Hydrogen POV

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BAIN & COMPANY

Key messages on hydrogen development

Hydrogen is expected to play a major role in the global energy transition

Clean hydrogen (and derivative) **market development has accelerated** in the last 12 months, with a step up in announced projects and supply capacity, and countries bolstering long term ambitions

Broad **commercial viability for clean hydrogen applications is expected to materialize this decade**, with specific pockets of development opportunity opening now, requiring detailed localized evaluation

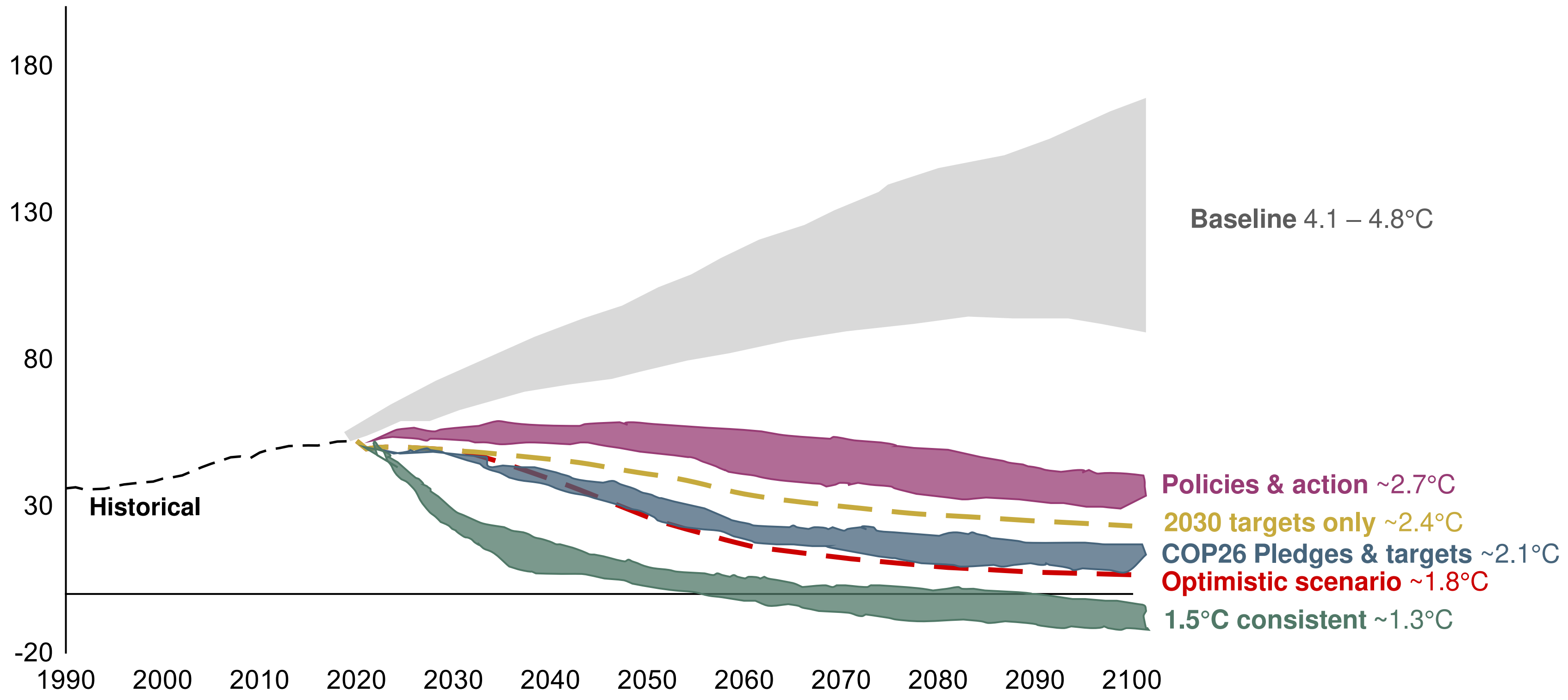
We see **3 business models to initiate successful hydrogen projects** during this early maturity phase, next to the **initiatives required to develop technologies and infrastructure** across the value chain

Critical for each business model is to **understand which anchor customers and value chain partners** are required – to secure offtake and bring in the required capabilities – to gain experience early on

Market makers in clean hydrogen identify critical **supply and demand trade-offs**, lock in **attractive initial offtake,** and deliver a robust **business case and execution plan**

Hydrogen has the potential to play a major role in the energy transition

Global greenhouse gas emissions $GtCO_2$/per year

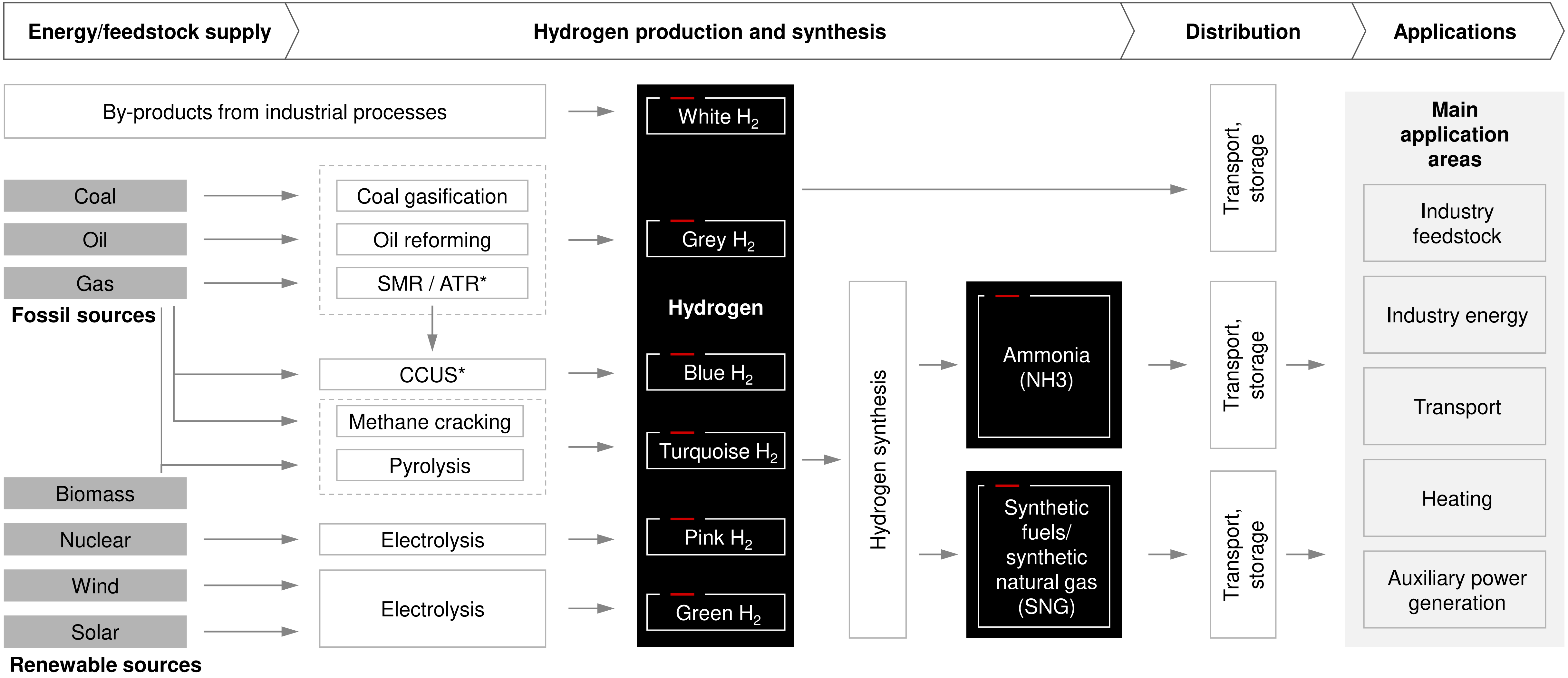


Source: Climate Action Tracker, November 2021

Key observations

- A further increase of energy efficiency and direct use of renewable energy will decrease emissions; however, it is **not sufficient to reach decarbonization in line with Paris Agreement**
- Solutions to close the **remaining gap**:
  - Biofuels – though Area for biomass generation limited & in competition with food
  - Carbon capture usage & storage (CCUS) – though limited scale & no full CO_2 reduction
  - Hydrogen/Power-to-X – though some challenges to overcome (volume, flammability, technology/cost)
- **Hydrogen will be key to include in the mix to achieve decarbonisation** in otherwise hard to decarbonize sectors, particularly as an energy carrier, due to its energy density, ease of long-term storage and its **potential to be produced carbon-free** as 'Green' H_2

Hydrogen can be used pure or to produce other energy carriers like ammonia and synthetic fuels, and is especially relevant where few green alternatives exist



* SMR = Steam Methane Reforming; ATR = Autothermal Reforming; CCUS = Carbon Capture, Utilization and Storage
Source: IEA, IRENA, Bain & Company analysis

Hydrogen is mainly produced from fossil sources today; Blue and green hydrogen are low carbon alternatives but currently at a higher cost

Lower disruption → **Higher disruption**

"GREY" (Fossil)

Steam methane reforming (SMR)

- Hydrogen produced from natural gas[2], but has high CO_2 emissions
- Current solution to develop hydrogen market in low carbon price environment, used as industrial feedstock for ~40+ years

"BLUE" (Climate Neutral)

'Grey' + CCUS[1]

- 'Grey' hydrogen supplemented by CCUS technology to capture CO_2 emissions
- Serves as a bridge to longer-term sustainable supply of hydrogen

"GREEN" (Sustainable)

Electrolysis

- Hydrogen produced by using electricity to split water into hydrogen and oxygen
- Long-term potential for supply disruption given zero emission product when electricity from renewable energy sources

	"GREY" (Fossil)	"BLUE" (Climate Neutral)	"GREEN" (Sustainable)
2020 supply, Mt	~95%	N/A	~5%
2020 average production cost	~$**1-1.5**/kg H_2	~$**1.5-2**/kg H_2	~$**4-4.5**/kg H_2 (global average) ~$**3-8**/kg H_2 (range)
GHG emissions	**11** tCO_2/tH_2	**0.2** tCO_2/tH_2	**0** tCO_2/tH_2

Notes: 1) CCUS = Carbon Capture, Utilisation, and Storage; 2) Hydrogen produced from coal gasification or oil reforming also referred to as "black" hydrogen but is included under grey in this overview
Source: Navigant, Hydrogen Council, Aurora, BNEF, FCH, IEA, IRENA, Shell, BP Energy Outlook 2020, Deloitte

Clean hydrogen adoption is dependent on four key criteria

/ PRELIMINARY

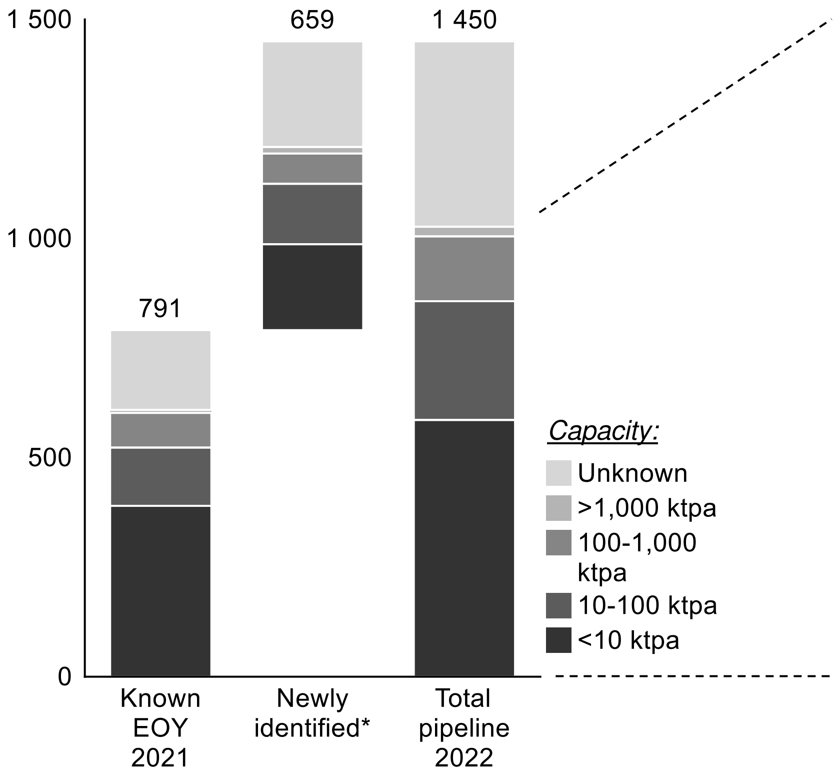
Regulations	**Regulations set by governing bodies**, whether by governmental or industry organizations, mandating emissions targets **drive adoption of** decarbonization solutions; Moreover **subsidies** (e.g., tax benefits, investments) **are required to accelerate**
Cost competitiveness	There is a **need for cost of alternative fuels to be competitive** with existing fuels and competing decarbonization pathways **for clean hydrogen adoption to be widespread**
Customer willingness to pay	Driven by product visibility, share of product cost, regulatory pressure, environmental impact, and customer sentiment, **willingness to pay a premium plays an important role in the early uptake of clean hydrogen**
Infrastructure	**Infrastructure advancements** (e.g., fuel stations / systems, localized production facilities, transport mechanisms) are necessary to **support the uptake** especially of **new clean hydrogen applications**

The clean hydrogen project pipeline shows a strong uptick, with many initiatives in feasibility stage targeting production start after 2025

ESTIMATE

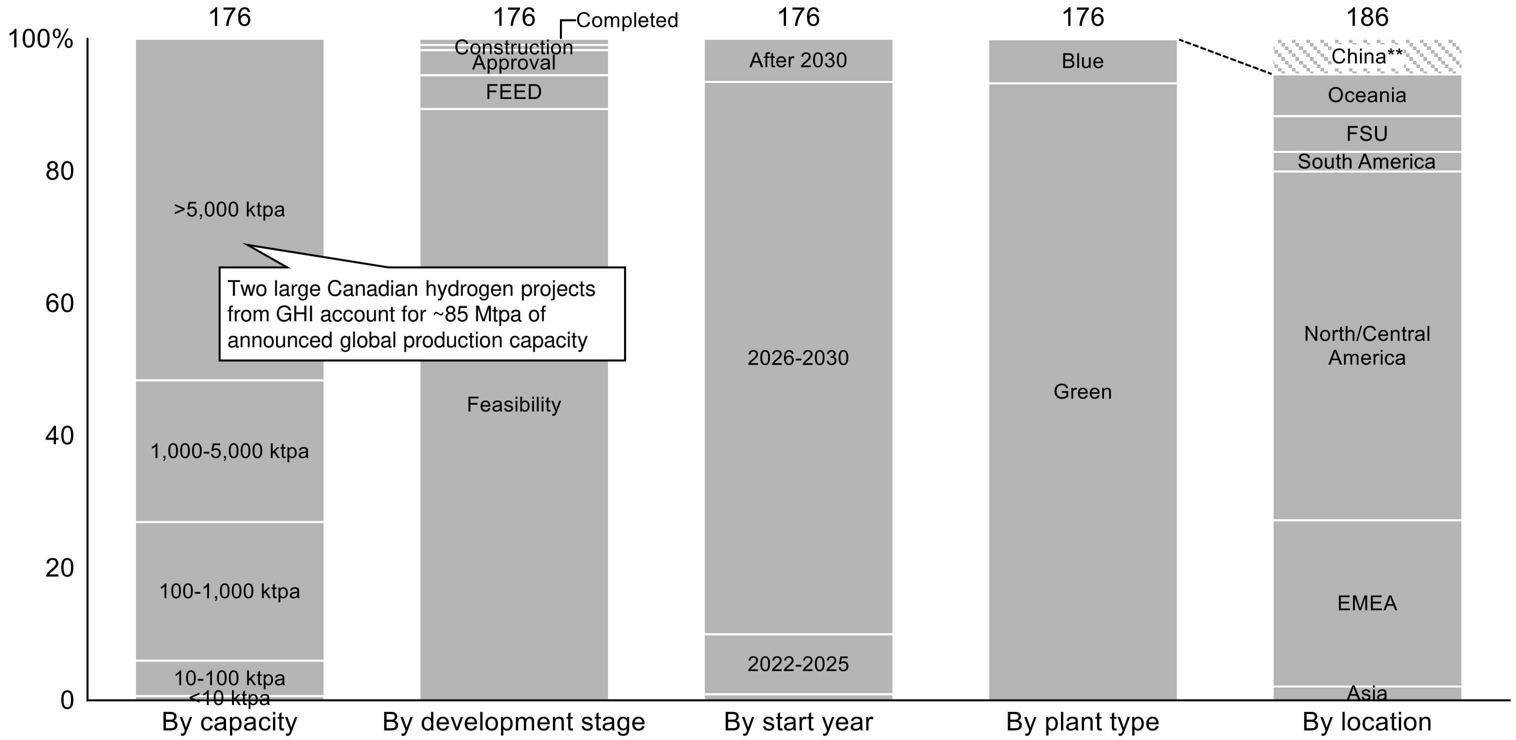
+81% H2 projects in 2022*...

Global hydrogen projects (count)**



... ~10% of projects drive >90%of capacity, mostly early stage and green

Global hydrogen projects (planned capacity, in Mtpa)



*Estimate based on communication date, not reflecting exact timing of project initiation and does not include projects which have not been communicated to the market
**China projects are underrepresented in the overall project count and capacity estimates and are thus excluded and only added in aggregate for the planned capacity by location (based on ~10 mmtpa 2030 supply estimate)
Source: Bain assessment based on Globaldata Hydrogen Plant database (January 2023 update); Literature search

Large share of announced / planned projects appear to be contingent on government subsidies and direct investments

PRELIMINARY

Project	Location	Developer	Size (GW)	Description
Acorn Hydrogen Project	Aberdeenshire, Scotland	Pale Blue Dot.	0.7	• Project will **reform natural gas into blue hydrogen**, with the associated CO2 emissions captured and stored offshore • Project is **contingent on receiving $43 million in funding** from Scottish Government
AquaVentus Electrolyser Plant	Heligoland, Germany	RWE, GASCADE, gasunie, Shell	10	• **Offshore wind-to-hydrogen project** intended to produce 5GW by 2030 and 10GW by 2035 • **Expected to receive ~$10bn in funding from Germany** as part of the Important Projects of Common European Interest (IPCEI) initiative
Yuri Pilbara Hydrogen Hub	Western Australia	YARA, ENGIE	0.5	• **Hydrogen** / **ammonia pipeline initiative** to connect strategic industrial areas • Project dependent on Western Australia's **state government funding of $84.6m**
Hydrogen to Humber (H2H) Saltend	Saltend, England	equinor	0.6	• Hydrogen production facility that will **convert natural gas to blue hydrogen** while capturing the associated CO2 emissions • Project submitted for round two (second cluster) of decarbonization funding program; **UK government will invest up to £1 billion to support the establishment of CCUS in 4 industrial clusters**
Edmonton Hydrogen Plant	Edmonton, Canada	AIR PRODUCTS	3	• Plant would produce **hydrogen-fuelled electricity and liquid hydrogen for transportation** • Project subject to final completion of agreements and funding between Canadian authorities and Air Products; Air Products has already **received $15 million from the province's carbon levy**

Source: FitchSolutions, AquaVentus

Key countries and regions are bolstering hydrogen ambition and investments

/ SELECTION OF RECENT DEVELOPMENTS

Country	Recent hydrogen policy developments
United States	• In 2022, the **Inflation Reduction Act** was passed which includes a climate package the provides ~$369B in incentives that reduces the cost of clean energy projects • In 2021 the Department of Energy introduced the **Bipartisan Infrastructure Law**, including $9.5B in clean hydrogen initiatives • In 2020, the Department of Energy established the **Hydrogen Program Plan**, a strategic framework that incorporates the research, development, and demonstration efforts to advance the production, transport, storage, and use of hydrogen across different sectors of the economy
China	• In March 2022, China's National Development and Reform Commission and energy regulator National Energy Administration released a **hydrogen development plan (2021-25)**: – Produce 100-200 KTPA of green hydrogen by 2025 and roll out 50,000 fuel cell vehicles by 2025 – Build innovative hydrogen technology platforms and promote hydrogen use in transport, energy storage, heavy industries etc.
EU	• In 2023, the EC proposed a legislative framework for the **European Hydrogen Bank** aimed to incentivize early projects • In 2023, the **revised Renewable Energy Directive (RED III)** includes green hydrogen targets and taxonomy on what is renewable • In 2022, **REPowerEU** aims at decreasing EU's dependency on Russian fossil fuels, a.o. supporting the switch to renewable hydrogen • In 2021, the EU released a **hydrogen and decarbonized gas market package** proposing new rules and guidelines for low carbon hydrogen, aimed at establishing a market for hydrogen, create the right environment for investment, and enable the development of dedicated infrastructure
India	• In 2021, India launched its **national hydrogen mission** that targets production of 5M mt/year of green hydrogen by 2030 • India's green **hydrogen policy offers a range of incentives** such as 25 years of free power transmission for any new renewable energy plants set up to supply power for green hydrogen production before July 2025
Japan	• In 2023, Japan **updated its Hydrogen strategy** from 2017, implementing more ambitious goals (incl. 2040/50 supply targets and target electrolyzer market share), increased investments (¥15T / $113B in hydrogen and renewables over the next 15 years) and specific use-case targets (e.g., FCEVs, power plants)
South Korea	• In 2021, Korea announced its **basic hydrogen economy plan** aiming to provide 27.9M mt/year of clean hydrogen (3M mt green and 2M mt blue hydrogen production, plus 22.9M mt green hydrogen from overseas) by 2050
Australia	• In 2022, Australia **committed ~$975M for hydrogen, clean energy, and CCUS** in its budget • In 2021, Australian government extended their **national gas regulatory framework** to hydrogen blends and renewable gases in order to provide regulatory certainty to support investment in innovative projects
Saudi Arabia	• Currently, Saudi Arabia is developing a national hydrogen strategy focusing on **production, exports and domestic use**. Several investments have already been announced
UAE	• UAE has launched seven strategic hydrogen production projects worth $1.7bn and is **targeting 25% of global hydrogen market** by 2030

Source: Lit. search

Multiple technology paths could shape demand and supply

Production

Generation

Blue H2
- Methane Pyrolysis/Cracking
- Autothermal Reforming
- Steam Methane Reforming (SMR) + CCS

Green H2 (Electrolysis)
- Polymer Electrolyte Membrane
- Membrane-less
- Solid Oxide Electrolysers
- Alkaline

Distribution & Transport

Transport
- **LOHC** (e.g., formic acid)
- **Methanol**
- **Ammonia**
- **LH2**
- **Compressed H2**

Storage
- **Ammonia**
- **Compressed H2**
  - Storage tanks
  - Salt caverns
  - Aquifers
  - Gas fields
- **LH2 storage**

Reconversion
- **LOHC → De-hydrogenation**
- **Methanol → SMR**
- **Liquid H2 Regasification**
- **Ammonia → Cracking**

Distribution
- **Blending**
- **100% H2**
  - Refurbish
  - Replace

Through:
- **Liquid H2 Tankers**
- **Pipelines**
- **Gaseous tube trailers**

Application by Sector

Usage

Power Generation
- Hydrogen gas turbines (pure)
- Ammonia gas turbines (pure)
- H2 blend

Maritime
- Ammonia engines
- Methanol engines

Industrials
- Feedstock
  - Domestic grey
  - Domestic blue
  - Imported blue
  - Imported green
- Fuel
  - H2
  - Electrification

Aviation
- Sustainable aviation fuel
- LH2

Related technologies

Renewable energy
As input for green H2 or as substitute for power generation, heating

Nuclear (SMR, gen IV, fusion)
As input for pink H2 or as substitute for baseload power generation

Catalysts and critical minerals
To ease bottlenecks on electrolysis expansion (new or recycled)

Batteries
As substitute in transport and power storage, or fuel cells / hydrides for using and transporting H2

Biofuels
Alternative decarb route for some forms of transport

Direct Air Capture
Substituting for H2-based decarb, or allow net-zero production from fossil fuels

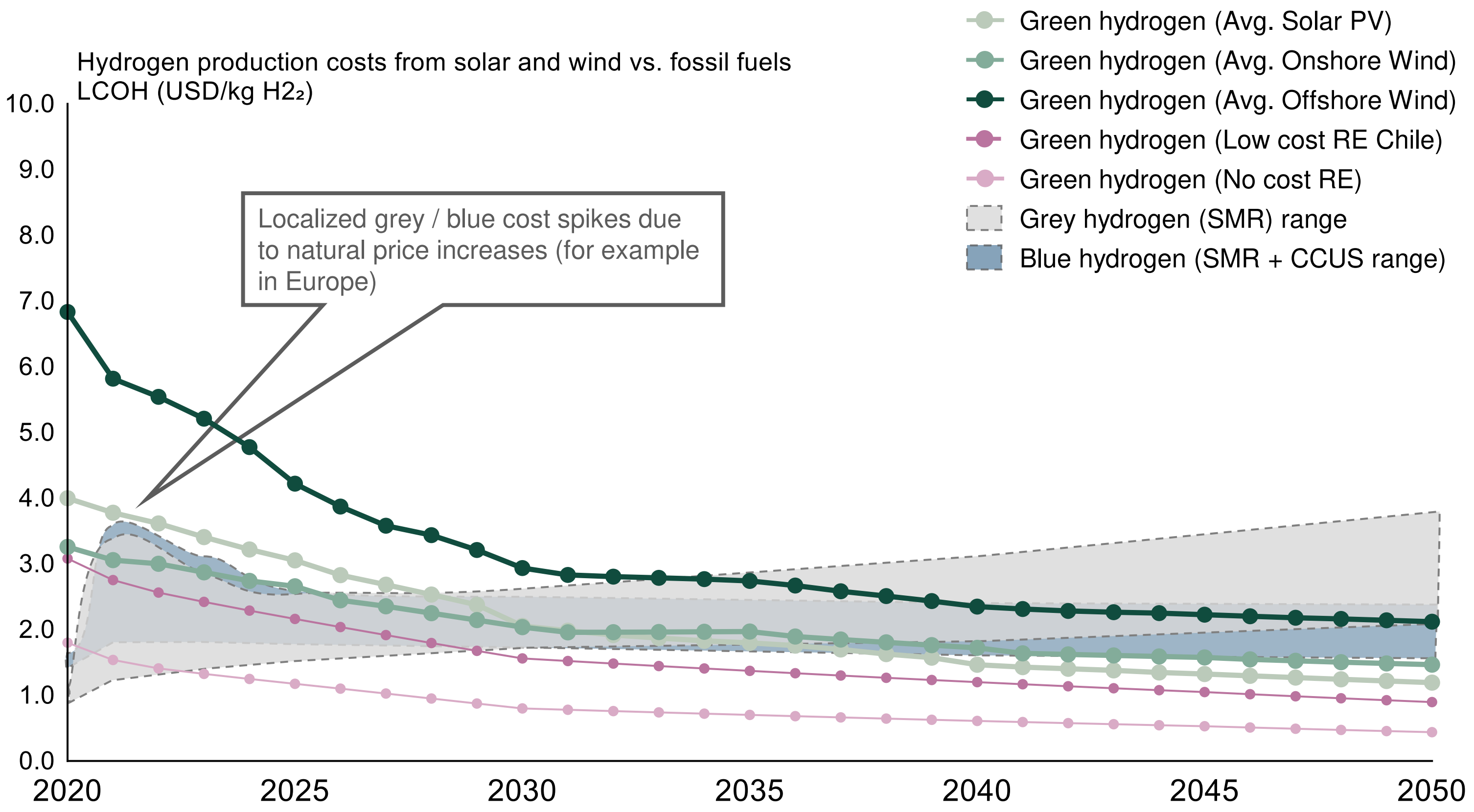
Novel carbon uses
Changing the economics of gas-led hydrogen paths

Legend: Demonstrations | Market Introduction | Mass Production | **Tech areas critical for H2 strategy** *(illustrative)*

Source: Lit Search, Bain Analysis

Long term, green hydrogen will be cost advantaged versus grey and blue

Levelised cost of hydrogen production from solar and wind vs. fossil fuels ($/kg)



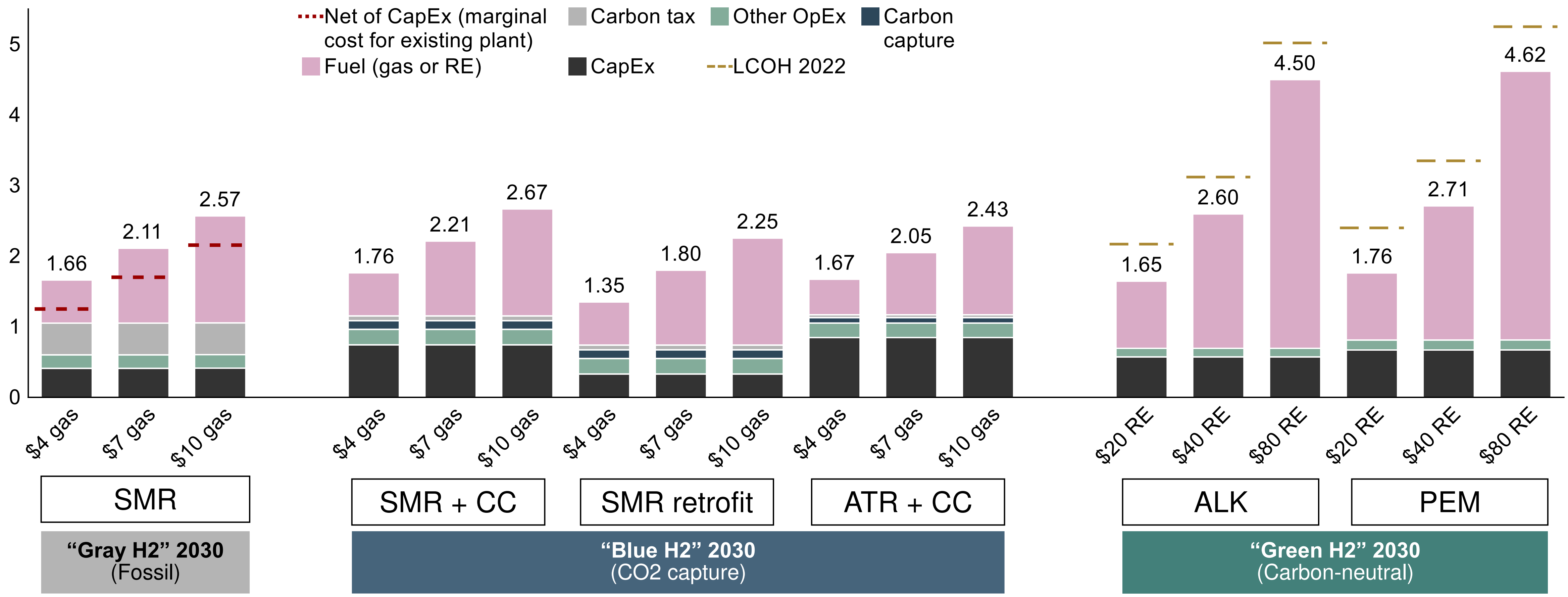
Key observations

- Future costs of green hydrogen will be lower than SMR and SMR/ATR + CCUS (grey, blue)
- Today's high natural gas prices drive up grey and blue production cost (e.g., early 2022 WEU grey hydrogen costs were >4x versus 2020)
- Around 2030, average-cost green hydrogen production becomes competitive, driven by:
  - Ongoing renewable energy price decreases
  - Capex reductions driven by electrolyser learning
  - Legislation including carbon tax pricing increases
  - Expected long term natural gas price dynamics
  - Supporting government subsidies
- In the best locations, renewable hydrogen is competitive today or in the next few years
  - Access to low-cost renewable energy given localized conditions (e.g., current curtailment)
  - Known and proximate demand to serve as an off-taker with limited transportation infrastructure required
  - Supportive regulatory policies

Note: Remaining CO_2, emissions are from fossil fuel hydrogen production with CCS. Electrolyser costs: 990 USD/kW (2020), 460 USD/kW (2030), 330 USD/kW (2040) and 260 USD/kW (2050). Electrolyzer efficiency: 65% in 2020, 70% in 2030, and 80% by 2050. CO_2 prices: USD 50 per tonne (2030), USD 50-100 per tonne (2040) and USD 100-200 per tonne (2050). Low range for fossil fuel hydrogen $3/MMBTU, high range $8/MMBTU
Source: IRENA 2019, NREL, EIA, BNEF, Lazard, Chile Department of Energy, Wood Mac, Bain analysis

By 2030, green H2 may be cost advantaged versus gray / blue if renewable energy prices continue to fall, a carbon tax is implemented, or if natural gas prices rise

Levalized cost of hydrogen ($/kg) at $50/tCO2 tax

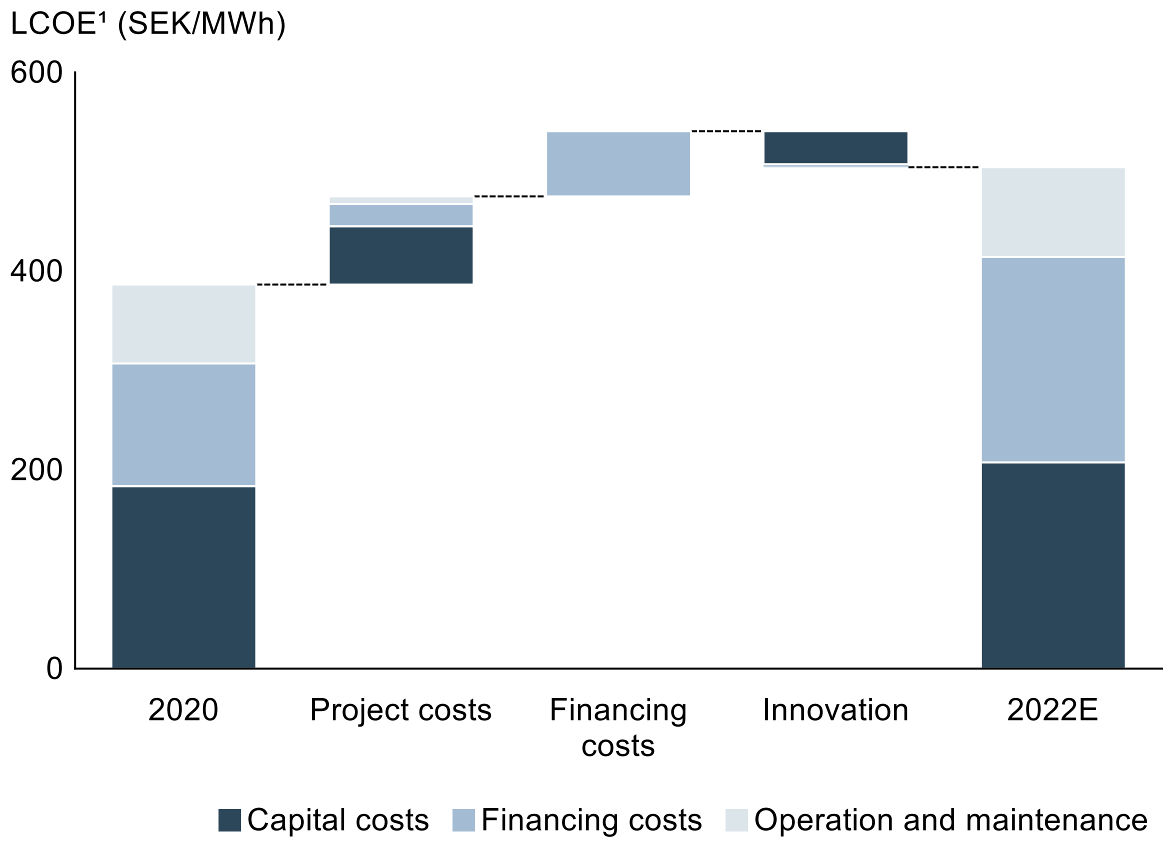


Note: Carbon tax $50/tCO2; ATR CC 91%, SMR 85%; electrolyzer learning rate at 15% at 107,000MW global installed capacity 2030, 644MW 2022 capacity; PEM/ALK efficiency at 70%; operating capacity factor at 40%; CCUS cost at $16/tCO2
Source: Bain analysis

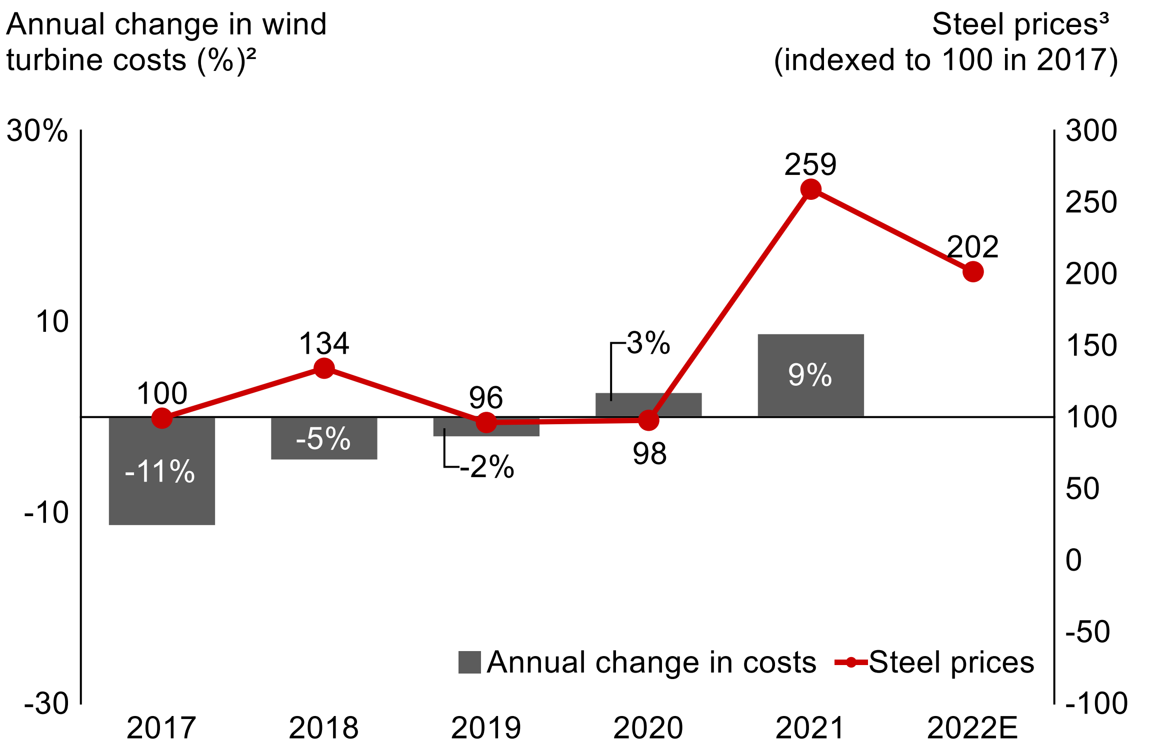
Production cost declines for green hydrogen are now pressured by changing macro conditions impacting capital and financing costs and thus renewable energy LCOE

/ WIND POWER EXAMPLE

Increasing financing and capital costs are the main drivers of increasing wind power LCOE



Core material price increases such as steel is the key driver of higher CAPEX



Note: 1) Based on a benchmark project in Europe/ North America with revenue support mechanism. Converted from USD to SEK at current exchange rate; 2) Based on global average prices excluding installation costs by signing date; 3) 2022 price based on average prices between January and March
Source: IEA World Energy Investment Report

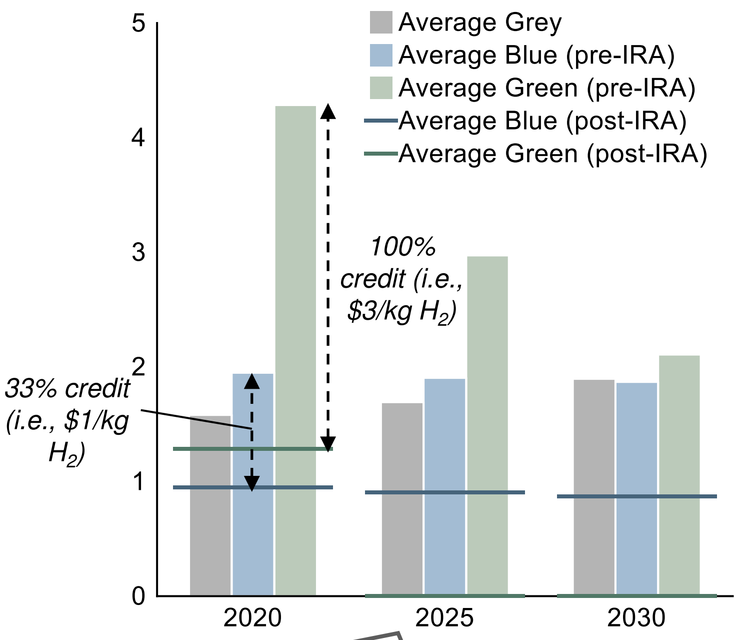
The US Inflation Reduction Act is likely to accelerate the shift to clean hydrogen

The clean hydrogen tax credit decreases costs of clean H_2

- Greenfield or retrofit facilities **constructed before 2033** are eligible for the CHTC[1] for **10 years** from the start of producing clean H_2
- Green and blue H_2 projects qualify for **different levels of support**
  - **Green**: 0kg CO_2 emissions; up to $3/kg H_2 produced
  - **Blue**: 0.5 - 1kg CO_2 emissions/kg H_2; up to $1/kg H_2 produced
- The **CHTC cannot be combined with other carbon capture credit programs** included in the IRA (i.e., blue H_2 cannot receive credit for both clean H_2 and carbon captured)

IRA could bring green production cost decline forward >10 years

Levelised cost of hydrogen production by type ($/kg)



Post 2025, cost of green H_2 production **forecast to be below maximum CHTC credit** (i.e., below $3/kg)

*Prior to IRA, green hydrogen **only cost-competitive by 2030+***

Rate of change transition to green hydrogen still uncertain

IRA causes **green H_2 to become cost competitive today** rather than after 2030

Unclear whether H_2 demand will increase significantly in the short-term; novel use-cases (e.g., transport) not expected to scale for some years

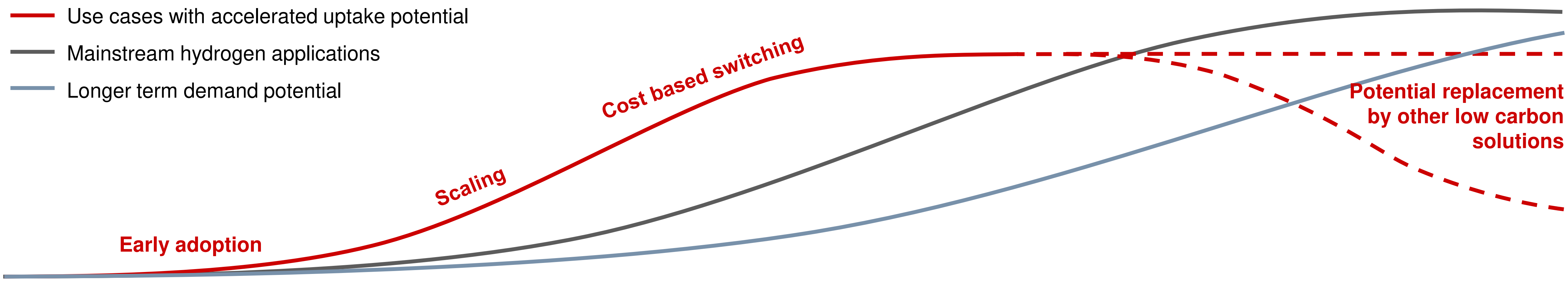
IRA is **likely to accelerate the greening of ongoing H_2 applications** with existing demand (i.e., industrial processes)

Note: [1]CHTC = Clean hydrogen tax credit; H_2 = Hydrogen; ITC = Investment tax credit; Electrolyser costs: 990 USD/kW (2020), 460 USD/kW (2030), 330 USD/kW (2040) and 260 USD/kW (2050). Electrolyzer efficiency: 65% in 2020, 70% in 2030, and 80% by 2050. CO_2 prices: USD 50 per tonne (2030), USD 50-100 per tonne (2040) and USD 100-200 per tonne (2050). Low range for fossil fuel hydrogen $3/MMBTU, high range $8/MMBTU;.
Source: RMI, DLA Piper; IRENA 2019, NREL, EIA, BNEF, Lazard, Chile Department of Energy

Clean hydrogen applications are being developed to build out demand, though speed of market adoption will vary significantly across use cases

/ILLUSTRATIVE

Clean hydrogen adoption pathways



Examples	2020 – 2030	2030 – 2040	2040 – 2050+
Natural Gas & **H2 blending**	• **Early outlet for H2** supply from low-cost renewable energy, targeted at **using existing NG infrastructure** with limited investment (for existing heat and power applications)	• Reaches scale more rapidly as a solution to **extend lifespan of NG infrastructure** by enabling some decarbonization, benefitting from lower H2 cost, without major investment	• Potential outcomes include **replacement by more efficient power/storage options** (e.g., super batteries), or **persistence as a long-run option** in some advantaged geographies
H2 for **green steel**	• Steady adoption driven by early movers, to **test & learn** and gain early experience, often driven by a **strong ESG ambition**	• Growing penetration, enabled by **more competitive H2 costs**, and cost / emission **benefits for H2** vs original / alternatives	• Switching towards full potential H2 penetration due to **clear competitive advantage in cost and overall value proposition**
NH3 for **maritime**	• Explore **early opportunity and feasibility** including early application (vessel) and infrastructure (terminal, bunkering) development	• Adoption of **targeted solutions** (e.g., harbor support vessels, dual-fuel vessels), build out of required **infrastructure**, accelerated **vessel conversion**	• Further scaling and **acceleration of NH3 penetration** to meet regulatory emissions requirements, **competing against fossil and low-carbon solutions** (e.g., biofuels)

In many alternative fuel / energy cases potential hydrogen customers generally have a low willingness to pay a premium unlike, for example, bio-based plastics

PRELIMINARY

End-customer visibility

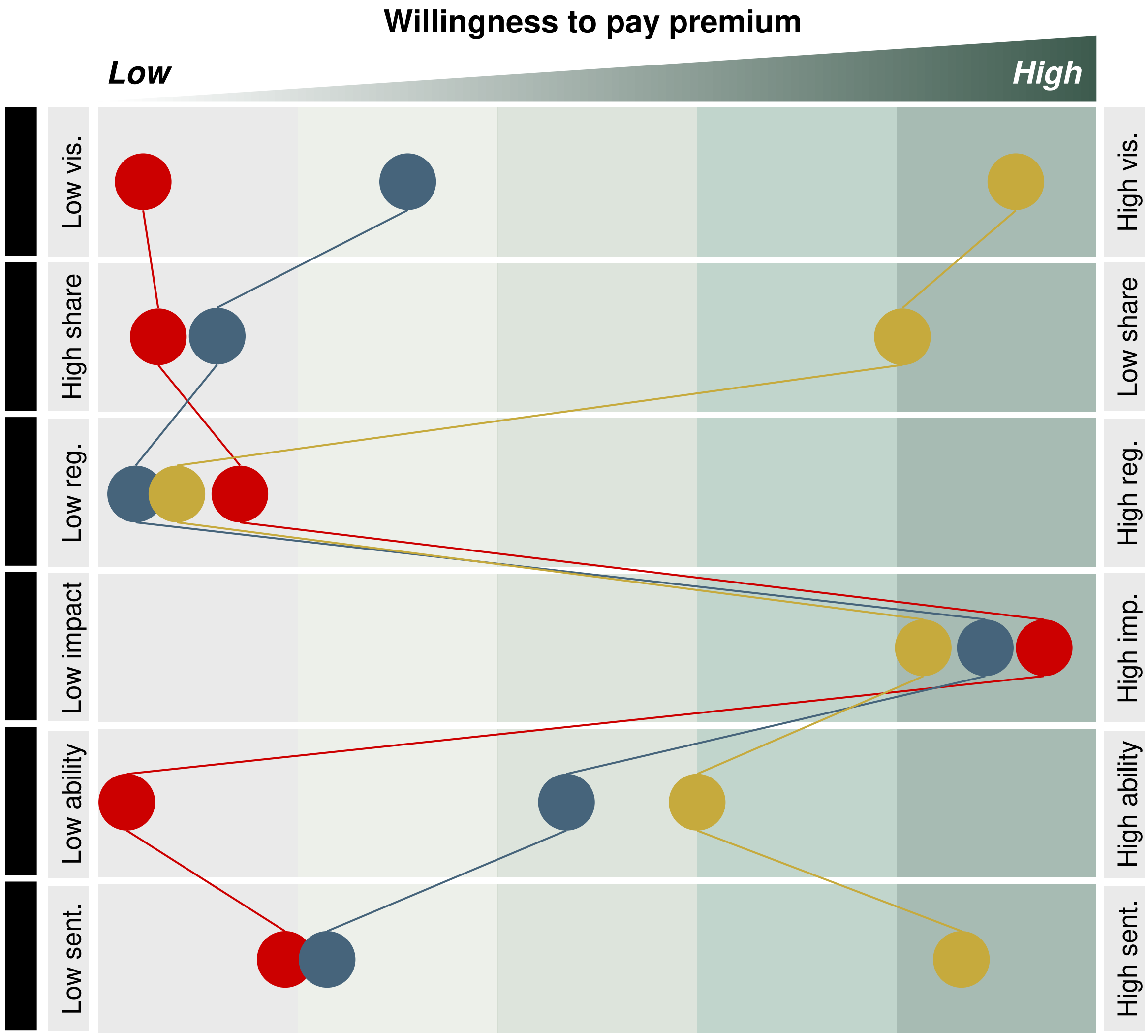
Share of product cost (decision maker)

Regulatory pressure

Environmental impact

Ability to pass through prices

Customer sentiment



Rationale

- Higher visibility products garner greater attention and are likely to lead to a **higher willingness to pay a premium to avoid significant scrutiny**; most hydrogen fuel / energy applications are hidden from the public eye
- **Fuel costs represent a significant portion of the overall product cost across many segments**, resulting in a lower willingness to pay a premium because the overall cost will be exponentially higher than if the fuel costs only made up a small portion of the total product cost
- Regulations help drive greater adoption of alternative fuel / input sources; however, those **regulations are not aggressive enough** in most markets to force an immediate transition
- The **shift away from fossil-based fuels to environmentally-friendly fuel sources has a high impact across all industries** as fuel inputs are key drivers of GHG emissions globally
- **Most of the segments are very cost-competitive**, therefore, the ability to pass through prices in the market is low; pipeline blending can within reason due to established price bands
- For consumer-oriented items customer sentiment would play a more significant role in the decision to pay a premium because a **company may lose customers as a result of not appealing to their customers' preferences**

Bio-polyethylene · Maritime transport · Pipeline blending

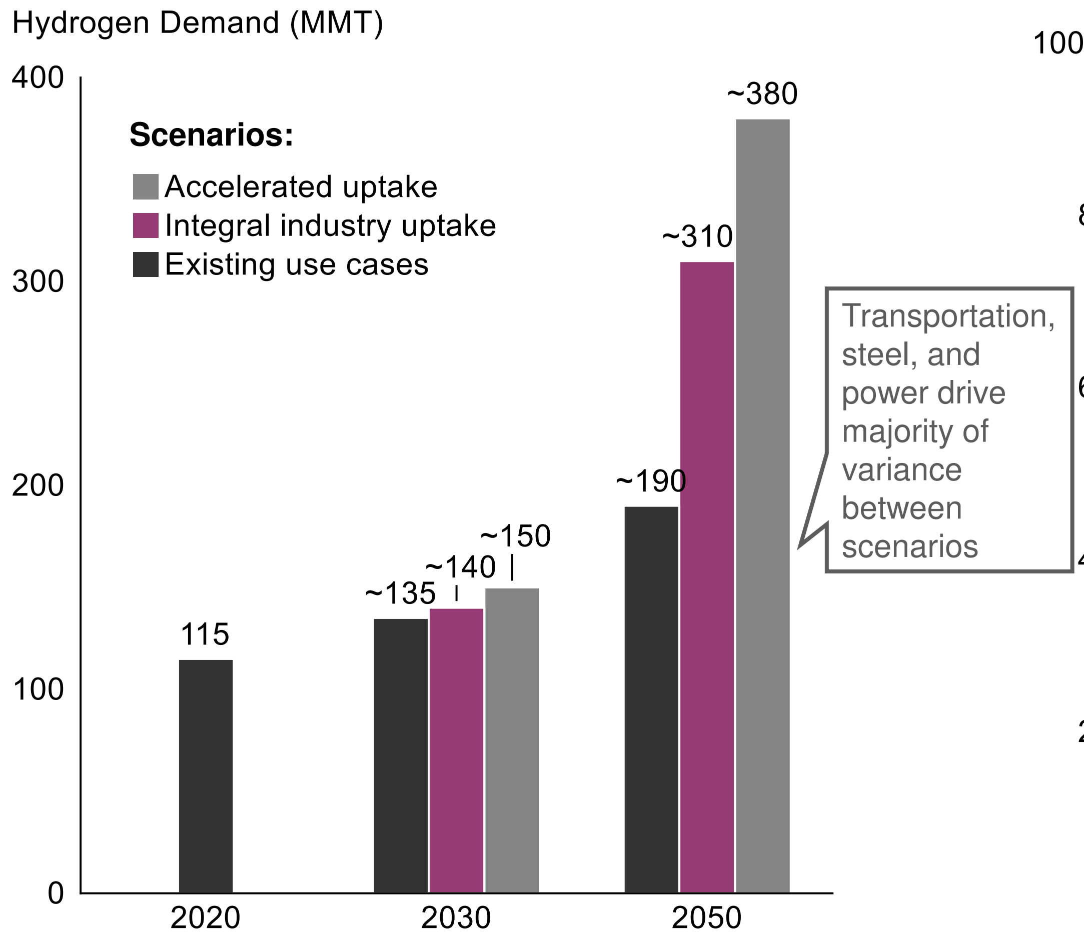
Source: Lit. search

We envision a number of feasible paths for hydrogen demand, based on degree to which policy, investment, and innovation enable competitiveness and early adoption

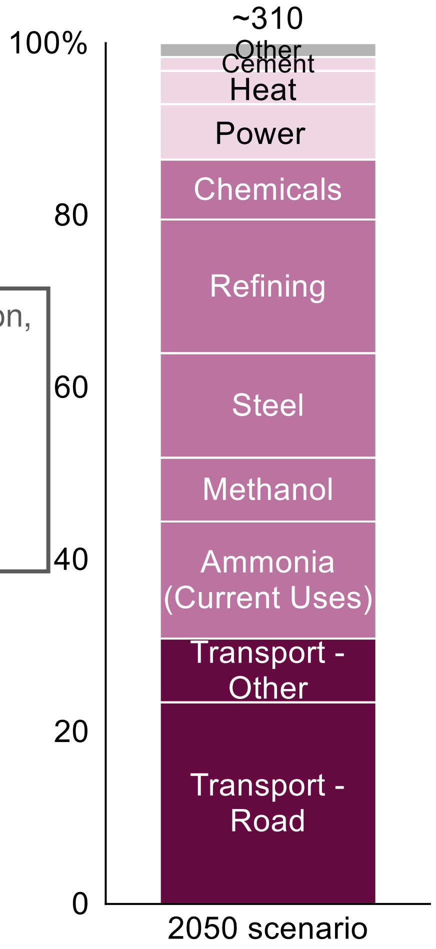
Scenario	High-level assumptions on the evolution of the hydrogen market and demand
"Focused" uptake	• Hydrogen demand mostly persists in **industries where it is present today** with low-growth to 2050 • Some **incremental uptake** likely in core applications with limited decarbonization alternatives (e.g., steel) • For other end markets where **non-hydrogen but low-carbon alternatives exist**, hydrogen fails to reach cost competitiveness or gain a foothold against competing alternatives (e.g., BEV) • **Investments are directed accordingly** and promote alternative solutions towards emission reduction
"Integral industry" uptake	• Hydrogen plays a **meaningful role in the decarbonization of the world** • By 2030, core applications of hydrogen have **matured and provided scale**, driving down the cost of hydrogen and enabling cost competitiveness in new applications • **Investments in hydrogen market and infrastructure enable the acceleration of adoption**, particularly in end markets such as transportation
"Accelerated" uptake	• Hydrogen is a **central component of decarbonization**, emerging as a leading technology even in select end markets where non-hydrogen alternatives exist today • Above and beyond the "integral industry" scenario, **nascent applications gain a foothold earlier** (e.g., hydrogen as fuel in aviation, hydrogen use in power) • Investments behind hydrogen are a **core element of decarbonization strategy and policy**, and are undertaken on a more rapid timeline

Based on supply capacity, legislation developments, and long-term demand potential across applications, we expect 2050 H2 demand to be ~310 to 380 MMT

Hydrogen demand scenarios (M tons)



Growth drivers in the 2050 “integral industry uptake” scenario



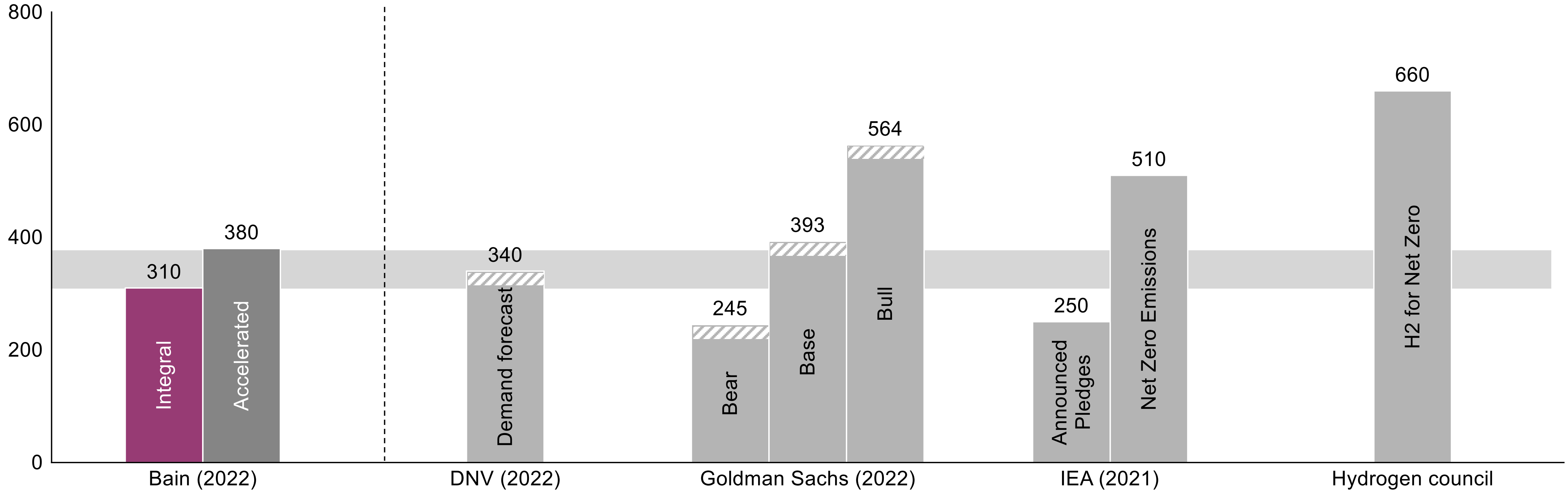
- High-grade heat for cement applications
- High/medium industrial heating (>100°C)
- Blending into residential heat networks
- In-grid power storage and flexible generation
- Other industrial chemicals and gas-to-liquid
- Refining (e.g., crude oil as basis for plastics)
- DRI penetration of primary steel production
- Byproduct consumption for remaining BOF production
- Methanol and derived synthetic materials
- Ammonia for fertilizer and existing industrial use cases
- Ammonia fuel as alternative to LNG, VLSFO in ships
- Synfuel for aviation
- Long-haul HDV fuel cell
- H_2 use in public transit (buses)
- FCEV powered forklifts

Transport Industrials Power & Heat Other

Source: IEA, Hydrogen Council, BNEF, IRENA

Bain's H2 scenarios broadly align with other recent market forecasts, though uncertainty remains, and net-zero derived scenarios tend to assume higher uptake

2050 Hydrogen demand scenarios* (in MMTPA)



Note: *Where scenarios do not include the contribution of by-products (white hydrogen), 25 mmtpa has been added to the scenario total, which is also indicated by the shaded area on the chart
Source: DNV, Goldman Sachs, IEA, Bain analysis

Local market, customer and regulatory dynamics will also show varying adoption of green versus blue hydrogen across regions (example U.S. Gulf Coast, pre-IRA)

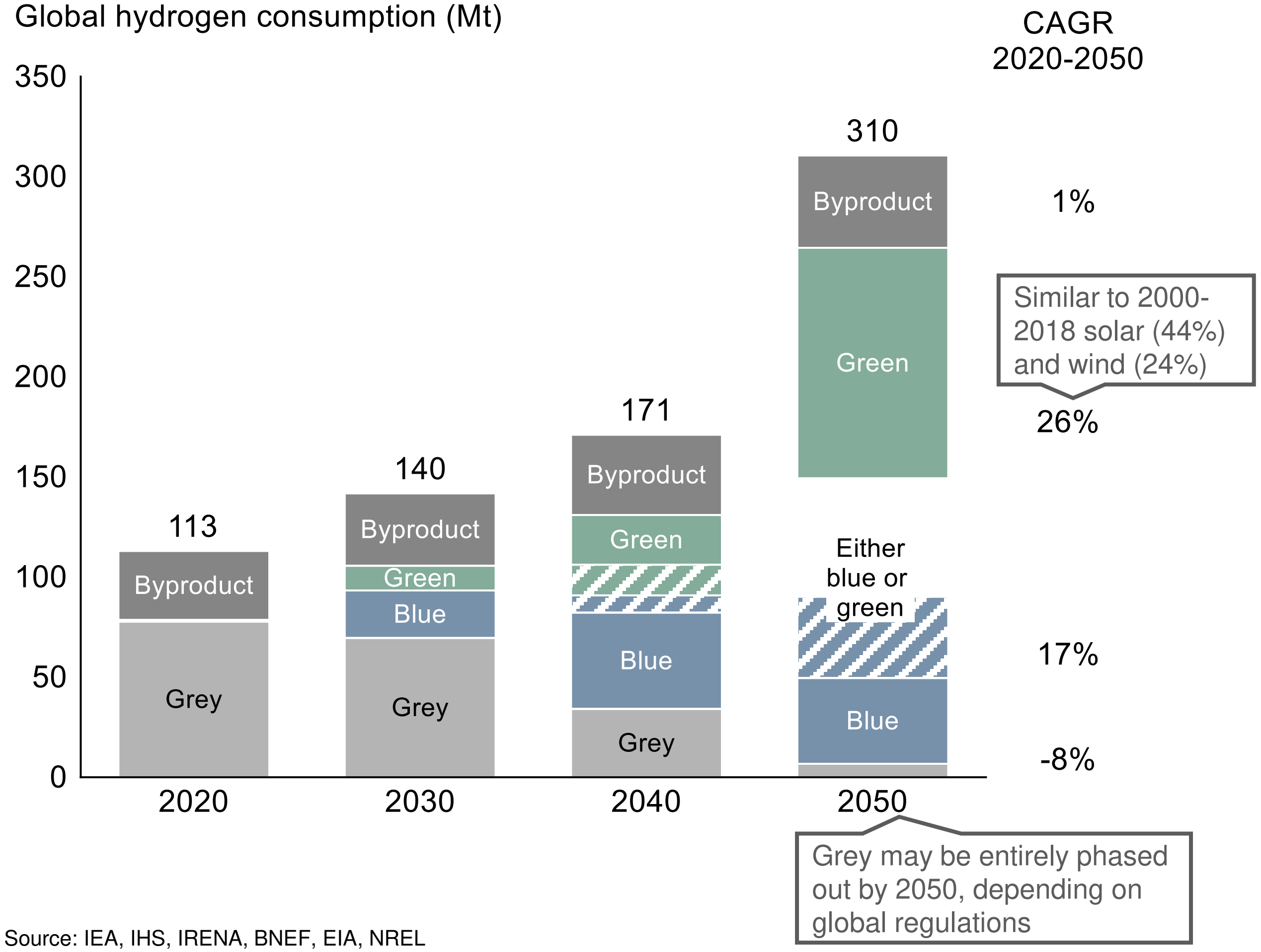
	Main end use	Consumption	Outlook for H2	Likely source of H2: Today	2030	2035	2050
Existing	**Chemicals / refining**	Centralized	• Low-cost NG in USGC will continue to win on cost into early 2030's • Green H2 will need significant cost reduction through lower capex and renewable costs; refining likely remains blue, but potential small pockets of adoption in chemicals by 2050	Grey H2	Grey/Blue H2 mixed use	Blue H2	Blue/Green H2 mixed use
Existing	**Steel**	Distributed	• Targeted regulatory requirements will drive near-term transition to blue • Due to the distributed nature of steel production, even within the USGC, on-site production of green H2 will be best long-term option	Grey H2	Blue H2	Blue/Green H2 mixed use	Green H2
New use cases	**Transportation – Road**	Distributed	• New use case of H2 to decarbonize transport likely to skew green as soon as it is economical (mid 2030's to 2040's)	H2 Not used	Grey/Blue H2 mixed use	Blue/Green H2 mixed use	Green H2
New use cases	**Heat**	Centralized / Distributed	• Existing industrial H2 feedstock customers will likely mirror feedstock H2 source • All other industrial or residential users likely to use green H2 from the beginning of the conversion, though large-scale residential heat adoption unlikely to happen	H2 Not used	Blue H2	Blue/Green H2 mixed use	Blue/Green H2 mixed use
New use cases	**Power**	Centralized / Distributed	• Low % H2 blending (~1-5%) into NG streams is nearest-term power application; H2 retrofitted turbines for higher-% H2 stream will play an increasingly large role in utility-scale power gen • Green H2 highly unlikely to be involved in power gen in lieu of connecting renewable to grid	H2 Not used	Grey/Blue H2 mixed use	Blue H2	Blue H2
New use cases	**Transportation – Marine**	Distributed	• Centralized production in port cities, but robust global market • Green vs. blue will depend on energy input costs, with US likely using blue before 2030 and other shipping countries (e.g., Japan, EU) using green or importing ammonia from USGC	H2 Not used	Blue/Green H2 mixed use	Blue/Green H2 mixed use	Green H2
New use cases	**Transportation – Rail**	Distributed	• Similar to other types of transportation, new use cases of H2 to decarbonize rail are likely to skew green as soon as it is economical	H2 Not used	Grey/Blue H2 mixed use	Blue/Green H2 mixed use	Green H2
New use cases	**Ammonia / regas exports**	Distributed	• Given regulatory tailwinds, global ammonia exports are likely to shift to blue / green as countries look to satisfy emission requirements and net-zero pledges	H2 Not used	Blue H2	Blue/Green H2 mixed use	Blue/Green H2 mixed use

Key: H2 Not used · Grey H2 · Grey/Blue H2 mixed use · Blue H2 · Blue/Green H2 mixed use · Green H2

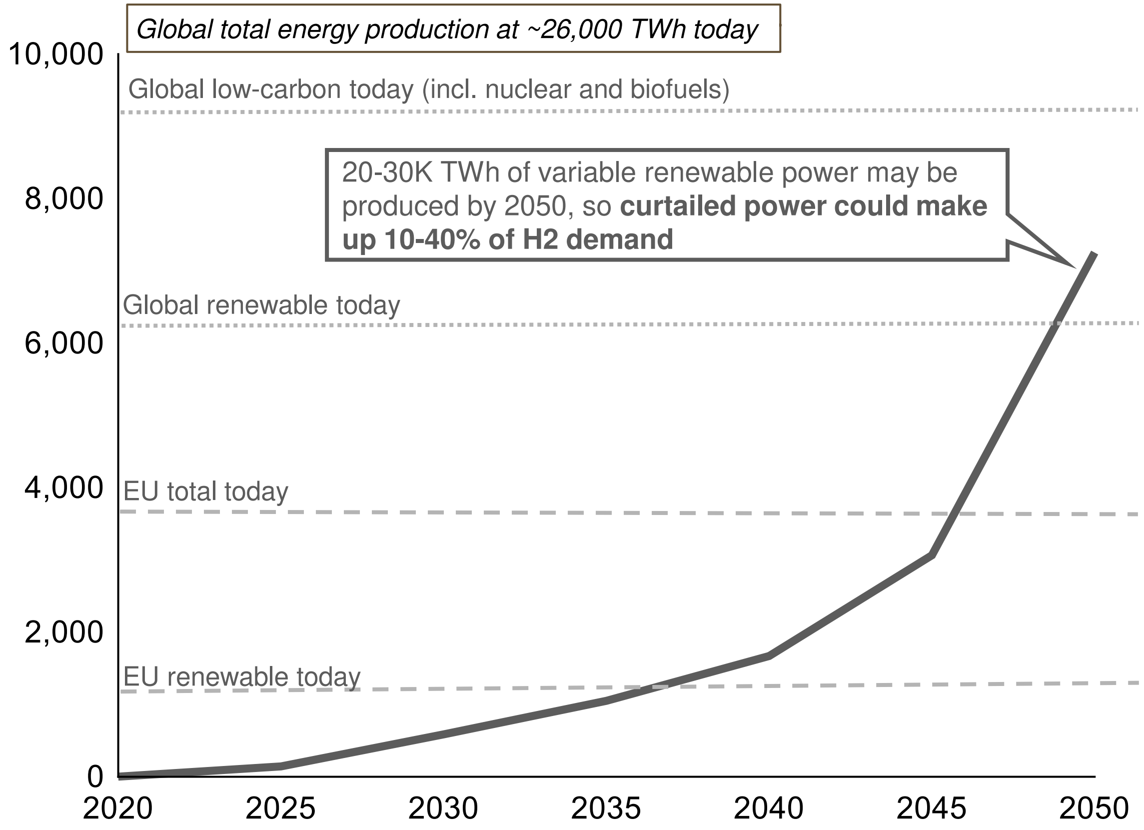
Green uptake will depend on energy input prices and ability to scale renewables

PRELIMINARY

All sources of H_2 will contribute through 2050, green could be 40-70% in the "Integral Industry" scenario



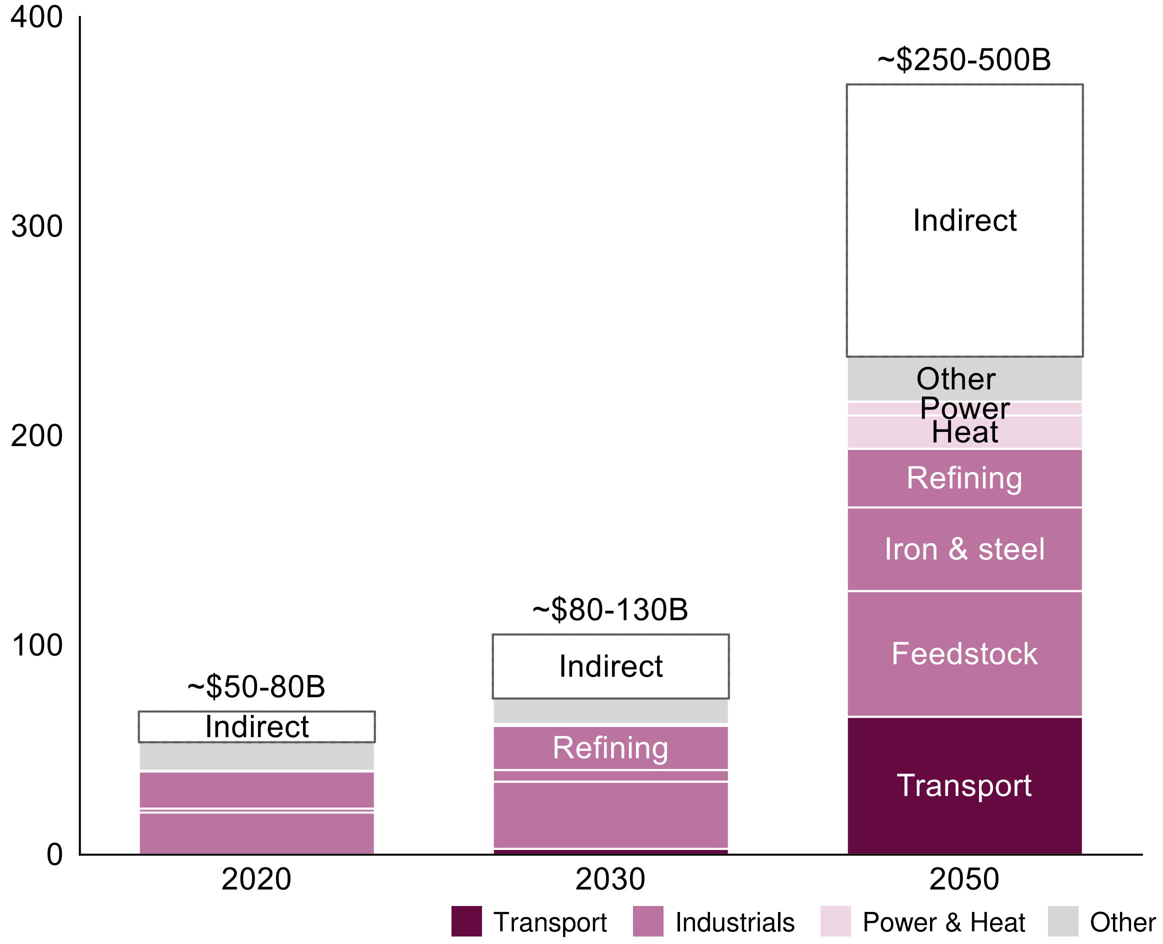
To meet this, green hydrogen production would require ~7,300TWh of renewable energy supply by 2050



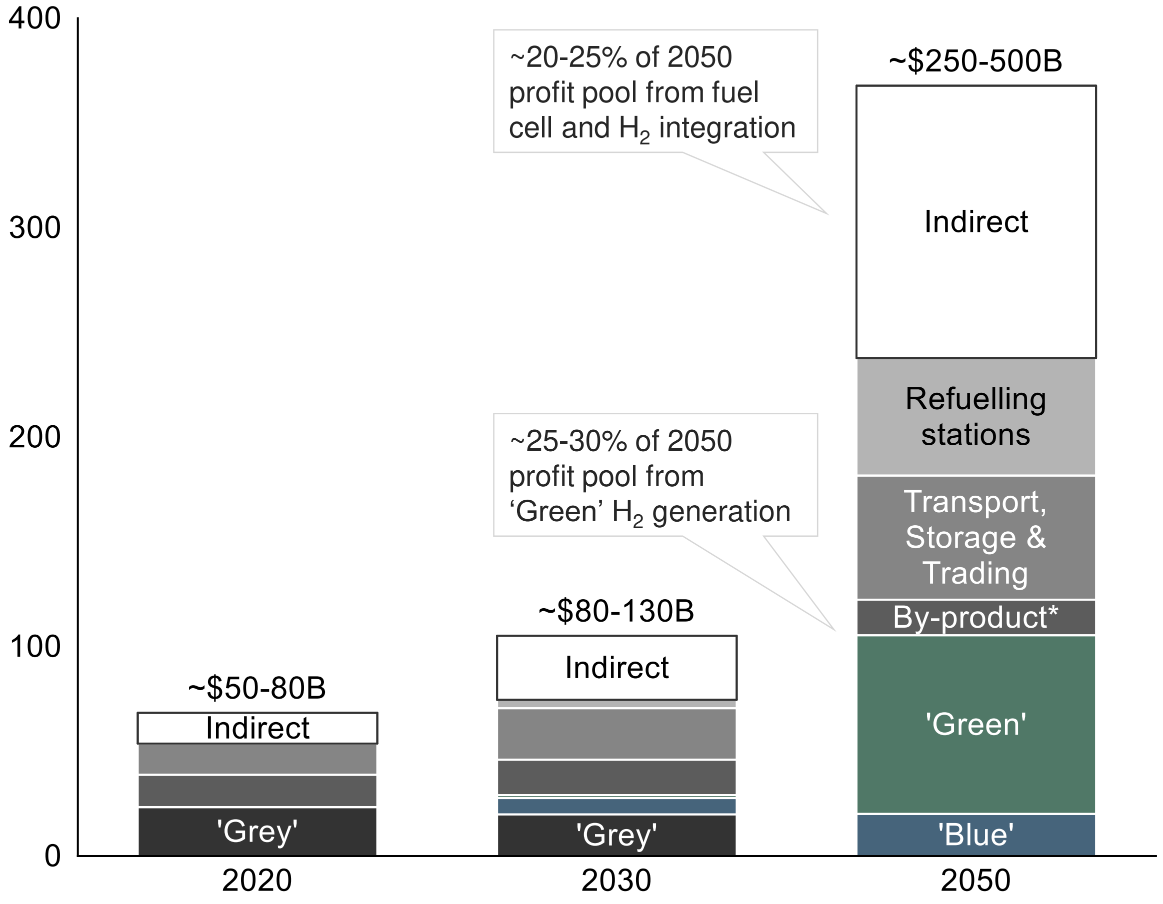
Source: IEA, IHS, IRENA, BNEF, EIA, NREL

The "integral industry uptake" scenario could lead to profit pools of $250-500B by 2050 albeit with long lead time to maturity

Profit Pools by Application (EBIT, $B)



Profit Pools by Value Chain Segment (EBIT, $B)



Note: Indirect profit pools include supply of commodities, development of H_2-related technology (electrolysers, fuel cells), integration services (fuel cells and H_2 in processes), and advisory roles; (*) Hydrogen produced as waste from industrial electrochemical processes that is captured and consumed within the same facility or sold into the merchant market for use by others

Given uncertainty on market development, monitoring key signposts is required to drive adaptability as the market evolves

/ NOT EXHAUSTIVE

Policy

- Broader and more aggressive **carbon tax**
  - Example: US federal carbon tax at $70+/ton
- Explicit **hydrogen policy, pledges, and investment**, to incent expanded role
  - Example: Danish Road Towards 2030
- Policy shift on role of **next generation nuclear**
- Increasing **restrictions on water consumption**
  - Example: Cape Town, SA

Technology

- **Cost and experience curve** impacts on key hydrogen technologies, including substitutes
  - Wind (onshore, offshore)
  - Solar
  - Electrolyzers, by tech
  - Battery storage (short and long duration)
  - Fuel cells
  - CCUS
  - Nuclear (SMR, Gen IV, fusion)
- Cost and experience curve effects for **electrification**
  - Heat pumps
  - BEVs

Infrastructure

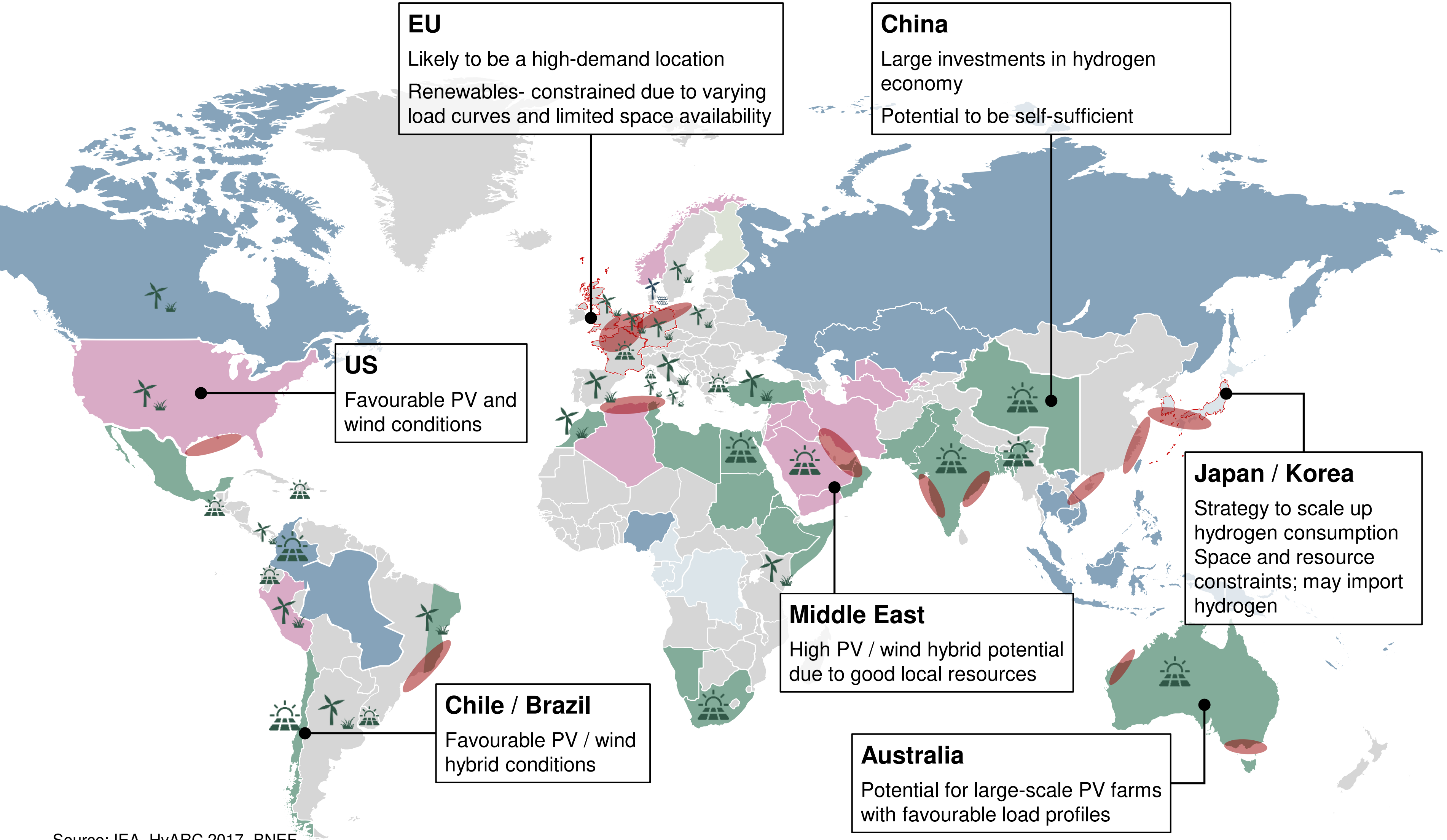
- **Technical progress** on storage, including safety
- Accelerated **distribution investment**
  - Liquefied H_2 tankers (new / LNG retrofit)
  - H_2 refueling stations or local H_2 ecosystems
- Formation of a **hydrogen "market"**
  - Excess H_2 storage/ marketing
  - H_2 commodity trading
- Elimination of **end market bottlenecks** (e.g., dry dock capacity for marine)

Customer

- Growth rate on **committed customer demand** for hydrogen or related OEM products
  - Gray hydrogen conversion (gray to blue/green)
  - Blue/green ammonia
  - Blue/green steel
  - Marine (green ammonia, synfuels)
  - Transportation / H_2 HDVs
- **Viable projects**, at scale
- Change in **customer willingness to pay**
  - Products/services certified as "net zero"

Important for signposts to monitor a range of potential alternatives for how the hydrogen market may evolve

Hydrogen opportunities will mature at different speeds depending on local supply dynamics and proximity to key demand clusters



Hydrogen production potential

- Proximity to industrial demand clusters **(suitable for green and blue H_2)**
- Optimal renewable and low-carbon resources **(suitable for green and blue H_2)**
- Optimal/average low-carbon resources **(blue H_2)**
- Optimal renewable resources **(green H_2)**
- Average renewable resources **(green H_2)**

Expected green hydrogen first mover countries

- First mover countries based on regulatory changes and incentives

Cheapest source of new renewable electricity

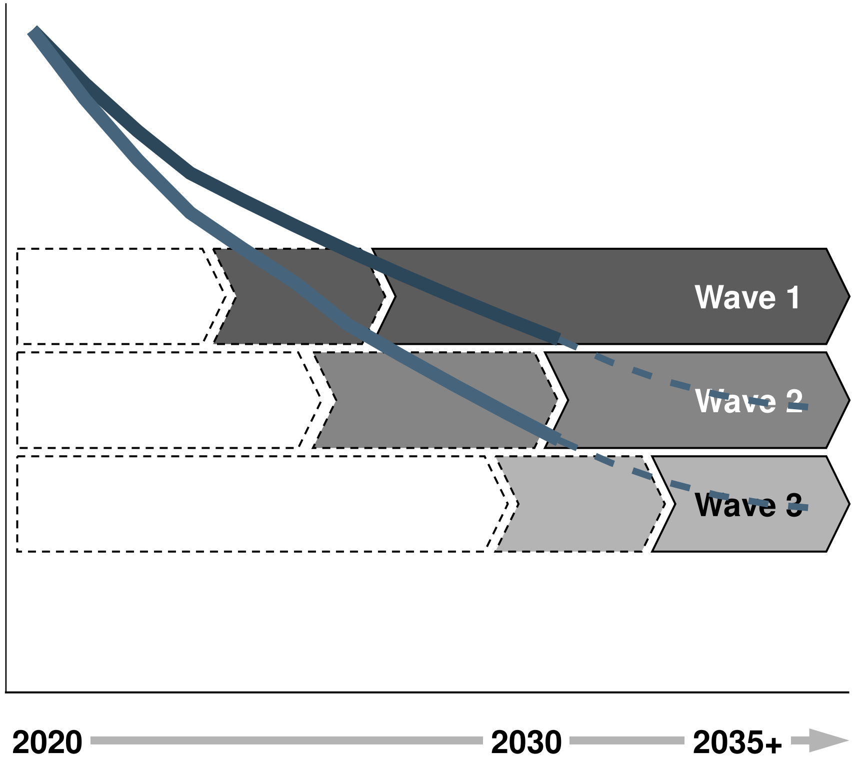
- Onshore
- Offshore
- PV

Source: IEA, HyARC 2017, BNEF

At the application level, we expect different waves of adoption and especially scaling – first wave likely to include converting existing grey to blue and green

3 waves of application driving demand for green H_2 as cost of production come down

Indexed cost of hydrogen
(in $/kg)



Small scale/ R&D — Early applications — Potential commercial viability and scaling

Wave 1
Greening existing H_2 demand as industrial feedstock

Wave 2
New demand from selected transportation cases and auxiliary power solutions

Uncertainty largely driven by adoption within transportation

Wave 3
Wider adoption in aviation and industrial heat processes

Illustrative for annual demand in 2050 in million tonnes H_2: Low — High

Primary application areas

Ammonia & Methanol

Oil refining

Iron & Steel

General industry feedstock

Building heat: Gas/H2 blending as early demand outlet (limited long-term upside)

Heavy duty vehicles: Hydrogen fuel cells

Auxiliary power generation: Hydrogen power & storage units

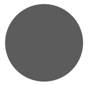
Maritime: Ammonia

Aviation: Synthetic kerosene

Industrial heating: Heat for production including cement and steel

Source: IEA; BNEF; Expert interviews; Bain & Company analysis

As part of the current market acceleration, we see three partly reinforcing business models emerging, plus scale up of technology and market enablers

Low LCOE global supply hubs	**Scale hydrogen clusters**			**Localized solutions**
	Supply-led	Integrated hubs	Demand-led	
Large scale integrated projects using NG and off-grid RE systems in lowest LCOE regions	*Proximity to local hydrogen source, e.g., offshore wind and H_2 production on land or integrated at sea*	*Integrated hubs around multiple use cases, connected to green / blue H_2 at scale, mostly to decarbonize industries*	*Linkage of concentrated demand in locations without direct access to low-cost hydrogen (e.g., co-firing in Japan)*	*Localized pilot projects or decarbonization efforts around specific use cases, including decarbonization-as-a-service models*
Winning capabilities:				
• Financing, project development and EPC • RE & electrolyser integration • End-market understanding	• OW scale and track record • Electrolyser integration • Power market & customer position	• Anchor demand; use case understanding • Competitive scalable supply • Local regulatory shaping	• Deep understanding of application technology and performance vs alternatives • Scalable and reliable supply infrastructure	• Local market position • B2B customers and org. • Holistic technology and cost knowledge for alternatives
Share of 2040 H2 supply:				
40-60%	10-20%	30-40%	<1%*	<10%
Degree of standardization:				
				

Enabling technologies and infrastructure scaling

*Very limited share in supply – could be 10-30% of future demand
Source: IEA, Hydrogen Council, BNEF, IRENA; Bain analysis

Projects are now emerging at scale across these business models

GREEN H2 ONLY / SELECT EXAMPLES

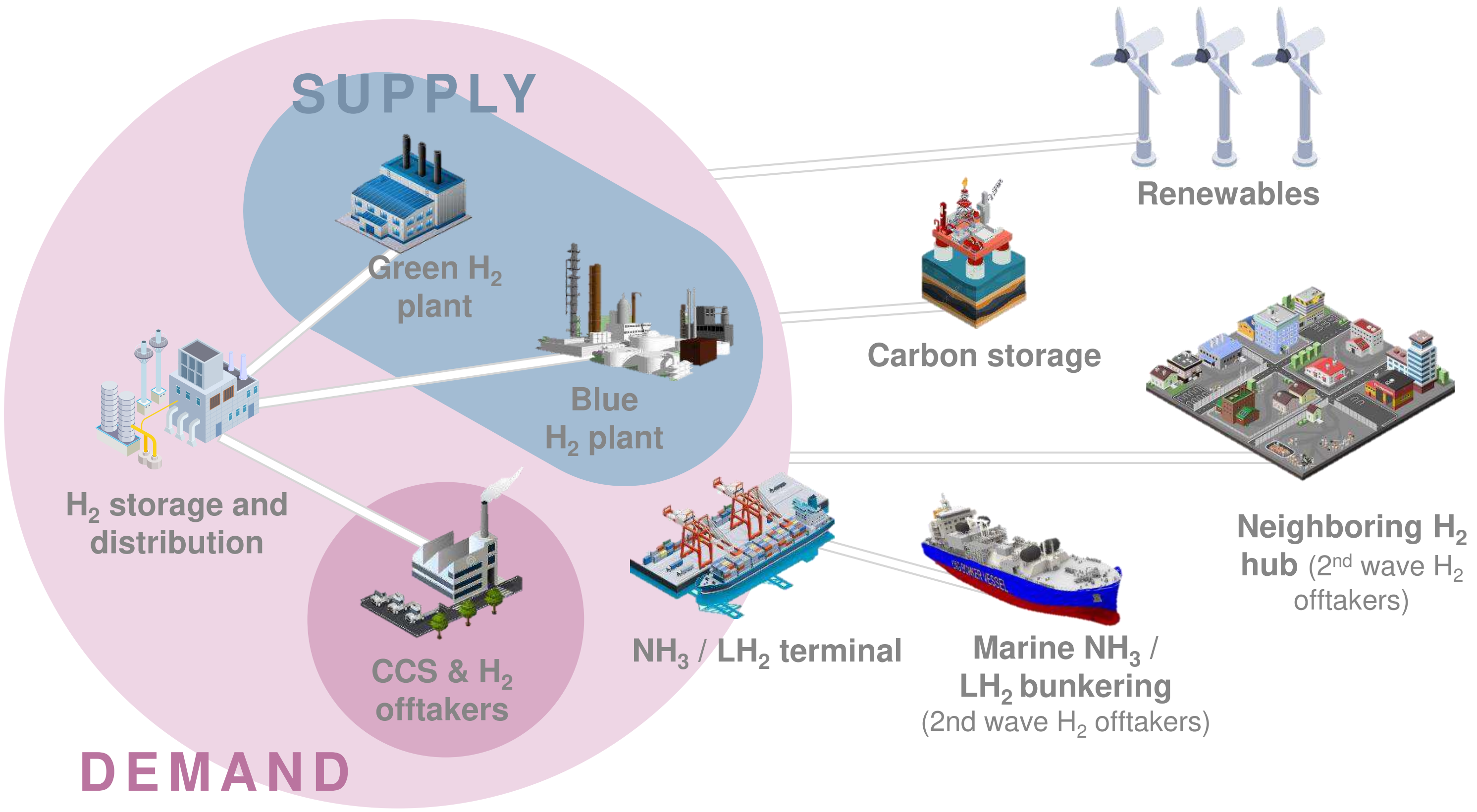
	Project name	Country	Production start year	Description	Electrolyzer size / KTPA	Participants
Low LCOE supply hubs	**Project Nour Green Hydrogen**	Mauritania	2024	• **Chariot**, an African focused transitional energy company is collaborating with the govt. of Mauritania to develop a potential **10 GW green hydrogen** project using solar and wind energy	4214 (600* ktpa)	Chariot Transitional Energy
Low LCOE supply hubs	**TransHydrogen Alliance Port of Pecem**	Brazil	2026	• A consortium of Proton Ventures, Global energy storage and Varo Energy called **Transhydrogen** are investing **$2B** aiming to produce green hydrogen and green ammonia	3512*(500 ktpa)	Proton Ventures, Varo, GES Global Energy Storage
Low LCOE supply hubs	**H2Perth Green Hydrogen**	Australia	2027 (Phase 2)	• **Woodside** launched the H2Perth project to establish a **hydrogen and ammonia** production facility with an initial electrolyzer capacity of 250MW with potential to scale to more than 3GW in the 2nd phase	3000 (438* ktpa)	Woodside
Supply-led cluster	**H2opZee Hydrogen Project**	Netherlands	2030	• **Neptune Energy** and **RWE** are collaborating to develop H2opZee offshore green hydrogen project which aims to build **300-500 MW** of electrolyzer capacity in the North Sea	500 (71* ktpa)	Neptune Energy, RWE
Supply-led cluster	**Enterprize Energy Thang Long Hydrogen Project**	Vietnam	2030	• **Enterprize Energy** and the Vietnamese Institute of Energy are collaborating to develop the **3.4GW** Thang Long offshore wind farm to produce more than **330,000 tonnes** of green hydrogen in Vietnam	2318* (330)	Enterprize Energy
Integrated hub	**Hydrogen city, Texas Hub**	US	2026 (Phase 1)	• **Green Hydrogen International** (GHI) plans to develop an integrated green hydrogen production, storage, and transport hub growing to **60GW** renewable capacity (solar & wind power) in Texas	2000 (*285 ktpa)	GHI
Integrated hub	**HyDeal Espana**	Spain	2030	• HyDeal Espana is the first industrial implementation of the HyDeal ambition platform that aims to achieve electrolyzer capacity of **67GW** and **3.6M tonnes** of green hydrogen production by 2030	7400 (330 ktpa)	DH2 energy, Fertiberia, enagas, ArcelorMittal

*Calculated using a fixed conversion factor; Source: GlobalData, Lit. search

Strong early traction on development of industrial clusters

NOT EXHAUSTIVE

Industrial clusters: co-location of H2 supply & demand



Significant investments for industrial clusters

€30B+

Invested to develop **35 H2 valleys** across 20 EU countries

$8B+

Invested to develop **4 H2 hubs**, amounting to **84%** of total infra budget for low-carbon H2

£1B+

Invested to develop **4 'SuperPlaces'** (low-carbon industrial zones)

C$2B+

Invested to develop low-carbon infrastructure in Alberta for blue H2 acceleration

To unlock attractive H2 and derivative projects in the near term, multiple supply-side and demand-side drivers need to come into place

GREEN AMMONIA EXAMPLE

Low attractiveness ⟷ ***High attractiveness***

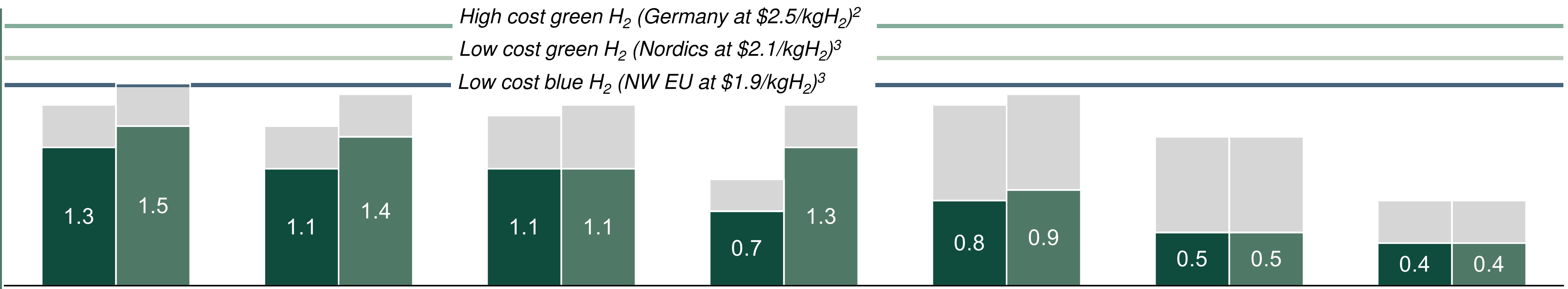
<table>
<tr><td rowspan="4">Supply-side</td><td>Access to cheap RE electricity</td><td colspan="6">Regions with largely uncompetitive RE costs (>$30/MWh)</td><td colspan="6">Regions with access to competitive RE costs (<$30/MWh)</td><td rowspan="4">Largely localized trade-offs</td></tr>
<tr><td>Maturity of relevant infrastructure</td><td colspan="3">Limited infrastructure</td><td colspan="3">Some infrastructure for relevant industries*</td><td colspan="3">Significant infrastructure for relevant industries*</td><td colspan="3">Significant existing H2 infrastructure</td></tr>
<tr><td>Scale capacity enabled by infra</td><td colspan="4">Significant infrastructure required (e.g., H2 dedicated pipeline)</td><td colspan="4">Significant infrastructure required, generation on site (e.g., large feedstock sites)</td><td colspan="4">Low to moderate infrastructure required, generation on site (e.g., grid connected electrolyzer)</td></tr>
<tr><td>Government support (e.g., subsidies)</td><td colspan="4">No green subsidies</td><td colspan="4">Limited/lagging green subsidies</td><td colspan="4">Significant/leading green subsidies</td></tr>
<tr><td rowspan="4">Demand-side</td><td>Cost of best alternate (e.g., coal, oil, gas)</td><td colspan="3">Low NH3 efficiency and alternative costs</td><td colspan="3">Medium NH3 efficiency and alternative costs</td><td colspan="3">High NH3 efficiency, but competitive alternatives</td><td colspan="3">Drop-in and best decarbonization option</td><td rowspan="4">Largely driven by the specific use-case</td></tr>
<tr><td>Regulation impact (Carbon costs and)</td><td colspan="3">No carbon tax or incentive</td><td colspan="3">Limited carbon tax impact and incentives</td><td colspan="3">Medium carbon tax impact and incentives</td><td colspan="3">High carbon tax impact and blend in or other incentive</td></tr>
<tr><td>Willingness to pay for green (CO2 value)</td><td colspan="6">Limited premium on green solutions (<20% green premium)</td><td colspan="6">Significant premium on green solutions (>20% green premium)</td></tr>
<tr><td>Use case maturity</td><td colspan="3">Technology and infra. barriers remaining (e.g., H2 carrier, direct power gen)</td><td colspan="3">Immature, but existing tech and infrastructure (Ammonia for shipping)</td><td colspan="3">Mature tech, may need infra to be scaled (e.g., co-firing)</td><td colspan="3">NH3 drop-in opportunity (e.g., fertilizer, industrials/chemicals)</td></tr>
</table>

Demand-side attractiveness varies across use cases, and individual customers, but on average for the next 5 years will require project CAPEX/OPEX support

/ILLUSTRATIVE /GREEN AMMONIA EXAMPLE

- Significant H_2 support
- Limited H_2 support
- H_2 neutral/disadvantage

Demand-side

	Ammonia (current uses)	Refining	Transport (HDV)	Industrial heat	Steel	Shipping/ Aviation	Chemicals
Breakeven cost of H_2 vs. best alternative (e.g. coal, oil, gas) *USD/kg H_2*							
Regulation impact (e.g. Carbon costs)	Emerging incentives	Emerging incentives	Taxes and incentives	Tightening carbon tax	Carbon tax and border mechanism	Tightening regulation and blending targets	Scope 1 so far
Willingness to pay for green (CO_2 value)	Only very select use cases	Only select use case	Select B2B niches	Initial use cases	Initial use cases	Emerging WTP for scope 3	Select niches
Use case maturity	Drop in	Drop in	Infrastructure and FC maturity barrier	Some conversion costs	Pilot stage, but proven	Drop-in (except for Ammonia)	Drop-in

- Alternative cost EU low
- Alternative cost EU high
- 50\$/TCO_2 carbon tax

Source: IEA, Hydrogen Council, BNEF, IRENA, Bain project experience

Indicators are that green H2 is tipping to meet customers' zero carbon energy needs

'Tipping point' indicators (Bain methodology)

Experience curve
Unit cost

- Multiple pilot plant developments in last 12 months
- Line of sight to $3-4kg by 2025 with modest declines in capex / electrolyser efficiency and renewables

Elements of Value®
Customer lens

- Higher order customer needs (sustainability, flexibility) coming to the fore
- Select customers demonstrating willingness to jump to green H2 and pay

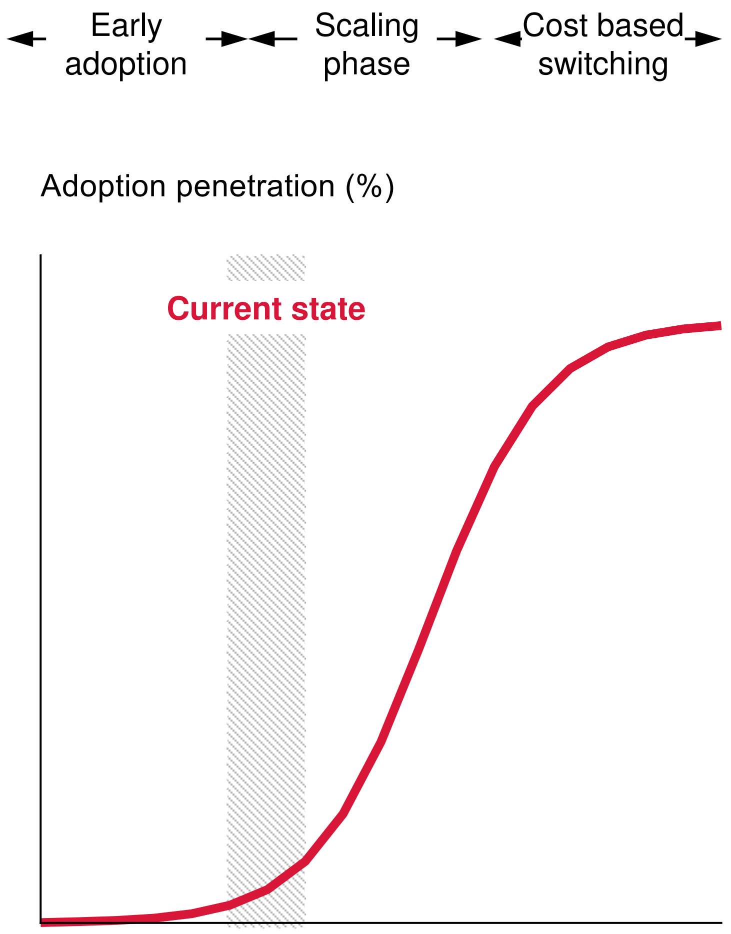
Adoption triggers and alternatives

- Fuel: Attractive case for scale H2 adoption in trucking with expected fuel price parity and niche H2 application in long range vs EVs
- Storage: Battery a substitute in some cases (e.g., passenger vehicles) but H2 likely to be competitive for other (e.g., heavy vehicles). Physical constraints at scale.

Barriers and accelerators

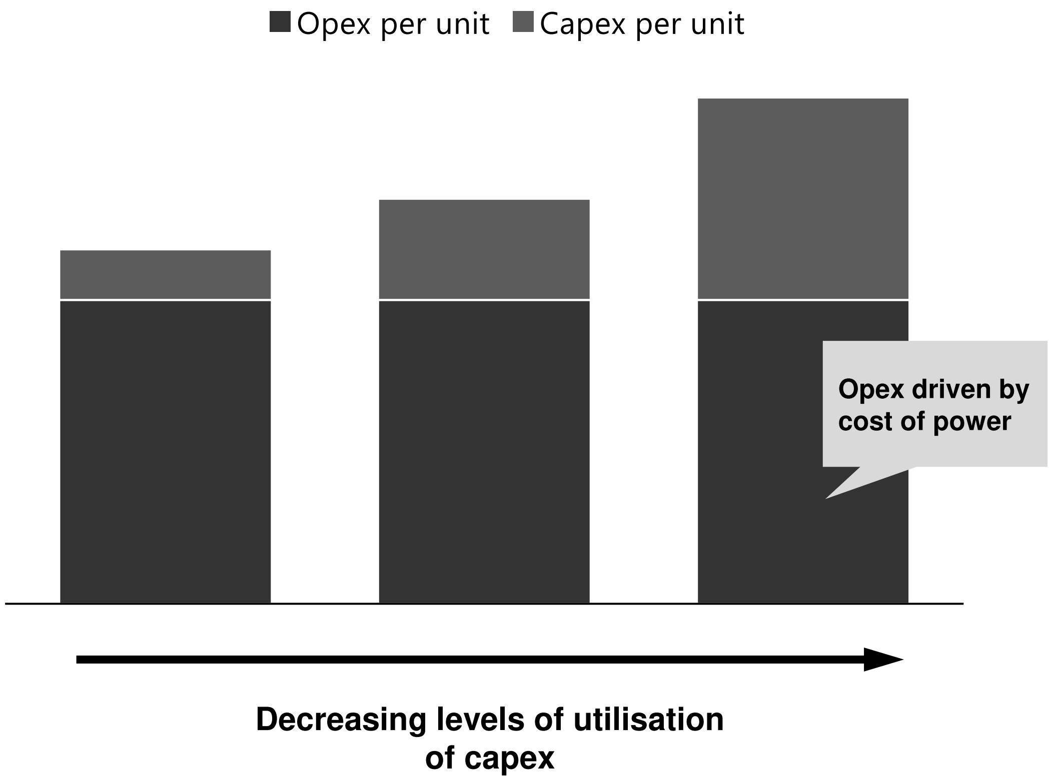
- Current public settings (e.g. green regulation, policy support and subsidies) favour steeper adoption. Cannot be assumed in long term.
- Early leap-frogs to green by institutional customers an important trigger

Growth phases



Current hydrogen economics dependent on specific customer characteristics

Unit costs dependent on customer



Attractive initial customers have distinct characteristics

Level of importance

- **Have a need for zero carbon energy** at high availability (e.g. a 'green lean') and therefore willing to pay X/kg today
- Are in locations that give access to **attractive government incentives**
- Have access / are in close proximity to sources of **cheap green electrons**
- **Lack of access** to renewable resources that would **meet energy requirements** (e.g. need 24/7 power but only have access to wind / solar renewable resources)
- Energy is not a **primary component of customer cost stack** and therefore likely less price sensitive

A wide range of potential hydrogen participation choices exist across the value chain, also implying coordination across multiple stakeholders is required

	Production: H_2 Inputs	**Production:** Generation	**Distribution & Transport:** Transport	**Distribution & Transport:** Storage	**Distribution & Transport:** Distribution	**Distribution & Transport:** Trading	**Application:** Usage	**Application:** End of life / recycling
Direct: Produce, distribute, consume hydrogen	Renewable power producer	'Gray' H_2 generator (producer, by-product)	Compressed gas transporter	Storage provider	Pipeline distributor	H_2 trader	Pure H_2 consumer (refining, chemicals, industrial)	
	Other inputs producer (natural gas, oil)	'Blue' H_2 generator	Liquefied transporter		Ground distributor (rail, trucks)		H_2 derivative producer (ammonia, SNG/synfuel)	
		'Green' H_2 generator	Materials-based transporter		Shipping distributor		H_2 fuel station operator	
Indirect: Provide inputs to producers, distributors, consumers	Commodity supplier							Recycler
	Renewables technology developer	'Green' H_2 technology developer (electrolysers)	Compression and liquefaction tech developer	Storage technology developer	New infrastructure developer		H_2 integrator (Feedstock & Industrials)	
		CCUS technology developer	Transport technology developer		Existing infrastructure retrofitter		Fuel cell developer	
	Capital projects manager						Fuel cell integrator (Power & Transport)	
	Hydrogen / Decarbonisation advisor							

For each value chain step a range of potential participation model options exist

BUY

PARTNER

BUILD

Traditional M&A

Acquire growing companies with strategic importance to the firm

CVC – Corporate Venture Capital

Invest in growing companies with strategic importance to the firm

Partnership / Joint Venture

Shared deployment of capital with other companies to co-develop / co-market technology or to stand up a joint venture

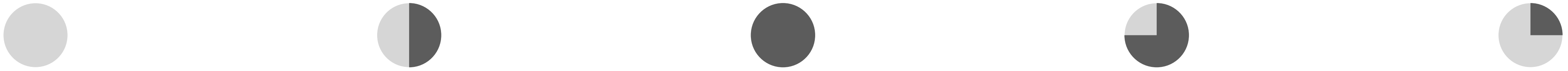
Purchase Agreement/ Outsourcing

Agreements (sometimes exclusive) to **purchase specific goods and services** to support new technology development / delivery

In-house Development

Investment in **capabilities or assets in-house** to support new technology development / delivery

Current hydrogen market activity level:



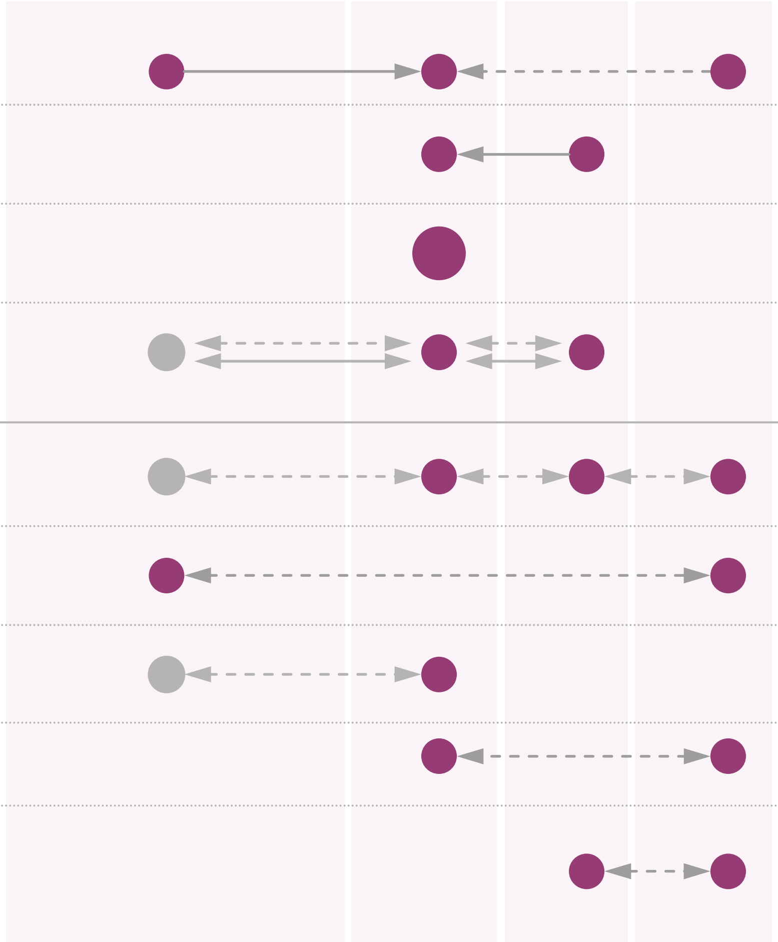
Low activity High activity

Most participants in the H2 market have formed partnerships to de-risk entry

/ NOT EXHAUSTIVE / PRELIMINARY

Potential business models

Inputs e.g.: RES, components & CCM → OEMs → T&D → End usage



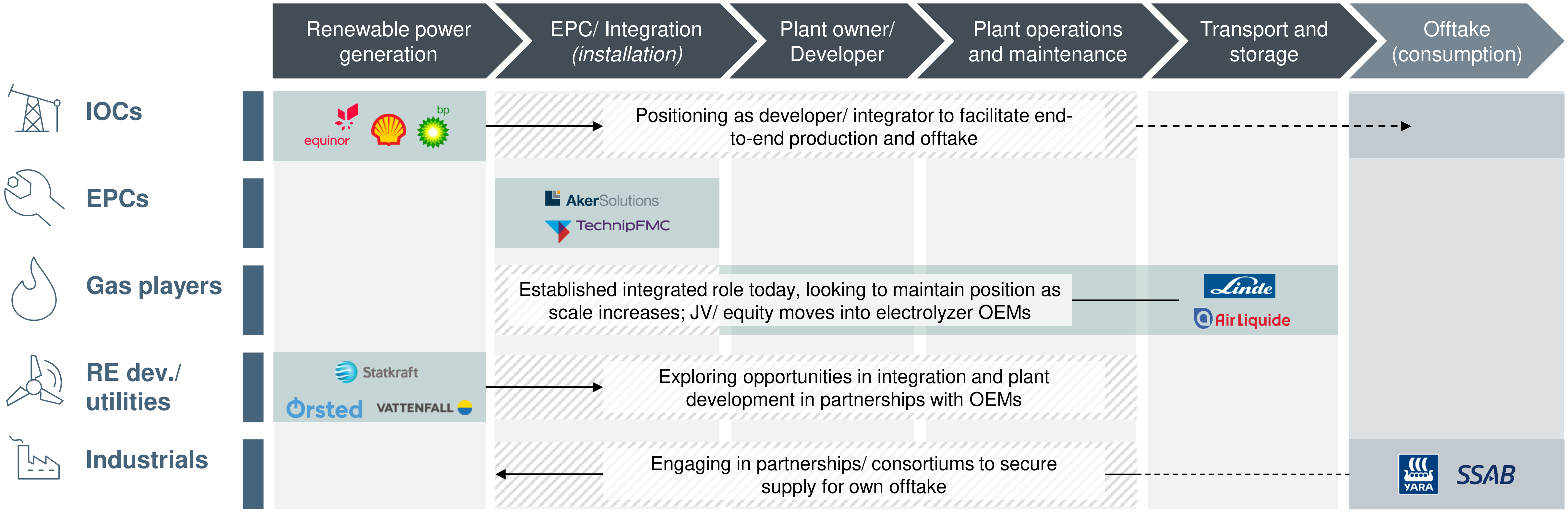
Examples

	Potential business models	Examples
Equity investment / M&A	Utility participates in OEM	EDF + McPhy | ENGIE + H2 SITE | ENGIE + H2 + MICHELIN
	Midstream operator participates in OEM	THE LINDE GROUP + ITM POWER | Air Liquide + HYDROGENICS | snam + ITM POWER, DE NORA
	Industrial solution supplier expands in H_2 sector	MAN Energy Solutions + H-TEC SYSTEMS
	"One-stop-shop" creation with dedicated brand	HYON (HEXAGON + POWERCELL + nel)
Strategic partnership / cooperation agreement	Consortium along the entire value chain	RAFFINERIE HEIDE + Ørsted + EDF | Ørsted + nel + Everfuel + DSV + ENERGINET/DK + GREENHYDROGEN
	Partnership between utility and user	HYBRIT (VATTENFALL + SSAB + LKAB) | ENGIE + YARA, ANGLO AMERICAN
	Partnership between input and OEM	Ørsted + ITM POWER | e.on + HYDROGENICS | hystar + JM
	Partnership between OEM and user	ITM POWER + Shell + REFHYNE
	Partnership between midstream operator and user	Nouryon + bp + Port of Rotterdam | Shell + Everfuel

Source: Market participant interviews, Lit. search

Most renewable energy players are expected to enter market as owner & operators, and are partnering with OEMs and Offtakers

PRELIMINARY



Legend

Observed moves | Main business focus | Business presence

Source: Market participant interviews, Lit. search

For hydrogen, owner & operators and integrator roles likely to stay attractive; Pure transportation role will be less important during the early phases

Legend
Low / Medium / High indicate level of attractiveness

Green H2 value chain

	Renewable power generation	EPC/ Integration *(installation)*	Plant owner/ Developer	Plant operations and maintenance	Transport and storage	Offtake (consumption)
PRE-2030: Subsidized, nascent market driving profitability across value chain		**High** • Driving **reduction in capex from superior project execution** and sourcing	**High** • **Strong market power** controlling offtake, and **can take large profit shares** given higher risks/ investments	**High** • Likely to obtain a premium driven by **high complexity of H2 production**	**Low** • **Limited need for transportation** initially as projects are captive/ local hubs	
POST-2030: As the industry matures, market-based pricing driving down overall value		**Medium** • **O&G EPC competition expected**, but significant barriers to entry due to complex combination of power and gas	**High** • **Scale and risk are barriers to entry**, however, profits slightly lower due to decrease in subsidies	**Medium** • Opportunity for **fair profit shares** given system complexity and ability to optimize demand and supply	**Medium** • Tech development and build-out of infrastructure **will drive growth,** but high competition and low returns given lower risk	

Combined integrator, owner and operator likely most attractive part of the value chain

Source: Market participant interviews

Offtakers (IOCs, Industrials) have an early advantage in being able to pilot hydrogen asset development with captive demand

PRELIMINARY

	IOCs	EPCs	Gas players	RE dev./ utilities	Industrials
	equinor, bp	AkerSolutions, TechnipFMC	Linde, Air Liquide	Statkraft, IBERDROLA, Ørsted, VATTENFALL	YARA, SSAB
Entry point into H2 value chain	• Renewable power generation • Offtake	• EPC/ Integration	• Owner/ operator • Plant O&M • Transport & storage	• Renewable power generation	• Offtake
Why they could win in H2	• Large potential **captive demand** and **willingness/ need to invest** to drive scaling	• **Engineering capabilities** and **experience** from large and complex industrial processes	• Early advantage as **integrated H2 players** with ownership of infrastructure today	• **Control over renewable energy production** and/ or distribution infrastructure provides unparalleled access to key input factor	• Large potential captive demand **enables early phase piloting**

Source: Market participant interviews

There are a wide range of capabilities that are beneficial to enter the hydrogen value chain; plant O&M likely to be the most important

PRELIMINARY

	Renewable power generation	EPC / Integration *(installation)*	Plant owner / developer	Plant operations & maintenance	Transport & storage	Offtake *(consumption)*
Potential capabilities needed	• Access to renewable power sources	• Selecting, negotiating with, and managing EPCs • Sourcing raw materials and equipment	• End-to-end development of a project	• Management and maintenance of complex plants • Expertise in optimizing high-complexity processes	• H2 conversion and storage expertise • Transport expertise (e.g., pipeline, shipping or truck capabilities)	• Footprint located in attractive H2 regions • Access to offtakers with high willingness to pay for Green H2 (e.g., cosmetics industry)
Importance						
Rationale	• **Limited sources of renewable energy makes this a scarce resource** • **Particularly challenging to secure renewable sources close to pipelines or offtakers**	• Many aspects of EPC management are similar to EPC management in adjacent spaces – although the complexity level and the **potential for cost overruns/delays is significantly higher**	• Plant development is a **complex and multi-faceted process** • The complexity is **amplified given the nascent stage** of the technology	• H2 plants are extremely **complex chemical facilities**, with significant potential for safety issues • Given the nascency of the technology, there is significant potential for **constant optimization of operations**	• Limited need for transportation **initially as projects are captive/ local hubs**	• Viable offtake agreements are necessary to **secure project financing** • Given the **relatively small scale** of many H2 projects, finding sufficient offtakers is not expected to be a key hurdle

Key
Low Medium High

Source: Market participant interviews

Entrants need to assess their capabilities against other players in each step of the value chain to determine where to play, and how to enter

		Renewable power generation	EPC/ Integration *(installation)*	Plant owner/ developer	Plant operations and maintenance	Transport and storage	Offtake (consumption)
IOCs	[redacted]	Clear capabilities	Some capabilities	Clear capabilities	Clear capabilities	Some capabilities	Clear capabilities
OEMs	[redacted]	No/ limited capabilities	Clear capabilities	No/ limited capabilities	No/ limited capabilities	No/ limited capabilities	No/ limited capabilities
EPC	[redacted]	No/ limited capabilities	Clear capabilities	No/ limited capabilities	Clear capabilities	No/ limited capabilities	No/ limited capabilities
Gas (inc. IGCs)	[redacted]	No/ limited capabilities	Some capabilities	Clear capabilities	Clear capabilities	Clear capabilities	No/ limited capabilities
RE dev./ utilities	[redacted]	Clear capabilities	Some capabilities	Clear capabilities	Some capabilities	No/ limited capabilities	No/ limited capabilities
Industrials	[redacted]	No/ limited capabilities	Some capabilities	Clear capabilities	Clear capabilities	No/ limited capabilities	Clear capabilities

Legend
Clear capabilities | Some capabilities | No/ limited capabilities

Source: Market participant interviews

Key questions to address for companies considering participation in hydrogen

- How does our current **strategy** clarify our level of leadership in the future Hydrogen market? What is the relevance of Hydrogen for our **operations**?

- What are the **critical signposts** we must watch to guide our strategy and what decisions would we make differently when said signposts are triggered?

- What are the **participation models** (e.g. direct ownership, joint ventures and partnerships) we are comfortable pursuing in the context of our strategy?

- How aggressively should we move to **proactively shape policy** to support the acceleration of the Hydrogen market and infrastructure?

- Given the above, how do we **get started** and mobilize the organization around the potential Hydrogen will bring?