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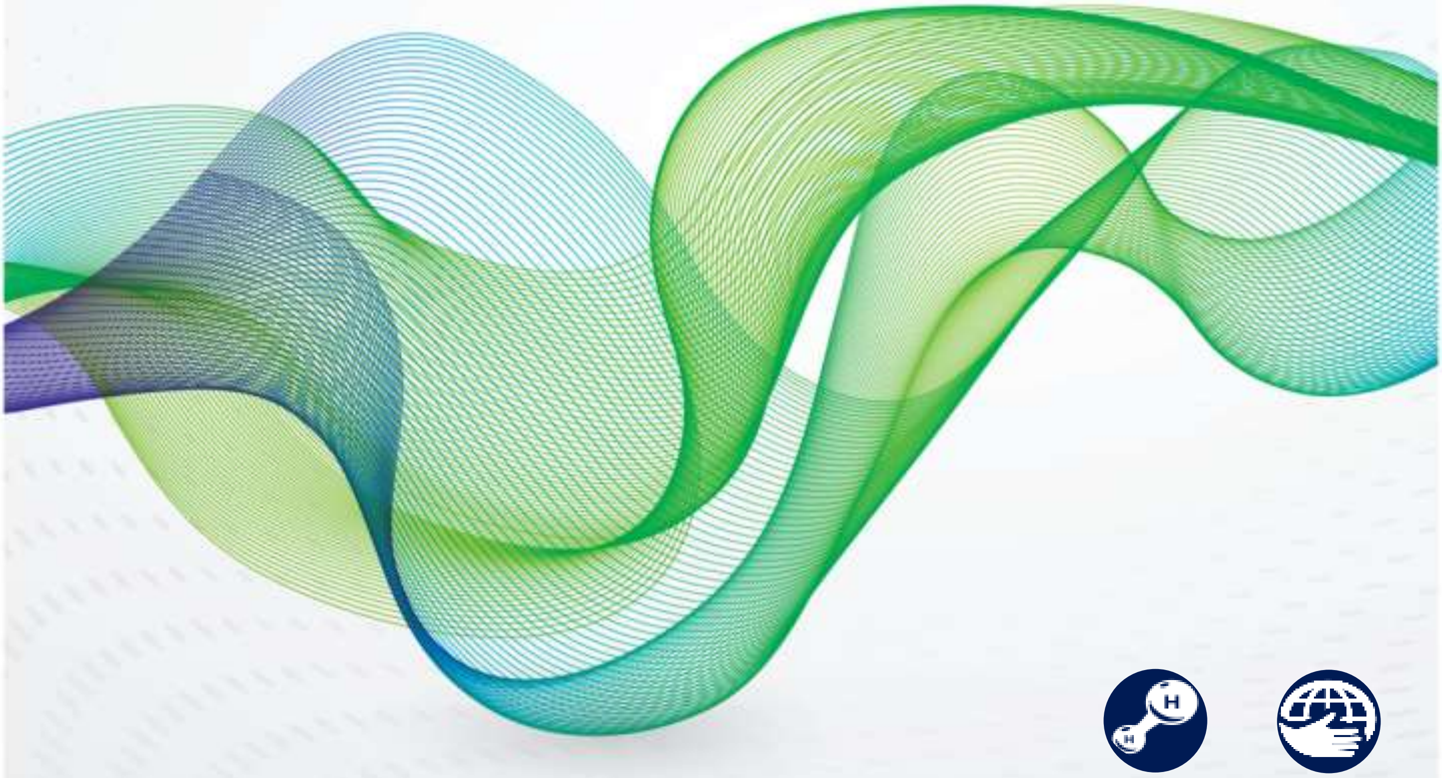
Clean Hydrogen Roadmap:
is greater realism leading to more credible paths forward?



Hydrogen

ENERGY TRANSITION

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Introduction

The Oxford Institute for Energy Studies (OIES) started researching the role of hydrogen in the energy transition in 2020.[1] Since then the interest in hydrogen has continued to grow globally across the energy industry. A key research question has been the extent to which clean hydrogen[2] can be scaled up at reasonable cost and whether it can play a significant role in the global energy system. In April 2022, OIES launched a new Hydrogen Research Programme under the overarching theme of 'building business cases for a hydrogen economy'. This overarching theme was selected based on the observation that most clean hydrogen developments to date had been relatively small-scale pilot or demonstration projects, typically funded by government grants or subsidies. For clean hydrogen to play a significant role there will need to be business cases developed in order to attract the many hundreds of billions of dollars of investment required,[3] most of which will need to come from the private sector, albeit ultimately underpinned by government-backed decarbonisation policies.

Just over a year has passed since the start of the Hydrogen Research Programme, and the intention of this paper is to pull together key themes which have emerged from the research so far and which can form a useful framework for further research, both by OIES and others. The original 2020 paper[1] concluded that 'hydrogen will certainly play a role in decarbonisation of the energy system, although the size of the role may be more limited than envisaged in some more optimistic projections'. In the intervening three years, we perceive that more realism has developed about the role which hydrogen is likely to play in a decarbonised energy system. Various publications by the Hydrogen Council, a global CEO-led initiative to promote the role of hydrogen, provide evidence of this increasing realism. A 2020 publication[4] included excited references to hydrogen being the most competitive low-carbon solution for many applications including boilers for home heating on an existing network, large passenger vehicles, SUVs, and taxi fleets. It also made reference to the 2019 Energy Ministerial in Japan which had set a '10-10-10' global target to reach 10 million fuel cell vehicles and 10,000 hydrogen refuelling stations within the 10 years to 2030. By contrast, the Hydrogen Council's 2023 Hydrogen Insights[5] made no reference at all to hydrogen boilers and reported a total of 80,000 fuel cell vehicles, with the fleet growing at less than 20,000 units per year. The same Hydrogen Insights report also notes that while $320 billion of investments in hydrogen projects have been announced, only $29 billion of those projects have reached Final Investment Decision (FID). This increasing realism is to be welcomed, as once the challenges are identified, all interested stakeholders can work together to seek solutions to those challenges. The six key themes in this paper, listed below, are intended to create a framework to at least start to address the challenges:

1. Hydrogen is **in competition** with other decarbonisation alternatives.
2. The business case for clean hydrogen relies on **government policy** to drive decarbonisation.
3. It is essential to understand **emissions** associated with potential hydrogen investments.
4. Hydrogen investments need to consider the **full value chain** and its geopolitics**.**
5. **Transport of hydrogen** is expensive and so should be minimised.
6. **Storage of hydrogen** is an essential part of the value chain and requires more focus.

After considering each of these key themes in turn, the paper will draw some conclusions and suggest how to build on the current growing realism to chart a reasonable path forward.

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[1] https://www.oxfordenergy.org/publications/hydrogen-and-decarbonisation-of-gas-false-dawn-or-silver-bullet/

[2] We use 'clean hydrogen' as a generic term to cover both hydrogen from fossil fuels with carbon capture and storage (sometimes called 'blue hydrogen') as well as hydrogen from electrolysis using renewable electricity (sometimes called 'green hydrogen').

[3] At this early stage of development, we believe it is highly speculative to try to put an accurate number on the level of investment required, not least given uncertainties about levels of clean hydrogen demand. For example McKinsey/Hydrogen Council see a need for $700 billion of investment by 2030, while Deloitte estimates a hydrogen market size of $1.4 trillion by 2050.

[4] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf p.9

[5] https://hydrogencouncil.com/wp-content/uploads/2023/05/Hydrogen-Insights-2023.pdf

1. Hydrogen is in competition with other decarbonisation alternatives

The importance of considering clean hydrogen in the context of other alternative routes for decarbonisation was already a key topic in the first OIES hydrogen paper in 2020.[6] At that time, many claims were being made suggesting that hydrogen would be a ‘silver bullet’ as referenced in the title of that paper. Over the last three years, with greater realism a more widespread understanding has developed of an important principle that direct electrification will always be preferred to clean hydrogen from a cost and efficiency perspective, provided that the end-use application is suitable to be electrified.

For example, the idea that hydrogen might have a significant role for space heating has been largely replaced by an understanding of the approximately six-fold higher efficiency of electric heat pumps compared to boilers using green hydrogen. The UK had been a particular front-runner in considering hydrogen for home heating, and official government policy is still that a decision will be made in 2026 after sufficient data has been gathered from various trials in small geographic areas. One of those trials, a ‘hydrogen village’ in the northwest of England has recently been abandoned.[7] A June 2023 announcement by the UK Energy Minister[8] suggests that use of hydrogen in homes is ‘unlikely to be the way forward’, so it is possible that the 2026 decision date may be brought forward to accelerate consumer uptake of heat pumps. On the other hand, in a recent vote in a small town in the Netherlands, over 70 per cent of the community voted in favour of converting from natural gas to hydrogen – albeit with a low price guarantee for 15 years.[9]

Similarly, a few years ago, the use of hydrogen in fuel cell electric vehicles (FCEV) for road transport had been widely considered to be an important contributor to a decarbonised energy system. With the accelerating roll out of battery electric vehicles (BEVs), it is becoming clear that FCEVs are much less likely to play a significant role. By the end of 2022 there were 72,000 FCEVs worldwide compared to nearly 20 million BEVs, with sales of new BEVs at around 7 million units in 2022.[10] There remains a potential niche for FCEV for long-distance heavy duty road transport, but as battery technology improves and the prospect of MW-scale chargers able to recharge a truck in the time needed for the driver to take a rest break, the size of that niche may gradually shrink.[11] It is likely that the preferred solution for heavy duty road transport will vary by location and by specific circumstances. OIES is currently researching the likely role for fuel cell heavy duty road transport in more detail.

On the other hand, there are also applications where hydrogen appears to remain the most competitive route to decarbonisation. This includes reducing the carbon intensity of the current industrial feedstock use of grey hydrogen in oil refining, petrochemicals, and ammonia. Even though demand for oil products and hence the need for oil refining is expected to decline as the energy system decarbonises, particularly as more road transport switches to BEVs, it is envisaged that at least some refineries will transition to manufacture synthetic fuels like renewable diesel or sustainable aviation fuel.[12] In any case, to reduce the impact on the limited carbon budget, it would make sense for governments to introduce policies to promote the use of clean hydrogen in place of the current high-carbon hydrogen as rapidly as possible (subject to considerations regarding competitiveness and industrial relocation – see Section 2 below).

Production of ammonia is also expected to remain a significant contributor to hydrogen demand. Nearly all current ammonia production (around 170 million tonnes, consuming around 35 million tonnes of H_2 per year in 2020[13]) is manufactured from fossil fuels. Similarly to the case of oil refining, in pursuit of decarbonisation objectives it would be beneficial for governments to mandate the use of clean hydrogen rather than high-carbon hydrogen in current ammonia production. In addition, there is considerable

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[6] https://www.oxfordenergy.org/publications/hydrogen-and-decarbonisation-of-gas-false-dawn-or-silver-bullet/

[7] https://www.bbc.co.uk/news/uk-england-merseyside-66165484

[8] https://www.hydrogeninsight.com/policy/hydrogen-heating-in-homes-unlikely-to-be-the-way-forward-uk-energy-minister/2-1-1467365

[9] https://www.hydrogeninsight.com/innovation/world-first-dutch-city-votes-to-switch-its-heating-from-natural-gas-to-green-hydrogen/2-1-1479452

[10] IEA Global EV Outlook (2023) https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf

[11] See this article for a balanced view of the pros and cons https://www.world-energy.org/article/33038.html

[12] https://www.mckinsey.com/industries/oil-and-gas/our-insights/converting-refineries-to-renewable-fuels-no-simple-switch

[13] IEA (2021): https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

potential for new uses of ammonia as a fuel or hydrogen carrier.[14] Production of ammonia is likely to remain an application where clean hydrogen retains a competitive advantage in the absence of currently unforeseen technological innovation.

A third major application where clean hydrogen is likely to remain a competitive decarbonisation pathway is in steel making, or more accurately in the direct reduction of iron ore. Most iron ore reduction today is carried out using coal in blast furnaces and the steel industry is responsible for around 9 per cent of total energy-related global emissions. On a pathway to decarbonisation, consistent with the principle of using as much electrification as possible, steel production is expected to make increasing use of electric arc furnaces particularly for the recycling of scrap steel. For reduction of iron ore, however, there appears to be little alternative to using hydrogen. It is possible that carbon capture and storage (CCS) may also play a role, but the large number of emission sources and relatively low concentration of CO_2 streams in steel plants makes this more challenging than in other applications.[15]

Hydrogen is also likely to play a role in power generation, although the nature of this role is likely to differ in different regional contexts. For example, in those areas (e.g. northern Europe, USA) with relatively abundant renewable energy resources, hydrogen is likely to play an important role for long duration energy storage (see section 6 below). In other areas (e.g. Japan) with insufficient local renewable energy resources and hence a need to import energy, importing hydrogen or derivatives like ammonia will be an essential part of a decarbonised energy system.

Finally, hydrogen derivatives are also likely to play a role in the decarbonisation of international shipping and production of sustainable aviation fuel (SAF), although these applications are still at a relatively early stage of development. In international shipping, for example, there remains uncertainty about the extent to which ammonia, methanol, or other hydrogen derivatives will play a role. For SAF, the role of clean hydrogen is likely to be in the manufacture of fuels derived from biomass. Both these areas are also the subject of ongoing OIES hydrogen research.

There are also some areas where the extent to which hydrogen will play a role is not yet clear. An example of this is high temperature industrial heat as used in the glass or ceramics industries. While some electrification may be possible there may be specific reasons, like the flow rate of molten glass, where hydrogen will be required.[16] Similarly in ceramics, the UK government is currently funding a research project to evaluate alternative pathways to decarbonise this industry, including hydrogen, electrification, carbon capture, and bioenergy.[17]

As clearly illustrated by the changed perception of the role for FCEVs in heavy road transport, the competitiveness of clean hydrogen against other potential decarbonisation pathways remains an evolving picture and will be influenced by a combination of technology development, economics, government policy, and the development of commercial and financing structures. It is intended that OIES will continue to revisit this competitive landscape as it continues to evolve.

2. The business case for clean hydrogen relies on government policy to drive decarbonisation

Approximately 94 million tonnes per year of hydrogen was used in 2021, almost entirely as a feedstock in oil refineries, ammonia plants, and for production of other chemicals. Of that quantity, less than 1 million tonnes was low-emission hydrogen, most of that being from fossil fuels with CCUS, and less than 35,000 tonnes from electrolysis of water.[18] The associated emissions from the remaining 'high-carbon' hydrogen production are estimated at around 900 million tonnes CO_2 per year, and given that global hydrogen production grew by 4 million tonnes per year between 2020 and 2021, the total

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[14] See for example: https://www.oxfordenergy.org/publications/global-trade-of-hydrogen-what-is-the-best-way-to-transfer-hydrogen-over-long-distances/

[15] For a longer discussion of hydrogen and decarbonisation of steel making see Schöffel (2021) p.22 in https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/05/OEF-127.pdf

[16] https://www.thechemicalengineer.com/features/energy-using-hydrogen-for-glass/

[17] https://www.iom3.org/resource/uk-ceramic-industry-receives-funding-for-hydrogen-research.html

[18] IEA Global Hydrogen Review 2022: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

associated CO_2 emissions are continuing to increase. For a commercial enterprise, this continued growth in high-carbon hydrogen production is logical as the lowest cost method to produce hydrogen will continue to be from fossil fuels without CCS. Therefore, government policy will be required to drive investments either (a) to add CCS to hydrogen production from fossil fuels or (b) to switch to hydrogen production from electrolysis of water using renewable electricity.

While some small-scale investments, typically pilot or demonstration hydrogen production projects, are already progressing, these are typically research projects to prove a new technology, and/or funded with a significant contribution from public subsidies. For example, the Hybrit demonstration project in Sweden, although not yet having taken a final investment decision, aims to construct a 500 MW electrolyser as part of a demonstration of hydrogen-based iron and steelmaking and was one of seven recipients of EU funding totalling €1.1 billion under the Innovation Fund.[19] Similarly, Shell's investment in the Holland Hydrogen 1 project with 200MW electrolyser capacity, now under construction, was conditional on receiving a €150m grant from the EU as an Important Project of Common European Interest (IPCEI).[20]

While such pilot or demonstration projects are important stepping stones, they will not be sufficient to enable a large scale roll-out of clean hydrogen. For example, the Shell 200 MW project, while being the largest electrolyser under construction in Europe, will supply somewhat less than 10 per cent of the current hydrogen use at the company's Rotterdam refinery. Since budgets for government subsidies are necessarily limited and decarbonisation is just one aspect of government policy which needs to share scarce resources, other policies beyond project subsidies will be required. A key issue, which the OIES hydrogen programme is considering, is to identify the most appropriate forms of commercial structures and government policy to promote a large-scale clean hydrogen roll-out. There will clearly not be a 'one-size fits all' approach, as appropriate policies will vary from country to country as well as depending on specific industries and sectors, and different policy measures will be relevant at different stages of industry development.

On a much larger scale, the Neom green hydrogen project in Saudia Arabia with 2.2GW electrolyser capacity associated with 4.6GW of wind and solar power generation, has demonstrated that it is possible to secure very significant private finance along with government funding. According to a filing on the Saudi Exchange, the Saudi Arabian government will provide $2.75bn of funding, with $6.33bn from a consortium of commercial banks. The revenue stream appears to be underwritten by an offtake agreement with Air Products, one of the shareholders, for all of the green ammonia output.[21] While full details of the project structuring are not yet available publicly, this project does demonstrate the feasibility of funding a large-scale project with a combination of government support and private finance.

Broadly, government policies can be divided into two categories: (a) 'sticks' which are policies which compel industry players to take certain actions, and (b) 'carrots' which are policies to incentivise industry players to adopt solutions in support of government policy. Effective policy is likely to involve a combination of both.

A detailed consideration of the pros and cons of various policy instruments is beyond the scope of this overview paper, but Table 1 provides a high-level overview of some of the main instruments which are being considered and or have been implemented.

It appears that the choice of policy instrument in a particular jurisdiction is sometimes driven by a combination of previous experience as well as by certain policy ideologies. For example, the US Inflation Reduction Act (IRA) passed in August 2022 introduced four tiers of hydrogen production tax credit (referred to as 45V) ranging from 3.0 $/kg for carbon intensities less than 0.45kg CO2/kg H_2 to 0.6 $/kg for carbon intensities between 2.5 and 4.0 kg CO2/kg H_2.[22] This use of tax credits follows a similar

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[19] https://www.hybritdevelopment.se/en/hybrit-support-from-eu-innovation-fund/

[20] In fact there was some controversy regarding whether the project was entitled to receive the grant due to a perceived premature announcement of the final investment decision: https://www.hydrogeninsight.com/production/shell-received-150m-of-subsidies-for-green-hydrogen-project-that-was-ineligible-for-support-report/2-1-1453515

[21] https://www.hydrogeninsight.com/production/neom-becomes-first-gigawatt-scale-green-hydrogen-project-to-secure-funding-with-8-5bn-lined-up/2-1-1412727

[22] See, for example: https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects

production tax credit approach (45Q) which had been introduced as early as 2008 to incentivise CCUS and was updated as part of the IRA to a level of 85 $/tonne CO_2 permanently stored.

Table 1: Summary of Forms of Government Policy Support

Sticks	Carrots
Emissions Trading Scheme (ETS): the level of carbon emissions is capped, and emitters purchase permits in the market to cover their emissions. Industry players therefore pay a penalty for their emissions	**Feed-in tariff:** provides a specified price for production delivered, typically to a government entity. Typically allocated to projects by auction
Carbon Tax: similar to ETS, emitters pay a penalty for their emissions, but in this case at a set amount per unit of emissions	**Tax credit/incentive:** provides a tax reduction to a project developer under certain circumstances, e.g. US IRA Production Tax Credit for hydrogen below a specified emission intensity
Mandates, bans and targets: policymakers specify mandatory action to be taken by a certain date, e.g. 'by 2030, 50 per cent of all hydrogen produced must have a carbon intensity less than ….'	**Contract for Difference (CfD):** Government entity commits to pay (or receive) the difference between strike price and reference price. Can be for carbon or hydrogen - challenge of no established market price for hydrogen
Standards: similar to mandates, but specified as minimum standards, e.g. defines a measurement system for hydrogen's carbon intensity, and requires average intensity to be below a specified level	**Direct Financial Support:** For example government commits a grant or low interest loan to support project development

Source: OIES analysis

On the other hand, much of the discussion in Europe has been driven by a desire to avoid 'picking winners'. This issue was identified as early as 2012[23] and is still being debated now.[24] Interestingly, despite the stated desire not to pick winners, some aspects of EU policy such as the rules defining Renewable Fuels of Non-Biological Origin[25] are effectively doing exactly that. Probably the purest way to 'not pick winners' would be to establish a universally applied global carbon price mechanism and then let the market decide the most cost-effective way to reduce carbon emissions. Unfortunately, it would be politically impossible to establish a global carbon price and even in those parts of the world with an established carbon price (e.g. within the EU), it is not universally applied, with some sectors being outside the scheme or being granted 'free allowances'. Against this background, relying simply on a carbon pricing scheme would not result in sufficiently rapid change to meet the aspired targets.

For clean hydrogen, the level of production is at such an early stage and at such a small scale that it would be difficult to see any policy approach as 'picking winners'. Introducing policy measures (whether sticks or carrots) to promote a reduction in the carbon footprint of current hydrogen production would be better characterised as 'promoting early production scale up' rather than picking winners. For example, the March 2023 EU agreement on the update to the Renewable Energy Directive specifies that industry must procure at least 42 per cent of its hydrogen from renewable fuels of non-biological origin (RFNBOs) by 2030.[26] While this directive still needs to be translated into specific legislation by member states, it is a clear mandate which should result in industry players finding the most cost-effective way to meet the target. The potential drawback for policymakers from this type of approach is that since it only applies to industrial use of hydrogen within Europe, it may have the unwelcome

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[23] Gross et al (2012): https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/icept/On-Picking-Winners-low-res.pdf

[24] See for example: Meckling et al (2022): https://www.nature.com/articles/s41560-022-01081-y

[25] See for example: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/03/The-EU-Hydrogen-and-Gas-Decarbonisation-Package-ET22.pdf

[26] https://hydrogeneurope.eu/h2-is-cornerstone-of-eus-renewable-energy-directive/#:~:text=Industry%20must%20procure%20at%20least,that%20target%20reduced%20by%2020%25.

consequence of moving this industrial production to other jurisdictions where the use of unabated fossil-based hydrogen remains more acceptable.

As a final example of the choice of policy instrument for clean hydrogen reflecting previous experience, the UK has built on it successful Contract for Difference (CfD) programme introduced in 2014 to support deployment of large-scale renewable power projects, particularly for offshore wind.[27] The CfD concept involves a contract with a government entity comparing the strike price with the market price and payments between the project developer and the government entity based on the difference between the two prices. The scheme works well in the electricity industry where there is a clearly defined market price. Lack of an established market for clean hydrogen adds an additional complexity, but the UK government has been developing innovative solutions to achieve a similar result.[28]

It is clear that there is not, and is unlikely to be in future, a universally preferred policy mechanism, as there are many factors influencing the choice of individual governments. An important political consideration for any government policy will be to determine who ultimately pays the higher price resulting from the use of low-carbon hydrogen – ultimately the cost will need to be borne by taxpayers or consumers of energy or products (like green steel) manufactured using low carbon hydrogen. Governments will also be concerned to ensure policies are seen to be fair and equitable and, in democracies, to consider the impact on voters. As part of the hydrogen research programme, OIES will continue to assess the range of support mechanisms to review which ones are proving most effective in particular circumstances. It will also consider the appropriate commercial structures, pricing arrangements, and the required agreements along the value chain to work together with such policy incentives.

3. It is essential to understand emissions associated with potential hydrogen investments

As noted in Section 2 the only driver for switching to clean hydrogen is in support of decarbonisation policies, so it follows that there is little point in committing to significant investments in clean hydrogen infrastructure (whether it be production, transmission, or use of the hydrogen) without understanding the emissions resulting from the process. Accurate measurement of life cycle emissions from any energy supply chain can be extremely complex, requiring various assumptions and calculations for values which cannot be measured directly. This has resulted in significant variability in results of life cycle assessments, although considerable work has been done to harmonise such assessments.[29]

For an investor, the most important question is the level of emissions which will be assessed by the appropriate government agency or customer, or any other way in which assessment of emissions could impact a project's future revenue stream. For example, when the US IRA became law in August 2022, there was a lot of focus on the very generous sounding $3.0/kg production tax credit for the cleanest form of hydrogen. (For completeness, Table 2 shows how the production tax credit varies by level of lifecycle GHG emission.) There is clearly a very strong incentive for a project to be below the 0.45 kg CO_2/kg H_2 threshold, but the implementation rules and the procedure for measurement of emissions have not yet been clearly defined. Indeed, a key question relates to the use of grid electricity. With the current US power generation mix as the source of electricity for electrolysers, use of average grid emission intensity could result in life cycle emissions being even higher than the approximately 10 kg CO_2/kg H_2 for hydrogen from unabated natural gas.[30] This uncertainty helps to explain why, despite the initial excitement around the hydrogen provisions of the IRA, there has not yet been a surge of projects reaching FID.

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[27] https://www.iea.org/policies/5731-contract-for-difference-cfd

[28] https://www.gov.uk/government/publications/hydrogen-production-business-model

[29] See for example NREL (2021): https://www.nrel.gov/analysis/life-cycle-assessment.html

[30] Kaufman and Corbeau (2023): https://www.energypolicy.columbia.edu/the-battle-for-the-us-hydrogen-production-tax-credits/

Table 2: Inflation Reduction Act Production Tax Credit by emission level

Lifecycle GHG emissions (kg CO_2/kg H_2)	Production Tax Credit (\$/kg H_2)
0-0.45	3.0
0.45-1.5	1.0
1.5-2.5	0.75
2.5-4.0	0.6

Source: US Department of Energy

Similarly in the EU, there has been a long debate on the rules which would apply for electrolytic hydrogen to qualify as ‘renewable’, depending on the temporal and geographical correlation of hydrogen production with the availability of renewable electricity. A finally agreed position on this so-called ‘additionality’ mechanism was published in June 2023, which should provide some reassurance to potential investors.[31]

An additional emissions-related complication for potential investors relates to certification of emissions as part of standards for clean hydrogen. A 2022 study[32] identified at least 11 different certification schemes across North America, Europe, China, Japan, and Australia. A 2023 report from the International Renewable Energy Agency (IRENA)[33] built on the analysis including making a distinction between voluntary and mandatory hydrogen certification schemes. There is general agreement that there would be a benefit in agreeing on one unified global clean hydrogen certification scheme, particularly for those projects which are contemplating potential international trade in clean hydrogen: there would clearly be little point in developing a project which produced a product defined as clean hydrogen in one country, but not in others.

There is an initiative currently underway, led by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), with support from the International Energy Agency (IEA), which aims to develop a global certification standard and methodology for emissions from clean hydrogen.[34] This initiative also links with work by the International Standards Organisation (ISO) to develop a three-part standard covering production, conditioning, and transport of hydrogen, but acknowledges that the process of developing an ISO standard could take several years.

This difficulty in reaching an agreed international standard has necessarily resulted in the proliferation of individual region, country, and state certification schemes, and it looks likely that the industry will need to live with that proliferation for some years to come. In the meantime, to create a robust business case for hydrogen investments, there will need to be a clear agreement between stakeholders along the value chain, including the relevant government authorities, regarding the deemed level of emissions, probably on a case-by-case basis for the time being. This is likely to prove a further hurdle to the rapid roll out of clean hydrogen projects. OIES intends to continue to monitor developments in this area in future papers.

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[31] https://energy.ec.europa.eu/news/renewable-hydrogen-production-new-rules-formally-adopted-2023-06-20_en

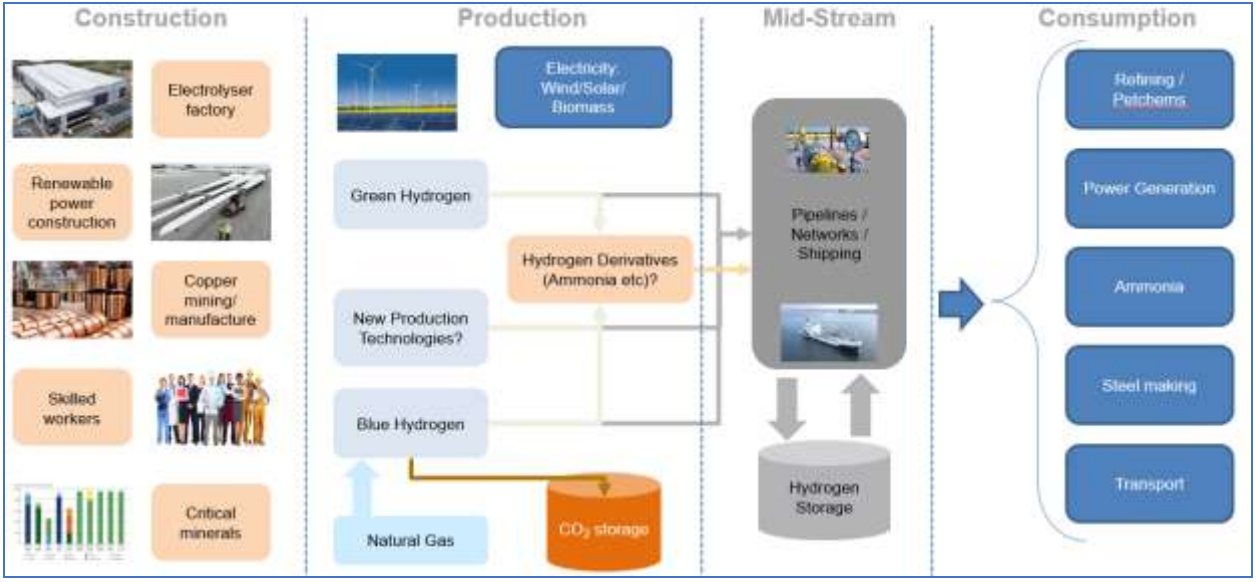
[32] DENA (2022): https://www.weltenergierat.de/wp-content/uploads/2022/01/dena_WEC_Harmonisation-of-Hydrogen-Certification_digital_final.pdf

[33] IRENA (2023): https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jan/IRENA_Creating_a_global_hydrogen_market_2023.pdf

[34] See IEA (2023): https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf

4. Hydrogen investments need to consider the full value chain and its geopolitics

Figure 1: Conceptual hydrogen value chain



Source: OIES analysis

For all clean hydrogen production it is necessary to consider both how the product will be consumed and the infrastructure which links production and consumption. There have been some suggestions that a possible convenient outlet for clean hydrogen would be to blend it into the existing natural gas grid. While it has been demonstrated that this can be achieved safely[35] and this could provide a 'disposal route' for early small-scale production of hydrogen, there has been a growing understanding that this would bring 'little decarbonisation benefit and a large increase in energy costs'.[36]

As clean hydrogen production scales up, in order to ensure that the product achieves full value in the market, it will become increasingly important to consider the entire value chain from production to consumption as illustrated in Figure 1. As discussed further in Section 5 below, while it is likely that, at least initially, much clean hydrogen will be consumed relatively close to where it is manufactured, larger quantities of hydrogen will require appropriate infrastructure and commercial arrangements to link production and consumption. The details of the specific supply chain are likely to vary depending on the local or regional context, and depend on the role of hydrogen in the broader context of the overall energy system. For example, within a relatively small region like Europe, it is likely that pipelines will play a significant role, perhaps linking areas in the south with more sun to areas in northwest Europe with higher density of population and industry. For supply to Japan, by contrast, with limited capacity for local renewable power generation and where pipelines are likely to be unfeasible, it is likely that seaborne trade in hydrogen derivatives will play a more significant role.

Whether a pipeline linking production and consumption is a few hundred metres or over a thousand kilometres long, or if the linkage involves conversion processes and shipping, there will be a similar need to consider integration of infrastructure and commercial arrangements. To illustrate some of the possible configurations available and the impact on infrastructure and commercial arrangements, OIES has developed four archetypes to consider how clean hydrogen supply chains may develop. The four archetypes are by no means exhaustive, but cover a range of the likely alternative structures at various stages of development of the clean hydrogen market. We anticipate that we will continue to refine these archetypes as our research progresses.

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[35] For example in the HyDeploy trial in two locations in the UK carried out in 2021 and 2022: https://hydeploy.co.uk/project-phases/

[36] https://www.rechargenews.com/energy-transition/hydrogen-blending-in-gas-grid-would-lead-to-limited-co2-benefits-and-a-large-increase-in-energy-costs-irena/2-1-1213821

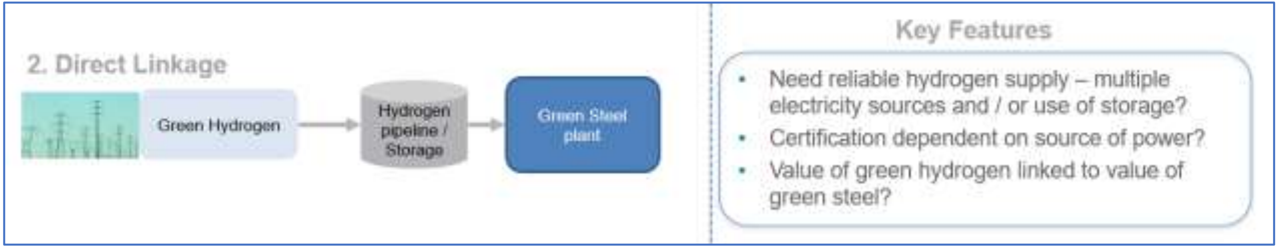
The shape of the overall value chain will also be affected by security of supply and geopolitical considerations. Government policy will therefore need to balance the overarching decarbonisation objective with economic optimisation, building a diverse and hence secure supply chain together with industrial and social policy considerations.

Figure 2: Archetype 1 - Early Stage

- Green hydrogen <~25% of total hydrogen demand (grey hydrogen as backup)
- Little problem of intermittency – outlet when available
- Need incentive / compulsion to (a) invest in electrolyser and / or (b) use green rather than grey

Initial clean hydrogen projects were very small (typically 1MW electrical input capacity or less) and produced correspondingly small amounts of hydrogen (only 150 tonnes per year for 1 MW electrical input operating for a rather high 7500 hours per year) which was relatively easy to store or transport by truck-trailer to a suitable consumer. Somewhat larger projects, such as the 6MW Audi Werlte project to manufacture synthetic natural gas[37] which came on stream in 2013, or the 10MW Refhyne[38] project in Germany (onstream 2021) were designed to supply clean hydrogen to an adjacent manufacturing facility which would consume it. In the case of Refhyne, the approximately 1,300 tonnes per year of hydrogen produced represents around just 1 per cent of the total hydrogen demand of the adjacent Shell Rhineland Energy and Chemicals Park. Similarly in China, Sinopec's first green hydrogen production plant in Xinjiang which started production in 2023 supplies around 10,000 tonnes H_2 per year to the adjacent refinery, replacing hydrogen supplied by natural gas.[39] For such projects, there is a ready demand for the hydrogen produced, without the need for complex downstream infrastructure and commercial arrangements, and it is not particularly important to the consumer's security of supply whether the clean hydrogen is produced or not, since there is a ready alternative supply of high-carbon hydrogen to make up any shortfalls. This archetype is likely to continue to be common for at least the next few years, as clean hydrogen gradually replaces existing use of grey hydrogen in refineries and ammonia plants.

Figure 3: Archetype 2 - Direct Linkage



- Need reliable hydrogen supply – multiple electricity sources and / or use of storage?
- Certification dependent on source of power?
- Value of green hydrogen linked to value of green steel?

This archetype envisages a single clean hydrogen production facility, perhaps linked to a dedicated wind or solar renewable energy supply, supplying a single offtaker, maybe a green steel or fertiliser plant. This arrangement will almost certainly involve some hydrogen pipelines, although these could vary in length from a few hundred metres to many kilometres. It is also likely to involve some hydrogen storage, particularly where production is linked to intermittent renewables like wind and solar.

A good example of this archetype is currently under development at the Hybrit green steel project in Sweden.[40] In this example, fossil-free electricity is supplied from the grid and the hydrogen production

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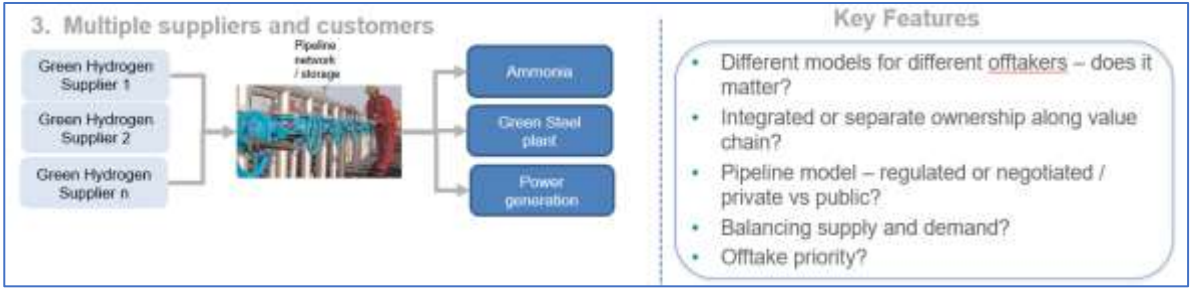
[37] https://task44.ieabioenergy.com/wp-content/uploads/sites/12/2021/12/Task-44-Best-Practice_e-gas-Werlte_Germany.pdf
[38] https://www.refhyne.eu/
[39] https://www.reuters.com/business/energy/sinopecs-first-green-hydrogen-plant-xinjiang-starts-production-xinhua-2023-06-30/
[40] https://www.hybritdevelopment.se/en/

is carried out on the same site as the steel production. Nevertheless, recognising that there will be variation in the availability of sufficient renewable electricity, the project is also constructing a pilot hydrogen storage facility in a lined rock cavern.[41] In the longer term, it is envisaged that a full-size sponge iron facility would require around 100,000m^3 of hydrogen storage in order to store around 100GWh of hydrogen which would be sufficient to supply the sponge iron facility for three to four days.

In terms of commercial structure, it is likely to be most straightforward if the entire integrated supply chain is owned by one entity, but it would also be possible for the different components to be owned separately with contractual arrangements between the players. This separate ownership model with the risk of non-performance of one part of the chain would be likely to make financing arrangements more complex than in the integrated model. Despite appearing to be a simple model, the direct linkage between supply and consumption and lack of ability to draw on flexibility from the wider energy system may make the commercial realisation of this model more difficult.

Figure 4: Archetype 3 - Multiple Suppliers and Customers (hydrogen network)



Key Features

- Different models for different offtakers – does it matter?
- Integrated or separate ownership along value chain?
- Pipeline model – regulated or negotiated / private vs public?
- Balancing supply and demand?
- Offtake priority?

This archetype envisages multiple hydrogen producers linked by a pipeline network, including storage, to multiple offtakers potentially over a wide geographical area (although the model could also apply within a single industrial cluster). It is widely envisaged to be the likely future state of a country or region’s hydrogen system, and the portfolio of multiple suppliers and customers may facilitate load balancing while reducing overall storage requirements, but the pathway to reach this network system is far from clear. In Europe, for example, the European Hydrogen Backbone consortium of energy infrastructure operators has been advocating for construction of a pan-European hydrogen pipeline network, partly by repurposing existing natural gas pipelines. Their latest publication in July 2023 suggests that by 2030 the network should comprise over 32,000 km of hydrogen pipelines.[42] The business case for construction of such a network in advance of significant commitment of investments to produce and consume the hydrogen remains unclear – a classic ‘chicken and egg’ problem. Indeed, it seems more likely that initial developments will be of smaller networks in industrial clusters (e.g. in areas like Rotterdam in the Netherlands, the Ruhr in Germany, Texas or Louisiana in the USA, or the Yangtze River Delta in China) and in the longer term it may prove economically attractive to construct links between such industrial clusters.

OIES has already published papers considering the regulatory requirements in Europe to support development of such networks[43] and intends to examine the commercial arrangements for the incremental development of such industrial clusters and larger networks in future research.

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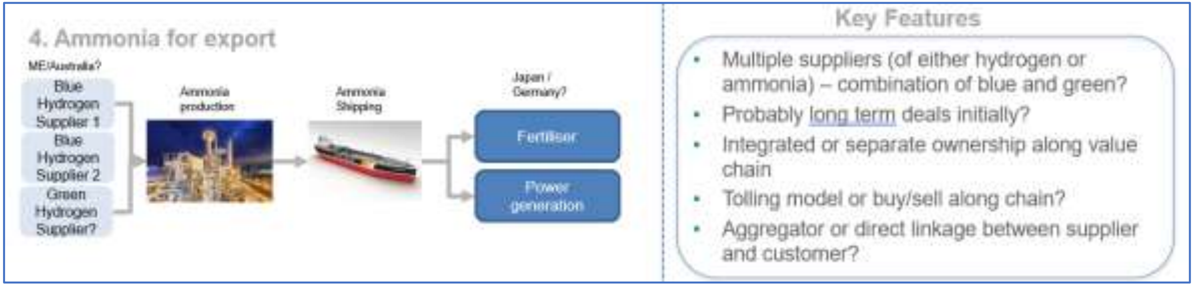
[41] https://www.ssab.com/en/news/2022/06/hybrit-a-unique-underground-fossilfree-hydrogen-gas-storage-facility-is-being-inaugurated-in-lule

[42] https://ehb.eu/files/downloads/EHB-initiative-to-provide-insights-on-infrastructure-development-by-2030.pdf

[43] https://www.oxfordenergy.org/publications/the-eu-hydrogen-and-gas-decarbonisation-package-help-or-hindrance-for-the-development-of-a-european-hydrogen-market/

Figure 5: Archetype 4 - Ammonia Export by Ship



- Multiple suppliers (of either hydrogen or ammonia) – combination of blue and green?
- Probably long term deals initially?
- Integrated or separate ownership along value chain
- Tolling model or buy/sell along chain?
- Aggregator or direct linkage between supplier and customer?

Given the costs and challenges of liquefying hydrogen and transporting it by ship,[44] it is envisaged that initial ship-borne international trade of hydrogen is likely to be in the form of ammonia. Similar considerations could also apply to transport of methanol or other liquid organic hydrogen carriers derived from clean hydrogen with the commercial and policy challenges being similar. The archetype envisages that potentially multiple producers could supply the product which would then be shipped to a country with limited renewable energy resources (e.g. Germany or Japan) where it would be consumed, potentially in multiple facilities.

For this model, OIES has already published a paper considering how the risks should be shared out along the value chain in order to secure financing for the required production and transportation infrastructure.[45] Broadly, the model, involving creditworthy offtakers, long-term sale and purchase commitments and government support is likely to draw lessons from the early days of the LNG business as well as the development of renewable power (particularly offshore wind). In future research, OIES intends to consider the appropriate mechanisms for such commercial structures in more detail, as well as considering the financing of the significant investments required by clean hydrogen consumers like green steel plants or large-scale power generation.

While these archetypes are far from exhaustive, they do provide a framework for further research and underline the importance of considering the full value chain in order to support the required multi-billion dollar investments in creation of a clean hydrogen industry.

The final two sections of this paper on transport and storage of hydrogen consider two important aspects of that overall value chain in more detail.

5. Transport of hydrogen is expensive and so should be minimized

At various stages since the term 'hydrogen economy' was coined by John Bockris of General Motors in 1970[46] there have been suggestions that hydrogen could be considered the 'new oil'. More recently, this idea has been picked up by several countries with abundant renewable energy resources (for example, Australia, Saudi Arabia, and Chile) which have developed strategies to develop major hydrogen export businesses. Somewhat illogically, in some cases these plans to export hydrogen have been associated with continuing significant use of fossil fuels for domestic power generation and other energy consumption in the same countries.

However, considering hydrogen as the 'new oil' is very misleading. It is important to recognise that hydrogen is much more difficult and expensive to transport than oil. Natural gas is significantly more costly to transport than oil, while transport of both hydrogen and electricity is an order of magnitude more expensive than natural gas. According to one comparative analysis, after transport of 1000km, the transport cost of oil would be around 1 or 2 per cent of the delivered energy cost, for natural gas it would be 3 to 5 per cent while for electricity or hydrogen it would be 5 to 20 per cent.[47] While the cost ranges are necessarily wide as they will vary depending on specific circumstances, it becomes clear why most hydrogen today is produced close to where it is used, and there is a good reason why transport of hydrogen should continue to be minimised in future. These differential costs are largely the

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[44] https://www.oxfordenergy.org/publications/global-trade-of-hydrogen-what-is-the-best-way-to-transfer-hydrogen-over-long-distances/

[45] https://www.oxfordenergy.org/publications/financing-a-world-scale-hydrogen-export-project/

[46] https://royalsocietypublishing.org/doi/10.1098/rsta.2016.0400

[47] Saadi et al (2018) https://authors.library.caltech.edu/84666/3/c7ee01987d.pdf

result of the physical properties of hydrogen compared to the other fuels. For example, in gaseous form in a pipeline, hydrogen has about one-third of the volumetric energy density of natural gas.

Having recognised the challenges, it must be acknowledged that hydrogen certainly can be safely transported by pipeline and as of 2022 there were around 4,500km of hydrogen pipelines in operation globally, mainly in the US and Europe. By comparison, there are more than 1.2 million km of natural gas transmission pipelines, so while technically feasible, commercial deployment of hydrogen pipelines is much more limited.[48] However, in a future decarbonised energy system, transport of oil or natural gas will need to be reduced significantly (if not eliminated completely) so transport of energy over long distances will largely be a choice between transport of electrons or molecules. An important topic which is the subject of a current OIES research project is to compare the transportation of electrons (typically via a high voltage direct current (HVDC) line) with the transportation of molecules. Increasing use of both HVDC lines and hydrogen pipelines is likely to be an important part of a decarbonised energy system.

Transport of hydrogen over longer distances, beyond the capability of pipelines, adds further complexity and was considered in an OIES paper published in 2022.[49] While transport of liquid hydrogen (after cooling to -253°C) is technically feasible and has been demonstrated by a purpose-built ship sailing between Australia and Japan,[50] the analysis concluded that it is significantly more expensive than alternative seaborne transportation options. It is also noteworthy that the liquefaction process alone requires around 25 per cent or more of the energy contained in the hydrogen, with further losses during shipment and regasification, making the overall process rather inefficient.

Alternative ways of transporting hydrogen by ship include ammonia, methanol, and other liquid organic hydrogen carriers like toluene/methylcyclohexane. At the current state of technology there is little cost differential between these alternatives. Probably the most promising alternative is the shipping of ammonia, particularly when ammonia can be used directly as an end product. For example, use of imported ammonia for co-firing with coal in power generation in Japan is under active consideration.[51] Transport of ammonia (albeit from high-carbon hydrogen) by sea is a long-established practice with around 20 million tonnes per year being shipped globally. The process of cracking ammonia back to hydrogen in the case where hydrogen is required as the end-product requires further scale up and would add additional energy losses and costs.

As noted above, most hydrogen today is consumed near to where it is produced. The difficulties and costs of transporting hydrogen make it likely that, as far as possible, this will continue to be the case in the future. In some cases, for example where there is insufficient renewable power generation to support manufacture of sufficient green hydrogen or insufficient CCS capacity to support blue hydrogen, there will be no alternative to importing hydrogen or derivatives like ammonia, but economics will dictate that transport of hydrogen should be minimised as far as possible. This could have significant implications also from an industrial policy perspective. For example, in Europe, it may make sense to relocate steel making from areas like the Ruhr region in Germany with relatively limited low-cost renewables to southern Italy or Spain which have a more abundant low-cost solar resource.

There has also been considerable discussion about the need for a 'European Hydrogen Backbone' [52] which suggests that Europe may need over 30,000km of hydrogen pipelines by 2030 (of which around half could be repurposed natural gas pipelines). The business case for building such an extensive network is, however, rather uncertain, until the locations of significant clean hydrogen production and consumption becomes clearer. The only significant committed investments in Europe in green hydrogen production so far have been associated with adjacent or nearby refineries or steel plants[53] and so it remains uncertain the extent to which a pan-European hydrogen network will be necessary. It seems

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[48] IEA Global Hydrogen Review 2022, p. 106 and 109.

[49] https://www.oxfordenergy.org/publications/global-trade-of-hydrogen-what-is-the-best-way-to-transfer-hydrogen-over-long-distances/

[50] Suiso Frontier: https://www.hydrogenenergysupplychain.com/

[51] https://www.jera.co.jp/en/news/information/20220531_917

[52] https://ehb.eu/

[53] Refhyne in Germany: https://www.refhyne.eu/ , Holland Hydrogen 1 in Netherlands: https://www.portofrotterdam.com/en/news-and-press-releases/shell-to-start-building-europes-biggest-green-hydrogen-plant and Hybrit Steel in Sweden: https://www.hybritdevelopment.se/en/hybrit-demonstration/

more likely, for the next several years at least, that clean hydrogen production will continue to be built near to the point of consumption, expanding current facilities or in more refineries and chemical plants. At the next stage of development, it is then more likely that pipelines will be built gradually in response to supply and demand to link industrial clusters to surplus hydrogen production some distance away. If a decision were made to build a hydrogen pipeline network in advance of a clear line of sight to the production and consumption which would use the pipeline, there would be a considerable risk of over investment and stranded assets.

This topic of the development of alternatives for hydrogen transport and the required commercial arrangements will remain an important area of further research by OIES.

6. Storage of hydrogen is an essential and underexplored part of the value chain

For any energy carrier it is important to balance supply and demand. The ease of doing so varies considerably depending on the product in question, and has some parallels with the comparative ease of transportation discussed in the previous section. With oil and gas, for example, supply and demand can be balanced by varying the level of production: once a reservoir has been connected the flow rate can be adjusted (within limits) to meet demand. Storage also provides a convenient buffer between supply and demand. Oil can be easily stored in tanks relatively cheaply. Natural gas is somewhat more complex and expensive to store, but can be stored underground in suitable geological structures, to a limited extent as linepack in pipelines, and in tanks in the form of LNG. Storage of electricity is more difficult and typically fossil fuel power generation has been ramped up and down to align with demand. With increasing shares of intermittent renewables there is increasing deployment of grid-scale battery storage to help balance supply and demand, but long duration energy storage, to cope with seasonal fluctuations in renewable power output, remains somewhat challenging and various potential options are being developed.

One of those options for long duration energy storage involves making green hydrogen when supply of renewable electricity is abundant, storing it and using it for power generation when intermittent renewable power is limited. In addition, there will be a need for hydrogen storage to enable intermittent production to be aligned with offtakers requiring steady hydrogen supply. For example, use of hydrogen in an ammonia or green steel plant requires a reliable and continuous supply of hydrogen as the production process is not suitable for ramping up and down as available renewable power varies.[54] With current hydrogen production from natural gas, ensuring a steady flow of hydrogen has not been particularly problematic, but with hydrogen from intermittent renewables significant storage will be required.

Thus storage of clean hydrogen is a key part of the supply chain, but hydrogen is neither easy nor cheap to store. The alternative approaches for hydrogen storage to suit various applications was discussed in detail in an OIES paper published in April 2022.[55] That paper noted that despite the high potential value of hydrogen storage, investment in such storage has so far been limited. This limited investment is at least partly due to the lack of a compelling business model to give confidence that such investments would be profitable. The paper considered various options to create the required business models, but ultimately it will require policy decisions by governments and regulators.

For large scale hydrogen storage (say in excess of 100 GWh of energy stored[56]) the only currently proven option is in salt caverns. While this has been successfully demonstrated in both UK and US, the geographical distribution of suitable salt structures means that it is only available in a limited number of locations. For example, an analysis of potential salt storage in Europe[57] shows that most suitable locations are in northern Europe (Poland/Germany/UK) with very little potential in southern Europe.

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[54] Some work is considering alternatives to the current steady flow Haber-Bosch process for making ammonia – see for example: https://pubs.rsc.org/en/content/articlehtml/2020/ee/c9ee02873k

[55] https://www.oxfordenergy.org/publications/hydrogen-storage-for-a-net-zero-carbon-future/

[56] https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2015/05/3380-ETI-Hydrogen-Insights-paper.pdf

[57] https://www.gie.eu/press/gie-new-study-picturing-the-value-of-underground-gas-storage-to-the-eu-h2-system/

Alternatively underground storage of compressed hydrogen is being tested in lined rock caverns[58] and in depleted hydrocarbon fields.[59] The latter has the potential issue that the stored hydrogen will be contaminated by other components present in the reservoir, but this is subject to further technical research. For smaller scale storage, alternative approaches such as above grounds tanks, liquid hydrogen, and ammonia are also likely to play a role, depending on specific circumstances.

Given the importance of hydrogen storage as a key part of a future decarbonised energy system and for building a credible clean hydrogen supply chain, OIES will continue further research regarding the appropriate solutions and business models to enable the required developments in this area.

Conclusions and Way Forward

This paper started by noting the increasing realism in the last couple of years regarding the potential role for clean hydrogen and the challenges of bringing the required investments to fruition. Under each of the six 'Key Themes' it has identified the most important topics to be addressed in order to enable a robust framework to provide confidence to potential investors in the required hydrogen infrastructure. Development of the hydrogen economy is still at a very early stage and so governments, regulators, and investors in potential projects are all faced with inventing new policy measures and commercial structures to create robust and financeable projects. This has parallels with other nascent industries (for example the LNG industry in the 1970s) when the first pioneering projects had to learn by doing but once a workable model has been developed it can be (reasonably) quickly followed by others.

This paper sets a framework for further research, but it is clear that much work remains to be done in order to develop robust business cases to enable investments in clean hydrogen such that the product can play a significant role in the future decarbonised energy system.

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[58] https://www.hybritdevelopment.se/en/hybrit-milestone-reached-pilot-facility-for-hydrogen-storage-up-and-running/

[59] https://www.h2euplusstore.com/en/hydrogen-for-eu/european-hydrogen-infrastructure/rag-hydrogen-storage-uss-2030.html