Hydrogen Market Primer

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ABOUT THIS DOCUMENT

- This primer provides foundational background information on the global and US markets for clean hydrogen (low to zero carbon hydrogen)
- The contents have been assembled from a curated set of secondary sources, including from government bodies, industry groups, and market analysts
- The intent is not to provide definitive forecasts and conclusions but to show the range of views and assumptions and to highlight the opportunities and challenges associated with development of the clean hydrogen market in the future
- The document is organized into the following sections:
  1. Context on hydrogen
  2. Global market outlook
  3. US market outlook

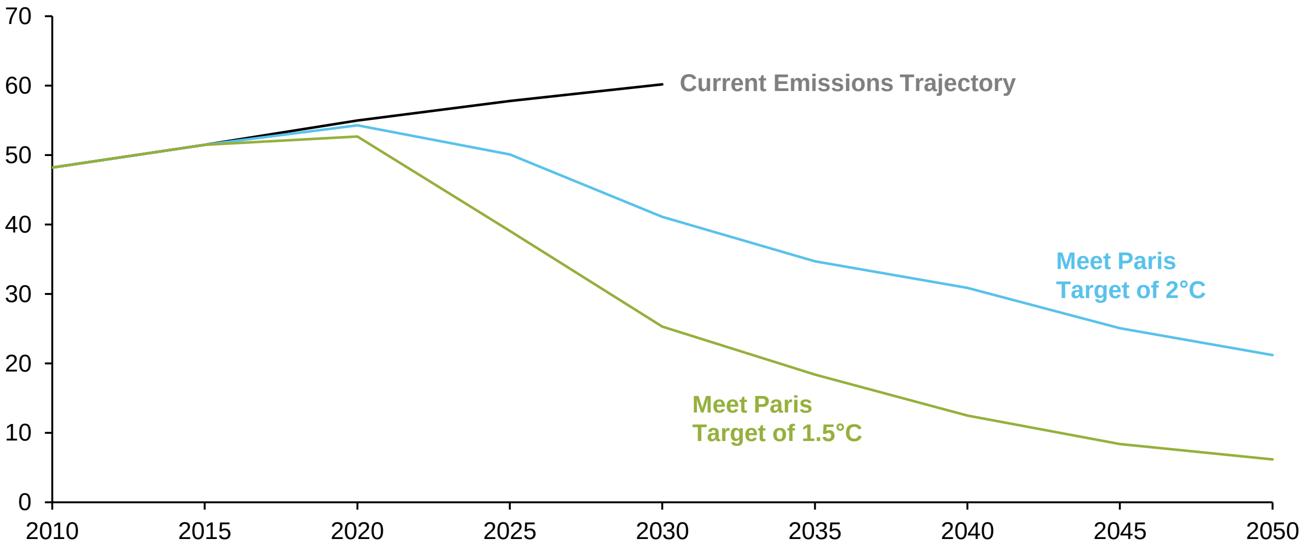
SUMMARY

- Clean hydrogen is emerging as a potential solution to support economy-wide decarbonization in complement to electrification given its (1) potential versatility across end-use sectors (e.g., transport, industry, building, energy storage) and (2) potential to resolve the energy trilemma of sustainability, supply security, and affordability as technologies scale up
- Today, almost all hydrogen supply is fossil-based (contributing ~2% of global CO_2 emissions); in the near term, high production cost and inefficient transportation and storage remain key barriers to larger scale adoption of clean hydrogen
- The industry is making progress in addressing these issues, and it is expected that further cost reductions and efficiency improvements could make clean hydrogen more competitive in the medium term for some end-uses
- There is still a high degree of uncertainty on the market outlook for clean hydrogen, and wide ranging views exist (ranging from 4-10x scale up by 2050 relative to today):
  - Optimistic industry bodies predict demand growth driven by significant penetration into new end-markets in transport, industrial heat, building heat, and power
  - Some academic and government views are more conservative, in recognition of the increasing viability of electrification for many end-markets
  - Practically, clean hydrogen is expected to first replace some of the dedicated production for existing end uses, followed by application into new end uses with few low-carbon alternatives
  - Large-scale energy storage is also viewed as an important application for hydrogen given the growth of intermittent renewables on the grid
- In the US, forecasts for demand growth and future mix between production methods are also highly varied; the US also has relatively under-developed policy direction compared to many OECD peers
- Significant US regional variation is expected in pace and nature of market development, driven by differences in end-use demand dynamics, production viability given climate and geology, and state-level regulatory stance
- The macro environments in the Southwest US and the Gulf Coast are particularly favorable for growth: the Southwest given proximity to potential demand centers (especially from California) and production viability via electrolysis, and the Gulf Coast given existing hydrogen infrastructure that can be retrofitted with carbon capture and storage
- In all jurisdictions across the world, significant policy support will be needed to trigger the massive level of investment required – starting in this decade – to enable a meaningful role for clean hydrogen going forward

MACRO CONTEXT

Achieving ambitious decarbonization objectives such as the Paris Agreement requires extensive economy-wide changes in energy consumption and supply at an unprecedented scale

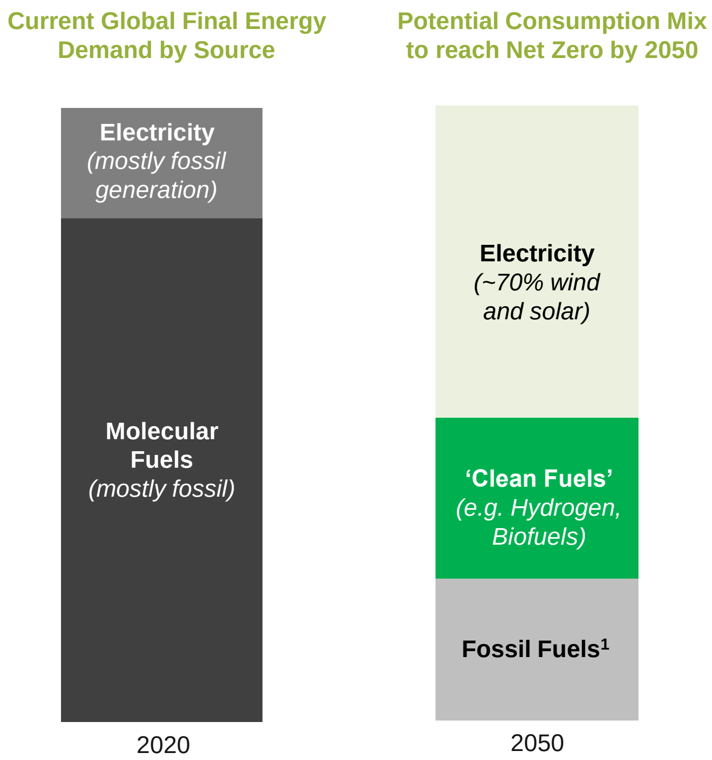
Greenhouse Gas Emissions, Gigatons of CO_2 equivalent



Source: UNEP Emission Gap Report 2019, IEA

FUTURE NEED FOR 'CLEAN FUELS'

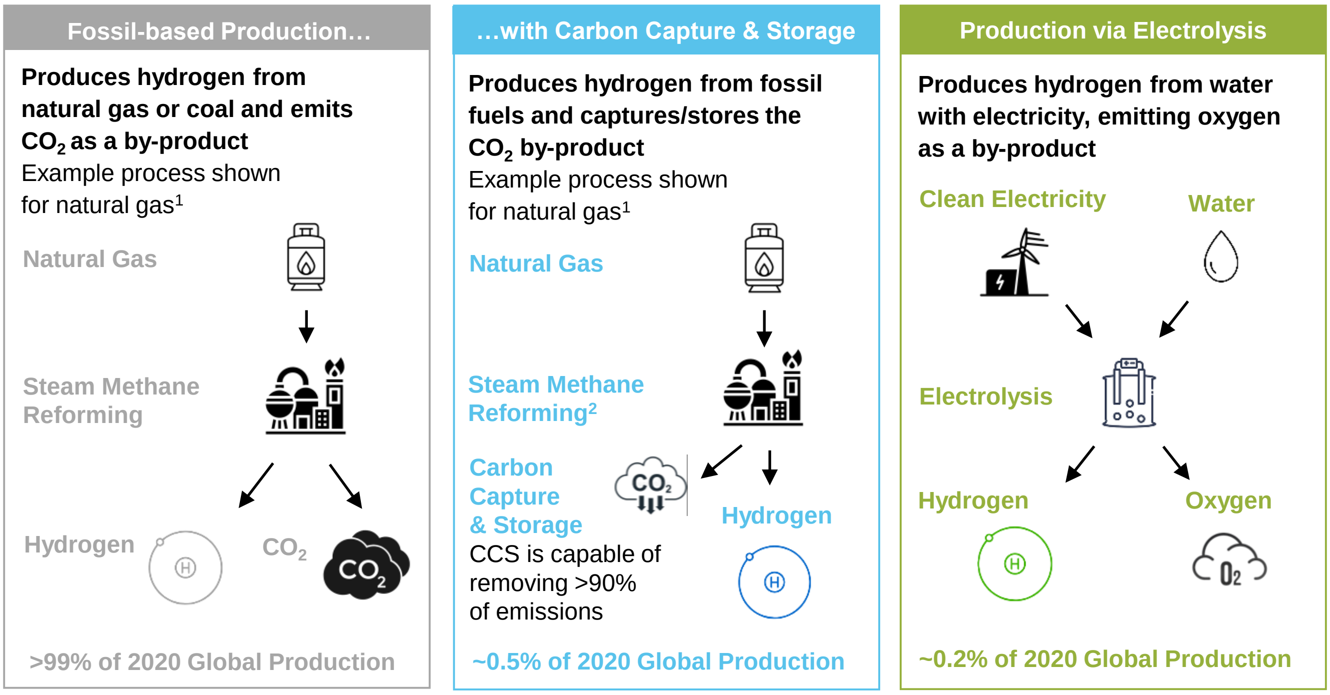
The majority of global energy demand today is met by fossil fuels; some of this demand is from sectors where electrification is challenging, requiring alternative 'clean fuels'



- Today most energy demand is not met by electricity, but by solid, liquid and gaseous molecular fuels. The majority of these are fossil fuels (e.g., transport is powered by petrol, diesel, bunker fuel)
- Meeting decarbonization targets such as the Paris Agreement (which aims to limit global warming to 1.5°C) will require replacing fossil fuels with cleaner energy sources, such as renewable electricity
- Some 'hard to abate sectors' have energy needs that are not easily or economically served by renewable electricity; here, **'clean fuels'** such as hydrogen could play a role in decarbonization
- For example, liquid hydrogen has higher energy density than batteries, and it can store energy for longer durations; this opens up uses such as for long-distance transport
- Additionally, as renewables penetration increases, hydrogen could become an important energy storage mechanism, allowing grids dependent on intermittent solar and wind to provide more reliable power at moments of peak demand

Note: 1. This includes fossil fuels abated with CCS or other methods. Source: IEA

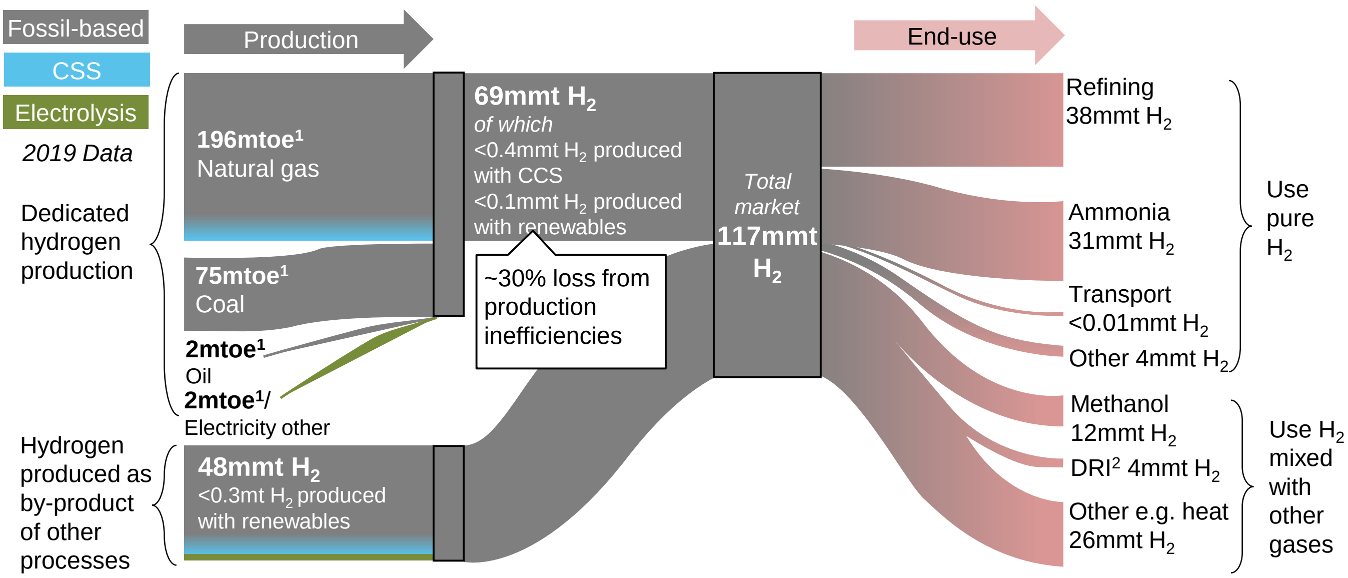
METHODS OF HYDROGEN PRODUCTION



Note: 1. Can also be made from coal via gasification, however natural gas is more common in the US. 2. New reforming technologies such as Autothermal Reforming are also emerging; in the long term, these may be better suited for efficient application of CCS. Source: EIA, Forbes, Hydrogen Council, S&P

CURRENT HYDROGEN VALUE CHAIN

Today, hydrogen is a $150bn market; almost all hydrogen is produced from fossil fuels for use mainly in refining and chemical manufacturing



- In 2019, 117 million metric tons (mmt) of hydrogen were produced globally
- 69mmt came from dedicated production through steam methane reforming (SMR) and coal gasification
- The rest was produced as a by-product of another process (e.g. steam cracking in refineries), needing further processing before use
- Hydrogen production today emits 2% of global CO_2 emissions, equivalent to the total emissions of the UK and Indonesia combined
- Most production is located close to end use to minimize transport costs and maximize synergies (e.g. hydrogen from steam cracking is used in refineries)

Note: 1. million tons of oil equivalent. 2. Refers to production of steel through Direct Reduction of Iron. Source: IEA

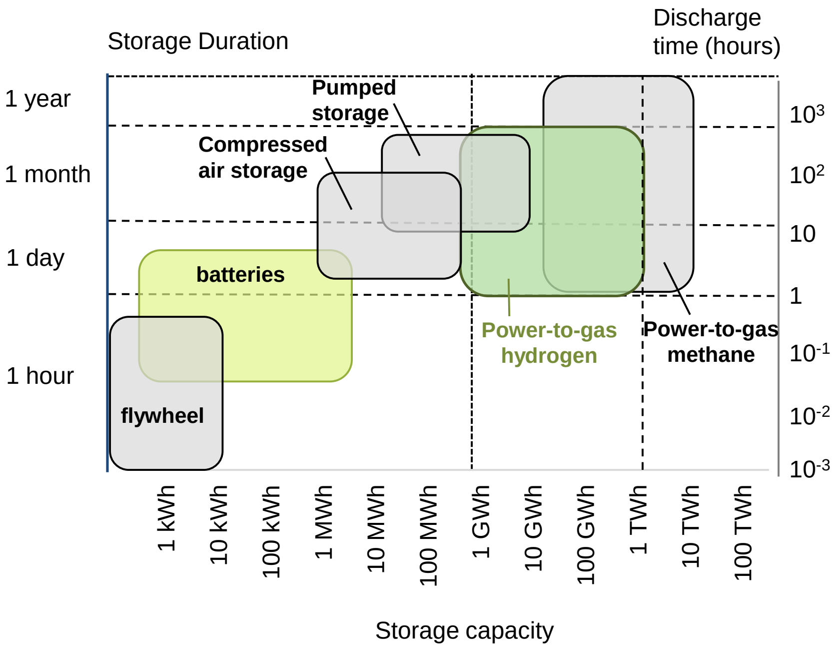
HYDROGEN PRODUCTION: CCS VS. ELECTROLYSIS

	Carbon Capture & Storage	Electrolysis
Optimal Conditions	• Cheap/reliable source of natural gas • Underground caverns for carbon storage • Off-takers for captured carbon	• Cheap zero-carbon electric power • Consistent power supply allowing high capacity factor • Proximity to abundant water supply
Pros	• Currently cheaper than electrolytic hydrogen • CCS technology has been demonstrated at scale • Ability to leverage existing grey hydrogen production via retrofitting CCS	• Electricity and water both readily available • No geological limitations • Can be used to store excess electricity generation • Potential for costs to fall as technology scales up
Cons	• Not 100% carbon-neutral; still generates harmful greenhouse gases as by-product	• Currently expensive relative to other technologies • Yet to be proven at scale • Low round-trip efficiency when used for energy storage

These cleaner hydrogen alternatives are expected to first replace some of the dedicated production for existing end-uses; over the energy transition, production could then increase to meet demand from new end-markets

HYDROGEN VS ALTERNATIVE ENERGY STORAGE SOLUTIONS

Hydrogen's physical properties enable it to have high storage capacity and longer energy dispatch times, making it a better alternative over batteries for seasonal or long-duration storage



- Storage will become particularly important as renewables penetration increases, allowing energy systems dependent on intermittent inputs to meet moments of peak demand
- Batteries are likely to be the dominant solution for short-term storage given high efficiency and rapid dispatch times
- However, batteries become less effective when used for long duration storage; optimal battery usage is measured in hours, not days
- Hydrogen can provide higher capacity and longer durations than batteries while maintaining a smaller footprint and losing less energy over time
- Applied to the power sector, hydrogen can help reconcile seasonal differences in energy demand, e.g., storing Solar PV generation to use in the winter

Source: Office for Budget Responsibility, Economic and Fiscal Outlook, November 2020

ELECTROLYSIS POWER AND EFFICIENCY CONSIDERATIONS

Hydrogen's physical properties also make it an inefficient energy carrier for some applications

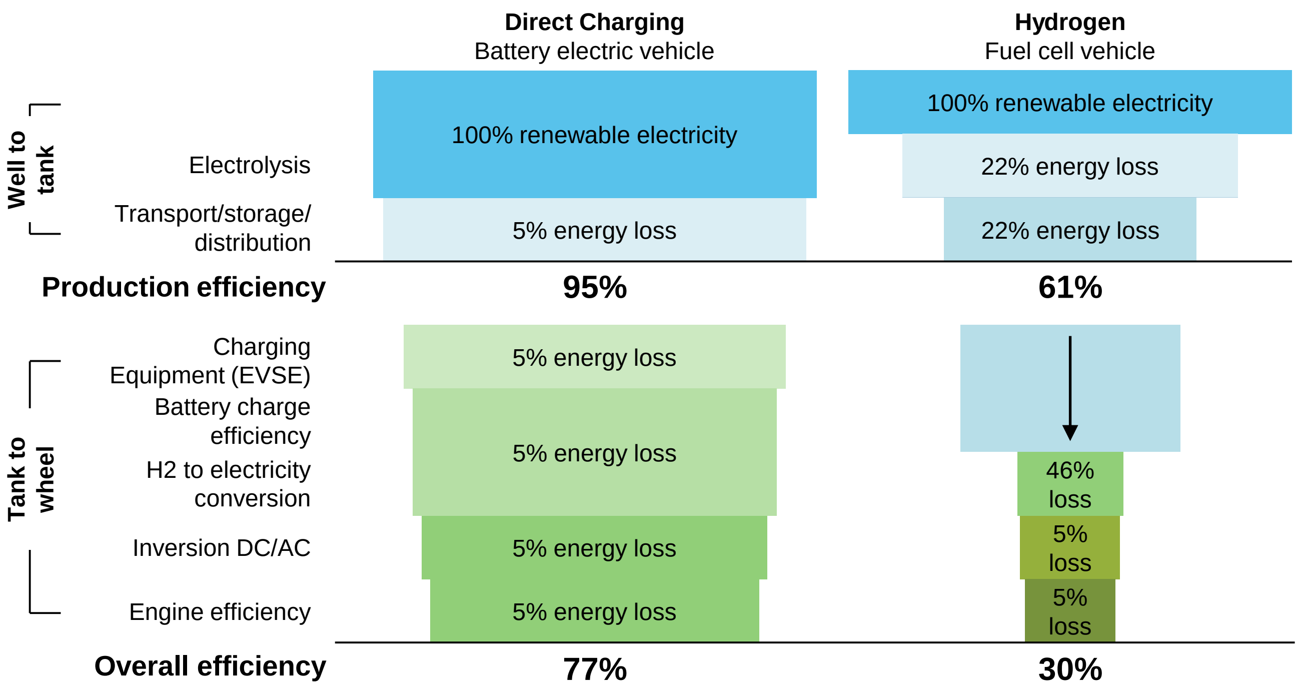
Electrolytic Hydrogen: Power Requirements

	Hydrogen	Electricity Required
Specific Energy of Hydrogen[1]	1kg	~52kWh
Global Dedicated Hydrogen Production	~69mmt	3,600TWh
Total European Electricity Supply[2]		3,600TWh

- At current electrolysis efficiency levels, 1kg of hydrogen requires ~50kWh of electricity to produce[1]
- This necessitates consideration of the opportunity cost of electricity use when scaling up electrolysis projects
- Hydrogen use is likely to be most viable where direct electrification is unfeasible, or where there are more pressing considerations than total energy requirements

Note: 1. Theoretical minimum figure, assuming 100% efficiency; current technology requires >50Wh/kg for production. 2. From IEA Electricity Market Report (December 2020). Source: IEA

IMPACT OF ROUND TRIP EFFICIENCY: MOBILITY EXAMPLE



- Fuel cell vehicles have higher energy requirements than battery powered vehicles, due to low efficiencies of fuel cells and electrolyzers
- The case for fuel cell vehicles relies primarily on other factors
  - Higher utilization and faster refueling than battery (e.g. trucking; fleets)
  - Large quantities of hydrogen weigh less than large batteries, reducing fuel requirements for propulsion over long distances

Source: Transport and Environment (Think Tank)

ESTABLISHED ELECTROLYZER TECHNOLOGIES

Alkaline and PEM are the two main ‘low temperature’ electrolyzer technologies (LTE), while SOEC uses ‘high temperature’ electrolysis (HTE); efficiency is expected to improve in all technologies with scale up

	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

EMERGING ELECTROLYZER TECHNOLOGIES

E-TAC and Methane Pyrolosis are new technologies with potential to deliver greater efficiency and cost improvements over established options; there is higher uncertainty over their scale up potential

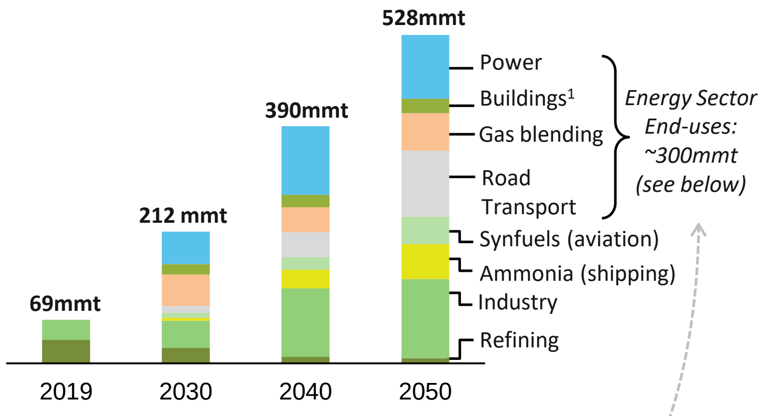
	Electrochemical, Thermally Activated Chemical (E-TAC)	Methane Pyrolysis[1]
Relative Maturity	Nascent	Nascent
Developer	• H2Pro	• Monolith
Technology	• Similar structure to alkaline electrolysis cell • Cell initially at 25 degrees; electricity splits water and creates H_2 • Then heated to 95 degrees; heat used to produce O_2	• Natural gas superheated by electricity, so there is no flame • Heat breaks bonds between carbon and hydrogen, • Carbon black and Hydrogen gas evolved as outputs
Key Indicators	• Operating temperatures of 25-95°C	• Operating temperature of >1000°C • Monolith claim costs are lower than electrolysis
Future developments	• H2Pro aim to sell first electrolyzers before 2030 with 95% efficiency, $1/kg cost	• Currently under development in plant in Hallam, Nebraska
Considerations	• Currently only in lab trials • Efficiency/cost targets seen as very optimistic by analysts • Raised $22m from investors including Bill Gates, Hyundai	• Can utilize waste heat from electricity generation • Process also produces carbon black, which can be sold to offtakers including tires, plastics and rubber goods

Note: 1. Alternative technology; does not use an electrolyzer; uses natural gas (methane) and heat. Source: Credit Suisse, Hydrogen Council

GLOBAL HYDROGEN OUTLOOK: LONG-TERM FORECASTS

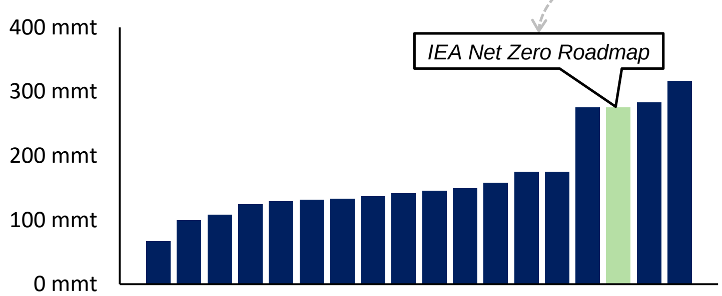
Optimistic Hydrogen Demand Forecast (IEA)

Total Hydrogen Demand under IEA Net Zero Roadmap to 2050 (mmt)



Range of Hydrogen Demand Forecasts in 2050 (IEA)

Hydrogen Consumption in the Energy Sector under 18 Net Zero Scenarios (Including power, heating, and transport)



Scale Up Required: What You Have to Believe

- To decarbonize existing supply and meet growing demand, CCS and electrolysis will need to scale up exponentially in the coming decade
- E.g. electrolyzer capacity will have to increase by >1000x between 2020 and 2030, while CCS capacity will have to rise by >20x
- Varying views exist on the future mix between CCS and electrolysis production methods
- Different production technologies will be suited to different regions, resource profiles and applications

Scenario Drivers

- Different scenarios to decarbonization exist, involving varying levels of hydrogen adoption in power, industry and transport
- Optimistic scenarios (high energy consumption from hydrogen) involve widespread use of hydrogen as fuel and feedstock, starting with decarbonization of existing uses then to new uses, e.g. transport, power, buildings heat
- Pessimistic scenarios are driven by deep electrification or use of alternative low-carbon fuels (e.g., biofuels); these prevent hydrogen penetration into new end-uses

Note: 1. Refers to use in both residential and commercial applications. 2. Refers to synthetic fuels for aviation and other uses; 3. Refers to Ammonia specifically for shipping fuel; Ammonia for other uses is contained in the Industry category. Source: IEA, IPCC

GLOBAL HYDROGEN DEMAND: PERSPECTIVE ON END-MARKET ADOPTION

Clean hydrogen will likely be adopted first in existing hydrogen markets, beyond which the sequence of adoption into new markets will be primarily influenced by the feasibility of electrification as an alternative

INDICATIVE

Carbon Price Needed to be Economic[1]	Viability via Electrification: Low		Viability via Electrification: High
High (>$150/ton)	Freight Shipping (1)		Building Heat Gas power (5)
		Cement, Steel, Aluminum (3)	
Low (<$50/ton)		Heavy duty Transport (2)	Light duty Transport (4)

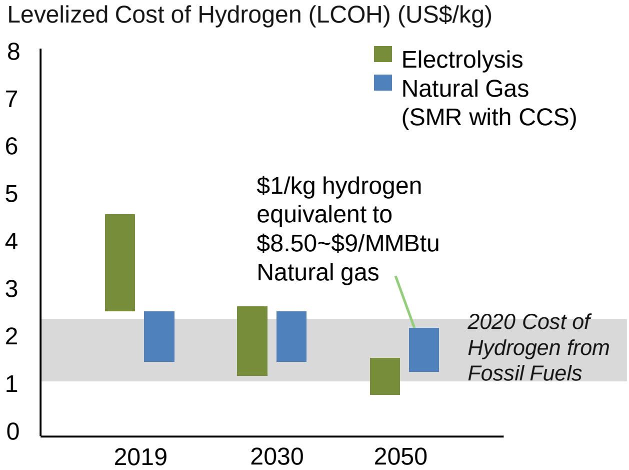
1. Shipping could be the first major adopter of hydrogen-based fuel (e.g. ammonia); however, high costs and long equipment lifespans mean conversion by 2050 will likely still be only partial
2. Heavy duty transport is seen as promising, due to advantages of fuel cells over batteries at long ranges; European nations such as Switzerland and France are trialing hydrogen trucks and trains respectively
3. The right incentives could enable hydrogen adoption as fuel or feedstock in industrial processes; however, electrification may prove an easier path to decarbonization in some applications
4. For personal transport, the rapid growth of battery electric vehicles represent a significant barrier to scale up of FCEVs and the need for associated infrastructure
5. Pilots are ongoing to blend 10-30% hydrogen into gas power plants and the gas grid; however, gas replacement with 100% hydrogen will be constrained by high infrastructure replacement costs

Note: 1. Carbon price assumptions from Bank of America Global Research and Bloomberg

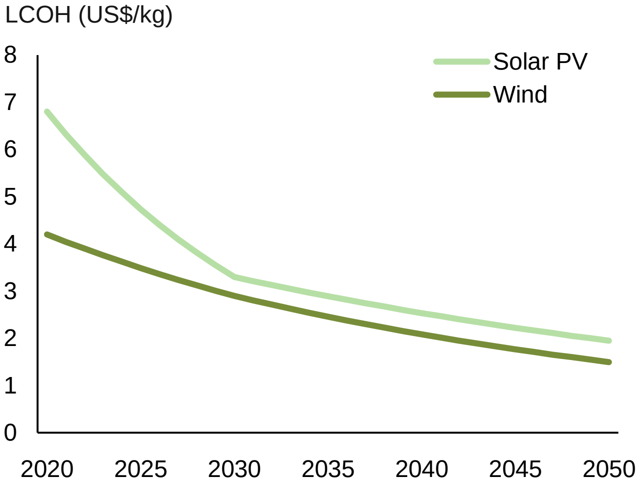
GLOBAL HYDROGEN COSTS

Hydrogen production cost via electrolysis could fall sharply driven by decline in renewable and electrolyzer costs; cost of hydrogen via CCS is expected to be relatively stable over time

Hydrogen Production Cost: Best Case (Bloomberg)



Hydrogen Costs from Electrolysis (IRENA)

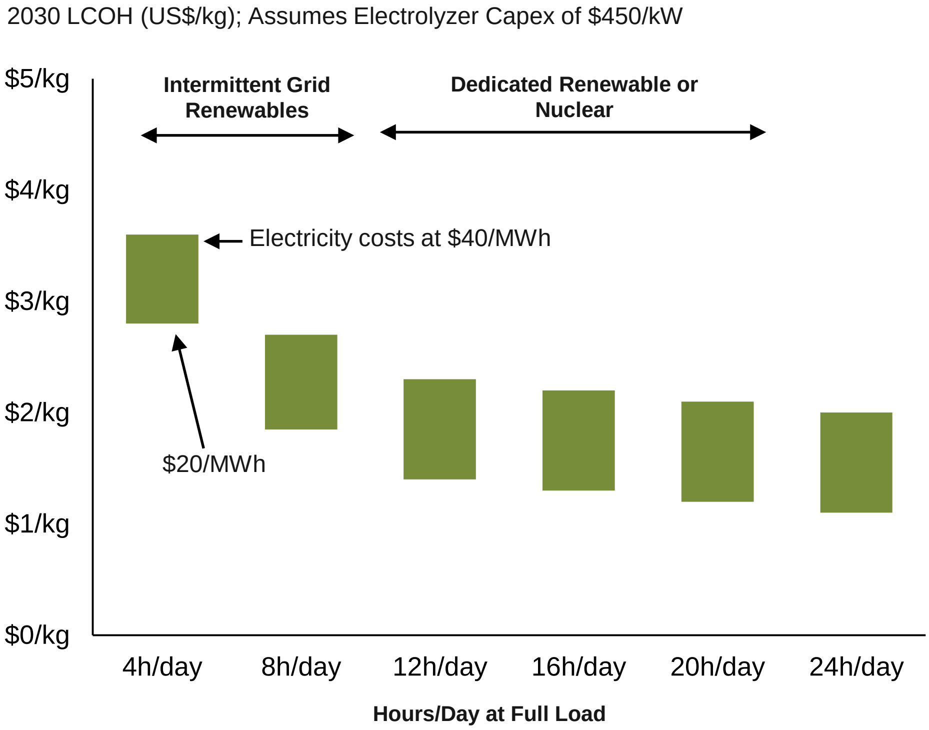


Note: Based on large projects with optimistic capex projections; cost estimates shown are optimistic and based primarily on the trajectories of renewables and electrolyzer costs; they may not account for other material costs of hydrogen production

GLOBAL HYDROGEN COSTS: IMPACT OF ELECTROLYZER UTILIZATION

Hydrogen production through electrolysis is expected to be economically advantaged where higher electrolyzer utilization can be achieved, i.e., via dedicated renewable or nuclear power

2030 Cost of Electrolytic Hydrogen by Load Hours (IEA)



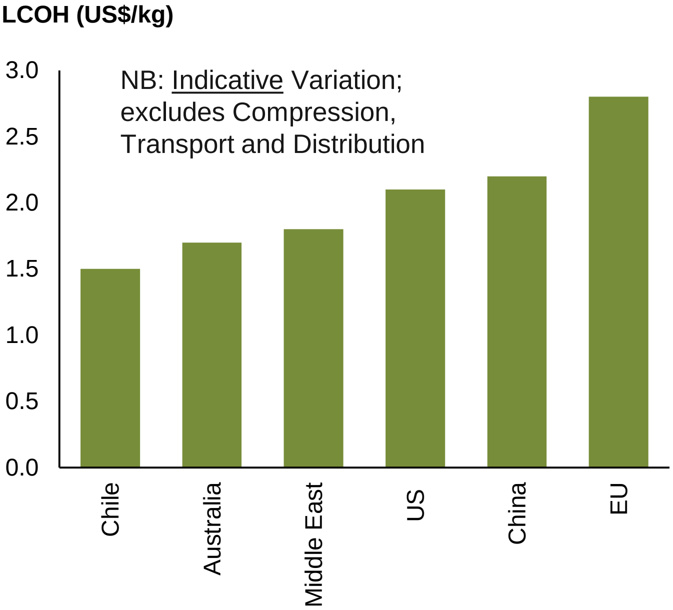
- Consistent and low-cost electricity supply is essential for electrolyzers to operate cost efficiently
- Grid renewables can provide lower electricity prices due to excess supply during peak generation hours…
- …However, this supply is often intermittent and leads to lower utilization of the electrolyzer
- Dedicated renewables (including solar/wind in combination or hybrid systems) or nuclear can provide a more reliable power source, leading to higher load hours and lower cost of hydrogen production

Source: IEA

GLOBAL HYDROGEN COSTS: REGIONAL VARIATION

There is significant regional variation in hydrogen production costs via electrolysis, driven largely by the availability of inexpensive renewables

2030 Cost of Hydrogen Electrolysis Production (Argus)



Source: Argus, Hydrogen Council

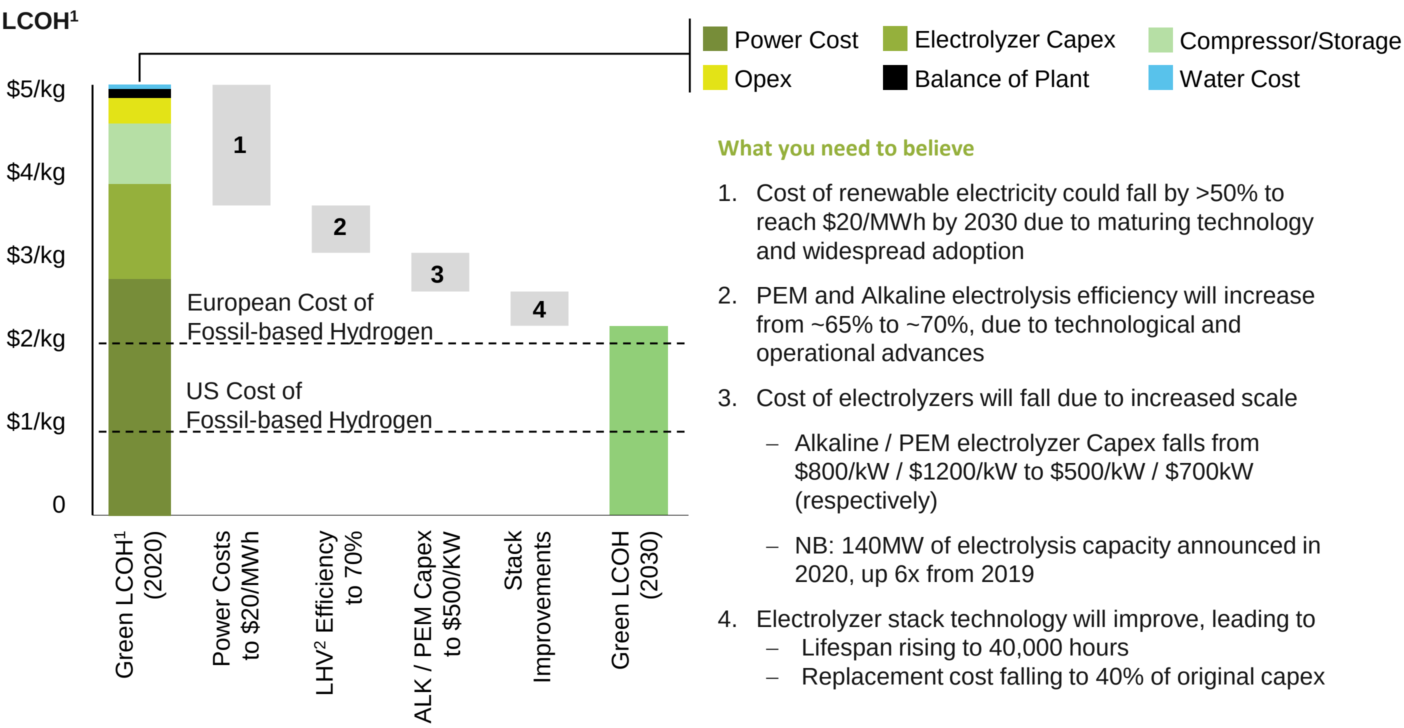
Regional Dynamics

- Chile, Australia and Saudi Arabia are expected to leverage cheap wind =/solar generation to position themselves as net exporters of electrolytic hydrogen
- The EU, China, and East Asia are likely to be demand centers, and are unlikely to have sufficient renewables capacity to be self-sufficient in hydrogen; the EU forecasts that half its 2030 hydrogen demand will be met by imports
- The US has the potential to become a major producer of electrolytic hydrogen, but…
  - Relative to other developed economies, policy direction is less clear to date
  - Hydrogen produced with CCS could potentially play a bigger role, given cheap natural gas pricing and abundant carbon storage potential
- …Favorable policy elsewhere (e.g. EU) may be sufficient to drive down electrolytic hydrogen costs irrespective of US policy stance

GLOBAL HYDROGEN COSTS: POTENTIAL COST EVOLUTION IN EUROPE

European hydrogen electrolysis costs could reach parity with fossil-based production by 2030

Possible Pathway to Cost Parity (Credit Suisse)



What you need to believe

1. Cost of renewable electricity could fall by >50% to reach $20/MWh by 2030 due to maturing technology and widespread adoption
2. PEM and Alkaline electrolysis efficiency will increase from ~65% to ~70%, due to technological and operational advances
3. Cost of electrolyzers will fall due to increased scale
   - Alkaline / PEM electrolyzer Capex falls from $800/kW / $1200/kW to $500/kW / $700kW (respectively)
   - NB: 140MW of electrolysis capacity announced in 2020, up 6x from 2019
4. Electrolyzer stack technology will improve, leading to
   - Lifespan rising to 40,000 hours
   - Replacement cost falling to 40% of original capex

Note: 1. Levelized cost of Hydrogen. 2. Lower Heating Value Efficiency. Source: Credit Suisse European Utilities

MAJOR ELECTROLYSIS PROJECTS ANNOUNCED: EU

The EU is leading the way in electrolytic hydrogen. Out of the ~200GW of electrolyzer projects globally, ~85% are in Europe[1]. The EU is committed to installing at least 40GW of capacity before 2030; it aims to do this by supporting large electrolysis projects through state funding and policy support

	Expected cost	Electrolysis Capacity	Annual H_2 output	Target completion	H_2 end use	Developers
HyDeal Ambition	TBD	67GW	3.6 mmt	2030	General sale across Europe	Consortium of 30 companies including Snam, Enagás, McPhy
NorthH2	TBD	10GW	1 mmt	2040	Heavy industry in NED/GER	Shell, Equinor, Gasunie, RWE
AquaVentus	TBD	10GW	1 mmt	2035	General sale across Europe	Consortium of 27 companies including RWE, Vattenfall, Shell
Enel Group (multiple projects)	TBD	2GW	TBD	2030	Refining (initially)	Enel, Eni
Blue Danube	TBD	1.8GW	0.1 mmt	TBD	Industry, mobility	Verbund, DB Schenker, Chemgas
White Dragon	$10bn	1.5GW	0.3mmt	2029	Mostly power generation	Consortium led by DEPA (Greek utility)
Black Horse	TBD	1.4GW	0.1 mmt	TBD	Transport (trucking)	Consortium led by Bioway
Greater Copenhagen	TBD	1.3GW	TBD	2030	Mobility, incl. buses, trucks, shipping and aviation	Ørsted, Maersk, DSV, Nel, DFDS
HySynergy	TBD	1.1GW	TBD	TBD	TBD	Everfuel, Shell
SeaH2Land	TBD	1GW	0.6 mmt	2030	Industrial uses including steel, ammonia, ethylene	Ørsted, Dow, ArcelorMittal, Zeeland
Esbjerg	$1.2bn	1GW	TBD	2026	Ammonia for food, fertilizer, shipping fuel	CIP, Maersk, Ørsted, Vestas
H2 Sines	$1.8bn	1GW	TBD	2030	H_2 for domestic, export	EDP Bandeirante, Galp Energia, Martifer, REN, Vestas
Rostock	TBD	1GW	TBD	TBD	TBD	Consortium led by RWE

1. Source: Aurora; Press Reports

MAJOR ELECTROLYSIS PROJECTS ANNOUNCED: REST OF THE WORLD

Outside of the EU, Australia is leading market development aiming to become the primary supplier of electrolytic hydrogen across Asia; other early movers include Chile and Saudi Arabia

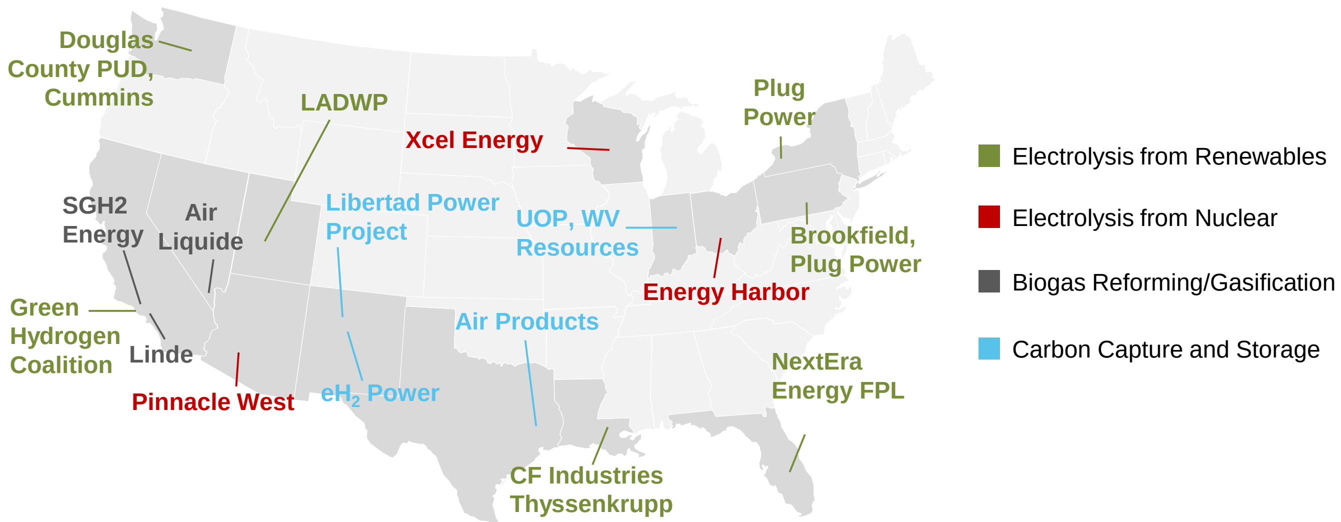
	Expected cost	Electrolysis Capacity	Annual H_2 output	Target completion	H_2 end use	Developers
Kazakhstan (unnamed project)	TBD	30GW	3 mmt	TBD	General Sales	Svevino
Aman Mauritania	TBD	16GW	TBD	TBD	Steel, Shipping and Ammonia	CWP
Asian Renewable Energy Hub	$36bn	14GW	1.75 mmt	2027-28	Ammonia for export to Asia	Vestas, InterContinental Energy, Macquarie Group, CWP
Oman (unnamed project)	TBD	14GW	TBD	2038	For sale on international markets	Oman Oil Company (OQ), Intercontinental Energy
HyEnergy	TBD	8GW	TBD	2030	Ammonia, Mobility, Industry	Province Resources Ltd.
Murchison Renewable Hydrogen Project	$10-12bn	5GW	TBD	2028	Export, mobility, blend into gas supply	HRA
Beijing Jingneng Inner Mongolia	$4bn	5GW	0.4 mmt	2021	TBD	Beijing Jingneng Clean Energy Co.
Helios Green Fuels Project	$5bn	4GW	0.2 mmt	2025	Transport as ammonia; change back to H_2 for end use	Acwa Power, Thyssenkrupp AG, Haldor Topsøe, Air Products
Pacific Solar Hydrogen	TBD	3.6GW	0.2 mmt	TBD	Export to Japan/South Korea	Austrom Hydrogen
Base One	$5.4bn	3.4GW	0.6 mmt	2025	TBD	Enegix
H2 Hub Gladstone	$1.6bn	3GW	TBD	2025[1]	Ammonia for export to Japan	H2U
Yellow Sea	TBD	2GW	TBD	TBD	TBD	Consortium led by Qingdao Blue Valley Industrial Development Zone
HyEx	TBD	1.6GW	0.1 mmt	2020	Ammonia for chemical plant, fuel, fertilizer, export	Engie, Enaex
Geraldton	TBD	1.5GW	TBD	TBD	Ammonia for domestic, export	Lightsource BP
HNH	$3bn	1.4GW	TBD	2026	1 million tons per year of Green ammonia for export	OKWIND, Austria Energy

Note: 1. Date set for initial operation. Source: Press Reports

US MARKET: RECENTLY ANNOUNCED LOW-CARBON HYDROGEN PROJECTS

The US has several notable hydrogen projects but generally lags Europe in market development; electrolysis project developments are currently limited to megawatt scale projects, not gigawatt

Project Locations



Project Output

Main Operator	State	Capacity (MW)	H_2 output (tons/year)
Plug Power	NY	120	~16,000
Plug Power	PA	TBD	~5,000
CF Industries	LA	~20	~3,500
Pinnacle West	AZ	~20	~2,500
NextEra Energy	FL	~20	TBD
Douglas County PUD	WA	5	~700
Energy Harbor	OH	1	~300
Xcel Energy	MN	0.5	~200
LADWP	UT	TBD	TBD
Green Hydrogen Coalition	CA	TBD	TBD

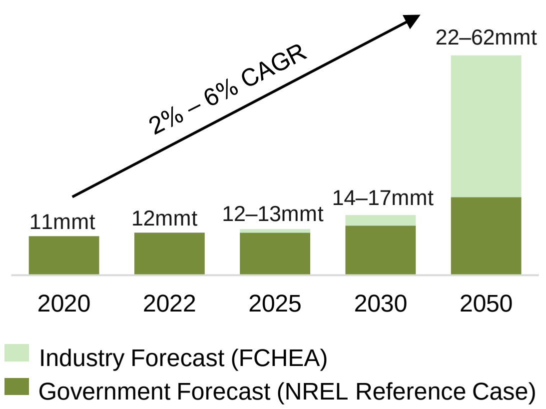
Non-Electrolysis Projects

Main Operator	State	H_2 Output (tons/year)
Air Products	TX	~400,000
Air Liquide	NV	~11,000
SG H2 Energy	CA	~4,000
Linde	CA	~1,000
WV Resources	IN	TBD
Libertad Power Project	NM	TBD
eH_2 Power	NM	TBD

US HYDROGEN DEMAND: LONG-TERM FORECASTS

There is a wide range of forecasts for the US hydrogen market into 2050; similar to the global forecasts, the bullish forecasts from industry advocates assume penetration of hydrogen into multiple new end-markets

Forecast Comparison



Key Assumptions

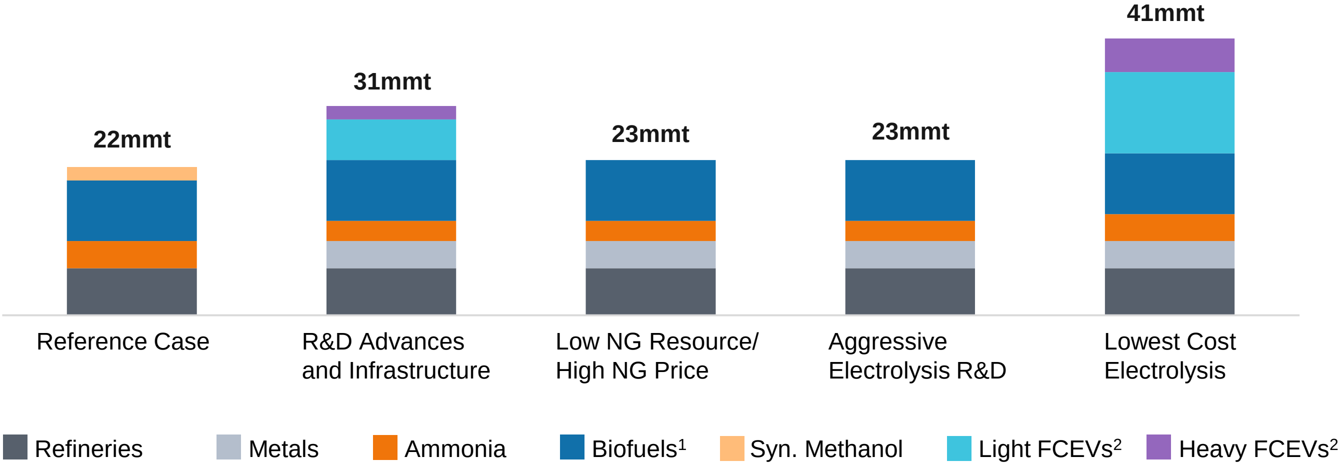
- The conservative reference case from National Renewable Energy Laboratory (NREL) assumes largely status quo in policy and R&D
  - Demand comes from existing end uses (e.g. ammonia, refineries)
  - Other markets will either fail to decarbonize or use other methods (e.g. electrification)
- Aggressive forecasts from the Fuel Cell and Hydrogen Energy Association (FCHEA) assume hydrogen adoption in markets such as transport, building heat/power, industrial heating and energy storage
  - Growth accelerated by technology advances, cheap renewables and decarbonization incentives
  - Material growth is expected after 2030
  - R&D during 2020s builds capabilities that allow for rapid growth in subsequent decades

Source: National Renewable Energy Laboratory, Fuel Cell and Hydrogen Energy Association

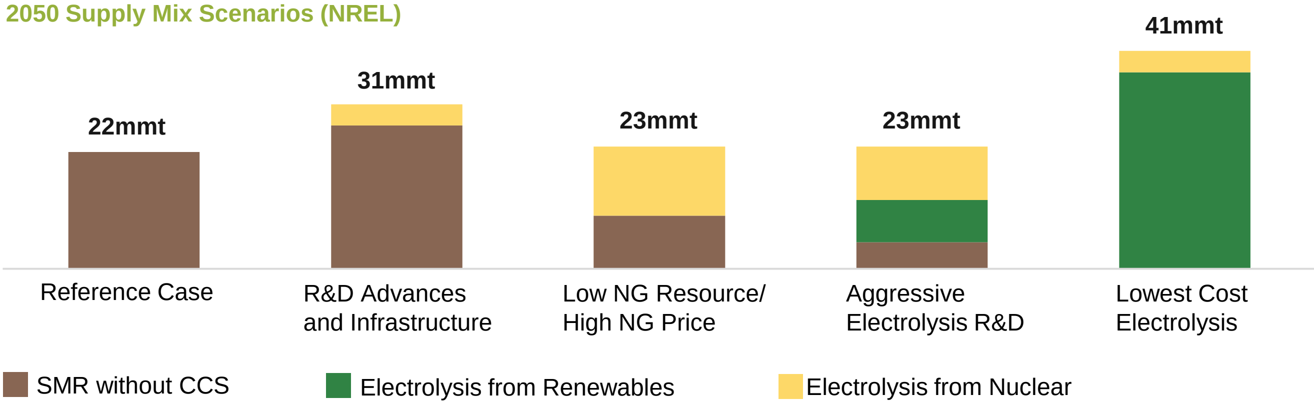
RANGE OF GOVERNMENT FORECASTS

The DOE/NREL forecasts five scenarios with the best case predicting market size of up to 41mt by 2050, driven by high natural gas prices and access to cheap renewables

2050 End Use Scenarios (NREL)



2050 Supply Mix Scenarios (NREL)



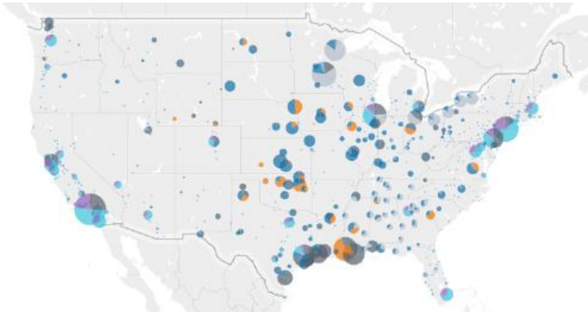
1	**Reference Case**	Hydrogen technology and FCEV infrastructure remain at status quo Natural gas prices remain low High cost of decarbonization means all hydrogen is produced via SMR for feedstock use
2	**R&D Advances and Infrastructure**	Electrolysis capex falls to ~$400/kW; FCEV refueling infrastructure installed Adoption in FCEVs and metals Renewables at retail price, making hydrogen from renewables too expensive for general use
3	**Low NG Resource/ High NG Price**	*R&D advances and Infrastructure* + high NG Prices limiting SMR[3] Higher cost of SMR means hydrogen too expensive for FCEV use; nuclear gains a >50% market share
4	**Aggressive Electrolysis R&D**	*Low NG Resource / High NG Price* + renewable electrolysis capex falls to $200/kW with subsidized electricity Low cost of electrolyzers and results in renewable hydrogen gaining substantial market share
5	**Lowest Cost Electrolysis**	*Aggressive Electrolysis R&D* + renewable electrolysis capex falls to $100/kW with wholesale electricity prices Due to low costs, renewables gain 90% market share and low hydrogen market prices

Note: 1. Organic fuels made from ammonia (fertilizer) and possibly hydrogen (feedstock in processing). 2. Fuel Cell Electric Vehicles. 3. NG Prices from AEO 2017 LOGR instead of Reference. Source: National Renewable Energy Laboratory, Department of Energy

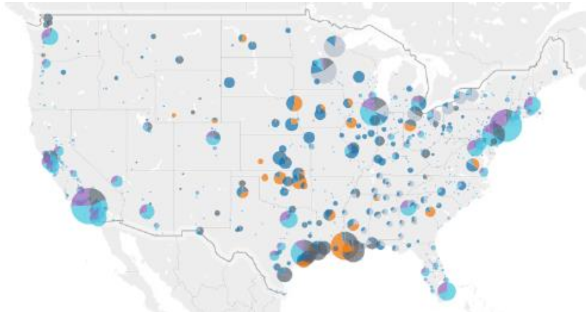
GOVERNMENT FORECAST: REGIONAL SUPPLY/DEMAND VARIATION

Demand for hydrogen is expected to be centered around ports, industrials and urban centers; supply is expected to be focused in industrial clusters or renewable energy hotspots depending on whether electrolysis or SMR dominates

Scenario 2: R&D Advances and Infrastructure



Scenario 5: Lowest Cost Electrolysis

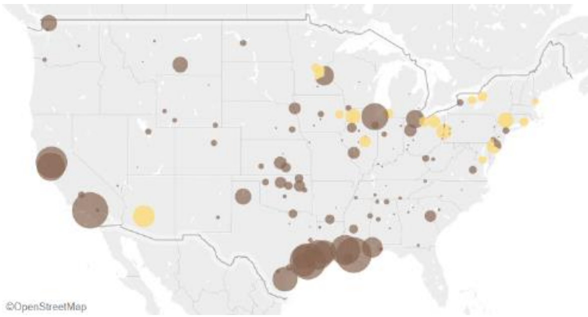


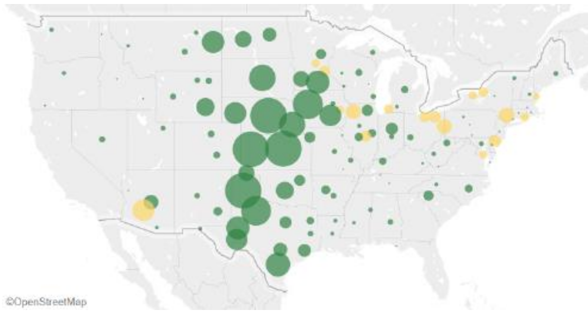
Demand:

Refineries | Metals | Ammonia | Biofuels | Syn. Methanol | Light FCEVs | Heavy FCEVs

Adoption of hydrogen in FCEVs and industrial processes, centered around urban areas in California, Texas, and the East Coast

Further penetration of hydrogen in all markets (due to low prices) leading to higher demand in more cities than other scenarios





Supply:

SMR | Electrolysis from Nuclear | Electrolysis from Renewables

Installation of electrolysis at existing nuclear facilities; continuing dominance of SMR from the Gulf Coast

Widespread installation of electrolysis in areas with high solar irradiation/winds and cheap land; SMR outcompeted by renewables

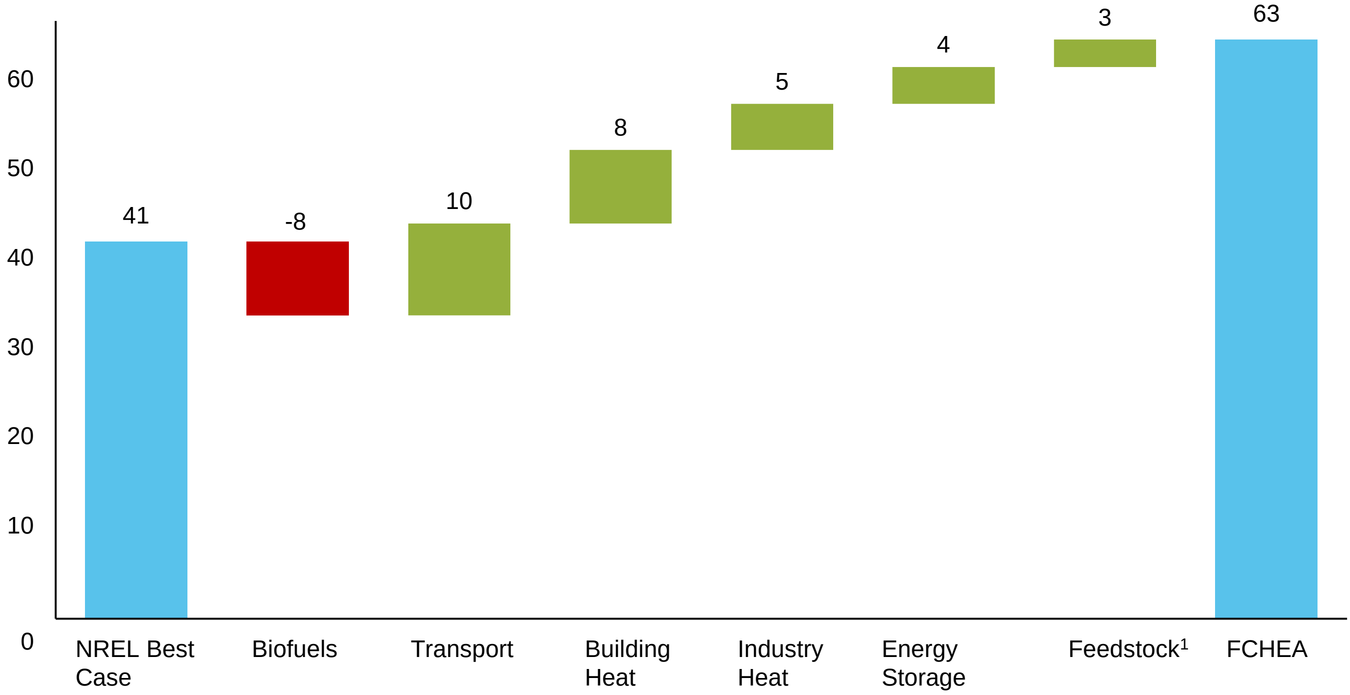
Source: National Renewable Energy Laboratory, Department of Energy

GOVERNMENT VS. INDUSTRY BODY FORECASTS

The industry forecast from the FCHEA assumes higher FCEV demand as well as additional adoption in seasonal energy storage and residential/industrial heating

Optimistic Case Comparison in 2050 (DOE/NREL vs. FCHEA)

Market Volume (mmt)



- FCHEA assumes hydrogen adoption into additional end segments that NREL does not forecast
- FCHEA also assumes biofuels are replaced by directly using hydrogen in end sectors (vs. NREL which assumes hydrogen as feedstock)

Optimistic Timeline for Decarbonization (FCHEA)

- **2020s:** Some installation of CCS and electrolyzer facilities – either SMR being retrofitted with CCS, or new development by players making moves into the space
- **2030:** All production methods of hydrogen have material shares of the market (fossil-based; CCS; electrolysis)
- **2030s/40s**: As electrolysis becomes cost competitive, accelerated development expected with more GW-scale projects. Pressure to decarbonize also quickens CCS development
- **2050:** Almost all fossil-based hydrogen is converted to CCS, and large scale CCS and electrolysis facilities have also been installed

Note: 1. Includes uses in refineries, metals, ammonia, and methanol production. Source: National Renewable Energy Laboratory, Fuel Cell and Hydrogen Energy Association

OPTIMISTIC INDUSTRY FORECASTS: GROWTH ASSUMPTIONS (FCHEA)

In the industry optimistic case, transport is expected to drive a large share of growth, followed by new industrial feedstock and additional markets in industrial high grade heat, building space/water heating and energy storage

Transport

2050 demand: up to 27mmt

- Decarbonize heavy/long-distance transport
- High energy density allows for long ranges without need for excessive weight
- Focus on fleets and commercial trucking enables growth without need for widespread refueling infrastructure

Early Signs

- >30,000 FCEV forklifts already in use on commercial sites (e.g. Walmart warehouses)
- Toyota FCEV trucks being trialed in LA port
- Toyota, Hyundai sell FCEV cars to retail customers in California

Industrial Heat

2050 demand: up to 5mmt

- High grade heat accounts for 25% of US heat consumption; hydrogen is currently the only option for decarbonization
- By 2050, hydrogen could meet 20-25% of high grade, 5-10% of medium grade and 5% of low grade heat requirements

Early Signs

- Pilots in Sweden (STEPWISE project) and Japan (Toyota Plant Zero CO_2 Emissions Challenge)
- None in the USA

Building Heat/Power

2050 demand: up to 8mmt

- Hydrogen can be blended with natural gas to decarbonize water/space heating
- Pure hydrogen heating feasible, but requires replacing infrastructure and appliances
- Focus on areas of high gas consumption (East North Central, Mid Atlantic, West Coast)

Early Signs

- Green hydrogen pilots explore blending hydrogen into gas provision, e.g. Florida P&L in Okeechobee

Energy Storage

2050 demand: up to 4mmt

- Store large amounts of energy over long periods, e.g. seasonal storage of renewables
- Dispatch to isolated areas as zero-carbon distributed generation or backup for low renewables supply
- Dispatched hydrogen demand could vary by region
- Higher share of energy use in areas with low hydropower/ nuclear/transmission capability
- E.g. <1% in NY but could be 18% in TX

Early Signs

- None

Feedstock

2050 demand: up to 18mmt

- Grey hydrogen already used for ammonia and methanol production
- Emerging applications to decarbonize other industries, e.g. steel, aviation/shipping fuel
- In ambitious case, 14% of US steel production could switch to hydrogen by 2050, with adoption accelerating as current plants need replacement in ~2040

Early Signs

- Midrex Technologies pilots in TX, OH to demonstrate low-carbon steel with hydrogen from electrolysis

Note: 1. Medium grade heat defined as 100-500 degrees Celsius; high grade heat defined as 500+ degrees Celsius Source: Fuel Cell and Hydrogen Energy Association.

OPTIMISTIC INDUSTRY FORECASTS: SIGNPOSTS (FCHEA)

For the optimistic case forecasts to be attainable, a number of market and policy milestones must be reached in the 2020s; increased capabilities should then facilitate rapid growth in the 2030s and beyond

Immediate Steps

Market signposts

- Mid-scale electrolyzers installed (10–50 MW)
- Hydrogen-tolerant equipment introduced in gas plants
- First hydrogen production facilities dedicated to mobility
- First-gen heavy FCEVs, fueling stations brought to market[1]
- FCEV car sales reach 30,000

Possible policy support

- Net-zero targets adopted at state and federal level
- Hydrogen codes and safety standards published
- Direct support to bridge cost barriers for initial market launch

2022 potential market size: 12mmt

Early Scale-Up

Market signposts

- Large scale electrolyzers installed (50 MW+)
- Pure hydrogen equipment introduced in power plants
- Hydrogen pipeline/delivery systems in industry clusters
- New FCEV car models introduced to US market
- FCEV car sales reach 150,000

Possible Policy Support

- Phasing out of direct support mechanisms (subsidies and tax credits) in early markets

2025 potential market size: 13mmt

Diversification

Market signposts

- Development of large scale electrolysis with dedicated renewable/nuclear generation
- First hydrogen pipelines to connect production with demand centers
- Scale up of hydrogen equipment production
- Gas grid includes hydrogen at 90/10 (gas/hydrogen) ratio in high demand states

Possible Policy Support

- Phasing out of direct support mechanisms in fast-following markets
- Specific incentives for non-mobility sectors aimed at expanding applications

2030 potential market size: 17mmt

Broad rollout

Market signposts

- Expanding use of hydrogen across sectors, leading to further cost reductions and performance improvements
- Gas systems compatible with hydrogen, allowing for easy increase in scale
- Existing grey hydrogen production retrofitted with CCS
- Open competition between CCS/electrolysis on cost

Possible Policy Support

- Reduced/no direct policy support once cost parity is reached
- Robust hydrogen code at federal level

2050 potential market size: 63mmt

Note: 1. 'Heavy' includes trucks, buses, and material-handling vehicles e.g. forklifts. Source: Fuel Cell and Hydrogen Energy Association

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