

# Hydrogen Demand

## Global Markets Outlook

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An aerial photograph of a suburban neighborhood with a winding river. The houses are mostly two-story with dark roofs. The river is blue and has several bridges. A large white 'H2' is overlaid in the center of the image.

# H<sub>2</sub>

INSIGHTS

Hydrogen Reports Series



Stirling Infrastructure  
LIMITED



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## EXECUTIVE SUMMARY

The world is transitioning to renewable power from a need to combat climate change and diversify the global energy mix. Demand for hydrogen globally has been dominated for decades by its use as a chemical feedstock across many industries. However, as the global energy transition takes place and we see an increase in the use of renewable power, hydrogen can serve another role. It is Stirling Infrastructure's view that an informed assessment of the demand side of regional markets is required by our clients to best inform investment decisions and the following insights and conclusions which are reached in this paper are taken from our own bespoke forecast modelling as well as extensive research.

### Europe

Europe has positioned itself as a leading hydrogen innovation hub with the greatest number of hydrogen pilot projects, start-ups, and research centres. Of the total 228 global hydrogen projects, 126 are in Europe. The continent has also positioned itself as the largest hydrogen consumer, a fact that is reaffirmed by generous government incentives and subsidies. The European Union has announced a collective effort to install 6 GW of renewable electrolyzers, expanding to 40 GW during 2025-2030. Countries including the United Kingdom, Austria, Belgium, France, Germany, Italy, the Netherlands, Norway, and Spain have also released individual hydrogen strategies and roadmaps.

### North America (comprising US, Canada, Mexico and the Caribbean)

The USA and Canada already produce a large amount of hydrogen (13 MMT) between them, although Mexico presently produces very little. This hydrogen is used mainly for petroleum refining and ammonia production, with these industries located in the Gulf states of Louisiana and Texas and the industrial heartlands of western Canada. Trinidad and Tobago is one of the largest exporters of ammonia worldwide, accounting for 14.6% of global exports which also makes it a large hydrogen producer.

### Asia Pacific (APAC)

The APAC region contains both strong consumers and suppliers of hydrogen. In 2020, China was the single largest consumer of total energy in the world (24%) with India in third place (6%). Meanwhile, other countries including Australia are rich in renewable energy. This provides opportunities to form regional hydrogen partnerships. Overall, countries in the APAC region have quite positive sentiments towards the adoption of hydrogen, and we believe that green hydrogen will take the lead in the region.

### South America

There is limited internal demand as the continent focuses on hydrogen exports however, a large mining industry will foster some demand for hydrogen. Furthermore, there is a healthy chemicals industry (often linked to mining) which will utilise some of the growing green hydrogen production. The continent currently relies heavily on hydropower for its energy mix, however due to changing weather conditions year on year, this can be unreliable. As such, utilising hydrogen to store renewable energy in the medium to long term should be explored. As a method to do this, currently ammonia is favoured due to the large industry already present in the continent. However, liquid organic hydrogen carriers (henceforth referred to as LOHC) are also under consideration as are compression and liquification techniques. With most of the research in this area being led outside of the region it has further strengthened ties with Europe and the USA.

### Africa

Africa has huge potential for producing green hydrogen at a low cost due to the continent's abundance of renewable potential. Due to a lack of internal demand, however, Africa is expected to export most of its hydrogen, with the rest going into a handful of African countries like Morocco who have a well-established fertiliser industry, currently the biggest demand for hydrogen globally.

### Middle East

The Middle East has the world's largest reserves of fossil fuels upon which its economies largely depend, whether it be for exports or domestic energy consumption. With its abundant fossil fuels, ideal for blue hydrogen, and renewables, ideal for green hydrogen, the Middle East's hydrogen production has huge potential for export growth if these resources are exploited for the hydrogen economy. Countries like Saudi Arabia are taking the lead to invest heavily in its hydrogen economy. As Europe gradually grows its hydrogen economy and adds carbon taxes to fossil fuel imports, we believe that other countries in the Middle East will be forced to speed up their decarbonisation and transition into hydrogen by scaling up hydrogen production and exports.

## ACTION POINTS FOR INVESTORS – HYDROGEN DEMAND

- 1 In terms of geography, Europe provides the most attractive location for investors in hydrogen use due to its strong decarbonisation policy commitments, subsidies and incentives. Countries where individual hydrogen strategies and roadmaps have been published, including the UK, France and Germany, are especially worth monitoring for investment opportunities.
- 2 The development and emergence of regional hubs, where hydrogen end use cases are located close to its production, creates commercially valuable opportunities and efficiencies along the hydrogen value chain. Particular regional hubs for investors to monitor include the Asia Pacific region, where the large demand centres of China and India are regionally aligned with large green and blue hydrogen production potential in countries such as Australia.
- 3 Ammonia production (for use in the fertiliser industry and, potentially, as a zero carbon fuel), currently constitutes the largest single demand for hydrogen globally and presents a huge opportunity for the adoption of green hydrogen by way of reducing the industry's carbon emissions. This switch-over has the potential to create a large array of investment opportunities over the coming years.
- 4 Vehicle use in heavy industry also shows promise as a bankable hydrogen investment opportunity, due to fast refuelling times compared with electric equivalents and the fact that many heavy industrial operations are coming under increased scrutiny in terms of their emissions. Hydrogen combustion engines seem a more economical route at first although, in the future, it is possible that hydrogen fuel cells could also become cost competitive.
- 5 Hydrogen in heating has potential as a use case and creates investment opportunities, especially when blended with natural gas in order for it to work with existing equipment (boilers, gas cookers, pipes). New companies will specialise in this blending process and could provide attractive growth potential. However, investors should be aware that this development could end up acting as a relatively short-lived carbon reduction "bridge" before a greater rollout of more efficient and cost effective heat pumps.
- 6 In terms of passenger transport, hydrogen fuel cell trains offer the most compelling investment opportunity. Relative to electric trains, hydrogen fuel cell trains offer a longer range, lower total cost of ownership and less electrical infrastructure change. Continental Europe is a region to watch in terms of likely political and economic support for the rollout of hydrogen train networks.
- 7 As demand grows, the logistical issues surrounding delivery of hydrogen from centralised production facilities to end users will need to be resolved. However, this challenge also presents investment opportunities as the infrastructure supporting hydrogen supply chains is built out.

## USING THIS PAPER

This paper is our investor's primer on how the world will switch to using hydrogen from fossil fuels, in the context of the global energy mix and the push to net-zero. This document provides insight into the opportunities and factors that our investment banking team considers necessary for our clients to make effective capital allocations within the demand side of the global hydrogen economy.

# INTRODUCTION

The complex challenges associated with addressing climate change came to the fore again in November 2021 when representatives from around the world gathered in Glasgow for COP26. A non-legally binding agreement was signed which will help shape the global agenda on climate change for the next decade. Glasgow builds on the Paris Agreement, a legally binding treaty signed in 2016 between 196 state parties and which aimed to limit global warming to below 2 degrees above pre-industrial levels. At COP26, countries agreed to meet again in 2022 to pledge further cuts to emissions of CO<sub>2</sub> in a bid to keep global temperature rises within 1.5 degrees, which scientists now say is required to prevent a “climate catastrophe”.

Meeting this goal will require a rapid reduction in global CO<sub>2</sub> emissions until they reach net zero by the middle of the century. For the first time at a COP meeting, the Glasgow Agreement included an explicit plan to “phase down” coal use. To support this ambitious decarbonisation agenda, global energy use will need to transition to renewable sources, including clean hydrogen (defined as hydrogen produced with zero or very low emissions). Hydrogen’s potential as a facilitator of the energy transition was explicitly recognised at COP26 where 28 companies including the global majors BP, Shell and TotalEnergies pledged to accelerate the use of clean hydrogen.

# EUROPE

## OVERVIEW

Europe has positioned itself as a leading hydrogen innovation hub with the greatest number of hydrogen pilot projects, start-ups, and research centres. Of the total 228 global hydrogen projects, 126 are in Europe. The continent has also positioned itself as the largest hydrogen consumer, a fact that is reaffirmed by generous government incentives and subsidies. The European Union has announced a collective effort to install 6 GW of renewable electrolyzers, expanded to 40GW during 2025-2030. Countries including the United Kingdom, Austria, Belgium, France, Germany, Italy, the Netherlands, Norway, and Spain have also released individual hydrogen strategies and roadmaps.

Europe is the ideal hydrogen innovation location, due to the strong, optimistic government sentiment. Hydrogen serves two main purposes in Europe:

### 1. European Green Deal

European countries have pledged to be at the forefront of decarbonisation initiatives. Hydrogen is being used to accelerate movement towards net-zero emissions to help European countries achieve goals set at COP15. For carbon-intensive industries, such as long-haul transportation, chemicals, and industrials, hydrogen may be a feasible replacement for natural gas and coal. In fact, several countries anticipate that hydrogen will be a largely traded commodity in the future.

### 2. Next Generation EU Recovery Package

Europe also strives to use hydrogen to rebound from the COVID-19 pandemic as a part of its EU Recovery Package, which is largely tied to the European Green Deal. For example, the hydrogen economy is expected to generate \$25 billion and create 75,000 jobs over the next 15 years, just in the UK alone.

Hydrogen will thus be crucial for the European post-pandemic economic recovery and will set a precedent for decarbonisation through alternative energy.

## Policies

Overall, the European Commission has pledged to invest up to \$550 billion in renewable hydrogen over the next 30 years. Individual countries, including Germany, France, and Italy, have pledged up to \$11 billion each. Although subsidies are currently available primarily for the transportation industry, countries including Germany are sizing up investment for decarbonising carbon-intensive industries including steel and cement.

## Types of Hydrogen

The primary goal of the European Union is to transition from grey hydrogen to green hydrogen. Nevertheless, green hydrogen is only easily accessible for countries with high zero carbon power-generating capacity, such as Spain, Portugal, Norway, and France (which primarily uses nuclear power).

Meanwhile, natural gas users and producers, including the United Kingdom and the Netherlands, are looking towards blue hydrogen and CCUS (Carbon Capture, Utilisation, and Storage). Blue hydrogen is regarded as a transitional tool, which will allow countries and companies to transfer core competencies out of carbon-intensive energy sources.

## Partnerships and Key Use Cases

The European Hydrogen Economy will only be constructed successfully through collaboration within the European continent and with adjacent countries that have large renewables capacity. Currently, Germany, France, and the Netherlands are emerging as the largest future consumers of green hydrogen. However, the shared renewables capacity between the three countries is insufficient for projected hydrogen demand. For this reason, hydrogen will be sourced from neighbouring countries. The largest exporters of hydrogen to the UK are expected to be North African countries, Southern Europe, Saudi Arabia and Eastern Europe.

North Africa, particularly Morocco, has abundant solar power. Although the current installed solar capacity is 735MW, there are over 2,000MW of solar projects being planned. Germany and Morocco signed an agreement to cooperate on green hydrogen development in North Africa, announcing two projects that will be completed in cooperation between the two countries. Germany even estimated that \$2.4 billion of its estimated \$8.2 billion national strategy on hydrogen, would be allocated to the development of hydrogen projects in partner countries.<sup>1</sup> However, partnering with Morocco brings recurring historical risk, as Morocco halted its green hydrogen agreement with Germany due to rising political tensions in March 2021.<sup>2</sup>

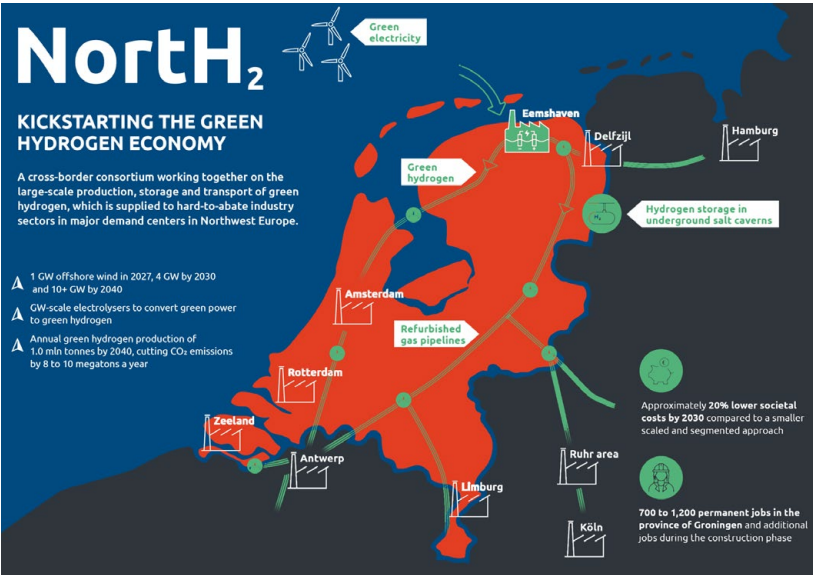
Italy, Spain and other Mediterranean countries have been actively researching electrolysis production and distribution. These countries are preparing to become the middle-ground between hydrogen exporters and importers. If hydrogen is produced in North Africa or Saudi Arabia, it can be distributed via pipelines or shipping containers to southern European ports, which will then transport hydrogen to the consumers in Northern Europe. Snam, an Italian energy infrastructure company, estimates that to date, more than 70% of its pipelines are ready to carry hydrogen. The company has adopted new regulations which allow its pipelines to transport not only natural gas and biomethane, but also 100% hydrogen.<sup>3</sup>

Germany will be the largest consumer of hydrogen and expects to utilise most of the commodity in the transportation industry. The country is projecting that hydrogen-fuelled trains and long-haul heavy-duty vehicles will be the most feasible investments.

## CASE STUDY - NORTH<sub>2</sub> PROJECT IN THE NETHERLANDS

The Netherlands is another country positioned to become a hydrogen hub, with several advantages making it competitive to become the largest hydrogen distribution centre in Europe. First, it is home to the largest European port, Rotterdam, which has already developed partnerships to import hydrogen with Chile, Brazil, Portugal, Oman, and Australia. Second, the ports, industrial centres, and renewable infrastructure of the Netherlands, Germany and Belgium, are extremely well connected with existing natural gas, methane, and alternative materials pipelines. These pipelines are currently being retrofitted for hydrogen, while new hydrogen pipelines are being placed parallel to the existing infrastructure.

The North<sub>2</sub> project is expected to be the largest green hydrogen “value chain” in the world, with the region of Groningen becoming the world’s first “Green Hydrogen Valley”. A consortium of companies, including Gasunie, Groningen Seaports, Equinor, Shell, RWE, is constructing an entire hydrogen value chain, including offshore wind farms in the North Sea, a 4GW electrolyser in Eemshaven, a distribution network towards Belgium and Germany, and natural storage caverns for excess hydrogen. This project is effectively ensuring sustainability of the local hydrogen ecosystem. It is guaranteeing that there will be sufficient hydrogen supply and a reliable distribution network that is well-connected to hydrogen consumers. This project is expected to scale up to 10GW by 2040 and will begin producing the first hydrogen in 2027. By initiating this expansive project, the Netherlands will stay ahead of the learning curve related to hydrogen technology and it will retain its position as the largest European port.



1 Morocco, Germany Sign Green Hydrogen Cooperation Agreement - FuelCellsWorks  
2 Morocco Blocks Green Hydrogen Deal With Germany Over Western Sahara (moroccoworldnews.com)  
3 Snam and hydrogen



## NORTH AMERICA

### OVERVIEW

The North American region consists of the USA, Canada, Mexico and the Caribbean. The USA and Canada produce a large amount of hydrogen (13 MMT) between them and Mexico does not produce much at all. This hydrogen is used mainly for petroleum refining and ammonia production at the moment. These industries are located in the Gulf states – Louisiana and Texas and the industrial heartlands of western Canada. Trinidad and Tobago is one of the largest exporters of ammonia worldwide, accounting for 14.6% of global exports which also makes it a large hydrogen producer.

### Partnerships

The cluster of the USA, Canada and Mexico have existing trade agreements such as the CUSMA (Canada United States Mexico Agreement) which means that trading between the countries is precedented. This would mean that hydrogen trading could become more widespread. California and Quebec even have an existing cap-and-trade program through the Western Climate initiative, so existing relationships between states in Canada and the US could be extended to a hydrogen partnership.

North America may benefit through relationships with South America where the abundant renewable resources make green hydrogen production easier. These countries could export hydrogen to the US for use in their existing hydrogen networks.

### Use Cases and Infrastructure

Trinidad and Tobago is one of the largest exporters of ammonia in the world. Although the production method is currently through steam methane reformation (grey hydrogen), there are initiatives aimed at moving this production to green methods. The first green hydrogen project in Trinidad and Tobago is named NewGen which is focused on the development of an industrial scale green hydrogen plant. The small size of Trinidad and Tobago could make it ideal for other hydrogen projects in the future. There are only 1.4 million people on the islands which could act as a small enough sample to significantly decarbonise with hydrogen. However, there are no other major projects planned.

The USA is difficult to analyse unless done state by state. California is one of the largest hydrogen producing states in the US. Here demand has been built through incentives for hydrogen fuelled vehicles as well as building the required infrastructure. It has one of the largest hydrogen refuelling networks in the world – planning to have 100 stations by 2022 -and the most FCEVs of any state. California is looking to use green hydrogen to supply their refuelling network.

Texas and Louisiana have a large amount of industry on the Gulf coast. This could make it ideal for supplying blue hydrogen to decarbonise this. As well as this, the extensive hydrogen pipeline network would allow hydrogen to be produced and exported. Currently, this production is used for petroleum and ammonia refining. However, scaling up this hydrogen production could help decarbonise industrial sectors.

Canada is looking to invest in green hydrogen in the east, where hydropower makes up a large amount of its energy supply, and blue hydrogen in the west, where there is lots of industry and low-cost natural resources. As Canada is well suited to both types of hydrogen, this makes it a great case for supply to outweigh demand. Hydrogen could then be exported for use in other countries in Europe and states in the USA. The Government of Canada has set federal targets for zero emission vehicles (ZEV) to reach 10% of light-duty vehicles sales per year by 2025, 30% by 2030 and 100% by 2040. Canada considers battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs) to qualify as ZEVs. Canada also aims to reduce its emissions through initiatives such as the zero emissions bus (ZEB) initiative which aims to encourage government to support the purchase of 5000 ZEBs over the next 5 years. California already has a similar initiative which states that new buses must be ZEBs by 2029. Fuel cells are an established technology in buses and could provide some needed demand. Heating accounts for 80% of use in homes in Canada. If hydrogen were to be used for heating, then demand for hydrogen would increase massively.<sup>4</sup>

Mexico has very few hydrogen projects in both supply and demand. It could be capable of producing and supplying hydrogen to Canada and the USA, but it would have to begin to invest in projects in this space.

4 Canada Hydrogen Strategy



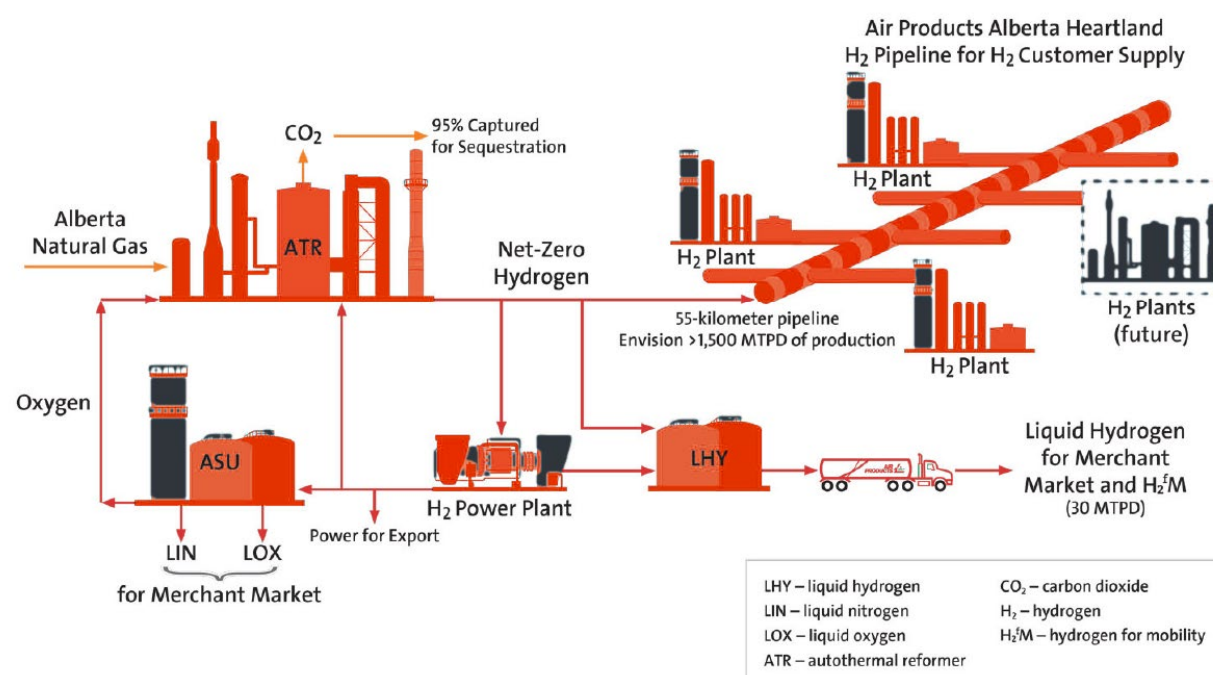


## CASE STUDY - HYDROGEN ENERGY COMPLEX PROJECT IN CANADA

One large project that is being run in North America is the hydrogen energy complex in Edmonton, Canada. Air Products, in conjunction with the government of Canada and the province of Alberta are looking to take advantage of the industrial heartland area. The west of Canada is rich in low-cost natural resources, such as natural gas, as well as deep saline aquifers. This is perfect for blue hydrogen production. The complex is being built to supply hydrogen for use in the area.

The project is estimated to cost \$1.11 billion USD and is expected to be onstream in 2024. The complex will make use of 55 km of existing hydrogen pipelines in the area which are currently operated by Air Products. The hydrogen will be supplied to industry where it can be used by pipeline. It will also be liquefied and transported by truck for use in FCEVs and other uses.

### Air Products' World-Scale Net-Zero Hydrogen Energy Complex



## ASIA-PACIFIC (APAC)

### OVERVIEW

The APAC region contains both strong consumers and suppliers for hydrogen. China is the largest consumer of energy in the world (24%) and India is the third largest (6%) in 2020. Meanwhile, countries including Australia are rich in renewable energy. This provides opportunities to form regional hydrogen partnerships. Overall, countries in the APAC region have quite positive sentiments towards the adoption of hydrogen, and we believe that green hydrogen will take the lead in the region.

### Partnerships within the Region

Australia is at the forefront in building partnerships within the APAC region. From the resource side, the country has a vast amount of land, wind energy and solar energy. From the policy side, the Australian government is supportive to hydrogen production, and will devote USD 409 million to develop new international technology partnerships in reducing emissions.

The great potential to achieve large scale production of green hydrogen and green ammonia creates favourable conditions for the country to form regional partnerships. For example, Australia and Singapore announced in June 2021 that they will establish a USD 21.6 million partnership to apply hydrogen to decarbonise maritime and port operations. Japan and Korea have formed a cooperation on hydrogen and fuel cells with Australia in 2020 and 2019 respectively.

The development of partnerships also moves beyond the APAC region. Germany and Australia signed a bilateral alliance in June 2021, aiming to develop a green hydrogen supply chain between the two countries.<sup>5</sup>

<sup>5</sup> [www.reuters.com/business/sustainable-business/germany-prepares-set-up-hydrogen-accord-with-australia-2021-06-13/](https://www.reuters.com/business/sustainable-business/germany-prepares-set-up-hydrogen-accord-with-australia-2021-06-13/)

## Use Cases and Infrastructure

In the APAC region, it is common for hydrogen to be used as feedstock in industrial processes. In the future, there could be growth in other emerging sectors including transportation and energy storage.

70% of the current hydrogen demand in China is used in the production of ammonia and methanol. In the future, the transportation sector could be a major demand driver in China, mainly from the adoption of fuel cell commercial vehicles. The promotion of FCEVs in China is frequently mentioned in various policies. The stock of FCEVs was around 6,000 in 2019, and the country targets 50,000 in 2025 and 1 million in 2030.<sup>6</sup> Meanwhile, the development of infrastructure is also underway. For example, the major state-owned gas and chemical company Sinopec announced that the company will construct 1,000 hydrogen refuelling stations by 2025<sup>7</sup>, leveraging its existing gas and petrol station network. Such approach could reduce the cost and speed up the process of infrastructure development for FCEVs.

Japan has more than 40 years of history in developing hydrogen and fuel cell related technologies. It is the first country to introduce commercially viable fuel cell electric vehicles (FCEV). In the Strategic Roadmap for Hydrogen and Fuel Cells published in 2014, Japan announced goals to promote fuel cell technology, including having 200,000 FCEVs and 320 hydrogen refilling stations around 2025, and having 800,000 FCEVs by 2030.<sup>8</sup>

Korea has been developing a comprehensive national hydrogen blueprint since 2005. In January 2019, the government announced its Hydrogen Economy Roadmap, setting goals for various hydrogen production technologies and use cases. In terms of fuel cells, Korea aims to have 79,000 passenger FCEVs by 2022 and 5.9 million by 2040. The goal for hydrogen stations is 310 by 2022 and 1,200 by 2040. Besides the transportation sector, Korea also aims to use fuel cells for power generation. The country aims to develop 15 GW of fuel cell power plants and 2.1 GW residential fuel cell capacity by 2040.

## CASE STUDY – 500 HYDROGEN FUEL CELL DUMP TRUCKS ADOPTED IN GUANGZHOU CITY OF CHINA<sup>9</sup>

We expect transportation, especially hydrogen fuel cell commercial vehicles and trains, to be the area where the demand for hydrogen would grow more rapidly. For example, the city of Guangzhou in China, has already deployed 500 hydrogen fuel cell dump trucks in the city's waste management system. The fuel cell trucks are produced locally in Guangzhou, and they can travel 400km per refuelling. Each refuelling only takes around 8-15 minutes, which facilitates less downtime for the fleet. The adoption of the fuel cell fleet helps Guangzhou city to improve its environment. Compared to traditional dump trucks, it is estimated that those 500 trucks would reduce carbon emissions by 35,000 tons per year.

In the Hydrogen Industry Development Plan 2019-2030 announced by the city of Guangzhou, it is indicated that by 2022, 10% of the new vehicles in its dump truck fleets will be fuel cell ones, and at least 30% of the vehicles in the city's bus and dump truck fleets will be fuel cell by 2025.

Currently, hydrogen fuel cell dump trucks cost twice as much as traditional dump trucks and carry around 15% less load than traditional ones. Therefore, it is important for hydrogen trucks to improve their cost competitiveness and performance in the next decade, in order to implement on a larger scale.

## SOUTH AMERICA

### OVERVIEW

There is limited internal demand as the continent focuses on hydrogen exports however, a large mining industry will exhibit some demand for hydrogen. Furthermore, there is a healthy chemicals industry (often linked to mining) which will utilise some of the green hydrogen production. The continent currently relies heavily on hydropower for its energy mix however due to changing weather conditions year on year, this can be unreliable. As such, utilising hydrogen to store the renewable energy in the medium to long term should be explored. Hydrogen is not the only technology being considered in the region however with several large-scale battery projects underway as a different solution to the reliability issue. It is also key to consider the storage solutions in this region. Currently ammonia is favoured due to the large industry already present however, Liquid organic hydrogen carriers (henceforth referred to as LOHC) are also under consideration as are compression and liquification techniques. With most of the research in this area being led outside of the region it has further strengthened ties with Europe and the USA.

<sup>6</sup> [www.theicct.org/blog/staff/china-sketching-roadmap-hydrogen-vehicles-aug2020](https://www.theicct.org/blog/staff/china-sketching-roadmap-hydrogen-vehicles-aug2020)

<sup>7</sup> [www.reuters.com/business/sustainable-business/sinopec-launch-first-green-hydrogen-project-2022-05-25/](https://www.reuters.com/business/sustainable-business/sinopec-launch-first-green-hydrogen-project-2022-05-25/)

<sup>8</sup> [www.eu-japan.eu/sites/default/files/publications/docs/hydrogen\\_and\\_fuel\\_cells\\_in\\_japan.pdf](https://www.eu-japan.eu/sites/default/files/publications/docs/hydrogen_and_fuel_cells_in_japan.pdf)

<sup>9</sup> [www.inf.news/en/economy/c611167818b706da71f7aae02db05035.html](https://www.inf.news/en/economy/c611167818b706da71f7aae02db05035.html)



## Mining/heavy industry

With a substantial proportion (c. 50%) of the world's copper supply originating in this region as well as silver and gold, decarbonising this industry is of high importance. The carbon intensive nature of mining and refining means a transition to hydrogen and renewable power would have significant impact. Furthermore, the policy makers in the region are keen to work towards decarbonising this industry using hydrogen as it is believed electrification is not possible.

### CASE STUDY – RAGLAN MINE QUEBEC

An example of a mine whereby renewable power is used to generate green hydrogen on site. Initially used due to the remote location and good capacity from wind power making the hydrogen generation commercially viable. However, should technology continue to improve we may see an increase in similar projects especially in South America where renewable capacity is so widespread.

In this mine we see a combination of electricity generated by diesel electric generators as well as by wind turbines. Hydrogen is stored on site as backup power for when the turbines cannot match the required load. This provides us with an example of renewable energy storage using hydrogen and demonstrates the use case.

This use of wind power accounts for 10% of the mine's electricity usage and is equivalent to removing 2,700 vehicles from the road network (12,000 tonnes of CO<sub>2</sub>). Although not a perfect example, as the mine is not powered by solely renewable power the use concept is proved.

In conclusion, the use case for temporary storage of hydrogen has been proven and as development and investment continues, South America presents itself as an ideal candidate for such a project.

## Regional Energy Storage

Many of the regions in South America (e.g., Ceara, Brazil) operate near 100% renewable power grids and so the cost/environmental impact of generating green hydrogen is minimal. This means the opportunity for both island type and grid connected electrolyzers are feasible throughout the region but also a necessity to increase storage capacity for renewable power allowing a greater dependence on it without the drawbacks discussed.<sup>10</sup>

Development of this infrastructure also leads to capability for excess hydrogen generation – this may be utilised in areas where electrification is not possible e.g., rail and trucking networks.

## Export

The low cost of renewables in the region leads to low-cost green hydrogen – see supply section. Hydrogen usage globally will rise as technology continues to develop and more transport/heavy industry begins to rely upon it. Europe and the USA may be priced into importing low-cost hydrogen from South America due to the low-cost renewables. Furthermore, much of South America has well established shipping and export routes due to mining and other exports therefore, hydrogen would easily funnel into similar transport links.<sup>11</sup>

## Chemical Manufacture

South America is not world leading in many exports aside from mining, however, there are still significant explosive and ammonia exports from these countries. As these enterprises become more environmentally considerate and costs fall, we should expect these exports to increase - especially as the world's shift towards zero carbon materials accelerates.

## Key potential importers

It is important to note much of the exports rely on Europe, China and the USA with China and the USA taking a lion share. This is due to geographical proximity and establishment of current trade routes.

<sup>10</sup> [www.fch.cl](http://www.fch.cl)  
<sup>11</sup> [www.lea.org](http://www.lea.org)





## AFRICA

### OVERVIEW

Africa has huge potential in producing green hydrogen at a low-cost due to its abundance in renewable potential. Due to a lack of internal demand, however, Africa is expected to export most of its hydrogen, with the rest possibly going into certain African countries like Morocco who have a well-established fertiliser industry, currently the biggest demand for hydrogen globally.

#### Export

Africa has a substantial amount of potential renewable capacity that is able to produce green hydrogen at a low cost. However, this capacity is unexplored – see supply paper. The lack of renewable capacity in Europe to meet its hydrogen demand could see Europe investing in African renewable capacity and developing Africa as its hydrogen producer. With significant amount of investment Europe brings in, green hydrogen production in Africa is likely to rocket after installation of renewable farms. Although currently hydrogen is blended in natural gas grids with a maximum share of 20%, development of LOHC which has diesel property can largely accelerate exports of hydrogen by existing well-established fossil fuel pipeline network that connects Africa and Europe.

#### Mining

The mineral industry in Africa is the largest in the world with the largest reserves in many minerals like platinum group metals (PGM), which South Africa holds 80% of its global reserves. PGMs are indispensable in electrode and electrolyte for green hydrogen production. As the globe transitions into hydrogen economy, escalating demand and supply for green hydrogen will expand mining of PGMs in Africa to a very large scale, which makes decarbonisation of PGMs mining industry for Africa crucial for environmental concerns and economical concerns due to possible future carbon tax on imports. Hydrogen is the ideal fuel for heavy duty vehicles in the mining industry because hydrogen's high energy density ensures their required long mile range and large horsepower. To give an example, Anglo American, a global mining company, announced its collaboration with Engie to design hydrogen powered mine haul trucks and build a 3.5MW electrolyser onsite for fuelling in Mogalakwena PGMs mine in South Africa owned as part of its plan to decarbonise its mine industry.

### CASE STUDY – GREEN AMMONIA IN MOROCCO

Morocco is the world leading fertiliser exporter with a strong presence in the international market. Morocco's mostly state-owned OCP Group is the largest fertiliser exporter to Africa, with 58% market share in 2019, and is also the dominant exporter to both America and Europe with market shares of 35% and 33% respectively. While being a large fertiliser exporter, Morocco is the fifth largest ammonia importer worldwide, which is the feedstock to synthesis fertiliser, importing around 1.6Mt of grey ammonia in 2019.<sup>12</sup> Production of grey ammonia relies on production of grey hydrogen, which currently uses fossil fuels as feedstock – see Ammonia Briefing Sheet Green ammonia, however, is synthesised from green hydrogen produced from electrolysis. With the abundant renewable capacity in Morocco, green ammonia can potentially be produced at a comparable cost with grey ammonia, thus integrating and decarbonising Morocco's fertiliser industry. Efforts have been made. HEVO Ammonia Morocco Project with an investment of \$850m plans to produce 183,000t of green ammonia per year from off-grid solar-hydrogen farms.<sup>13</sup>

<sup>12</sup> Morocco World News (2020), Morocco Remains World's Largest Exporter of Phosphate, Phosphoric Acid

<sup>13</sup> Clifford Chance (2021), FOCUS ON HYDROGEN: A NEW ENERGY FRONTIER FOR AFRICA

## MIDDLE EAST

### OVERVIEW

The Middle East has world's largest reserves of fossil fuels upon which its economy largely depends, whether it be for exports or domestic energy consumption. With its abundant fossil fuels, ideal for blue hydrogen, and renewables, ideal for green hydrogen, the Middle East's hydrogen production has huge potential to escalate for exports if these resources are exploited for the hydrogen economy. Countries like Saudi Arabia are taking the lead to invest heavily in its hydrogen economy. As Europe gradually transitions into a hydrogen economy and puts carbon tax on fossil fuels imports, we believe that other countries in the Middle East will be forced to speed up their decarbonisation and transition into hydrogen by scaling up hydrogen production and exports.

#### Export

The Middle East has geological proximity as a future hydrogen exporter. It sits equidistant between the two biggest hydrogen consuming markets - Europe and Asia. It connects these together with well-established network of fossil fuel pipelines and marine transport networks. By exploiting existing infrastructure, hydrogen can be transported from the Middle East to end users at a relatively low cost. With the development of LOHC which has diesel-like properties to transport hydrogen in the future, we believe that the Middle East is expected to be one of the world's top hydrogen exporters. Hydrogen can then be synthesised into LOHC and transported in the same way as oil and gas nowadays in existing pipelines, marine fleets and trucks. Because of its large reserves of fossil fuels and depleted oil and gas fields, the Middle East is expected to focus on producing blue hydrogen before 2050. Producing blue hydrogen does not need water like green hydrogen does, which is a scarce resource in many parts of the world, and the focus on blue hydrogen allows Middle East to produce hydrogen with a stable output and relatively low cost, giving it comparative advantage over other green hydrogen exporters.

#### Refinery

Currently the second largest demand for hydrogen comes from the oil refinery industry. As the Middle East largely exports crude oil, it has relatively a small size of refinery capacity: Saudi Arabia, Iran and UAE (United Arab Emirates) had the 7th, 8th and 15th largest refinery capacity in 2020, which in combined was still smaller than the United States. While the potential market size for hydrogen in this sector is small in the Middle East, by leveraging its potential low cost of green and blue hydrogen comparable to grey hydrogen, the Middle East has the driving force to decarbonise its refinery industry by using these low or zero carbon hydrogen.



## USE CASE EXECUTIVE SUMMARIES

For detailed analysis please refer to the industry specific briefing sheet.

### HYDROGEN USE CASES FOR HEAVY INDUSTRY, AVIATION, TRUCKING, SHIPPING, CONSTRUCTION AND MINING

Across the industries mentioned the need to transition to renewable energy is paramount due to the high carbon footprint associated with their usage. The current methodology of how this transition will occur is split between hydrogen combustion engines and fuel cell technologies. This is because electrification is not possible within such working vehicles given the long recharge times compared with long working days these machines are required to work. Each industry will require a bespoke solution although currently aviation and shipping are far from ready for this transition. In the case of trucking and HGVs' fuel cell technologies dominate with large investments already present throughout much of Japan and Europe. Hydrogen technologies also face competition from electrification in the trucking industry however generally hydrogen is accepted as a superior solution. Whilst in the construction and mining industry cost competitiveness of hydrogen combustion engines make them the most favoured option.

### PASSENGER TRANSPORT – PASSENGER CARS AND TRAINS

Hydrogen FCEVs (Fuel Cell Electric Vehicles) have the potential to be an important driver for the decarbonisation of the transportation sector. For hydrogen vehicles, hydrogen is stored in hydrogen tanks and is converted in fuel cells to electricity to power electric motors. They have two major advantages over their competitors EVs (Electric Vehicles): much longer range and shorter refuelling time. However, current sales figure of hydrogen FCEVs is significantly lower than EVs because of the lack of hydrogen refuelling stations and safety concerns regarding hydrogen. For hydrogen fuel cell trains, the use faces less barriers. Hydrogen fuel cell trains function similarly to FCEVs. Apart from longer range and less downtime, hydrogen trains have another advantage over electric trains in terms of lower total cost of ownership. As they require less electrical infrastructure change, hydrogen trains could be an ideal replacement for the diesel fleet over electric trains.

### AMMONIA (CHEMICAL USE CASE) – FERTILISER AND MARINE FUEL

Ammonia production is likely to be one of the first industries to adopt green hydrogen for decarbonisation. Ammonia currently has the biggest demand for hydrogen because of its strong use case in fertiliser production, but almost all hydrogen used is grey hydrogen. Scientifically transition of ammonia production plants into green hydrogen is easy, and low renewable electricity price in some countries is already able to produce green ammonia (ammonia produced from green hydrogen with zero carbon emission) at a cost comparable to conventional ammonia. The fertiliser industry can be decarbonised by using green ammonia, and carbon taxation scheme in the EU acts as a driving force for this transition. The other use case of green ammonia is as a marine fuel. This concept is far from the reality as governments currently are unengaged in decarbonising marine transport and scientific breakthrough in ammonia engine is slow as a result. However, as governments realise the importance in decarbonisation of marine transport, green ammonia as well as green hydrogen's demand is expected to boom thanks to the ammonia's superior property as marine fuel: relatively high energy density and zero carbon emission nature; and mature industry experience in handling with its transport and storage.

### HEATING – HYDROGEN BLENDED HEATING AND HYDROGEN HEATING

There are two main methods for using hydrogen for heating. Firstly, hydrogen can be blended with natural gas. This will only reduce the amount of natural gas used, not eliminate it, but allows existing natural gas infrastructure to be used. Secondly, hydrogen can be used on its own. This requires specialised hydrogen infrastructure but could allow heating to be fully decarbonised. This means that while blended hydrogen heating could be a short-term solution to reduce carbon emissions, only hydrogen heating is likely to be the long-term solution to reach carbon neutrality. The main risk of these two concepts is heat pumps, which can operate at a much higher efficiency than hydrogen heating.

### INDUSTRY – STEEL AND CEMENT

Hydrogen can be used to reduce carbon emissions in the steel industry by replacing coal, coke, natural gas, or any other polluting compounds as a reducing agent. Hydrogen-reduced steel is currently produced by retrofitting existing steel mines and constructing on-site electrolyzers, a methodology that does not

require significant infrastructure development. As current cost of production of green steel is higher than traditional steel, steel manufacturers must conduct a thorough assessment of anticipated green steel demand and should secure necessary partnerships within themselves and with big steel consumers, otherwise the increased steel price may result in consumers switching to alternative traditional steel suppliers. Unlike steel industry, the cement industry does not plan on using hydrogen exclusively as a kiln fuel, as it is too expensive and unabundant. Instead, the industry will focus on using CCUS to reduce carbon emissions



# HYDROGEN USE CASES FOR HEAVY INDUSTRY, AVIATION, TRUCKING, SHIPPING, CONSTRUCTION AND MINING

## WHY IS HYDROGEN BEING CONSIDERED FOR USE IN HEAVY INDUSTRY, SHIPPING AND HGVs?

The freight and heavy industry sector contributes a significant proportion of global carbon emissions and as carbon taxes and similar penalties begin to take hold, running costs in these industries are set to rise. One solution to decarbonising these industries is electrification. However, as will be discussed, many of the heavy industries are not well suited to this. Hydrogen fuel cells require large amounts of storage space for the hydrogen tanks. Therefore, because space is at less of a premium in HGVs and heavy vehicles compared with passenger vehicles; hydrogen is more suited for these larger vehicles. Throughout this paper the scientific use case of hydrogen and industry specific analysis will be explored.

## SCIENTIFIC OVERVIEW OF USE CASE – HOW DOES HYDROGEN FIT INTO THESE INDUSTRIES?

### Hydrogen fuel cells

This method uses the electrochemical recombination of hydrogen with oxygen to produce electricity; the only direct product is water. Technology is moving into a commercial stage now with operating temperature of cells approaching 200°C. Fuel cells boast excellent efficiency of up to 80% compared with traditional fossil fuels which have an efficiency of order 25%<sup>1</sup>. However, fuel cells still require an electric motor and in-situ hydrogen storage for use. If the hydrogen is stored as a compressed gas, then it presents both a safety risk and will fill a large space.

Due to these requirements fuel cells are a highly expensive technology; costs will fall as technology matures and investment continues, but this is longer-term. The lack of moving parts does result in lower maintenance costs compared with combustion engines due to lower wear and tear.

### Hydrogen combustion engine

This method is very similar to the conventional combustion of fossil fuels we use currently, a very mature technology with recent development minimising NOx production – previously one of the downsides to hydrogen internal combustion. The efficiency of this method is roughly equal to that of combustion engines (between 25% and 30%).

Combusting hydrogen allows current drivetrains to be used leading to far lower costs, it is also very competitive with fossil fuel vehicles due to maturity of technology. Furthermore, it also has low build cost of the engine compared with a fuel cell.

## INDIVIDUAL USE CASE ASSESSMENT

### Aviation

Aviation shows little to no promise in utilising hydrogen the next 10 years when it comes to long haul flights. A handful of ventures are claiming to be developing short haul passenger flights but making these commercially viable is still a distant prospect.<sup>2 3</sup>

### Opportunities

Building the infrastructure early on will give a dominant market position and, due to the lack of competition in the infrastructure space for this industry, it would give a solid head-start for development of both infrastructure and expertise.

### Risks

Any investment into this sector is a long-term affair. Multiple companies are already developing needed technology, however, due to the infancy of this technology, there is likely little uptake for infrastructure in the near future.

<sup>1</sup> Energy Environ. Sci., 2019,12, 463-491  
Kumar, A. and Sehgal, M., "Hydrogen Fuel Cell Technology for a Sustainable Future: A Review," SAE Technical Paper 2018-01-1307, 2018

<sup>2</sup> lea.org  
<sup>3</sup> Zeroavia.com

### Stirling Infrastructure's View

Aviation is too early in its hydrogen development to begin significant infrastructure development.

### Heavy Machinery – Excavators, forklifts, and dump trucks etc.

Both the construction and mining industry present examples of successful hydrogen implementation. Several of these are due to difficulty providing fossil fuels to site, so production of hydrogen in-situ by electrolysis from wind or solar power is more economically viable. There is a use case for both fuel cells and combustion engines.

### Opportunities

The difficulty with electrification in this sector comes from the long working days of many machines (running double shifts up to 18 hours). Electrification would incur a massive increase in weight of machines due to the large batteries required. Long charge times of electrified vehicles also compare poorly with the 5 to 10-minute hydrogen refuelling time. However, combustion engines are currently approximately a third of the cost compared with fuel cells – which gives combustion engines a near term advantage.

In order to maintain refuelling stations on site, this would require the development of hydrogen distribution hubs when local production is not possible. Mining favours local production due to long term fuelling requirement of the site.<sup>4</sup>

### Risks

The cost of green hydrogen is high, yet this will decrease as the level of distribution increases. To minimise costs, hydrogen solutions must be rolled out on a large scale. For a large scale roll out to be successful, massive subsidies are required and due to the lack of government policy commitments regarding hydrogen solutions the risks associated with this are heightened. There is no consensus on the best path to take as different market leaders are presenting different solutions. Furthermore, the only current commercial example of hydrogen in this industry is use in a microgrid. Although a microgrid presents a demonstration of the concept it lacks the size to demonstrate economic viability for a large-scale rollout. As such further confirmation projects would be required to push the industry towards a hydrogen economy.

### Stirling Infrastructure's View

Heavy industry shows promise with hydrogen due to fast refuelling times compared with electric equivalents. Hydrogen combustion engines seem a more economical route at first although, in the future it is possible fuel cells could become cost competitive. The issue surrounding delivery of hydrogen and cost of the fuel for the end user remains to be resolved however the need for subsidy to enable implementation is a certainty.

### HGVs

With hydrogen trucking fleets already in operation on a pay by use basis, the concept is proven. The large-scale implementation is planned in certain geographies however many countries are yet to release a full strategy. Some countries have highly aggressive FCEV deployment targets, such as Japan, and with a majority of FCEVs predicted to be HGVs due to the lower premium on space the outlook is positive.<sup>5</sup> Currently Japanese manufacturer, Hyundai, is in partnership with a Swiss firm whereby they operate a FCEV trucking fleet on a pay by use basis to lower costs to the end user.

### Opportunities

The HGV sector places greater demand on refuelling time, range and reliability than the passenger market where cost and space are at a premium. The competition is between fuel cells and combustion engines however, several companies have already formed partnerships to bring economic viability to fuel cell trucks which can cost three times that of a diesel truck and twice that of an electric counterpart. There is far less development in the HGV combustion engine space with respect to hydrogen than we see in the heavy machinery sector.

<sup>4</sup> jcb.com  
<sup>5</sup> Tesla.com



Market leaders are keen to press the roll out of fuel cell trucks compared with hydrogen combustion engines. With many refuelling stations under development. Furthermore, HGV routes are pre-planned and as such a relatively small number of refuelling depots would be required compared to the passenger vehicle market. These depots would likely be larger in scale with several market leaders suggesting in-situ hydrogen generation from renewable grid supply or island type nearby renewable supply.<sup>6</sup>

**Risks**

The lack of consensus behind refuelling and hydrogen storage both on the trucks and at depots is cause for concern as a large scale roll out would require a universal supply. The current leading view is to use liquified hydrogen on board the trucks as the universal fuel with no on-board reformation of hydrogen required. Whilst at the depots to reform/generate hydrogen from either a loaded carrier source or electrolyser. The development of any infrastructure in this industry will still require massive subsidy due to the high cost of the fuel cell trucks and the hydrogen industry to fuel them. If this is provided in the geography in question it would seem a sensible investment.<sup>7</sup>

**Stirling Infrastructure’s View**

Hydrogen takes the edge over electric vehicles however high initial costs and lack of supply network on a national level for fuelling present initial difficulty. There are commercial examples of partnerships taking on the capital expenditure and leasing trucks out alongside providing the fuel to them in order to encourage use and prove the concept. The trucks themselves work well with the only sticking point being subsidy requirement for the operation.

**Shipping**

A strong use case similar to the other heavy industry due to the carbon intensity of the industry. However the lack of ships capable of running on the fuel makes the need to implement infrastructure in ports and alike obsolete. It is widely accepted large freight ships which run on hydrogen will not be commercially available for at least a decade.

**Opportunities**

Small scale ferries are in operation and under development with several cargo sized ships reportedly under development for delivery within the next five years. These are however all one-off pilot projects to prove a concept and as such commercial viability will not be reached for a minimum of 15 years. Once again ships have massive capacity for fuel storage and batteries are not a solution for energy storage. Alongside this the storage on ships could be carried out using a LOHC or other hydrogen storage medium due to the space on board allowing for a reforming device. The Shipping industry is a prolific carbon producer globally therefore a large push on this industry to carbon zero is required to reach Paris agreement goals. Retrofitting of hydrogen technology is also a possibility.<sup>8</sup>

**Risks**

Any investment into the industry is a very early play relying on subsidies which are currently not present. Although electrification of ships is highly impractical it remains to be seen how hydrogen can fill the gap given a lack of consensus on the technology which is best placed. The fuel cell, combustion engine debate is in its early stages within this industry. Furthermore, the discussion on which form of hydrogen to fuel ships with is even less mature making refuelling investment a shot in the dark without a prior purchase agreement of fuel.<sup>9</sup>

**Stirling Infrastructure’s View**

There is an excellent reason to push the shipping industry to carbon zero given its global impact. The relative ease of refuelling infrastructure due to well defined routes and port locations further supports the use case. Globally there is a lack of ships capable of using the fuel and with little consensus on the position of hydrogen in the sector it is too early for significant investment.

6 lea.org  
7 Ourworldindata.org  
8 Swzmaritime.nl  
9 statkraft.com

**PASSENGER TRANSPORT – PASSENGER CARS AND TRAINS**

**HYDROGEN FUEL CELL PASSENGER CARS**

**POLICY SUPPORT – DEMAND PROJECTION AND CURRENT ADOPTION**

Hydrogen FCEVs (Fuel Cell Electric Vehicle) have the potential to be an important driver for the decarbonisation of the transportation sector. Many countries have set targets for the adoption of FCEVs, and Japan, Korea, China, and the U.S. are leading in the targets. In 2019, Japan announced that the country is expected to have 200,000 FCEVs by 2025 and 800,000 by 2030, of which 1,200 will be buses. Korea set a target of 2.9mn FCEVs by 2040 in its Hydrogen Economy Roadmap published in 2019. China is also ambitious in promoting FCEVs. The country targets 50,000 FCEVs by 2025 and 1mn by 2030. The state of California in the U.S. also announced that the state will have 1mn FCEVs by 2030.

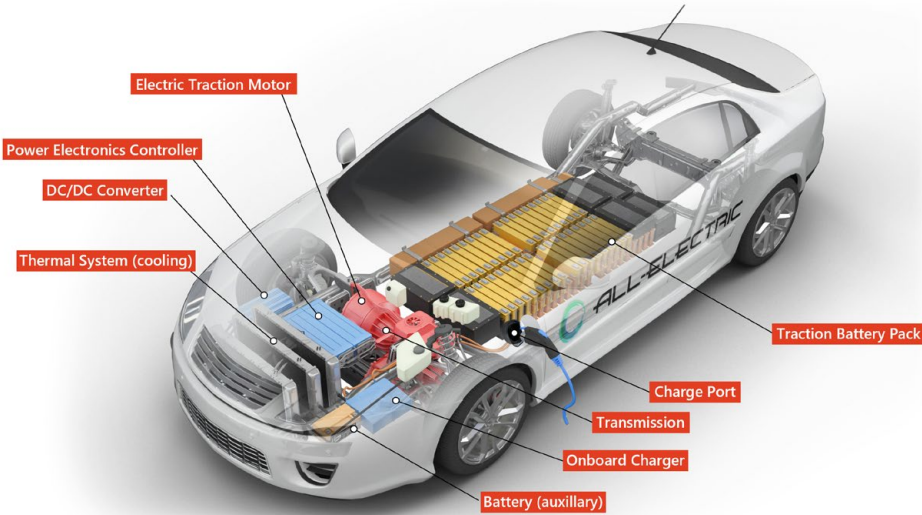
**COMPETITION WITH ELECTRIC VEHICLES**

The tank-to-wheel energy efficiency of EVs (Electric Vehicle) can reach 70%-90%, while FCEVs have significantly lower efficiency, ranging from 25% to 35%. A source of such efficiency difference is the different working processes of their power systems. For EVs, the electric motor is directly powered by the electric battery while for FCEVs, the fuel cell battery first uses the hydrogen stored in its tank to generate electricity, and then the electricity is used to power the motor. The efficiency discrepancy leads to performance disparities between FCEVs and EVs.

Table 1 Comparison between FCEV and EV

Car Type	Toyota Mirai	Tesla Model 3	BMW 3 Series
Fuel Type	Hydrogen fuel cell	Lithium-ion battery	Petrol/Lithium-ion battery
Price	\$49,500-\$66,000	\$39,490- \$56,990	\$41,450-\$54,700
Acceleration 0-60mph	9.2s	3.5-5.1s	4.4-5.6s
Range	400miles	263-353miles	>400miles
Charging time	~3min	0.5-13h	~3min
Technology readiness	Infant	Growing	Matured
Infrastructure readiness	Low	Medium	High
Sustainability	High	Medium	Low

Figure 1 - Key components of an EV<sup>1</sup>

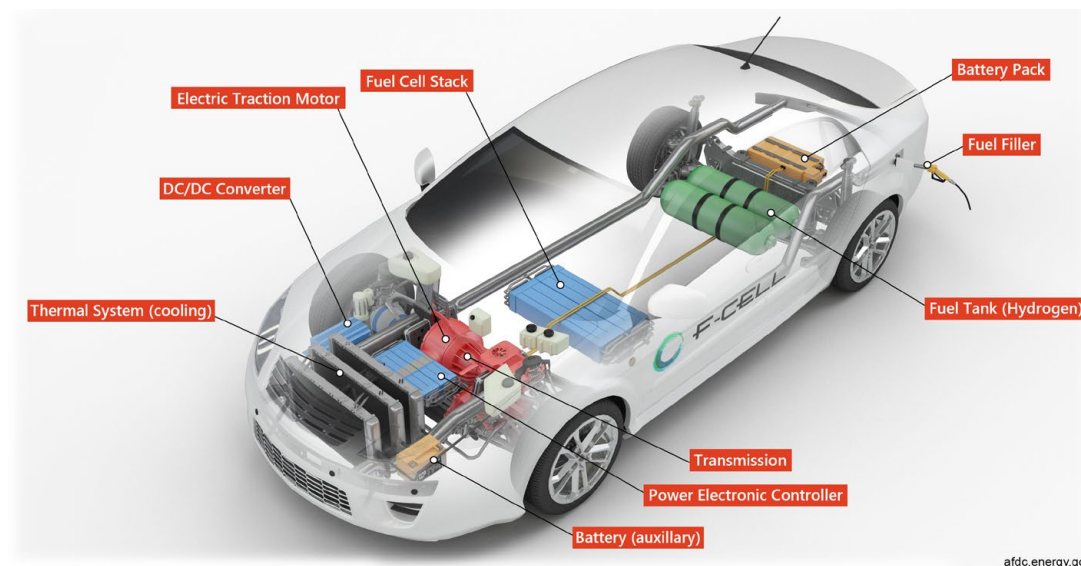


1 US Department of Energy

afdc.energy.gov



Figure 2 - Key components of a FCEV<sup>1</sup>



However, FCEVs have 2 major advantages over EVs. The energy density of fuel cells can reach 33 kWh/kg, while that of EVs is around 0.25 kWh/kg. This allows FCEVs to have a much longer range (>400 miles) than EVs (around 300 miles) given that they carry batteries of the same size. Another advantage of FCEVs is that they have much shorter refuelling time (around 3-5 minutes), compared to the charging time of EVs (30-720 minutes, depending on types and charging method). It is important to note that the relative refuelling convenience of FCEVs also depends on the availability of hydrogen refuelling stations, considering that EV charging stations experienced rapid development across major markets over the past 5 years, while the construction of hydrogen stations is still in the early stage.

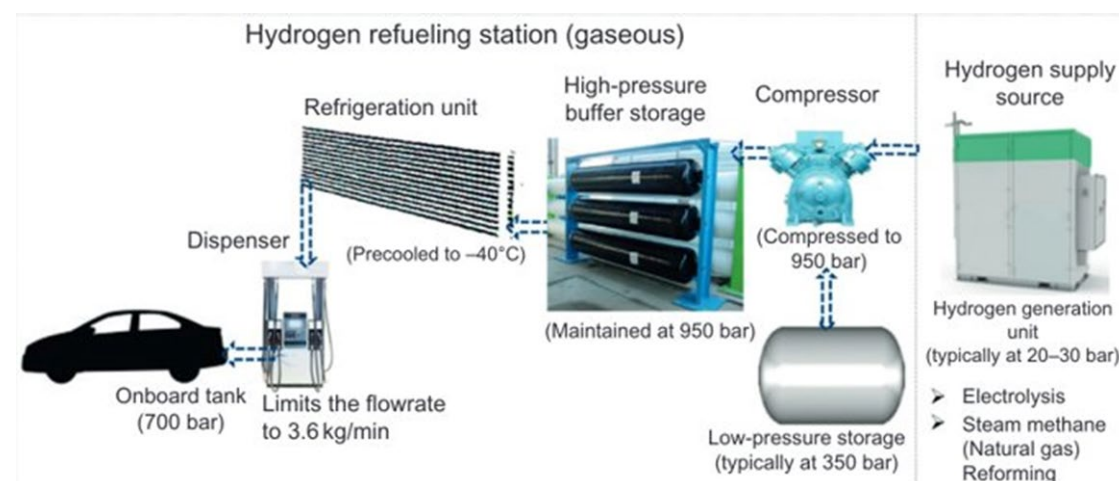
## PASSENGER VEHICLE INFRASTRUCTURE: HYDROGEN REFUELLING STATIONS

### Hydrogen refuelling station (HRS) components

Hydrogen refuelling stations (henceforth HRS) can be divided into 2 broad types depending on the source of its hydrogen supply. For those with on-site hydrogen production, a hydrogen generation unit is fitted within the station and hydrogen can be produced either by electrolysis or steam methane reforming. For those with off-site hydrogen production, hydrogen is transported to the HRS using pipelines or trucks.

As the HRS relies on pressure differences to move hydrogen into the tank of FCEVs, the compressor is a core component for the station, and accounts for 32% of the cost for a HRS with off-site hydrogen production. Another major cost component is the dispenser, which accounts for 14% of cost. Parts like pipelines and storage tanks take 13% and 11% of the total cost respectively.

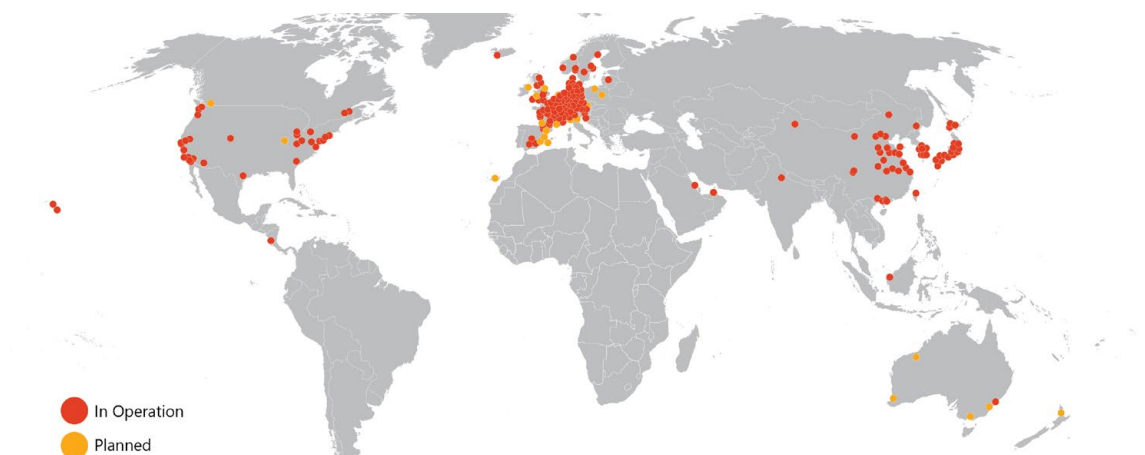
Figure 3 - Overview of a hydrogen refuelling station



### Hydrogen station volume projection

By the end of 2020, Asia had 275 HRS in operation and is the continent with the highest amount of HRS, accounting for nearly half of world's total. Japan is leading the construction of HRS within Asia, with 142 HRS in operation and it is expected to have 900 HRS by 2030. Korea has 60 HRS and China has 69 HRS. However, most of the HRS in China are supplying hydrogen to commercial vehicles including fuel cell buses and trucks, considering the small amount of fuel cell passenger vehicles in the country. China targets 5,000 HRS by 2035 and this implies a period of rapid development for HRS over the next 15 years. Europe had 200 HRS by the end of 2020, with 100 in Germany and 34 in France. The European Union is expected to have 3,700 HRS by 2030. There are 75 HRS in North America, where 49 of them are in the state of California.

Figure 4 - Hydrogen refuelling stations worldwide locations



Source: [www.lbst.de](http://www.lbst.de)

## OPPORTUNITIES

The passenger FCEVs might not have strong growth within the next decade. Commercial FCEVs, instead, is more promising in applying hydrogen to decarbonise in the near term. However, we would not neglect the market of passenger FCEVs, considering the huge market size and potential. There could be greater growth momentum when the performance and relative cost of hydrogen FCEVs becomes more competitive than battery electric vehicles and broader network of hydrogen refuelling infrastructure is in place.

## RISKS

### Slow Adoption of FCEVs

Currently, the sales figure of FCEVs is significantly lower than EVs. By the end of 2020, there were around 33,398 FCEVs (including both passenger and commercial ones) in use around the world, while the figure for EVs is more than 10mn. Considering such a difference, it is hard for FCEVs to catch up with EVs in sales in the near term. The slow adoption of FCEVs relative to EVs may become an important risk in investing in the FCEV industry, as the demand might remain low for the next decade.

### Lack of Convenient Infrastructure

The current development of hydrogen refuelling stations is in the early stage. The convenience of hydrogen refuelling is far less than the charging electricity and gas, considering the huge volume difference between hydrogen stations and charging point and gas stations.

### Safety Concerns

The chemical property of hydrogen makes it a flammable and unstable gas. This leads to safety concerns towards hydrogen FCEVs and hydrogen stations. Several accidents have happened due to hydrogen leakage in hydrogen refuelling stations. Some indoor parking spaces and tunnels may ban FCEVs due to hydrogen leakage concerns. For example, the Eurotunnel bans FCEVs from using it but does provide free charging points for EVs, indicating the current gap in infrastructure development and public adoption between FCEVs and EVs.

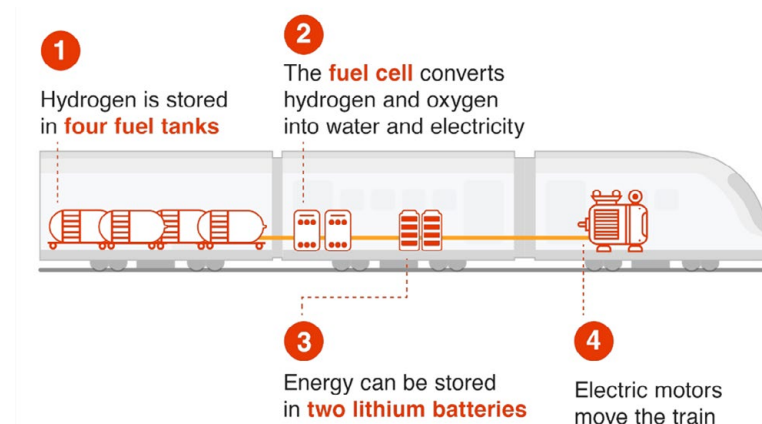


# HYDROGEN FUEL CELL TRAINS

## INTRODUCTION

Hydrogen fuel cell trains function similarly to FCEVs. Hydrogen is used for energy storage and can be converted into electricity to power electric motors. It is a promising area where hydrogen can be used for the decarbonisation of passenger transportation in the near term. At the current stage, hydrogen fuel cells are mainly used to power multiple units, and there are less attempts for shunters and mainline locomotives.

Figure 5 - How a zero-emission train works



Source: University of Birmingham

## OPPORTUNITIES

### Deployment convenience

Hydrogen trains are best suited for longer distances (>100km) where lines have not been electrified or are hard to electrify (e.g., due to lack of urban space). It requires less electrical infrastructure change and could be an ideal replacement for the diesel fleet.

### Less Downtime

Hydrogen trains have less downtime than electric trains. It takes around 20 minutes to refuel, and hydrogen trains can run for 18 hours without more refuelling. There could be centralised hydrogen refuelling stations ready to cut down cost of infrastructure.

### Competitive Total Cost of Ownership

At the current stage, the total cost of ownership for hydrogen trains are lower than electric trains but are higher than diesel trains. The fuel in hydrogen trains accounts for 40-50% of cost today, and the fraction is expected to decrease to 20-30% in 2030, with a hydrogen cost of \$4.5/kg.

## RISKS

The use of hydrogen fuel cell trains faces less barriers than FCEVs, mainly due to its competitiveness in cost, environment, and convenience aspects. However, hydrogen fuel cell trains are not suitable for high-speed services (> 90mph), and the efficiency loss of fuel cells should be considered.

## EXAMPLE PROJECT – ALSTOM'S CORADIA ILINT<sup>2</sup>

The Coradia ILint developed by Alstom is the world's first hydrogen fuel cell passenger train. It started commercial use in 2018 in Germany. With up to 160 passenger seats and 1,000 km autonomy, the train has already been on service for 200,000 km in Germany and Austria.

The fuel cell on the train supplies electricity for both traction and on-board equipment, with a lithium-ion battery to store part of the extra energy and kinetic energy recovered during braking. The train is equipped with an on-board energy storage and intelligent management system to control its energy consumption.

The USD 9.4 million funding of the development comes from Germany's National Innovation Program

<sup>2</sup> <https://www.alstom.com/solutions/rolling-stock/coradia-ilinttm-worlds-1st-hydrogen-powered-train>

for Hydrogen and Fuel Cell Technology. The trains are ordered by several companies in Europe. For example, in May 2019, RMV's subsidiary Fahma had a USD 558.4 million order for 27 fuel cell trains to replace its diesel fleets in the Taunus region. The delivery is expected in September 2022.<sup>3</sup> The order also includes the supply of hydrogen, reserve capacities and maintenance for the next 25 years.

<sup>3</sup> <https://www.railway-technology.com/projects/coradia-ilint-regional-train/>



# AMMONIA (CHEMICAL USE CASE) – FERTILISER AND MARINE FUEL

## INTRODUCTION

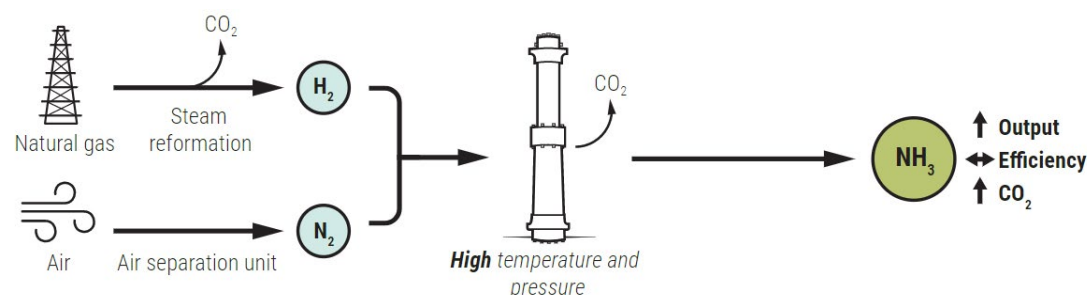
Ammonia has two major use cases: fertiliser and zero-carbon fuel. Since the invention of the Haber Process to produce ammonia at a large scale, it has been one of the most important and widely produced chemicals in the world thanks to its indispensable role as fertiliser in agriculture: currently around 180 million tonnes of ammonia is produced annually and 70%, 126 million tonnes, is used in the fertiliser industry.

Currently ammonia production constitutes the largest demand for hydrogen as its feedstock with 55% of global hydrogen production going into ammonia synthesis. Because of its strong presence in the fertiliser industry over the decades, there is already safety know-how and established infrastructures to store and transport ammonia globally.

## PRODUCTION OF AMMONIA

Ammonia is produced through the Haber Process, a century-old chemical process, which uses nitrogen and hydrogen as feedstocks. They are pressurised and fed into a reactor with high temperature and pressure and iron as catalysts to speed up reactions. Hydrogen gas is produced on-site from either natural gas through Steam Methane Reformation (grey hydrogen) or from coal through coal gasification (brown hydrogen), while nitrogen gas is extracted directly from the air of which over 70% is nitrogen. Currently most ammonia plants globally use natural gas as feedstock except for China, where most plants still use coal which is more polluting than natural gas. The fact that current ammonia production still relies on fossil fuels to produce hydrogen leads to a substantial amount of carbon emissions, accounting for 1.8% of total global carbon emissions. To make the process more environmentally friendly, instead of using natural gas and coal, hydrogen can be produced on-site through water electrolysis from renewable electricity (green hydrogen) which leads to zero carbon emissions for hydrogen production. As no pollutant gases like carbon dioxide and sulphur dioxide are produced, production units to remove these gases are no longer needed so that the design of ammonia production plant can be simplified. There are already some green ammonia projects announced. For example, Air Products, Acwa Power and Neom plan to build the largest green ammonia plant in Saudi Arabia with an annual capacity of 1.2 million tonnes by integrating 4GW of renewable power from solar and wind.

Figure 1 Ammonia production, Source: IRENA



## AMMONIA AS FERTILISER

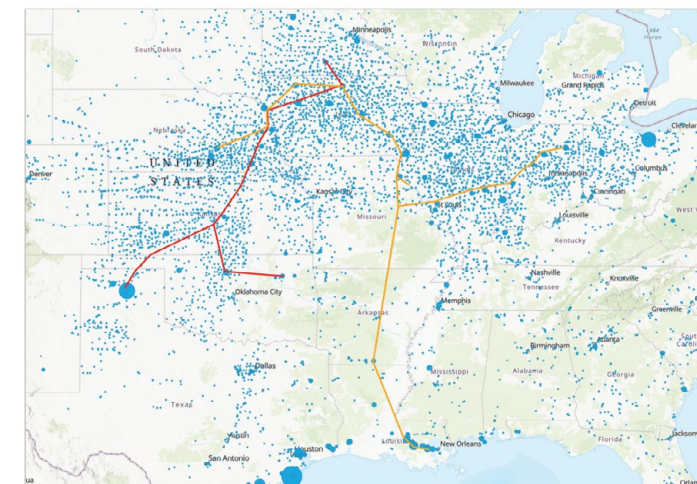
### Existing infrastructure

There are many existing ammonia production plants all over the world, and current ammonia production plants only need minor modifications to introduce green hydrogen for decarbonisation which involves replacing SMR facilities with electrolyzers and sourcing renewable electricity from grid or island solar/wind farms. There is also an established network of ports in the world that handle ammonia at large scale, which facilitates the international trade of ammonia. Considering ammonia's use case as fertilisers, most countries have ammonia pipeline and storage units. For example, in the United States, the fourth largest ammonia production country in 2019, had 3,281 km of ammonia pipelines in operation (with an annual transport capacity of 2 million tonnes) together with 10,000 ammonia storage units.

1 <https://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon>

Figure 2 - Ammonia Infrastructure in USA

Liquefied ammonia storage and pipeline distribution networks in the US Mid-West. The Kaneb (orange line) and Magellan Midstream (red line) ammonia pipelines are respectively 2,000 miles and 1,100 miles long.



Note: The Magellan Midstream pipeline will be decommissioned in 2020. Circle areas are indicative of ammonia tonnage. The largest circles correspond to 100,000 tonne facilities.

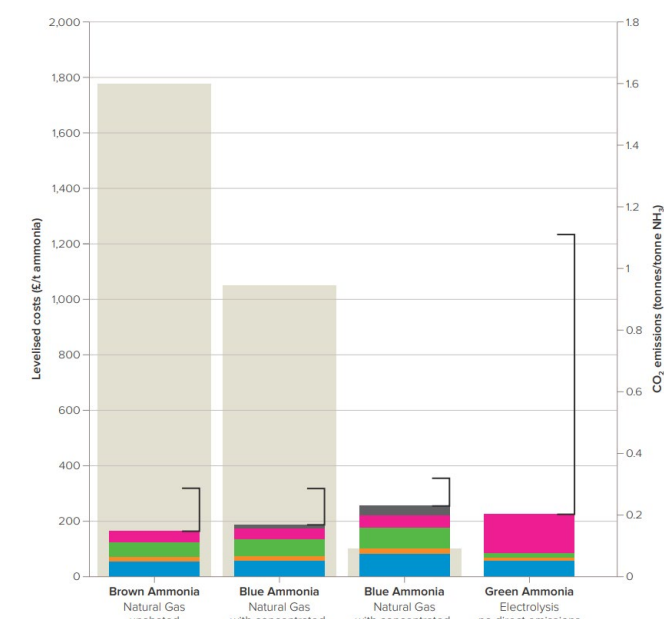
2

## Risks

Currently the cost of producing green ammonia is high, about two to three times higher compared to that of conventional ammonia. This is largely due to the price of renewable electricity, which makes up 85% of the total cost, for producing green hydrogen because renewable electricity is much more expensive than natural gas in most counties.

While the ammonia industry is still carbon intensive using natural gas as feedstock, there are low incentives for governments to decarbonise the fertiliser industry for political reasons. Governments are under pressure to exempt the fertiliser industry from carbon tax due to concerns of rising food prices, which could potentially lead to lowered living standard for the poor and a lost competitiveness in the international food export market. Direct subsidies to green ammonia plants might not be a long-term solution as well, as the cost of green ammonia is not a matter of economic scale but of the cost of renewable electricity.

Figure 3 Ammonia production cost breakdown by method



Note: Range refers to the range of total levelised costs across regions, the lower end of the range is disaggregated into cost categories. Electrolysis is assumed to be powered by 100% renewable electricity; the 'feedstock cost' is the electricity for the electrolyser, and 'fuel cost' is additional electricity for the air separation unit, synthesis loop etc. CCUS costs include capture, transport and storage of carbon dioxide; process CCUS is only process emissions; total is process and energy related

3

2 <https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf>  
3 <https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf>



According to The International Energy Agency, by assuming a gas price at 3 to 10 US cents/MMBtu, electrolysis is cost competitive with Steam Methane with electricity prices between 1 to 4 US cents/kWh. However, from research on renewable power generation costs in IRENA, global electricity costs from solar PV, onshore wind and offshore wind are 6.8, 5.3 and 11.5 US cents/kWh respectively.<sup>4</sup>

Although current renewable electricity prices remain high globally, as more renewable power generation plants are installed, and more countries roll out their national decarbonisation plan, we expect green ammonia to be cost competitive with conventional ammonia soon. On a country scale, in countries with abundant renewable potential like Chile and Saudi Arabia, auction prices of electricity from solar PV are 3.2 and 2.3 US cents/kWh respectively, and green ammonia projects in these countries are already announced.

## AMMONIA AS A ZERO-CARBON FUEL IN THE MARINE INDUSTRY

### Ammonia as a zero-carbon fuel

Ammonia has the potential to be a marine fuel thanks to its relatively high energy density and zero carbon emissions nature. Compared with pure liquid hydrogen, ammonia as a hydrogen carrier is less energy intensive to transport and store and has a higher energy density by weight. Thanks to a long history of handling ammonia as fertiliser, there are already established methods regarding the transportation and storage of ammonia. Compared with diesel and petrol, ammonia is less energy dense but there is zero carbon emission when using ammonia as a fuel by either direct combustion in engines or electrolysis in fuel cells.

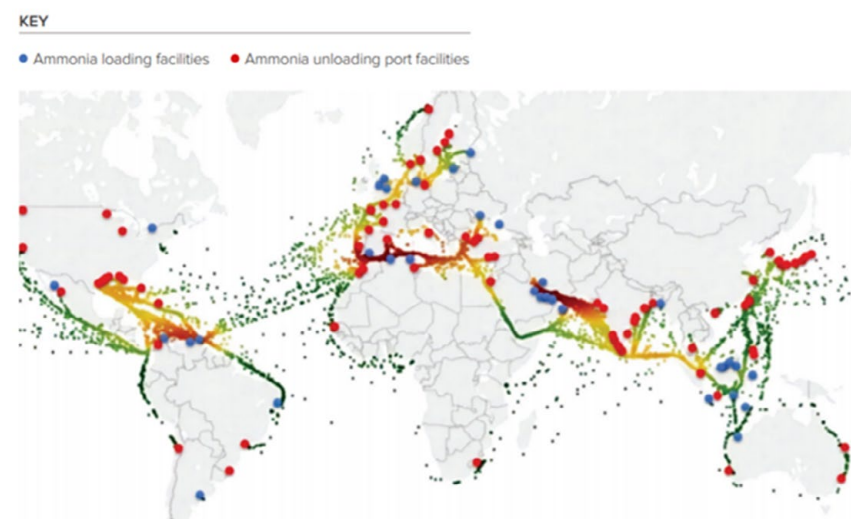
### Ammonia in road and marine transport

Ammonia has potential to be a fuel in heavy industries because its significantly higher energy density than batteries is able to meet the demand for energy for heavy duty vehicles on road and in seagoing marine vehicles. While it is costly to build a network of refuelling stations for ammonia on road and dangerous for ammonia-powered vehicles to carry pressurised ammonia storage tanks, marine industries can make use of existing ammonia storage sites in ports to be refuelling stations and safety issues are not a big concern. Seagoing vehicles like cargo vessels travel on sea where there is low population density, and decades of industry experience to transport ammonia on sea at a large scale has proved the feasibility to store and transport ammonia on ships safely.

### Existing infrastructure

There is a well-established network of ports worldwide that handle ammonia at large scale making refuelling of ammonia easy and possible. As ammonia has been traded internationally on sea for decades, there are existing loading and unloading facilities and large scale ammonia storage tanks in ports. This combination of these two kinds of facilities lays foundations of building potential ammonia refuelling stations for ammonia-powered ships. As an example of scale, there is an ammonia storage tank in the port of LA with a capacity of 150,000 tonnes.

Figure 4 - Existing Ammonia Infrastructure in port



4 IRENA (2019), Renewable Power Generation

## Risks

Little progress has been made in the decarbonisation of the marine industry because of unengaged government attitudes and slow technological developments in ammonia-based engines.

Compared with the decarbonisation of road transport, governments pay little attention to marine transport. No countries have set up plans to ban fossil-fuel ships, but in contrast the EU plans to ban fossil-fuel road vehicles by 2035. Nevertheless, most countries do not take emissions from the marine industry into account when outlining their carbon neutral strategies for 2050. The International Maritime Organisation (IMO), a specialised agency of the United Nations responsible for international shipping, has yet to include ammonia as a legitimate marine fuel. Although the IMO has a decarbonisation plan to cut emissions by 50% compared to 2008 by 2050, its top priority is to stick with conventional fuels and reduce emissions by boosting engine efficiencies and limiting speed.

Due to a lack of government support, private sectors are hindered by these uncertainties to develop ammonia-based engines: no prototype of ships based on ammonia has been completed yet. However, efforts have been made to develop engines powered by ammonia. Current research focus, which is at a very early stage, is to develop internal combustion engines that burn ammonia directly instead of through ammonia fuel cells. To give an example of current progress in ammonia engines, Man Energy Solution, a German ship engine manufacturer, is cooperating with a group of tech companies in Denmark to develop dual fuel internal combustion engines that can burn ammonia as well as diesel. This dual fuel engine aims to offset the uncertainties and cost of building entirely new engines if ammonia fails to be the mainstream fuel in the future.

## STIRLING INFRASTRUCTURE'S VIEW

Ammonia production is likely to be one of the first industries to adopt green hydrogen for decarbonisation. From a scientific perspective, decarbonisation of ammonia production is straightforward by replacing SMR facilities with electrolyzers without significant modification to their overall design. From an economic perspective, cheap renewable electricity prices in some countries already gives the ammonia industry an advantage to produce green ammonia at a comparative cost compared with conventional ammonia. As renewable electricity prices decrease further in the future, we expect to see a strong demand for green hydrogen in the ammonia industry for fertiliser production. Ammonia's potential in marine fuels is huge but it is not expected to become significant in the next two decades unless governments are more engaged in decarbonising the marine industry.

## APPENDIX

### CASE STUDY: YARA

Yara, headquartered in Norway, is one of the largest ammonia manufacturers and distributors in the world, and is pioneering a transition into green ammonia production. It has ammonia production plants all over the world, including countries with abundant renewable capacities, showing great potential to produce green ammonia at a competitive cost. Yara's decarbonisation plan has two initiatives, firstly decarbonise existing ammonia plants to be green by plugging in electrolyzers while secondly building new green ammonia plants.

An example of the first initiative is Yara Pilbara Hydrogen Hub. Yara is cooperating with Engie to turn the largest ammonia production site in the world, located in Pilbara, Australia, into a green plant. With current production capacity of grey ammonia with 850,000 tonnes per year, Yara plans to build a 10MW electrolyser and on-site facility of 18MW PV panels to generate hydrogen as an additional 0.6% of current inputs, with an objective of 3700 tonnes of green ammonia per year.

The second example is Yara's green ammonia project in Porsgrunn Norway. This new green ammonia plant is expected to have a production capacity of 500,000 tonnes per year by using electricity from Norway's energy grid, which is 98% renewable thanks to abundant hydroelectric resources. Yara's intention is for the green ammonia produced from this project to be particularly used as marine fuel.

With the completion of these pioneering projects, Yara is able to represent to the world the feasibility of decarbonising the ammonia industry through green hydrogen. It is also demonstrating its confidence in future green ammonia demand in fertiliser and marine fuel use, which coincides with our conclusion that ammonia production is likely to be the first industry to adopt green hydrogen.



# HEATING – HYDROGEN BLENDED HEATING AND HYDROGEN HEATING

## SUMMARY

### WHY IS HEATING BEING CONSIDERED AS A USE OF HYDROGEN?

Domestic and commercial heating constitutes a significant portion of global carbon dioxide emissions. In fact, ~18% of global CO<sub>2</sub>e emissions were produced by space and water heating in 2018.<sup>1</sup> Hydrogen can be used to help decarbonise this sector because its combustion only produces water and oxygen. This means, if the process used to produce the hydrogen is less emitting than combusting natural gas, hydrogen would be superior to gas heating.

Heating infrastructure varies globally, depending on the resources available and the policies in place. For example, in Iceland, 90% of energy for heating comes from geothermal sources.<sup>2</sup> Here, there would be no use for hydrogen heating because geothermal energy is more efficient and less polluting than most forms of hydrogen production. However, in the USA, over 40% of households are supplied by natural gas for heating. This constitutes a market that will be driven to be decarbonised, and therefore where hydrogen can be used.<sup>3</sup>

There are two main methods for using hydrogen for heating. Firstly, hydrogen can be blended with natural gas. This will only reduce the amount of natural gas used, not eliminate it, but allows existing natural gas infrastructure to be used. Secondly, hydrogen can be used on its own. This requires specialised hydrogen infrastructure but could allow heating to be fully decarbonised.

## OVERVIEW OF USE CASES

### HYDROGEN BLENDED HEATING

#### Science behind blended hydrogen heating

Hydrogen blended heating works in the same way as gas heating works currently. The hydrogen-natural gas blend is combusted within a boiler or gas cooker to produce heat. This means that the consumer does not have to make any behavioral changes.

When hydrogen is blended with natural gas, existing natural gas infrastructure can be used. A blend of up to 20% hydrogen means that gas boilers and cookers will function the same way as they do currently. Furthermore, natural gas pipelines can be used to deliver hydrogen without significant change. A trial project at Keele University, HyDeploy, has provided evidence that consumers do not need to change their behavior when using a 20% hydrogen blend and many do not even notice the difference.<sup>4</sup> However, hydrogen blending can only be used to reduce natural gas use for heating, not to eliminate it. A 20% volume hydrogen blend will only reduce natural gas consumption by ~7% due to the different calorific values of natural gas and hydrogen. Therefore, hydrogen blending can only be used as a transition technology for economies looking to reach net zero.

#### Infrastructure

Because blended hydrogen and natural gas can use existing natural gas infrastructure, most of the infrastructure required for hydrogen blending is already in place. Natural gas boilers do not need to be replaced and gas cookers will function normally. Natural gas pipelines delivering the blend from producers to consumers do not need to be retrofitted when using a blend of up to 20% volume. Therefore, the only real change to infrastructure required would be hydrogen production capacity to introduce the hydrogen. Blended natural gas and hydrogen systems could be a case for increasing production capacity.

The key milestones required for blended natural gas and hydrogen would be:

1. A large sample project proving the effects and feasibility of blending.
2. Hydrogen production infrastructure increases to meet the demand from gas companies looking to reduce their carbon footprint.

#### Risks

- 1 IEA
- 2 ThinkGeoEnergy
- 3 U.S. Energy Information Administration
- 4 HyDeploy

The main risks with hydrogen blending are twofold. Firstly, blending would never be a final outcome and therefore is unlikely to be a long-term solution; the blend will only slightly reduce emissions, not eliminate them. This means that investors and natural gas suppliers are unlikely to see opportunities in this technology. Combined with this, introducing hydrogen is unlikely to be economically viable in the short term when production is limited. This could be alleviated if projects are linked inherently to production, for example if it were combined with an electrolyser in a microgrid.

#### Opportunities

The introduction of blended hydrogen heating can begin the process of decarbonising heating. It could be used as a steppingstone to reach full hydrogen heating. Blended hydrogen heating would increase the demand for hydrogen which the production could then meet. This could provide the groundwork for full hydrogen heating and other hydrogen projects.

### HYDROGEN HEATING

#### Science behind hydrogen heating and comparison with heat pumps

Hydrogen used for heating without blending could be used to reach net zero, provided the hydrogen was produced from green sources. To use hydrogen on its own, boilers and pipelines would have to be retrofitted because natural gas pipelines cannot be used without adaption.

#### Competition with heat pumps

Heat pumps are the main competitor when it comes to net zero heating. They operate by transferring stored heat from the environment (usually the air or ground) to homes. By doing this, heat pumps can operate with efficiencies in excess of 300%. This means that, if only green hydrogen is used to heat homes, heat pumps would be in the order of 6 times more efficient and therefore use 6 times less energy. For this reason, this paper concludes that green hydrogen cannot compete with heat pumps.

As heat pump efficiencies are much higher than hydrogen heating, electricity demand from heat pumps is much less than hydrogen produced by electrolysis. In 2020, if UK domestic natural gas usage was replaced with hydrogen, ~7.7 million metric tonnes (MMT) of hydrogen would be required which is about 460 TWh of electricity. In 2019, if US domestic natural gas usage was replaced with hydrogen, ~41 MMT of hydrogen would be required which is about 2450 TWh of electricity.

#### Infrastructure

Although hydrogen has many similarities with natural gas heating, it is unable to use most of the infrastructure in place. For example, steel natural gas pipelines are unable to transport hydrogen alone because hydrogen will embrittle the metal by a process called hydrogen embrittlement. Instead, plastic pipes must be used to stop this. The added advantage of plastic pipes is the reduction in leakage of hydrogen and, if natural gas is transported in them, natural gas. The UK has already converted a portion of its old iron gas pipelines to new plastic pipes in order to reduce emissions due to leakage. Hydrogen boilers operate similarly to natural gas boilers but will not feasibly be able to be plugged in to existing ones. New hydrogen boilers would be able to function on both natural gas or hydrogen, meaning homes can be hydrogen ready before hydrogen is able to be delivered to them. As with blended hydrogen heating, hydrogen production would need to be scaled up to meet the required demand. If the USA were to convert all of their domestic natural gas usage to hydrogen, they would need to increase their hydrogen production by an order of 5 from 2019 levels.

The key milestones required for blended natural gas and hydrogen would be:

1. A large sample project proving hydrogen heating is able to function in the place of natural gas.
2. Hydrogen production infrastructure increases to meet the demand from gas companies looking to reduce their carbon footprint.

#### Risks

The main risk associated with hydrogen heating is its comparison with heat pumps. Heat pumps can operate at a much higher efficiency than hydrogen heating. This means, if the production of hydrogen is from electricity via electrolysis, for example green hydrogen, then the initial electricity requirement from hydrogen will be ~5-6 times higher.



Replacing domestic heating with heat pumps would increase US energy consumption by ~1/8, so replacing with electrolysed hydrogen and seeing an increase in consumption by ~5/8 is not feasible.

### Opportunities

The opportunity that can be seen with hydrogen heating comes from the use of blue hydrogen. If blue hydrogen was used to supply homes (hydrogen from natural gas with CCUS), then this could remove the efficiency comparison with heat pumps. However, this use of blue hydrogen would also mean that emissions from heating are not completely eliminated as natural gas will still be extracted from the ground and CCUS only reduces emissions by ~80%-95%.

### CONCLUSION

Generally, the view is that hydrogen can only compete with heat pumps if either the relevant subsidies are introduced, or if hydrogen is not produced through the process of electrolysis. If steam methane reforming is used to produce hydrogen, then it is no longer subject to the efficiency comparison. Assuming heat pumps run on the grid, as long as enough carbon dioxide is sequestered in the production process, the use of hydrogen in heating could even be comparable to heat pumps in terms of the positive environmental impact its development could produce.

## INDUSTRY – STEEL AND CEMENT

### INTRODUCTION

Metals, stone, and mud have been the key building blocks for the earliest civilisations. Today, however, the most consumed materials such as steel and cement are also the greatest polluters, respectively emitting 1.85 and 0.5 tonnes of CO<sub>2</sub> per tonne of material produced.<sup>1</sup>

To reduce carbon emissions in this industry, companies will be required to switch to alternative “green” materials, seek a method to reduce the environmental impact of the current processes, or become subject to carbon taxation. With the current European average carbon tax of \$42.49/tonne of CO<sub>2</sub><sup>2</sup>, a European steel company without free allowances or other mitigating measures would be taxed \$78.61 per tonne steel produced.

### STEEL INDUSTRY, SCIENTIFIC OVERVIEW

Steel is the world’s most-used metal. The \$2.5 trillion industry produces ~2 billion tonnes of steel per year and emits 7-9% of global CO<sub>2</sub> emissions due to the energy-intensive process of converting iron ore into pure steel. The production of iron and steel requires temperatures up to 2,000 °C, which is difficult to simulate at a low cost without using carbon, a material that helps generate high temperatures necessary to smelt raw materials.

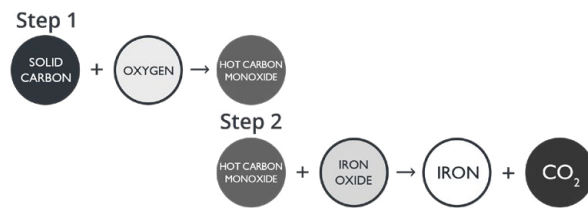
Iron ore and metallurgical coal are currently the two main raw materials used for steelmaking. The mined iron ore must be reduced, meaning that oxygen needs to be removed. This is done by bonding the oxygen molecules with a reducing agent. The carbon intensity of steelmaking largely depends on the type of reducing agent and the technology used.

Two of the most popular methods of steelmaking include:

#### Basic oxygen furnace (BOF) with blast furnace

- 75% of global steel is produced via BOF, with inputs including carbon, minerals, oxygen, iron ore (which is an iron oxide).
- Hot air is injected into a feed of minerals, namely coke, sinter, and lime.
- The reduction process results in liquid iron, which is transported to the basic oxygen furnace, as well as CO<sub>2</sub> and slag.
- In the basic oxygen furnace, oxygen is blown onto the molten iron to reduce its carbon content, creating CO<sub>2</sub> and steel.<sup>3</sup>

Figure 1: Step-by-step process of iron production



#### Electric arc furnace (EAF)<sup>4</sup>

- 25% of global steel is produced with the EAF, developed to overcome the difficulties of conventional BOF.
- The EAF uses recycled scrap metal and electrical power via an electrical arc to convert scraps into liquid metal.
- EAF often produces steel from direct reduced iron (DRI), which is created by reducing iron ore pellets with natural gas instead of coke, to reduce emissions.
- The process is more environmentally friendly, as it uses recycled steel scraps and is less carbon intensive than BOF. In addition, EAF are smaller and more efficient.

<sup>1</sup> <https://www.sciencedirect.com/science/article/abs/pii/S1350630714000387#:~:text=Abstract,all%20other%20building%20materials%20combined>

<sup>2</sup> Where Is Carbon Taxed in Europe? | Tax Foundation

<sup>3</sup> Basic Oxygen Furnace Processing | Thermo-Calc Software (thermocalc.com)

<sup>4</sup> Making iron & steel - DRI furnace | ArcelorMittal



# HYDROGEN OVERVIEW, STEEL

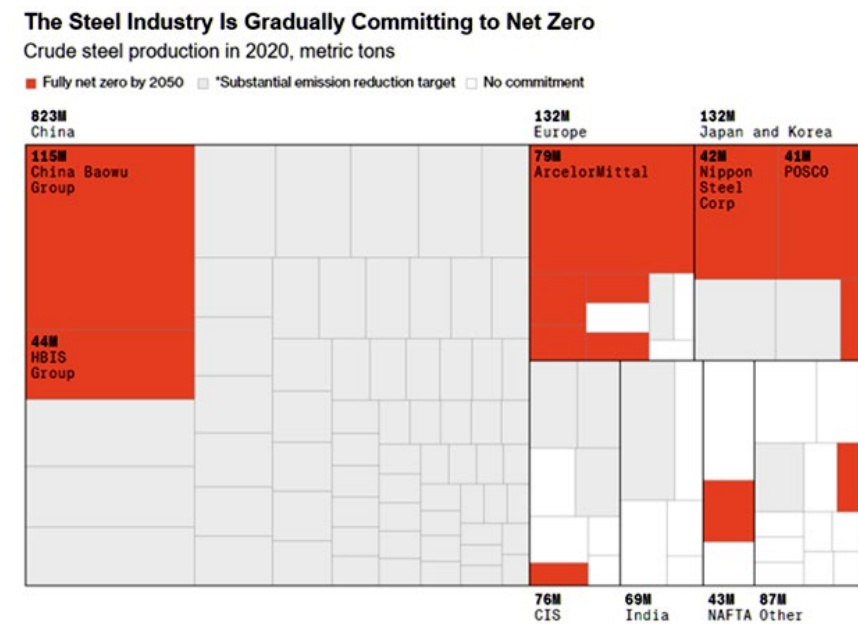
Hydrogen can be used to reduce carbon emissions in the steel industry by replacing coal, coke, natural gas, or any other polluting compounds as a reducing agent. Reducing iron ore with hydrogen would create iron and water vapour as outputs.

# EXISTING INFRASTRUCTURE, STEEL

The top seven of ten largest steel-producing countries have initiated at least one green steel project<sup>5</sup>, particularly in regions with ambitious climate change goals. Although China is the largest steel producer in the world, with Chinese companies occupying 12 positions of the top 20 global players in terms of tonnes of steel produced, it has been reluctant to sacrifice growth to achieve climate plans. In the first half of 2021, coal-dependent steelmaking capacity was expanded to 35 million tonnes by constructing 18 blast furnaces and 43 coal-fired power plants<sup>6</sup> in China.

European steelmakers, pressured by stricter environmental rules, account for 31 of 47 existing green steel projects. Sweden, home to the highest carbon tax in the world at \$137 per tonne CO<sub>2</sub><sup>7</sup>, is investing \$22-51 billion in six projects. Hydrogen-reduced steel is currently produced by retrofitting existing steel mines and constructing on-site electrolyzers, a methodology that does not require significant infrastructure development.

Figure 2: Net-zero goals of companies in China, CIS (Commonwealth of Independent States), NAFTA (North American Free Trade Agreement), and others.



# OPPORTUNITIES, STEEL

## I) Ease of Development

The limited infrastructure required for constructing small-scale green steel operations smooths the transition from fossil-fuel to hydrogen-based steel. Steel producers are gradually substituting their reducing agent from coke to natural gas, to a mix of hydrogen and natural gas, with an end goal of full hydrogen reduction. For this reason, producers can work towards green steel production and hydrogen facility production, without severely interrupting steel production in the existing plant.

## II) Government Support and Incentives

Unlike the transportation industry, the steel industry does not receive significant decarbonisation incentives for hydrogen initiatives. Until recently, it was prohibited to provide state aid to steelmakers in locations including the EU<sup>8</sup>. However, as energy-intensive industries pursue decarbonisation initiatives, there is a greater movement towards funds and subsidies for steel companies. The Innovation Fund

5 Green Steel Tracker - Leadership Group for Industry Transition  
6 China puts growth ahead of climate with surge in coal-powered steel mills | Financial Times (ft.com)  
7 Where Is Carbon Taxed in Europe? | Tax Foundation  
8 FEATURE: Green steel: who's paying? | S&P Global Platts (spglobal.com)

under the EU Emissions Trading Systems is providing \$21 billion over 2021-2030 for low-carbon initiatives in energy-intensive industries, such as steel<sup>9</sup>. In coming years, steel manufacturers may expect increased support for decarbonisation.

## III) Client partnerships with steel consumers

Large steel consumers are also expressing interest in purchasing sustainable metals. The automotive industry makes up 16% of global steel consumption, as the metal is used for the frame, hoods, doors, bumpers, mufflers, fuel tanks and lithium-ion battery casing. Volvo is the first automotive company to commit to consuming green steel. In June 2021 it announced a partnership with the Swedish steel maker SSAB to jointly develop green steel through the HYBRIT initiative, a joint venture between Swedish mining and energy companies to decarbonise the steel industry.

## IV) Segmentation of steel product

Different steel production methodologies produce steel of varying quality. If green steel proves to be equally high or higher quality than regular steel, it may create a niche market for high-quality sustainable steel, which will be able to justify elevated prices. Baowu Steel Group has partnered with Honeywell to create hydrogen-reduced non-oriented silicon steel, which is used as a component for battery electric vehicles (BEVs).

# RISKS, STEEL

## I) Increasing Costs

According to early assessments, green steel is estimated to cost 20-30% more than traditional steel, due to an increase in renewables capacity, hydrogen production, and technology costs<sup>10</sup>. ArcelorMittal, the second largest global steel manufacturer, estimates that costs related to carbon-neutralising will total \$35-47 billion for hydrogen integration and \$236 billion for renewables infrastructure in Europe by 2050<sup>11</sup>. Thus, elevated price risk must be reduced by securing partnerships with consumers and funding from public markets.

## II) Limited Resources

Out of the two primary steelmaking practices, EAF is more popular as the furnaces are smaller, flexible, and use electricity and recycled steel for smelting. However, steel scraps are limited and may create quality problems due to sorting and contamination problems. Thus, green steel producers must explore alternative input production, such as DRI.

## III) Loss of clients

The 20-30% steel price increase may result in consumers switching to alternative steel suppliers or to seek alternative materials for their operations. Thus, steel manufacturers must conduct a thorough assessment of anticipated green steel demand and should secure necessary partnerships.

# CONCLUSION & RECOMMENDATION, STEEL

On a research and experimental scale, with electrolyser capacity at ~5MW as with the Swedish HYBRIT project, hydrogen-induced steel production is feasible and straightforward. However, for the entire industry to decarbonise, green steel producers will need to reconsider steel mill location and infrastructure.

Manufacturers should seek to be well-connected to industrial hubs and ports, which will be key hydrogen suppliers. ThyssenKrupp is constructing a hydrogen pipeline parallel to natural gas infrastructure to supply hydrogen from an electrolyser site in Lingen to a steel mill in Duisberg, Germany<sup>12</sup>. Similar initiatives are being conducted around the Port of Rotterdam in the Netherlands<sup>13</sup>, and in Hamburg, Germany<sup>14</sup>. These large European ports are already securing partnerships for hydrogen import with players including Portugal, Morocco, Oman, Australia, Chile, Brazil, and Canada<sup>15</sup>.

9 swd-competitive-clean-european-steel\_en.pdf (europa.eu)  
10 Microsoft PowerPoint - Electricity\_Generation\_2020\_en\_b.pptx (fraunhofer.de)  
Steel, Hydrogen And Renewables: Strange Bedfellows? Maybe Not... (forbes.com)

11 FEATURE: Green steel: who's paying? | S&P Global Platts (spglobal.com)  
12 Green hydrogen for steel production: RWE and thyssenkrupp plan partnership  
13 Hydrogen in Rotterdam | Port of Rotterdam  
14 https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-iii2-pistol.pdf  
15 Port of Rotterdam Authority and RRP to Study Feasibility of Hydrogen Delta Corridor Pipelines Between The Netherlands and Germany -





## CONCLUSION, CEMENT

As the cement industry has not been actively investing in hydrogen-fuelled kilns, it is unlikely that green sustainable cement will be produced with the help of hydrogen in the next decade. Instead, it is likely that the industry will focus on the implementation of CCUS to reduce carbon emissions. Once carbon capture becomes economically feasible and efficient, cement companies will be able to extend their product offering to include synthetic gas produced from captured CO<sub>2</sub> and hydrogen.

## CEMENT INDUSTRY, SCIENTIFIC OVERVIEW

Cement is the second-most consumed material after water, with three tonnes used per year per capita globally. Like steel, cement requires a high temperature at ~1500°C, which can only be achieved by using carbon-emitting kiln fuels, such as coal, coke, fuel oil and natural gas which are the largest sources of CO<sub>2</sub> emissions. These fuels are difficult to replace, as they are easily combustible, cheap, and readily available.

Minerals including limestone, clay, chalk and silica are ground and baked in a kiln at this high temperature, producing clinker. This powder substance is combined with gypsum, a mineral found in sedimentary rocks, to create powdered cement.

## HYDROGEN OVERVIEW

Unlike the steel industry, the cement industry does not plan on using hydrogen exclusively as a kiln fuel, as it is too expensive and unabundant. Additionally, the safety of hydrogen in a kiln has not yet been tested. Further, cement production is generally centred around abundant raw materials and mines, making it very expensive to connect to hydrogen infrastructure. Instead, cement producers are looking more towards biofuels for decarbonisation methods.

## EXISTING INFRASTRUCTURE

Although the use of hydrogen in the cement industry is still being explored and developed, with the first consortiums submitting funding applications in July 2021, electrolyzers are being installed to include hydrogen in the fuel mix. Hanson, a subsidiary of the sixth largest global cement producer HeidelbergCement, has been producing green hydrogen to replace some of the natural gas used to power the plant.<sup>16</sup>

## OPPORTUNITIES

Alternatively, cement companies are examining hydrogen to expand their product value chain. Instead of using hydrogen to decarbonise the combustion process, an international consortium is planning to capture CO<sub>2</sub> and use green hydrogen to produce hydrocarbons. Hydrocarbons can then be converted into synthetic fuels and various renewable chemicals. “Concrete Chemicals” is a project announced in July 2021 and is run by an international consortium including Cemex, renewable energy company ENERTRAG, and electrolysis company Sunfire.

## RISKS

Hydrogen has not been extensively researched in the cement industry, which creates high barriers to usage. Considering hydrogen will mostly be used for hydrocarbon processing, the greatest risks will be related to carbon capture technology and costs.

<sup>16</sup> Hydrogen Central (hydrogen-central.com)  
Collaboration on green hydrogen research | Hanson UK



## FOR FURTHER INFORMATION

This paper provides insights into trend data with analysis for investors to make an informed investment decision into the hydrogen value chain.

The firm provides a comprehensive range of services which includes M&A transaction services, raising both debt and equity to finance hydrogen projects globally.

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