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Dispelling Myths around Hydrogen

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Key findings

Hydrogen today is currently almost entirely used in either refining or industry. It is mostly produced from natural gas or methanol, with less than 1% of hydrogen production coming from low emissions technologies. However, in the last decade, numerous additional use-cases for hydrogen have surfaced, while plans for green hydrogen production have grown. These have created the impetus for transformational change in the hydrogen sector. In this paper we focus on these new use cases for hydrogen, and how they will evolve in coming decades. We also examine expectations for green hydrogen production costs, and whether hydrogen can eventually compete with other fuels without subsidies. We examine challenges within the hydrogen industry, and how those challenges may be resolved. Lastly, we dispel many of the myths that surround hydrogen.

- ✔ **Hydrogen is versatile, with many use-cases.** Unlike traditional fuels, which tend to have a limited number of markets, hydrogen can be used in many applications, from the oil and gas industry use of today, to steelmaking, chemical production, transportation, and electric power. This versatility is one of the keys to its prospective growth - though also puts pressure on supply to keep up with expected demand from many sectors..
- ✔ **Hydrogen is expensive - but costs will fall.** Just as the cost of producing electricity from wind and solar has fallen dramatically in the last two decades, it is reasonable to expect similar cost reductions in hydrogen production. And there are clear expectations for areas where costs can fall. Economies of scale should lower costs dramatically, as facilities that are able to make many and larger electrolyzers come online. New electrolyzer technologies - such as solid state electrolyzers - offer the hope of lower costs. And changes in the raw materials used to build electrolyzers also suggest cost reductions.
- ✔ **Many challenges remain.** There are many uncertainties that still face hydrogen. Can challenges around transporting a volatile, low energy density, acidic commodity that only becomes a liquid at -253C be overcome? Will a global hydrogen market develop? Or will end users simply opt to develop their own local hydrogen production as a way to vertically integrate? What policy support will help hydrogen develop into a true global commodity?

Hydrogen: an introduction to a next-gen fuel

Hydrogen, long touted as the fuel of the future, is finally poised to play a crucial role in the global transition to clean energy. As countries and industries seek to reduce carbon emissions and combat climate change, hydrogen offers a safe and clean alternative to fossil fuels. However, it is not without its challenges - some of which are substantial. This paper aims to demystify hydrogen as an energy solution, discuss the issues (and, in some cases, myths) associated with the fuel, and explore the factors driving the growth of the hydrogen industry and its projected impact in coming decades.

One of the reasons that hydrogen is seen as potentially so crucial to achieving carbon emissions reductions is its tremendous versatility and potential to help decarbonize many sectors, which include oil refining and upgrading, industrial green steel production, chemicals production such as ammonia and fertilisers, land-based transportation such as in fuel cell electric vehicles, and emerging use cases in sea- and air-based transportation, through derivatives such as e-methanol and sustainable aviation fuel (SAF), respectively.

> ***"One of the reasons that hydrogen is seen as potentially so crucial to achieving carbon emissions reductions is its tremendous versatility and potential to help decarbonize many sectors***

When produced using carbon-neutral sources, such as renewable electricity, hydrogen production has a minimal carbon footprint. It is particularly valuable in hard-to-abate industries like steel production, heavy transportation, and aviation, where electrification alone is insufficient or impractical. Hydrogen can also enhance energy storage capabilities, balancing intermittent renewable energy supplies and ensuring grid stability without the use of traditional baseload fuels (which globally are primarily the fossil fuels, coal and natural gas, along with nuclear and hydro). Furthermore, its use in fuel cells can provide zero-emission power for vehicles and backup systems. By integrating hydrogen into the energy mix, countries can diversify their energy sources, increase energy security, and make substantial progress toward their climate goals, thereby playing an indispensable role in the global transition to a sustainable, low-carbon economy.

New use-cases for hydrogen

One of the major advantages of hydrogen is its broad applicability to many industries. And many industries are moving at least directionally towards hydrogen given its ability either to be a green fuel today, or to at least be on a trajectory to be a green fuel.

Hydrogen in the electric power sector

Electric power grids continue to face a major challenge: decarbonizing while maintaining reliability. This challenge has become an even bigger one as expectations for power demand growth have evolved. Until fairly recently, the expectation was that longer term growth in power demand would be limited; in Europe and the United States, for example, there has been little power demand growth for the last 15 years. But with the world steadily moving towards electric vehicles, a rapid growth trajectory for extremely electric demand-intensive data centers (with the recent AI boom further pushing this), and electrification of industry (eg. moving steelmaking away from coal-fueled blast furnaces towards electric arc furnaces), grid operators now need to balance both growth needs and reliability requirements against the need to decarbonize.

The biggest part of this challenge is that most electric grids still require "baseload" generation - power generation technologies that can run around the clock. Historically this has been a role filled by coal and natural gas, and to a lesser extent hydro and nuclear. Most countries are moving away from coal and natural gas, while nuclear is much more limited and hydro generation is already maximized in most geographies. And removing coal and natural gas too quickly from power grids, risks reliability issues when wind is low or outside daylight hours when solar is offline.

The traditional suggested solution to this has been batteries. These are expensive, though it is reasonable to say that their costs will fall. But a more important challenge is that battery raw materials look set to be tight for decades to come - constraining the amount to which batteries can grow.

This is where the opportunity lies for hydrogen. Hydrogen can effectively function as a proxy battery. When there is excess renewable energy (eg. if it is windy through the night when demand is low), that excess energy can be used to produce hydrogen. The hydrogen can then be stored and consumed to produce electricity in times when renewables are offline. In this way the combination of wind and solar plus hydrogen can proxy baseload generation. There are additional synergies too: for example, co-locating electrolyzers with renewable energy plants can reduce transmission losses and infrastructure costs. As the share of variable renewable energy in power grids increases, this integrated approach becomes increasingly valuable.

One of the challenges cited for hydrogen production is that electricity prices are volatile. However, power purchase agreements provide a hedge against this volatility, and are seen as a cornerstone of hydrogen production. The onset of the Russia-Ukraine war in 2022 provides a useful example of this. In the summer following the war's beginning, European electricity prices skyrocketed due to the disruption of natural gas flows and sanctions on both Russian gas and coal into Europe. According to figures collected from Eurostat, electricity prices across the EU member countries averaged €0.27/kWh just before the war, and well into 2022 power prices hit new highs in Germany of €0.40/kWh.

Against this background of high and volatile power prices, solar and wind-powered H2 projects that had locked in PPAs were left almost unaffected by the surge in prices. PPA contracts showed how renewables could avoid price volatility and support the reduction of uncertainty for the zero-carbon industry.

Hydrogen in transportation and mobility

The hydrogen fuel cell vehicle market, while still nascent, is expected to grow substantially in the next decade. Fuel cell technology is particularly promising for long-haul trucking, buses, and other heavy-duty vehicles where battery electric options may be less practical. Major automakers and transportation companies are investing heavily in hydrogen technology, signaling its potential in this sector.

Hydrogen holds significant potential in the transportation and mobility sector, offering a promising path to decarbonization. Fuel cell electric vehicles (FCEVs) powered by hydrogen are emerging as a compelling alternative to battery electric vehicles, particularly for long-range and heavy-duty applications. FCEVs boast quick refueling times and longer ranges compared to battery-powered vehicles, making them attractive for trucking, buses, and long-distance passenger vehicles.

In the maritime sector, hydrogen and hydrogen-derived fuels like ammonia are being explored for shipping, potentially offering a zero-emission solution for an industry that has traditionally been difficult to decarbonize. The aviation industry is also investigating hydrogen as a future fuel, with several companies developing hydrogen-powered aircraft for short to medium-haul flights.

For rail transport, hydrogen-powered trains are already in operation in some countries, providing a clean alternative to diesel locomotives on non-electrified routes. Additionally, hydrogen's potential extends to off-road vehicles and equipment in mining and construction, where the high energy density of hydrogen fuel cells can meet demanding power requirements.

Hydrogen: a critical part of decarbonizing the steel sector

MYTH	REALITY
Using hydrogen results in high costs and makes the steelmaking process uneconomical.	In regions with abundant renewable energy resources, strong trade protection measures, regulatory support, and buyers willing to pay premiums for low-emission steel, hydrogen-based steelmaking will grow, even given current high costs.
Hydrogen-based steel-making will become the prevailing choice for the industry's decarbonisation path.	H2-DRI-EAF is an emerging steelmaking technology with promising potential, it is still transitioning from research and development to broader application. It will become a significant production route, but its expansion will be constrained by resource availability and cost challenges.

The steel industry, responsible for emitting approximately 2.6 billion tonnes of CO2 in 2020 (7-9% of global emissions), is gradually adopting lower-carbon production methods. Steelmakers worldwide are now offering "green steel" products with reduced embedded CO2 emissions or produced without fossil fuels like coal or natural gas. The pace of this transition varies by region, with European steelmakers leading the trend, accounting for around 50% of all projects due to regulatory obligations.

The European Climate Law, adopted by the EU in 2021, mandates a 55% reduction in greenhouse gas (GHG) emissions by 2030 (compared to 1990 levels) and carbon neutrality by 2050. Mechanisms such as the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM) have been put in place to drive this transition.

The ETS, launched in 2005, requires polluters to pay for emissions exceeding a cap, reduced each year in line with the climate target of the EU. And CBAM, set to fully operate from January 2026, will require European importers of certain products, including steel, to pay for the CO2 emissions embedded in imported goods. CBAM incentivizes steelmakers outside Europe to adopt emissions-reducing technologies to remain competitive in the European market.

The two most common routes of modern steelmaking are blast furnace - basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) technologies.

Put simply, BFs use coking coal as a reduction agent to produce pig iron from iron ore concentrate or pellets. Then by decarbonizing pig iron in BOFs, crude steel is produced. This route is the most carbon-intensive, emitting over 2 tonnes of CO2 per tonne of steel.

EAFs melt ferrous scrap or direct reduced iron (DRI), also called sponge iron, into steel. Scrap-based process has a smaller CO2 footprint of around 0.68 tonnes of CO2-e per tonne of steel if the furnace operates on fossil electricity and around 0.2 to 0.4 tonnes of CO2-e per tonne of steel if power is renewable. Emissions intensity is higher at DRI-based facilities, with 1.37-1.4 tonnes of CO2 emitted per tonne of steel (global average) on average globally, and as high as 3 tonnes of CO2 if DRI is produced using coal, not natural gas.

Main steelmaking technology routes

Steel production route	Description	Share of global steel production	Average tonne CO2 emissions per tonne of crude steel
Blast furnace-basic oxygen furnace (BF-BOF)	Iron ore is converted into iron in the blast furnace, with coke (made from metallurgical coal) acting as a reductant. BOF turns molten iron into steel. Carbon from the coke bonds with oxygen in the iron ore, releasing CO2	71.6%	2.33
Direct-reduced iron -electric arc furnace (DRI-EAF)	Iron ore is first reduced into metallic iron without melting, and later melted in EAF to make steel. To date this process primarily utilizes natural gas, or, in India, coal. Carbon from the natural gas bonds with oxygen in the iron ore, releasing CO2. This process is being adapted to use hydrogen instead of fossil fuels, and in that process hydrogen bonds with oxygen in the iron ore, releasing H2O instead of CO2.	6.5%	1.37
Scrap-electric arc furnace (Scrap-EAF)	Recycled scrap steel is melted and refined in EAF into steel. There is a smaller carbon footprint owing to carbon added in the process, though the 'green-ness' of the process is primarily a function of how green the electricity used is.	21.4%	0.68
Global average			**1.91**

Notes: 2022 data; Other processes, including the open-hearth furnace route, added to 0.5% of global crude steel production

Sources: WSA, Midrex

The shift from BF-BOF to EAF steel production will drive the transition to green steel. But with the supply of scrap limited, DRI and its transportable modification - hot briquetted iron (HBI) - are another long-term intake solution for EAF-based steel production.

And here comes hydrogen. Generally, DRI is produced from iron ore pellets by removing oxygen in the solid state, using coal or natural gas as reducing agents. Complete or partial switching to hydrogen decreases the carbon footprint of DRI production to almost zero with water being the main by-product of the chemical reaction.

Traditional steelmaking	Iron oxide + carbon (coal/natural gas) → iron + carbon dioxide
Hydrogen steelmaking	Iron oxide + hydrogen → iron + water

Hydrogen-based projects dominate the steel decarbonising agenda

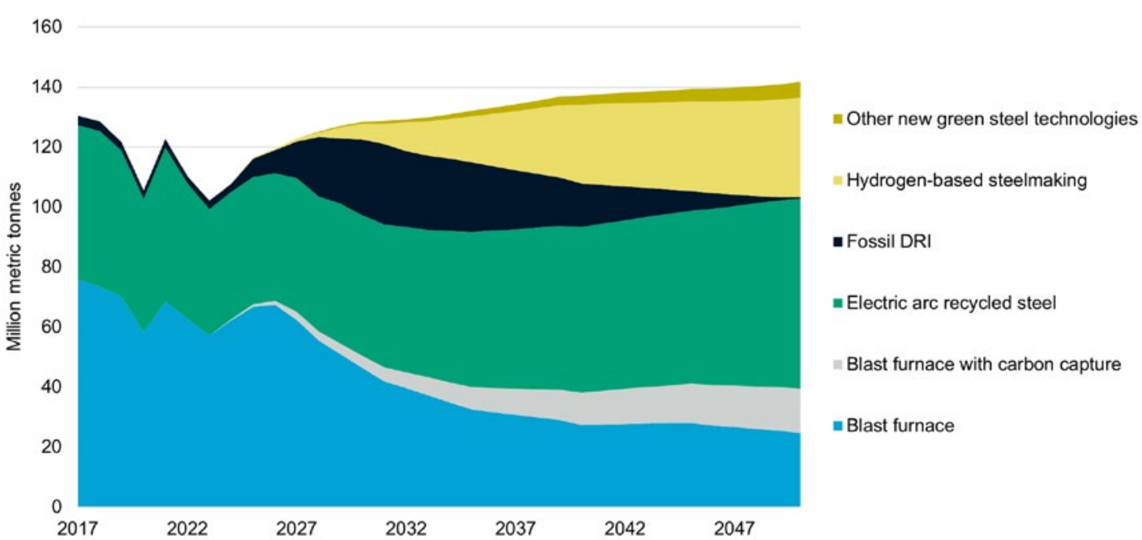
McCloskey's database of green steel projects shows that hydrogen-based schemes account for nearly half of all initiatives worldwide, with about 80% focused on developing new H2-DRI-EAF steel production chains, whether greenfield or replacing existing carbon-intensive operations. The scale and approach of these H2-DRI-EAF projects vary by country, depending on factors like renewable energy availability, legislation, state financial support, and the age of existing facilities.

For instance, Sweden benefits from a surplus of non-fossil energy, such as nuclear and wind power, particularly in the north, where most green steel projects are concentrated. The Swedish government plans to add 2.5 TWh of new capacity by 2045 through 12 nuclear reactors, alongside almost 10 TWh of new wind capacity by 2026. As the EU's largest iron ore and pellet producer, exporting over 80% of its output, Sweden is well-positioned to develop a complete green steel production chain—from hydrogen electrolysers to DRI plants to EAF mini-mills—ensuring minimal carbon footprint. The Stegra and HYBRIT projects are examples of this integrated approach.

Stegra is a greenfield project aiming to establish a hydrogen electrolyser, a DRI plant, and an EAF mill to produce flat steel in Boden, northern Sweden. HYBRIT, a joint venture between LKAB (the EU's largest iron ore producer), steelmaker SSAB, and energy company Vattenfall, plans to produce green hydrogen for LKAB's future DRI plant, which will supply sponge iron for SSAB's new EAFs, replacing its existing BF-BOF facilities.

In Germany, Europe's largest steel producer with ambitious carbon neutrality goals, steelmakers are pursuing a more conservative approach of using market-supplied hydrogen-rich gases to produce carbon-reduced DRI for new EAFs, gradually replacing aging BF-BOF capacities. However, the timeline for transitioning to 100% hydrogen and fully replacing BF with EAF is uncertain, as German steelmakers are reevaluating plans amid weak market conditions and the risk of reduced or even cancelled state funding for

EU steel and green steel production outlook



Source: McCloskey

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green projects. In November 2023, Germany's Federal Constitutional Court ruled that the government's decision to finance its green transition by reallocating 60 billion euros of unused debt released during the COVID-19 pandemic was unconstitutional.

Thyssenkrupp, for example, intends to replace one of four blast furnaces at its Duisburg steelworks with a hydrogen-based DRI plant and submerged arc furnaces, gradually switching to 100% hydrogen. Similarly, the SHS Group, which already uses hydrogen-rich gases at the Rogesa pig iron plant, plans to build a new DRI plant and two new EAFs in Dillingen and Völklingen. Another major German steelmaker, Salzgitter, has approved the first phase of its green strategy, involving the construction of a hydrogen electrolyser, a DRI plant (operating with a mix of hydrogen and natural gas), and an EAF. Further expansion is still under consideration.

Sweden and Germany illustrate different approaches to decarbonization within the EU, where hydrogen-utilizing steelmaking facilities are being developed, with a project pipeline extending into the early 2030s. According to McCloskey estimates, by 2030, the EU will have over 37 million tonnes of greenfield or replacement steelmaking capacity running on hydrogen or ready to be switched to hydrogen.

China, the world's largest steel producer and exporter, is unlikely to lead in hydrogen-based technologies due to its relatively new production capacities and limited non-fossil energy supply. Nevertheless, some Chinese steelmakers, including Hebei Iron and Steel (HBIS), are developing hydrogen or mixed gas-based DRI plants with EAF smelting, though these represent only a small fraction of China's total steel production.

India, the world's largest DRI producer, is exploring hydrogen options but currently relies on cheaper coal or natural gas as reducing agents. Indian steelmakers are also expanding their BF-BOF capacities and are likely to equip BFs with carbon capture rather than transitioning to hydrogen-based steelmaking.

In South Korea, hydrogen-reduction ironmaking has been recognised as strategically important since 2019, but few projects have been announced. POSCO is taking cautious steps with its HyREX project, aiming to produce 300,000 tonnes of hydrogen-reduced DRI by 2027. HyREX could eventually replace POSCO's existing FINEX technology, which uses coal as a reducing agent.

Beyond the DRI-EAF route, other hydrogen-based options to reduce steelmaking's carbon footprint exist. For instance, hydrogen can be injected into a blast furnace as a hydrogen-rich gas, as tested by Tata Steel at its Jamshedpur plant and Thyssenkrupp at its Duisburg plant. Hydrogen can also replace natural gas in rolling mill reheating furnaces, as demonstrated by Swedish steel producer Ovako Hofors, which recently inaugurated a 20 MW hydrogen electrolyser.

Overall, most steelmakers are still in the early stages of adopting hydrogen-based technologies. McCloskey's data shows that about a third of announced projects are in the operational or early construction phase, while the rest remain in planning. This does not necessarily indicate that the projects will not be implemented, but rather shows that companies are carefully assessing the risks before committing to final configurations.

Challenges remain for hydrogen in steelmaking

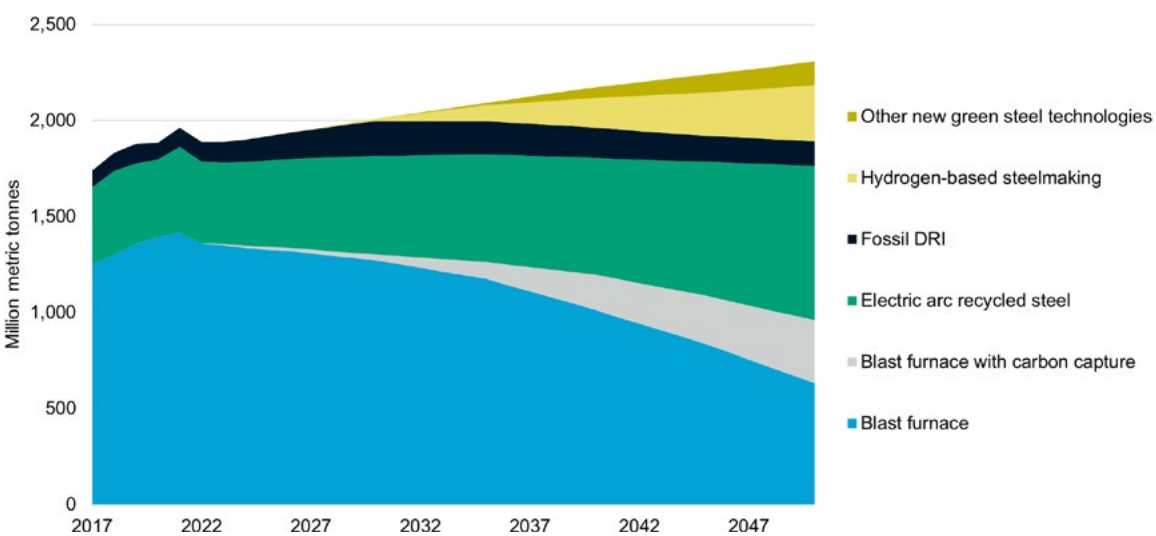
Several challenges must be addressed to enable the broader adoption of hydrogen-based steelmaking. The primary obstacle lies in the feedstock requirements, as DRI used in EAFs requires high-grade iron ore with minimal impurities. While blast furnaces typically use 62% Fe iron ore, DRI production generally requires at least 67% Fe, which is more expensive and in limited supply. Production of high-grade iron ore is expected to grow, with forecasts for output in 2050 ranging from 270 to 410 million tonnes, up from 128 million tonnes in 2019. But the availability of high-grade iron ore will be insufficient to meet the needs of an industry expected to produce over 2.2 billion tonnes of steel by then, according to McCloskey forecasts.

Potential solutions include adding a smelting step between DRI production and BOF, allowing the use of lower-grade iron ore, similar to the submerged arc furnace being installed by Thyssenkrupp in Germany. However, this smelting technology is still in the developmental phase and is unlikely to see widespread adoption before the 2040s. Another approach is POSCO's HyREX technology, which allows the use of iron ore fines directly, without pelletizing or agglomeration, and can operate with 65% Fe content.

Another significant challenge for steelmakers is the availability and cost of hydrogen. Producing one tonne of steel requires approximately 50 kg of hydrogen, and at current green hydrogen prices of $7/kg according to OPIS, this results in a cost of $350/tonne of steel. This is considerably higher than the cost of 0.8 tonnes of coal needed for the BF-BOF process, with prices around $260/tonne on average in 2024.

As hydrogen production scales up, costs are expected to decline, reducing financial pressures on steelmakers. The growing adoption of "green steel" price premiums by consumers, along with new regulations like the CBAM that penalize carbon emissions, should help level the playing field for mills investing in low-carbon steelmaking.

Global steel and green steel production outlook



Source: McCloskey

These cost pressures are reshaping the steel industry, with new low-carbon steelmaking hubs emerging in regions rich in natural resources like solar or hydro energy, such as Scandinavia and the Middle East.

However, due to resource and cost constraints, the adoption of hydrogen-based steelmaking is expected to slow after the completion of current projects in regions under the most regulatory pressure. In contrast, regions with strong steel demand growth, such as India and Southeast Asia, have set net-zero targets for as late as 2060 or 2070. These regions continue to invest in traditional BF-BOF and scrap-EAF steelmaking, where emissions may eventually be lowered through renewable energy or carbon capture technology.

Nevertheless, hydrogen-based steelmaking represents a significant technological shift, poised to transform the steel industry landscape. Based on ongoing and announced projects, we expect H2-DRI production to surpass fossil-based DRI by 2040, reaching approximately 300 million tonnes of H2-based steel by 2050.

Hydrogen in the chemical sector

Methanol

The methanol market in 2024 is approximately 94 million metric tons. Around 99% of existing methanol production is grey methanol; just below 60% is produced from natural gas and slightly over 35% from coal, almost all of which is in mainland China. The carbon footprint of coal-based methanol is 5-10 times higher than that of natural gas-based methanol.

Driven by targeted emission reductions in many companies and countries, there is growing interest in low-carbon methanol. Some of this will end up in the chemical sector – acetic acid, formaldehyde, MMA etc. – but fuels mandates and legislation mean that the majority will be consumed in the fuels sector. This includes traditional fuels such as MTBE, biodiesel, DME and the direct blending of methanol into gasoline, which is predominantly seen in mainland China. But the most obvious home for low-carbon methanol is the shipping sector, where methanol as a marine bunker fuel is gaining popularity: there are almost 400 vessels currently in existence or on order that are capable of running on methanol, although all are dual- or multi-fuel.

Methanol has the advantage of being sulfur-free, enabling shipowners to comply with increasingly stringent sulfur emission legislation imposed by the International Maritime Organisation (IMO).

There are various routes to low-carbon methanol:

- ✔ Biomethanol can be manufactured from various feedstocks, including biomass from crop waste or paper pulp; biogas gathered at landfills and sewage plants, or even from municipal solid waste
- ✔ Blue methanol is when CO2 is captured and sequestered, thus reducing carbon emissions
- ✔ The carbon footprint of traditional methanol units can be reduced by taking some part of the feedstock, usually CO2, from a neighbouring waste stream, e.g. flue gas

from a cement factory. This can have the dual advantage of both reducing emissions and increasing methanol production

- ✔ The "holy grail" of low-carbon methanol production is the manufacture of renewable or e-methanol, made by combining hydrogen from renewable electricity and carbon dioxide either from the exhaust fumes of power plants or other waste gas streams or, potentially, from direct air capture. Hydrogen is likely to be generated in locations where there are abundant renewable energy sources such as wind and solar.

There are no common definitions or approaches to low-carbon methanol production. Some companies are happy to adopt the mass balance approach, where a portion of low-carbon feedstock can be used to generate a certain volume of methanol production; others view this as merely an accounting trick. Some market participants argue that taking waste carbon dioxide and turning it into a useful product – methanol – is an example of carbon capture and utilization in action, reducing emissions and increasing methanol output. Others maintain that if the carbon dioxide is generated from a fossil fuel source, then it shouldn't count towards "carbon-free" production of methanol.

Sustainable methanol projects around the world:

CO2 to MeOH

- ***Anyang Shunli*** and ***Jiangsu Sailboat*** in China
- ***Celanese/Mitsui*** in the US

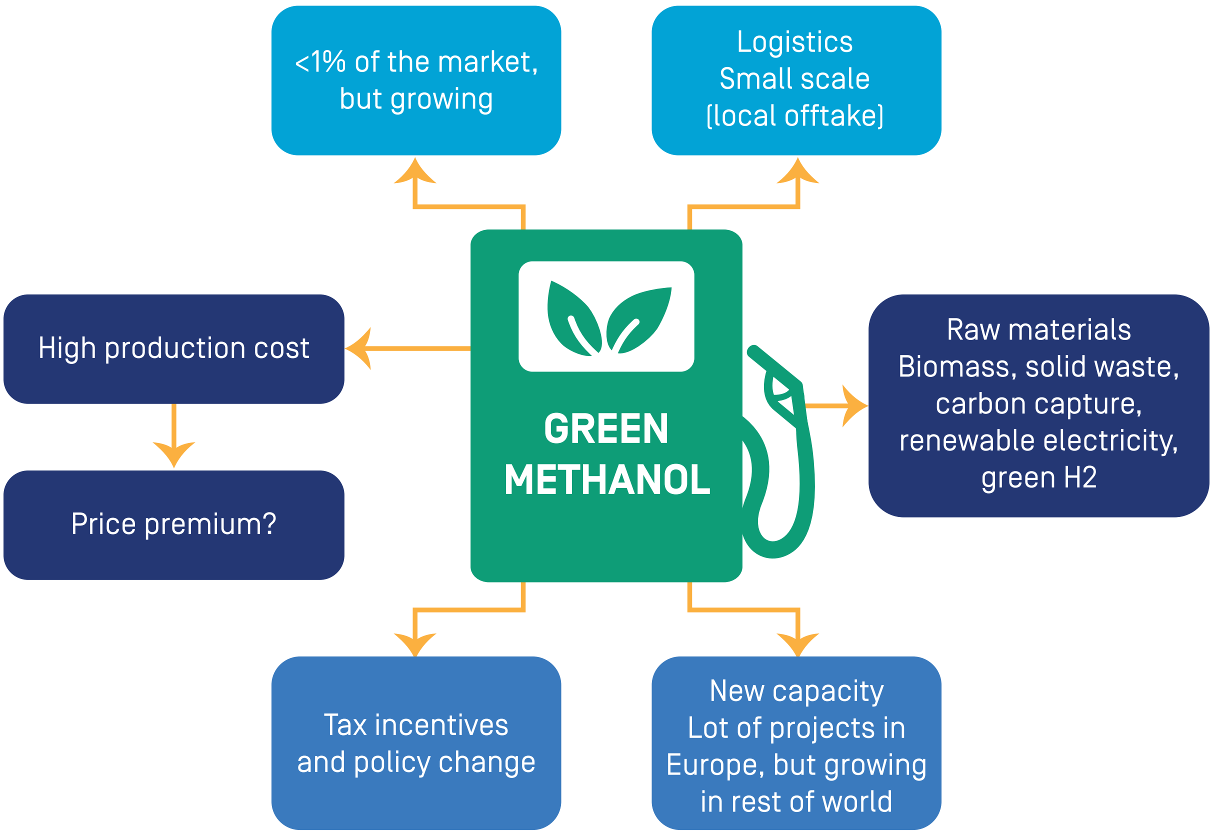
E-Methanol

- ***Perstorp*** in Sweden
- ***CRI*** in Iceland
- ***Goldwind*** in China

Bio-Methanol

- ***OCI*** and ***Methanex*** in the US
- ***BASF*** in Germany
- ***BioMCN*** in the Netherlands
- ***C2X*** in Spain

The new world of methanol: green methanol projects



E-methanol units are generally small-scale, with a typical annual capacity of 50-150 thousand tons. Many of the announced units are even smaller proof of concept pilot or technology demonstration plants. These capacities are significantly smaller than a world-scale methanol plant of 1-2 million tons. Unlike world-scale methanol units, however, most if not all of the output from these units is likely to be aimed at local demand, thus reducing the cost to serve. For this reason, in our longer-term supply-demand balances we tend to locate "hypothetical" e-methanol capacity near major bunkering hubs such as Rotterdam, Houston and Singapore. There is a chicken and egg situation in the industry, however, with many shipowners expressing concern that in the next five years, there will not be enough low-carbon methanol to satisfy demand. And in August 2024, e-methanol development received a major setback when Orsted announced that it has put its Swedish FlagshipONE e-methanol project on hold, citing slower than anticipated progress in the alternative fuels market, high e-methanol production costs and difficulty in agreeing long-term offtake contracts, particularly from shipping companies.

The interplay between methanol and hydrogen

Traditionally, methanol is used in chemical production, fuel blending, and as an industrial solvent. However, its role is rapidly expanding as a cleaner alternative to conventional fuels, especially in maritime shipping, where its lower emissions profile makes it a favored choice. Methanol can also be synthesized from a variety of feedstocks, including natural gas, coal, biomass, and even carbon dioxide when combined with green hydrogen, which positions it as a versatile and sustainable energy carrier. Rising demand for cleaner fuels and the adoption of methanol as an energy carrier and hydrogen storage medium likely ensure ongoing growth for the global methanol industry.

The synergies between hydrogen and methanol are particularly compelling. Methanol can serve as an efficient carrier for hydrogen, facilitating its storage and transportation. This is particularly useful in scenarios where hydrogen needs to be transported over long distances or where existing infrastructure can be leveraged, such as pipelines and storage facilities designed for liquid fuels. At the destination, methanol can be transformed back into hydrogen for use in fuel cells or other applications, providing a flexible and scalable solution for hydrogen distribution. This capability to act as a hydrogen carrier allows methanol to integrate into the broader hydrogen economy, enhancing its utility and facilitating the transition to hydrogen-based energy systems.

Furthermore, the production of green methanol using captured carbon dioxide and green hydrogen creates a utilisation pathway for carbon dioxide. In this scenario, carbon dioxide, which would otherwise contribute to atmospheric greenhouse gas levels, is instead utilized as a raw material, helping to mitigate climate change. This process not only reduces emissions but also offers a path for industries to continue using carbon-based fuels.

Green ammonia

Ammonia is a key chemical used in a number of applications, primarily in the agricultural sector as a fertilizer. It has two key relationships with hydrogen:

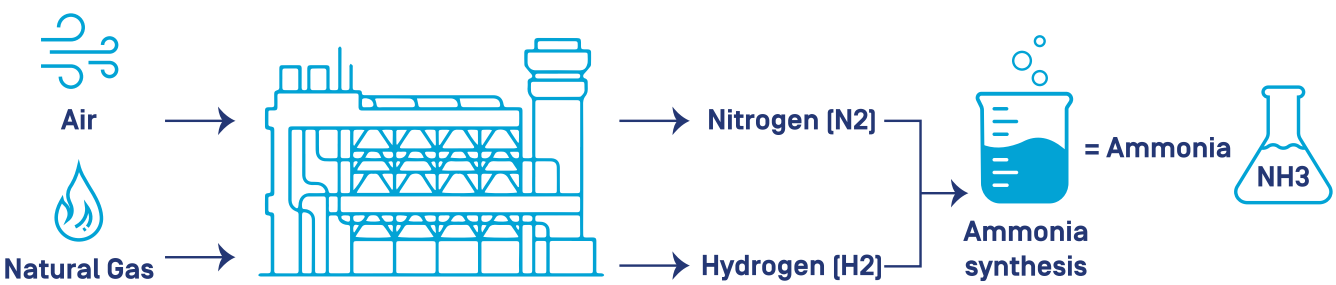
1. Hydrogen is seen as a prospective feedstock in the production of green ammonia, replacing natural gas (methane)
2. Ammonia is seen as a possible alternative way to transport hydrogen given its much easier transportation characteristics.

Only limited quantities of ammonia produced from renewable energy - termed green ammonia - are currently being manufactured, with this output sporadic and scattered globally. Fertilizer major Yara is among those already operational, opening its renewable hydrogen plant at Heroya, Norway this year, with an estimated output of around 21,000t/yr of green ammonia.

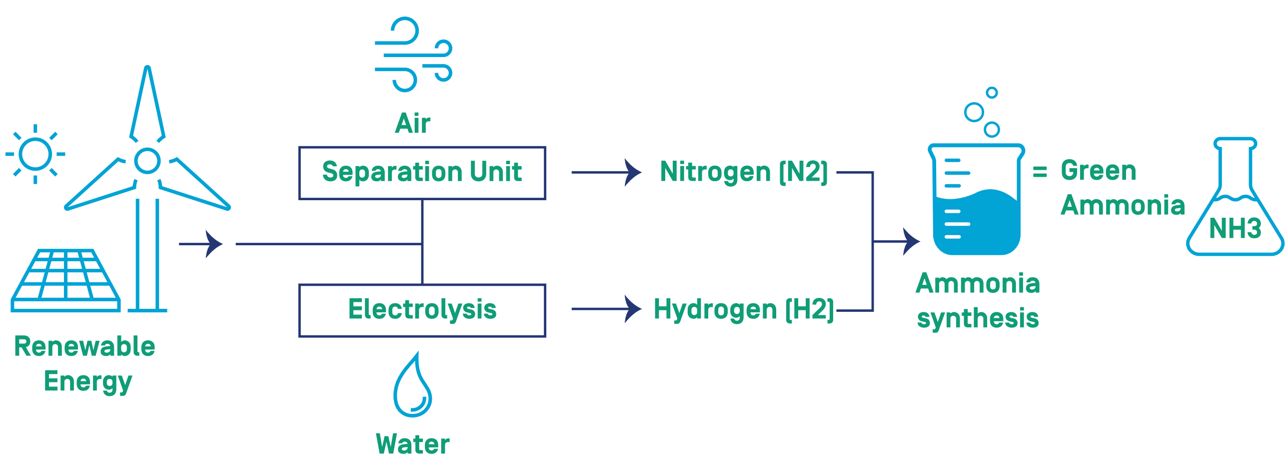
The NEOM Green Hydrogen Company (NGHC) in Saudi Arabia is among the major new green ammonia projects in the pipeline, proposed for start-up in 2026. It represents a substantial total investment of US$8.4bn, based on wind and solar generated renewable electricity with a targeted 1.2mn t/yr of green ammonia capacity. Hundreds of other green ammonia projects have been announced globally, but most have not progressed to Final Investment Decision (FID) stage for a number of reasons including the scale of investment required, high interest rates, a lack of confirmed off-takers and the need to prove green technology at scale. As a result, the first major wave of low-carbon ammonia supply will be produced conventionally with carbon capture and storage (CCS) – termed blue ammonia. This first wave will likely be led by US producers because of low costs of production (via natural gas) and government support in the form of Inflation Reduction Act tax credits.

Highlighting the difference in cost between green and blue ammonia, in August 2024, OCI sold its 1.1mn t/yr Beaumont Texas Blue Ammonia plant to Woodside Energy for US$2.35bn (compared to US$8.4bn for 1.2 mt/yr for NGHC's Saudi investment noted above).

Conventional Ammonia Production (via natural gas)



Green Ammonia Production



Hydrogen in North America: building momentum

Perspectives on growth and development in the United States

The last few years has seen an acceleration in the growth of low-carbon hydrogen as a core component of the energy system in North America. A key driver of this momentum is the United States' Regional Clean Hydrogen Hubs initiative, launched in October 2023, to accelerate the commercial-scale deployment of low-cost, clean hydrogen across the nation. This initiative, funded through the Bipartisan Infrastructure Law, provides $7 billion of Government funding, with a goal of catalysing up to $50 Billion in public-private sector Investment.

The hydrogen hubs are proposed to be integrated networks of clean hydrogen producers and consumers, together with the connective infrastructure to support activities of hydrogen production, storage, delivery and end-use. This initiative is projected to spur annual production of 3 million metric tons (MMT) of hydrogen, which is about one-third of the 2030 U.S. production target; U.S. hydrogen production targets are 10 MMT by 2030, 20 MMT by 2040 and 50 MMT by 2050.

There are 7 hydrogen hubs that have been announced and this includes: Appalachian Hydrogen Hub (Virginia, Ohio, Pennsylvania); California Hydrogen Hub; Gulf Coast Hydrogen Hub; Heartland Hydrogen Hub (Minnesota, North Dakota, South Dakota); Mid-Atlantic Hydrogen Hub (Pennsylvania, Delaware, New Jersey); Midwest Hydrogen Hub (Illinois, Indiana, Michigan); Pacific Northwest Hydrogen Hub (Washington, Oregon, Montana).

Selected Regional Clean Hydrogen Hubs

Source: US DOE Office of Clean Energy Demonstrations

Furthermore, concrete developments are beginning to occur in the developments of the hydrogen hubs, most notably with recent announcements (August 2024) on the first tranches of funding for 3 (of the 7) hydrogen hubs: California Hydrogen Hub, Pacific Northwest Hydrogen Hub and Appalachian Hydrogen Hub. This funding (approx. $30 million for each hub) is to support Phase 1 activities of the respective projects' plan and this includes activities such as planning, analysis and design activities, in addition to stakeholder and community engagement.

Each hydrogen hub is unique in its implementation of the production, transportation/storage and end-use activities that comprise its integrated "hub" network - often in line with the region's strengths and objectives. The California Hydrogen Hub, for example, has a focus on hydrogen to decarbonize transportation, port and drayage operations; the California "Shore to Store" project (2019-2023) demonstrated the feasibility of hydrogen-fueled "Class 8" heavy-duty trucks for cargo movement, from the Port of Los Angeles and Port of Long Beach, throughout the Southern California region, and this included testing of hydrogen fueling stations. This hub also proposes a "first-of-its-kind" hydrogen-powered marine research vessel (UC San Diego's Scripps Institution of Oceanography) - preliminary design of this vessel recently received approval from the American Bureau of Shipping (ABS).

The Pacific Northwest and Appalachian hydrogen hubs also show differences that are reflective of the unique strengths of each region. While the Pacific Northwest hub aims to produce all of its hydrogen via electrolysis (using clean, low emissions electricity), the Appalachian hub puts forward a production mix, including carbon capture-based technologies (reforming and pyrolysis of natural gas and biomass) that leverage the inherent natural resources and geological advantages of the region. Proposed end-use projects in these hubs include, amongst several others, hydrogen for sustainable aviation fuel (SAF), fertiliser production, baseload electricity for rural areas and as long duration energy storage (LDES) for subsequent peaking power needs. It should be noted, however, that specific projects within each hub could change, as the hubs advance from planning to implementation stages.

Perspectives on growth and development in Canada

In recent years, Canada has seen significant growth in the interest and development of low-carbon hydrogen, especially given the country's significant resources of natural gas and renewable energy potential, as well as established know-how and supply chains in related industries such as oil and gas and carbon capture. This momentum is further incentivized by the federal investment tax credits (ITC) that are available for industrial projects with associated hydrogen and carbon capture capital expenditure.

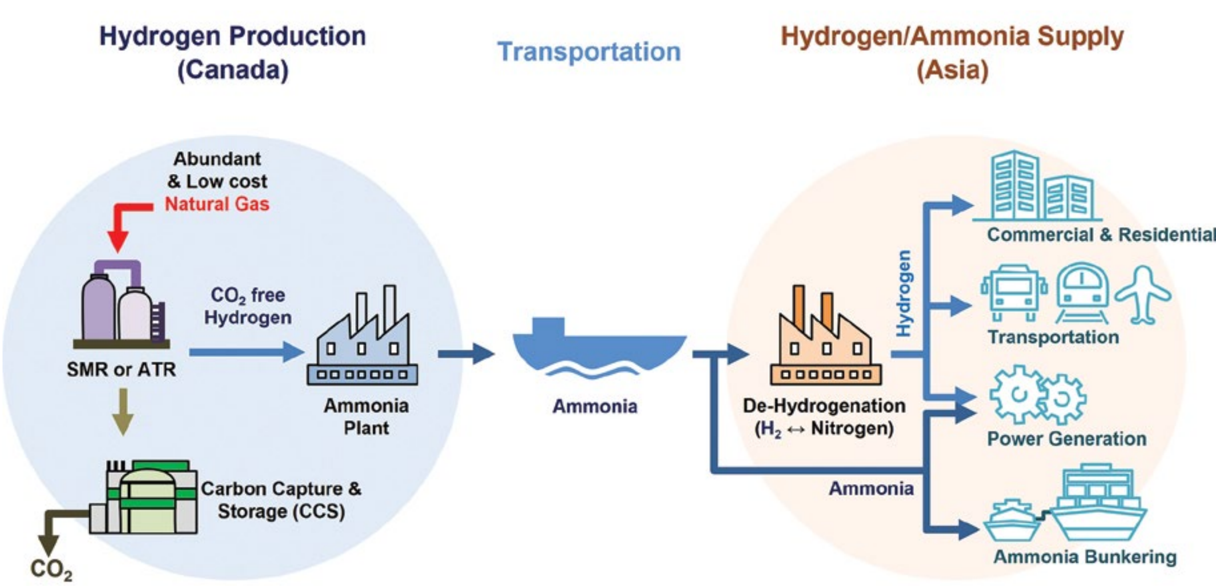
Further momentum is provided by intergovernmental relationships that seek to maximise Canada's potential as a global hydrogen supplier and exporter of choice, most notably to Europe and Asia, and agreements have been announced to this effect. This includes a Canada–Germany Hydrogen Alliance to support project investments and to establish a transatlantic Canada–Germany supply corridor; most recently, both governments announced $600 million to support Canadian projects to bid for an opportunity to supply the German market with clean hydrogen. This funding will help offset the "green hydrogen premium", that is, to close any gaps between the price producers offer and the price that buyers are willing to pay.

Another key bilateral relationship is with the Republic of Korea, and this is a key feature of Canada's Indo-Pacific Strategy. As part of the Comprehensive Strategic Partnership, hydrogen and its derivatives are identified as an area of cooperation to support energy security and develop sustainable energy sources. This commitment is supported by a memorandum of understanding (MOU) between Canadian federal departments and the Korean Ministry of Trade, Industry and Energy.

Consequently, there are Canadian projects in development with a focus on export opportunities for their clean hydrogen product. In Halifax, Nova Scotia, Everwind is currently advancing plans to develop a fully renewable-powered, electrolysis plant to produce hydrogen, which will be converted to ammonia, and subsequently shipped to the Port of Rotterdam in Europe. The first phase of the project, expected to be complete by 2026, targets annual production of 40,000 tonnes of hydrogen and 240,000 tonnes of ammonia; this is expected to grow to 145,000 and 600,000 tonnes, respectively, when the second phase is complete (expected by 2027). Everwind has secured approval for all 3 wind power plants for the facility (collectively over 500MW), and recently announced the completion of its phase 1 Front-End Engineering Design (FEED) and Front-End Loading Engineering (FEL-3).

Meanwhile in Western Canada, Hydrogen Canada Corp. announced the development of a low-carbon hydrogen/ammonia production facility in the Alberta Industrial Heartland, with the ammonia to be transported via rail to Canada's West Coast and then shipped to South Korea (and other Asian markets). The facility will take natural gas as a feedstock,

Clean Hydrogen/Ammonia Project Outline



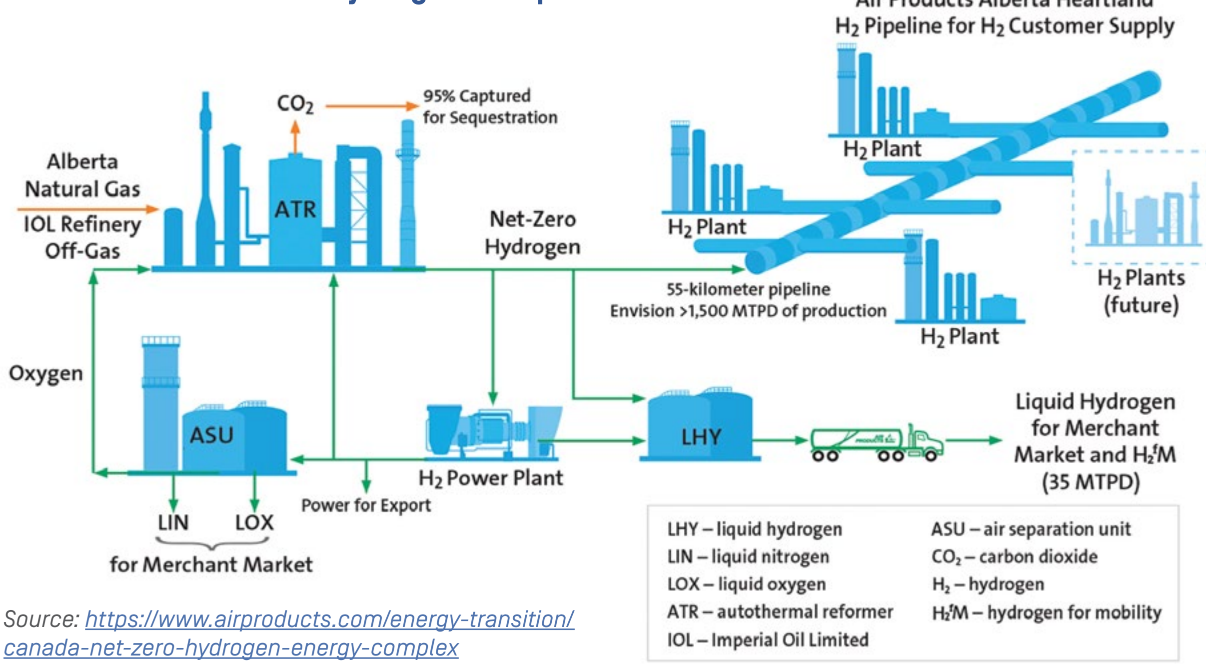
Source: https://www.hydrogencanadacorp.com/

and utilise Autothermal Reforming (ATR) technology with on site carbon capture and storage. At full operation, it is expected to produce 500 tonnes per day of hydrogen, and up to 1 million tonnes of ammonia per year. Hydrogen Canada Corp. recently announced that the project was selected as a pre-qualification consultation project for the upcoming Korean power auction (world's first auction for power from hydrogen). The project's FEED stage is expected for Q3 2024.

While the prior profiled projects have had a focus on export opportunities, there are significant developments within Canada that are focused on stimulating the local hydrogen economy. In Edmonton, Alberta, Air Product's Net Zero Hydrogen Complex is a facility, whose development is well advanced, that employs integrated production and end-use activities. The facility will utilise the ATR technology for production, with some of the product used in a 100% hydrogen-fueled power generation unit, for on-site electricity consumption and export to the grid. The rest of the hydrogen will be made available for merchant supply to other facilities, most notably, to Imperial Oil Limited's renewable diesel facility, which is integrated within the complex; this facility is expected to produce more than 1 billion litres per year of renewable diesel. In March 2024, Worley began procurement, fabrication and assembly services at its Edmonton modularisation yard, which is located adjacent to the Air Products site. The Net Zero Hydrogen Complex is slated to come on-stream in 2024, however, it is to be seen if this timeline will hold.

Apart from industrial applications, there are other sectors seeing significant developments in the country, most notably for transportation, and in particular, for heavy-duty trucking applications in Western Canada. In April 2023, the Edmonton Region Hydrogen Hub, a private-public coalition to kickstart the region's hydrogen economy, launched the "5,000 Vehicle Hydrogen Challenge" - an initiative to get 5,000 hydrogen

Air Product's Net Zero Hydrogen Complex



Source: https://www.airproducts.com/energy-transition/canada-net-zero-hydrogen-energy-complex vehicles on the road by 2028 (in Western Canada), with a larger goal of 30,000 hydrogen vehicles by 2035.

In March 2024, the first commercial hydrogen refuelling station in the region was launched and is described as "the beginning of an expanded hydrogen fueling network across Western Canada". The HYLA fuelling station, a representation of Nikola Corporation, is located at Leduc, which is a key transport node that links Alberta's two largest urban centres, Calgary and the Edmonton region. Momentum in this sector received a further boost, when at the 2024 Canadian Hydrogen Convention, Air Products announced that it would build a "hydrogen highway" in the region, that is, a network of permanent, commercial hydrogen fueling stations and associated infrastructure. The network will utilise liquid hydrogen from Air Product's Net Zero Hydrogen Complex.

Just over on the Albertan border, there is also building momentum for hydrogen deployment for transportation in British Columbia (BC). HTEC, which already owns and operates a refuelling network with 5 stations, announced in June 2024 its "H2 Gateway program". As part of this initiative, HTEC is looking to expand their hydrogen production and liquefaction capacity, expand refuelling network to 20 stations (in BC and Alberta), and deploy 100 hydrogen-powered Fuel Cell Electric Trucks (FCETs). In May 2024, an investment of $337 million from the Canadian Infrastructure Bank, to support the project, was announced ; the project cost is estimated at about $900 million CAD.

Challenges facing hydrogen adoption

While hydrogen has some clear advantages, broadly there are two main challenges around its growth and adoption:

- ✔ Hydrogen production is currently high cost
- ✔ Challenges around getting hydrogen to end users
    - *Logistical challenges*
    - *Uncertainty around how a global hydrogen market will develop*

Hydrogen production: will costs come down?

It is widely acknowledged that the cost of hydrogen is a key factor to achieving its potential wide scale adoption across the various sectors noted above. And while the incremental cost of clean hydrogen - the "green premium" - has different impacts on the different sectors' end user cost, it is important to understand the factors that could drive the cost trajectory over time.

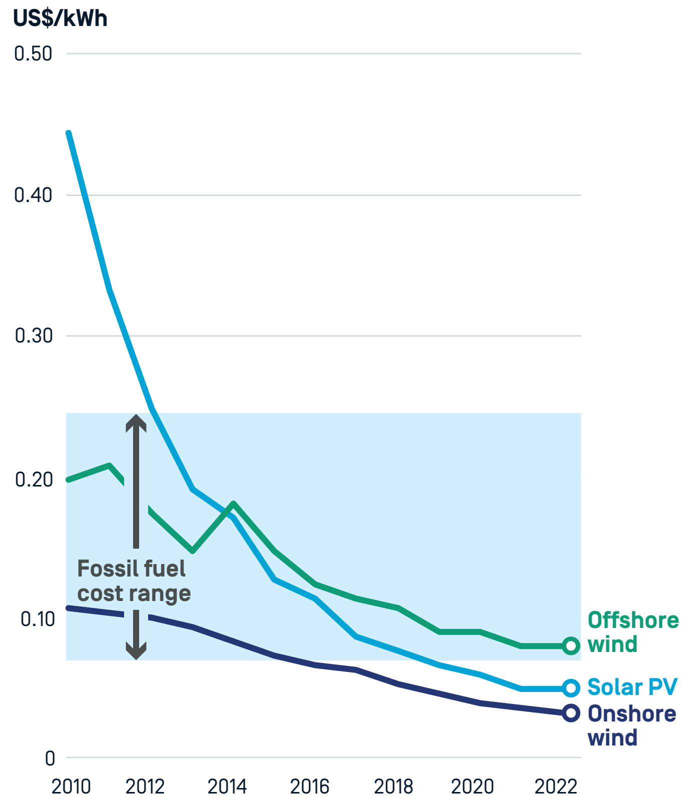
It is reasonable to expect that the cost of hydrogen production will fall, as it has already. For context, it is worth examining how the costs of renewable power technologies have fallen over the last 15 years. The figure below illustrates how renewable generation technology costs have fallen dramatically since 2010: 54% for offshore wind, 65% for onshore wind and 80% for solar photovoltaics.[1] While these reductions may not be summarily assigned to future clean hydrogen production, it is important to note that, especially with enabling policies, clean energy technologies can achieve significant cost reductions.

Current and projected costs for hydrogen

Clean hydrogen is projected to experience significant cost reductions over time, with an ambitious target being pursued by the US Department of Energy's (US DOE) "Hydrogen Shot", which seeks to reduce costs from currently around $5 per kg to $1 per kg by 2031. For context, conventional hydrogen, produced from fossil natural gas, is significantly cheaper than green hydrogen:

- ✔ Hydrogen produced from natural gas has costs as low as $0.98-$2.93/kg depending on the geography;
- ✔ Hydrogen produced from natural gas with carbon capture has costs of $1.80-$4.70/kg, again depending on geography;
- ✔ Hydrogen produced from electrolysis technology has costs from $4.50-$12.00/kg[2]

Weighted Average Levelized Cost of Electricity for Selected Renewable Energy Technologies and Fossil Fuel Comparison



Notes: $/kWh = dollars per kilowatt-hour; PV = photovoltaics.

Source: State of Climate Action 2023. World Resources Institute (2023)

Studies project that clean hydrogen would begin to achieve cost competitiveness with current fossil incumbents by 2030, and would exceed them by 2050; this would be driven by a combination of technical and policy factors. Estimates show that 2030 clean hydrogen costs could be as low as $2/kg [3], and by 2050, these could be at $0.65/kg [4].

Caution should be applied when considering cost estimates for clean hydrogen production. Given the nascency of the sector, estimates may be reliant on public data and may not capture most recent advancements, which are typically confidential for purposes of retaining competitive advantage. Furthermore, the boundaries of the estimates are often not consistent across studies, and at times may not even be specified, making comparisons of different studies difficult.

1 State of Climate Action 2023. World Resources Institute (2023)
2 Green Hydrogen to Undercut Gray Sibling by End of Decade (BNEF)
3 The price of green hydrogen: How and why we estimate future production costs (ICCT)
4 Global Hydrogen Trade (IRENA)

The primary production cost drivers for electrolysis-based hydrogen are typically dependent on 3 parameters:

1. cost of electricity for hydrogen production,
2. the cost of the electrolyzer system/facility, and
3. the cost of capital for the project developer, typically defined as the weighted average cost of capital (WACC).

For carbon capture-based hydrogen production, the costs are often driven by the cost of the carbon capture (and compression/transportation) system; to this end, several of the hydrogen production systems in development are utilising the autothermal reforming technology (ATR), rather than the more common steam methane reforming (SMR) technology, due to its ability to better incorporate carbon capture within its configuration.

The other cost component that warrants consideration is the hydrogen transportation cost, and this is particularly important for merchant cases where hydrogen (or a related product such as ammonia or methanol) is moved from the production facility to the end user. These costs are typically defined by the transport distance, transport method, hydrogen form, and the facility size, which benefits from economies of scale. Some identified transport options include hydrogen through new or repurposed pipelines, and ship/vessel transport of liquid hydrogen or a related product such as ammonia, methanol or a liquid organic hydrogen carrier.[5]

Drivers for potential future cost reduction

This section presents an outlook on factors that could drive hydrogen production cost reductions, particularly for electrolysis technologies. Within the "electrolysis technology" class, there are several distinct technology implementations, this includes more established technologies of alkaline electrolysis and proton exchange membrane (PEM) electrolysis, and more novel technologies of anion exchange membrane (AEM) and solid oxide electrolysis.

Broadly, cost reductions can be achieved in the CAPEX required to build and install the facility, and the OPEX required to run it. OPEX costs are very site specific, and facilities have less control over this. Careful planning is required to locate the facility in a location where there is ready access to low cost renewable energy, and ideally in areas where "behind the meter" costs (costs billed for energy infrastructure builds) are low. Once built, a facility may have little control over power costs and how they will evolve, though shrewd negotiation of power purchase agreements for renewable power can help keep OPEX minimal. Water costs are also a critical piece of ongoing OPEX. With water seen as a tightening commodity, water costs will likely rise. Avoiding the need to use desalinated water will help keep water costs low, but likely water costs will rise in coming decades in most geographies.

5 Global Hydrogen Trade (IRENA)

CAPEX is the main area where costs will fall. Technological innovation and economies of scale are expected to play an important role in cost reduction. A facility's system costs, a subset of capital expenditure, is defined as those associated with the electrolyzer stack, which includes costs of critical minerals and component manufacturing, and those associated with everything else in the facility, commonly referred to as "balance of plant" (BOP), and this includes costs such as electrical infrastructure for power supply, hydrogen treatment and processing, cooling and heating systems etc. According to a 2020 study, system costs are split at approximately 45% for the electrolyzer stack and 55% for the BOP components[6]. It is further determined that areas with the greatest potential for system cost reduction include power supply components, manufacturing of electrolyzer cells, water and hydrogen processing systems, and critical minerals.

> ***"According to a US DOE-sponsored study, a 70% reduction in the stack cost can be achieved by a facility scaling up annual production from 10 MW/year (~10 units) to 1 GW/year (~1000 units)...***

Notably, projected reductions to system costs (and consequently overall production costs) are expected to be primarily achieved by increasing the production scale of electrolyzers. This would enable favourable economics for the deployment of automated manufacturing and the accruing economies of scale that allow for reduced cost contributions per unit produced. According to a US DOE-sponsored study, a 70% reduction in the stack cost can be achieved by a facility scaling up annual production from 10 MW/year (~10 units) to 1 GW/year (~1000 units)[7], and stack assembly costs can be reduced 90% through automated manufacturing at scale. A similar cost reduction potential is seen for BOP costs, which can be reduced 40% at the same scale up level.

Development of new catalysts that use less or no noble metals (e.g., platinum, iridium) reduces costs and can enhance performance. Increased use of nanotechnology has also enabled the creation of more active and durable catalysts that increase the efficiency of the electrolyzers, as well as improved membrane materials that have higher ionic conductivity and stability are leading to better performance and longer lifespan. Advanced electrode designs facilitate better gas diffusion and reduce energy losses during the electrolysis process.

Some of the essential developments that have contributed to this increase in efficiency include advancements in Electrolyzer Technology such as Proton Exchange Membrane (PEM) Electrolyzers, which can operate at higher efficiencies (up to 70-80%) compared

6 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi

7 Mayyas, A. et al. (2019), Manufacturing cost analysis for proton exchange membrane water electrolyzers, Technical Report NREL/TP-6A20-72740, National Renewable Energy Laboratory, Golden, CO, United States.

to traditional alkaline electrolyzers. Furthermore they can quickly respond to changes in electricity supply, making them ideal for pairing with intermittent renewable energy sources like solar and wind.

Other breakthroughs include Solid Oxide Electrolyzers (SOE). SOEs operate at high temperatures (700-1,000°C), which can achieve efficiencies of 80-90% by utilizing waste heat from industrial processes. The higher operational temperature allows these for more efficient hydrogen production compared to PEM and alkaline electrolyzers.

Other contributions to cost reductions include the "learning curve", which represents the improvements achieved each successive time a technology is deployed. This "learning by doing" is typically seen as technologies move from "first of a kind" (FOAK) to "nth of a kind" (NOAK). Other drivers to hydrogen production cost reduction may also include technology advancements that reduce the quantity of expensive critical minerals currently required, and this may include advancements such as improved recycling technologies for spent electrolyzers and new electrolyzer designs that utilise alternate cheaper materials.

Government-Industry collaboration

Governments worldwide are increasingly recognizing hydrogen's potential and implementing supportive policies. Many countries have released national hydrogen strategies, setting ambitious targets for production and use. These policy frameworks, often backed by significant financial incentives, are creating a favorable environment for industry growth and attracting substantial investments. And significant investments by governments and private sectors in research and development have accelerated the pace of technological advancements. Numerous pilot projects and demonstration plants have helped to test and validate new technologies, leading to faster adoption and improvement.

Government subsidies play a crucial role in accelerating the growth and viability of green hydrogen production. As nations strive to meet ambitious climate targets, many governments have implemented supportive policies and financial incentives to stimulate the hydrogen economy. These subsidies often take the form of tax credits, grants, or favorable loan terms for green hydrogen projects. By offsetting initial capital costs and operational expenses, government support helps bridge the current price gap between green hydrogen and fossil fuel-derived alternatives. This financial backing encourages more companies to invest in hydrogen production facilities, driving economies of scale and fostering technological advancements. Additionally, subsidies can incentivize end-users to adopt hydrogen-based solutions, creating a robust demand that further propels industry growth. As the sector matures and costs decrease, these government interventions are expected to gradually phase out, leaving a self-sustaining and competitive green hydrogen market.

Challenges around getting hydrogen to end users

One of the main issues raised by developers who are considering utilizing hydrogen in their projects is uncertainty surrounding hydrogen availability. The transition from gas-fed networks to hydrogen poses significant challenges for widespread adoption. Although hydrogen shares some similarities with natural gas as a fuel, its unique requirements for safety, storage, transportation, mean that for the most part new storage and transportation infrastructure is required to manage it - increasing CAPEX requirements for hydrogen growth.

Hydrogen in pipelines and storage

Hydrogen is acidic, meaning that transportation of hydrogen in pipelines requires special pipelines to be built. Existing natural gas pipelines cannot be used to transport hydrogen beyond around an 80:20 methane:hydrogen mix. There is some ability to piggy-back on existing infrastructure though. Natural gas pipelines can incorporate a portion of hydrogen - as much as around 20% - without negative impacts. And at those levels it can be consumed by domestic and industrial appliances without issues, though there are still questions about just how much hydrogen could be incorporated for use in large infrastructure such as natural gas turbines.

Storage of hydrogen requires more specialized facilities than natural gas storage. The tiny size of the hydrogen molecule means that it can much more easily leak than methane can, and in some cases storage requires supplementing salt caverns with additional infrastructure to help limit leakage. Additionally, the low energy density of hydrogen means more storage is required per unit energy than for methane.

Shipping hydrogen

Transporting hydrogen on vessels requires liquefying it, which requires it to be cooled to around -253°C (20°K), and requires specialized vessels. At present there is only 1 small scale (1,250 cubic metres) dedicated hydrogen vessel on the water, the Suiso Frontier which delivered in 2020, and which currently loads hydrogen produced from lignite in Victoria, Australia, and takes it to Japan. Current construction costs for larger scale vessels are prohibitive, given the technical challenges of keeping a cargo at -253°C.

Transporting hydrogen also requires that liquefaction and regasification infrastructure be built. Anticipating the development of a global hydrogen market, some investments are being made - most notably by the Port of Rotterdam in the Netherlands, which is involved in both the importing, piping, and production of hydrogen (see Text Box).

Alternative ways to ship hydrogen

Since hydrogen is challenging for ocean shipping, as noted above, alternatives are considered. Hydrogen can be transported in alternative ways, with transportation as ammonia and transportation as methanol being the main two being considered. These two commodities are widely transported today.

However, adding hydrogen demand to these commodities adds considerably to their overall demand, with accompanying much higher transportation needs. According to a recent report by the International Chamber of Shipping, to meet the expected demand of 20mt of hydrogen to just meet the EU's 2030 targets, the global ammonia fleet will need to increase by up to 300 vessels (there are around 450 vessels today). To meet the anticipated 33mt of demand from just Japan and Korea would require more than a doubling of today's ammonia fleet, with around 500 additional vessels needed.

The Port of Rotterdam, Netherlands

The Port of Rotterdam is undertaking a massive hydrogen infrastructure development. By 2026, the port is expected to produce up to 500,000 tons of green hydrogen annually, with ambitions to scale this to 4.6 million tons by 2050. This production capacity is being supported by the construction of large-scale electrolysis plants, such as Shell's "Holland Hydrogen I" project, which alone is set to produce 60,000 kilograms of hydrogen per day, equivalent to approximately 20,000 tons per year. In addition to Shell, other major energy companies like BP, Equinor, and Air Liquide are also heavily involved in various hydrogen initiatives within the port, contributing to its position as a key player in the hydrogen economy.

To facilitate the importation of hydrogen, the port is working on developing significant infrastructure, including a dedicated hydrogen pipeline network, which will initially transport 10-15% of the port's total hydrogen demand and eventually expand to connect with major industrial clusters in Germany, Belgium, and beyond. By 2030, the Port of Rotterdam aims to handle up to 18 million tons of hydrogen, covering both production and importation.

These developments are not only transformative for the Netherlands but also for Europe as a whole. Rotterdam's hydrogen infrastructure is set to become a crucial link in the emerging European hydrogen backbone, a transcontinental network designed to enable large-scale hydrogen distribution across Europe. This infrastructure is expected to significantly lower the costs of hydrogen and accelerate its adoption across various sectors, from heavy industry to transportation. As a result, the Port of Rotterdam will play a pivotal role in Europe's transition to a low-carbon economy, helping the EU meet its ambitious climate targets and paving the way for a more sustainable energy future across the continent.

Aside from these large requirements for building of new vessels, transportation via ammonia or methanol has one other significant challenge: those commodities then have to be cracked to hydrogen in the destination. This is currently energy intensive and costly. However, there are hopes that the cost of cracking methanol or ammonia to hydrogen will come down along with other hydrogen related costs.

Will a global hydrogen market develop?

Hydrogen is currently not a globally traded commodity, with just a single hydrogen carrying vessel and negligible global trade. And the market appears somewhat split on whether it will become one.

On one hand, investments like the Port of Rotterdam and Tata Steel's conversion of its Ijmuiden Steel Mill to hydrogen-DRI are based on an expectation that hydrogen will commoditize and that global trade will develop with price reporting based on liquid pricing, physical trading, development of a secondary market, and financial trading. And global trading will take advantage of being able to produce hydrogen in areas with abundant renewable generation. Saudi Arabia and the UAE, for example, with their abundant solar resources, are trying to position themselves as hydrogen suppliers to the world; hydrogen production in places with abundant sun makes more sense than producing it in countries with less solar or wind resources.

However, challenges around transportation and concerns that there are many expected uses for hydrogen with fewer clear producers of hydrogen mean that some end users are opting to produce their own hydrogen for their own use. Steelmaker SSAB, for example, is partnering with LKAB and Vattenfall to produce their own hydrogen rather than rely on it being supplied from elsewhere. And in some ways hydrogen is the ideal material for local production - since for the most part electrolysers simply require water and electricity, which are generally available. Companies like SSAB reason that they can guarantee their own supply and de-risk their operation by vertically integrating, rather than buying on a potentially volatile global market that might not develop. Their risk is that they may end up paying more for hydrogen than they could in a market, but de-risking their cost of hydrogen also has monetary value.

The reality will likely be somewhere in the middle, with some hydrogen traded on a global market, and with some also produced in the end-use location. But if more end users opt to produce their own, the development of hydrogen as a global market may end up being stalled.

Hydrogen and geopolitics

If hydrogen does develop into a global market, it has the potential to reshape global energy trade. Countries with abundant renewable resources - such as Australia, Saudi Arabia, the UAE, Morocco, and Chile - are positioning themselves to become major exporters of green hydrogen. The development of international hydrogen supply chains is likely to be a major industry trend in the coming years.

Conversely, the recent global trend towards “onshoring” (removing supply chains and building domestic industries to source product), and “friendshoring” (only having supply chains that begin in friendly countries) could impact the hydrogen industry too - and could be a driver for companies developing local hydrogen production. This could easily hurt the development of a global market.

Myths and misconceptions regarding hydrogen

Hydrogen fuel is often heralded as a key player in the transition to cleaner energy, but it is also surrounded by a number of myths and misconceptions that can cloud public understanding.

One common myth is the idea that hydrogen itself is a primary energy source, much like coal, oil, or natural gas. In reality, hydrogen is not an energy source but rather an energy carrier. This distinction is crucial because hydrogen must be produced from a primary energy source, such as natural gas or biomass, or from a secondary one - electricity.

Another myth is the hydrogen “colour wheel/rainbow” that is often used to arbitrarily designate the environmental impact/benefit of hydrogen, and which is based solely on the hydrogen production method. Thus, there are commonly heard misconceptions, such as that “green hydrogen”, produced from water and electricity, is cleaner than “blue hydrogen” and “gray hydrogen”, which are produced from natural gas, with and without carbon capture, respectively. However, this is not necessarily accurate, as the true environmental impact depends on the environmental indicator (e.g., GHG emissions intensity) associated with the production method. Therefore, accurate determination of the environmental impact requires consideration of key parameters such as the emissions intensity of the electricity used to produce the “green hydrogen”, or the efficiency of the carbon capture used to produce the “blue hydrogen”. Consequently, climate regulations have shifted away from using “colours” to using the “emissions intensity”, which is a measure of the overall emissions (referred to as “lifecycle emissions”) associated with the production method; hence, this is currently reflected in global hydrogen climate legislations such as in the US IRA, Canadian investment tax credits, EU low-carbon fuels methodology and incoming carbon border adjustment mechanism (CBAM).

Similarly, there is the related misconception that the adoption by a given sector automatically makes it “clean”. While it is true that the “end use” of hydrogen (e.g., fuel cells for transport, combustion in turbines for power generation etc.) results in zero emissions, as it produces only water, it is important to consider the “lifecycle emissions” associated with the hydrogen production process (as described in the previous paragraph). Therefore, the adoption of hydrogen by a sector is only “cleaner” when overall emissions from the hydrogen production (and transport and storage) is less than the emissions of the fossil fuel incumbent being displaced.

Concerns about the safety of hydrogen are also common, with many people believing that hydrogen is too dangerous to use because of its high flammability, explosive potential and its use in existing infrastructure. However, this overlooks the fact that technology is evolving to handle hydrogen, just as it did for other widely used fuels/ energy sources (nuclear, gasoline, natural gas etc.) that also carry significant risks. Technological advancements and rigorous safety protocols are being developed to handle hydrogen safely through its production, transportation, storage and end use. As a result, there are now new developments such as 100% hydrogen-powered turbines, vehicles, ships, aircrafts, pipelines etc., with many more in various stages of development.

"The cost of hydrogen fuel is often cited as a barrier to its widespread adoption, with the assumption that hydrogen will always be more expensive than other fuels. This is not the case...

The efficiency of hydrogen fuel cells is another area rife with misconceptions. Some argue that hydrogen fuel cells are inherently less efficient than other energy technologies. In fact, hydrogen fuel cells are quite efficient, especially in vehicular applications, and this advantage is more stark when compared to existing fossil fuel use. According to the US DOE, hydrogen fuel cells can achieve up to 60% efficiency in both power generation and in vehicles, comparatively, vehicles with gasoline engines attain only 20% efficiency and conventional combustion-based power plants generate electricity at efficiencies of 33-35%.

The cost of hydrogen fuel is often cited as a barrier to its widespread adoption, with the assumption that hydrogen will always be more expensive than other fuels. This is not the case, as we address in the production cost section.

Another common myth is that there is no infrastructure to support hydrogen fuel, rendering it impractical for widespread use and that this will hamper the adoption of clean hydrogen. Yet, it is important to note that in 2022, 90% of all global hydrogen was produced on the same site location that it was used;[8] Hence, there is large scope for hydrogen adoption that does not require extensive transport infrastructure. That said, it is true that new infrastructure is needed, particularly for new hydrogen use cases (transport, synthetic fuels, export etc.), and while hydrogen infrastructure is not as developed as those for fossil fuels, significant progress is being made. Across Europe, North America and parts of Asia, there are significant investments in hydrogen infrastructure, and this is reflected in new announcements and projects on hydrogen hubs, shipping corridors, refuelling stations and associated infrastructure.

There is also a belief that hydrogen-powered vehicles, specifically fuel cell electric vehicles (FCEVs), are not as well suited for transportation compared to battery electric vehicles (BEVs). While BEVs have higher energy efficiency, from grid to wheel, charging infrastructure and are well suited to passenger transportation, hydrogen vehicles offer a distinct set of advantages, such as longer driving ranges, quicker refuelling times and much higher

8 Global Hydrogen Review, International Energy Agency (IEA). 2023.

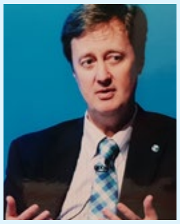
payloads, which make them particularly well-suited for applications like heavy duty and long-haul transportation, particularly for port and drayage operations. Consequently, BEVs and hydrogen FCEVs are both core components to transportation sector decarbonization, and are projected to play complimentary, rather than competing roles.

Another misunderstanding is that hydrogen, as the most abundant element in the universe, should be easy to extract and use. While hydrogen is indeed abundant, it has a highly reactive nature, hence, it is usually found combined in compounds, and energy is required to separate these compounds to obtain pure hydrogen. There are several methods used for this separation and they vary significantly in terms of efficiency and environmental impact. Thus, the hydrogen production challenge lies not in the availability of hydrogen, but in the sustainability and efficiency of its production.

The notion that hydrogen fuel will completely replace all other energy sources is another myth. Hydrogen is likely to play a crucial role in the future energy mix, but it is not projected to entirely supplant other energy sources. It is well agreed upon that the future energy system will be a mix of complementary energy sources and carriers, and hydrogen will have a place with other renewable, abated and low-carbon energy providers.

Understanding these myths and the realities behind them is essential for making informed decisions about the role of hydrogen in our energy future. As technology advances and public awareness grows, hydrogen is poised to become a vital component of a sustainable and diversified energy landscape.

Author Biographies



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Matias Poirrier

Senior Reporter - Research & Analysis

Matias is an experienced Research Analyst with a strong background in the energy sector, specializing in gas, electricity, and renewable energy, particularly hydrogen. With a demonstrated expertise in Policy Analysis, Political Economy, and Quantitative Comparative Analysis within the energy landscape, Matias is focused on enhancing hydrogen use in the European landscape and creating new insights into the broad H2 market.

Mike Nash

Vice President – Research and Analysis at Chemical Market Analytics by OPIS

Mike Nash works with a global team of regional consultants and overlays their analyses with a global perspective. His responsibilities include the World Methanol Report and World Methanol Analysis, as well as the Global Acetyls Market Reports and the related World Analyses for methanol, acetyls and formaldehyde. Mr. Nash also worked for BP's petrochemicals division for 19 years before a two-year stint in Total's UK fuels business. Mr. Nash holds a Master of Arts in English language and literature from Edinburgh University and an MBA from Kingston University, both in the United Kingdom.

Marina Maliushkina

Associate Director, Steel Research Lead at McCloskey by OPIS

Marina Maliushkina is the steel research lead at McCloskey and the editor of the Steel Market Briefing publication, which provides analysis of global steel market trends and steel price forecasts. Prior to joining McCloskey, Marina worked as a senior research analyst at Fastmarkets and S&P Global Platts. Marina holds bachelor's degrees in history from the Belarusian State University and Financial Management from the University of Sunderland.

Author Biographies

Sergey Babichenko

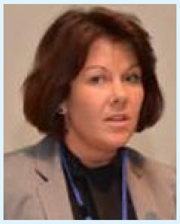
Senior Research Analyst at McCloskey by OPIS

Sergey Babichenko specializes in green steel transformation. He holds Master's degrees in International Journalism and Civil Law. His professional experience ranges from business and economic news journalism to corporate communications for multinational companies, including major steelmakers, to steel price analysis for leading market data providers. Sergey is also passionate about writing children's stories, drawing cartoons and animations.

Carl Roache

Ammonia-Urea Market Director, Chemical Market Analytics by OPIS

Carl Roache joined the company in 2024 and leads analysis and pricing globally from London, UK. Prior to joining CMA, Mr. Roache was EuroChem's global business development manager for NPK fertilizers, based in Dubai, UAE. From here he coordinated global sales for the company's 1.2mn t/yr Antwerp plant. Before this, he was EuroChem's Asia NPK business development lead, based in Singapore. Mr Roache is an NCTJ/NCE qualified newspaper journalist, starting his career with Northcliffe Media group in the UK.



Nicola Williams

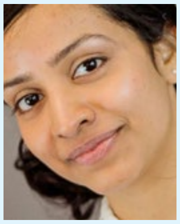
Director of Shipping

Nicola Williams has recently joined OPIS and is based in the London office. Nicola was previously employed from 1995-2023 as a Director of Clarksons, the world's largest shipping services provider. Since joining the Clarksons Gas & Specialised Broking Teams in 1999, she was responsible for analysis of market fundamentals and freight across all sectors of the Gas carrier fleet. Her responsibilities included preparing KPI's and benchmarking of COA's and Timecharters for clients, business development, market analysis, consultancy and logistics strategy evaluation. For the last 2 decades she was the Head Shipping Analyst for LPG, Ammonia and Petrochemical Gases and also covered LNG intermittently.

Benita Dreesan

Senior Journalist/Analyst Europe Renewable Energy at OPIS

Benita Dreesen has a solid background and over 20 years' experience working across global cultures and regions. Previously Benita acted as the EU Editor and EU Correspondent for Argus Media, covering evolutions in EU energy, financial and environmental regulations. She also worked for the United Nations Environment Programme (UNEP), developing business cases and market analyses on greenhouse gas emissions, on energy conservation and on biomass and carbon offset, covering 6 Asian countries (China, Japan, India, Indonesia, Singapore and Vietnam).



Cuckoo James

Associate Director for European Renewables at OPIS

Cuckoo Susan James oversees the solar and hydrogen team. Her broad experience in energy markets began with a seven-year tenure at ICIS, working with chemicals, plastics and refined products, before she joined OPIS in 2017. She previously worked at the national daily newspaper The New Indian Express before winning the European Commission scholarship to pursue a Masters in International Journalism in Europe, specialising in war journalism.

Products of Interest

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Projects and Policies Tracker: A compilation of the latest developments in the European hydrogen sector.

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OPIS has served as a leading Price Reporting Agency for energy commodities markets for 30 years. OPIS provides accurate pricing, real-time news and expert analysis across the global fuel supply chain, including the spot, wholesale rack and retail markets. OPIS and its brands, McCloskey, PetroChem Wire, Axxis and Chemical Market Analytics, enable customers to buy and sell energy commodities with confidence across the globe by providing transparent data, expert-level customer support educational events and energy data solutions. OPIS methodologies adhere to IOSCO (International Organization of Securities Commissions) principles for fuel Price Reporting Agencies and with European Union Benchmark Regulation (BMR).

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