OCBC TREASURY RESEARCH

Clean Energy Series: Hydrogen

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Hydrogen Primer

Fossil Fuels | Carbon Trading | **Hydrogen** | Natural Gas | Biofuels | Renewable Energy

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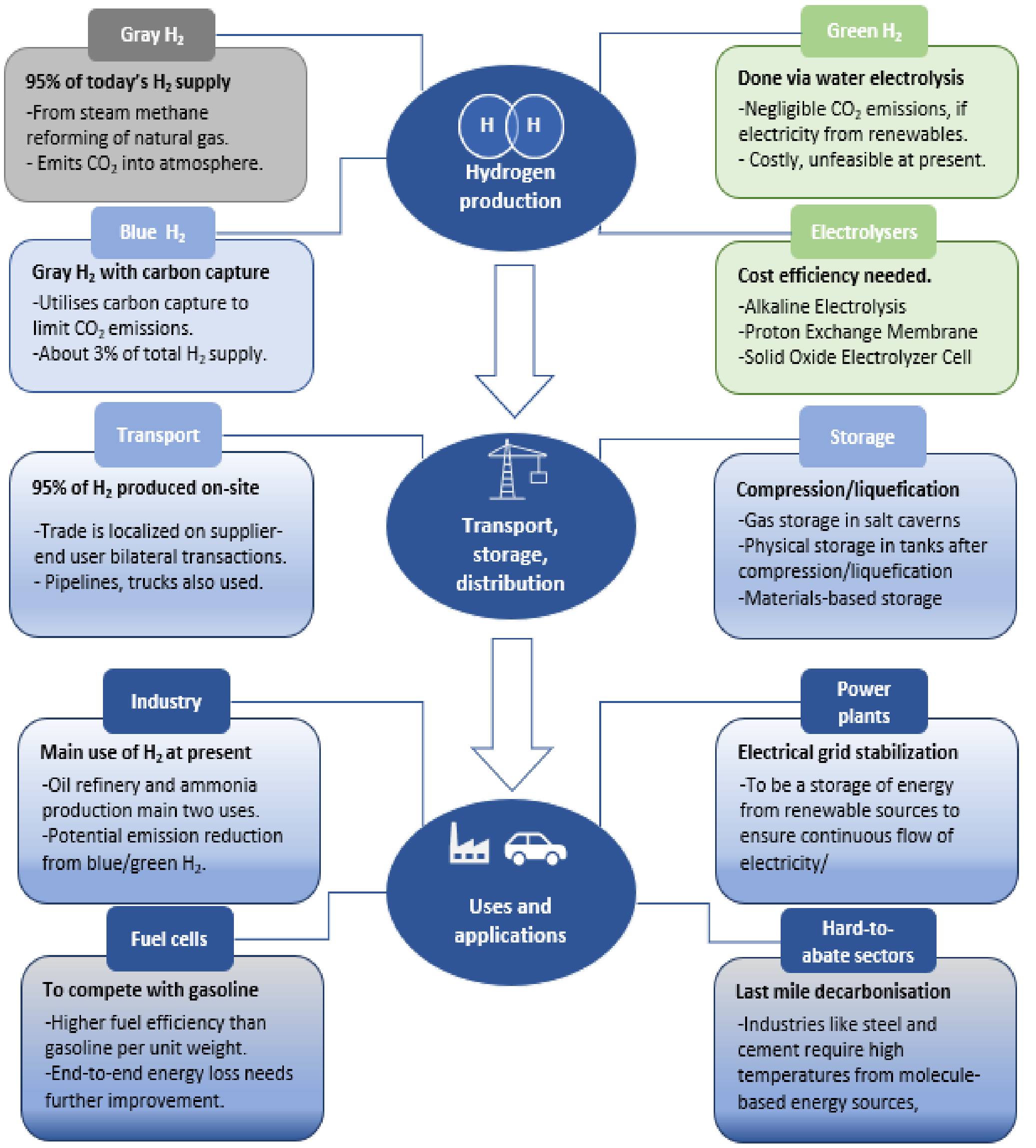
In the second part of this series, we look at the hydrogen market.

This paper serves as an elementary primer for understanding the basics of the hydrogen market.

The hydrogen ecosystem:



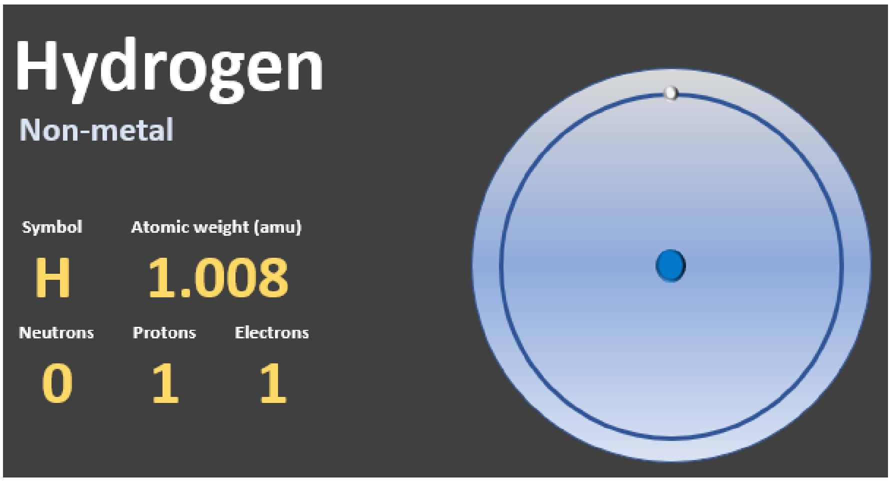
Source: OCBC Bank

Part 1: What is hydrogen's role in decarbonisation?

Fundamentals of hydrogen energy.

The molecular properties of hydrogen.
Hydrogen is the simplest element on Earth. It is the first element on the periodic table, consisting of one proton and one electron. The lightest element on earth, it is also the most plentiful element in the universe.

Despite its abundance, however, hydrogen doesn't normally combine with itself to form hydrogen gas. Instead, it is normally found in water (H_2O) ammonia gas (NH_3) or hydrocarbons such as natural gas and petroleum.



Source: OCBC Bank

Hydrogen fuel as clean energy.
Hydrogen is a clean fuel which on combustion, only produces water. This is because, unlike fossil fuels, hydrogen gas's absence of carbon mean it is theoretically incapable of producing carbon emissions.

$$2H_2 + O_2 \xrightarrow{\text{Combustion}} 2H_2O$$

Hydrogen can then be utilised in two ways.

1. **As a form of energy**, it may either undergo direct combustion (in a power plant, for example), or used in a fuel cell to produce electricity.
2. **For industrial use**, hydrogen is a key feedstock for oil refining and ammonia production.

As our Clean Energy series largely focuses on decarbonisation, we will largely concentrate on hydrogen's role in energy provision.

Why care about hydrogen?

Hard-to-abate sectors: As the world embarks towards decarbonisation goals, there are "hard to abate" sectors that have energy needs which cannot be met by electrification. Industries like steel, aluminium and cement require high temperatures during industrial production, which can only be produced by molecule-based energy sources like fossil fuels. Hydrogen may be used as an alternative to fossil fuels for these industries.

Smoothen renewable power provision: Even if the world successfully transits to largely using renewable energy sources, a backup storage of energy is needed. Recent rolling blackouts in California – a state at the forefront of decarbonising its power plants – shows the importance of possessing a ready standby source of energy for extreme weather events.

Improved long-distance fuel cells: Hydrogen has a much higher energy density compared to fossil fuels. Evolving technology may be able to tap hydrogen's higher energy density as improved long-distance fuel cells, which could then be used to power not only commercial vehicles, but long-haul bunkers and carriers as well as trains.

Part 2: The issues with hydrogen production

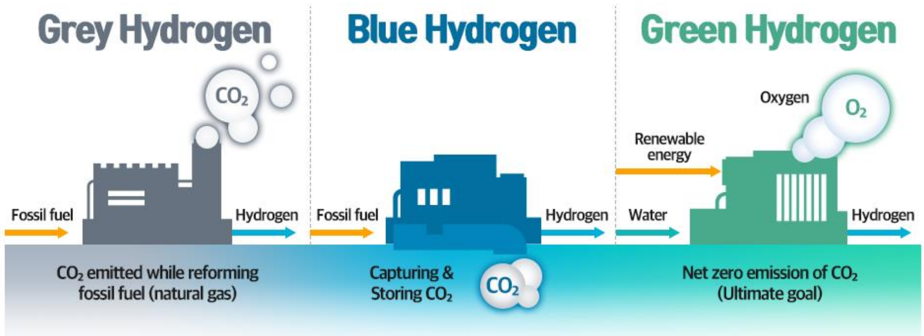
Differentiating grey, blue and green hydrogen.

Even though the combustion of hydrogen fuel is carbon free, the production of hydrogen is not necessarily so. The terms “grey”, “blue” and “green” hydrogen are used to describe the level of carbon emissions in the production of hydrogen gas.

Grey hydrogen
The overwhelming majority of hydrogen is currently produced from fossil fuels. This is done via a process called steam methane reforming (SMR), where hydrogen particles are separated from carbon in methane. The carbon is released into the atmosphere as carbon emissions. Hydrogen produced in this manner is called “grey” hydrogen.

Blue hydrogen
If carbon capture and storage (CCS) technology are used to mitigate carbon emissions from SMR into the atmosphere, then the hydrogen may be termed “blue hydrogen”.

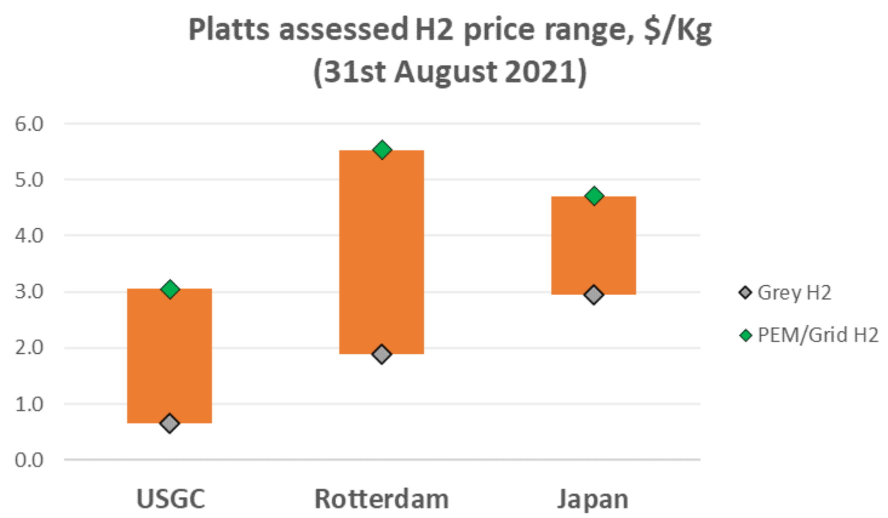
Green hydrogen
The other method of hydrogen production is via electrolysis. It involves passing a high current of electricity through water to separate the oxygen and hydrogen atoms. If the origin of the electricity passing through water is from renewable sources (for eg, wind or solar power), the hydrogen may be deemed as “green hydrogen”.



Source: POSCO

95% of current hydrogen production is “grey” hydrogen.
At present, 95% of global hydrogen production is “grey” hydrogen. “Blue” and “green” hydrogen are not the standard industry at present due to varying carbon laws internationally, limited infrastructure implementation and high costs of electrolysis.

Cost of green hydrogen is significantly higher than grey and blue hydrogen. According to data from S&P Global Platts, the cost of green hydrogen (Proton Exchange Membrane/Grid) is about $3/kg in the US Gulf Coast (USGC), and around $$5.50/kg and $4.70/kg in Rotterdam and Japan respectively. This is much greater than the cost of grey hydrogen, which costs about $0.70/kg in the USGC, $1.90/kg in Rotterdam and $2.90/kg in Japan. Even factoring in the costs of carbon sequestration from CCS, blue hydrogen is still considerably cheaper than green hydrogen.



Source: S&P Global Platts; pricing assessments are based on production plus cost basis

Part 3: The hydrogen market

Examining prices, transportation and storage of hydrogen.

Hydrogen is a highly localized commodity with little price discovery.
Unlike other commodities, hydrogen is hardly traded and has yet to reach a level of maturity that allows active trading. Trade is typically localized and takes place between supplier and end user on a cost plus spread basis, with little chance for price discovery.

Around 95% of hydrogen is produced near to its demand source. End-users enter into a deal with a hydrogen supplier for the construction of a production facility on-site to produce “on-purpose hydrogen.”

Transportation of hydrogen gas.
Hydrogen not produced on-site can be transported in two ways: via pipelines, or compress/liquefied in cryogenic containers and moved via rail or truck. Hydrogen shipping is, at present, still being pioneered.

- **Pipelines**: Hydrogen is blended with natural gas and then transported over existing natural gas pipelines before being separated at destination. This method only allows around 5-15% of hydrogen blend. A higher blend will require specially purposed pipelines that are about 50% wider in diameter.

- **Rail or truck:** Similar to other gases, hydrogen is normally compressed or liquefied being transported by rail or truck.

Storage of hydrogen gas.
Due to its molecular properties, hydrogen gas has a very low density. Increasing the storage density of hydrogen is key for storage of hydrogen to be economically viable. There are several methods to increase hydrogen’s storage density, but most require further input of energy – further reducing hydrogen’s end-to-end net energy efficiency.

- **Gas storage in salt caverns:** Gas storage in salt caverns is a mature practice and enables easy knowledge transfer. Other options for direct storage of hydrogen gas include depleted oil and gas fields.

- **Physical storage in tanks:** Hydrogen is first compressed or liquefied and stored in cryogenic tanks. Of the two, compression is relatively less costly and thus more widely used.

- **Materials-based storage:** This method combines hydrogen gas with other materials with higher storage density. The compounds should be easily separable. Ammonia, for example, offers a path for turning hydrogen into a liquid fuel.

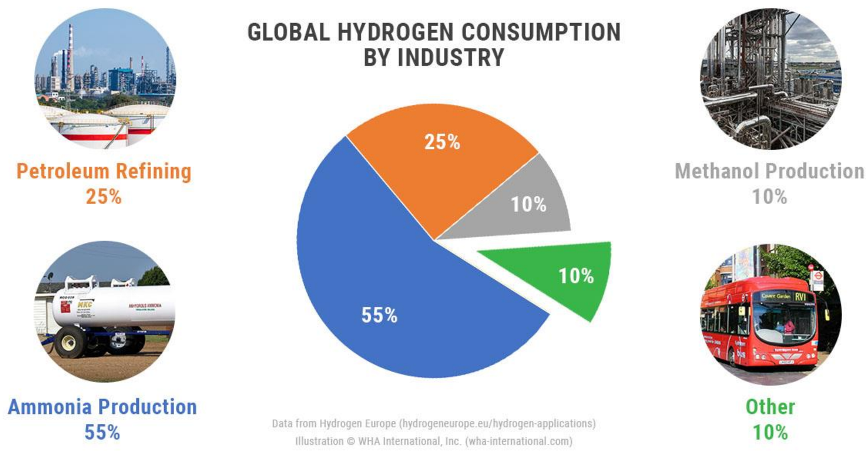
Part 4: Uses of hydrogen – the now and the future

The now: 95% of hydrogen is used in oil refining & ammonia production.

Current hydrogen use is centred around industrial usage, particularly oil refining and ammonia/methanol production for fertilizers.

Oil refining: Hydrogen is an important feedstock in the hydrocracking process i.e conversion of heavy gas oils and residues into lighter distillates like diesel, gasoline and jet fuel.

Ammonia production: Hydrogen is a key material in ammonia production, which in turn is an important component in fertilizer manufacturing.



Source: WHA International

As most hydrogen production at present is grey hydrogen, there exists significant potential for emissions reductions in this space.

The future: hydrogen's role as fuel in transportation and utilities.

Transportation and utilities – the top two producers of CO_2 emissions – are fast emerging markets for hydrogen use. Its relatively simple chemical structure allows hydrogen to be an effective energy carrier for both electrical energy storage as well as a fuel cell.

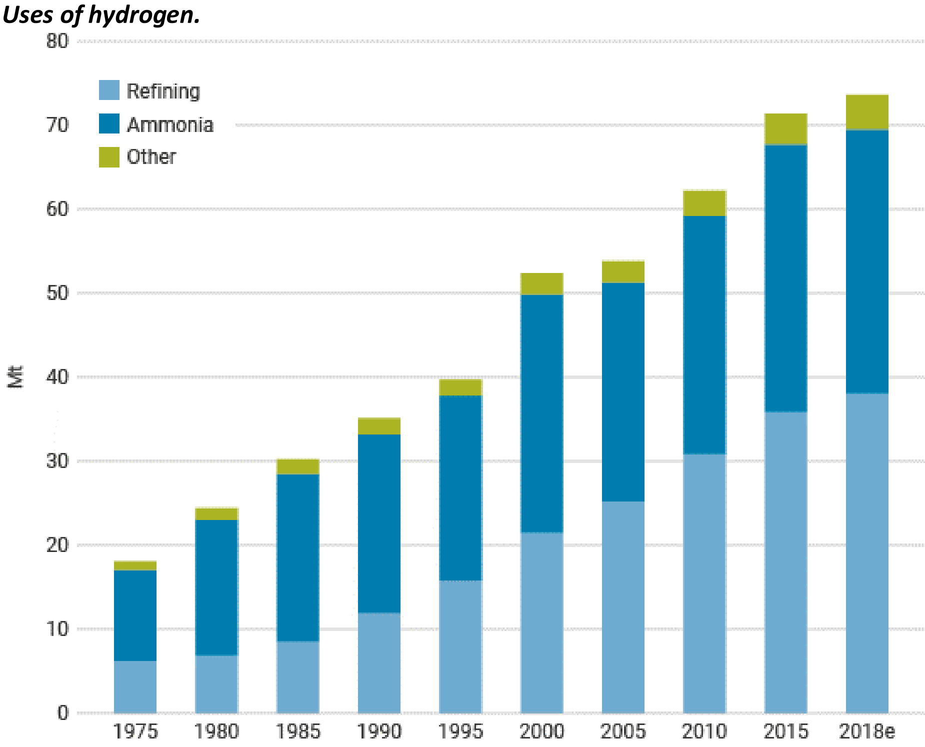
Utilities:
Hydrogen is a leading green option for the storage of renewable energy. It can be used a means for electrical grid stabilization via storage of electrical energy. This is especially important as the world transits into using renewable energy sources, where unpredictable blackouts and/or peak

loads are more frequent. Stationary fuel cells can be used in uninterruptible power supply (UPS) systems at a localised level to ensure critical facilities like hospitals and data centres have a continuous source of power.

Transportation:
The key advantage in hydrogen fuel cells is its long-range capability, due to hydrogen's high energy density. Hydrogen fuel cells are now being considered for uses in trains and buses, with the likes of Chicago and Vancouver experimenting with hydrogen-powered buses. Germany is also introducing hydrogen-powered trains. The main considerations in this space remain a) the price competitiveness of hydrogen fuel cells vis-à-vis competing fuels and lithium-ion batteries; b) the energy efficiency of hydrogen fuel cells; c) availability of refuelling stations. More of this is elaborated in Appendix II.

As the use of hydrogen as a fuel continues to grow, it will increasingly evolve from an on-purpose, on-site industrial feedstock into a commodity in its own right.

Uses of hydrogen.



Source: International Energy Agency

Part 5: Investment opportunities related to hydrogen

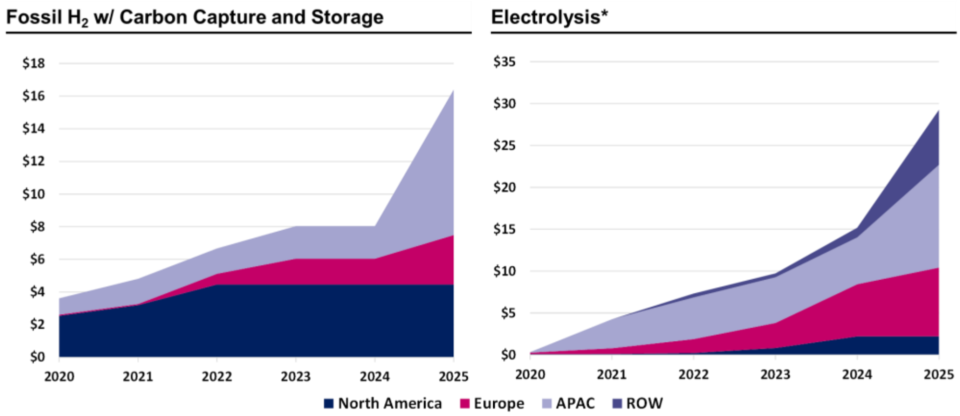
1. Green hydrogen may be one of electricity's largest consumer by 2050.
Green hydrogen comprises less than 5% of global hydrogen production at present, but is set to grow as electrolyser technology matures. As electrolysis requires intensive electricity usage, green hydrogen may eventually be one of electricity's largest consumer by 2050.

2. Investments in gas pipelines set to grow significantly.
Pipelines remain the most cost-effective and straightforward way of transporting hydrogen gas. Dedicated pipelines for hydrogen gas are estimated to need at least 50% wider in diameter compared to existing natural gas infrastructure to accommodate hydrogen's lower gas density. An overhaul of current pipeline infrastructure is likely necessary.

3. Shipping industry to start carrying hydrogen.
Countries with cheap renewable sources or have close proximity to natural gas fields may become major producers and exporters of "clean" energy, including (green/blue) hydrogen gas. The shipping industry may find itself in the centre of this development. Firstly, shipping of hydrogen gas would most definitely require specially repurposed vessels to carry liquefied hydrogen at -253degC. Few, if any, commercial carriers are capable of this at present. Secondly, the International Maritime Organisation (IMO) has ambitious goals to be net-neutral carbon by 2050. Shipping could be a major adopter of hydrogen-powered fuel in the coming decades.

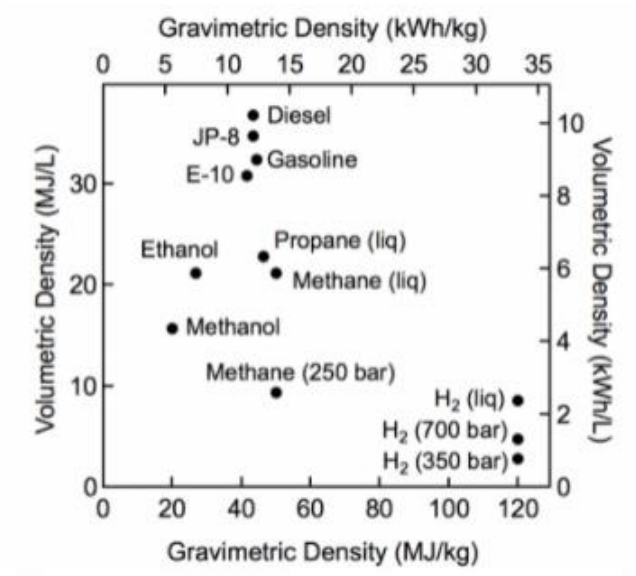
4. Carbon capture storage (CCS) technology needs to scale up.
Blue and green hydrogen constitute 5% of total global hydrogen production at present. To better decarbonise grey hydrogen, both CCS and electrolysis technology will need to be scaled up exponentially in the coming decade to meet demand. According to data from S&P Analytics, cumulative investments in fossil hydrogen with CCS technology is set to increase 4x by 2025 from 2020 levels to $16bn.

Investments on hydrogen production capacity, $bn



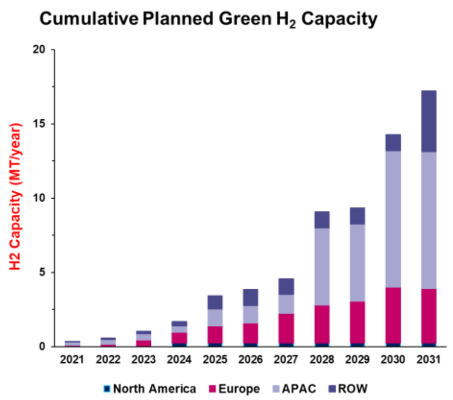
Source: Platts Analytics Hydrogen Production Database

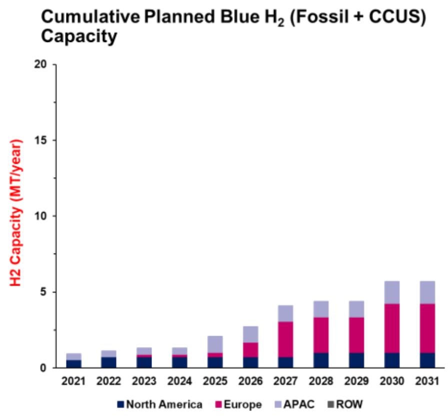
5. Hydrogen fuel cells remain promising, but require much more R&D.
Hydrogen fuel cells (HFCs) key advantage is its long-range capability due to its high energy density. HFCs, however, have an astonishingly low end-to-end energy efficiency rate of about 30%; in contrast, an EV battery has a rate of about 77%. Heavy duty transport (trucks and trains) involving HFCs are promising, but will require much more R&D to improve energy efficiency.



Source: Energy.gov

6. Asia to be the key supplier of green H_2 by 2028.
According to data from S&P Global Platts Analytics, Asia could likely own the biggest green hydrogen capacity by 2028 compared to North America and Europe. Global green H_2 capacity is expected to increase approximately 15x from 2021 levels, while blue H_2 could grow about 6x in the same period.





Source: S&P Global Platts Analytics. Estimates based on announced projects.

Summary

As the world embarks towards its net-zero carbon goals by 2050, hydrogen is set to play a key role as a clean fuel. While primarily used in industrial applications of oil refinery and ammonia production at present, it shows promise in the emerging growth drivers of utilities (electrical energy storage) and transportation (long-distance hydrogen fuel cells). There is also value-add in the direct combustion of hydrogen gas as a molecule-based fuel in hard-to-abate sectors like steel and cement.

While hydrogen is a clean energy, hydrogen production from its naturally occurring sources is largely not. 95% of current hydrogen production is deemed “grey” hydrogen, where the process of steam methane reforming releases carbon emissions into the atmosphere. Developing technology in carbon capture and storage (CCS) and electrolysers should assist the transition from “grey” to “blue” and “green” hydrogen.

Much of current hydrogen production is done on-site and near the source of end-user industrial consumption, typically in bilateral transactions. As such, there is little chance of price discovery for the market at present. Prices are largely cost-based plus a premium, instead of market-based. As the market for hydrogen as a fuel grows, it should evolve from an on-purpose feedstock into a commodity in its own right.

Finally, we see much investment opportunities associated with hydrogen, including a reconfiguration of existing natural gas pipelines, a scaling up of CCS and electrolyser technology, repurposed shipping vessels and increased R&D in hydrogen fuel cells.

Appendix I: Green hydrogen electrolysers

Electrolysis is the process of passing a current through a permeable barrier containing water to produce hydrogen (cathode) and oxygen (anode). To be classified "green", the electricity that is used should be obtained from renewable energy sources like wind turbines and solar panels. The hydrogen produced from this method effectively acts as a store for this renewable energy via the storage of electrical energy.

The two main types of renewable hydrogen electrolysis are Alkaline and Proton Exchange Membrane (PEM), while Solid Oxide Electrolyser Cell (SOEC) is also being tested.

- Alkaline electrolysis has been used for decades and is a mature technology. Hence, it is the cheapest option among the three but has the lowest energy efficiency.
- PEM is at the forefront of electrolyser technology interest given its highest efficiency rate than alkaline electrolysis. It also has higher power and energy density compared to alkaline electrolysis. It is, however, more costly.
- SOEC uses a solid ceramic material as the electrolyte. Electrolysis is performed at temperatures of around 500-850degC. This method is still very much in the research phase, but is receiving interest due to its ability to reduce energy requirements and improve energy efficiency.

	Alkaline	Proton Exchange Membrane (PEM)	Solid Oxide Electrolyzer Cell (SOEC)
Relative Maturity	Mature	Mature	Developing
Example Players	• Nel, Cummins, McPhy Energy	• Nel, Siemens, ITM Power	• Haldor Topsøe, Elcogen
Technology	• Electric current sent through water containing alkaline catalyst • Energy splits water into H_2 and O_2 to be produced at diodes	• Uses plastic membrane, permeable to hydrogen but not oxygen/water • No catalyst: electricity splits pure water into H_2 and O_2 • Hydrogen moves across membrane as output	• Uses heat as well as electric power • Pass heat / electricity through steam mixed with solid oxides • Energy used to split steam into H_2 and O_2
Key Indicators	• Operating temperature of 60-80°C • 60-65% energy efficiency • Hydrogen cost of ~$5/kg	→	• Operating temperature of 650-1000°C • 80% energy efficiency
Future developments	• Predicted to reach 70% efficiency and $2/kg by 2030 • Being considered for GW scale projects in EU, AUS, etc.	→	• Haldor Topsøe aiming for 90% efficiency by 2023 • Building factory with annual production capacity of 500MW; option to expand to 5GW
Considerations	• Most efficient with high/consistent base energy supply • Cannot operate at high pressure due to risk of hydrogen/oxygen coming into contact (hydrogen must be pressurized after production)	• More capable of handling low or intermittent energy supply e.g. from renewables • Can operate at high pressure (hydrogen and oxygen separated by membrane)	• Can utilize waste heat from electricity generation • Relatively new technology – electrolyzer capex likely to be high in near future

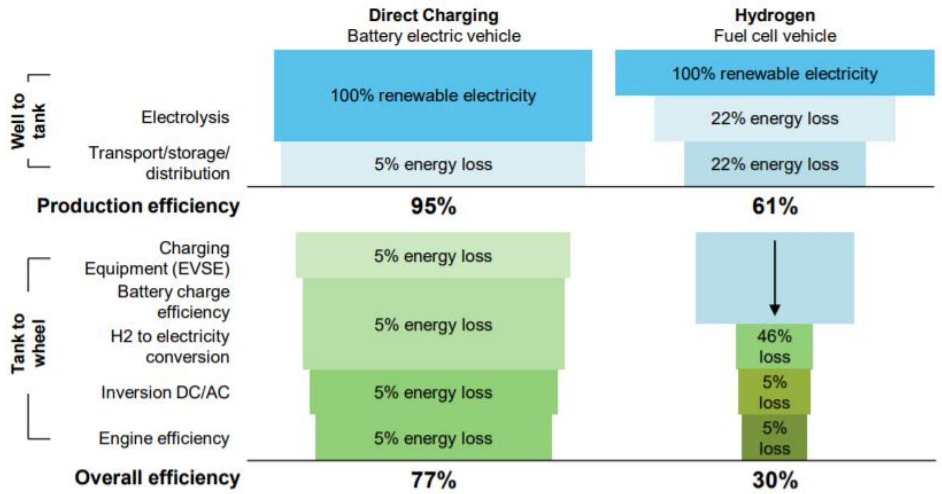
Source: Marakon, Charles River Associates

Appendix II: Hydrogen fuel cell efficiency

The main issue with hydrogen fuel cells is its efficiency from an end-to-end perspective, despite the higher energy density of hydrogen when viewed in silo. The process of electrolysis removes about 30% of the energy in the electricity, while a further 10% is wasted in the transport and storage of hydrogen has from compression/liquefication process. From here, the process of hydrogen to electricity conversion, engine efficiency, AC/DC inversion etc would see the hydrogen fuel cell waste another 30% of its original energy. It is eventually left with 30% of its original energy input.

This is, however, more effective than gasoline with an efficiency of around 20%. However, it highly pales in comparison to lithium-ion batteries in electric vehicles, which can boast an efficiency rate of around 77%.

The Copenhagen Centre on Energy Efficiency estimates that a Tesla Model 3 running on an EV battery has a mileage cost that is one-third that of a Toyota Mirai, which is powered by a hydrogen fuel cell.



Source: Marakon, Charles River Associates

	Tesla Model 3 (75kWh)	Toyota Mirai
Price to fully charge or fill	15 €	47.5 €
Range (km)	499	502
Price/km	0.030 €	0.095 €

Source: Copenhagen Centre on Energy Efficiency

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