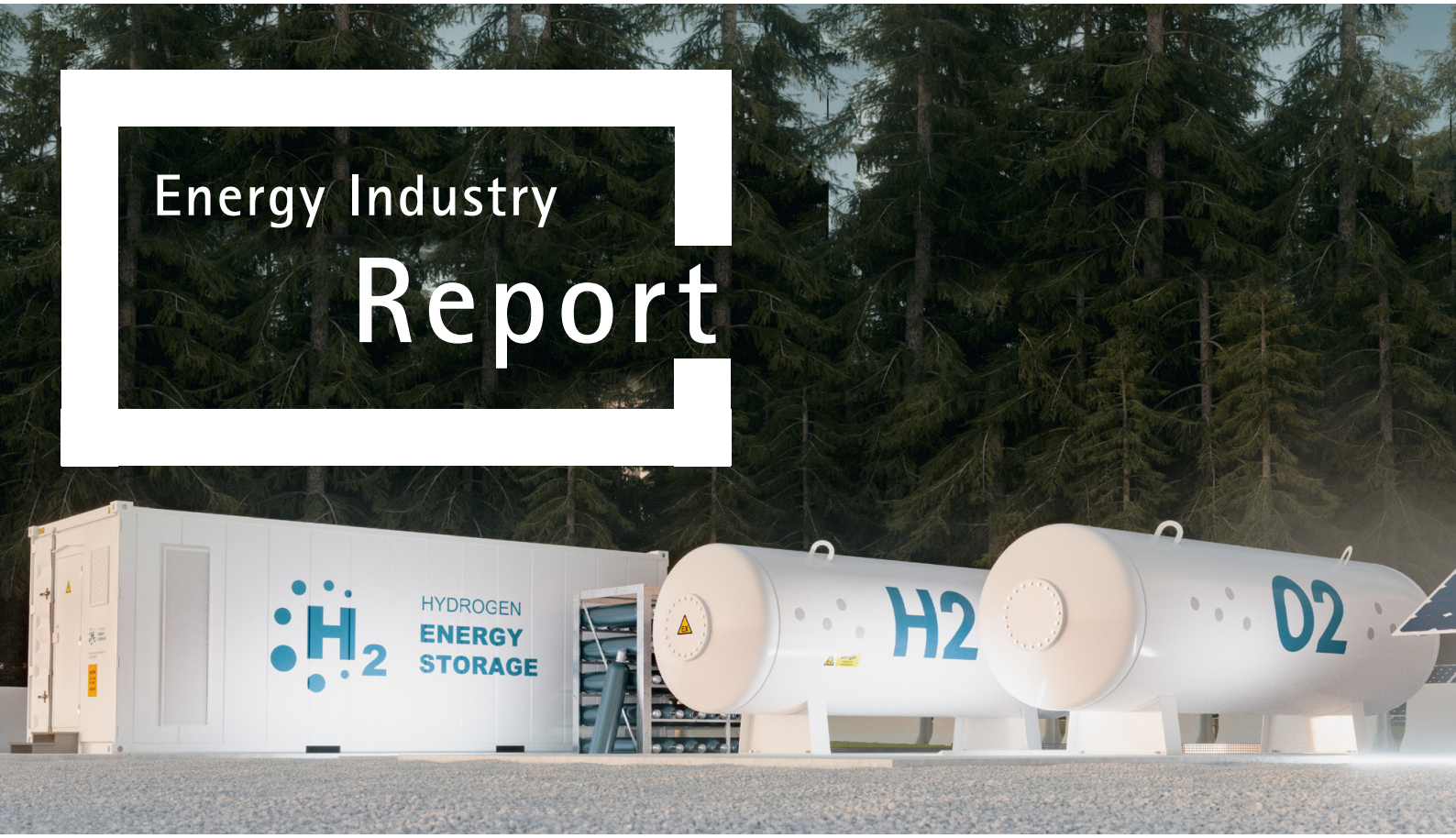
# Pathways to Hydrogen as an Energy Carrier: The Hydrogen Economy

May - 2020




The Abdullah Bin Hamad Al-Attiyah International Foundation for
Energy & Sustainable Development

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# INTRODUCTION

## PATHWAYS TO HYDROGEN AS AN ENERGY CARRIER: THE HYDROGEN ECONOMY

Since the term 'hydrogen economy' was first used in 1970, there have been several 'false dawns' with bold claims for the speed of transition to hydrogen. This paper argues that this time, for some applications at least, there are grounds for optimism about a future role for decarbonised hydrogen. However, the lesson from history is that bold claims need to be examined carefully and treated with some caution. There are no easy or low-cost solutions to decarbonisation of the energy system, and this is certainly the case for possible deployment of low-carbon hydrogen. This paper addresses the growing attraction of hydrogen as a clean energy carrier over a wide area of applications.

Energy Industry Report

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# EXECUTIVE SUMMARY

- Hydrogen is already used in significant quantities in specific applications but has recently emerged as a candidate as an attractive zero-carbon energy carrier.
- Hydrogen can be made from fossil fuels (requiring carbon capture, use and storage to be low-carbon 'blue hydrogen') or by water electrolysis using zero-carbon electricity to make 'green hydrogen'. Production from natural gas is likely to be the cheapest option, in most cases, for at least one to two decades.
- Hydrogen can fill key sectors that are otherwise hard to decarbonise, notably aviation, shipping fuel, industrial heat, building heating, some petrochemicals, and metal ore smelting.
- The economics of hydrogen are specific to each potential application, and most of them require additional research and development.
- Hydrogen is relatively expensive and difficult to transport over long distances because of its low density. Several different transport methods are under consideration. Hydrogen will not be as flexible or globalised an industry as oil or LNG.
- A growing number of significant hydrogen production projects are under development, mostly in Europe. The EU, Japan and Australia have all launched hydrogen strategies.

## IMPLICATIONS FOR LEADING OIL AND GAS PRODUCERS

- Hydrogen offers a way for major oil and gas producers to continue using their resources in a climate-compatible way, and re-purposing gas pipelines, distribution networks and possibly LNG terminals.
- For the EU and likely Japan, imported hydrogen or derivatives will have to emit zero-carbon. Therefore, production from natural gas, oil or coal will need to include Carbon Capture, Utilisation and Storage (CCUS).
- The climate challenge makes it urgent for hydrocarbon suppliers to turn to low-carbon products. However, hydrogen will take time and heavy investment in research and demonstration products, to reach maturity.
- To develop a hydrogen economy, major oil and gas producers could learn from countries that have well-developed strategies, technologies and interests, notably the EU and Japan (and Australia, but Australia may be more of a competitor for export markets).

## HYDROGEN AS AN ENERGY VECTOR IS INCREASINGLY GAINING MOMENTUM

Hydrogen, a clean energy carrier, is attracting growing interest from both supply and demand sides. Hydrogen is already widely used, mostly in oil refining and ammonia production. However more recently, attention has turned to its potential as a pillar of a future clean energy system.

The Paris Agreement, signed in 2016, calls on signatories to keep global warming to no more than 1.5°C, which would require global greenhouse gas (GHG) emissions to fall 7.6% annually to 2030. Even the Covid-19 crisis is estimated to have reduced global emissions by only 4-7% through 2020 as a whole[i]. Renewable energy has grown quickly in recent years, and gas has replaced coal in markets including the US and UK, reducing emissions from the power sector. But emissions from other major sectors, notably industry, transport, and heat, continue to rise and have few viable low-carbon alternatives. Long-term energy storage is another key area of focus, despite recent improvements in batteries. For this reason, Japan, China and Germany, amongst others, have shown recent and growing interest in hydrogen.

On the supply side, some countries with large energy resources are coming to see hydrogen as a new clean growth industry. This includes Australia (coal and solar) and the Middle East (natural gas and solar).

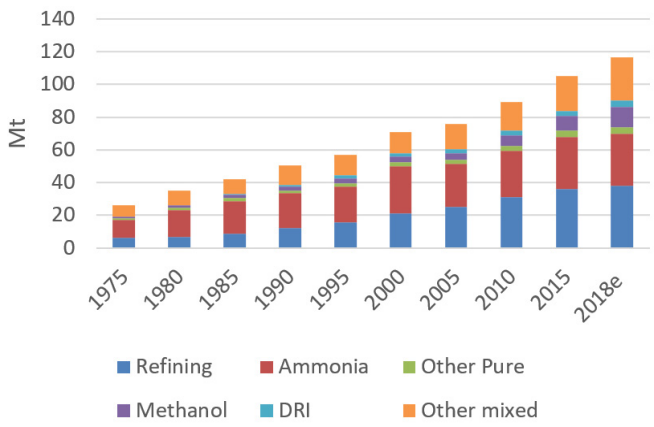
Hydrogen is in many ways an ideal fuel, yielding only water (and no carbon dioxide) when burnt, with high energy density, and manufactured from abundant materials (fossil fuels or water). However, its low density as a gas and small molecular size, requires heavy containment methods.

The Hydrogen Council believes that the 'hydrogen economy' could supply 18% of world energy demand, generate $2.5 trillion in revenues, 30 million jobs, and cut 6.5 gigatonnes of carbon dioxide-equivalent (Gt $CO^2$e) per year. This would require an investment of $280 billion up to 2030[ii].

Current investment in hydrogen is much lower than this but has been rising. The US Department of Energy has spent from $100- 280 million annually over the past decade; Japan's Ministry of Trade and Industry budgeted $560 million in 2019; and China was about to announce $17 billion of hydrogen transport investment up to 2023 (prior to Covid-19 outbreak).

Demand for hydrogen has increased more than threefold since 1975 (FIGURE 1). In 2018, about 115 million tonnes (Mt) of hydrogen was used worldwide, equivalent in energy content to about 353 billion cubic metres (BCM) of natural gas. World natural gas use in that year was 3849 BCM, so current hydrogen use is about 9% of the size of the natural gas market, not a negligible amount. So far, nearly all this hydrogen is produced from fossil fuels, releasing about 830 Mt $CO^2$e per year.

FIGURE 1 GLOBAL ANNUAL DEMAND FOR HYDROGEN, 1975-2018E [iii]



# HYDROGEN COULD FILL SEVERAL IMPORTANT ENERGY NEEDS

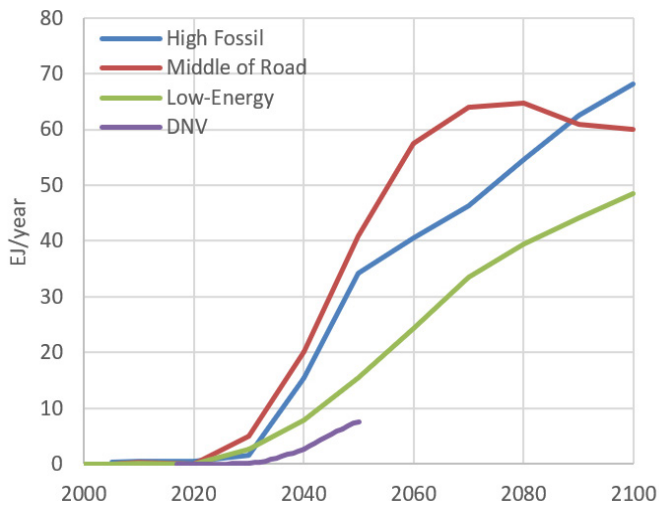
Most climate mitigation to date, has focussed on two areas: decarbonising the power sector by using coal-to-gas switching, and renewable energy using battery back-up (and to a lesser extent, nuclear and carbon capture, use and storage (CCUS)); and decarbonising transport with electric vehicles. Home heating is intended to be decarbonised by electrification. Several important emitting sectors lack currently viable mitigation options, or face additional challenges:

- Long-duration energy storage
- High-temperature heat for industry[iv]
- Reducing agents and feedstocks for iron/steel and some petrochemical industries
- Home heating in very cold temperatures and/or at times of low renewable generation
- Long-distance transport (trucks, ships, aviation)

Hydrogen could have a role in some or all of these areas. Each has their own requirements, economics, and level of technical maturity.

FIGURE 2 shows a comparison of forecasts of hydrogen demand from Det Norske Veritas (DNV) (2000-2050) and three scenarios that are compatible with the Paris Agreement: High Fossil, Middle of Road (a balanced mix of all energy sources), and Low Energy (focussed on efficiency). A fourth Paris-compatible scenario, Sustainable Development, does not include any hydrogen use.

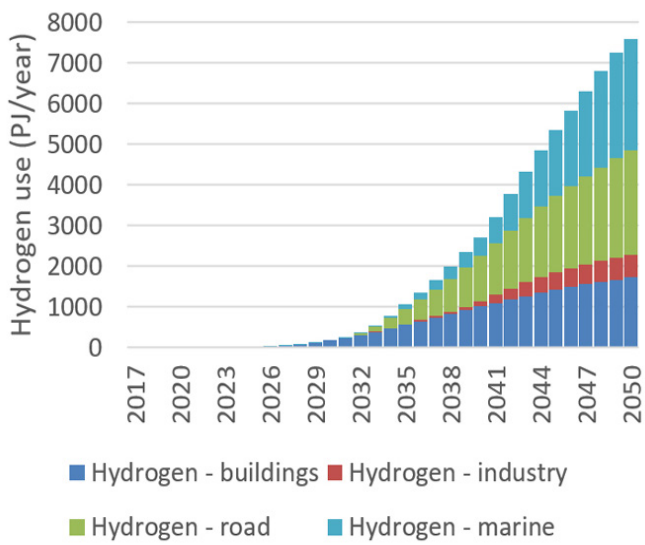
FIGURE 2 PROJECTIONS OF FINAL ENERGY HYDROGEN USE [v]




At their highest point, these scenarios have a world hydrogen business about 45% the size of the current natural gas industry.

FIGURE 3 shows DNV's view of the sectors of hydrogen use – in their view, primarily road, marine (shipping) and buildings (heating), with a limited market in industry. DNV does not see hydrogen being used in rail or aviation.

FIGURE 3 HYDROGEN USE BY SECTOR (DNV)[vi]



Hydrogen faces competition in most of its potential sectors (TABLE 1). In some, such as ground transport, these competitors (such as electric vehicles) seem very well-placed. In others, for instance, heavy industry, the role for hydrogen is more promising.

TABLE 1 COMPETITORS TO HYDROGEN IN KEY SECTORS

| Use sector | Competitors | Challenges |
|---|---|---|
| Ground vehicle transport | Electric<br>Biofuels | Heavy tanks<br>High cost of fuel cells versus batteries<br>Refuelling infrastructure |
| Shipping | LNG<br>Batteries (short-range)<br>On-board CCS<br>Biofuels | Refuelling infrastructure<br>Engine and tank refits<br>Lower cargo space |
| Aviation | Batteries (short-range)<br>Biofuels | Heavy tanks<br>Immature and high-spec engine technology |
| Long-duration storage | Batteries<br>Pumped hydro<br>Thermal storage | Round-trip efficiency |
| Building heating | Electric / heat pumps<br>Solar / geothermal heat | Safety of H2 in existing distribution grid |
| Distributed heat & power | Natural gas CHP<br>District heating<br>Heat pumps | Relatively high fuel-cell cost<br>Balancing heat & power output |
| Industrial heat | Electric<br>Biomass<br>Fossil fuels with CCUS | Relatively high cost of hydrogen |
| Industrial feedstock | Natural coal or coal with CCUS<br>Electrolysis (for metal ore reduction) | Relatively high cost of hydrogen<br>Conversion of existing equipment |

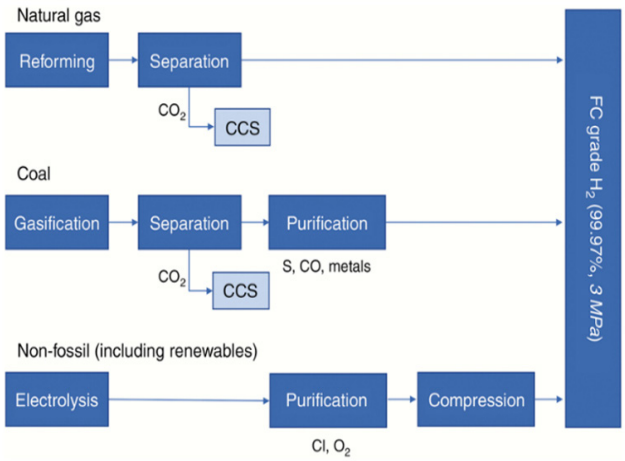
## THERE ARE TWO MAIN PRODUCTION ROUTES FOR HYDROGEN[vii]

Most hydrogen today (95%) is produced by Steam Methane Reforming (SMR) with natural gas as a feedstock. Methane reacts with steam in the presence of a nickel catalyst to produce carbon monoxide and hydrogen. The carbon monoxide then reacts with water to produce carbon dioxide and additional hydrogen. This is a technically mature and low-cost route but produces 'grey hydrogen' with a high carbon footprint of 222-325 $gCO^2$/kWh H2.

Gasification of coal is cheaper, yielding 'black' or 'brown' hydrogen with a high carbon footprint.

Large-scale use of hydrogen will require emissions during production to be near-zero. Production from fossil fuels would have to be done with CCUS to remove the resulting $CO^2$. Alternatively, hydrogen can be produced by the electrolysis of water using low-carbon electricity (renewable or nuclear), as shown in FIGURE 4.

FIGURE 4 ROUTES FOR LOW-CARBON HYDROGEN PRODUCTION

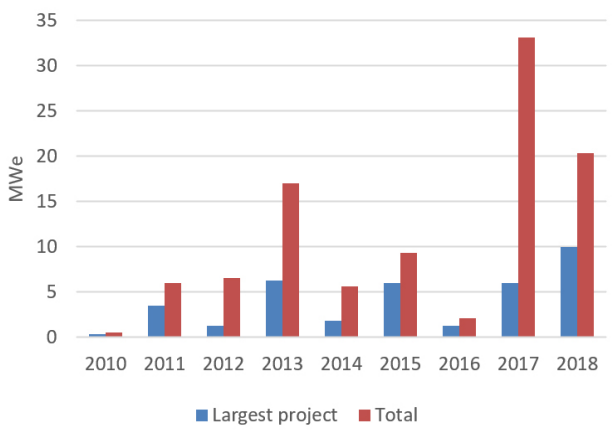


# THERE ARE TWO MAIN PRODUCTION ROUTES FOR HYDROGEN

Within the production process of hydrogen, there are three main types of electrolyser: alkaline, proton exchange membrane (PEM) and solid oxide. Alkaline is a mature technology with lower capital costs and a wide range of operating loads. PEM is suited to small scales, has a very wide range of operating load, and can produce highly compressed hydrogen, but has higher capital cost. PEM is relatively less mature, with room for improvement. Solid oxides are the least mature, require steam, but have high electrical efficiency and can operate in reverse (turning hydrogen into electricity).

Electrolyser installation has increased in recent years (FIGURE 5) but remains small at about 104 MW installed during 2010-18. For comparison, producing 2.7 EJ/year of hydrogen by 2040 as in the DNV scenario, a relative 'low case' amongst those considered, would require 107 GW of electrolysers running continuously, about 1000 times current capacity.

FIGURE 5 ELECTROLYSER CAPACITY INSTALLED, 2010-2018 [viii]




The business case for hydrogen production via electrolysis depends on using cheap electricity, such as renewables at times of surplus.

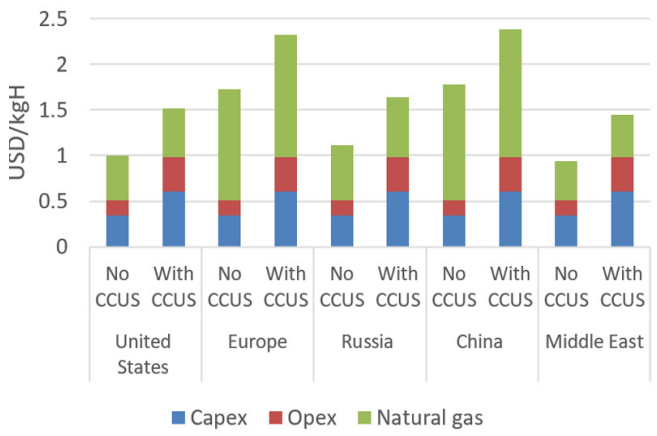
However, this means the electrolyser would run well below its full capacity, raising the cost of the produced hydrogen.

Future routes for hydrogen production include thermochemical water splitting[ix], and artificial photosynthesis[x], but these are only in the research stage.

## ECONOMICS OF HYDROGEN PRODUCTION CURRENTLY FAVOUR NATURAL GAS

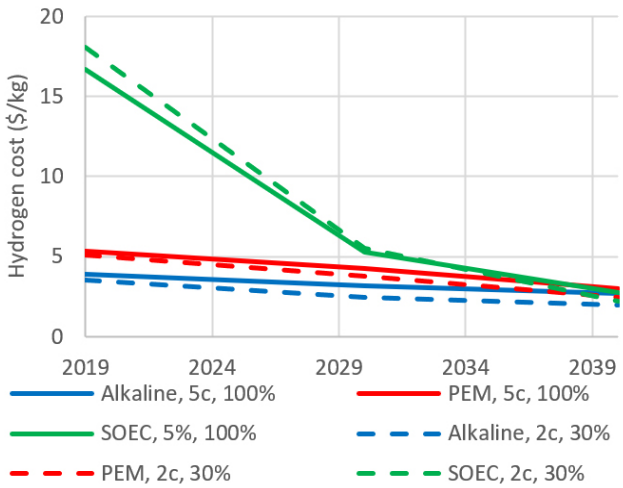
The cost of producing hydrogen via SMR from natural gas vary, depending on the gas price (FIGURE 6). The inclusion of CCUS raises the required gas input by about 10%, and the overall cost of the produced hydrogen by about 35-50%. The cost of low-carbon hydrogen (with CCUS) is in the range of $1-2.3 per kg, equivalent to $7.9-18.2/MMBtu of natural gas, expensive in current terms, but within the range of historic gas/LNG prices.

FIGURE 6 HYDROGEN PRODUCTION COSTS USING NATURAL GAS[xi]




The cost of hydrogen from electrolysis depends on the technology use, its costs, the cost of input electricity, the lifetime of the electrolyser, and its load factor (how much it is used relative to maximum capacity). FIGURE 7 shows how costs for the three main electrolyser technologies may evolve over the next twenty years. The technologies are shown in two cases: at 100% load factor with electricity at 5 USc/kwh (i.e. relatively cheap wholesale electricity), and at 30% load factor with electricity at 2 USc/kWh (i.e. cheap variable renewable electricity or off-peak power).

FIGURE 7 COST OF HYDROGEN PRODUCTION FROM ELECTROLYSIS[xii]




Solid oxide is expensive today, but all three technologies converge on about $2-3/kg of hydrogen by 2040. The options using the electrolyser at lower load factors with cheap electricity reduce the cost of the hydrogen by about $0.55-0.7/kg by 2040.

These costs are still above the cost of hydrogen from gas with CCUS in the lower-cost global locations. It is likely that transport costs from a lower-cost area to Europe or China, would still give a delivered price below that of electrolytic renewable hydrogen made on that region. Therefore, to be broadly competitive, electrolytic hydrogen will require further reductions in capital cost, increases in efficiency, and/or more favourable combinations of load factor and electricity price. The ability of solid oxide electrolysers to act in reverse, could also improve their economics as a combined hydrogen production and energy storage system.

# HYDROGEN CAN BE TRANSPORTED BY SHIP OR PIPELINE

An advantage of hydrogen is the potential for reusing the existing natural gas grid (the same applies to other decarbonised gases, such as biomethane or synthetic methane). Full electrification, in contrast, would likely require much reinforcement of local distribution grids to meet high winter peak loads.

There is some debate over how much hydrogen can safely be blended into natural gas for pipeline transport. Hydrogen's energy density is about a third of that of gas, i.e. a 3% blend of hydrogen by volume would carry only 98% as much energy. Up to 20% by volume (7% by energy) is probably achievable in conventional steel pipes. Polyethylene distribution pipes can carry 100% hydrogen and many appliances are certified for up to 23% hydrogen. Industrial facilities and gas turbines, though, would likely require modifications.

For long-distance transport by ship, hydrogen can be liquefied, as for liquefied natural gas (LNG). However, its density is much lower than LNG (requiring more or larger ships) and the energy required for conversion is 25-35% of the hydrogen's energy content, as compared to about 10% or less for LNG.

Another option, could be for hydrogen to be converted to ammonia (NH3), which is much easier to liquefy for tanker transport, and can also be transported by pipeline. At the destination, ammonia could either be used directly (it can be burnt directly in gas turbines) or reconverted to hydrogen. However, both these steps have costs and energy losses.

Alternatively, hydrogen can be combined with a liquid organic hydrogen carrier (LOHC), such as toluene or dibenzyl toluene, which can be carried in an ordinary oil product tanker, and is then reconverted at the destination. This also has energy costs, and the LOHC must be shipped back to be re-used.

Transporting hydrogen by pipeline costs about $1/kg for 1500 kilometres. If sent through existing gas pipelines, though, the delivered energy capacity is only about a third as much as for natural gas. Liquefaction of hydrogen or conversion to ammonia costs about $1/kg, but shipping of ammonia is much cheaper. However, ammonia incurs a further cost for reconversion on arrival if hydrogen is required.

Selection of the optimal transport method therefore depends on the distance and the desired end-use (e.g., whether ammonia can be used directly, or hydrogen is required). This implies that the value chain for hydrogen will be more complicated and less flexible than for LNG.

## SOME REAL PROJECTS ARE BEGINNING TO EMERGE

As noted, hydrogen has been used for decades in petrochemicals and oil refining. Real projects are now starting to emerge in other areas.

- In 2014, Engie launched a power-to-gas project in France to provide up to 20% hydrogen to a local gas grid[xiii].
- Japan adopted a 'Basic Hydrogen Strategy' in 2017, with the intention that it would substitute for gasoline, LNG and other fuels, and considering use throughout the value chain, as well as research and pilot projects in a full suite of technologies for production, transport, storage and use[xiv].
- In 2017, PowerHouse Energy Group signed a memorandum of understanding with Energy & Environment Holding, a Qatar-based group, to investigate the production of hydrogen from waste, to power fuel cell vehicles during World Cup 2022[xv].
- In 2018, Australia launched a national hydrogen roadmap, including both electrolysis and coal gasification from lignite resources in Victoria with CCUS in the Gippsland Basin, and estimated costs of $1.6-2.1/kg of H2. The strategy sees hydrogen as having various domestic applications, including power for remote communities and mines, as well as up to 3.8 Mt of exports to Japan, China, Singapore and South Korea by 2030, worth about US$7.5 billion[xvi].
- The Dubai Electricity & Water Authority, with Siemens, started constructing, in 2019, a pilot solar-powered hydrogen PEM electrolysis plant at its Expo site, to power fuel cell vehicles[xvii].

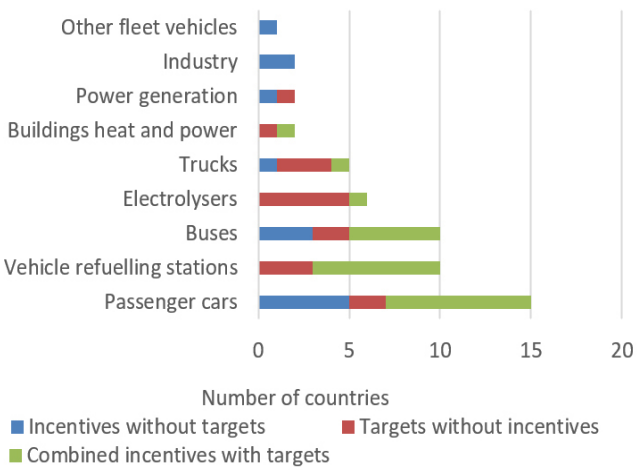
## SOME REAL PROJECTS ARE BEGINNING TO EMERGE

- In December 2019, price reporting agency, Platts, launched a series of assessments for hydrogen produced in various ways in key markets in North America, Europe and Japan[xviii].
- In January 2020, HyDeploy began feeding 20% hydrogen into the natural gas grid at Keele University, UK[xix].
- In February-March 2020, Engie, Alstom and partners ran a trial of a renewable hydrogen-powered fuel cell train in the Netherlands, with the intention to replace diesel on the country's 1000 km of non-electrified lines[xx].
- In late 2020, Kawasaki should deliver the world's first liquefied hydrogen carrying ship, with a capacity of 1250 m3, less than 1% the size of an LNG carrier[xxi].
- Vattenfall, Equinor and Gasunie are studying running the Magnum power plant in the Netherlands on hydrogen, produced from imported Norwegian natural gas with CCUS[xxii].
- The Neste biorefinery in Rotterdam will install a high-temperature 2.6 MW electrolyser to produce hydrogen for its operations by 2024[xxiii].
- The Ten Cities Programme in China to launch battery electric vehicles, would be replicated for hydrogen transport in Beijing, Shanghai, Chengdu and others. Wuhan is to become the first Chinese hydrogen city with up to 100 fuel cell automakers and enterprises and 300 filling stations by 2025[xxiv].
- Swedish utility Vattenfall is working with steel and mining groups on the HYBRIT project for hydrogen-based steelmaking, reducing Sweden's total $CO^2$ emissions by 10%[xxv].
- Northern Gas Networks in the UK proposes to begin converting 3.7 million buildings to hydrogen supply by 2028, and another 12 million by 2050[xxvi].
- Shell and Dutch gas grid operator Gasunie are carrying out feasibility studies for 3-4 GW of offshore wind in the Netherlands by 2030, and 10 GW by 2040, which would be dedicated to green hydrogen production[xxvii].

## MORE EFFORTS ARE NEEDED FOR ITS WIDE-SCALE ADOPTION

Current policy support for hydrogen is limited. About 15 countries have introduced incentives for hydrogen passenger cars (FIGURE 8), but this is one of the less promising areas for adoption. Only two countries have incentives for power, industry and buildings' heat and power. Otherwise, hydrogen will have to rely on carbon taxes or other restrictions on emissions to make it competitive.

FIGURE 8 CURRENT POLICY SUPPORT FOR HYDROGEN DEPLOYMENT, 2018[xxviii]



The EU is currently considering three options for gas infrastructure: a gradual shift towards renewable gas (which could include hydrogen); a green gas grid, with a rapid transition to hydrogen and other decarbonised gases; or full electrification with no future role for gases[xxix]. The EU's Green Deal mentions clean hydrogen as a priority area.

## THE COMPLEXITY OF THE VALUE CHAIN SUGGESTS DIFFERENT OPTIONS FOR PRODUCERS

The emerging hydrogen value chain is much more complicated than that for oil or gas/LNG (TABLE 2).

TABLE 2 VALUE CHAIN OF HYDROGEN COMPARED TO OIL AND GAS

| Fuel | Transport | Main end uses |
|---|---|---|
| Oil | Pipeline<br>Tanker | Transport<br>Petrochemicals<br>Industrial heat |
| Gas | Pipeline<br>Tanker (LNG) | Building heating<br>Power generation<br>Industrial heat<br>Petrochemicals<br>Reducing metal ores |
| Hydrogen | Pipeline (H2)<br>Tanker (liquid H2)<br>Tanker (LOHC) | Shipping fuel<br>Aviation fuel<br>Ground transport fuel<br>Power generation<br>Industrial heat<br>Building heating<br>Petrochemicals<br>Reducing metal ores |
| | Pipeline (NH3)<br>Tanker (NH3) | Shipping fuel<br>Aviation fuel<br>Power generation (NH3)<br>Reconversion to H2 |

Future producers of hydrogen could be located close to demand, or they could be exporters like today's oil and gas exporters.

Countries with a competitive advantage in hydrogen exports would have cheap and abundant renewable resources for electrolysis, and/or cheap and abundant oil, gas or coal for SMR with CCUS.

Such countries could possibly export their hydrogen via existing gas pipelines (with some modifications). They could export hydrogen or ammonia via new pipelines or ships as described above, but this may struggle to be competitive in destination markets given the high transport costs and inflexibility. Or, they could continue exporting natural gas/LNG, and accept a price penalty for the end-user to convert that gas to hydrogen with CCUS.

Alternatively, countries could use hydrogen to manufacture and export decarbonised products, including iron and steel, cement, methanol, fertiliser, synthetic methane and synthetic liquid fuels. This may be a more attractive route because of the higher density of most of these products, and because it would localise more of the value creation.

A step-by-step approach may be the most appropriate. Australia's strategy, for example, begins with small-scale production from electrolysers for use in high-value applications, and scales up to large projects including blue hydrogen, with export potential. Japan's technology-focussed approach is intended to demonstrate and commercialise a range of key technologies. The Hydrogen Council, which groups several oil and gas, power, industrial gas, automotive and engineering firms, has laid out a roadmap for scaling up hydrogen[xxx].

# CONCLUSIONS

Hydrogen is an attractive opportunity for oil and gas companies, because of its compatibility with their existing skill set and business model. It can play a major part in several key economic sectors that are otherwise hard to decarbonise. It also allows re-use of existing pipeline infrastructure, and perhaps retrofitting of LNG terminals.

Countries with low-cost hydrocarbon or coal resources and good CCUS sites, and/or with the best renewable resources, can produce hydrogen at lower cost. Costs are still significantly higher than gas/LNG prices, but will fall with scale-up and technology development.

Challenges to the hydrogen economy include a lack of investment (with $20-25 billion per year required until 2030), the absence of a hydrogen market (with localised trade, between supplier and end-user, limited price discovery), and limited $CO^2$ regulations and mandates.

Despite its attractions, hydrogen has various disadvantages. Because of its low volumetric energy density, it needs four times more volume than gasoline to store the same energy. For this, huge on-board storage tanks are required. Vehicles need compact, light, safe and affordable containment. This also makes hydrogen much more difficult and expensive to transport over long distances than oil or LNG.

Therefore, countries investigating hydrogen as a major new industry should consider domestic use and the production of decarbonised materials using hydrogen. Export opportunities will take longer to develop and be relatively expensive, except for nearby markets reached by pipeline.

The EU is likely to introduce border carbon tariffs or other regulation that will eventually make it impossible or expensive to export materials to the EU that have a high carbon footprint. This creates an opportunity to produce decarbonised materials such as steel, petrochemicals, fertilisers and synthetic fuels for the European market.

Because of the large capital costs and technical and commercial complexity, oil and gas exporting countries interested in hydrogen, should form suitable partnerships. The EU and Japan would be good partners due to their existing interest and technology. Australia has a well-thought-out strategy, but may be a competitor to other aspiring hydrogen producers. Within these broad partnerships, more specific alliances would be formed with engineering and technology providers such as Mitsubishi, oil, and gas companies such as Shell and Equinor, and utilities such as Engie. That would ensure that the new hydrogen market develops in a way that meets existing hydrocarbon suppliers' interests as well as those of their customers.

# APPENDIX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EAST
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# OUR MEMBERS

Currently the Foundation has over fifteen corporate members from Qatar's energy, insurance and banking industries as well as several partnership agreements with business and academia.




















**Our partners collaborate with us on various projects and research within the themes of energy and sustainable development.**

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ULUSLARARASI İŞBİRLİĞİ PLATFORMU
INTERNATIONAL COOPERATION PLATFORM
İSTANBUL

World Petroleum Council

MITSUI & CO.

مؤسسة قطر
Qatar Foundation
Unlocking human potential لإطلاق قدرات الإنسان

KAHRAMAA
المؤسسة العامة القطرية للكهرباء والماء
Qatar General Electricity & Water Corporation

NATIONAL COUNCIL ON U.S.-ARAB RELATIONS

ISAG
Istituto di Alti Studi in Geopolitica e Scienze Ausiliarie

مجلس قطر للمباني الخضراء
QATAR GREEN BUILDING COUNCIL

جامعة حمد بن خليفة
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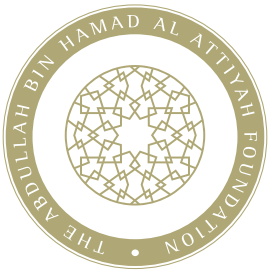
GULF TIMES

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