From Hydrogen Hype to Hydrogen Reality: A Horizon Scanning for the Business Opportunities

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ABSTRACT

There is growing interest in the hydrogen economy and businesses that deploy hydrogen worldwide. The desire to tackle the adverse effects of climate change, achieve a green transition and deep decarbonisation, ambitious future net-zero targets of numerous countries, increasing pressure for energy security, and being self-reliant are reasons behind this interest. However, hydrogen is not a new phenomenon. Nowadays, many people ask if the hydrogen economy has a future. The answer is not straightforward, as the hydrogen economy has numerous different application areas. The main question is which hydrogen applications can be deployed commercially and which business cases are not viable. This paper investigates 20 prominent hydrogen-related business opportunities and reviews a sample of 64 companies' business models from 18 countries worldwide. The paper aims to highlight which cases are viable now and which ones are likely to be viable in the future. Our aim is to present a broad horizon scanning along the value chain for the global use of hydrogen as a commercial entity. Figure A shows 20 business opportunities directly and indirectly related to the wider hydrogen economy and their viability assessment in the market, where grey indicates high carbon hydrogen, and the rest is low carbon hydrogen. Our initial horizon scanning reveals that majority of the business opportunities lack generating self-sustaining revenues, hence they are away from being mature businesses. In this paper, we listed several observations and remarks specific for each business and their viability.

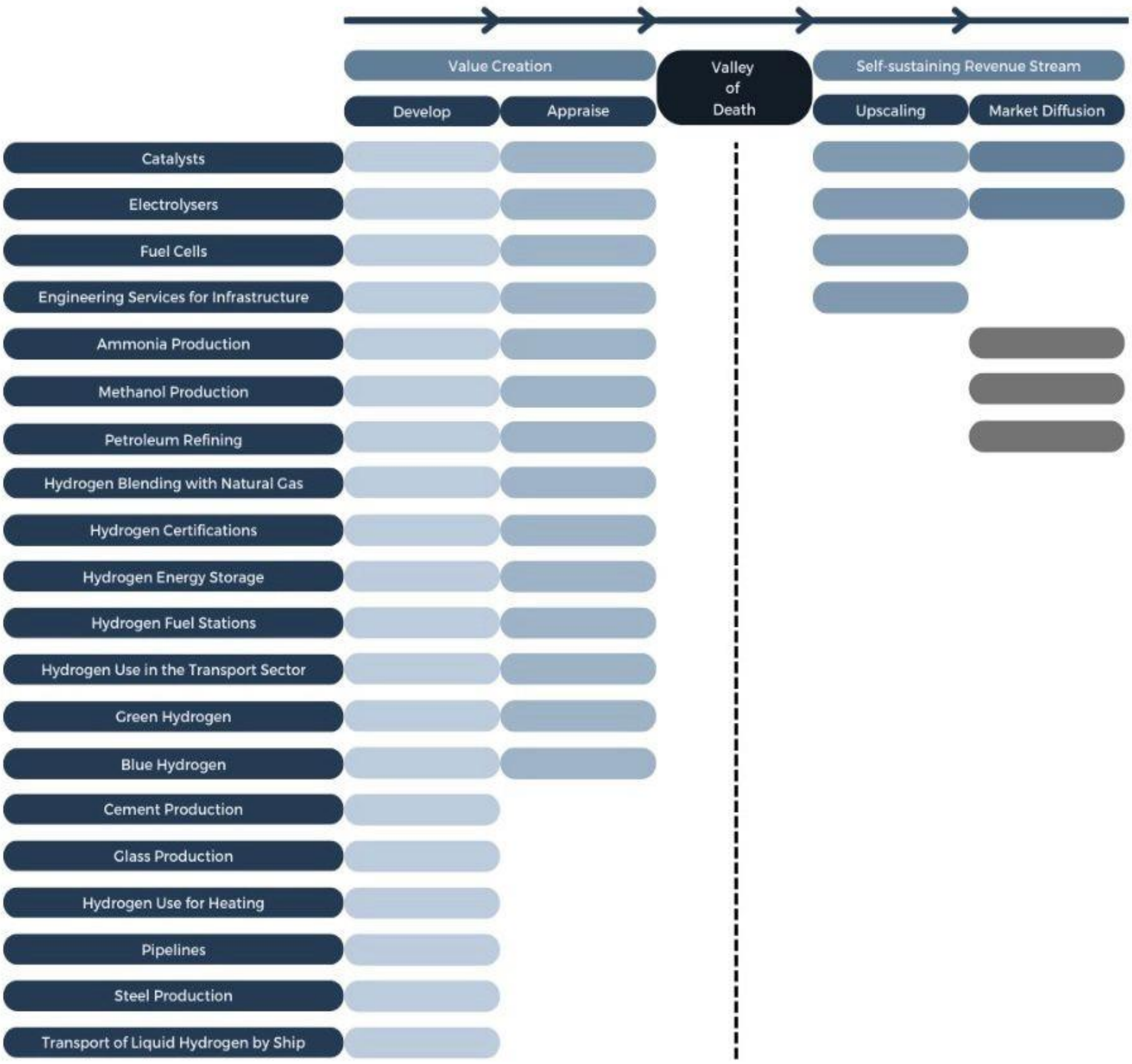

Figure A. Market Phases of Hydrogen Businesses

Key words: Hydrogen, Hydrogen economy, Energy, Business, Low carbon transition

1. Introduction

Hydrogen is the amplest chemical element in the universe, but on earth it generally needs to be separated from water, hydrocarbons, or other organic substances. Hydrogen use is not new, having been used as a feedstock in, for example, the refining and petrochemical industries for many years. The focus now is on hydrogen as a low-carbon fuel source, but much of this technology is also not new. For example, alkaline hydrolysis was patented initially by Amos Herbert Hobson from England on December 25, 1888[1]. Similarly, the first car to use a hydrogen fuel cell was invented by General Motors in 1966[2]. These applications did not penetrate the market because of the lack of value for money and revenue generation at that time. The economic viability of many of the hydrogen applications is still unproven or debatable today and, in many cases, will rely on government policy support.

The future hydrogen economy broadly means using hydrogen as a low-carbon energy source. Further extending this definition, the hydrogen economy covers the commercial use of hydrogen in all suitable economic sectors. The hydrogen value chain broadly covers:

i) upstream: input fuels/energy and production technologies,

ii) midstream: hydrogen and CO_2 storage and transportation,

iii) downstream: end uses, and links with related economic activities

The hydrogen economy can be regrouped under three dimensions: production, networks and use. To give further details, production covers grey, electrolytic ("green") and CCUS-enabled ("blue") hydrogen. Networks include pipelines and other infrastructure, including storage and facilities to ship hydrogen and derivatives. And finally, use is end-use activities such as industry, power, residential heating and transport (maritime, aviation and heavy long-haul freight). The value chain also includes derivatives such as ammonia, methanol and other substances, CO_2 capture (Carbon Capture Utilisation and Storage (CCUS)), as well as energy inputs such as renewables, natural gas, nuclear and biomass[3].

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[1] Wilson, J.H., 2014. The history of alkaline hydrolysis. Good Funeral Guide.

[2] GM Heritage Center, 2019. GM Hydrogen Fuel Cell Vehicles.

[3] HM Government, 2021. UK Hydrogen Strategy.

This paper covers an overview of 20 potential business opportunities in the low carbon hydrogen value chain. This includes production technologies, hydrogen and CO_2 transportation and storage, end-use of hydrogen as feedstock, and links with related economic activities. Section 2 summarises the contemporary challenges and various goals related to hydrogen use as a low carbon transition asset. Section 3 explains the adopted business model theory and its application. Section 4 introduces 20 direct and indirect hydrogen use cases and business opportunities. We then conclude that paper with a brief discussion and conclusion.

2. The Hydrogen Challenge

Drawing on examples from the United Kingdom (UK) and European Union (EU), this section outlines some of the ambitious targets envisaged for low carbon hydrogen and some of the challenges in achieving them.

The UK Energy Security Strategy outlines their goal of building up to 10GW of low-carbon hydrogen production capacity by 2030, subject to affordability and value for money, with electrolytic hydrogen accounting for at least half of it[4]. The UK has established a £240 million Net Zero Hydrogen Fund to support low-carbon hydrogen production projects, with funds expected to be awarded by the end of 2022. This will help the government meet its goal of installing up to 2GW of low-carbon hydrogen production capacity by 2025, and up to 10GW by 2030[5]. Moreover, the Industrial Decarbonisation and Hydrogen Revenue Support (IDHRS) initiative, which would fund the allocation of hydrogen business model contracts to both electrolytic and CCUS-enabled plants from 2023, was announced in the UK's Net Zero Strategy in 2021.

[4] British energy security strategy, 2022. Policy paper.

[5] The Net Zero Hydrogen Fund, 2022. Government response to consultation. UK Department for Business, Energy & Industrial Strategy.

According to IDHRS, it would contribute up to £100 million in 2023 to award contracts for the electrolytic hydrogen production capacity of up to 250MW[6].

Furthermore, the Industrial Hydrogen Accelerator is a £26 million innovation grant programme aimed at assisting the UK industry in embracing hydrogen as a clean, inexpensive fuel source for industries such as manufacturing by showing hydrogen's practicality and lowering the cost of switching energy systems. Lastly, the government has set aside a further £5 million to help accelerate the development of carbon capture and storage (CCS) technologies. CCS involves capturing, transferring, and storing greenhouse gas emissions that would otherwise be released into the environment, allowing for the storage and utilisation of traditional energy sources energy[7].

On the other hand, the European Union's (EU) latest REPowerEU plan states the aim of transforming industrial processes to replace gas, oil and coal with renewable electricity and fossil-free hydrogen[8]. To further diversify the energy imports in the EU, the document underlines the EU Energy Platform for the voluntary common purchase of hydrogen. By merging hydrogen and renewable energy development and trade, the EU also promises its international partners long-term opportunities for mutually beneficial cooperation. By 2030, REPowerEU aims to produce 10 million tonnes of local renewable hydrogen and import 10 million tonnes of renewable hydrogen. The plan also announces additional investment of EUR 200 million for the Clean Hydrogen Partnership through the Horizon Europe Programme[8]. To upgrade existing infrastructure to achieve this ambitious progress in clean hydrogen is a challenge for all. The total investment required for important hydrogen infrastructure categories is expected to be between EUR 28 and 38 billion for EU-internal pipelines and EUR 6 to 11 billion for storage[8].

Recent stakeholder consultation in the UK's hydrogen and energy sector outlines some concerns regarding the business model of a hydrogen economy[9]. Even though there are various ambitious supply targets for installing low-carbon hydrogen capacity

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[6] The Net Zero Hydrogen Fund, 2022. Government response to consultation. UK Department for Business, Energy & Industrial Strategy.
[7] GOV.UK, 2022. Press release. Government unveils investment for energy technologies of the future.
[8] REPowerEU, 2022. The European Commission, A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition.
[9] BEIS, 2022. Government response to the consultation on a Low Carbon Hydrogen Business Model.

in the future, many respondents to the consultation emphasised the importance of taking steps to boost hydrogen demand in order to reduce volume risk and encourage end-users to transition to low-carbon hydrogen[9]. Another concern was whether hydrogen usage and the hydrogen economy should be supported in all industries or whether policymakers should prioritise hydrogen use where no feasible or readily available alternative decarbonisation options exist[9].

Production costs for low-carbon hydrogen generation are worth mentioning. In 2021, the UK Department for Business, Energy and Industrial Strategy (BEIS) compiled the existing production methods and their current and future cost estimations, which are presented in Table A1[10].

Table A1. Hydrogen Production Costs and Future Estimations, amended from Hydrogen Production Costs Estimations[10]

Production method	Definition	Levelised Costs
Steam Methane Reforming (SMR) without CCUS	Methane from natural gas is pre-heated, mixed with steam and usually with a catalyst to produce H_2, CO and CO_2	SMR (300MW) 2020: £64/MWh 2050: £130/MWh
Autothermal Reforming (ATR) or Steam Methane Reforming (SMR) with CCUS	ATR is the process of producing syngas with H_2 and CO by partially oxidising a hydrocarbon feed with O_2 and steam and subsequent catalytic reforming.	ATR (300MW): 2020: £62/MWh 2050: £65/MWh SMR (300MW): 2020: £59/MWh 2050: £67/MWh
Grid electrolysis	Using grid power to produce electrolytic H_2	Polymer electrolyte membrane electrolysis (PEM) (10MW): 2020: £197/MWh 2050: £155/MWh

[10] BEIS, 2021. Hydrogen Production Costs. UK Department for Business, Energy & Industrial Strategy.

Renewable electrolysis	Using Renewable Energy Sources to produce electrolytic H_2	PEM (10MW) (with dedicated offshore wind): 2025: £112/MWh 2050: £71/MWh
Bioenergy with carbon capture and storage (BECCS)	Biomass gasification with CCUS	BECCS (473MW) 2030: £95/MWh (excl. carbon) £41/MWh (incl. carbon) 2050: £89/MWh (excl. carbon) -£28/MWh (incl. carbon)

The total cost includes the following: CAPEX, Fixed OPEX, Variable OPEX, Electricity cost, Fuel cost, CO_2 transport and storage cost, and Carbon cost. As we can see from Table A1, in many of the hydrogen production technologies, there is limited expected reduction in costs, and in some cases increases in costs by the year 2050. The main reason is the increased carbon cost estimation for the future, whereas with biomass a negative carbon cost component yields a reduction in the estimations. The overall cost trend estimation contrasts to the historical production costs of solar photovoltaic, wind power and battery storage costs, which have fallen dramatically in recent years. For example, Levelized cost of electricity (LCOE) of onshore wind and utility scale solar PV dropped 72 and 90% in nominal terms between 2009 and 2021[11]. As Table A1 highlights, a similar cost reduction trend for hydrogen is not expected in the future. This expectation is one of the major limitations or concerns over the hydrogen economy and its future viability.

The cost of hydrogen and its market price is just one concern. There are also reasonable doubts whether the ambitious supply targets are achievable due to logistics issues such as electrolyser manufacturing. However, considering the existing supply-driven nature of the hydrogen economy, there is also a non-trivial need to stimulate the demand for hydrogen. On the other hand, approaching from a technology-neutral perspective and keeping in mind that government support means taxpayers' money

[11] Lazard, 2021. Levelized Cost of Energy, Levelized Cost of Storage, and Levelized Cost of Hydrogen.

being spent, we believe that the hydrogen applications should only be supported where no viable or readily available low carbon alternative exists. Also, a need for support for small-scale projects is advisable to stimulate own consumption and reduce intermediaries.

One non-trivial question is, will carbon pricing impact the hydrogen uptake? The UK Emissions Trading Scheme (ETS) covers some sectors such as energy-intensive industries, the power generation sector and aviation. The UK ETS is a replacement mechanism for the EU ETS. This scheme does not cover sectors such as transport, agriculture, waste, certain industrial emissions, and the built environment for the time being. However, the extension of UK ETS might be proposed in the future. This means that carbon pricing will not affect all hydrogen economy applications for the time being. An extension of ETS scope is vital for the impact of the carbon pricing on all hydrogen businesses. We can observe from the existing regulatory and policy framework that there will be public money support in the short term. The business cases should start generating their own revenues in the long term. This brings us back to which hydrogen use cases are self-sufficient and viable.

Finally, we should mention the standardisation of hydrogen types. Whilst the UK prefers to use the term 'low carbon hydrogen' by adopting the threshold of 20gCO2e/MJ Lower Heating Value (LHV) through the proposed UK Low Carbon Hydrogen Standard (LCHS), we should remind that the EU has not got a certification mechanism for a 'clean hydrogen' or 'fossil-free hydrogen' standard yet. There are various colour codes assigned to each hydrogen generation method. The most extensive ones are green, blue and grey hydrogen. Green hydrogen is produced from the water electrolysis process by using renewable electricity. This source might also be called electrolytic hydrogen. The second one is blue hydrogen. This is sourced from traditional fossil fuels such as natural gas. However, the emitted CO_2 is captured and stored at the site of production. This process is called carbon sequestration. Many companies also use Carbon Capture, Utilisation and Storage (CCUS). However, to qualify as blue hydrogen, carbon sequestration is sufficient. Finally, grey hydrogen is produced from fossil fuels and commonly uses Autothermal Reformation (ATR) or Steam Methane Reforming (SMR) methods. The emissions, however, are released into the atmosphere. Thus, grey hydrogen is not classified as a green or renewable source. There is also numerous other colour coding assigned to specific hydrogen production technique. However, since the volume of these hydrogen is much lower than blue and green hydrogen, we omitted these in this paper.

3. The Business Model and Viable Use Cases

Before inspecting which business opportunities may be viable for hydrogen, it is important to first define how to assess its viability. To do that, we can begin by explaining the innovation process. Figure 1 summarises this process from the inception of the ideas to market penetration.

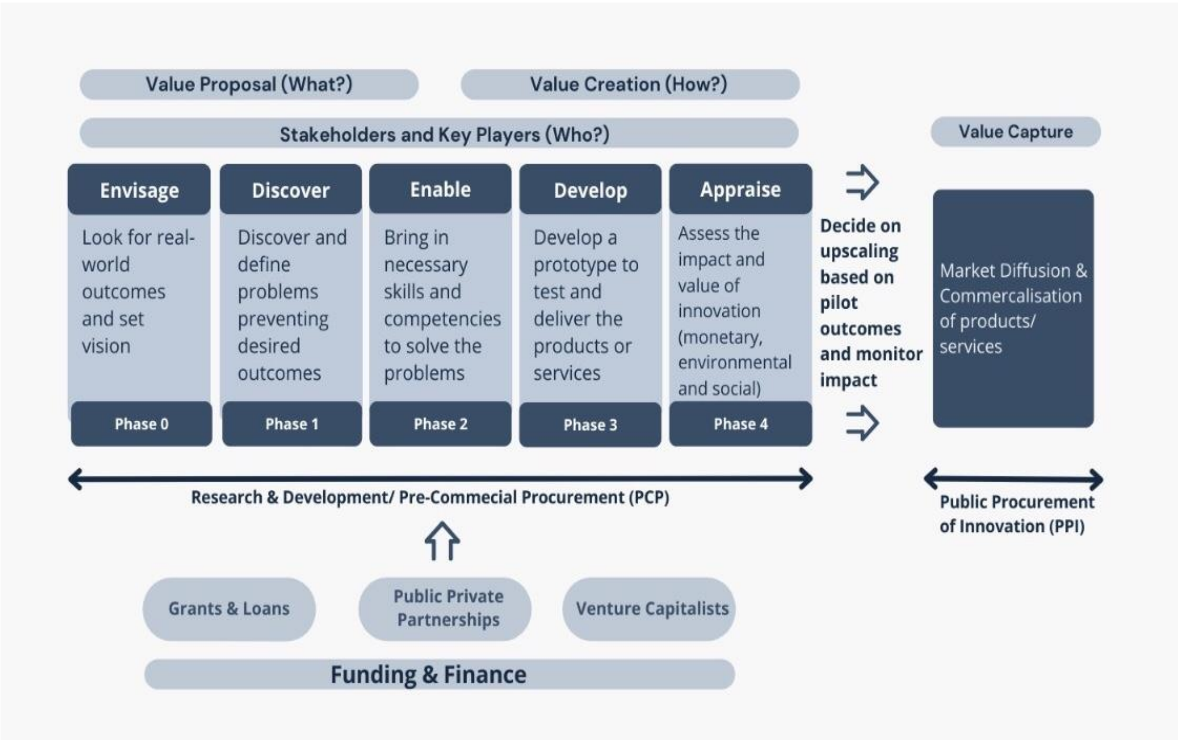

Figure 1. The Innovation Process[12].

Phase 0, Envisage, begins with a search for real-world outcomes and the creation of a vision. After that, we move on to the Discover phase. This phase identifies and outlines the issues that are hindering the desired objectives. After that, the company should be able to Enable the relevant skills and competencies to solve the difficulties described.

[12] Küfeoğlu, S., 2022. Emerging Technologies: Value Creation for Sustainable Development. Springer Nature.

When the company's skills are sufficient, it can move on to the Develop phase. A product or service prototype is created and tested at this phase. We go on to the Appraise phase if the results are satisfactory. Assessing the innovation's impact and value is critical in determining if the product/service will be scaled up for wider commercial use or remain a prototype. If market conditions indicate that the business should be scaled up, it will enter the market and reach a wider spectrum of consumers and customers. Funding and financing channels are critical to fostering product/service development during this entire process. Grants and loans may be a good place to start the process. As the trip progresses to the Develop and Appraise phases, public and private investors will notice the possibility and join in as Public-Private Partnerships or Venture Capitalists. As the product/service matures, innovators may adjust, adapt, or update their Value Proposals, Value Creation, and Value Capture, which will form the business models of the innovations. In the business model inspection, we followed the traditional business model theory and the basic three dimensions[13]:

Value Proposal: What the company offers as a product or service. (typically developed during the Envisage / Discover Phases)

Value Creation: How the company creates and delivers these products or services. (typically developed during the Develop / Appraise Phases)

Value Capture: What are the expected revenue sources, and how are they planning to create this?

It is important to note that revenue or monetary value is not the only consideration when discussing value. The demand for industry and enterprises to combat climate change and achieve sustainability is increasing. As a result, to boost their overall impact, acquire more finance, and achieve better market dispersion, the innovations should also give environmental, social, and ethical value and impact. This market diffusion and commercialisation of products and services is the part where we define business opportunities as 'viable'. The value of the business opportunities is captured in this phase. Our main purpose is to investigate the viability of these

[13] Gassmann, O., Frankenberger, K. and Csik, M., 2013. The St. Gallen business model navigator.

opportunities worldwide. We recognise that the low-carbon hydrogen economy is at an early stage, so we welcome feedback on how emerging technologies and business models may impact our current assessment. We should also remind that exogenous factors such as regulations, subsidies and carbon pricing will affect the viability of these businesses substantially. Being a horizon scanning work, this paper only covers a broad review of the business opportunities, thus leaving the detailed analyses of viable businesses as a follow-up future work.

We should note that the boundaries between each of these phases (Appraisal, Upscaling, Market Diffusion) are not precise whilst some businesses might span in between two phases. The distinction could be made as follows. If a business has numerous successful pilots/trials and some further evaluations are made in terms of revealing a comprehensive economic, environmental and social impact and value, then we can say that the business is in the Appraisal phase. When the business starts generating revenue and is deployed in a wide range of geographies and markets, then the business is in the Upscaling phase. In the Market Diffusion phase the business is mature and reliable. The business should start generating revenue to be a self-sustaining business. When we say self-sustaining business we mean that it will have a reliable customer base, a continuous demand, and most importantly a steady stream of revenue. The business should not be dependent on the external investments or the owners. In the next chapter, we will attempt to map the 20 business cases according to these criteria.

4. Hydrogen Business Cases

This paper reviews the business models of 64 companies from 18 countries worldwide[14]. Table D1 shows the locations of these countries. As we can see from Table D1, most companies that we reviewed in this paper are located either in Europe or North America. There could be two reasons for this. First, economic activity related to hydrogen is more concentrated in North America and Europe. And second, due to a language barrier, we could not reach sufficient number of sources from non-English speaking world.

[14] All information presented in Table 1-Table 20 are publicly available and were adopted from official websites of the companies. For reference, you may click on the hyperlinks on the company names.

Table A2. Location of Reviewed Companies

Country	number	Country	number
United States	14	South Korea	2
Germany	12	Spain	2
United Kingdom	9	Sweden	2
Canada	6	Switzerland	2
Netherlands	4	China	1
Japan	3	European Union	1
Australia	2	France	1
Italy	2	Luxembourg	1
Norway	2	Saudi Arabia	1

We conducted a market scan and picked up some leading players in their fields that do business in the selected fields. This means that the selected companies are not the only ones that are innovative or noteworthy. These are just representative examples. There are 20 business opportunities that we listed here as some prominent direct and indirect application areas in the hydrogen economy. We only listed business cases which reached the Value Creation phase (Develop and Appraise) in the innovation process shown in Figure 1. We deliberately excluded the use cases that are still in the Research and Development phase. We attempted to cover a representative sample of key and leading players in each sector. The companies are compiled from sources like the Hydrogen report of the International Energy Agency (IEA)[15], "Best Hydrogen Stocks to Watch in 2022"[16], "10 Hydrogen Fuel Cell Stocks to Buy Today"[17], "6 Green Hydrogen Stocks and ETFs to Watch"[18], "Top Hydrogen Start-ups"[19], "14 hydrogen production and hydrogen fuel cell stocks to watch"[20], "130+ Tech Companies Developing Hydrogen-Based Clean Energy Solutions"[21], and especially for the downstream and end-use business cases, a through a comprehensive market scanning.. However, we should stress that it does not mean that the companies presented here are the only noteworthy ones since it is

[15] IEA, 2021. Hydrogen, International Energy Agency, Paris.
[16] Admiral Markets, 2022. Best Hydrogen Stocks to Watch in 2022.
[17] Yahoo finance, 2022. 10 Hydrogen Fuel Cell Stocks to Buy Today.
[18] US News, 2022. 6 Green Hydrogen Stocks and ETFs to Watch.
[19] Venture Radar, 2022. Top Hydrogen Start-ups.
[20] CMC markets, 2022. 14 hydrogen production and hydrogen fuel cell stocks to watch.
[21] CB Insights, 2021. 130+ Tech Companies Developing Hydrogen-Based Clean Energy Solutions.

impossible to present all existing valuable companies and businesses in this paper. Figure 2 summarises hydrogen business cases in the value chain.

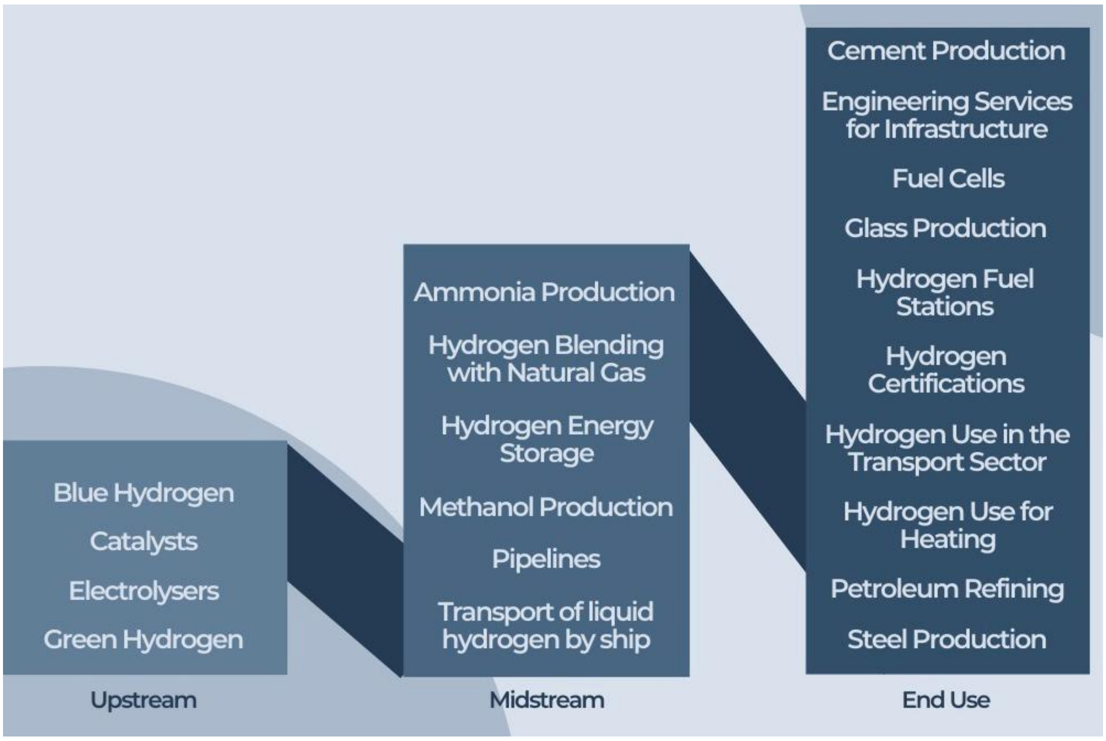

Figure 2. The Hydrogen Value Chain and Business Cases

Here we should remind that some businesses, such as ammonia or methanol, can extend more than one phase and be placed in multiple streams. The following sub-section reviews 20 business cases and summarises their business models[22].

4.1. Blue Hydrogen

Blue hydrogen is produced by steam methane reforming (SMR) combined with subsequent carbon sequestration, where the emitted atmospheric CO_2 is captured and stored. Auto-thermal reforming (ATR) is another method to produce hydrogen from natural gas, which has the benefit of producing a more concentrated stream of CO_2. Both technologies are commercially available and being used in many production sites worldwide. Table 1 summarises a few specific examples to investigate the business model and status.

[22] All information presented in Tables 1-20 are retrieved from official company websites. We did not include any comments or information on these tables as we are in no position to justify the official claims of the companies.

Table 1. Summary of Blue Hydrogen Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
SHELL Netherlands & UK	They offer blue hydrogen combining their Gas Partial Oxidation (SGP) and ADIP ULTRA technologies. Over 30 licensees for gas and residue gasification are now operating with SGP, and there are over 100 SGP gasifiers installed worldwide.	SGP technology uses a direct firing oxygen-based system in a reactor with a refractory lining. It is a non-catalytic process that produces high-pressure steam from waste heat rather than consuming it and emits no direct CO_2. It also requires little to no feed-gas pre-processing. ADIP ULTRA is a non-corrosive, high carrying capacity solvent for capturing CO_2 from high-pressure process streams. Together with UNIPER, the company is building a blue hydrogen production plant with a capacity of up to 720 megawatts in the UK.	Revenue stream is expected by the mass sales of blue hydrogen to decarbonise heavy industry, transport, heating and power in the region of the plant. They claim the SGP technology has 22% less levelized cost than ATR and much less than SMR technologies. They also claim CO_2 removal is increased by 25% - 30% thanks to the ADIP ULTRA technology. The UK plant is expected to perform the capture of around 1.6 million tonnes of CO_2 per year through CCS.

Johnson Matthey UK	The company promises to offer blue hydrogen at scale thanks to their LCH technology. The technology is incorporated at the HyNet North West hydrogen project in the UK.	LCH technology produced low-carbon hydrogen at scale from natural gas while capturing 98% of the CO_2 emissions. The company claims to deliver blue hydrogen with lower CAPEX and OPEX with their LCH technology.	They are targeting £200 million sales of all hydrogen technologies including blue hydrogen, green hydrogen and fuel cells by the end of 2024/2025. Once operational, the HyNet North West facility is expected to remove 600,000 tonnes of CO_2 per year.
TOYO Engineering Japan	The company is a prominent actor in the area of licensing, design and construction of SMR plants. Their products account for more than 10% of the blue hydrogen produced in the world by SMR technique.	They develop the SMR technologies with high efficiency for producing crude gas (syngas) consisting of hydrogen and carbon monoxide formed to produce blue hydrogen. Their Steam Reformers are used in ammonia, methanol, refinery hydrogen production and fuel cell power facilities. Their reformers are ideal for large	Revenue stream is generated by the sales of SMR plants. The company's products are widely used in the world. Extra value is captured by their steam reformers by size reduction, saving of fuel, extension of tube life and throughput increase.

		facilities to make production at scale.	

Remarks: When combined with Carbon Capture Utilisation and Storage (CCUS), the SMR process is commonly believed to capture over 90% of CO_2 emissions. However, a recent study suggests that blue hydrogen has serious Green House Gas (GHG) emissions mainly due to fugitive methane[23]. The same paper claims that the total CO_2 equivalent emissions for blue hydrogen are just 9% - 12% less than for grey hydrogen[23]. On the other hand, many companies claim that their hydrogen generation techniques reduce CAPEX and/or OPEX with various designated percentage rates. However, since we are still at the Value Creation and Appraisal phase of the blue hydrogen generation, we believe these claims need to be verified by a wide-scale market use. In addition, the recent high prices of natural gas in Europe and Asia pose additional challenges for the widespread deployment of blue hydrogen. For example, recent analysis by ING Bank reports that due to high natural gas prices, the hydrogen costs tripled in Europe[24]. Surely, geographical differences play a crucial role in the hydrogen production and this phenomenon needs further in-depth analysis.

4.2. Green Hydrogen

Renewable energy generation sources are rapidly increasing globally, and integration of hydrogen production into this network will result in sector coupling of power systems to other sectors such as heavy industry, transport, heating, and power to gas/"e-fuel" solutions. Green hydrogen usually refers to the electrolysis of water using renewable power generation, thus standing out as one of the clean or low-carbon energy carrier options. Intermittency in renewable power generation is a problem, and green hydrogen is a candidate to ease this challenge. As a result, the use of green hydrogen might enable the potential for accelerating the decarbonisation of energy-intensive sectors. However, according to the IEA's report from 2019, converting all existing global grey hydrogen generation to green hydrogen would require 3,600 TWh of renewable energy per year,

[23] Howarth, R.W. and Jacobson, M.Z., 2021. How green is blue hydrogen? Energy Science & Engineering, 9(10), pp.1676-1687.
[24] ING, 2021. High gas prices triple the cost of hydrogen production. Economic and Financial Analysis.

which was about the EU's entire annual electricity production[25]. In some cases, green hydrogen also refers to other forms of renewable hydrogen, not necessarily involving electrolysis. Table 2 compiles some business cases to closely examine the range of possibilities and business models.

Table 2. Summary of Green Hydrogen Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Siemens Germany	Siemens Gamesa and Siemens Energy have started joint work to produce green hydrogen at an offshore wind turbine. Siemens Gamesa also trials a land wind turbine-fed electrolyser system for on-grid and off-grid hydrogen generation.	They are testing a modular approach to see the hydrogen production performance at variable renewable generation rates. Also, electrolyser performance under harsh weather conditions is monitored. The trials aim to demonstrate the viability of dependable, efficient deployment of modular offshore wind-to-hydrogen systems and act as a test bed for making large-scale, cost-effective hydrogen generation a reality.	Revenue stream is expected from the generation of green hydrogen. Over the next five years, Siemens Gamesa and Siemens Energy plan to invest around €120 million in the development of modular offshore wind-to-hydrogen systems, with a full-scale offshore demonstration anticipated by 2025 or 2026.

[25] IEA, 2019. The Future of Hydrogen.

REPSOL Spain	Together with Enagas they are planning to offer green hydrogen produced from the direct use of solar energy, a process they name photo electrocatalysis. This solar-fed hydrogen generation technology does not deploy electrolysers.	In the typical electrolyser-based generation, electricity is generated at PV-panels and then fed to the electrolyser to separate oxygen from hydrogen. Their technology receives solar radiation and generates electrical charges that cause the separation by using its photoactive material. They aim to reach 1.9 GW of installed capacity by 2030.	Expected revenue stream through the sales of green hydrogen. The extra value will be created via increased efficiency thanks to their photo electrocatalysis process. They plan to invest around €2.549 billion by 2030. The company expects this business to be viable by 2030.
Hydrospider Switzerland	They offer procurement, production and logistics of green hydrogen, mainly produced from hydropower. They also provide marketing and sales support to producers of verifiable green hydrogen.	Their first green hydrogen demonstration project produces 300 tonnes of hydrogen per year at a hydropower plant with a 2-MW electrolyser. The hydrogen is transported to filling stations after being stored in custom-made containers.	Targeted customers are heavy commercial vehicles. The sales of green hydrogen generate revenue. Their existing production capacity can supply up to 40-50 trucks a year. The decarbonisation of the transport sector captures environmental value.

SGH2 U.S.	They offer the production of green hydrogen from any sort of waste ranging from paper to plastics, tires to textiles.	The company utilises a plasma-enhanced thermal catalytic conversion process optimised with oxygen-enriched gas. At high temperatures, the waste feedstock disintegrates into its molecular compounds. These molecules bind into very high-quality hydrogen-rich biosyngas, which are then used to produce hydrogen. They are launching a generation plant in California to produce 3800 tonnes of waste-based green hydrogen per year. This is the largest green hydrogen facility to be built in the world so far.	Revenue stream through sales of waste-based green hydrogen produced from plasma technology. Mass production promises economy of scale with a cost of US$2 per kg. This has parity with the cheapest brow hydrogen production in India. Whereas electrolytic hydrogen generation roughly costs US$10-15 per kg in the U.S.

Remarks: A key challenge for green hydrogen is to reduce costs and increase scale. Scaling up electrolyser production and producing sufficient low-cost renewable power in excess of that required to decarbonise the electricity grid is particularly challenging. Alternatives to electrolysis, such as plasma or photo electrocatalysis, as summarised in

Table 2, may prove to be value-adding. The production costs and environmental footprint vary depending on the input energy, production technology and the location of production plants. Various pilot and demonstration projects are being implemented globally. Even though green hydrogen could be regarded as an effective tool for decarbonising hard-to-abate sectors such as heavy transport, shipping, steel and cement, a requirement for mass production and an economy of scale is a must. The business is still in its Appraise phase, but as the amount of investment is booming, depending on strong demand, in a few years it might enter Upscaling before reaching the Market Diffusion.

4.3. Catalysts

Catalysts reduce the energy required to start a chemical process, speeding it up. Many industrial processes rely on chemical reactions to transform raw materials into usable products, and catalysts are the backbone of many of them[26]. In the hydrogen ecosystem, catalysts are used in a wide range of applications, including hydrogenation, electrolysers, fuel cells, hydrocracking, and hydrogen production. Table 3 briefs a few business cases related to the catalyst industry.

Table 3. Summary of Catalysts Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Sigma-Aldrich (Merck) Germany & U.S.	They provide homogeneous and heterogeneous catalysts for sectors such as pharmaceuticals, agrochemicals, industrial chemicals, or custom manufacturing.	Iridium, nickel, palladium, platinum, rhodium, or ruthenium are common hydrogenation catalysts used to initiate the chemical reaction between hydrogen and	Revenue stream through bulk sales of catalysts. A large supply-chain promises global availability. Furthermore, in addition to their product portfolio, they offer custom

[26] Lerner, L. 2011. 7 things you may not know about catalysis. Argonne National Laboratory.

		another substance. Heterogeneous catalysts are deployed to enable faster selective and large-scale production. The reactivity can be altered by adjusting the carbon's structure and metal content, which increases the range of possible applications. Homogeneous catalysts deliver a more selective and characterizable process, leading the mechanisms to be rationally manipulated for alternative outcomes.	catalyst synthesis depending on the customers' request.
Heraeus Germany	The company offers chemical process catalysts with a wide spectrum of homogeneous and heterogeneous catalysts.	They are delivering electrocatalysts for PEM electrolysers and PEM fuel cells. They provide customers with a complete loop of their precious metal needs by recovering precious metals from a catalyst-coated	Revenue by sales of catalysts. Further value is captured by providing customers with up to three times higher catalyst performance while reducing the precious metal loading in the catalyst-coated

		membrane. They use platinum in different PEM fuel cell catalysts, increasing performance and reducing costs. Their catalysts have cell reversal tolerance which protects the anode by allowing significantly lower damage throughout time.	membrane by 50–90% in comparison to other products in the market. Thus, the company promises more efficient use of iridium, allowing increasing performance and reducing costs, large scale application due to savings in precious metal content, and a substantial decrease in capital expenditure due to iridium and catalyst material savings.
Honeywell U.S.	They offer Proton Exchange Membrane (PEM) and Anion Exchange Membrane (AEM) electrolysers. They are also piloting a new catalyst-coated membrane (CCMs) technology to achieve substantial cost reduction.	They develop, manufacture and deliver membranes and catalysts for gas processing, refining, steel, petrochemical industries, and battery and power applications. In collaboration with ZoneFlow Reactor Technologies, they	Revenue stream though sales of catalysts for a wide range of applications. Further value is aimed to be captured by achieving a 25% reduction in electrolyser stack cost and further significant efficiency

		are in the process of commercialising a new technology called ZoneFlow Reactor. It is a structured catalyst module that replaces conventional catalyst pellets in steam methane reforming (SMR) tubes providing better heat transfer and pressure drop performance.	increases in catalyst design.

Remarks: Catalysts are essential tools in producing electrolytic hydrogen. The ambitious green hydrogen capacity installation targets necessitate the large-scale use of catalysts. The design of catalysts can vastly improve the efficiency of the green hydrogen production process. A radical increase in catalyst efficiency will vastly impact the cost of hydrogen production. Recent research suggests that the amorphous iridium hydroxide-based catalyst design exhibited efficiency 150 times that of its original perovskite structure. It also yielded an efficiency of almost three orders of magnitude better than the common commercial iridium oxide-based catalyst [27] (Oregon State University, 2021). However, we should wait and see whether similar R&D activities will translate into commercial products or not. Another concern not just related to catalysts but to overall hydrogen applications is the use of rare materials. There are some concerns regarding the availability of certain materials such as aluminium, copper, nickel, and zinc, platinum, iridium upon an ambitious uptake of hydrogen production and storage capacity in the future. A recent report published by the World Bank reassures that Most of the commodities involved in the production and use of clean hydrogen will not face

[27] Oregon State University, 2021. Oregon State researchers develop advanced catalysts for clean hydrogen production.

significant market issues due to the overall volume of material demand[28]. Nonetheless, the same report stresses that especially platinum and iridium supplies might be a challenge for the industry in the coming years[28]. Catalyst manufacturing is an old and mature business. It has market-proven products such as various homogeneous and heterogeneous catalysts. In addition, there is a vivid activity on the Value Creation side with some ambitious efficiency increase targets. So, the business is mature and spans from Value Creation to Market Diffusion.

4.4. Electrolysers

Electrolysers are devices that are used to decompose water molecules into hydrogen and oxygen through the electrolysis process. These come in various sizes, from small-sized ones suitable for compact appliances in hydrogen distribution, such as small industrial plants installed in shipping containers to massive central production plants connected directly to large-scale renewable energy sources. While some electrolyser customers favour large units (from 1MW and beyond), some place more emphasis on quantity than size by opting in modular residential and commercial designs (from 1 kW to 100 kW). For example, from the customer perspective, operators of large PV plants will find the first strategy appealing, whereas those of small systems will benefit more from the latter[29]. There are different electrolyser designs available commercially. Also, various designs are in the Research & Development and Piloting phases, waiting to be scaled up in the market. Alkaline Electrolysers and Proton Exchange Membrane (PEM) Electrolysers are widely used in the industry. Anion Exchange Membrane and Solid Oxide electrolysers are in the Develop and Appraise phase. Table 4 summarises a few examples illustrating the range of products and potential business models.

[28] World Bank Group, 2022. Sufficiency, sustainability, and circularity of critical materials for clean hydrogen. Susana Moreira, Tim Laing.
[29] PV Magazine, 2020. Electrolyzer overview: Lowering the cost of hydrogen and distributing its production.

Table 4. Summary of Electrolysers Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Ostermeier H2ydrogen Solutions Germany	They offer modular electrolysers in 1.2m X 1m X 2m sizes for residential and commercial use. The available nominal power of the electrolyser stacks is 1 kW, 2 kW, 3 kW or 5 kW.	The electrolysis consists of the electrolysis frame module, the electrolysis module, the water purification module, the electrolysis power module, the fuel cell and the cooling module. Thanks to the water purification module, tap water can be used in hydrogen generation at homes and commercial facilities. The produced hydrogen can then be stored in the fuel cell module to be converted to power whenever needed.	Revenue stream through sales of the modular design of electrolysers. They are planning to produce about 10 electrolysers in 2022 and 20 more in 2023. The water purification system inside the module adds further value to the product, as tap water could be used in hydrogen generation.
Next Hydrogen Canada	The company provides scalable Alkaline electrolyser cell design to generate electrolytic hydrogen at MW scales.	In their portfolio, they have three pre-assembled product types and ready to drop in at customers' sites.	Revenue is generated by the sales of alkaline electrolysers. Further value is aimed by installing MW systems and

		They have four demonstrations planned which include three with Canadian Tire and a proof of concept with Hyundai and Kia. They claim that their electrolysers can capture the entire intermittent power generation output range. The company is also working on PEM electrolysers.	significant economies of scale to drive down the cost of electrolytic hydrogen. They also provide utility-scale dispatchable loads and hydrogen for energy storage.
Nel Hydrogen Norway	The company is an actor in the design, manufacturing, and sales of Alkaline and PEM electrolysers. They have more than 3,500 electrolysers installed and operating globally.	Their electrolysers could be scaled to match numerous applications. Atmospheric Alkaline Electrolyser is claimed to be the world's most energy-efficient electrolyser featuring a cell stack power consumption as low as 3.8 kWh/Nm^3 and up to 2.2 MW of hydrogen gas produced. Depending on the module size, it can produce up-to 8	Revenue is generated by the sales of a wide range of electrolyser portfolios. On-site renewable generation eliminates hydrogen delivery and storage. The product range addresses the needs of different types of customers. The company is running a mature electrolyser business.

		tonnes of hydrogen per day.	
Enapter Italy	The company offers Anion Exchange Membrane (AEM) electrolysers and an energy management software system, especially for laboratories, power backup solutions and residential storage units.	AEM electrolysers utilise a semipermeable membrane designed to conduct anions. Steel can be utilised for the bipolar plates instead of titanium because the atmosphere is less corrosive. Additionally, AEM electrolysers may operate with less pure water, which minimises the complexity of the input water system and enables the use of filtered tap and rainwater.	AEM electrolysers are yet to be commercialised. Their value comes from being built with relatively less costly materials and being safer to handle when compared to other types of electrolysers.

Remarks: Electrolysers can be deployed commercially in a variety of applications. The expense of the materials needed to achieve a long-life span and satisfactory performance remains a major obstacle to the mass commercialisation of PEM electrolysers. On the other hand, Alkaline electrolysers have been available and widely used at reasonable prices. A recent study by the Fraunhofer Institute suggests that the price of the 100MW alkaline electrolyser might decrease from €663/kW in 2020 to €444/kW in 2030, whereas the PEM electrolyser price of the 5MW system should decrease from €949 to €726 per kW in the same time period[30]. Nonetheless, when used with intermittent energy sources, because of their poor response times to a changing power supply, it is challenging and expensive to combine alkaline electrolysers with renewable energy sources effectively. Developers of alkaline electrolysers are working to improve this (see, for example, Next Hydrogen above). The EU has an installed electrolyser capacity target of 80 GW, and the UK aims to have 10 GW by 2030. As of 2021, Europe has a 1.75 GW capacity for electrolyser manufacturing and the European electrolyser manufacturers committed to a tenfold increase of their capacity to manufacture electrolysers to 17.5 GW by 2025[31]. Recent IEA report highlights that according to business announcements, the global capacity for producing electrolysers is expected to increase tenfold to more than 100 GW annually by 2030[32]. However, the final investment decision has yet been made for only 8% of the announced expansion of the electrolyser manufacturing capacity. The IEA also emphasises the possibility of regional electrolyser manufacturing concentration, which could potentially result in supply chain disruptions[32]. Delivering these ambitious targets seems quite a big challenge when supply chain logistics are considered. The use of expensive materials in PEM electrolysers, poor performance of Alkaline electrolysers with intermittent sources, and the lack of commercialisation of Anion Exchange Membrane and Solid Oxide electrolysers increase this challenge to considerable levels. Overall, this is an old and mature business, and spans from Value Creation to Market Diffusion.

4.5. Ammonia Production

Ammonia is a critical substance in fertiliser production and, second only to sulphuric acid, is one of the world's most produced chemicals[33]. It is produced by combining hydrogen and nitrogen in the Haber-Bosch process with a catalyst at high temperatures and pressure. 237 million tonnes of ammonia were produced globally in 2021[34]. The

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[30] Holst, M., Aschbrenner, S., Smolinka, T., Voglstätter, C. and Grimm, G., 2021. Cost Forecast for Low-Temperature Electrolysis-Technology Driven Bottom-Up Prognosis for PEM and Alkaline Water Electrolysis Systems. A Cost Analysis Study on Behalf of Clean Air Task Force.
[31] European Electrolyser Summit, 2022. Europe Clean Hydrogen Alliance, Joint Declaration. Brussels.
[32] Energy Technology Perspectives, 2020. IEA Iron and Steel Technology Roadmap.
[33] Feng, X., 2018. A sustainable, energy-saving way to make the key ingredient in fertilisers.
[34] Statista, 2021a. Production capacity of ammonia worldwide from 2018 to 2021, with a forecast for 2026 and 2030.

majority of this production is done with the SMR technique[35]. Ammonia is used in various sectors such as animal nutrition, automotive, cosmetics, electronics, healthcare, household goods nutrition, explosives, textile, plastics & resins. In the context of decarbonisation, ammonia is expected to have a significant role as an energy carrier or for energy storage. Ammonia is now the largest hydrogen consumer, accounting for around 45% of the world's hydrogen offtake[36]. Nearly all ammonia production today uses grey hydrogen, emitting around 500 million tonnes of CO_2, equal to nearly 2% of global emissions. Table 5 presents the summary of the business models of some key players in the ammonia production business.

Table 5. Summary of Ammonia Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Casale Switzerland	The company licences technology designs and constructs ammonia production plants, as well as increasing capacity at the existing plants or switching from grey to blue or green ammonia and green methanol. They offer simple plant construction, operation and maintenance.	They deliver ammonia production plants of various sizes. Natural gas is first de-sulphurised on a typical blue ammonia plant and then fed into a steam reformer. After CO_2 removal, any remaining carbon oxides are converted back to methane by reaction with hydrogen. The final synthesis gas is cooled and fed to the	Revenue stream though sales of ammonia plant facilities, ammonia, and capacity increases. Further value is captured by promising longer operating life in comparison with traditional designs. Their products have a low minimum turn-down ratio; stable operation is possible even at 20%

[35] Royal Society, 2020. Ammonia: zero-carbon fertiliser, fuel and energy store, Policy Briefing.
[36] Hydrogen Insights, 2021. A perspective on hydrogen investment, market development and cost competitiveness. Hydrogen Council, McKinsey & Company.

	Modular construction is available for remote locations.	ammonia synthesis section. Through revamping, they deliver 100% super capacity and 30% moderate capacity increases at existing ammonia production plants.	of the design load. Increased efficiency is achieved by the utilisation of 100% of the catalyst volume for reaction. Environmental value is captured by reduced NOX emissions below the limit specified by the European Union for new plants (140 mg/Nm3, calculated at 3% oxygen excess).
KBR U.S.	They offer plants to produce ammonia and fertilisers from various sources. Also, nitric acid, ammonium nitrate, and urea ammonium nitrate production technologies are provided.	The company offers both green ammonia with K-Green technology and blue ammonia with the PurifierPlus process. They also deliver a portfolio of hydrogen generated from natural gas, heavy naphtha and other feedstocks through their SMR, reforming exchanger system, and aerothermal reformer. Their	Revenue stream through the sales of green and blue ammonia and hydrogen generation plants. Their Purifier technology captures extra monetary value by reducing operational and capital expenditures. Further reduction in expenses due to their joint ammonia and methanol production with Johnson Matthey when

		ammonia can be used directly in fuel cells and internal combustion engines.	compared to separate productions. Increased supply security and efficiency and flexible operation are supplementary values. Environmental value is captured by reduced CO_2 and NO_X emissions. When compared to the typical SMR method, the total amount of CO_2 produced per ton of NH_3 is reduced by around 15%.
Stamicarbon Netherlands	A green ammonia producer. They provide technical licences and engineering specifications for the construction of compact Green Ammonia plants with predetermined capacity. They also offer help to customers with project planning, finance, and feasibility studies in	They deliver modular designs depending on the customers' specifications. In particular, small-scale green ammonia plants are delivered. Their products can be used as a renewable feedstock for fertiliser plants to manufacture the necessary nitrogen fertilisers by using	Revenue is generated through the sales of green ammonia plants and increased capacities. The extra revenue is created by selling software for operator training simulators via Stami Digital. Further value is captured by saving energy and producing safely and cost-effectively

	green ammonia production.	renewable energy sources like solar and wind.	through reduced CAPEX. Environmental value is captured by reducing waste and emissions.
YARA Norway	They are the world's leading ammonia producer. They can transport ammonia via sea, road, or rail. They supply ammonia in both compressed liquid and cryogenic forms. They particularly excelled in logistics, shipping, and storage of ammonia.	The hydrogen is produced via SMR. With over 200 terminals and warehouses around the world, they can ship and deliver more than 20 million tons of chemical nitrogen products and nitrates a year. They have a fleet of 11 ammonia carriers and 18 marine ammonia terminals with 580 kilotons of storage capacity Together with ENGIE, they will install a PV-powered green ammonia plant with battery back-up with a 10 MW electrolyser. Together with JERA, they plan to supply blue and green ammonia and	Revenue stream through mass sales of ammonia thanks to an extensive logistics network. Environmental value is captured by the abatement of nitrogen oxides (NOx) and hydrogen sulphide (H_2S), reducing SOx emissions in the maritime sector.

		optimise logistics to Japan.	

Remarks: Ammonia fits in both the midstream and downstream sectors. The number of market players and their installed capacities is increasing steadily. However, especially for green ammonia, an economy of scale is needed to reduce capital expenditure (CAPEX). According to an IEA estimation in the Sustainable Development Scenario, ammonia demand will grow by 25% by 2050[37]. According to this report, both blue and green ammonia production amounts are negligible when compared to grey ammonia[37]. Traditional (grey) ammonia is a mature business in the market diffusion phase. Blue and green ammonia are still in the Value Creation phase (Appraisal), with numerous pilot projects going on or newly introduced. For the midstream, ammonia steps forth as one of the viable options in delivering and shipping low-carbon fuels.

4.6. Hydrogen Blending with Natural Gas

There is growing pressure on natural gas companies to decrease their carbon footprint and greenhouse gas emissions (GHG). At this point, some consider hydrogen blending into natural gas pipelines an option, as burning hydrogen emits no GHG emissions. Of course, this hydrogen must be clean or low-carbon, so the carbon footprint will go down. Various pilot projects and trials worldwide test this hydrogen blending into the existing natural gas infrastructure. There have been at least 26 hydrogen blending projects in the United States since 2020[38]. The country has 1,600 miles (~2,600 km) of dedicated hydrogen pipelines and a vast natural gas network[39]. To compare with the existing natural gas infrastructure, we should remember that the U.S. has nearly 500,000 km of natural gas pipelines[40]. Nonetheless, there are serious concerns regarding this potential business model. At what percentage of hydrogen should be blended with natural gas is still debatable. A study by Energy Innovation states that Due to the chemical differences

[37] Ammonia Technology Roadmap, 2021. IEA Towards more sustainable nitrogen fertiliser production.
[38] S&P Global, 2022. Market Intelligence, US hydrogen pilot projects build up as gas utilities seek low-carbon future.
[39] Hydrogen and Fuel Cell Technologies Office, 2021. HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines, U.S. Department of Energy.
[40] Offshore Technology, 2019. North America has the highest oil and gas pipeline length globally.

between hydrogen and methane, using hydrogen in buildings poses significant difficulties and safety issues throughout the current natural gas infrastructure system[41]. For example, an NREL study suggests that less than 5 to 15% of the volume of the gas blend can be hydrogen, which is practical and allows for the storage and delivery of renewable energy without considerably raising the risks of using the gas blend in end-use equipment like homes appliances[42]. At the same time, Energy Innovation states the same safety margin as 5 to 20%[41]. Existing demonstrations and deployments range from 1 to 30%[39]. In the UK, the HyDeploy project has demonstrated up to 20% of blends being distributed to a small number of domestic consumers[43]. National Grid's Future Grid project investigates the potential of various blend levels in the national transmission system[44]. However, blending less hydrogen into the gas network will raise doubts about the reduction of carbon footprint. Even a 20% blend by volume is only around 7% by energy content, so it has a limited decarbonisation impact. Table 6 presents some of the key players and their business models.

Table 6. Summary of Hydrogen Blending Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Enbridge Canada	They offer a utility-scale Power-to-Gas (P2G) service which is capable of producing nearly 400,000 kg hydrogen per day. They also run two green hydrogen blending trials in Canada.	The first trial started with injecting 2% of hydrogen volume into the gas network to feed about 3,600 customers. This pilot produces about 18,000 kg of hydrogen per year.	Potential revenue is expected from green hydrogen sales. Environmental value is captured by emissions reduction. The first pilot yielded an abatement of 117 tonnes of CO_2

[41] Baldwin, S., Esposito, D., and Tallackson, H., 2022. Assessing The Viability of Hydrogen Proposals: Considerations for State Utility Regulators and Policymakers, Energy Innovation, San Francisco.
[42] Melaina, M. W., Antonia, O., and Penev, M. 2013. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. National Renewable Energy Laboratory (NREL), Colorado.
[43] HyDeploy, 2022.
[44] Future Grid, 2022. National Grid.

		The second trial aims to install a 20-MW electrolyser plant to feed green hydrogen through a dedicated 15 km pipeline to connect this facility to the main gas network. They aim to inject up to 15% of hydrogen volume based on ongoing engineering assessment outcomes.	equivalent from the atmosphere.
HyBlend U.S.	An initiative by the U.S. Department of Energy to research and test hydrogen blending in natural gas pipelines. They are working on research and development for materials compatibility, techno-economic, and environmental life cycle analysis.	The conditions on how the blending limits will be decided will depend on the design and condition of the existing pipeline materials (e.g., integrity, dimensions, materials of construction), as well as the design and condition of pipeline infrastructure equipment (such as compressor stations) and applications that use natural gas (e.g.,	Potential revenue stream through sales of low-carbon hydrogen through the natural gas network. Environmental value is captured by decreasing GHG emissions. Further value is aimed at increasing supply security.

		building appliances, turbines, and chemical processes, such as plastics production). The aim is to develop tools for risk analysis, opportunities and cost analysis, and life cycle and pollutant emissions analysis.	
National Grid UK & U.S.	A theoretical exploration and a pilot project, HyGrid, aims to decarbonise the gas network in Long Island to heat around 800 homes and fuel ten municipal vehicles by blending green hydrogen into the distribution system. Further trials in the UK.	Hydrogen blending in heating and transportation is trialled. UK trials are exploring injections of 2, 5 and 20% between two terminals. They also trial deblending as certain customers might ask for deblending as they only use natural gas and inject the remaining hydrogen back into the network.	Potential revenue stream by using low-carbon hydrogen in the national gas network, increased hydrogen storage. Further value is proposed by delivering a hydrogen mix for fuel-sensitive customers that require specific gas mixtures with a certain ratio. Environmental value through decarbonisation and emissions reduction.
SNAM Italy	An energy company that trialled a 5% volume of hydrogen	Using the existing infrastructure, they are working on the	The revenue stream is expected by selling hydrogen to a wide

	blending into its existing gas network to feed two industrial customers in Italy for about a month in 2019. They replicated the same trial with 10% of volume again later in 2019.	standardisation and compatibility of injecting hydrogen into their gas network. Two successful trials with 5 and 10% of volume injection have been followed by the replacement and development of assets to standards which are compatible with hydrogen.	range of customers (from industry to transport). They aim to create additional value by employing their existing hydrogen storage, transport and distribution infrastructure. Environmental value is to be captured by deep decarbonisation.

Remarks: Among the most challenging subjects regarding net-zero targets of 2050 are the heating and transport sectors. Hydrogen blending could be one of the remedies for the decarbonisation of these sectors as it is regarded as a means of transport or transmission asset for the hydrogen economy. Numerous trials have been going on worldwide with varying volumes of hydrogen mixing in the existing gas network, typically from 1 to 20%. Nevertheless, these are all pilot projects with concerns over the compatibility of the existing gas infrastructure for injecting large portions of hydrogen volumes. Moreover, the revenue and value captures are also debatable. Due to these discussions, worldwide upscaling of the hydrogen blending business is not visible.

4.7. Hydrogen Energy Storage

Hydrogen is an intermediary in energy systems, and storage is vital. Hydrogen can be stored in compressed gaseous, liquid, or metal hydride forms. Hydrogen storage can also be classified according to its size (small-scale and large-scale storage). Even though the threshold is not clear, large-scale hydrogen storage can be expected to be from tens to thousands of tonnes. Small-scale hydrogen can be stored in pressurised vessels, solid metal hydrides, or nanotubes with a high density. On the other hand, metal hydrides, chemical hydrides, liquid organic hydrogen carriers, adsorption, liquification, and compression can store hydrogen in large quantities[45]. Furthermore, underground salt caverns offer extra large-scale storage possibilities. Achieving economically viable large-scale hydrogen storage is crucially important for the success of the hydrogen economy, as storage will be an integral part of the future hydrogen infrastructure. In Table 7, we reviewed various companies to examine the range of approaches and business models.

Table 7. Summary of Hydrogen Energy Storage Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
GKN Hydrogen Germany	The company offers decentralised and small-scale metal hydride hydrogen storage systems to be used for a long period of time. Their storage capacities range from 10 kg to 250 kg.	Their metal hydride storage systems operate at low temperatures and low pressures. The modular products can be deployed as backup systems, seasonal storage and in commercial buildings, microgrids, and maritime transport. They also provide digital management software for users to remotely monitor and control the operations.	Revenue through sales of a range of modular storage units. Further value is captured by the software management tool. Environmental value is generated by using 100% recyclable metals in the production, emitting only water during the operation and lasting for decades without any losses. They claim that their storage unit has 99% capacity after 3,500 cycles.

[45] Andersson, J. and Grönkvist, S., 2019. Large-scale storage of hydrogen. International journal of hydrogen energy, 44(23), pp.11901-11919.

Linde Germany	They provide vacuum-insulated cryogenic tanks to store liquid hydrogen from 3,000 to 100,000 litres (or 200 to 7000 kg).	To get the same amount of energy, four or five times less room is needed for liquid hydrogen than for compressed gaseous hydrogen. Therefore, storing this gas in liquid form in the tanks has benefits in terms of space and efficiency. Horizontal and vertical designs are available. The containers come with active cooling systems.	The cryogenic tank technology is old and mature. It provides safe and efficient storage of liquid hydrogen. This liquid hydrogen could be used in many applications. For example, combined with fuel cells, it can be the fuel in the maritime sector.
Steelhead Composites U.S.	The company offers aluminium or polymeric pressure vessels with capacities from 6 litres to 270 litres to store compressed gaseous hydrogen with pressure options ranging from 350, 500, and 700 bar. For example, a modular 90 litre vessel can store 2 kg of compressed hydrogen.	Hydrogen Cube and Hydrogen CubePlus gas storage systems can be deployed for medium and large-scale purposes. A modular design is possible by connecting multiple pressure vessels to customers' preferences. These are swappable modules meaning that whenever empty, new pressure	The revenue stream is generated in three ways: i) Distributed grid model, where the company bills customers at a per kWh rate for electricity used and owns the cubes and fuel cells. ii) Module replacement model, where the company bills customers per kg of hydrogen used

		vessels can be connected easily. This promises a continuity of supply. Empty cubes are returned for refilling. The company claims pressure vessels are cheaper and lighter options when compared with batteries to supply the same amount of energy.	and owns the cubes, and customers buy fuel cells. iii) Customer-owned model, where the company bills customers at a fixed cost for swapping cubes with filled cubes and customers' own cubes and fuel cells.

Remarks: Hydrogen storage is a key enabler for the hydrogen economy and has received relatively little attention in the recent drive to scale up hydrogen production. The economic viability of gaseous, liquid and metal hydride storage systems are still debatable. Quite a few companies offer commercial products, especially in small-scale storage, but large-scale storage, most likely in underground salt caverns will need to be developed. Research and development and piloting activities continue for further technologies such as nanotubes. Chemical hydrides, such as ammonia and methanol, enable high-density hydrogen storage in large quantities. We should also mention that hydrogen can be stored on a large scale in underground salt caverns. Salt caverns are commonly used for natural gas storage, and there are proposals to store hydrogen as well. Underground hydrogen storage is at its early stages of development and in-depth and comprehensive work is needed to address the challenges[46]. Linde is operating one commercial salt cavern hydrogen storage in Texas, United States[47]. SABIC[48] operates

[46] Muhammed, N.S., Haq, B., Al Shehri, D., Al-Ahmed, A., Rahman, M.M. and Zaman, E., 2022. A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. Energy Reports, 8, pp.461-499.
[47] Linde, 2022. Storing Hydrogen in Underground Salt Caverns.
[48] DNV, 2021. Initial Hydrogen Strategy Report. Northern Gas Networks (lead partner), Wales & West Utilities and National Grid Gas Transmission, Leeds, UK.

three salt cavern hydrogen storages in the Teesside, UK, where each cavern has a capacity of 70,000 m^3. There are numerous similar projects introduced or suggested worldwide. However, these trials have not reached the Appraise phase. The success of the hydrogen economy is dependent on the upscaling of the storage business. Obviously, a demand push is necessary to pass through this phase and reach market diffusion.

4.8. Methanol Production

Methanol is a type of alcohol utilised in various applications, such as in fuels, paints, cosmetics and plastics. It is a trending renewable energy resource piloted and commercially used in the power, automotive, and maritime industries. Methanol can be produced by using natural gas, coal, and renewables such as municipal waste, biomass, and recovered carbon dioxide. It is regarded as a viable option as an energy carrier for distribution, transmission, and storage assets in the wider hydrogen economy. Some might even suggest a methanol economy as an alternative to the hydrogen economy[49]. Conventional methanol production and sales is an old and mature business that has reached market diffusion already. About 40-45% of global methanol production is now used in the energy sector[50]. Renewable methanol, often known as bio-methanol, is an ultra-low carbon chemical made from sustainable biomass or recycled (or waste) CO_2 and H_2 from electricity. Table 8 compiles a few leading players and business cases to investigate the potential business model.

Table 8. Summary of Methanol Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Methanex Canada	They are the largest methanol producer in the world. They have production facilities in Canada, Chile,	The process of reforming natural gas with steam and converting and distilling the	Revenue is generated by the mass sales of methanol on a global scale thanks to the vast and reliable

[49] Sonthalia, A., Kumar, N., Tomar, M., 2021. Moving ahead from hydrogen to methanol economy: scope and challenges. Clean Techn Environ Policy.
[50] Methanol Institute, 2022. The methanol industry.

	Egypt, New Zealand, Trinidad, and United States, thus serving a global demand and supply chain.	resulting synthetic gas mixture to obtain pure methanol is the predominant way that methanol is manufactured. They are now working on a project to produce methanol from excess hydrogen from steam reforming plants coupled with access to natural gas. This Geismar 3 project has a budget of $1.25-1.3 billion.	supply chain. The further environmental value will be captured upon the completion of the Geismar 3 plant, where low-carbon methanol will be produced by utilising excess hydrogen from other production plants. This plant will emit 40% less CO_2 compared to other production facilities of the company.
Enerkem Canada	The company produces sustainable methanol from solid waste. They created and patented a method for chemically extracting and reusing carbon from non-recyclable garbage.	The waste feedstock is first separated and processed. The carbon-rich wastes are converted into synthesis gas (syngas), which is purified before being treated with catalysts to make biofuels and commercial chemicals. A new plant to be operational by 2026 is expected to process some 400,000 tonnes of non-	The sales of renewable methanol generate revenue. Further value is captured by licensing the technology, supplying equipment/modules, and participating in plant equity in addition to the technology and equipment provision.

		recyclable solid waste per year and produce close to 240,000 tonnes of methanol.	
Proman Switzerland	As the second largest methanol producer in the world, the company started a joint venture with Stena Bulk to operate methanol-powered ships.	The joint venture is now operating three methanol-powered ships, and they announced to build of three more vessels. Each vessel is expected to burn some 12,500 tonnes of methanol per annum. The use of methanol as a fuel is claimed to eliminate SOx and Particulate Matter emissions, cut NOx emissions by 60%, and reduce CO_2 emissions by up to 15% on a tank-to-wake basis versus conventional marine fuels.	Revenue is generated by the mass sales of methanol worldwide. The deep decarbonisation of maritime operations will capture further environmental value through their methanol-run vessels.
Hy2Gen Germany	The company offers renewable bio-methanol produced in a large-scale anaerobic digester	They use Catalytic Partial Oxidation (ATR) to convert non-conventional short-chain hydrocarbons into	Revenue through sales of renewable methanol, e-methanol, primarily as a transport fuel.

	that converts organic waste to biogas.	syngas, followed by the conversion to methanol. The green CO_2 is recovered from biogas plants, flue gas or exhaust gas. Renewable electricity such as hydro or wind power is used to produce hydrogen and the necessary energy input for the methanol production processes.	

Remarks: Methanol, as an energy asset for distribution and storage, as well as for transport fuel, is getting more and more attention. There are already well-established supply chains for methanol (albeit largely produced from fossil fuels), and it is being demonstrated for new uses, particularly as a shipping fuel. Methanol removes SOx and particulate matter emissions while reducing NOx emissions by up to 80%, and renewable methanol can reduce CO_2 emissions by up to 95% compared to traditional fuels[51]. Synthetic methanol production from solar power is still in the Research & Development phase. Bio methanol production, on the other hand, has successfully demonstrated numerous pilots worldwide and is now beginning its upscaling journey. The environmental benefits of using methanol in energy systems are quite convincing. When we look at the existing and proposed production plants, we can see that renewable methanol production will steadily increase in the coming years. The substance might be a viable alternative to aviation and maritime fuel. However, the business is still in its Appraisal and Upscaling phases and needs heavy demand from the market.

[51] Methanol Institute, 2022. The methanol industry.

4.9. Pipelines

Regardless of how hydrogen is produced, it must be delivered if it is not produced directly at the application site. This may be accomplished with several methods, such as high pressure or liquefied hydrogen in specialised containers or with liquid organic hydrogen carriers. On the other hand, hydrogen pipelines are better suited for large-scale, continuous hydrogen demands over moderate distances (up to around 2000 km, perhaps). The investment costs, or the initial capital expenditure for laying new dedicated hydrogen pipelines, are a substantial barrier to building new hydrogen pipeline infrastructure. Therefore, the industry and markets are seeking ways to repurpose the existing infrastructure for hydrogen use. Table 9 outlines various companies to examine their contemporary business models.

Table 9. Summary of Hydrogen Pipelines Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Air Products U.S.	The company has the world's largest hydrogen pipeline network, a total of 1,100 km worldwide, including the Gulf Coast system in the USA, stretching over 600 miles (~965 km) and linking 22 hydrogen plants with a daily capacity of more than 1 billion cubic feet per day (~1.3 million Nm^3/hr) of hydrogen.	The hydrogen pipeline is built in the Gulf of Mexico region in the United States. This project aims at reaching economies of scale and thus drive down the costs, supporting the future growth of hydrogen use in the region and providing a reliable alternative for large customers to be their primary and/or backup energy source.	The pipeline coupled with the hydrogen production plants promises the refinery and petrochemical consumers' continuity of supply in case a disruption with the traditional energy networks takes place. Value is created by building, owning, and operating hydrogen pipelines.

German Gas Transmission System Operators Germany	A consortium of German gas transmission system operators will initiate the H2-Startnetz 2030 project, which aims to construct a 1,200 km long hydrogen grid in Germany. Only 100 km of this network will be newly built hydrogen pipelines, whereas the rest will be the existing natural gas network repurposed.	The company is taking part in the rededication of an existing natural gas pipeline to be used for hydrogen transport in the Ruhr area. This planned grid has a length of 130 km, of which 118 km is repurposed gas pipelines and 12 km will be newly built hydrogen pipelines.	Value is aimed to be captured by supplying green hydrogen in large volumes to the large customers in the industrial areas in Germany. Security of supply via a dedicated pipeline network and decarbonisation of the heavy industrial processes are further values that will be created. Revenue through the transmission of hydrogen.
Smartpipe Technologies U.S.	The start-up offers a pipeline replacement technology that pulls a composite internal pipeline liner through an existing pipeline to increase structural integrity and allow for better monitoring.	It is a non-intrusive trenchless pipeline replacement technology and inserted in the existing pipelines, Smartpipe can also be laid as a fully structural, stand-alone high-pressure pipeline. Smartpipe meets the U.S. Hydrogen Piping Standard B31.12,	Revenue through sales of their technology as a low-cost way to repurpose pipelines for hydrogen.. The pipelines can be manufactured and inserted at a speed of 1 mile (1.6 km) per day. The pipes can operate under high pressure and meet

		Code Case 200. The pipelines can be manufactured and retrofitted according to the customers' needs.	the hydrogen transport standards in the United States.

Remarks: The hydrogen economy naturally necessitates a robust hydrogen infrastructure. Pipelines are the initial options for delivering large volumes of hydrogen, and there is already over 5000 km of hydrogen pipelines in operation worldwide. However, high initial investment costs for newbuild hydrogen pipelines leads to a strong interest in repurposing or rededication of existing gas infrastructure. The compatibility of pipelines, compressors, fittings, and other components in the existing gas network for the transmission of gaseous hydrogen or natural gas with a high hydrogen content raises concerns about hydrogen embrittlement, fracture toughness, and corrosion. The European Hydrogen Backbone study estimates that the hydrogen network in Europe can reach a length of about 53,000 km by 2040 with an estimated required investment of €80-143 billion[52]. According to the same estimate, 40% of the network will be dedicated to hydrogen pipelines, and 60% will be repurposed natural gas network[52]. Nevertheless, we should stress that this is a massive amount of investment, and it is highly questionable whether this can be realised or not, and each pipeline segment will need to be justified by a suitable business case.

4.10. Transport of Liquid Hydrogen by Ship

Together with storage, transport and distribution of hydrogen are troublesome subjects for planners and businesses as the nature of hydrogen transport differs from traditional commodities such as natural gas, LNG, or petroleum. The use of ships, especially for the transport of large amounts of hydrogen, is one of the prominent options for long-distance transportation. One of the major challenges that shipping liquid hydrogen over

[52] European Hydrogen Backbone, 2022. A European Hydrogen Infrastructure Vision Covering 28 Countries, April 2022.

long distances is the need to keep hydrogen at -253 Celsius while being transported. Hydrogen can be kept in liquid form in specially designed ships. The transport of hydrogen is also somewhat similar to the liquefaction of natural gas and transporting it in the form of LNG, but in this new case, the temperature required for transport is almost 100 degrees colder than for natural gas. To transport hydrogen at these temperatures, specific transport tanks and vessels must be produced. Alternatively, hydrogen can be shipped in the form of compressed hydrogen or derivatives such as ammonia or methanol, which have higher energy densities. The global trade of shipping hydrogen as cargo is expected to grow. Table 10 presents numerous key players and business models in the hydrogen shipping business.

Table 10. Summary of Transport of Liquid Hydrogen by Ship Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Kawasaki Japan	The company offers various hydrogen storage and transportation solutions. Together with Iwatani Corporation, Shell Japan Limited, and Electric Power Development (J-POWER), they launched Suiso Frontier, the world's first liquefied hydrogen carrier with a capacity of 1,250 m3.	The vessel is certified by the International Maritime Organisation and can carry 75 tonnes of liquefied hydrogen in one trip. The liquefied hydrogen is produced by cooling gaseous hydrogen to minus 253°C, therefore, reducing its volume to 1/800. In early 2022, the ship carried a liquified hydrogen cargo from Australia to Kobe, Japan. For the pilot phase,	The revenue stream is expected from carrying hydrogen as cargo over long distances. There is also a potential future market for hydrogen exports and imports.

		carbon credits were purchased for the CO_2 produced, and a CCS system will be implemented for the commercial phase to export and transport blue hydrogen in the future.	
Korea Shipbuilding & Offshore Engineering South Korea	They are planning to pilot a concept ship with a capacity of 20,000 cubic metres to transport liquified hydrogen overseas.	The company is preparing for the hydrogen shipping trial in 2025. The cargo size, 20,000 cubic metres, is expected to increase over time. Around 20 ships with a 20,000 cubic meters capacity are expected to be built in the decade starting in 2030. Depending on the market demand, another 200 vessels with 170,000 cubic metres capacity are expected to be built after 2040.	The future revenue stream is expected to be generated by the sales of large-scale liquid hydrogen carriers. Extra value capture is aimed by capturing the leaked hydrogen from tanks and turn it as a fuel to generate power with hydrogen fuel cells.

Remarks: Transporting hydrogen is a huge challenge and adds significantly to the supply chain cost. In addition to carrying with trucks and through pipelines, shipping hydrogen overseas over long distances is one of the options being experimented with and trialled by the industry. For now, the business is in its very early development stages.

Only one successful trial took place recently, which was carrying liquified hydrogen as cargo from Australia to Japan. Another trial is expected in South Korea. The odds seem to be great in this business opportunity as the economy of scale is too far away. Whether or when commercialisation can be achieved is highly questionable. More promising alternatives could be shipping hydrogen derivatives such as liquid ammonia, methanol, and toluene-methylcyclohexane (MCH)[53].

4.11. Cement Production

Cement production is an energy-intensive industry where CO_2 emissions in cement plants are sourced mainly from combustion and calcination. Combustion-generated emissions have resulted from fuel use and consist of around 40% of the total emissions. Calcination-generated emissions, consisting of the remaining 60%, are due to the raw materials heated to around 1400 ^oC and CO_2 released from the decomposed minerals. Cement production accounts for around 8% of the world's CO_2 emissions[54]. Global Cement and Concrete Association (GCCA) aims to decrease the CO_2 emission caused by cement production by 20% by 2030[55]. Reducing the demand for cement is not expected in the near future. Therefore, deep decarbonisation of the cement industry is being discussed. Many countries use fossil fuels such as coal in the cement production process. However, the utilisation of low-carbon fuels is increasing especially in European Union countries[56]. At this point, hydrogen is seen as one of the low-carbon alternatives to cut down emissions in cement production. Table 11 summarises various players and their business cases that utilise hydrogen in the cement industry.

Table 11. Summary of Hydrogen use in Cement Production Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture

[53] Patonia, A. & Poudineh, R., 2022. Global trade of hydrogen: what is the best way to transfer hydrogen over long distances? The Oxford Institute for Energy Studies, OIES Paper: ET16, September 2022.
[54] Nature, 2021. Concrete needs to lose its colossal carbon footprint.
[55] GCCA, 2021. Concrete Future. The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. London, UK.
[56] El-Emam, R.S., Bagria, N. and Gabriel, K.S. (2021). Integration of Cement and Hydrogen Industries for Canada's Climate Plan: Case Study. In: Proceedings of the 8th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'21). Canada.

HeidelbergCement Germany	The company trialled the use of hydrogen in commercial-scale cement manufacture at the Ribblesdale plant in the UK.	As a commercial demonstration, hydrogen is used in the kiln process instead of coal. In addition to hydrogen, the fuel mix also included biomass and plasma energy. This fuel consists of almost 39% hydrogen, 12% meat and bone meal (MBM) and 49% glycerine. The company claims that about 180,000 tonnes of CO_2 could be avoided at the same plant each year by just using this fuel mix.	UK BEIS funded the trial as part of its Industrial Fuel Switching Competition programme, which had a budget of £3.2 million. Environmental value is to be captured by deeply cutting CO_2 emissions in cement production.
CEMEX Spain	The company is using hydrogen commercially as part of its fuel mix in all of its plants in Europe and is now extending this to all of its plants in the rest of the world.	The company successfully used hydrogen in the fuel mix at the Alicante Cement Plant in Spain in July 2019 and then extended this to all its European plants in 2020. The company recently invested in a British start-up,	Using hydrogen in the fuel mix is a part of a US$40 million investment program. The technology is now integrated into almost all of their plants globally. Environmental value is captured by reducing the carbon

		HiiROC, a clean hydrogen production start-up that uses thermal plasma electrolysis to convert biomethane, flare gas, or natural gas into hydrogen.	emissions in cement production.

Remarks: Using hydrogen in cement production is highly discussed by many; however, the number of commercial applications is rather limited. The existing trials show that hydrogen is being evaluated as an additional asset in the overall low-carbon fuel mix instead of using it as the stand-alone fuel source. Decarbonisation of cement production is a must to achieve Paris agreement targets. A feasibility study prepared for the UK Department for Business, Energy and Industrial Strategy (BEIS) discusses several scenarios of fuel mix at the kiln (thermal fuel use) and calciner processes[57]. A scenario suggests that using a kiln mix of 50% hydrogen and 50% biomass and an 83.3% biomass with 16.7% plasma in the calciner removes fossil fuel CO_2 completely by leaving only process CO_2 from the breakdown of raw materials and CO_2 from biomass fuels (BEIS, 2019). Obviously, a clean-fuel mix promises a lot to bring down emissions; however, the application of this technology is at its early stages. We should also mention that utilising just CCUS to decarbonise cement production is also an option[58]. Hydrogen use in the cement production business is still in the Develop phase and needs many more industry players to adopt it and commercially demonstrate that the use of hydrogen is a viable option for tackling emissions.

[57] BEIS, 2019. Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility. London, UK.
[58] Abdelshafy, A., Lambert, M., Walther, G., 2022. The role of CCUS in decarbonizing the cement industry: A German case study. Energy Insights 115, The Oxford Institute for Energy Studies, May 2022.

4.12. Engineering Services for Hydrogen Infrastructure

Constructing an infrastructure for a low-carbon economy is a challenge when considering to capital expenditure needed. Sustaining this low-carbon energy system hardens operational profitability since carbon-free or low-carbon technologies require additional operational processes and maintenance investments. At this point, several companies offer engineering and consultancy services for hydrogen projects to install, operate and maintain plants and infrastructure. Table 12 compiles some of the business models of engineering services for hydrogen infrastructure.

Table 12. Summary of Engineering Services for Hydrogen Infrastructure Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Worley Australia	They offer maintenance, modifications and operational services to hydrogen-based customers to ensure risk and cost reduction in their projects.	The company delivers feasibility studies, plant designs, consultancy for technical and market analysis, engineering, procurement and construction, and technical council for numerous hydrogen-related projects all around the world.	Revenue through consultancy services in a broad range of technical and economic subjects.
Ricardo UK	An engineering and environmental consultancy company offering technical and non-technical solutions for hydrogen	The company has a broad range of services, including hydrogen powertrain development and integration,	Revenue is captured by a broad range of engineering and consultancy services for hydrogen-related projects, investments and infrastructure.

	operations and infrastructure. They deliver services from policy development to infrastructure feasibility through to the implementation and integration of hydrogen-based technologies.	vehicle optimisation, including thermal management and power distribution, simulation and modelling, fuel cell system and hydrogen engine test facilities, retrofit solutions, leak detection, cost reduction, lifecycle analysis, testing and development, technology road mapping and market forecasting, regulatory and policy analysis, market and technology studies, hydrogen fuel cell technology strategy, product development and market entry strategies, scenario planning for decarbonisation, the total cost of ownership and return on investment modelling,	

		infrastructure analysis, air quality, supply chain development, data collection, and technical due diligence.	
Lean Hydrogen Spain	They are a green hydrogen project engineering and consulting company.	They offer support throughout the bidding process, market research, key player analysis, and studies of industrial safety and standards, in addition to techno-economic feasibility analysis for electrolytic hydrogen projects. They also deliver design solutions for the construction, commissioning, operations, and maintenance of green hydrogen plants.	Revenue stream through engineering service for hydrogen production plants and hydrogen refuelling stations, hydrogen project consulting, assistance in environmental permits and procedures, and control systems programming.

Remarks: The business opportunity with engineering and consultancy services for hydrogen infrastructure can be extended into strategy and planning, project development or pre-development, and advisory services for operations and maintenance. Engineering services firms have similar revenue streams, with more distinctions occurring in pre-development phases and the scope of advisory processes, including due diligence and risk management. Apart from these, commercial value capture is based on predictive maintenance and discovering opportunities for bottom-line improvements. Further sources of revenue capture are feasibility studies with technical and economic scope, advisory support for technology adoption decisions, and identification of cost efficiencies and benefits regarding capital and operational costs. As the number of hydrogen projects and operational plants increases steadily worldwide, the need for such services will increase accordingly. We believe the business has already completed its Appraisal phase and is now in Upscaling. Whether this business will reach market diffusion or not totally depends on the overall commercial success of the hydrogen economy.

4.13. Fuel Cells

A fuel cell is an electrochemical medium that is utilised for generating electricity. Fuel cells generate electricity by using chemical bonding energy between hydrogen and oxygen atoms. The only wastes are water and heat. Stationary fuel cells can be used for the cogeneration of heat and power, distributed power generation, backup power, and remote location power. Some might claim that almost all portable devices, including hand-held devices and portable generators, that traditionally utilise batteries can theoretically be powered by fuel cells. Additionally, fuel cells can power contemporary transportation, including cars, trucks, buses, and ships, as the only power source or as a complementary or auxiliary power source[59]. When used with low-carbon hydrogen, fuel cells promise to reduce CO_2 emissions and provide a reliable energy source radically. Some of the key issues regarding the hydrogen fuel cells can be summarised as weight and volume concerns, efficiency, durability, refuelling time, cost, the lack of standards, life cycle and efficiency analyses[60] . Table 13 summarises a few business cases to examine some business models.

Table 13. Summary of Fuel Cells Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture

[59] U.S. Department of Energy, 2008. Hydrogen Fuel Cells.
[60] Energy.Gov, 2022. Hydrogen Storage Challenges.

Ballard Canada	They offer fuel cells and commercialise them for different use areas such as buses, trucks, trains, ships, backup power at critical infrastructure, and grid-scale renewable energy storage.	The company promises high fuel efficiency, low noise and vibration, compact size, quick response to changes in electrical demand, and modular design with its products. Together with the vertical integration of Membrane Electrode Assembly and stack design, the company can provide fuel cell solutions for a wide range of customers' needs from 5kW to 200kW.	Revenue is generated by the sales of fuel cells. The company has already delivered 850MW of fuel cell stacks, modules and systems to its customers. The modular design makes it possible to reach a broad range of customers with different use requirements, from transport to stationary power solutions.
Plug Power U.S.	The company provides hydrogen and fuel cell solutions through its end-to-end green hydrogen ecosystem, including production, transportation, storage & handling, dispensing, and usage of hydrogen to various markets such as zero-emission on-road vehicles, data centres,	ProGen is a fuel cell engine designed for use in motive and stationery products. GenDrive is offered for material handling applications, and GenSure is a backup power solution for low and high-power stationary applications.	Revenue through the sales of fuel cells. They are expanding their customer portfolio towards on-road vehicles, robotics, and data centres.

	robotics, and microgrids.		
FuelCell Energy U.S.	The company provides on-site power plants that use natural gas or renewable biogas as input and then reform it inside a fuel cell into hydrogen, which then electrochemically reacts with air to generate power and heat.	The product SureSource enables on-site and large-scale hydrogen generation to either power transportation or industrial applications or provide excess hydrogen for other uses. The most trivial advantage is to produce and consume hydrogen in urban locations. A typical 1.4 MW module emits 445 kg/MWh of CO_2 (236-308 kg/MWh with heat recovery). (2019 U.S. national average: 401 kg/MWh).	Revenue is generated by the sales of SureSource, which produces hydrogen and then clean water and electricity in urban locations. SureSource is commercially used as a part of a 2.3MW project with Toyota Motor Corporation in California.
HyAxiom U.S.	They provide single-fuel cell applications for commercial buildings and multi-fuel cell installations for data centres, industrial facilities, and microgrids.	They have a range of scalable and modular products that can fit various needs. PureCell Model 400 Hydrogen is a hydrogen energy solution generating 460 kW of clean	Revenue through sales of PureCell Model 400 Hydrogen fuel cell as a clean and reliable power and heat source. 50% electricity and 35% heat comprises a

		energy and water. This system also produces 1.7 million BTU/hour of usable heat and is able to run off of green hydrogen.	total of 85% overall efficiency.

Remarks: Hydrogen fuel cells can generate electricity at an efficiency of 40-60%, which is higher than a conventional combustion-based power plant's typical efficiency of 35%[61]. However, we should stress that the power conversion efficiency is around 99% with Li-Ion batteries, so in many applications, batteries will be preferred. Of course, recovering the output heat will enable increasing the overall fuel cell efficiency depending on the product and application. Fuel cells have certain advantages, such as being emissions-free (or low emissions depending on the hydrogen source), using an infinite source of energy (electrolytic hydrogen), promising a high range for transport solutions, and fast refuelling capabilities. However, we should also underline some disadvantages, such as lower efficiency compared to batteries, highly flammable hydrogen, poor infrastructure for refuelling purposes, and very high costs. We can see that the supply side of the fuel cells is working quite well as the technology is now mature and well known. Nonetheless, the demand for fuel cells is rather limited even though the application areas are quite broad. The business is at its Upscaling phase. A boost in demand is necessary before it reaches the market diffusion phase. Volvo Group reaffirms our observation by stating that the hydrogen fuel cell business is some years away before it becomes commercially available[62].

4.14. Glass Production

Being an energy-intensive sector, the glass manufacturing industry plays a crucial role in mitigating the adverse effects of climate change and to meet the goals set by the global framework of the Paris Agreement. Despite this energy-intensive process, since the

[61] U.S. Department of Energy, 2008. Hydrogen Fuel Cells.
[62] Volvo Group, 2022. What are hydrogen fuel cells?

volumes of glass delivery are lower than those of other energy-intensive products, the share of energy consumption in the glass industry is comparably low. U.S. Energy Information Agency reports that the sector accounted for 1% of total industrial energy use in the U.S. in 2018[63]. The decomposition of the energy input was natural gas (73%) and electricity (24%), and other (3%)[63]. Another study from the UK highlights that glass manufacturing is causing only 3% of the UK industry's GHG emissions[64]. Many stakeholders in the glass market feel the responsibility for finding the most cost-efficient and reliable ways of producing glass without emitting CO_2. At this stage, hydrogen steps forth as a green or low-carbon heating alternative to drive this shift. However, switching from traditional carbon-intensive sources to hydrogen is not an easy task when considering old equipment tailored for natural gas might not be directly suitable for hydrogen use in the manufacturing process. Surely, the cost of this transformation is another big challenge. Table 14 presents the business models of some key players in using hydrogen in the glass production industry.

Table 14. Summary of Glass Production Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Air Products U.S.	They offer hydrogen for atmosphere control to prevent oxidation, improving efficiency in cutting, polishing, heat treating, and melting and softening applications in the glass industry.	Their hydrogen can be used to supplement or replace air-fuel combustion applications for increasing heat transfer and achieving more efficient glass cutting and polishing,	Hydrogen sales through bulk deliveries or pipelines, on-site generation plants and storage systems. For the glass industry, further value is captured via improved efficiency in cutting, polishing,

[63] EIA, 2018. U.S. Energy Information Agency, Glass manufacturing is an energy-intensive industry mainly fueled by natural gas.
[64] Griffin, P.W., Hammond, G.P. and McKenna, R.C., 2021. Industrial energy use and decarbonisation in the glass sector: A UK perspective. Advances in Applied Energy, 3, p.100037.

		annealing, tempering, strengthening, and toughening, faster melting or softening of glass, and preventing negative reactions like the formation of glass defects and helping to protect the chambers and/or equipment.	heat treating, and melting and softening applications.
HyGear Netherlands	They offer on-site small-scale hydrogen generators to glass manufacturers. They provide products for gas recovery of the polluted gas mixtures from the tin bath in float glass production. They also offer on-site nitrogen generation necessary for float glass production.	Hy.GEN is a small-scale SMR-type hydrogen generator that can be installed at the customer's site. Hy.RECmix recovers a portion of hydrogen and nitrogen from the output gas and reuses this reductive gas mixture in the manufacturing as input. In the process of making float glass, this reductive gas mixture of hydrogen and nitrogen is required over the tin	A revenue stream is generated by the sales of products such as Hy.GEN and Hy.RECmix. Further environmental value is captured by reducing GHG emissions. Electrolytic hydrogen generation is also available for customers through Hy.GEN-E. This means further reductions in emissions also improve supply security by being on-

		bath to stop the glass from oxidising.	site self-sufficient energy generation.
Pilkington UK	They conducted the first trial of using hydrogen in the architectural glass production process in the world in 2021.	By switching from natural gas to hydrogen, they trialled running the float furnace to heat it around 1,600 degrees centigrade. This three-week trial on the float glass line made use of around 60 road tankers of hydrogen. This was a part of UK's HyNet Industrial Fuel Switching initiative, which aims to cut 10 million tonnes of carbon per year by 2030.	Expected value capture from the use of hydrogen as a low-carbon fuel. Being a government-supported trial project, they received £5.3M funding through Energy Innovation Programme in 2020.

Remarks: The idea of using hydrogen in the glass industry has emerged, but the number of applications and demonstrations is rather limited. Glass manufacturing is a complex process with various steps. Hydrogen might be used in furnaces where around 20% of the whole energy consumption occurs. Whether hydrogen can be used in these furnaces as the only energy source or a hybrid design is better is still debatable. Increasing NOx emissions with increasing temperatures in the production process is another concern regarding hydrogen use[65]. SCHOTT from Germany is about to start its own trial of hydrogen use in glass manufacturing with a €714,000 R&D budget, of which €338,000

[65] Energy: Using Hydrogen for Glass, 2022. Andrew Keeley and Mike Haden, The Chemical Engineer.

came from the European Regional Development Fund[66]. We can clearly see that R&D activities are still going on, and a self-sustaining business is not viable yet. This means that the business case is still in the Value Proposal and Value Creation phase, and there needs to be much more effort before the business case goes into the upscaling phase. We should stress that the claim of "improving efficiency in cutting, polishing, heat treating, and melting and softening applications in the glass industry" needs further evidence and substantiation.

4.15. Hydrogen Certifications

As plans for the clean hydrogen economy develop, many players are developing projects along with a variety of specifications. This trend brings regulatory challenges. There is a need for standardisations and hydrogen certification mechanisms to provide hydrogen stakeholders with an independent and globally recognised verification system for sustainable and carbon-neutral futures. This provides an opportunity for companies to develop certification systems. Table 15 presents various companies and their business models in the hydrogen certification field.

Table 15. Summary of Hydrogen Certifications Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
TÜV Rheinland Germany	The company offers testing and carbon-neutral hydrogen certifications, including green hydrogen and green ammonia certificates.	Standard H2.21 is a Carbon-Neutral Hydrogen certification. The status is issued if Corporate Carbon Footprint, which is measured by the amount of greenhouse gases emitted resulting	Revenue is generated by standardisation and certification sales. The hydrogen customers capture further value by acquiring an independent and internationally recognised

[66] SCHOTT, 2022. SCHOTT developing climate-friendly glass production using hydrogen.

		from the operation of a company per time period or Product Carbon Footprint, which is measured by the amount of greenhouse gases emitted associated with a product's life cycle or life cycle stage is fully offset by appropriate mitigation or Carbon Capture and Storage measures.	verification of the climate neutrality of their hydrogen.
CertifHy EU	They provide hydrogen certification schemes across Europe that constitute a basis for customers to track hydrogen flows and their environmental impacts.	CertifHy certification enables customers to track hydrogen's origin and environmental attributes. According to the European Renewable Energy Directive, they are developing an EU Voluntary Scheme for the certification of hydrogen as Renewable Fuel of Non-Biological Origin. CertifHy GO scheme grants a tradable value to	The scheme has been initiated at the request of the European Commission and is financed by the Clean Hydrogen Partnership. Current certifications are given in Europe; however, they are planning to expand globally. The cost of certifications varies depending customer's profile. The certificate expires automatically

		renewable and non-renewable hydrogen.	12 months after the end of the production period for the related production batch. Revenue is generated by issuing certificates.
Intertek UK	They provide testing and certification of hydrogen refuelling stations, hydrogen fuel components and systems, including dispensing, compression, and storage systems, electrolysers, chiller, reformers, and stationary fuel cell systems.	The company offers Atmosphere Explosibles (ATEX), International Electrotechnical Commission for Explosive Atmospheres (IECEx) and Electrical Testing Labs (ETL) certifications. ATEX is a mandatory certification for all products to be sold across Europe. IECEx means that products must go through a monitored process by the International Electrotechnical Commission to ensure that they meet the minimum safety requirements in Europe, Canada, Australia, Russia,	The company's certifications ensure the customers access potential markets in Asia, Europe, and North America.

		China, the United States and South Africa. ETL means that products have been tested to set safety standards in North America.	

Remarks: The business opportunities in the hydrogen economy are expanding into the transportation, chemical, heavy industries and power generation sectors globally. There is an emerging need for safety standardisations of hydrogen and its derivatives as the substance is flammable and explosive. Furthermore, as there is a lack of internationally accepted metrics for low-carbon hydrogen and confusion with colour coding, certification mechanisms are needed worldwide. As the business model for testing and certifications has the nature of "renewal" after certain periods, the business can generate a self-sustaining revenue stream if a sufficient number of customers can be reached. The hydrogen certifications business seems to have completed its Value Creation phase, but the upscaling will require time as the certifications might differ regionally in the world. A globally accepted standardisation of low-carbon hydrogen and a certification mechanism surely will gain a lot of momentum in terms of generating a sound and sustainable revenue stream.

4.16. Hydrogen Fuel Stations

Developing new hydrogen technologies results in new business models and transformation in existing sectors. Hydrogen fuel stations are such examples. While they resemble traditional fuel stations initially, the process behind them differs from the conventional stations. They have an intermediate step to transform stored hydrogen into high-pressure hydrogen for refuelling, which requires additional equipment. They are divided into two groups depending on whether the hydrogen they provide is gaseous or liquid. Compared to fossil fuels, the advantages of hydrogen fuel for the transportation sector include comparable recharge durations and driving ranges.

Consumers are looking for zero-emission vehicles which have performance comparable to today's fossil-fuelled vehicles. Like standard fuel infrastructure, hydrogen infrastructure can be constructed at any gas station. Hydrogen fuel stations represent the hydrogen trade's final process before reaching end users, especially in the transport sector. There are various concerns and challenges regarding the hydrogen fuel stations. Fire and explosion, hydrogen leak in piping, leak in electrolyser, leak in storage tank, leak at breakaway fitting, compressor failure, hose pressure rating verification error, improper fill speed at fuel dispenser, incorrect check valve installation, and vehicle crashing into refuelling station could be listed as some of these concerns[67]. Table 16 summarises some of the business models of hydrogen fuel stations.

Table 16. Summary of Hydrogen Fuel Stations Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
HTEC Canada	They construct and operate hydrogen fuel stations for fuel cell transport units in Canada and United States.	The company is actively running four stations as businesses, with two more in late-stage development and eight in early-stage development. The fuel station in California has its own electrolyser with a capacity to produce 40 kilograms of hydrogen per day. They also offer modular hydrogen	A revenue stream is generated by the sales of hydrogen as fuel at the stations. On-site green hydrogen generation and storage units add further value added to the business. They develop, own, and operate hydrogen production facilities, distribution systems, and fuel stations.

[67] Vereš, J., Ochodek, T., and Koloničný, J, 2022. Aspects of Hydrogen Fuelling Stations. Chemical Engineering Transactions Vol. 91.

		storage systems for transportation and/or ground storage.	
Linde Germany	They offer a full project lifecycle for the hydrogen fuel stations from planning and design through build and commissioning to service and maintenance.	The company has already built more than 200 hydrogen refuelling stations worldwide. They deliver both gaseous and liquid refuelling with their Ionic Compressor and the Cryo Pump technologies. They also developed FuelBox, an all-in-one transportable hydrogen refuelling station with an intermediate H_2 storage tank and dispenser. This unit is 12 m^2, ready-to-run and can be deployed anywhere depending on the need in a short time.	A revenue stream is generated by the sales of project lifecycle services (LCS) as well as fuel stations. Offering both liquid and gaseous solutions and portable units adds further value to their business.

Remarks: The future of the hydrogen fuel station business depends on the success of hydrogen use in the transport sector. While the number of companies offering hydrogen refuelling stations is increasing steadily, a radical boost in the number of stations is still not on the horizon. According to statistics from 2021, Japan has the highest number of fuel stations in the world (154), followed by South Korea (112) and Germany (91)[68]. The Japanese government announced a plan to increase this number to 1000 by the end of 2030[69]. Surely these numbers are dwarfed when compared to the existing and future projections of the electric vehicle charging stations. The number of public EV charging stations reached 1.8 million worldwide by 2021[70]. About 500 000 EV charging stations were installed just in 2021[70]. The hydrogen fuel station business is still at its Value Creation phase, and Upscaling seems to require some more decades.

4.17. Hydrogen Use in the Transport Sector

The transportation sector was responsible for around 20% of the CO_2 emissions globally in 2021[71]. Of this, aviation stands for 8%, shipping 11% and rail 3%, where around 78% of the transport sector emissions have resulted from road surface transport[71]. To achieve the Paris Agreement targets, a radical transformation from fossil fuels to clean fuels must be realised in the transportation sector. To experience this vast transformation, hydrogen-fuelled cars like electric cars are thought to be a viable alternative to petrol-fuelled cars. Many companies are working in this field, and the resulting products are generally based on the presence of fuel cell technology in vehicles or the use of hybrid systems. In hybrid systems, diesel fuel is generally used together with hydrogen. Efforts are also being made to make the internal combustion engine fully hydrogen-fuelled, but it is a bit more difficult to produce fully hydrogen-powered internal combustion engines because special injection systems have to be developed for these engines[72]. Another alternative is the use of fuel cells in vehicles. This technology stores hydrogen in special hydrogen tanks in transportation vehicles. These vehicles are electrically powered, so they have an electric motor. Fuel cells power up like batteries but do not need to be recharged. As long as fuel is supplied, these cells continue to produce electricity and heat. Various businesses emerged in almost all aspects of the hydrogen-fuelled transport sector. Table 17 summarises some of the key actors and their business models.

[68] Statista, 2021b. Number of hydrogen fueling stations for road vehicles worldwide as of 2021, by country.
[69] Hydrogen Central, 2021. Japan Targets 1,000 Hydrogen Stations by End of Decade.
[70] Global EV Outlook, 2022. Trends in charging infrastructure.
[71] Statista Research Department, 2022. Transportation emissions worldwide - statistics & facts.
[72] Nebergall, J., 2022. How do hydrogen engines work? | Cummins Inc.

Table 17. Summary of Hydrogen in the Transport Sector Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
ZeroAvia UK	The company provides zero-emission powertrain and hydrogen-electric engines for aviation.	They replace conventional aircraft engines with hydrogen-electric powertrains. They trialled hydrogen fuelled flights from 20-seat regional trips to over 100-seat long-distance flights. Green hydrogen stored in tanks is converted to electricity in flight using a fuel cell, which then powers the electric motors.	Revenue is generated by the sales of hydrogen-electric powertrains. The company claims that hydrogen-electric powertrains offer 90% lower life cycle emissions compared to turbines, 60% lower powertrain operating costs compared to turbines, and 75% lower hourly maintenance costs.
Alstom France	Coradia iLint is a commercial hydrogen-powered passenger train trialled in Germany in 2018. The train has travelled more than 200,000 km since then.	The train is powered by hydrogen fuel cells. Together with Linde, Alstom built the world's first hydrogen filling station for passenger trains in Germany. A total of 14 hydrogen fuel cell trains will be built and put on rails in Germany in 2022.	Revenue through the sales of hydrogen trains. Environmental value is captured by lowering emissions in rail transport. The hydrogen fuel station promises continuity of supply.

New Times Shipbuilding China	The company delivered the world's first ammonia-ready ship Kriti Future. The ship is running on conventional fuel, but it is convertible to use ammonia as the main fuel.	The Kriti Future received the American Bureau of Shipping's classification of ABS Ammonia Ready Class 1. According to the regulations, anhydrous ammonia is extremely harmful to aquatic life, so relief or direct discharge to seawater is to be avoided.	Value is captured by the use of ammonia as a high-density and low-carbon shipping fuel in maritime operations.
Hyundai South Korea	They offer several hydrogen-powered road transport vehicles.	NEXO series cars make use of fuel cells with a five-minute fill-up time and 413 miles (666 km) of range. The car has a maximum speed of 111 mph (179 kph). XCIENT is a hydrogen-powered fuel cell truck. The truck's fuel cell delivers 180 kW of power and a driving range of 400 km. XCIENT fuel cell does not require urea and engine oil which	The revenue stream is generated by the sales of hydrogen cars and trucks. Renting is also offered in some countries. The company claims that its second-generation fuel cell technology has the highest system efficiency in the world, consuming 1kg of hydrogen per 100km.

		makes it superior to diesel engine trucks.	

Remarks: The use of hydrogen in road transport is not new, as the first hydrogen car was introduced in 1966. Similarly, the first hydrogen fuelled aircraft (Tupolev 155) was successfully tested in the Soviet Union back in 1988. The upscaling of the business has not taken place since then. Perhaps we should mention the factor of alternatives and competition here. The use of battery electric vehicles in road transport has achieved momentum and has already reached the commercialisation and market diffusion phase. So, to achieve a low-carbon road transport transition, hydrogen has a strong competitor and probably has already lost this competition. In comparison, the picture differs in aviation and maritime operations. For long-haul and heavy-duty road surface transport, hydrogen might stand a chance as well. Being low-energy-density options, batteries are not viable solutions in these sectors. Here, hydrogen might be deployed as the primary low-carbon technology. The use of LNG, methanol, ethane, liquefied petroleum gas (LPG), hydrogen, and ammonia as an alternative to traditional residual or distillate marine fuels may be anticipated to become more widely adopted by the marine industry as a result of an increased commitment from the International Maritime Organization (IMO) to reduce emissions from shipping. According to a survey, to meet the IMO's 2050 decarbonisation targets, 47% of the stakeholders mentioned LNG, 40% hydrogen, 8% ammonia, and 5% mentioned methanol as the future fuel for maritime operations[73]. For example, this year, the Danish company Maersk ordered 12 methanol-powered container vessels from Hyundai Heavy Industries. The ships are to be delivered in 2024 and 2025. The expectation might be on a smaller scale in the aviation sector as the existing number of hydrogen-powered aircraft is quite few for the time being. Therefore, in summary, the business as a whole is still in the Value Creation phase with numerous pilots, and efforts are still needed to go upscaling.

[73] Ship Technology, 2022. LNG and hydrogen fuel option to help shipping meet IMO targets.

4.18. Hydrogen Use for Heating

In 2018, heat accounted for 50% of all final energy consumption worldwide and contributed 40% of all CO_2 emissions globally[74]. As a result of the global climate problem, there is a surge in eco-awareness, which drives demand for environmentally sound heating systems. One alternative to conventional fossil fuel energy sources is hydrogen-based heating. It is simple to convert low-carbon hydrogen into thermal energy or combined heat and power if the hydrogen can be delivered or stored on-site. Some businesses encourage this environmentally friendly move by releasing hydrogen-powered household heating appliances for both commercial and residential use. The compatibility of the existing infrastructure and heating equipment, risk of explosion due to flammable nature of hydrogen, uncertainties in retail pricing and capability of meeting the peak demand are some of the key concerns and challenges of using hydrogen for heating. Table 18 summarises some business models of hydrogen use in heating systems.

Table 18. Summary of Hydrogen for Heating Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Panasonic Japan	They offer H2 KIBOU hydrogen fuel cell, which can produce 5kW of power and uses waste heat for heating hot water.	The generator's total energy efficiency, which includes heat recovery, can reach 95%, enabling efficient energy use with zero waste. The company also offers ENE-FARM for residential use. This household fuel cell cogeneration system is claimed to	A revenue stream is generated by the sales of hydrogen fuel cell systems for combined heat and power purposes to commercial and residential customers. Environmental value is captured by reducing emissions in heating as long as

[74] IEA Renewables, 2019. Heat.

		achieve a total efficiency of 97%.	low-carbon hydrogen is used.
Heatlie Australia	The company offers hydrogen-fuelled barbeque.	They claim the hydrogen barbeque consumes roughly half as much fuel as natural gas and LPG while creating equal heat output.	Value is created by increased heating efficiency achieved by hydrogen use. They claim the product reduces emissions, thus creating environmental value; however, the source of hydrogen is not specified. Revenue stream through the sales of hydrogen barbeque.
Worcester Bosch UK	They offer hydrogen boilers for home heating.	The company's all boilers are now hydrogen-blend ready, meaning that they can run on a blend of 80% natural gas and 20% hydrogen. Hydrogen-ready boilers, which can run on 100% hydrogen, are not commercially available yet.	The hydrogen boilers are safer in terms of not emitting CO, meaning there's no chance of a leak. Lower GHG emissions, NOx emissions and easy installation and commissioning are further advantages.

Remarks: Heating is one of the major problems regarding emissions and climate change. Hydrogen use in heating purposes, such as boilers for household heating or domestic appliances like barbeques, has started to appear on the market. Furthermore, many market players and researchers also propose large-scale heating, such as district heating. However, when we evaluate the viability of a business, we should also consider alternative options. Heating with natural gas is a robust and mature business; replacing it with a low-carbon alternative will not be easy. Heat pumps are also available to decarbonise the heating and replace natural gas with a low-emission option. The first comparative advantage of heat pumps is their efficiency. A study shows an example where 100 kWh of renewable energy is used as input for heating[75]. The hydrogen boiler gives 46 kWh of heat, whereas a traditional electric space heater 86 kWh and thanks to the Coefficient of Performance, the heat pump yields 270 kWh of heat energy[75]. The overall efficiency of a typical heat pump is around six times higher than that of a hydrogen boiler. Hydrogen for heating is still at its piloting and appraisal phases, and it is highly doubtful whether it will ever reach its Upscaling phase.

4.19. Petroleum Refining

The sectors that use the output products of the refinery process include agriculture, manufacturing, construction, and mining. Thus, one might say that the output of refinery processes touches nearly all sectors of the global economy. The refinery process includes the conversion of crude oil to an energy source including gasoline, jet fuel, diesel, propane and butane, or fuel oils, coke, and industrial chemicals. In the petroleum refining sector, hydrogen is used, for example, to lower the sulphur content of diesel fuel. As sulphur specifications become tighter and the demand for diesel fuel has increased, the refinery demand for hydrogen has increased. Hydrogen is mainly used in the hydrotreating and hydrocracking steps in refineries. To lower refined products' carbon footprint, several players seek to use increasing amounts of low-carbon hydrogen in their refining operations. In Table 19, we reviewed the various business models to examine low carbon hydrogen use in petroleum refining.

[75] Cebon, D., 2022. Hydrogen for heating? A comparison with heat pumps.

Table 19. Summary of Hydrogen Use in Petroleum Refining Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Aramco Saudi Arabia	They use blue hydrogen in hydrotreating, hydrocracking, and hydroisomerisation processes to produce gasoline, jet fuel, diesel, kerosene, and other end-products.	They are building a hydrogen plant with Air Products in Neom to produce 240,000 tonnes of both blue and green hydrogen by 2025. They also created a joint venture to produce an air separation unit, gasification, and power plant at Jazan. The Jazan Refinery is to process 400,000 barrels of crude oil per day, and the joint venture will supply hydrogen for this refinery.	Neom project has a budget of $5 billion, and the joint venture at Jazan is $15 billion.
ExxonMobil U.S.	The company is planning to use hydrogen as fuel at one of its refineries in Texas.	They are constructing hydrogen production, carbon capture, and storage plants at its integrated refining and petrochemical site in Texas. This plant is to produce 1	The deep decarbonisation of refinery sites will capture the environmental value when hydrogen is used as fuel for petroleum refining.

		billion cubic feet (~ 28 million m3) of blue hydrogen per day. The carbon capture infrastructure will be able to transport and store up to 10 million metric tons of CO_2 per year.	
Shell The Netherlands-UK	They will be using green hydrogen in Shell's Rhineland refinery.	10 MW of electrolyser is being built on-site to produce 1,300 tonnes of green hydrogen per year. ITM Power will produce the hydrogen, and Shell will operate the plant.	The REFHYNE project is a part of Clean Refinery Hydrogen for Europe, funded by the European Commission.

Remarks: The hydrogen demand for refineries can be estimated with low error margins as the process and technology are well known and mature. Almost 80% of hydrogen is currently produced through emissions-intensive natural gas reforming and coal gasification[76]. And petroleum refining is one of the largest markets for hydrogen, accounting for about 32 million tonnes per year, nearly 30-35% of global hydrogen demand in 2020[77]. The main business opportunity arises at the point of producing low-carbon hydrogen for the refining industry. The other opportunity is whether to produce the necessary amount of hydrogen on-site or buy it externally. For example, in the United States, the on-site refinery hydrogen production increased by less than 1%, while hydrogen supplied by merchant producers increased by 135% between 2008 and 2014

[76] IEA, 2021. Hydrogen, IEA, Paris.
[77] Wood Mackenzie, 2022. Low-carbon hydrogen demand in refining could reach 50 Mtpa by 2050.

whilst the hydrogen demand of the refineries increased by 60% in the same period[78]. To answer the challenge, the European Commission is now financing a project to install a 10 MW electrolyser for one of the Shell refineries in Germany to produce on-site 1,300 tonnes of green hydrogen per year[79]. Furthermore, Saudi Aramco will need 1.93 million tonnes of blue hydrogen by 2030[80]. Enhanced reliability is a natural result of on-site generation. On the other hand, ExxonMobil is also planning to produce on-site hydrogen and use this as fuel at one of their refineries. The main advantage of hydrogen use in petroleum refining is to reduce emissions. For instance, ExxonMobil claims that if one of its refineries is fuelled by hydrogen, the integrated site emissions would be reduced by up to 30%[81]. Hydrogen use in petroleum refining is a mature business. Yet the use of low carbon hydrogen at the refinery sites is still in the Develop phase with some pilot projects.

4.20. Steel Production

Steel production is another highly energy-intensive process. International Energy Association's study reports that steel making is responsible for about 8% of global final energy demand and 7% of energy sector CO_2 emissions[82]. A study underlines that around 2.8 billion tonnes of CO_2 were emitted annually from the steel industry worldwide in 2020, making up 7% of all CO_2 emissions globally. The emission from the steel sector should be reduced to a level of 400-600 million tonnes per year in 2050[83]. On the other hand, global steel production is expected to grow by 25–30% by 2050[84]. These necessitate an emerging need for decarbonising the steel industry. Hydrogen is one of the proposed solutions for decarbonisation efforts. It can be used as an alternative injection material or auxiliary reducing agent in pulverised coal injection in a blast furnace to improve the performance of conventional blast furnaces. Furthermore,

78 EIA, 2014. U.S. Energy Information Administration. Hydrogen for refineries is increasingly provided by industrial suppliers.
79 Refhyne, 2022. Clean Refinery Hydrogen for Europe.
80 Recharge, 2022. Aramco targets 12GW wind and solar and two million tonnes of blue hydrogen.
81 ExxonMobil, 2022. ExxonMobil planning hydrogen production, carbon capture and storage at Baytown complex.
82 Energy Technology Perspectives, 2020. IEA Iron and Steel Technology Roadmap.
83 Pei, et al., 2020. Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland Metals 2020, 10(7), 972.
84 Holappa, L., 2020. A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry. Metals 2020, 10(9), 1117; https://doi.org/10.3390/met10091117.

hydrogen can also be used to produce direct reduced iron. Table 20 introduces some of the business models of hydrogen use in steel production.

Table 20. Summary of Hydrogen Use in Steel Production Business Models

Company	Value Proposal (what?)	Value Creation (how?)	Value Capture
Ovako Sweden	They trialled the first commercial use of hydrogen in steel manufacturing at one of their plants in Sweden.	Instead of using LPG, in collaboration with Linde, they used hydrogen to heat steel furnaces before rolling.	The deep decarbonisation of steel making will capture the value. The environmental value will be captured by mitigating 20,000 tonnes of CO_2 each year. Further funding and industry collaborations are needed for a wider-scale application.
ArcelorMittal Luxembourg	The company successfully tests using green hydrogen in the production of direct reduced iron at one of their steel plants in Canada.	They wanted to evaluate the ability to replace the use of natural gas with green hydrogen in the iron ore reduction process. In this initial test, green hydrogen replaced 6.8% of natural gas over the course of 24 hours, resulting in a noticeable drop in CO_2 emissions. The	The company is aiming to continue further tests by gradually increasing the hydrogen content in direct reduced iron production. The environmental value will be to deeply decarbonise steel making process by cutting several hundred thousand

		green hydrogen utilised in the test was generated by an electrolyser owned by a third party and then shipped to the steel mill location.	tonnes of CO_2 per year.
SSAB Sweden	The steel manufacturer developed a pilot plant, HYBRIT, together with the mining company LKAB and the energy company Vattenfall.	The blast furnaces process traditionally uses coal and coke to eliminate oxygen from iron ore and produce iron. In the HYBRIT process, hydrogen gas is intended to take the place of coal and coke as sustainable substitutes. Hydrogen will first be produced through the electrolysis of water using fossil-free electricity. Solid iron (sponge iron) is subsequently melted down in an electric arc furnace. Fossil-free pellets trial is already completed. Hydrogen-based reduction and smelting trials and hydrogen storage	By 2026, SSAB aims to offer commercially viable fossil-free steel to the market. The environmental value will be captured by deeply decarbonising steel industry by achieving fossil-free production. The plant in Sweden produced world's first fossil-free sponge iron.

		installations are still going on.	

Remarks: It is evident that the steel industry is a major energy consumer and CO_2 emitter. The urgent need for decarbonising steel manufacturing is acknowledged by many. The first question, perhaps, would be whether we aim to decarbonise the entire steel industry or do it partly. Hydrogen is a candidate to deliver both of these aims. For the time being, the industry trials show that the new hydrogen heating method can yield the same quality steel. Voestalpine, Thyssenkrupp, TATA, and Dillinger/Saarstahl are other companies that are conducting or preparing hydrogen trials at their steel plants[85]. The business is in its Develop phase, and further external funding and industrial cooperation are needed to boost it to undergo Appraisal and Upscaling phases.

5. Discussion

The businesses we reviewed here are the ones which have already passed numerous successful pilots. The use cases which are still in the Research and Development phase are omitted intentionally. The companies are chosen according to their expertise in their fields after a thorough and extensive market scan. The authors attempted to compile as many relevant companies and businesses as possible in the hydrogen economy. However, it is impossible to present all existing valuable companies and businesses in this paper.

The hydrogen economy is not a new phenomenon to us. There have been attempts to incorporate hydrogen into our lives for the last 150 years. There are some who might claim that hydrogen is hype, and the practical applications are doubtful. For example, Joseph Room wrote his book "The Hype About Hydrogen" in 2004[86]. The book states that despite all the talk of hydrogen-powered fuel-cell cars dominating the motorways in the future, gasoline-electric hybrids will continue to hold the technological

[85] Bellona Europa, 2021. Hydrogen in steel production: what is happening in Europe – part one.
[86] Joseph J. Room, 2004. The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate.

and environmental high ground for many decades to come (Joseph J. Room, 2004). After almost twenty years, fuel cell vehicles remain a very small niche.

Achieving a low-carbon economy by using hydrogen in various aspects of the economy will not be easy. The first challenge is the definition of low-carbon hydrogen. As we mentioned earlier, there are various definitions such as low-carbon, fossil-free and clean hydrogen; however, an international standardisation has not been achieved yet. This means measurement, standardisation, and certification is a preliminary condition to start discussing a low-carbon hydrogen economy. From our existing knowledge, consultations with the experts in the field and review of the hydrogen businesses, we can draw the following remarks:

- For now, the hydrogen economy is supply-driven.
- Many hydrogen businesses depend on external funding, primarily government support, and the continuity of this funding and financing mechanism is questionable as there are concerns for future incentives and government support.
- Much emphasis is given to colour coding of hydrogen production, whilst the significant point should be to produce low-carbon hydrogen.
- Stimulation of demand for low carbon hydrogen is essential.
- Carbon pricing is a key element in the success of the hydrogen businesses and further research on the impact of carbon pricing on the hydrogen businesses is necessary.
- Clearer policy and regulatory frameworks are necessary.
- Policy support for long-term demand creation is critical and the role of regulations and subsidies should be discussed.
- Especially, transportation and storage of hydrogen are challenging topics.
- There are numerous pilot projects. Yet, whether these projects will convert into sustainable businesses is questionable.
- Measurement, standardisation, and certifications are prominent subjects.
- Hydrogen infrastructure is crucial. Using just the existing gas infrastructure for hydrogen is not viable. Additional investment is necessary.

The hydrogen economy is vast, and there are numerous other business cases that we did not include in the study. Some additional 20 business cases that we should mention are:

Case 21: Hydrogen use in Grid Balancing

Case 22: Compressed Hydrogen Selling

Case 23: Fuel Cell Car Leasing

Case 24: Fuel Cell Hydrogen Bus Operating

Case 25: Fuel Cell Truck - Logistics Service Provider

Case 26: Hydrogen Application Standardisation Audit

Case 27: Hydrogen as Back-Up supply

Case 28: Oxy-Combustion of Hydrogen-Enriched Methane

Case 29: Hydrogen Consultancy

Case 30: Hydrogen Financing

Case 31: Hydrogen Flow Measurement

Case 32: Hydrogen for decarbonising explosives in the mining industry

Case 33: Hydrogen for Paper Production

Case 34: Hydrogen in the Food sector

Case 35: Hydrogen Plant Management Software

Case 36: Hydrogen Plant Modules Export

Case 37: Hydrogen Power Plant Construction

Case 38: Hydrogen Production by Recycling

Case 39: Hydrogen Purification

Case 40: Hydrogenating Oil

6. Conclusions

The hydrogen economy is a vast phenomenon with many application areas and business cases. Each application area has its own opportunities, challenges, and alternatives. There is no doubt hydrogen will play a role in decarbonisation and low-carbon energy transition. However, one must admit that hydrogen alone is not "the silver bullet" as achieving the vast energy transition will require a combination of many solutions including hydrogen. Therefore, hydrogen must be regarded as a complimentary asset in the wider energy economy rather than being considered as the ultimate solution.

After reviewing the 20 prominent application areas of hydrogen, we made a qualitative assessment of spotting the market phase of the use cases according to Figure

1, the Innovation Process. The market phases will be designated as Value Creation (Develop & Appraise), Upscaling and Value Capture (Market Diffusion). The Value Creation phase means numerous successful pilots have been done, and additional monetary and environmental value are sought. The appraisal of the true value and impact of the business is completed. In the Upscaling phase the business case has started to be bought and adopted nationally and internationally. The number of users, buyers and sellers increases steadily. Finally, Market Diffusion means the successful commercialisation and widespread use of the business case. At this stage, the business reaches its maturity. It has become self-sufficient, meaning it can generate its own revenue and is not dependent on external funding such as grants or government incentives.

We should note that these are preliminary and subjective judgements and are open to discussion and further evaluations. Another point is that the hydrogen business is on the move, and the market conditions change quickly. Furthermore, the market stages are fluid and do not have visible and strict boundaries. Moreover, the stages are not always forward-looking. This means that a business in one stage, does not necessarily mean that, after a period of time, it will reach the next stage. For example, hydrogen cars were first introduced in the 1960s and Fuel Cells, and Hydrogen in the Transport Sector have been stuck in the Upscaling phase since then. The businesses have not reached maturity and market penetration yet.

Another crucial point is that a single business case might have subsections or sub-sectors at different market phases. For example, even though we designated electrolysers in the Market Diffusion phase, this is only applicable for the Alkaline technology. PEM electrolysers can be claimed to be in the Upscaling phase, and various other electrolyser technologies are in the Research and Development and Value Creation phases. Figure 3 summarises the market phases of these businesses where grey parts stand for grey hydrogen, grey methanol and grey ammonia where high-carbon hydrogen is used in established businesses.

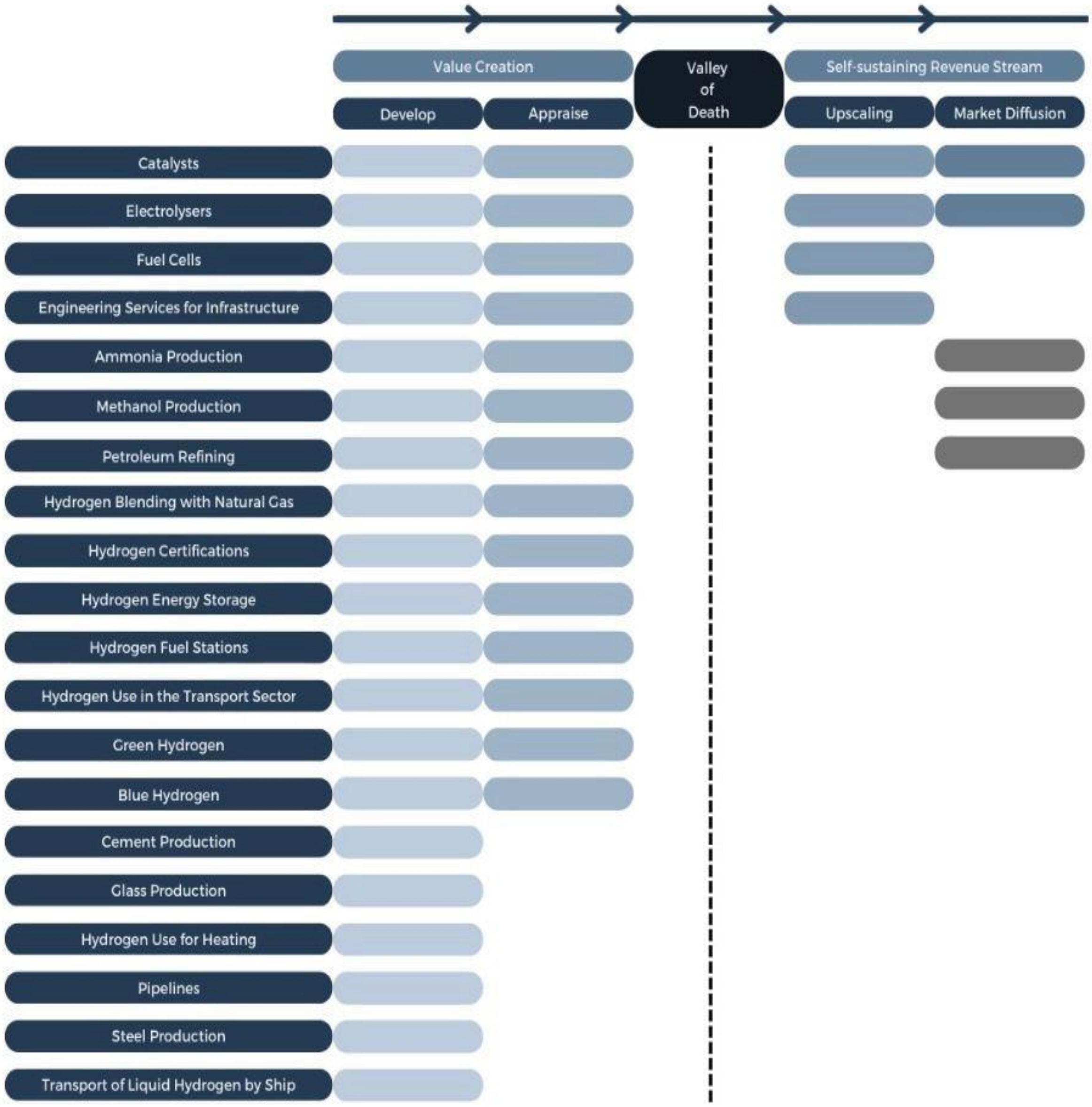

Figure 3. Market Phases of Hydrogen Businesses

There are no distinct boundaries between market phases. As the market economy is quite vivid, shifting between phases could happen in time. As we can see from Figure 3, quite a few businesses have reached market diffusion. The majority of the businesses still depend on external funding such as project funds, subsidies, grants and government support. Achieving a self-sustaining revenue stream is a must for a business to be viable. And the most difficult step is to shift from Value Creation to Upscaling. Some businesses have been stuck there for decades. And some will likely fail to make that forward transition. We can perhaps make an analogy between passing from Appraisal to

Upscaling as the "Valley of Death" from the technology hype cycle phenomenon. The most challenging part for the business cases is to start generating self-sustaining revenue and many businesses might fail to achieve that and become stranded in the valley of death.

Finally, we acknowledge that exogenous factors such as regulations, subsidies and carbon pricing will affect the viability of these businesses substantially. For example, regulated versus non-regulated business models across the value chain will have different characteristics. Some of the business models that we inspect here such as those related to network infrastructure and storage are likely to be regulated whereas those related to production and consumption are likely to be not. A regulated business model has a fundamentally different economics compared with a market-driven business model. Similarly, as we mentioned earlier, government support, incentives and subsidies are vitally important especially for the initial stages of a business. On the other hand, carbon pricing especially affects the cost of hydrogen production methods. As a follow-up future work, we will pick up some of the business opportunities and carry out a business model readiness level analysis. We shall carry out further qualitative and quantitative analysis to study and underline the impact of exogenous factors and identify conditions under which a particular hydrogen business model moves from one stage to another.

References

Abdelshafy et al., 2022. Ali Abdelshafy, Martin Lambert, Grit Walther. The role of CCUS in decarbonizing the cement industry: A German case study. Energy Insights 115, The Oxford Institute for Energy Studies, May 2022.

Admiral Markets, 2022. Best Hydrogen Stocks to Watch in 2022 [WWW Document]. URL https://admiralmarkets.com/education/articles/shares/hydrogen-stocks (accessed 28.7.22).

Ammonia Technology Roadmap, 2021. IEA Towards more sustainable nitrogen fertiliser production [WWW Document]. URL https://iea.blob.core.windows.net/assets/23c82928-ab51-4725-836b-8efc8ea540d2/Ammonia_Launchpresentation.pdf (accessed 30.7.22).

Andersson, J. and Grönkvist, S., 2019. Large-scale storage of hydrogen. International journal of hydrogen energy, 44(23), pp.11901-11919.

Baldwin, S., Esposito, D., and Tallackson, H., 2022. Assessing The Viability of Hydrogen Proposals: Considerations for State Utility Regulators And Policymakers, Energy Innovation, San Francisco.

Bellona Europa, 2021. Hydrogen in steel production: what is happening in Europe – part one. [WWW Document]. URL https://bellona.org/news/climate-change/2021-03-hydrogen-in-steel-production-what-is-happening-in-europe-part-one (accessed 28.8.22).

BEIS, 2022. Government response to the consultation on a Low Carbon Hydrogen Business Model. UK Department for Business, Energy & Industrial Strategy.

BEIS, 2021. Hydrogen Production Costs. UK Department for Business, Energy & Industrial Strategy.

BEIS, 2019. Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility. London, UK.

British energy security strategy, 2022. Policy paper [WWW Document]. URL https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy (accessed 30.7.22).

CB Insights, 2021. 130+ Tech Companies Developing Hydrogen-Based Clean Energy Solutions [WWW Document]. URL https://app.cbinsights.com/research/hydrogen-economy-market-map/ (accessed 28.7.22).

Cebon, D., 2022. Hydrogen for heating? A comparison with heat pumps. [WWW Document]. URL https://h2sciencecoalition.com/blog/hydrogen-for-heating-a-comparison-with-heat-pumps-part-1/ (accessed 28.7.22).

CMC markets, 2022. 14 hydrogen production and hydrogen fuel cell stocks to watch [WWW Document]. URL https://www.cmcmarkets.com/en-gb/trading-guides/hydrogen-stocks (accessed 28.7.22).

DNV, 2021. Initial Hydrogen Strategy Report. Northern Gas Networks (lead partner), Wales & West Utilities and National Grid Gas Transmission, Leeds, UK.

EIA, 2018. U.S. Energy Information Agency, Glass manufacturing is an energy-intensive industry mainly fueled by natural gas [WWW Document]. URL https://www.eia.gov/todayinenergy/detail.php?id=12631 (accessed 30.7.22).

EIA, 2014. U.S. Energy Information Administration. Hydrogen for refineries is increasingly provided by industrial suppliers. [WWW Document]. URL

https://www.eia.gov/todayinenergy/detail.php?id=24612#:~:text=Refineries%20use%20hydrogen%20to%20lower,regulations%20have%20become%20more%20stringent (accessed 30.7.22).
El-Emam, R.S., Bagria, N. and Gabriel, K.S. (2021). Integration of Cement and Hydrogen Industries for Canada's Climate Plan: Case Study. In: Proceedings of the 8th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'21). Canada.
Energy.Gov, 2022. Hydrogen Storage Challenges [WWW Document]. URL https://www.energy.gov/eere/fuelcells/hydrogen-storage-challenges (accessed 5.10.22).
Energy Technology Perspectives, 2020. IEA Iron and Steel Technology Roadmap. [WWW Document]. URL https://www.iea.org/reports/iron-and-steel-technology-roadmap (accessed 30.7.22).
Energy Technology Perspectives, 2023. IEA. [WWW Document]. URL https://iea.blob.core.windows.net/assets/d1ec36e9-fb41-466b-b265-45b0e7a4af36/EnergyTechnologyPerspectives2023.pdf (accessed 15.1.23).
Energy: Using Hydrogen for Glass, 2022. Andrew Keeley and Mike Haden, The Chemical Engineer [WWW Document]. URL https://www.thechemicalengineer.com/features/energy-using-hydrogen-for-glass/ (accessed 30.7.22).
European Electrolyser Summit, 2022. Europe Clean Hydrogen Alliance, Joint Declaration. Brussels.
European Hydrogen Backbone, 2022. A European Hydrogen Infrastructure Vision Covering 28 Countries, April 2022.
ExxonMobil, 2022. ExxonMobil planning hydrogen production, carbon capture and storage at Baytown complex. [WWW Document]. URL https://corporate.exxonmobil.com/News/Newsroom/News-releases/2022/0301_ExxonMobil-planning-hydrogen-production-carbon-capture-and-storage-at-Baytown-complex (accessed 28.8.22).
Feng, X., 2018. A sustainable, energy-saving way to make the key ingredient in fertilisers [WWW Document]. URL http://theconversation.com/a-sustainable-energy-saving-way-to-make-the-key-ingredient-in-fertilizers-96693 (accessed 6.6.22).
Future Grid, 2022. National Grid [WWW Document]. URL https://www.nationalgrid.com/gas-transmission/insight-and-innovation/transmission-innovation/futuregrid (accessed 30.7.22).
Gassmann, O., Frankenberger, K. and Csik, M., 2013. The St. Gallen business model navigator.
GCCA, 2021. Concrete Future. The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. London, UK.
Global EV Outlook, 2022. Trends in charging infrastructure [WWW Document]. URL https://www.iea.org/reports/global-ev-outlook-2022/trends-in-charging-infrastructure (accessed 5.10.22).
GM Heritage Center, 2019. GM Hydrogen Fuel Cell Vehicles [WWW Document]. URL https://www.gmheritagecenter.com/featured/Fuel_Cell_Vehicles.html (accessed 30.7.22).
GOV.UK, 2022. Press release. Government unveils investment for energy technologies of the future. [WWW Document]. URL https://www.gov.uk/government/news/government-unveils-investment-for-energy-technologies-of-the-future (accessed 30.7.22).
Griffin, P.W., Hammond, G.P. and McKenna, R.C., 2021. Industrial energy use and decarbonisation in the glass sector: A UK perspective. Advances in Applied Energy, 3, p.100037.
HM Government, 2021. UK Hydrogen Strategy. ISBN 978-1-5286-2670-5

Holappa, L., 2020. A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry. Metals 2020, 10(9), 1117; https://doi.org/10.3390/met10091117.

Holst, M., Aschbrenner, S., Smolinka, T., Voglstätter, C. and Grimm, G., 2021. Cost Forecast for Low-Temperature Electrolysis-Technology Driven Bottom-Up Prognosis for PEM and Alkaline Water Electrolysis Systems. A Cost Analysis Study on Behalf of Clean Air Task Force.

Howarth, R.W. and Jacobson, M.Z., 2021. How green is blue hydrogen?. Energy Science & Engineering, 9(10), pp.1676-1687.

HyDeploy, 2022. [WWW Document]. URL https://hydeploy.co.uk/ (accessed 30.7.22).

Hydrogen and Fuel Cell Technologies Office, 2021. HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines, U.S. Department of Energy.

Hydrogen Central, 2021. Japan Targets 1,000 Hydrogen Stations By End Of Decade. [WWW Document]. URL https://hydrogen-central.com/japan-1000-hydrogen-stations/ (accessed 28.8.22).

Hydrogen Insights, 2021. A perspective on hydrogen investment, market development and cost competitiveness. Hydrogen Council, McKinsey & Company.

IEA, 2021. Hydrogen, International Energy Agency, Paris [WWW Document]. URL https://www.iea.org/reports/hydrogen (accessed 6.6.22).

IEA, 2019. International Energy Agency, The Future of Hydrogen.

IEA Renewables, 2019. International Energy Agency, Heat. [WWW Document]. URL https://www.iea.org/reports/renewables-2019/heat (accessed 28.8.22).

ING, 2021. High gas prices triple the cost of hydrogen production. Economic and Financial Analysis.

Joseph J. Room, 2004. The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate.

Küfeoğlu, S., 2022. Emerging Technologies: Value Creation for Sustainable Development. Springer Nature.

Lazard, 2021. Levelized Cost Of Energy, Levelized Cost Of Storage, and Levelized Cost Of Hydrogen [WWW Document]. URL https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/ (accessed 13.9.22).

Lerner, L. 2011. 7 things you may not know about catalysis. Argonne National Laboratory [WWW Document]. URL https://www.anl.gov/article/7-things-you-may-not-know-about-catalysis (accessed 13.9.22).

Linde, 2022. Storing Hydrogen in Underground Salt Caverns [WWW Document]. URL https://www.lindehydrogen.com/technology/hydrogen-storage (accessed 13.9.22).

Melaina, M. W., Antonia, O., and Penev, M. 2013. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. National Renewable Energy Laboratory (NREL), Colorado.

Methanol Institute, 2022. The methanol industry. [WWW Document]. URL https://www.methanol.org/the-methanol-industry/ (accessed 28.8.22).

Muhammed, N.S., Haq, B., Al Shehri, D., Al-Ahmed, A., Rahman, M.M. and Zaman, E., 2022. A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. Energy Reports, 8, pp.461-499.

Nature, 2021. Concrete needs to lose its colossal carbon footprint. [WWW Document]. URL https://www.nature.com/articles/d41586-021-02612-5 (accessed 28.8.22).

Nebergall, J., 2022. How do hydrogen engines work? | Cummins Inc.. [WWW Document]. URL https://www.cummins.com/news/2022/01/26/how-do-hydrogen-engines-work (accessed 28.8.22).

Net Zero Strategy, 2021. Net Zero Strategy: Build Back Greener. UK HM Government.

Offshore Technology, 2019. North America has the highest oil and gas pipeline length globally. [WWW Document]. URL https://www.offshore-technology.com/ (accessed 30.7.22).
Oregon State University, 2021. Oregon State researchers develop advanced catalysts for clean hydrogen production https://today.oregonstate.edu/news/oregon-state-researchers-develop-advanced-catalysts-clean-hydrogen-production (accessed 28.8.22).
Patonia, A. & Poudineh, R., 2022. Global trade of hydrogen: what is the best way to transfer hydrogen over long distances? The Oxford Institute for Energy Studies, OIES Paper: ET16, September 2022.
Pei, et al., 2020. Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland Metals 2020, 10(7), 972; https://doi.org/10.3390/met10070972
PV Magazine, 2020. Electrolyzer overview: Lowering the cost of hydrogen and distributing its production [WWW Document]. URL https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/ (accessed 28.8.22).
Recharge, 2022. Aramco targets 12GW wind and solar and two million tonnes of blue hydrogen. [WWW Document]. URL https://www.rechargenews.com/energy-transition/aramco-targets-12gw-wind-and-solar-and-two-million-tonnes-of-blue-hydrogen/2-1-1239743 (accessed 28.8.22).
Refhyne, 2022. Clean Refinery Hydrogen for Europe. [WWW Document]. URL https://refhyne.eu/ (accessed 28.8.22).
REPowerEU, 2022. The European Commission, A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition [WWW Document]. URL https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131 (accessed 30.7.22).
Royal Society, 2020. Ammonia: zero-carbon fertiliser, fuel and energy store, Policy Briefing [WWW Document]. URL https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf (accessed 30.7.22).
SCHOTT, 2022. SCHOTT developing climate-friendly glass production using hydrogen [WWW Document]. URL https://www.schott.com/en-au/news-and-media/media-releases/2022/schott-developing-climate-friendly-glass-production-using-hydrogen (accessed 30.7.22).
S&P Global, 2022. Market Intelligence, US hydrogen pilot projects build up as gas utilities seek low-carbon future [WWW Document]. URL https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/us-hydrogen-pilot-projects-build-up-as-gas-utilities-seek-low-carbon-future-65570349 (accessed 29.7.22).
Ship Technology, 2022. LNG and hydrogen fuel option to help shipping meet IMO targets [WWW Document]. URL https://www.ship-technology.com/news/lng-hydrogen-fuel-shipping-imo-targets/ (accessed 28.8.22).
Sonthalia, A., Kumar, N., Tomar, M., 2021. Moving ahead from hydrogen to methanol economy: scope and challenges. Clean Techn Environ Policy. https://doi.org/10.1007/s10098-021-02193-x (accessed 30.7.22).
Statista, 2021a. Production capacity of ammonia worldwide from 2018 to 2021, with a forecast for 2026 and 2030 [WWW Document]. URL https://www.statista.com/statistics/1065865/ammonia-production-capacity-globally/ (accessed 30.7.22).
Statista, 2021b. Number of hydrogen fueling stations for road vehicles worldwide as of 2021, by country. [WWW Document]. URL https://www.statista.com/statistics/1026719/number-of-hydrogen-fuel-stations-by-country/ (accessed 28.8.22).

Statista Research Department, 2022. Transportation emissions worldwide - statistics & facts. [WWW Document]. URL https://www.statista.com/topics/7476/transportation-emissions-worldwide/#topicHeader__wrapper (accessed 28.8.22).
The Net Zero Hydrogen Fund, 2022. Government response to consultation. UK Department for Business, Energy & Industrial Strategy.
U.S. Department of Energy, 2008. Hydrogen Fuel Cells. [WWW Document]. URL https://www.nrc.gov/docs/ML1002/ML100280723.pdf (accessed 28.8.22).
US News, 2022. 6 Green Hydrogen Stocks and ETFs to Watch [WWW Document]. URL https://money.usnews.com/investing/stock-market-news/slideshows/green-hydrogen-stocks-to-watch?slide=3 (accessed 28.7.22).
Venture Radar, 2022. Top Hydrogen Start-ups [WWW Document]. URL https://www.ventureradar.com/startup/Hydrogen (accessed 28.7.22).
Vereš, J., Ochodek, T., and Koloničný, J, 2022. Aspects of Hydrogen Fuelling Stations. Chemical Engineering Transactions Vol. 91.
Volvo Group, 2022. What are hydrogen fuel cells? [WWW Document]. URL https://www.volvogroup.com/en/future-of-transportation/innovation/electromobility/hydrogen-fuel-cells.html#:~:text=Fuel%20cells%20as%20a%20concept,before%20it%20becomes%20commercially%20available (accessed 5.10.22).
Yahoo finance, 2022. 10 Hydrogen Fuel Cell Stocks to Buy Today [WWW Document]. URL https://finance.yahoo.com/news/10-hydrogen-fuel-cell-stocks-173303405.html (accessed 28.7.22).
Wilson, J.H., 2014. The history of alkaline hydrolysis. Good Funeral Guide.
Wood Mackenzie, 2022. Low-carbon hydrogen demand in refining could reach 50 Mtpa by 2050 [WWW Document]. URL https://www.woodmac.com/press-releases/low-carbon-hydrogen-demand-in-refining-could-reach-50-mtpa-by-2050/ (accessed 28.8.22).
World Bank Group, 2022. Sufficiency, sustainability, and circularity of critical materials for clean hydrogen. Susana Moreira, Tim Laing.