RYSTAD ENERGY

RYSTAD ENERGY TRANSITION REPORT

FEBRUARY 2021 FREE EDITION

HYDROGEN SOCIETY

The Rystad Energy Transition Report

The Rystad Energy Transition Report series leverages the full breadth of our data expertise to explore what a future decarbonized energy system may look like through three conceptual societies. Each society serves as a model primarily dependent upon one of the technologies currently competing to become dominant on the pathway to net-zero – carbon capture and storage (CCS), hydrogen and batteries.

Our hydrogen society illuminates the tremendous decarbonizing potential of H_2 across four key demand segments: transportation, industry, power & buildings, and energy. In the following free edition, we discuss some key developments and highlights. In the full report, we dive deeply into the topic, covering key end-use applications for hydrogen, the demand forecast up to 2050 in addition to hydrogen supply and its competitiveness.

To gain access to the complete report, we encourage you to contact us at your earliest convenience. *We look forward to sharing our Battery Report with you in the next month.*

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Hydrogen – set to quintuple by 2050

Our energy transition story continues this month as we explore the decarbonizing potential of hydrogen in our Hydrogen Society. Hydrogen has received much attention in recent years as a potentially carbon-free commodity with many of the same advantages of traditional fossil fuel; it offers good energy density and can be applied to a variety of sectors. Yet a true hydrogen economy has yet to take off, hindered by economic constraints and the immaturity of many end-use hydrogen technologies.

In this edition of the Rystad Energy Transition Report these obstacles are deconstructed, revealing that 51% of global CO_2 emissions are fully or partially addressable with hydrogen. This amounts to carbon savings of over 20 gigatons (Gt). We begin to understand this potential by examining hydrogen's applicability to four key demand sectors comprised of 10 end-used segments. In our Transportation chapter, hydrogen-powered Fuel Cell Electric Vehicles are hindered by fierce competition from Battery Electric Vehicles, while aviation and shipping benefit from hydrogen products such as ammonia and synthetic jet fuel. In our Industry chapter, ammonia and methanol derived from green H_2 take center stage as powerful tools in the fertilizer and plastic markets, while H_2 has direct applications in steel making. Hydrogen could have a role to play in grid balancing, as discussed in the Power and Buildings chapter, while the need for hydrogen in the Refineries chapter is robust but faces long-term decline, falling in tandem with decreasing demand for oil products.

Together, these end-use segments would consume 340 Mt of hydrogen in 2050, five times as much as H_2 production today. Such a massive demand increase would require a ramp up of supply from both blue and green hydrogen. Green H_2 has the deepest decarbonizing potential, but blue H_2 can utilize existing production pathways and can achieve near-zero hydrogen when paired with supplementary carbon capture and storage (CCS) mechanisms.

Given current infrastructure and production pathways, this means that blue H_2 is more cost competitive in all regions and could be less costly to scale quickly than green H_2. However, the cost of green H_2 is primarily driven by the price of the electricity consumed in the electrolysis process, and renewable energy prices are falling precipitously as renewable generation soars. In the past five years alone, operational costs related to wind and solar have fallen by 58% and 19% respectively, while capacity from wind and solar has risen 100% in the same timeframe. Assuming the price of renewable electricity continues to fall, the only remaining economic hurdle for green H_2 will be the capital expenditure required for development, a cost that will also decline as learning curves continue to play out and infrastructure becomes increasingly standardized. As the costs of green H_2 fall, it will become increasingly attractive relative to its blue H_2 counterpart.

The nuances of this price discussion are explored further in the Competitiveness of Future Supply chapter. Regardless of whether blue or green will color the future of hydrogen, one thing is clear: hydrogen will be a key solution driving the energy transition forward.

Source: Rystad Energy research and analysis

Contents

***This free edition report includes 16 of 32 pages that are available in the full report**

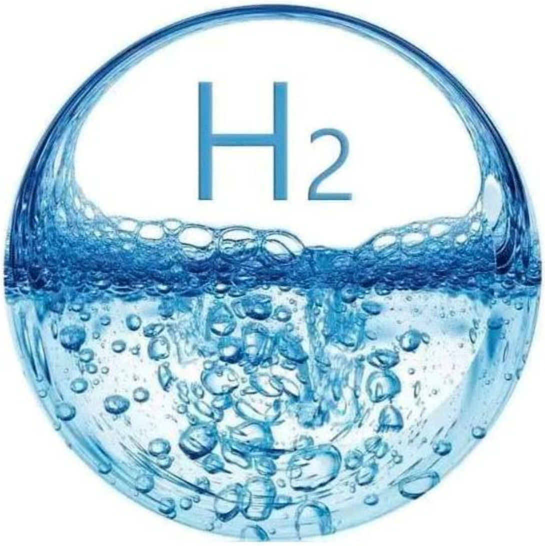


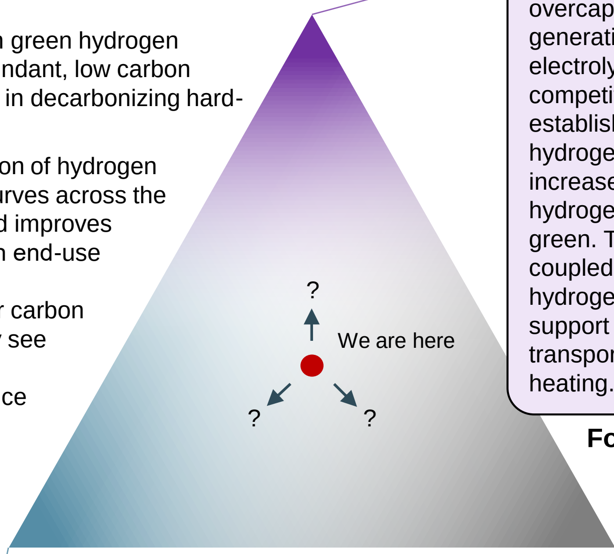
Photo: Ørsted

The Hydrogen Society

In our inaugural Rystad Energy Transition Report from December 2020, we introduced the three Rystad Energy Societies: CCS, Hydrogen and Battery. These societies are conceptual futures wherein each of the three key technologies becomes the dominant supplement to renewable power towards a decarbonized energy system. Each society will contain elements of all three, but with varying degrees of technological penetration. Through the first quarter of 2021, we will continue to elaborate on the status quo of each technology, the direction each is heading, and the pace of development. Regardless of where we end up as a global society, each technology is already vying to achieve winning market share.

Key dynamics of the Hydrogen Society:

- Continued reductions in renewable energy cost and subsequent continued ramp up in renewable generation improves the economics of green hydrogen projects.
- A policy-led increase in green hydrogen production creates abundant, low carbon hydrogen to be utilized in decarbonizing hard-to-abate sectors.
- Large scale consumption of hydrogen accelerates learning curves across the hydrogen economy and improves hydrogen's efficiency in end-use applications.
- If combined with higher carbon pricing, we would likely see sufficient scale in CCS implementation to reduce the cost of CCS technologies and improve the competitiveness of blue hydrogen, in addition to green.



Hydrogen Society

In a Hydrogen Society, the overcapacity in renewable generation and cost reduction in electrolyzers would result in competitive green hydrogen. The establishment of a widespread hydrogen economy would increase demand for blue hydrogen in addition to green. This demand increase, coupled with the mainstreaming of hydrogen pipeline grids, would support everything from transportation to power and heating.

Focus of this report

Battery Society

Within a Battery Society, battery costs continue to plummet, allowing for cheap grid storage that can deal with intraday intermittency, as well as supplying electricity for days. In this scenario there are no substantial supply-side bottlenecks. Cheap batteries also support the rapid electrification of transportation and would (in combination with cheap solar, wind, and a strengthened power grid) become a lethal blow to the fossil industry. CCS and hydrogen would become niche technologies within industry and certain parts of transportation.

CCS Society

A CCS society is predicated on the introduction of global carbon taxes and improved cost/economies of scale for CCS technologies. In this scenario, CCS is deployed on a massive scale in everything from industry and blue hydrogen to the power sector and direct air capture. The quick adoption of carbon taxes ensures a relatively quick adoption rate for CCS technologies, alleviating carbon budgets, and supporting prolonged business as usual for the fossil industry. Batteries would be largely constrained to the lighter segments of the transportation sector, and blue hydrogen would play a pivotal role in decarbonizing industry and hard-to-abate transport.

Source: Rystad Energy research and analysis

Hydrogen decarbonization strategies rely on both blue and green hydrogen

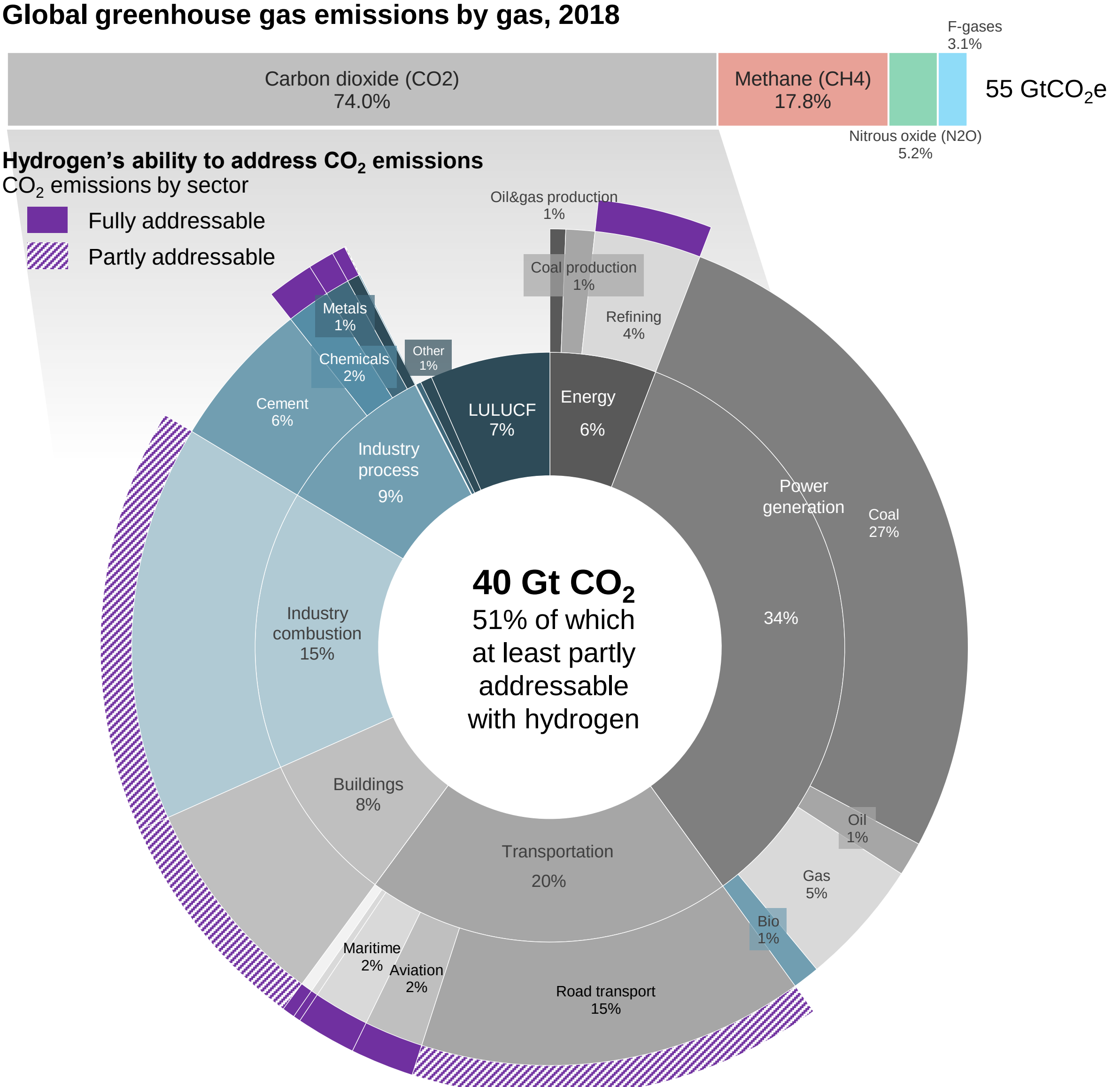
Type	Description	Pros	Cons
Grey hydrogen	Today, almost all hydrogen production is grey, meaning it is produced from fossil fuels. Grey H_2 is used in the chemical industry, fertilizer production, and in petroleum refineries.	• Well suited to large-scale production due to abundant access of natural gas • Cost competitive • Production technology already exists, and it is well established in the industry	• High CO_2 emissions in production • Exposed to increasing CO_2 taxes
Blue hydrogen	Similarly, blue hydrogen originates from fossil fuels, but production of blue H_2 involves carbon capture and storage. Blue hydrogen could become an important pathway towards decarbonizing the energy system by suppling sectors that have few sources of H_2 supply.	• Carbon emissions from grey hydrogen production could be reduced substantially if carbon capture and storage is applied • Currently, blue H_2 is cheaper and "greener" than electrolysis • Blue H_2 has the potential to scale quickly as existing production capacity is retrofitted with CCS	• Dependent on the further development of CCS technology, as well as transportation and storage. Current technology is not 100% carbon-free • There is investment risk as green hydrogen becomes cheaper and might eventually outcompete blue H_2
Green hydrogen	Green hydrogen is produced through the electrolysis of water, with renewable electricity. Currently, only 4% of Europe's hydrogen production is from electrolysis, and the electricity is not necessarily renewable.	• Requires only access to water and electricity. • Is less dependent on infrastructure than blue or grey hydrogen • Potentially carbon-free • Can be flexibly deployed near large demand centers	• Still costly, but costs are expected to fall • Competitiveness is highly dependent on low electricity prices and equipment load factor • Competes with electricity consumption from other sectors for green electricity

Sources: Rystad Energy research and analysis

51% of global CO_2 emissions are at least partly addressable by hydrogen

Our hydrogen society illuminates the tremendous decarbonizing potential of H_2 across four key demand segments: transportation, industry, power & buildings, and energy. When applied to these segments, where technologically feasible, we estimate hydrogen can completely or partially address 51% of the 40 gigatons (Gt) of CO_2 emitted annually, a feat which would be achievable with a huge ramp up of hydrogen supply. As mentioned, existing H_2 supply streams primarily produce grey hydrogen derived from natural gas. To unlock the full decarbonizing potential of H_2, the production of blue H_2 (hydrogen from natural gas with CCS) and green H_2 from electrolysis must be scaled. The economic viability of this ramp up will be contingent upon cheap electricity, the result of a huge increase in renewable generation.

Global greenhouse gas emissions by gas, 2018



Source: Rystad Energy research and analysis, IPCC

Key end-use applications for hydrogen

Sector	Application	Long term competitive assessment	Main competition
Transport	*Passenger vehicles*	Recent developments point to battery electric vehicles winning this segment. However, there may be niche applications or geographical pockets where FCEVs can get a foothold.	• Battery
	Road freight	Battery electric technology is gaining a foothold in road freight as well, but hydrogen might still have a role to play in the heavier segments.	• Battery
	Aviation	Decarbonization pathways for aviation are still immature and unproven. Hydrogen-based synthetic jet fuel shows promise, along with biojet, but battery electric has the potential to capture a large share of the short haul market.	• Synfuels • Biojet • Battery
	Shipping	Zero-carbon fuels, such as ammonia and biofuel, seem the likely pathway for most shipping applications. Batteries show potential in short-sea voyages.	• Synfuels • Biofuel • Battery
Industry	*Steel production*	Decarbonizing technologies for steel production are still in the pilot phase, with promising technologies being developed as both H_2 and purely electric solutions. CCS will likely be a transition solution, but the segment will never achieve net-zero with CCS alone.	• Iron ore electrolysis • CCS
	Chemical industry	Although recycling is expected to reduce plastic feedstock demand, virgin feedstock will still be needed. H_2 could prove a key pathway to decarbonize plastic production. Fertilizers will need to transition to green ammonia to become truly net-zero.	• CCS • Bioplastics • Recycling
	Heat to industry	Within the heat to industry segment, H_2 will primarily be used for process heat in industrial boilers. Efficient electric boilers and heat pumps will offer alternatives to traditional techniques as well, but this will depend on the required temperatures of various processes.	• Electricity • CCS
Power and buildings	*Power generation*	The decarbonization technology of choice will likely depend on how much of the storage market can be covered by lithium-ion batteries and how much needs to be covered by long term storage, such as hydrogen and other energy storage systems.	• Other energy storage solutions
	Buildings	The energy needed to heat buildings with hydrogen is five to six times that of electric heat pumps. This implies that hydrogen will likely have limited potential in this segment. This market will likely be nearly 100% electrified.	• Electricity
Energy	*Refineries*	Hydrogen is utilized for refining processes to sweeten crude (reduce the sulphur content) and hydrocarbon cracking. This is relevant for jet fuel, gasoil, gasoline and diesel. The competitiveness of the application is dependent on the displacement of oil in these sectors.	• Battery • Synfuels

Source: Rystad Energy research and analysis

Road transportation

Passenger vehicles

H_2 technology

Hydrogen fuel cell

Hydrogen can be applicable to the passenger vehicle segment through the use of hydrogen fuel cells in fuel cell electric vehicles (FCEV). Unlike battery electric vehicles (BEV), wherein electricity is generated via external charging, hydrogen fuel cells function by creating an electrochemical reaction that powers an electric drive train, releasing only water vapor and heat as byproducts.

Key advantages:
Quickly refillable, long range relative to weight

Key disadvantages:
Lacking H_2 infrastructure, immature supply chains, large volume

Legacy technology

Gasoline/diesel internal combustion

Competitors

Battery electric

Technological feasibility

Competitiveness

FCEVs are already commercially available as passenger vehicles. However, BEVs have quickly gained market dominance and have established significant infrastructural support in the form of widespread charging station availability and robust manufacturing streams. This stands in contrast to the relatively limited H_2 infrastructure in the vast majority of regions, making H_2 refueling a challenge. Additionally, the advantages gained by using a hydrogen fuel cell – somewhat lighter drivetrain and longer range – diminish for every incremental improvement in battery electric technology. This, combined with low consumer demand, points to BEVs likely being the decarbonizing technology of choice for light-duty transportation. However, FCEVs may be able to establish market share in some niche markets or geographies, as some countries still push policies dedicated to FCEVs.

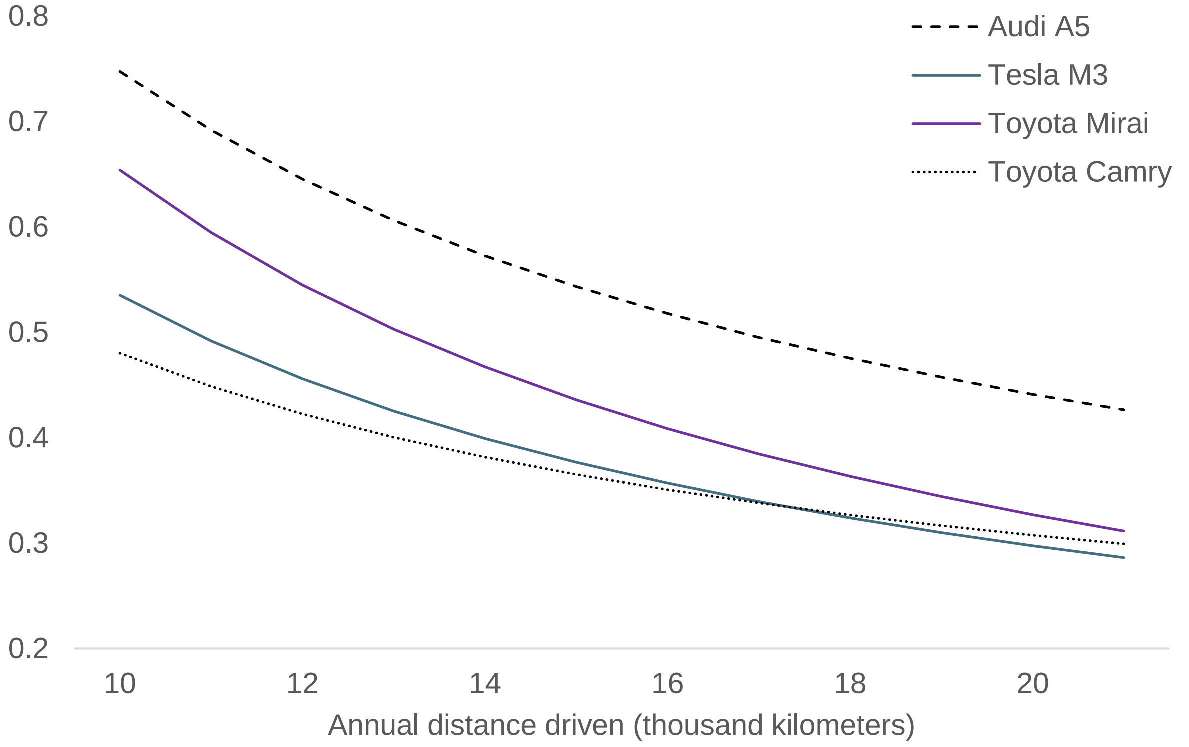
Toyota Mirai FCEV Photo: Toyota

Source: Rystad Energy research and analysis

H_2-powered passenger vehicles to remain more costly than BEVs

Passenger vehicles

Total cost of ownership over five years
USD per kilometer



Assumptions	Audi A5	Toyota Camry	Toyota Mirai	Tesla M3
Purchase price	$44,200	$24,600	$49,500	$39,190 (LR)
Fuel cost	$1.50 per liter (L)	$1.50 per L	$0 per kg H_2*	$0.40 per kilowatt hour (kWh)
Fuel consumption (per 100 km)	9 L	9 L	0.76 kg	15 kWh

*Toyota recently started to offer complementary fuel for the first six years of ownership
Source: Rystad Energy research and analysis

Hydrogen demand to quintuple by 2050

It's still early days, but hydrogen shows promise as a decarbonization pathway in several hard-to-abate sectors. The chart below shows Rystad Energy's outlook for hydrogen demand across the demand sectors discussed in the previous sections. The overall legacy consumption of hydrogen is expected to decline as global oil demand reduces refinery throughput towards 2050. Fertilizer and other ammonia use will follow these general socio-economic developments, although technological developments in agriculture might pose both upside and downside risks to these estimates.

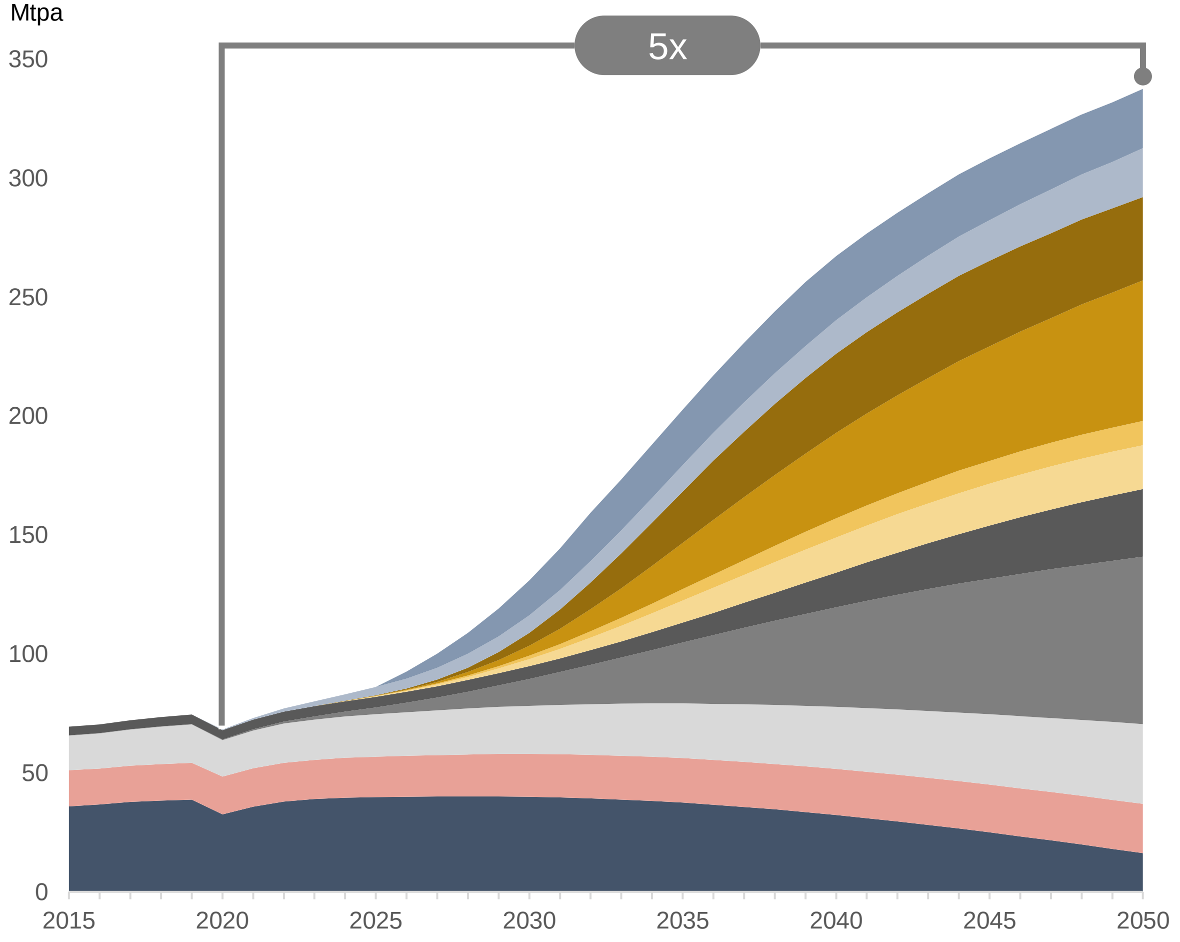
The new major end-use markets for hydrogen include:

- Steel, where H-DRI seems to be the most promising decarbonization technology
- Aviation, where long haul to a large extent is likely to be covered by hydrogen-based fuels (direct H_2 or synjet)
- Shipping, where deep sea shipping will benefit from ammonia or other H_2 derived fuels

Road transport and power & buildings are less obvious and will hinge on regional policy support.

Global hydrogen demand by sector

Mtpa



*Other ammonia includes refrigerants, pharmaceuticals and textiles
Source: Rystad Energy research and analysis, HydrogenCube beta

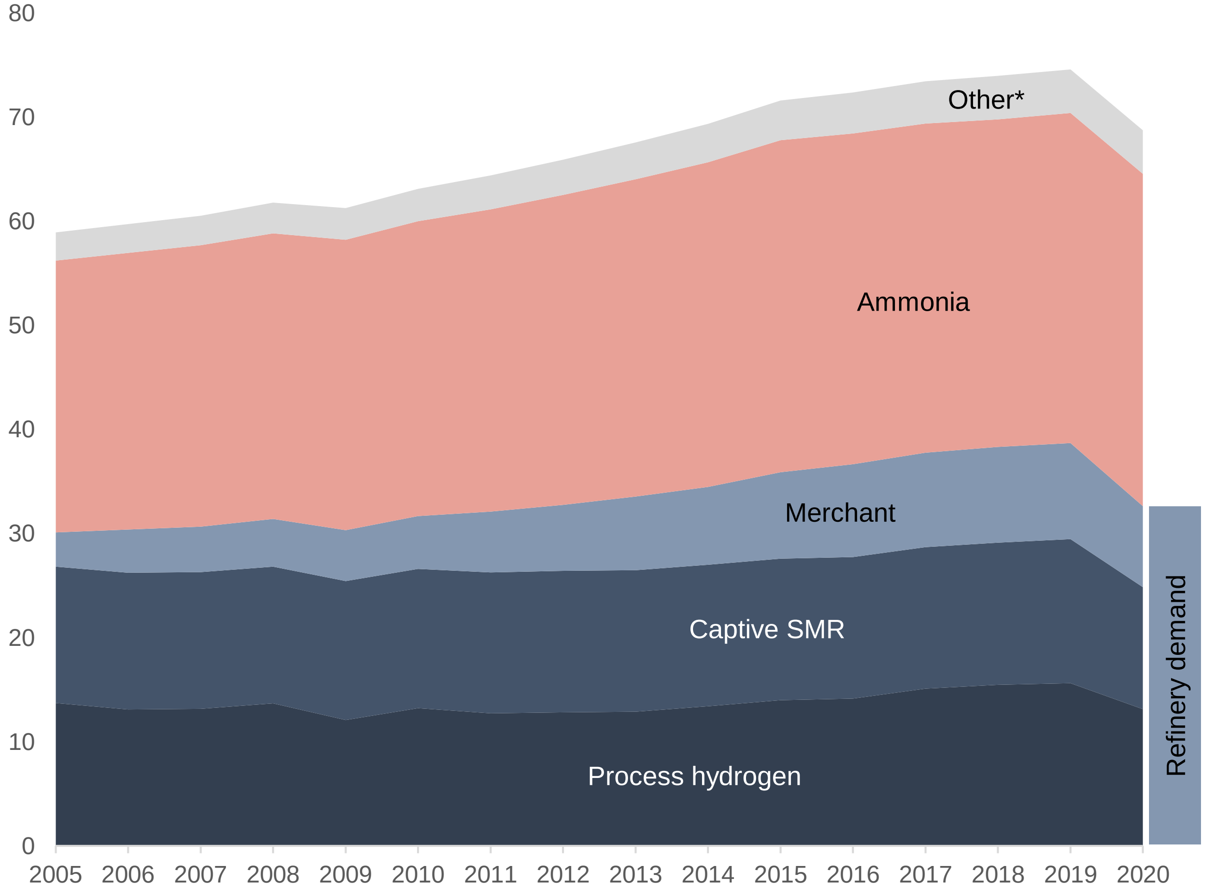
Historical production dominated by refineries and ammonia

Historical production has traditionally taken place at three distinct locations:

1. In dedicated ammonia production facilities, with most output going to fertilizer production
2. At refineries for local consumption, either as a refinery by-product or to feed on-site SMR facilities
3. At merchant hydrogen plants with most output dedicated to the refining sector.

As new end-use segments emerge, we expect the merchant fleet of H_2 plants will grow to outpace other existing sources. In order to produce hydrogen with a zero carbon or low carbon footprint, these new commercial facilities will need to either produce green or blue H_2. The following pages discuss the current costs of these two sources of supply and highlight the key sensitivities that determine the competitiveness of each.

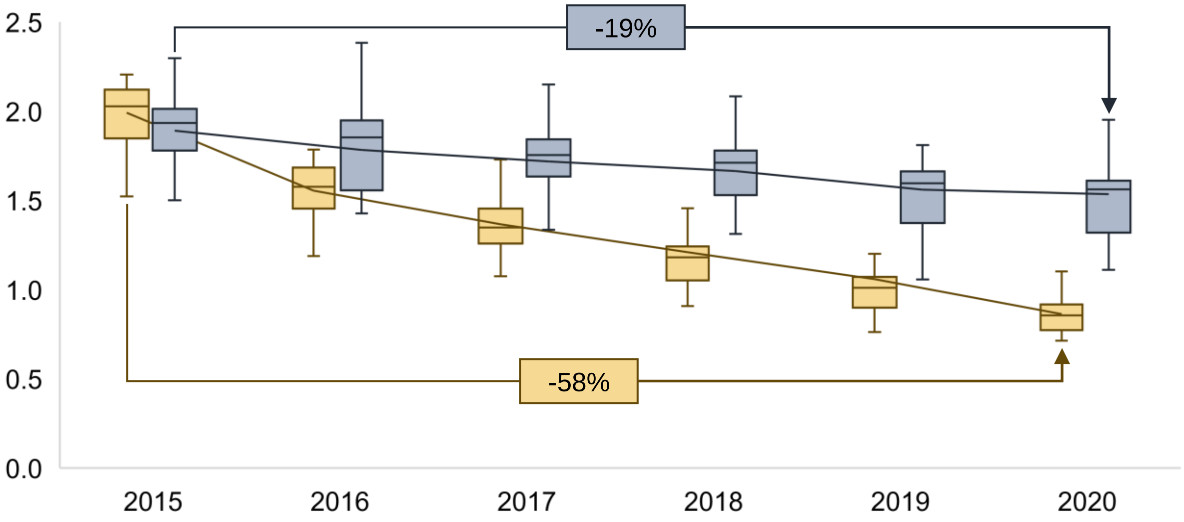
Historical hydrogen production
Million tonnes per annum (Mtpa)



*Other is primarily methanol production for plastics production (MTO)
Source: Rystad Energy research and analysis, HydrogenCube beta

Amid policy push, plummeting costs spawn a massive ramp up in renewable capacity

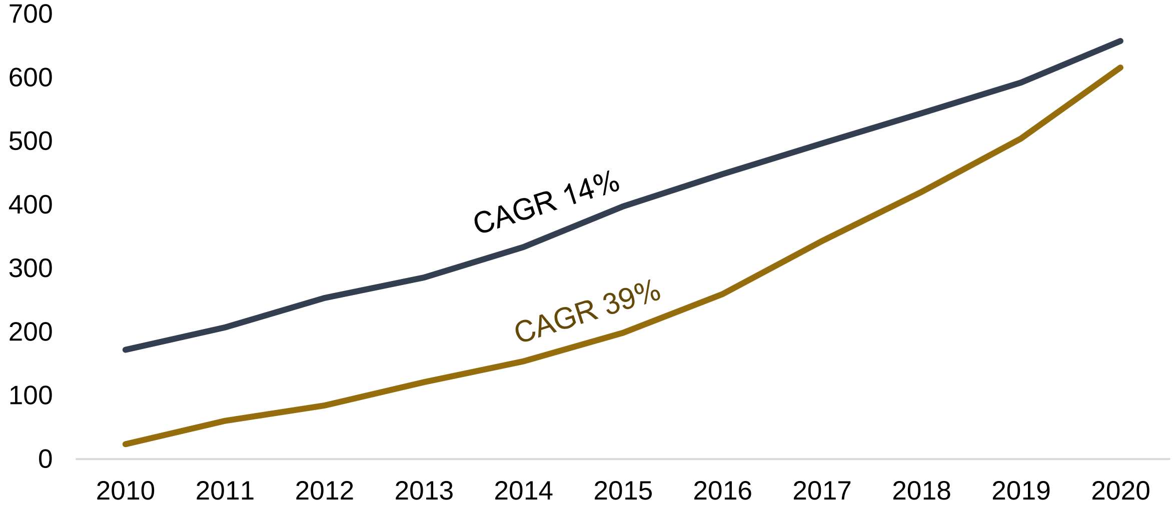
Utility PV and wind capex
USD per watt



The cost of renewable energy development is the key obstacle for green hydrogen, as the cost of solar and wind generation has already dropped by 58% and 19%, respectively, in the past five years.

In combination with a policy push, this has resulted in a massive ramp up in renewable generation capacity, making green hydrogen increasingly more enticing as an alternative to its fossil counterparts.

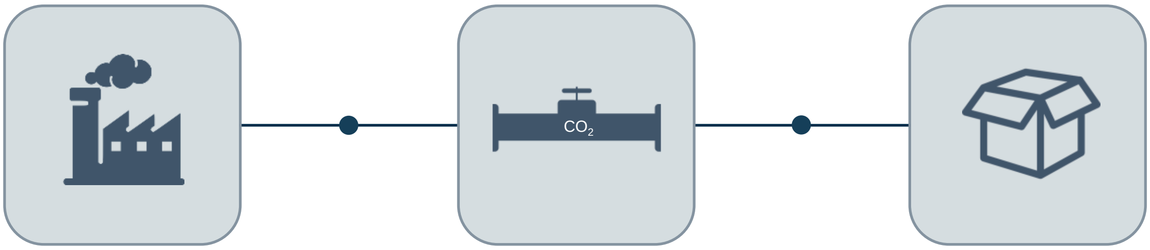
Global power capacity from solar* and wind
GW



*Including Rooftop Solar
Source: Rystad Energy RenewableCube

Blue hydrogen

Just a transition fuel or does it have a role to play in a world with abundant renewable energy?



Favorable factors for blue hydrogen in a transition phase	
Maturity of technology	Steam methane reforming (SMR) is a mature and widely used technology. Most of the world's grey hydrogen production today is produced through SMR. Autothermal reforming (ATR) is also in a state of medium commercial deployment, and better suited for blue hydrogen production given its higher CO_2 capture rate and lower capex.
Scalability	Both SMR and ATR are deployable at large scale, making it possible to produce large volumes of blue hydrogen without further technology development. Blue hydrogen production at large scale favors centralized production, which requires large-scale demand within close proximity. Green hydrogen is favorable for smaller scale distributed production.
Existing natural gas infrastructure	Both Europe and the US have well-developed natural gas infrastructure, making it possible to feed hydrogen plants with large volumes of natural gas.
Lead time	There is less need for infrastructure investment for blue hydrogen, meaning that lead times for the construction of large-scale production plants are shorter in areas where natural gas infrastructure already exists. However, blue H_2 still requires large investment as the production plant must have scale to be economical.

Willingness to pay for 100% clean products is increasing and often higher than the market price of CO_2. The increase in price seen by the end consumer is often small compared to the total product cost. This might favor green hydrogen, even when blue hydrogen is considerably cheaper to produce.

Get access to the complete report…

Please contact us to access the full report, where we expand on the nuances of hydrogen, with deep data insights covering the addressable market and the current and future supply picture.

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Be among the first to access Rystad Energy's HydrogenCube

Scheduled for release in 2021

- Country and sector level hydrogen/ammonia demand
- Asset by asset overview of hydrogen/ammonia supply by source, operator, and capacity
- Hydrogen project costs
- Hydrogen infrastructure
- Price formation and cost developments for both blue and green hydrogen
- CO_2 storage infrastructure relevant for blue hydrogen
- Renewable power generation relevant for green hydrogen
- Hydrogen related policy developments

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Rystad Energy is an independent energy consulting services and business intelligence data firm offering global databases, strategy advisory and research products for energy companies and suppliers, investors, investment banks, organizations, and governments. Rystad Energy's headquarters are located in Oslo, Norway.

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