Power to Gas	PtG	Conversion of electrical power to produce gas (including hydrogen)		
Preparation	-	In the context of hydrogen, preparation includes all the processes that change one or more properties of hydrogen (form, pressure, blend...) to be suitable for the subsequent stages of operation.		

Term	**Acronym**	**Definition / Description**	**Link**	**Source**
Production	-	In the context of hydrogen, production refers to the creation of hydrogen or hydrogen carrier from another energy vector (electricity, natural gas, waste etc). The term "Preparation" is used in this document to refer to the conversion from one hydrogen form to another (gas, liquid, LOHC).		
Prospering from the Energy Revolution	PFER	A challenge that will bring together businesses working with the best research and expertise. Together they will develop and demonstrate new approaches to provide cleaner, cheaper and more resilient energy. This includes providing energy in ways that consumers want by linking low-carbon power, heating and transport systems with energy storage and advanced IT to create intelligent, local energy systems and services.		ERIS Starter Guide Glossary
Pyrolysis				
Renewable Transport Fuel Obligation	RTFO	The RTFO Order regulates biofuels used for transport and non-road mobile machinery.	https://www.gov.uk/guidance/renewable-transport-fuels-obligation	
Security (Energy)	-	The IEA defines energy security as the uninterrupted availability of energy sources at an affordable price. Energy security has many aspects: long-term energy security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply-demand balance.	https://www.iea.org/topics/energy-security	IEA
Smart Local Energy Systems	SLES			
Steam Methane Reforming	SMR			ESC SSH Acronyms and Glossary
Storage	-	For all energy vectors, storage is the capture of energy for use at a later time.		
Synthetic Natural Gas	SNG	Produced fuel gas composed of predominantly methane (CH_4)		ESC SSH Acronyms and Glossary
System Operator	SO			
Systems Modelling Language	SysML			
Technology Readiness Level	TRL			ESC SSH Acronyms and Glossary
The Office of Gas and Electricity Markets	Ofgem			ESC SSH Acronyms and Glossary
Transport and Distribution	T&D	In the context of hydrogen, the physical movement of hydrogen from one location to another through pipeline or container/tanker.		
Unique Selling Proposition	USP	Refers to the unique benefit exhibited by a company, service, product or brand that enables it to stand out from competitors.	https://en.wikipedia.org/wiki/Unique_selling_proposition	Wikipedia
United Kingdom	UK			

Term	Acronym	Definition / Description	Link	Source
Variable blend	-	In a blended system (consisting of hydrogen and natural gas) a variable blend indicates the scenario where the percentages of each gas can vary, up to a maximum quantity.		
Vector, or Energy Vector	-	This term is used to describe a mechanism that enables the transfer, in space and time, of a quantity of energy. It may be a system that utilises electricity, heat, natural gas, hydrogen or some other agent.		FPSA
Virtual Lead Party	VLP			

19. Appendix H – Acknowledgements

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Sea Wind Technology
Marine Energy Wales
Pembrokeshire Coastal Forum
Creas - Cranbourne Energy Consulting Ltd
Steamology
Wales and West Utilities
ARUP
Excal Ltd
Milford Haven Port Authority
Blue Energy
Element Energy
Innovate UK
CEPLEAF - Community Energy Pembrokeshire, Local Energy Action Force
Pembrokeshire Country Council
BEIS Department for Business, Energy and Industrial Strategy
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Costain
Swansea University
Riversimple
CRPlus
Energy Local
Hwb Cymru
Western Power Distribution
Puma Energy
RWE
PD Partnership
Octopus Energy
Renewable UK
Fuel Cell Systems
Egnedol Ltd
Starfish Collective
Valero
Balancing Rocks Ltd

Energy Systems Catapult supports innovators in unleashing opportunities from the transition to a clean, intelligent energy system.

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