WE MEAN BUSINESS COALITION

CORPORATE CLIMATE STOCKTAKE: HYDROGEN SECTOR

October 2023

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The cost to produce low-carbon alternatives like “blue” and “green” hydrogen remain higher than conventional “grey” production methods

	Grey Hydrogen (Fossil-dependent)	Blue Hydrogen (Climate neutral)	Green Hydrogen (Sustainable)
Emissions intensity	~1 (t CO_2/t H_2)	~0.2 (t CO_2/t H_2)	~0 (t CO_2/t H_2)
Share of global supply	~99%	<1%	<1%
Fuel sources	• Coal, oil, or natural gas	• Natural gas	• Renewable electricity
Notes	• Industrial processes like fracking can create small amounts of “white” hydrogen as a byproduct	• “Turquoise” hydrogen is produced using methane pyrolysis, but has yet to be proven at scale	• Using nuclear energy in place of renewable electricity creates “Pink” hydrogen
Methods of production	• **Coal gasification:** Coal gasification involves heating coal with steam and oxygen, producing syngas, a mixture of carbon monoxide and hydrogen - the hydrogen is then separated from syngas using purification methods • **Oil reforming:** During oil reforming, hydrocarbons in oil interact with steam at elevated temperatures, generating a syngas made of hydrogen and carbon monoxide - hydrogen is then isolated and separated • **SMR/ATR*:** Methane is reacted with steam at high temperatures, producing syngas where hydrogen can then be extracted	• **CCUS applied to SMR/ATR*:** Carbon capture systems are integrated with conventional SMR-based production to minimize emissions, but further development is required to maximize capture rates • **Methane pyrolysis:** Hydrogen is produced by thermally decomposing methane at high temperatures (1,000-1,500°C) yielding hydrogen and solid carbon and avoiding CO_2 emissions - treatment, heating, decomposition, separation, and cooling steps are involved, with further development needed for commercial viability	• **Electrolysis:** Green hydrogen production via electrolysis involves splitting water into hydrogen and oxygen using an electrolyzer powered by renewable energy • The process requires water purification, an electric current created with an anode and cathode, gas collection equipment, and hydrogen purification resulting in zero carbon emissions • Further technology learnings and decreased renewable electricity costs are required before capacity can be commercially-scaled

Preparation & transport

- Hydrogen gas can be **compressed to extreme pressures** (up to 10,000 psi) so that it can be more efficiently stored in tanks or transported using existing pipelines
- Gas can also be **cooled to extremely low temperatures** (down to -423°F) to create liquid that can be stored in cryogenic tanks
- Liquid hydrogen can be then be **transported by ship, road, or rail** to end-customers to be reconverted and used across various industrial applications

* SMR = Steam Methane Reforming; ATR = Autothermal Reforming; CCUS = Carbon Capture, Utilization and Storage; Blue is considered climate neutral via CCUS; Green is considered sustainable via renewable energy
Source: IEA, IRENA, Bain & Company analysis

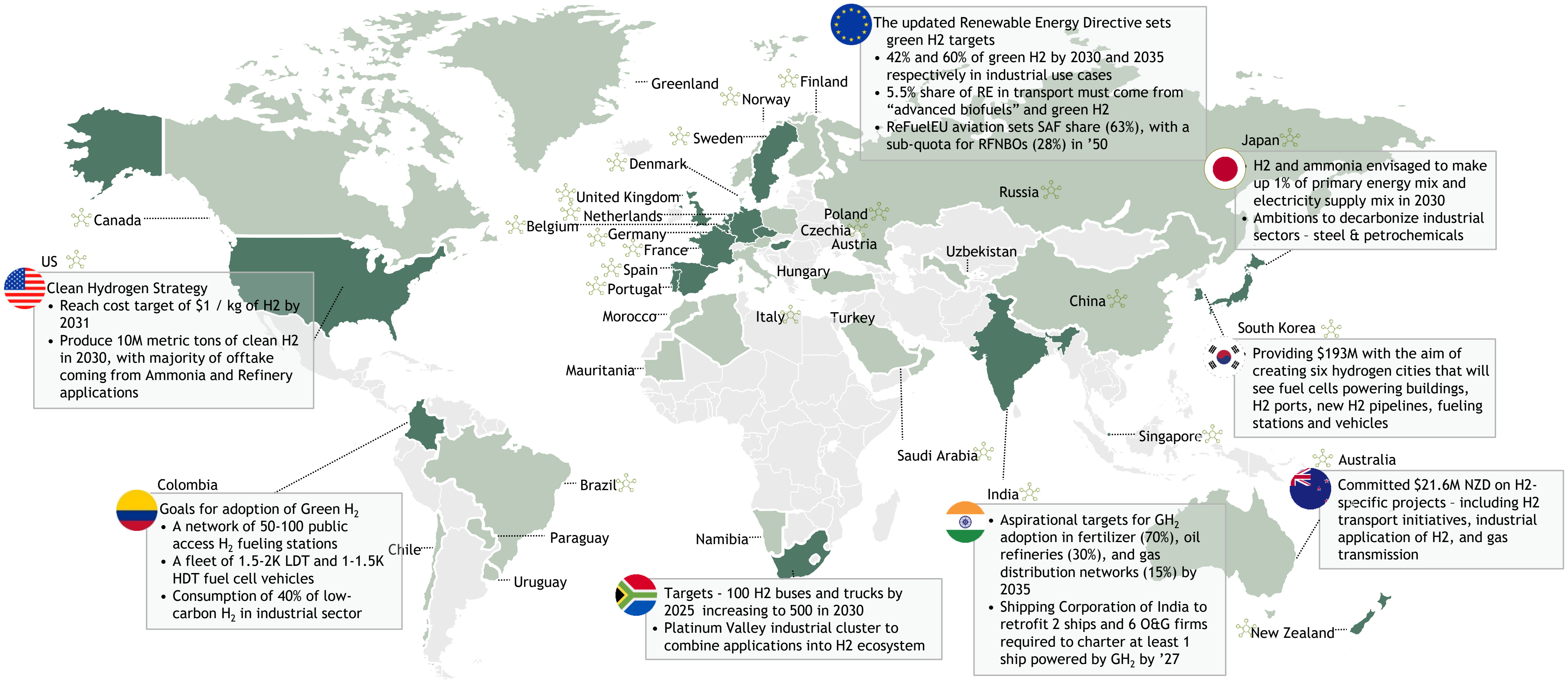
There are several potential uses for hydrogen, though novel use cases are at varying stages of tech readiness

End use	Details on pathway
Current H_2 uses Ammonia, methanol, refining	• Majority of H_2 today is produced in low-cost fossil / natural gas geographies (e.g., Middle East, US, Russia) • Existing plants can be retrofitted with CCUS to produce blue hydrogen that targets emissions reductions of ~90%, though best-in-class capture rates today are still sub-70% (~68% at Shell Quest facility in Canada), with high-cost demonstration projects (e.g., Tomokomai in Japan) exceeding targets • Conversion of facilities to electrolysis-produced hydrogen would materially disrupt production operations, requiring extended full plant shutdowns and reconfiguration
Shipping Hydrogen-based fuels and bunkering	• Hydrogen-based fuels (e.g., ammonia, methanol) are long-term alternatives to heavy fuel oil for ships with the highest potential for cost effectiveness and carbon-zero production • Hydrogen-based bunkering, for hydrogen and its derivatives (ammonia, methanol), will be critical to support shipping vessels' consumption of alternative fuels, especially along high-volume trade routes
Aviation Synthetic fuels	• Entirely new fleets will be required for hydrogen to be used in the low-turnover airline industry (~20-30 lifespans for aircraft) • Estimates suggest that the world's first airplane fueled by 100% green hydrogen will be ready for commercial flight in 2035
Steel H-DRI primary steel production	• Demonstration projects for hydrogen-based direct iron reduction exist in Sweden and China with potential to replace blast furnaces in primary steel production and reduce carbon emission intensity by up to 95% • Firms are making announcements and final investment decisions to expand deployment of H-DRI capacity, with pipeline of announcements targeting 83 Mt in 2030
Power Long duration grid balancing	• Hydrogen has the long-term potential to be used as an energy carrier for long-term storage and grid balancing, serve as a source of power when used in fuel cells, and be used as fuel for gas turbines for power generation
Road Long distance trucks	• Today, hydrogen fuel cell vehicles require double the power to achieve the same propulsion outcomes as battery electric vehicles, necessitating additional investment in order to become a viable alternative to BEVs • Limitations to the driving range of battery electric trucks lead business leaders to believe that some trucking applications (e.g., longer-haul) may require hydrogen fuel cells
Industrial heat	• Fossil fuels are the primary source of high-temperature heat (> 400°C) today, but demonstration projects are investigating the use of hydrogen in industrial heating applications for the cement, glass, aluminum, waste recycling, and paper sectors • While minor equipment modifications are needed to utilize hydrogen in heating, it remains significantly more expensive than fossil fuels

***"We see three main use cases for hydrogen: shipping, fertilizers, and steel. Global coordination is required to get hydrogen into these three sectors"* -** CEO Carbon Technologies, Utility Co #5

Source: Lit search,

40+ countries across the globe have released green hydrogen strategies



Sources: 1) Hydrogen Transition Outlook and Trends, Global Data, Q4 2022; 2) JP Morgan, Global Hydrogen, 2023

Legend: Supply-side strategies or targets; Supply and demand-side strategies or targets; Hub strategy

Executive Summary: The State of the Transition in Hydrogen

Dimension of sector	**Low-carbon hydrogen demand**	**Low-carbon hydrogen supply**	**Enabling infrastructure**
Future decarbonization scenario	Demand for low-carbon hydrogen products is created across end-uses	Production scales to meet demand for hydrogen in new sectors (e.g., fuels in shipping and aviation)	Physical infrastructure and regulation enable use of hydrogen across end markets at scale
Indicators of progress towards accelerating decarbonization	Hydrogen production could more **than double by 2050, with green hydrogen** the **primary source** of the potential growth **Global demand** for green hydrogen is being catalyzed through **policy -** including mandates, direct funding, and subsidies. **Offtake agreements** are also beginning to emerge, albeit it's early days for the market, with limited clarity on volumes or prices	There is no shortage of announced low-carbon hydrogen projects, with 1,000+ around the world creating **a project pipeline tracking to 160M+ tons by 2030** **Blue vs green hydrogen** mix depends on the **industry and application**, with blue hydrogen a potential bridge to decarbonization The development of **electrolyzer technologies** and **increasing scale of deployment projects** creates confidence in green h2 **costs falling** Green H2 production costs will be increasingly influenced by electricity costs, making **grid upgrades** and **new flexible production** incentives key	In the short term, **hydrogen hubs are enabling the co-location** of production, demand, and favorable market conditions **Limited existing infrastructure** constrains utilization beyond regional hubs In the longer-term, business leaders **require alignment on anticipated transportation methods** and **lower storage costs** for hydrogen **Regulatory clarity** with respect to interstate hydrogen infrastructure, including the retrofitting of natural gas will be important to **drive investment**

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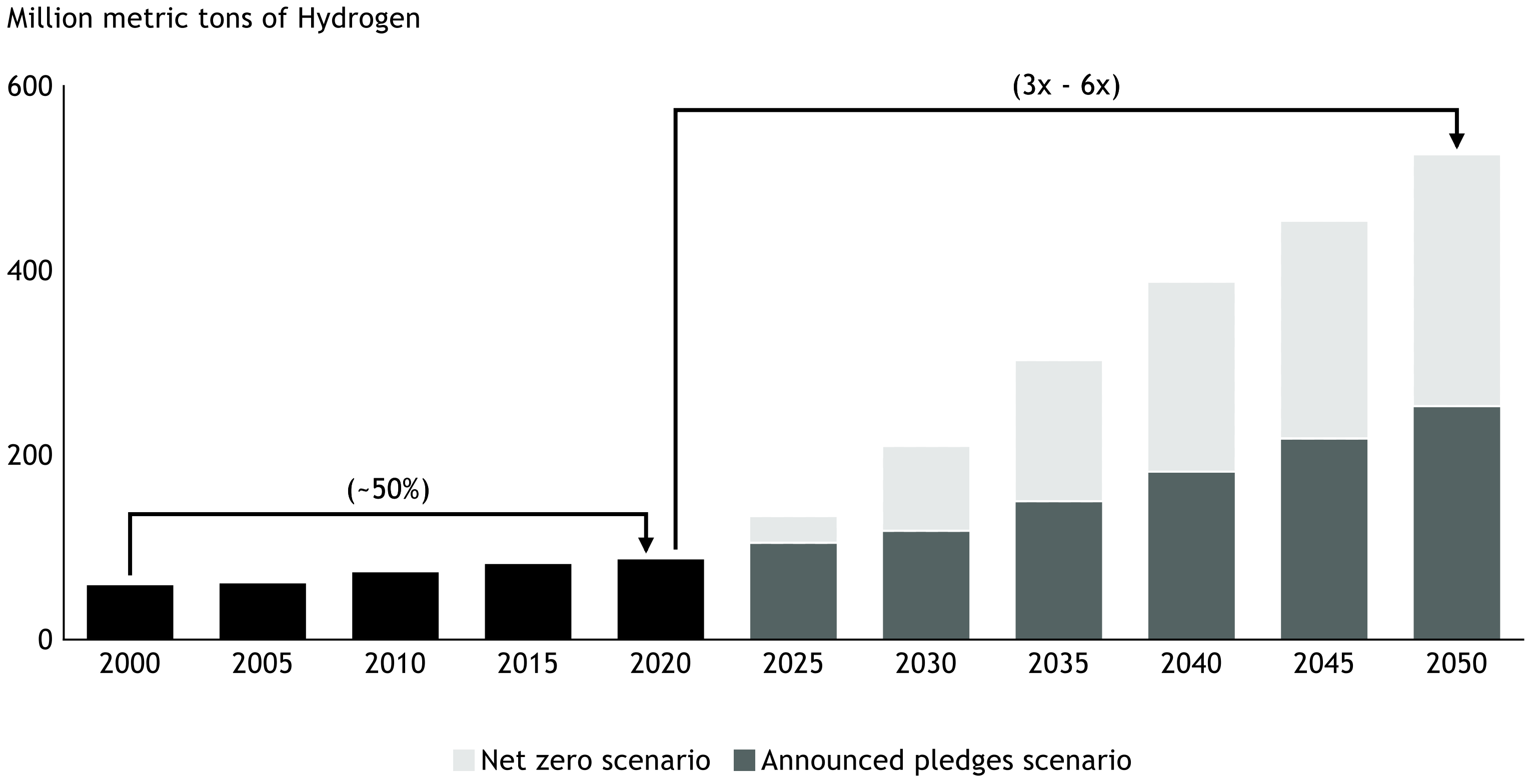
Hydrogen demand has grown significantly over the last 2 decades and could grow to more than double by 2050

Hydrogen demand grew 50% in 20 years with rapid expansion ahead



Commentary

- Global hydrogen demand in 2020 was around 90 Mt H2, a 50% increase since 2000, and is expected to grow 3x to 6x based on IEA scenarios
- Currently dominated by gray hydrogen, future growth will be led by
  - **Chemical industry**: shifting from fossil-based plants to produce ammonia and methanol for eco-friendly shipping and fertilizers
  - **Iron and steel industry**: using hydrogen over natural gas and phasing out coal-driven blast furnaces
  - **Power sector**: using hydrogen in gas-fired power plants and stationary fuel cells to balance grids
- Green hydrogen is poised to be the primary source to respond to this future demand

Notes: Announced pledges scenario accounts for climate commitments made by countries while the Net zero scenario is the pathway to achieve net-zero emissions by 2050
Source: IEA Global hydrogen review 2021, OECD Green hydrogen opportunities for emerging and developing economies

Offtake agreements for low carbon hydrogen are beginning to emerge, but it's early days, with limited clarity over volumes and prices

*"For us, **offtake agreements are driving our confidence** in hydrogen project investments. We decided to invest before any subsidies were in place"*

- CCO of PtX business, Technology provider #1

*"Clarity in what the offtake is willing to take on board in terms of actual volumes and price points **has not necessarily materialized** to the level expected"*

- Head of the Just Transition Office, Renewable power producer #4

*"We **love the CFD mechanism**. As a company, we get a **guaranteed price** - we can put that into our business case"*

- CCO of PtX business, Technology provider #1

*"On the off-take side, we've **signed quite a lot of agreements** with a number of key players. We're optimistic and we see great progress. There's a **demand pull** both on the green hydrogen side as well as its derivatives"*

- Head, CO2 reporting, Renewable power producer #5

Source: Corporate interviews

Voluntary demand won't be enough to get the market going – the most important driver is the policy governments put in place to meet targets

EU

- **42% of all H_2** used in industry-fertilizer, chemicals & oil refining to be **green by '30** (60% in '35)[1]
- **Renewable Energy Directive** sets green H_2 targets in transport
  - MS to choose either a **14.5% GHG reduction** in transport from RE or at least **29% RE in energy consumption** by '30
  - **5.5% share of RE** in transport must come from "advanced biofuels" and green H_2
  - **ReFuelEU aviation** sets sustainable fuels share (63%), with a sub-quota for RFNBOs (28%) in '50 (5 & 0.7% in '30)

US

- Does not have mandates, but have **set milestones** over the strategy period[2]

2022-23
- **1 MW scale electrolyzer** and fueling **marine applications**

2024-28
- 1 ton/week **iron reduction with H2**, road to 5K tons/day
- 4+ Regional Clean H_2 Hubs

2029-36
- Achieve **$80/kW HDT fuel cell** cost vs $200/kW baseline
- **40,000-hr durability** fuel-flexible stationary fuel cells
- **4+ end-use demos**(ammonia, steel, storage) at scale

China

- Have not issued mandates for industrial adoption, however, it is creating infrastructure to fuel demand[3]
  - Targets to bring **50K H_2 fuel-cell vehicles** on road by 2025 and to build a **network of H_2 refueling stations**
  - The plan envisages the use of clean hydrogen in other sectors: **energy storage, electricity generation and industry**
- **No specific targets** on electrolyzers, H_2 costs nor H_2 as % of energy consumption

India

- Aspirational targets for green H_2 adoption[5]
  - **Fertilizer** industry to run on **70% GH2 by '35** (15% in '25)
  - **Oil refineries** to replace **30% of grey H_2 by green H_2 by '35** (3% in '25)
  - **Urban gas distributors** to replace **15% of fuel volume with GH_2 by '35** (3% in '25)
- GoI **piloting** 1,000 trucks, 50 boats, and 10 aircrafts to enable these for running on GH_2 by '30
- Mandates for use of GH_2
  - **Shipping Corporation of India** to retrofit **at least 2 ships** and **6 O&G firms** required to charter **at least 1 ship** powered by GH_2 by '27[4]

Chile

- **Does not have specific mandates** for industrial adoption, however, have set overall milestones[6]
  - Supply **domestic demand in the short term** till '25
  - Accelerate deployment of green H_2 in **6 applications** to build local supply chains and acquire experience: Oil refineries, ammonia, mining haul trucks, HDT, long-range buses, and blending into gas grids (up to 20%)
  - After 2025 the country will seek to become a **major exporter** of green hydrogen and ammonia[9]

*"I'm **skeptical of voluntary demand driving market growth** [..] Both **EU and US approach to policies are important** depending on whether you're an asset owner or a technology provider"* – CCO of PtX business, Technology provider #1

*"**Mandates can be very powerful**. Look at what has happened in road after emissions targets were set – it really kicked off development [..] help ensure infrastructure is built quickly"* - Dr. Werner Ponikwar, CEO of thyssenkrupp nucera

Sources: 1) EU supporting clean H2; 2) U.S. National Clean Hydrogen Strategy and Roadmap; 3) JP Morgan, Global Hydrogen, 2023; 4) SCI to retrofit ships, Maritime Economy; 5) Harnessing Green H2, NITI Aayog; 6) National Green H2 Strategy, Chile

In the EU, a wide range of policies are enabling the development of the hydrogen economy

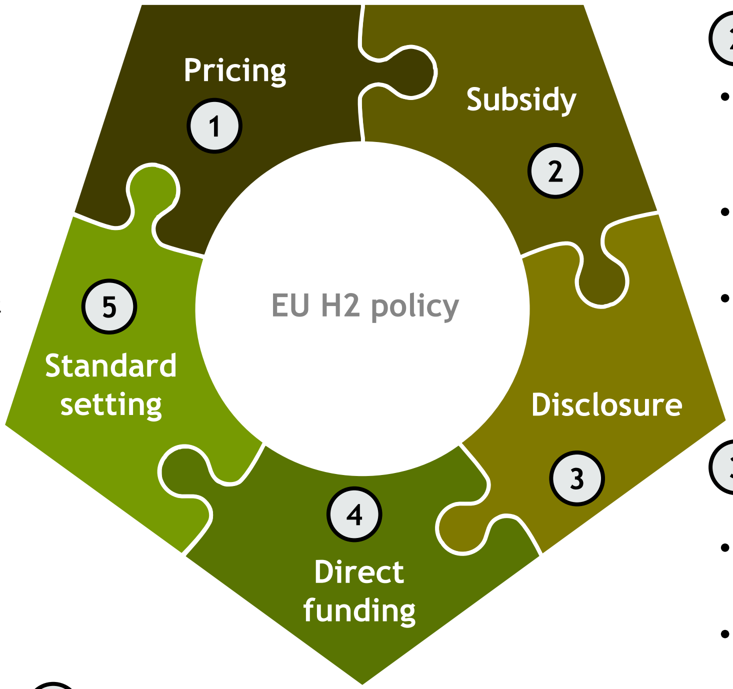
1 Carbon pricing to limit GHG emissions

- All H_2 **production will be included in ETS,** and installations can **benefit from free allocation of ETS allowances**
- **Phase out of free allowances** from sectors with risk of carbon leakage (e.g., cement, steel, etc.) will **begin from 2026** increasing Green H_2 adoption
- Free allowances under ETS to be **phased out using CBAM** (H_2 to be included from the start)

5 Setting standards for domestic production and boosting demand in end sectors

- **42%** of hydrogen used in industry to be **renewable by 2030** and increased to **60% in 2035**
- **Binding targets across multiple-sectors**
  - **5.5% of the share of RE in transport** must come from "advanced biofuels" and green H2
  - Mandatory minimum shares for **sustainable aviation fuels**, with a specific **sub-quota for RFNBOs** from 2030
  - Introduction of a **RFNBO target in maritime** from 2034 if the RFNBO share in 2030 is less than 1 %
- Support **deployment of refueling points for hydrogen** (refueling station at every 150 km)
- **Delegated Regulation** to define when H2, H2-based fuels or other energy carriers **can be considered as RFNBOs**

Source: Lit search



4 Funding support for hydrogen projects

- **~€10B funding support for IPCEI Projects**
  - **IPECIE €5.2 billion** for **35 projects** under IPCEI Hy2Use **for developing H_2 related infra across the value chain**
  - **€5.4 billion for 41 projects** under IPCEI Hy2Tech to support **research & innovation** and 1st **industrial deployment** in H2 tech
- EU granted **€3.6bn** from the **innovation fund** to **low-carbon tech projects**; >50% dedicated to green hydrogen

2 European Hydrogen Bank to subsidize H_2 production

- Commission announced creation of a **Hydrogen Bank**, to invest **€3 billion** to start the H_2 market
  - **Subsidy of up to €4/kg** for H_2 producers from **€800M**
- **€900 Mn scheme** to support **production and import** of from countries located outside EU
- **Loosened state-aid rules** allowing member states to support investments in H_2 production & transition

3 H_2 based fuels eligible under EU Taxonomy and dedicated acts for conditions & methodology

- **H_2-based fuels** eligible under **EU Taxonomy for sustainable activities**
- As per the Climate Delegated Act, GHG emissions threshold for H_2 production has been set at 73.4% **favoring green H_2**
- Dedicated act providing **methodology** for **calculating life-cycle GHG emissions for RFNBOs**

The EU's Renewable Energy Directive is driving a focus on green hydrogen

EU's Renewable Energy Directive sets a significant net zero ambition

Overall target
- **Minimum 42.5% renewables share** of energy consumption by 2030 *(with aim of 45%)* in line with EU's aim to become climate-neutral by 2050

Philosophy and ambition
- Increase share of renewable energy in EU to **reduce emissions**, increase energy security, and transition to a low-carbon economy while creating jobs and growth

Policy levers
- Providing a **stable and predictable policy framework** through a combination of mandatory national targets, common principles and rules for support schemes

Key technologies
- Covers a **wide range of renewable energy technologies**, including hydrogen *(mostly green)*, solar, wind, and bioenergy

Timeline of Renewable energy directive *(non-exhaustive)*:

2009
Introduction of RED
Target of 20% renewables by 2020

2018
Revised RED
Revised target of 32% renewables by 2030

2021
Proposal to revise RED
European Commission proposal to raise target to 40% by 2030

2022
Proposal to revise RED
European Commission proposal to raise target to 45% by 2030

Proposal based on EU's increased need to further step-up energy independence from fossil fuels following Russia-Ukraine war

2023
Revised RED
Provisional agreement to raise 2030 target to min. 42.5% (aiming for 45%)

Source: Lit search

Key implications for hydrogen

- **Accelerated transition towards green H_2** within existing use-cases of hydrogen
  - Industry specific targets of **42% and 60% green H_2 by 2030** and 2035 for use-cases such as fertilizers, chemicals and refining

  Provisionally agreed targets from March 30th, lower than initial proposal of 50% and 75% *(Sept. 2022)*
- **Still opportunity for blue H_2 in several new use-cases**, including e.g., power generation and industrial heat
  - Scaling green H_2 is challenging to achieve in these use-cases *(as of today)*
- **Potential local differences in adoption of blue and green hydrogen** across sectors
  - Caused by variations in national policies and subsidies implemented by individual governments to deliver on RED targets

The updated Renewable Energy Directive establishes clear demand signals – this is critical for providing fuel supplies with the confidence to take projects to FID

EU policies (e.g., European Green Deal, Renewable Energy Directive III, etc.) are using multiple levers to drive hydrogen demand

- **Mandates:** Specific demand targets across existing and novel use cases
- **Carbon pricing:** Companies exceeding specified emissions limits must buy carbon credits on the ETS market
- **Direct funding:** Support for R&D of hydrogen technologies across sectors
- **Subsidy:** Given to cover the cost premium associated with novel green hydrogen tech

*"It's very **difficult for projects to reach FID without regulatory certainty** [..] Red three has **bold ambitions** but it's important to **translate these in EUR in years** and pull forward those subsidies to the CapEx phase wherever possible. The local and national subsidies also depend a lot on basic government certainty"* - Head, CO2 reporting, Renewable power producer #5

*"RED 3 has **made things clearer**, but there are still some aspects that need to be thought through"* - Dr. Werner Ponikwar, CEO of thyssenkrupp nucera

Today → 2030 → 2035 → 2050 net-zero target

Sector	Existing policy	Policy defining 2030 targets	Implied demand (2030, million Mt)	Policy defining 2035 targets
Steel	ETS IV and CBAM come into force	30% of EU steel to be green	2.3	-
Maritime	ETS IV and CBAM come into force	2% of maritime fuel demand met with e-fuels	0.5	-
Aviation	ETS IV and CBAM come into force	1.2% e-fuel blend-in mandate	0.6	5% e-fuel blend-in mandate
Industry *(refineries, fertilizer, and chemicals)*	ETS IV and CBAM come into force	42% of H_2 to be green	4.1	60% of H_2 to be green

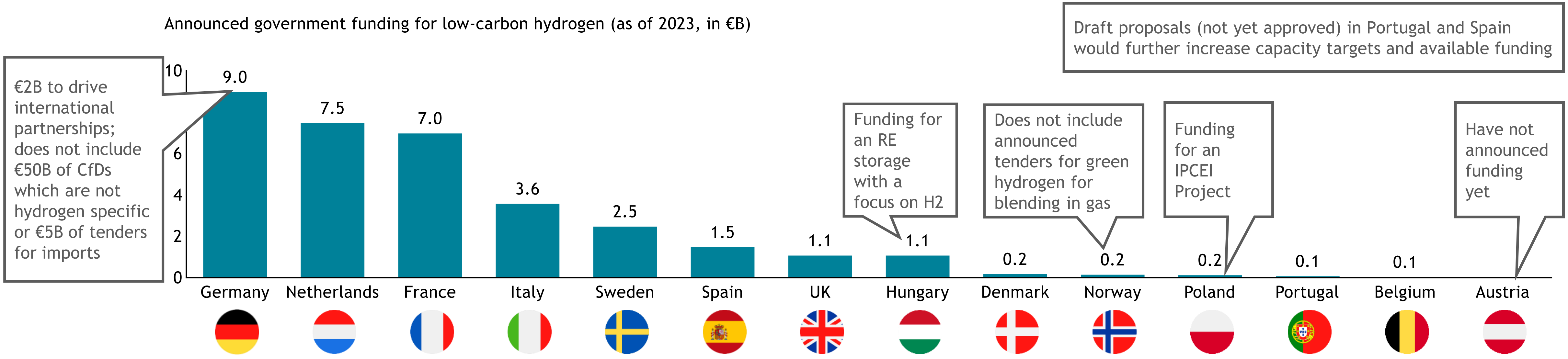
Note: EU steel demand assumed to be 150 million Mt in 2030 (World Steel Association), EU maritime fuel demand assumed to be 210 million Mt in 2030 (International Maritime Org.), EU aviation fuel demand assumed to be 53 million Mt in 2030 (Bain Aviation POV and Global Economy dataset), EU industry demand for hydrogen assumed to be 10 million Mt in 2030 assuming a 1.2% CAGR from 9 million Mt in 2023 (Reuters, S&P Global, DNV, Goldman Sachs)

Across the EU, countries are increasing government funding and implementing industry-specific targets to achieve EU goals

01 | **02 HYDROGEN DEMAND** | 03 | 04

NON-EXHAUSTIVE

Announced government funding for low-carbon hydrogen (as of 2023, in €B)



	Germany	Netherlands	France	Italy	Sweden	Spain	UK	Hungary	Denmark	Norway	Poland	Portugal	Belgium	Austria
Electrolysis capacity targets (in GW, by 2030)	10	4	6.5	5	5	4	10	0.25	6	2	2	2.5	0.15 *(2026)*	1
Application-specific targets	*No specific targets at present beyond broad EU targets*	*Gas grid obligations moving towards 10-20% H_2 injection*	*10% green H_2 used in industry by 2023 and 20-40% by 2028*	*No specific targets at present beyond broad EU targets*	*Produce 5Mt of H2 for steel prod. by 2030*	*25% of industrial H_2 to be green by 2030; H_2 blending up to 10% of H_2 in natural gas network*	*No specific targets, but ambition for H_2 blending in existing natural gas network*	*Min. 2% per year volume blending ratio in the natural gas system*	*No specific targets at present beyond broad EU targets*	*No specific targets at present beyond broad EU targets*	*No specific targets at present beyond broad EU targets*	*Targets 2-5% final energy consumption being H_2 by 2030; H_2 blending up to 1% of natural gas supply*	*Ambition to emerge as an import & transition hub for western EU*	*No specific targets at present beyond broad EU targets*

Total target of ~60GW in electrolyzer capacity by 2030

Source: S&P Global Platts; Country hydrogen announcements; IEA; Lit. search

“The IRA presents an opportunity for incentivizing green hydrogen production, but it’s still too early to tell what the long-term impact will be”

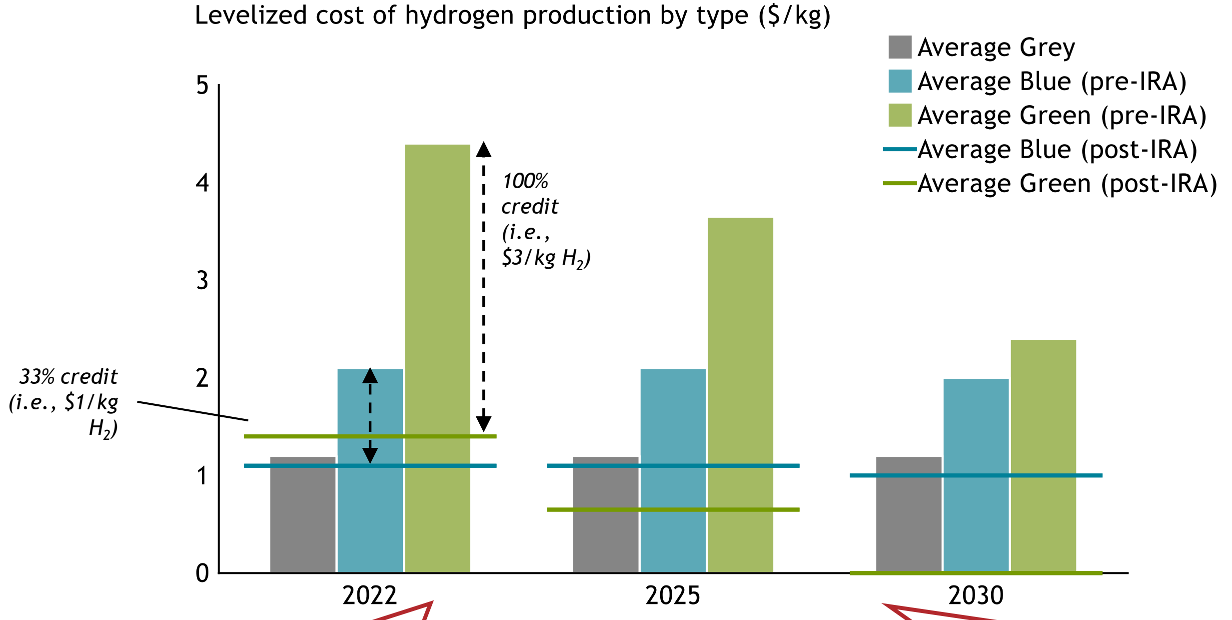
IRA introduced the 45V H_2 Production Tax Credit to support that decreases the levelized cost of clean H_2

- Greenfield or retrofit facilities **constructed before 2033** are eligible for the 45V Hydrogen Production Tax Credit for **10 years** from the start of producing clean H_2
  - Tax credits are a **dollar-for-dollar reduction** of tax that would have been normally owed
- Clean H_2 projects earn credit based on volume of H_2 produced and qualify for different tiers of credit based on the **emissions intensity of production**
  - **<0.45kg CO_2 emissions/kg H_2:** up to \$3/kg H_2
  - **0.45-1.5kg CO_2 emissions/kg H_2:** up to \$1/kg H_2
  - **1.5-2.5kg CO_2 emissions/kg H_2:** up to \$0.75/kg H_2
  - **2.5-4.0kg CO_2 emissions/kg H_2:** up to \$0.60/kg H_2
- The **tax credit 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)

*"The IRA has **put a lot of pressure on the EU** to try to compete with the incentives. The **regulatory environment is critical** to kick off these projects”* - Head, CO2 Reporting, Renewable power producer #5

*"We're all **excited about the IRA**, but we're still **waiting to see the full impact**”* - CCO of PtX business, Technology provider #1

IRA benefits have the potential to bring the reduction in cost of green H_2 production forward >10 years



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

Post 2025, cost of green H_2 production **forecast to be below maximum 45V credit** (i.e., below \$3/kg) **-** prior to IRA, green hydrogen only cost-competitive by 2030+

Note: Levelized cost of hydrogen production reflects the impact of the IRA and 45V tax credits on the cost of production for green and blue hydrogen (assuming its emissions intensity is between 0.45-1.5kg CO2 / kg H2); The cost of green hydrogen continues to decrease due to electrolyser technology learning cost reductions, Title quote from Head of the Just Transition Office, Renewable power producer #4
Source: IRA, RMI, DLA Piper; IRENA 2019, NREL, EIA, BNEF, Lazard

Business leaders call for demand-side policies to overcome structural challenge in the hydrogen market alongside supply side support

*"Industries like petrochemical refining and ammonia fertilizer production are **slow to transition**, with **existing contracts** for gray hydrogen supply. They've invested in existing infrastructure that may result in **stranded assets**. Just because 45V makes green hydrogen cost competitive doesn't mean they can switch overnight economically."*

- VP Policy, Electrolyzer materials provider #2

*"On the demand side, there should be **mandates**. E.g., 40% of your portfolio needs to be green"*

- CCO of PtX business, Technology provider #1

*"The **next big policy lever is demand side policies**. There's a lot more supply side policies through IRA incentives. If the **federal government would adopt buy clean policies**, it would create certainty and predictability for industries like steel production and drive investment"*

- VP Policy, Electrolyzer materials provider #2

*"The real **problem** is the **regulation for off-takers**. If you don't regulate, there won't be adoption"*

- CEO Carbon Technologies, Utility company #5

*"The focus should be on **subsidizing the asset owners**, i.e., the ones producing the molecule"*

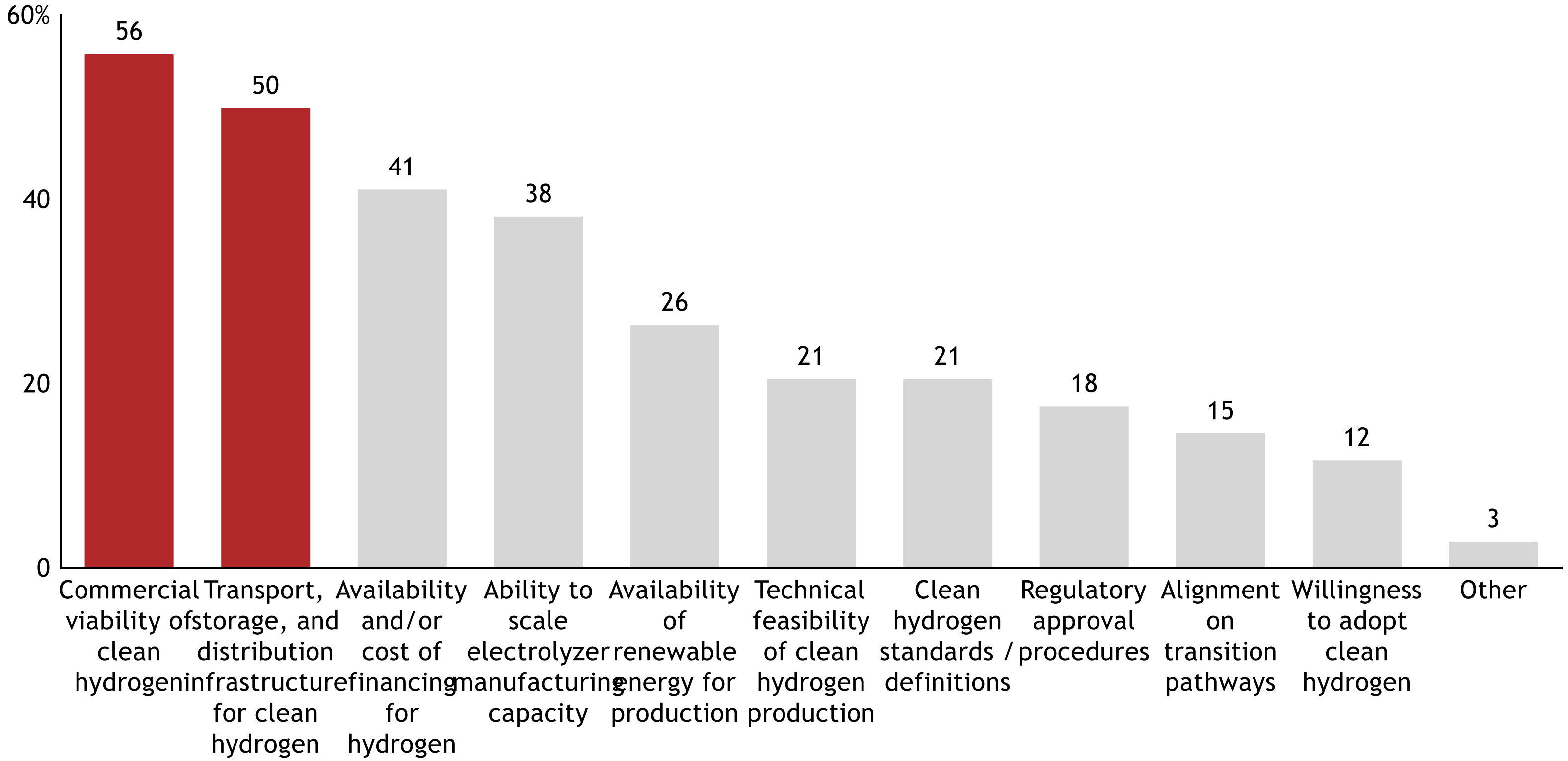
- CCO of PtX business, Technology provider #1

Source: Corporate interviews

Business leaders highlighted commercial viability and availability of infrastructure as barriers to developing a clean hydrogen economy

***Which of the following do you view as the Hydrogen sector's largest barriers towards accelerating its clean energy transition?** Please select the top 3 most impactful barriers.*

Share of survey respondents selecting barrier in the top 3 (%)



Note: Chart includes data from respondents with experience in the hydrogen sector (N = 34)
Source: Bain / WMBC Global Stocktake Survey (N = 215); Corporate interviews

Commentary

*"Our view is that **green hydrogen has a specific role** in the decarbonization of the hard to abate sectors. We started focusing on projects where there was already a real demand of grey hydrogen, and we are providing a solution to replace it with green hydrogen. **There are many challenges but, clearly, demand needs to be further incentivized**"*

-Gonzalo Sáenz de Miera, Global Director of Climate Change and Alliances, Iberdrola

*"The burden that we see at the moment is that these projects that would be the entrance to the hydrogen economy have **very long timespans** where we apply for funding as they're **still very expensive**."*

-Manager of Sustainability, Renewable power producer #3

*"It's **chicken and egg**. The demand will come also from the competitiveness perspective… the fast switch [to the United States] is not because we created the demand, but because the competitiveness is there. So, it's a **combination of competitiveness**, **demand pressure**, **and infrastructure** to supply the volumes."*

- Chief Sustainability Officer, Electrolyzer materials provider #1

Policy measures are propelling demand-side markets for low-carbon hydrogen, though end technologies need to further develop

Policy-driven markets

- Recent policy measures including **standards and targets** are creating demand signals for clean hydrogen
- **Preferential technology policies** particularly in the EU are shaping the development of **end-markets** (e.g., green hydrogen for 'industry' and sustainable aviation fuels)
- **Technology-agnostic policies** in other geographies (e.g., production tax credits for both carbon capture and green hydrogen in the US IRA) may result in the adoption of both hydrogen pathways across end-markets

"What Americans are doing is the most direct support that we see, whereas Europe is very normative and pushing for an obligation for industrial uses." - Chief Sustainability Officer, Electrolyzer materials provider #1

Commercial viability

- Although costs of green hydrogen are declining, existing hydrogen producers operate in relatively commoditized industries with **limited ability to pass incremental costs on** to customers
- **Offtake commitments** and consistent indications of **industry-wide preferences** for specific fuels are required to scale hydrogen in novel end markets (e.g., shipping, road freight)

"For the hardest-to-abate industry, we need to target between $1 and $2 per kilo of H2. Those are the most demanding customers from a pure competitiveness perspective." - Chief Sustainability Officer, Electrolyzer materials provider #1

End-market uncertainty

- **Absent policy intervention, CCUS retrofitting rather than electrolytic production would likely be the more economic pathway** to avoid disrupting operations
- The maturity of **demand-side technologies are highly variable** and will require time to advance beyond demonstration stages or through incremental R&D (e.g., H-DRI production processes in steel, methanol and ammonia-fueled ships, SAF-fueled planes)

"I don't have a definitive view on what would be most effective…We need rapid build out of renewables and green hydrogen for these projects to materialize." - Manager of Climate Action, Auto manufacturer #1

Long-term demand signals using policy will de-risk investments and enable development of the hydrogen market

Increase clarity and coordination

- **Greater coordination on demand-side policy** across regions, including **prioritizing different use cases and hydrogen derivatives**, would help ensure a more attractive investment environment for hydrogen producers, given the diversified nature of hydrogen use cases
- The revisions to the Renewable Energy Directive, and related EU sector-specific policies, are by far the most significant effort to signal future regulatory demand; however, most industry leaders will need more **clarity on how MS will support the achievement of EU policy before taking projects to FID**

Develop long-term demand signals

- **Uncertainty over long-term demand for green hydrogen can disincentivize capital flow,** which is particularly true when the expected decline in technology costs has the potential to further deter end-users from green hydrogen uptake in the short-term or when investors view the policy approach as politically or fiscally unsustainable (e.g., subsidizing energy for export)
- While the IRA has placed attractive supply-side policies, **demand-side policy, which covers the life of projects, is important for creating long term investment certainty** and enabling the rational development of the hydrogen economy
- **Governments can play an important role in making the market** - whether indirectly through establishing sectoral mandates for green hydrogen (in tandem to supply-side policy) or directly through instruments such as CFD, which are ideally suited for technologies that are expected to come down learning curves

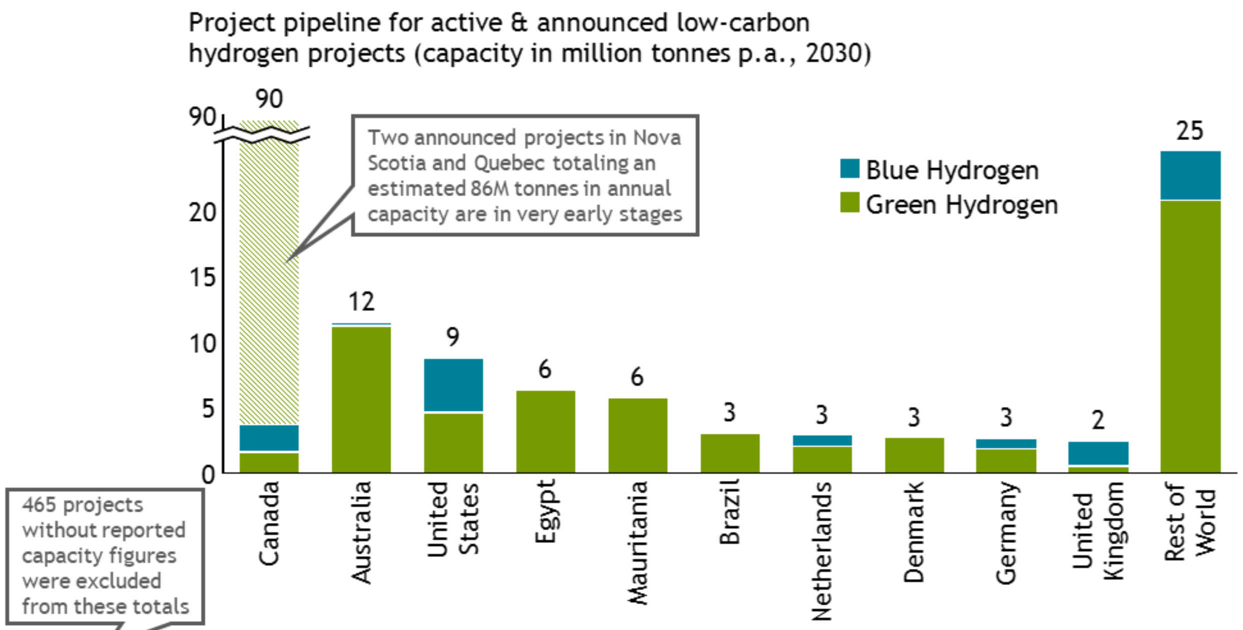
Supporting the frontier of innovation

- **Financiers of offtake agreements utilizing newer technologies** can also perceive **risks to be higher** with respect to timing, technology compatibility, etc.
- Successful demonstration of such novel technologies, as well as application in other regions, can address these concerns

Hydrogen: Table of Contents

"More and more people are interested in green hydrogen, but it will also depend on how fast we can scale production"

By 2030, business leaders believe that announced and existing clean H_2 projects could create ~160M tonnes of capacity



	Canada	Australia	United States	Egypt	Mauritania	Brazil	Netherlands	Denmark	Germany	United Kingdom	Rest of World
Project Count	34	137	96	20	5	16	64	37	125	73	598
Share of capacity in early-stage	98.5%	98.2%	93.8%	99.8%	100.0%	99.7%	99.9%	98.8%	99.2%	98.5%	91.3%

Commentary

- By 2030, Canada has plans to open **two green H_2 plants** that business leaders believe could produce of as much as **86M tonnes / yr**
  - These two plants have the largest capacity of any announced plant to date
  - Each plant will produce hydrogen equivalent to 450TWh of energy or enough to power 73% of Germany's electricity needs
- **Project volumes vary greatly** due to CapEx or regional demand differences
  - Mauritania's 5 new plants will have an average capacity 12x higher than the average US plant in 2030
- **Nearly 50% of U.S. announced clean hydrogen capacity is blue** due to the abundant supply and low cost of natural gas
  - Countries with an abundance of local natural gas and access to depleted oil wells used for CCUS processes could drive deployment of blue capacity

*"By next year (2024), North America will have **3 GW of production capacity** between US, Canada, Mexico – that's a **steep increase** from a few years ago where there was <1 GW of capacity"* - VP Policy, Electrolyzer materials provider #1

*"If you look at the pipeline, projects for **blue H2 are quite large** from a capacity POV. While there's a lot of investment in **green H2**, **91% project target seems a little high**"* - CCO of PtX business, Technology provider #1

Note: Capacity and project count figures assume any non-stalled project projected to start production by 2030 will be in production by 2030; Early-stage projects are those in the approval, feasibility, or FEED (front-end engineering and design) stage, late-stage projects are those in the approval, commissioning, or construction stage. Title quote from Head of Group Sustainability, Utility company #2
Source: GlobalData Low-Carbon Hydrogen Database, Lit. Search

"The mix of green and blue hydrogen production depends on the industry and application"

Local conditions may impact whether H_2 production is green or blue

Conditions favoring blue hydrogen uptake
(fossil-fuel based hydrogen production leveraging CCUS)

- **Technology neutral** regulation
- **Low-cost natural gas** availability
- **Established production facilities** (e.g., adding CCUS to existing SMR) for onsite consumption

Mix of green and blue production, based on local conditions

Because of specific location conditions, blue and green are not in direct competition and will both contribute to the evolution of an H2 economy

Conditions favoring green hydrogen uptake
(Electrolysis-based hydrogen production leveraging zero-emission electricity)

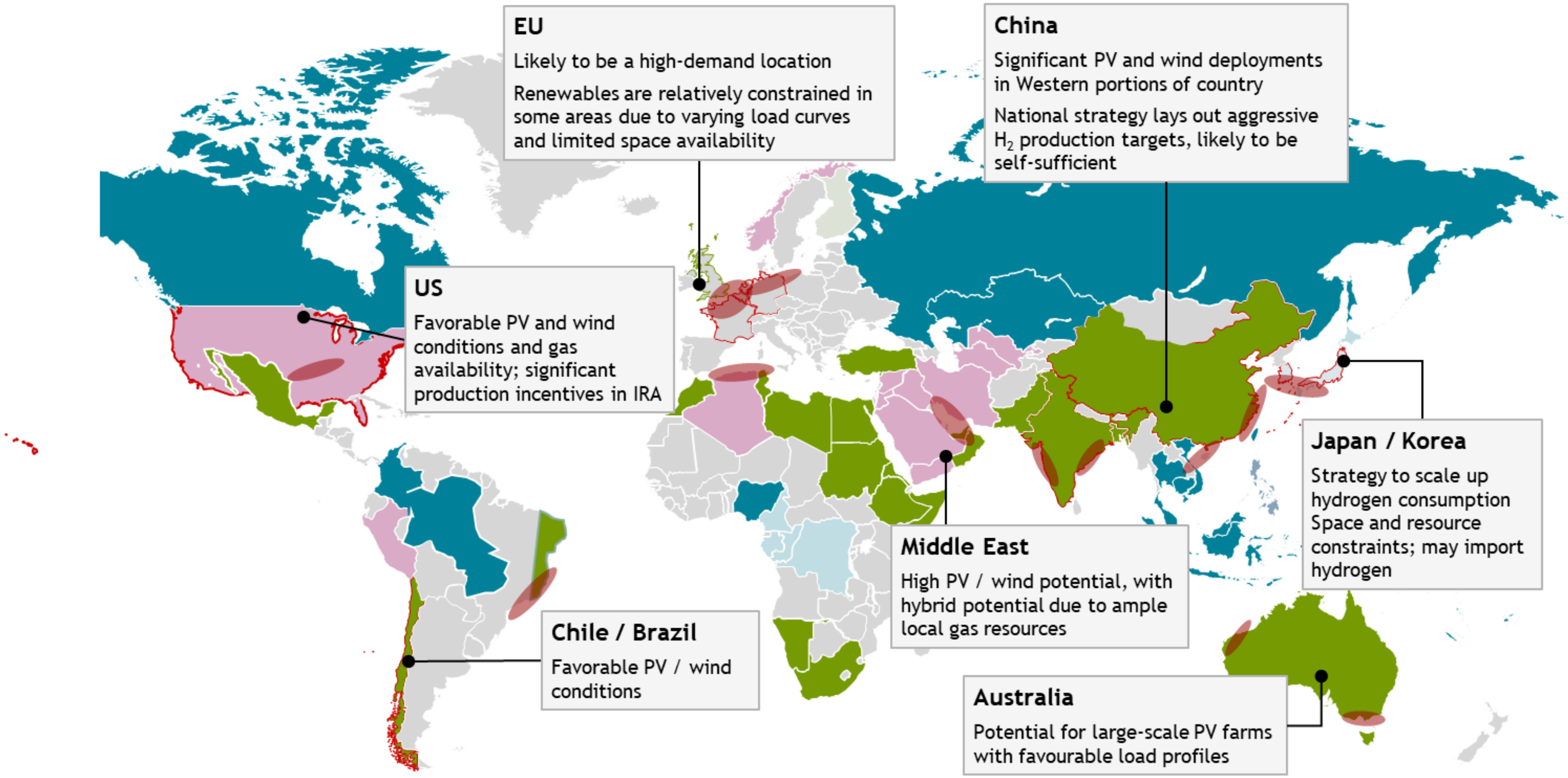
- **Increased demand for renewable fuels** (e.g., synthetic fuels relying on low-emission inputs)
- **Low-cost renewable electricity** availability
- **Government incentives** (e.g., subsidies, production tax credits)

Commentary

- Local **policies / mandates** and **input costs** will play a major role in shaping in hydrogen investment decisions
  - E.g., existing producers of hydrogen in **Europe are more likely to adopt green** than blue due to natural gas costs and policy strongly favoring green hydrogen
- **Additional factors** can steer producers towards specific technologies:
  - Stakeholders with clear **ESG commitments** or investment goals will likely favor green hydrogen production
  - Companies with **desire to "test and learn"** can favor lower initial profitability in exchange for long term competitive advantage

Note: Title quote from CCO of PtX business, Technology provider #1
Source: Lit. search

“Although currently hydrogen is mainly about agreements with local industries, global opportunities will arise once the infrastructure is developed, and the technology scales up”



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

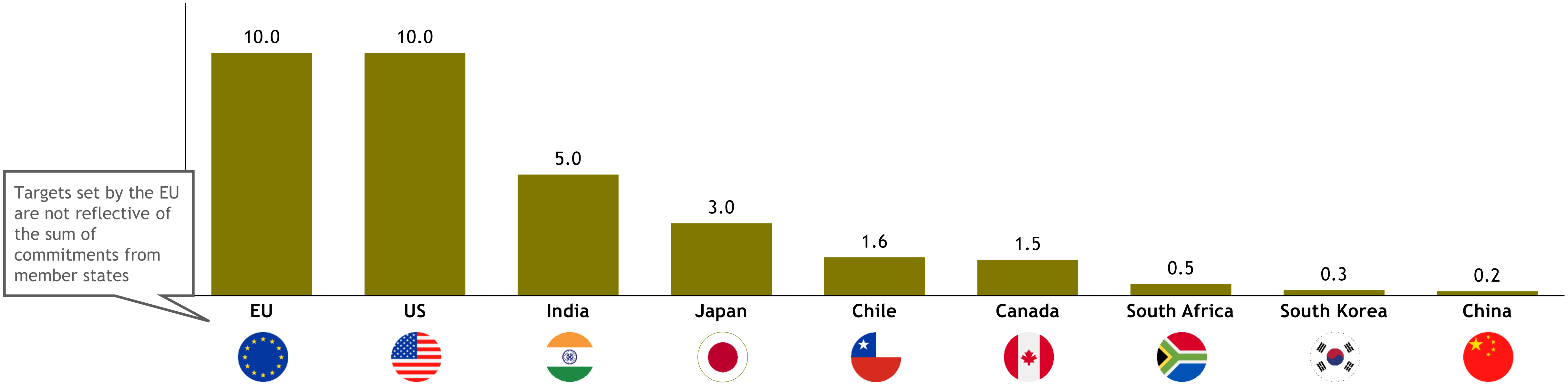
*“This process should be tackled **minimising** the **cost** of new infrastructure and the **risk** of stranded assets”* -Gonzalo Sáenz de Miera, Global Director of Climate Change and Alliances, Iberdrola

Notes: Coloration based on mix of renewable potential and existing natural gas resource access, Title quote from Gonzalo Sáenz de Miera, Global Director of Climate Change and Alliances, Iberdrola
Sources: IEA, HyARC 2017, BNEF

Several countries have now set ambitious green hydrogen production targets and are committing to build out domestic electrolysis capacity

/ NON-EXHAUSTIVE

Announced government green hydrogen production targets (as of 2023, in million tonnes)



	EU	US	India	Japan	Chile	Canada	South Africa	South Korea	China
Year of target achievement	2030	2030	2030	2030	2040	2030	2030	2030	2025
Electrolysis capacity (in GW)	100	70[1]-100[2]	60-100[2]	20[1]	25 (by 2030)	10[1]	10	2[1]	38 (by 2030)[2]

Notes: 1) Required (calculated) capacity – To produced 0.15Mn MT of Green H2 approximately 1GW of electrolysis capacity is required; 2) Estimated capacity
Sources: 1) EU supporting clean H2; 2) U.S. National Clean Hydrogen Strategy and Roadmap; 3) JP Morgan, Global Hydrogen, 2023; 4) National Green H2 Mission, India; 5) SCI to retrofit ships, Maritime Economy; 6) Harnessing Green H2, NITI Aayog; 7) National Green H2 Strategy, Chile

Chile's National Green Hydrogen Strategy aims to leverage existing solar generation to become a net exporter of green hydrogen

Chile has plentiful, low-cost renewables…

- Chile has plentiful, low-cost solar to support green hydrogen, with a **renewable energy potential equivalent of ~1900GW per year**
  - Renewable energy potential of Chile is 70x of its domestic demand which can be **sufficiently utilized in green hydrogen production**
- Chile has the potential to produce **160M metric tons of green hydrogen per year** given its huge **renewable potential**
  - **Best solar irradiation** in the world in the north and the **best winds in the south**, ideal for the generation of green hydrogen

Sources: 1) Chile National Green Hydrogen Strategy

…and aims to become a leading green hydrogen exporter…

Chile's National Green Hydrogen Strategy lays out the following ambitions:

2025

- **$5B investment** in green hydrogen (#1 in green hydrogen investments in Latin America)
- **5 GW of electricity capacity built** & under development
- **200k ton / year** of production in at least 2 green hydrogen valleys

2030

- **#1 in global exports** of green hydrogen and derivatives (~$2.5B per year)
- Cheapest green hydrogen globally at **<$1.5 per Kg**
- **#1 in global production** of green hydrogen by **electrolysis** (25 GW)

…with clearly laid out implementation plan via its "National Green Hydrogen Strategy"

Promotion of the domestic and export markets

- Funding round to **leverage green hydrogen projects for USD $50M**
- Public-private table to discuss the route at a **carbon price and taxes**
- Deployment of a **green hydrogen diplomacy** to position Chile internationally

Regulations, safety and piloting

- Regulation and standards of green hydrogen to **protect safety aspects and provide certainty**
- Operational team to accompany the **processing of permits** and the development of **hydrogen pilots**
- Review of natural gas regulation and infrastructure to **promote green hydrogen quotas**

Social and territorial development

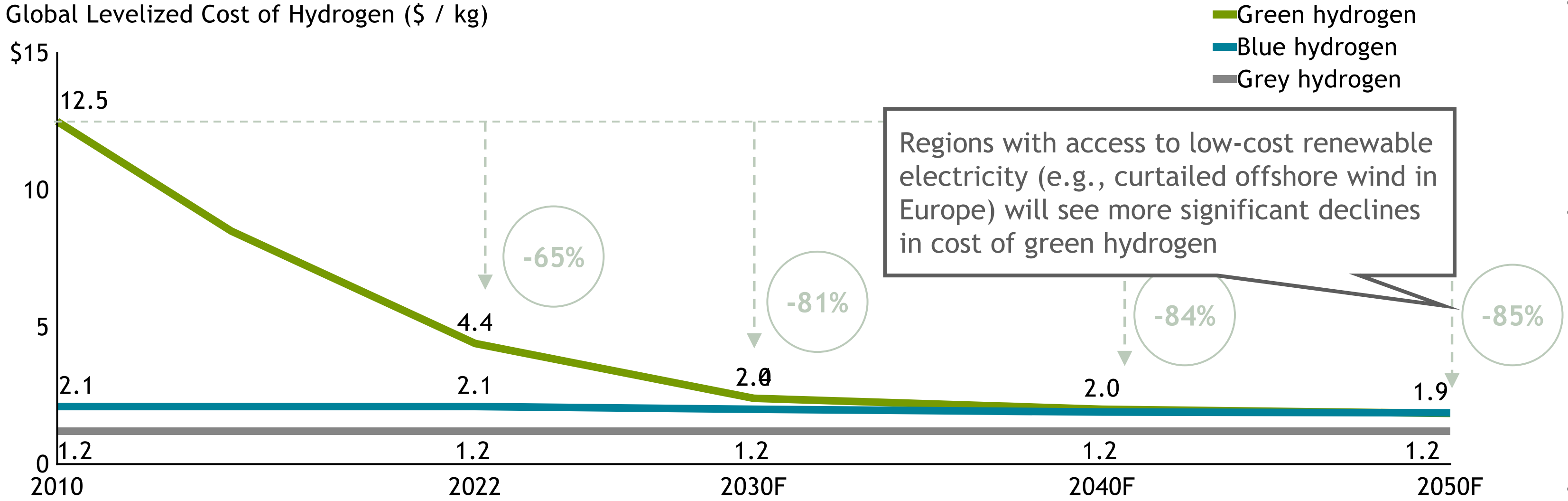
- Early and continuous **participation of the communities** close to projects
- Use of green hydrogen to supplement or **replace electricity generation based on fossil fuels**
- Evaluation of **opportunities and challenges of hydrogen** in territorial policies, regulations and plans

Capacity building and innovation

- **Connecting actors** from industry, academia and training centers
- Roadmap in **R&D** with the industry, to **solve local implementation challenges**
- Working group with State companies to **accelerate the adoption of green hydrogen** in them

“High production costs are a key barrier. More subsidies will incentivize scale, enable supply chain optimization, and further drive down costs”

Consensus forecast suggests looming parity in cost of blue and green hydrogen



*“While some estimates say **cost parity with gray hydrogen** will be reached by 2030, we think it’s a bit ambitious. But **by 2035**, we should there. It depends on a lot of factors, including gas prices”*
- Head, CO2 Reporting, Renewable power producer #5

*"We should be looking at minimum **30% cost reduction by 2030**. For the larger projects, the **LCOE has to go down**, performance has to go up, EPC costs have to go down and the supply chain has to be optimized”*
- CCO of PtX business, Technology provider #1

Commentary

- Production costs of green hydrogen have **declined ~65% from 2010 to 2022**
  - This decline was mostly driven by **reductions in electrolyzer CapEx** (~60% reduction in the last decade)
- Green hydrogen **costs are highly variable based on the cost of the renewable electricity used as input**
  - In regions using exclusively curtailed renewables (e.g., Denmark), electricity prices are effectively $0/MWh, pulling green hydrogen production costs down to $1.8/kg
- Production cost of green hydrogen may **decline 45% from present to 2030,** but will remain twice as expensive as traditional grey hydrogen
  - Green hydrogen reaches **cost parity with blue hydrogen by 2050**
  - Cost declines assume additional decreases in **electrolysis costs** and **electricity costs**

Note: Excludes impact of domestic subsidies, assumes no future change in carbon pricing or cost of natural gas (holds gas price constant going forward and historically at $6 / mmbtu to avoid gas price related volatility); curves based on consensus of estimates across various sources, but imply assumptions of roughly ~$45-$50 / MWh of electricity, 60-65% electrolyzer efficiency (varies across PEM & Alkaline), discount rate of 8% over a 20 year lifetime, with electrolyzer capex of ~$900-$1100 / kWe (varies across PEM & Alkaline), Title quote from CCO of PtX business, Technology provider #1
Source: IEA; IRENA; BNEF; Goldman Sachs; NETL; DNV Global

"Electrolyzer CapEx and renewable electricity are the primary cost drivers across green hydrogen production's value chain"

CapEx

- Plant cost, **predominately electrolyzer stack and related equipment** (e.g., compressors, short term storage)
- Scaling electrolyzer production enables producers to optimize system costs (e.g., reduce power electronics and power density) and **manufacture more efficiently**
- **Proton Exchange Membrane (PEM) electrolyzers slightly more expensive** than alkaline today, but have longer lifespans

Renewable energy

- Green hydrogen production will depend on the **cost of renewable electricity**, either provided by the grid or from dedicated generation source, which can be highly dependent on geography source
- **Lowest cost in PV solar, on-shore wind, and hydro**, but are projects investigating others (e.g., off-shore wind)
- **Power Purchase Agreements (PPAs)** are emerging as principal price-hedging tool for subsidy-free project development with varying traction across European countries

Other OpEx

- **Water** is required as an input, as electrolysis splits water into hydrogen and water
  - Alkaline water electrolysis uses electrodes in a liquid alkaline electrolyte solution, usually potassium hydroxide (KOH)
  - PEM water electrolysis required pure water that is deionized or distilled
- **Maintenance and repair**
  - Stack replacement cost

*"**Cost is a regional question**. It's all about the cost of electricity and green electrons. With a lot of space, and good wind and solar resources, **you can produce at very very competitive prices** right now. It's of course a different story for regions where they don't have abundant renewable energy sources available. In general, we will **see green hydrogen prices come down significantly**. **Prices are already lowering -** we used to think 7$/kg was good. Now we think 3-4$ is. We can even go below 2$ if systems are large enough and renewable power is cheap enough. This is achievable within a short time frame"* - Dr. Werner Ponikwar, CEO of thyssenkrupp nucera

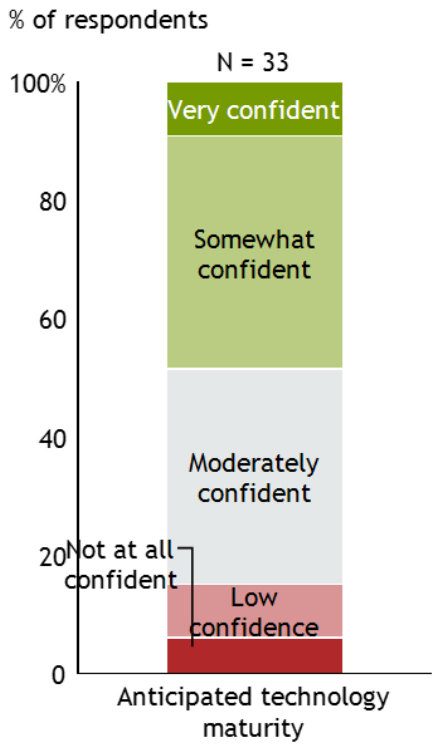
CapEx costs will decline based on economies of scale and speed of deployment

Renewable energy costs will vary by region, depending on capacity deployment and market structures

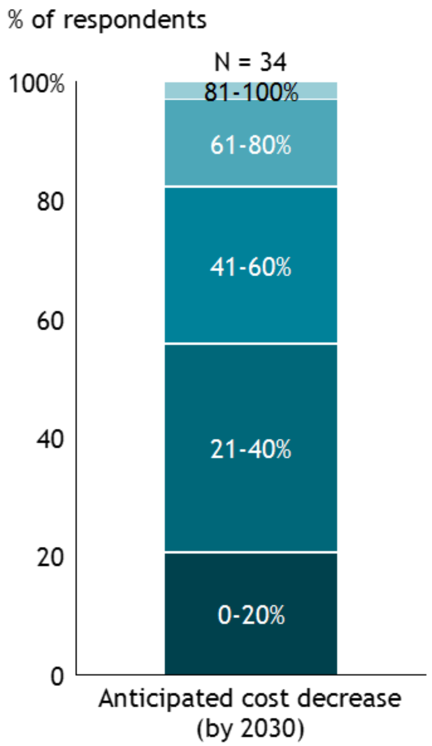
Other OpEx not a primary driver on cost reductions or variance

Business leaders expect electrolyzer costs to come down in-line with forecasts

*How confident are you that **electrolyzer technology will be mature enough** to meet your organization's desired electrolyzer-driven hydrogen (i.e., green, pink) production targets **by 2030?***



Between now and 2030, by what percentage do you estimate the upfront cost of electrolyzer technology for hydrogen production will decrease?



Commentary

- **Recent deployments** of electrolyzer technologies and **announcements of larger-scale projects** have **inspired confidence** in continued evolution of electrolyzer technology
  - Over the last decade, electrolyzer equipment **costs have decreased ~60%**
  - Questions now center more on optimal technology pathways (i.e., alkaline vs PEM vs solid oxide) than technology effectiveness
- Business leaders have **historically underestimated rates of cost declines** in renewable energy spaces (e.g., onshore wind)
  - History suggests cost declines are more likely to **skew towards top end** of anticipated reductions

*"**Alkaline electrolysis is a very robust system already** - **learning curve is not that steep anymore**. If we want to ramp up infrastructure, the first bet is on alkaline"* - Dr. Werner Ponikwar, CEO of thyssenkrupp nucera

*"**Two technologies are competing or** can reach competitiveness: alkaline water electrolysis which is the most mature but dedicated to the big units and less flexible and PEM which is more flexible and adapted for mobility [..] it's **fast moving**, we started with cost more in the range of $9 and now it's **getting closer to the targets**. We expect the **evolution of the cost curve** to be **linked to the scale of the electrolyzer**."* - Chief Sustainability Officer, Electrolyzer materials provider #1

*"**Economies of scale** and **learning curve** will be the key to **bringing down the cost curve** for electrolyzers. The Alkaline players are relatively smaller and newer. So it's not just about price, but also durability. In the PEM space, the firm are a little bigger or have parents with stronger balance sheets. But either way, the whole **value chain needs to be developed**"* - Head, CO2 Reporting, Renewable power producer #5

Note: Right chart includes an extra respondent that was a finance provider with expertise in Hydrogen
Source: Bain / WMBC Global Stocktake Survey (N = 215)

“We expect the evolution of the cost curve to be linked to the scale of the electrolyzer”

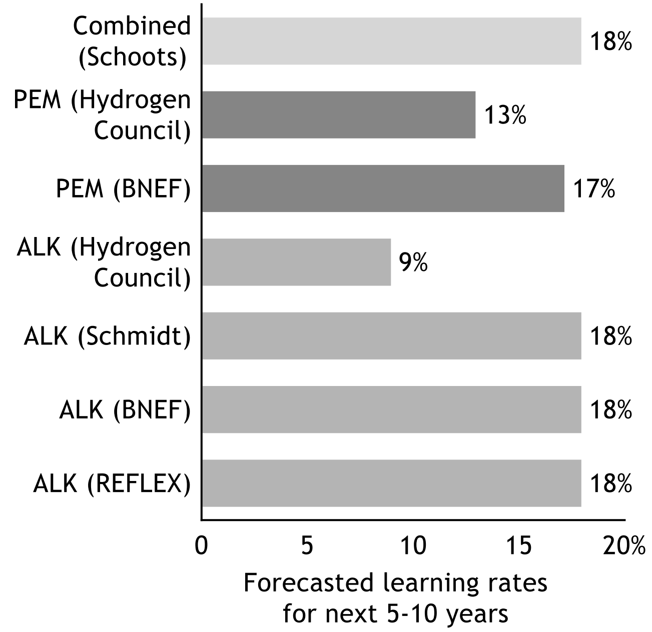
/ NON-EXHAUSTIVE

While analog experience curves range from 12-36% learning rates...

Tech.	Learning rate	Comparability to electrolyzer
Solar PV	35.6% (2008-2019)	Modular design, Chinese investment
Onshore Wind	12.8% (2008-2019)	High capital cost, more mature technology
Li-Ion Battery	19.6% (2000-2019)	New technology, recent spike in investment
Fuel Cells	18% (2000-2019)	Same technology, similar dev. timeline

Electrolyzers’ learning rate represents declines in cost based on a doubling of the install base of electrolyzer capacity (in GW)

…analysts expect an ~9-18% electrolyzer learning rate for the next 5 to 10 years



Hydrogen Council estimates (13% learning rate) indicate a ~60% CapEx reduction by 2030 if global capacity scales to >100GW

A selection of announced projects confirms the rapid decline in costs as tech matures and plants scale

Project	Refhyne (Shell)	Leuna chemical (Linde)	H20K (Woodside)	*Undisclosed*
Electrolyzer provider	ITM Power	ITM Power	nel	nel
Technology	PEM (System)	PEM (Electrolyzer stack)	Alkaline (Electrolyzer stack)	Alkaline (Electrolyzer stack)
Capacity (MW)	10	24	200	200
Delivery	2021	2022	2024	2024
Total cost (EUR M)	20	14.4	56	46
Implied CapEx (EUR/kW)	**2,000**	**600**	**285**	**225**

Electrolyzer projects in the pipeline imply a ~90% decline in CapEx per kW in just 3 years

Note: 9% and 13% from Hydrogen Council use different base starting points of installed capacity, Title quote from Pascal Chalvon, Chief Sustainability Officer, Solvay
Source: IEA Hydrogen Database, IRENA, E4 Tech, BNEF, REFLEX, Nel; Refhyne; Recharge; ITM Power; Reuters; Renewables Now; Lit. search

Firms are developing solutions to maximize efficiency of hydrogen production across the value chain, especially electrolyzers

SOLVAY **Case Study: Solvay**

Overview

- **Description:** Solvay is a materials, chemicals, and scientific solutions company that provides components for products in the transport, healthcare, and industrial sectors
- **Founded:** 1863
- **Headquarters:** Brussels, Belgium
- **Ownership:** Public (SOLB.BR)
- **Revenue (2022):** €13.4B

Technology overview

Solutions for electrolyzers

- Developing **specialty ionomers for alkaline electrolyzers** and other polymer and **membrane technologies for PEM applications**
- Technology has potential to **improve electrolyzer efficiency**, power density, durability and manufacturing productivity

Advanced materials for fuel cells

- Designing advanced components like **membrane electrode assemblies** that improve the efficiency, performance, and durability of **fuel cells** during operation

Activities

Hydrogen platform

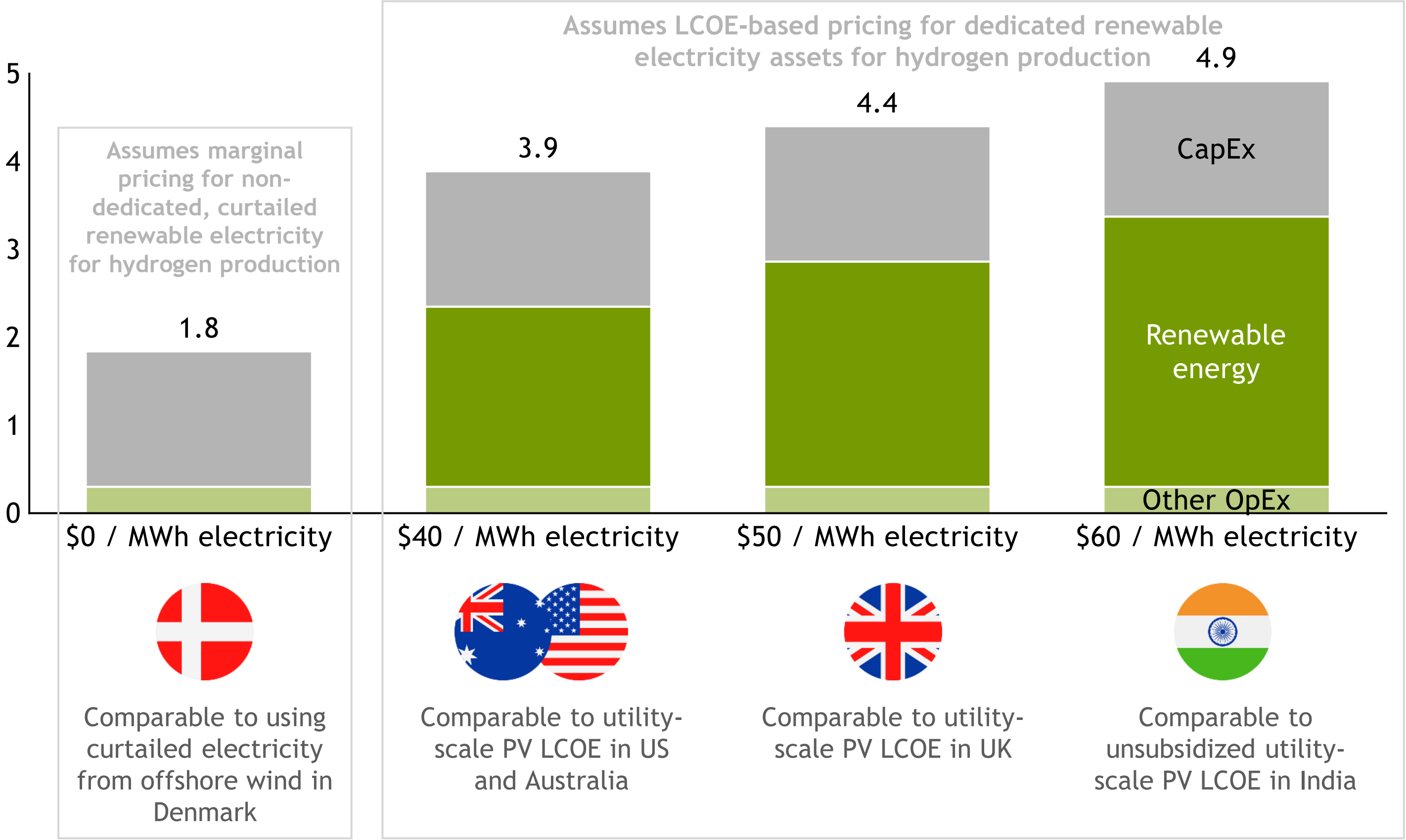
- In January 2021, Solvay launched their **"Hydrogen Platform" bringing together all the innovative material and chemical solutions** the company has to offer to advance the emerging hydrogen economy
  - The platform created **fully dedicated research, engineering, sales, and marketing teams** working together to accelerate the commercial viability of green hydrogen
- The heart of the platform is **Solvay's membrane technology**, which constitutes a necessary component in the process of hydrogen production using electrolyzers
  - The membrane leverages Solvay's **Aquivion Ion Conducting Polymer** tech that claims to provide superior conductivity and stability
- Aside from electrolyzers, Solvay has the intention of **impacting every stage of the hydrogen value chain** from production to infrastructure and end-uses
  - Solvay is planning to leverage their membrane technology within **hydrogen fuel cells** with the hopes of accelerating its adoption within the transportation sector
  - Other advanced materials used in hydrogen storage tanks are a key focus of the hydrogen platform effort

Source: Solvay, Bloomberg, Lit. search

“The hydrogen market will be determined by power prices, since the biggest cost is OpEx - if LCOE goes down, LOX will also dramatically go down”

Variability in renewable electricity cost and model swings the LCOH

Levelized cost of green hydrogen ($ / kg)



Commentary

- Production costs of green hydrogen have **declined ~65% from 2010 to 2022**
  - Decline mostly driven by **reductions in electrolyzer CapEx** (~60% reduction in the last decade)
  - Electrolyzer technology has been estimated to have **learning rates between 9-18%**
- Regions with **access to low-cost renewable electricity** will have built-in cost advantages in hydrogen production
- Power pricing models based on **marginal electricity costs** rather than levelized costs can **drive LCOH lower** than other models
  - Currently being planned in Nordic nations, where green hydrogen will leverage electricity from offshore wind that would **otherwise be curtailed**

*“One of the reasons that we are **so interested in hydrogen** generation is that if we only continue to build renewable energy capacity at the pace with which transmission lines can essentially suck up the additional energy, it won't go very fast… So instead, we would like to **build as much [renewable electricity]** that is, if not directly dedicated to hydrogen production, then at least **situated next to hydrogen production**.”* - Manager of Sustainability, Renewable power producer #3

*“You need a lot of cheap green electrons because **LCOE is 65-80%** of project costs. It’s a key lever”* – Head, CO2 Reporting, Renewable power producer #5

Note: Cost of green hydrogen today, assuming RE LCOE ranges $40-$60/MWh operating at 40% capacity and 65% energy efficiency, Title quote from CCO of PtX business, Technology provider #1
Source: IEA, IRENA, BNEF, ICCT, NREL

Innovation focused on specific technology pathways is expected to further increase technology readiness and scale

Case Study: ITM

Overview

- **Description:** The first hydrogen related company to join the London Stock Exchange, ITM designs and supplies proton exchange membrane (PEM) electrolyzer systems that produce green hydrogen for customers in the energy, transport, and industrial sectors
- **Founded:** 2000
- **Headquarters:** Sheffield, United Kingdom
- **Ownership:** Public (OTCMKTS: ITMPF)
- **Revenue (2022):** £5.6M

Technology overview

HGAS3SP: PEM electrolyzer system	• Plug and play, medium-sized containerized electrolyzer system • Contains everything needed for small scale production, the customer only needs to connect water and power
3MEP CUBE: Modular PEM electrolyzer units	• For reliable and versatile large-scale production • Designed with hydraulic rams for heat expansion and simplified maintenance

Notable projects and partnerships

United Kingdom

- ITM's Bessemer Park factory located in the UK is one of the region's **largest electrolyzer manufacturing facilities**
  - ITM originally planned to open a second UK factory but have instead decided to expand their Bessemer Park factory due to considerations regarding the 2022 business climate and cost escalation
  - Bessemer Park's capacity will be ~700 MW by early 2023 and will grow to 1.5 GW within the next two financial years

Germany

- ITM was selected to build electrolyzer units for the **pan-European REFHYNE project** which aims to provide **green hydrogen to oil refineries**
  - The 10MW electrolyzer built by ITM provides 1,300 metric tons per year of green hydrogen and is the largest scale of PEM technology today
  - The REFHYNE II project plans for ITM to develop a 100MW electrolyzer unit by 2024 for Shell's Energy and Chemical Park
- In 2021, ITM sold a 24MW electrolyzer unit to Linde, the largest PEM unit globally at the time, for the Leuna Chemical Complex in Germany which operates in oil refining

Norway

- ITM sold a **24MW electrolyzer** to a Norwegian ammonia production site where it will provide ~**5% of the plant's hydrogen consumption**
  - This project will produce a potential maximum of 3,800 metric tons of green hydrogen per year and serve as a feasibility study for future upscaling

Source: ITM, Bloomberg, Lit. search

Industrials call for grid upgrades and new flexible production incentives to support the build out of electrolytic capacity

"As the electrolysis industry grows, we're talking about adding big loads to the electrical grid at the same time you're electrifying end uses. This will require a lot more capacity on the grid. We need to resolve some of the ***transmission bottlenecks and interconnection queues*** *that renewables like solar and wind have been experiencing."*

- VP Policy, Electrolyzer materials provider #2

"Policy makers, Public utilities, and FERC need to think about how to create demand response incentives for hydrogen productions to ***run their electrolytic hydrogen production flexibly****. For example, adding an inflexible 100MW electrolyzer running close to 100% utilization to a capacity constrained grid during peak summer months in Texas would have significant impacts."*

- VP Policy, Electrolyzer materials provider #2

"For green hydrogen, a key priority is ***needing a bigger grid****. We're currently* ***relying on the existing grid****. Since in Sweden, most is renewables, it works. In the US, it is still small. As we move towards the end of the decade, a lot of projects will rely on new build out of renewables"*

- CCO of PtX business, Technology provider #1

"A key challenge is a ***regulatory framework that is stable enough,*** *but provides* ***enough flexibility to build up infrastructure****"*

- Dr. Werner Ponikwar, CEO of thyssenkrupp nucera

Source: Corporate interviews

Scale-up of electrolyzer capacity faces constraints from potential restrictions on PFAS, coupled with short supplies of iridium and renewable electricity

PFAS - a vital input for PEM electrolyzers - may be banned in Europe

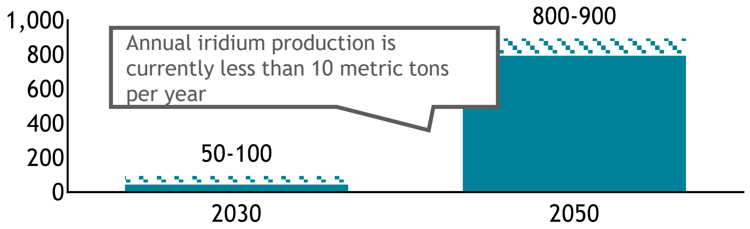
- A proposal to restrict use of per-and polyfluoroalkyl substances (PFAS) was submitted as part of EU's chemicals strategy
  - PEM electrolyzers leverage fluoropolymers, a PFAS subtype, as a critical component in their membranes
  - While implementation is not yet confirmed, uncertainty increases risk for electrolyzer manufacturers making technology investments
- This proposal could jeopardize access to a critical electrolyzer input absent adjustments to the proposal to create an exception

*"Another element is the risk of restrictions linked to the PFAS…which are critical for the membrane for the PEM. This is a real question because there's **no substitute**. There's **no time to invent a new chemistry**, to develop new technologies. We cannot waste time on overall PFAS consultation, which is also complex, it may last a couple of years before getting to the final solution. We **need to make decisions now** for implementation."* - Chief Sustainability Officer, Electrolyzer materials provider #1

Critical minerals for PEM electrolyzers like iridium are in short supply

- **Available iridium supplies do not match demand** in 2030 and 2050 for electrolysis capacity using PEM
- **Alternative technology pathways** (e.g., alkaline, solid oxide) or **reductions in required iridium** per PEM electrolyzer could help circumvent constraints

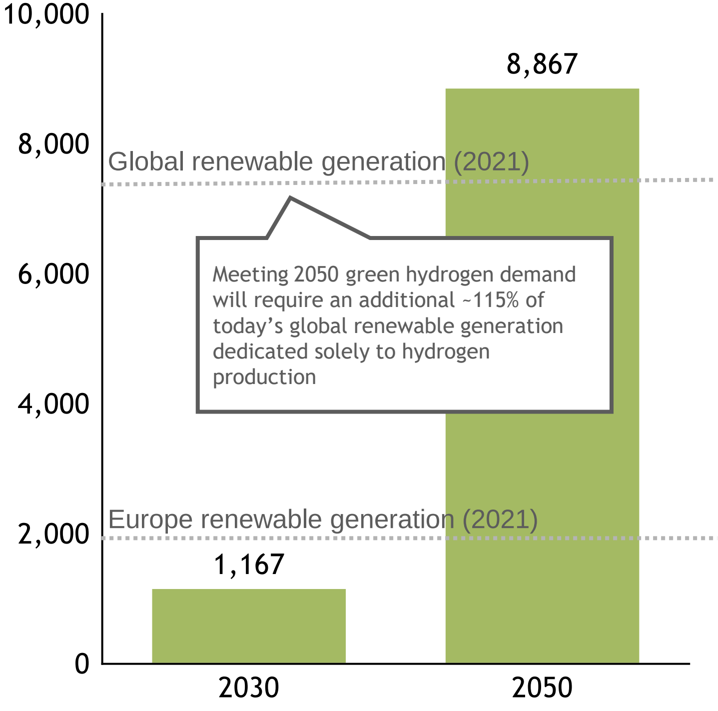
Iridium (tonnes) required to meet projected installed electrolysis capacity (if all PEM)



*"Meeting **just the EU's goals** for green hydrogen production could by 2030 lead to demand for iridium for electrolyzers that is **several times current global supply**… the green hydrogen industry is aiming to grow rapidly, and a materials supply chain that is rooted almost entirely in southern Africa and Russia looks like a **critical vulnerability**."* - Wood Mackenzie, 2022

RE does not currently exist at required scale to support H_2 growth

Implied renewable energy generation to support green hydrogen production (TWh)



Total global generation including fossil fuels is ~28K TWh (as of 2021)

Note: Forecasts assumes ~25 Mt of green hydrogen production in 2030 and ~190 Mt of green hydrogen production in 2050 with electrolyzers operating at 70% efficiency
Source: Credit Suisse, Goldman Sachs, DNV, IEA, Ember, Wood Mackenzie, Hydrogen Tech World, Hydrogen Europe

“To meet demand, Germany is looking at imports - even if it is a more expensive route because of the efficiency losses”

Enhancing domestic production

- National Hydrogen Strategy’s ambition is to **double** 5GW of **installed electrolyzer capacity** to 10GW by 2030
  - **€7 billion investment** has been earmarked for the rollout of hydrogen technology in Germany
- Under **Ostend Declaration**, Germany, Denmark, Netherlands, and the UK target **30 GW of onshore and offshore electrolysis capacity by 2030** through RE from North Seas
  - Additional **10 GW of offshore H_2 capacity** by 2035
- Plan to fund **62 IPCEIs in Germany** with over **€8B**
  - These IPCEI projects will be present **on the coast of northern Germany**, where states will **use wind energy capacity** to **produce green hydrogen**

Developing global production

- **National Hydrogen Strategy** earmarked **€2B** for **fostering international partnerships** to support production in partner countries
  - Launched **Hydrogen Ramp-up Program** (H2Upp) **-** PPP measure to support pilot projects of SMEs **in developing economies** using German technology
    - A total of up to **€200K in funding** possible with **intensive advisory services**
- German International funding provides **Non-repayable grants** as partial funding
  - Grants cover **25-45% of fundable costs** (€5-15 Mn per project)
- **Power-to-X (PtX) Development and Growth funds** were created to **establish local value chains** and support international market ramp-up of green H_2
  - PtX implies conversion of energy from renewable sources into hydrogen
  - PtX serves as one area for **funding windows** managed by Germany’s development bank

Orchestrating imports

- Germany is organizing **competitive tenders** under the **H_2 Global auction scheme** for the import of green hydrogen via **ten-year Purchase Agreements**
  - **€4 billion** for new auction rounds will enable the global development of green hydrogen
- Multiple **international partnerships** across the globe (incl. Australia, India, Brazil, EU countries, South Africa, Canada, etc.) for:
  - Supporting project opportunities for **consumption, transportation, and storage** of green hydrogen
  - **Trade of Green Hydrogen** and / or its derivatives
  - Creation of a **close network between the government and industry** for ease of export / import policies
- Coastal states will develop infrastructure as a part of **IPCEI Projects** for **seaborne import of hydrogen**

While hydrogen transport is expected to be costly (resulting in regional hydrogen hubs as prominent market-type), countries that are unable to meet demand with domestic supplies may require imports while domestic production scales

Note: Title quote from CCO of PtX business, Technology provider #1
Source: National Hydrogen Strategy, Germany , Lit search

While most of the focus is on electrolyzer production, some market players are also exploring pyrolysis

BASF **Case Study: BASF**

Overview

- **Description:** World's leading chemical company whose portfolio includes:
  - Chemicals
  - Plastics
  - Performance products
  - Crop Protection Products
  - Oil and Gas
- **Founded:** 1865
- **Headquarters:** Florham Park, New Jersey
- **Ownership:** Public (OTCMKTS: BASFY)
- **Revenue (2022):** €87.3B EUR

Targets

2025
- Invest up to €1B in CapEx to develop low-emission technologies and scale deployment

2030
- Increase CapEx investments to £2-3B to develop low-emission technologies and scale deployment
- 25% CO_2 emissions reduction compared to 2018
- Deploy large-scale plant using methane pyrolysis
- Obtain 100% of BASF'S 2021 global power demand from renewable sources

2050
- Net-zero emissions

Activities

Created CO_2 emissions free methanol production process

- BASF is investing in low carbon methanol production, an important basic chemical used throughout the chemical industry for consumer and industrial products
  - Typical methanol production creates emissions when producing syngas, the material that is converted into crude methanol, whereas BASF generates syngas through partial oxidation of natural gas, which is emissions-free
  - BASF's process creates methane, CO, CO_2, and H_2 waste gas streams which are incinerated in an Oxyfuel process with pure oxygen, resulting in a small volume of flue gas containing CO_2
    - The CO_2 is recovered using BASF's OASE process then fed back into the methanol synthesis process to be used again
  - BASF expects to implement the process at scale by 2029
- BASF's process **requires green hydrogen** as an input **to be CO_2 free**, it plans to source this through water electrolysis and methane pyrolysis processes when ready

Methane pyrolysis to produce clean hydrogen

- Since 2010, BASF has been researching and developing methane pyrolysis to **produce clean hydrogen in a carbon-free process** when powered with renewable electricity
  - Pyrolysis splits methane from natural gas or biogas into hydrogen and solid carbon using only 20% of the electricity required in electrolysis
  - Technical barriers include the need for high temperatures of over 1,000 degrees Celsius which can require significant fuel inputs
  - Project is funded by the German Federal Ministry of Education and Research and a pilot reactor is operating in Ludwigshafen, Germany

Note: Emission targets refer to Scope 1 emissions which include emissions from sources owned and operated by BASF and scope 2 emissions which include emissions from energy BASF purchases to operate.
Source: BASF, Lit. Search

Several large-scale green hydrogen projects are already under construction to serve Europe's targeted 2030 energy mix

/ NON-EXHAUSTIVE

Holland Hydrogen I

- **200MW electrolyzer at the Port of Rotterdam** will be Europe's largest green hydrogen plant once operational
- Expected to be operational in 2025
- **Powered by** electricity from Hollandse Kust (Noord), **a 759MW offshore wind farm**
- Shell to use HyTransPortRTM hydrogen pipeline developed by Gasunie in **collaboration with the Port of Rotterdam to transport the hydrogen**

H2 Green Steel Boden plant

- **~800MW electrolyzer in Boden in Northern Sweden,** facilitating the production of ~5 million metric tons of green steel
- The plant and its electrolyzers will be **powered by hydro and wind**
- Most hydrogen produced for own use in steel production, but the Boden plant will also look to export
- Expected to be operational in 2030

H2opZee Hydrogen Project

- Neptune Energy and RWE are collaborating to develop H2opZee offshore green hydrogen project
- The project aims to build **300-500MW** of electrolyzer capacity **in the North Sea**
- The project **plans to leverage offshore wind power** to generate the power for the electrolyzers
- Expected to be operational in 2030

HyDeal Espana

- **HyDeal is located across Western Europe** including Spain, France, and Germany
  - HyDeal Espana is the first industrial implementation of the HyDeal ambition
- The project aims to **leverage solar power to drive its 67GW of electrolyzers** and **3.6M metric tons annually** of green hydrogen production
  - Expected to be operational in 2030 with the goal to bring green hydrogen costs to €1.50 per kg
- It is expected that ~30 energy partners will be involved to make the project possible

Reckaz

- German-based Svevind Energy is collaborating with KazakhInvest in the Reckaz inivtiative
- The project is scoped to capture capture 45GW of **wind and solar power** to power the project
- The project aims to generate **30GW of electrolyzer capacity,** yielding ~3M tons of green hydrogen each year
- Expected to be operational in 2028

*"We would like to see **governments pushing more towards a larger scale system**. The time of MW scale and demonstration projects should be over. We need GW scale projects in Europe because 2030 is only 7 years down the road [..] Where projects are reaching FID, it's because **someone is building a complete ecosystem** - like H2 Green steel. They are investing in the end use of green hydrogen where there is already a market"* - Dr. Werner Ponikwar, CEO of thyssenkrupp nucera

Source: Lit. search

US and Canada are also witnessing emergence of such large-scale projects

Case Study: GHI

Overview

- **Description:** Green Hydrogen International is a low-cost, green hydrogen developer that is focusing on the deployment of commercial-scale facilities that provide hydrogen for:
  - Sustainable aviation and rocket fuels
  - Ammonia exports and fertilizers
  - Power generation
- **Founded:** 2019
- **Headquarters:** Austin, Texas
- **Ownership:** Private

Strategy overview

Low-cost renewable energy

- Large-scale projects in the U.S. and Canada where renewable power source is abundant (e.g., offshore, deserts, etc.)

Salt cavern storage

- GHI acquires rare salt storage rights at key sites globally and has amassed a total potential storage capacity of 100TWh of energy
- Geologically pure salt deposits used as storage caverns allow for large-scale, long-term H_2 storage

Notable projects and partnerships

Canada

- GHI has announced **two projects in Canada** that business leaders believe could each produce as much as **43 Mt per year** of green hydrogen as early as 2030
  - **Spirit of Scotia**, located in Nova Scotia, will be powered through offshore wind and have a size of 500GW
    - It will be Canada's largest green energy project, delivering green hydrogen to European and North American markets
  - **Fleur-de-lys**, located in Quebec, will be powered through offshore wind and have a size of 500GW
    - It will enable expansion of Quebec's ammonia production capabilities
  - Together, the projects have secured **170,000 acres of storage grade salt rights,** allowing for the large quantities of hydrogen storage needed for projects of this groundbreaking scale

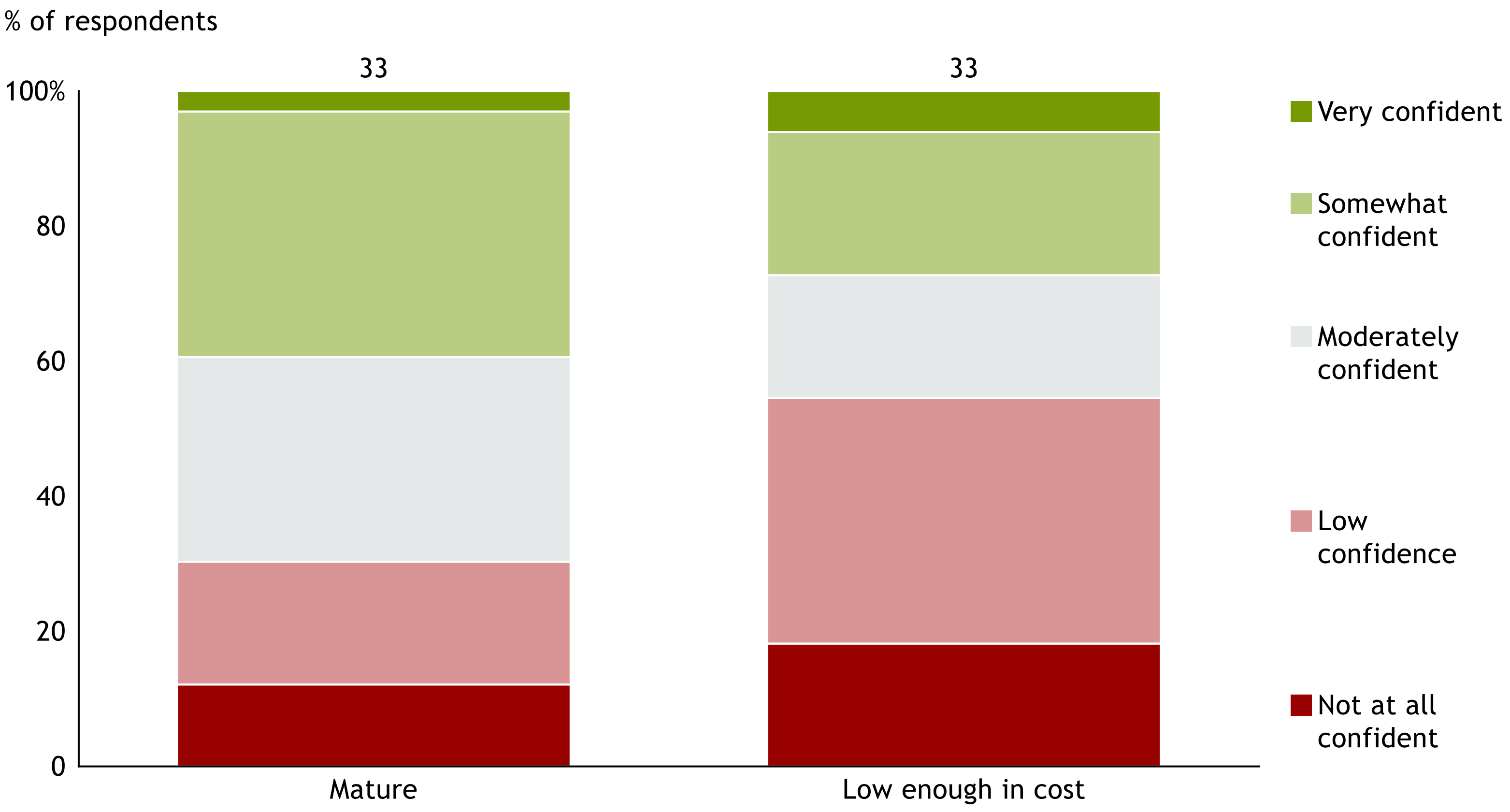
United States

- **"Hydrogen City"** located in Texas will be the **world's first-to-market** green hydrogen production and storage hub starting in 2026
  - It will be powered by onshore wind and solar with a size of 60GW and produce 3 Mt per year of green hydrogen
  - It is being built in phases and will open in 2026 with 2GW of production and two storage caverns at the Pierdas Pintas salt dome
  - Salt dome capacity can grow to 50+ caverns, an equivalent to 6TWh of energy storage, equipping the area to become a major green hydrogen hub

Source: GHI, Lit. search

Business leaders have confidence in the technical viability of applying CCUS technologies to hydrogen production, but are more concerned about cost

How confident are you that **CCUS technology will be [mature enough / low enough in cost] to be applied** to a significant share (i.e., >20%) of your organization's hydrogen production by 2030?



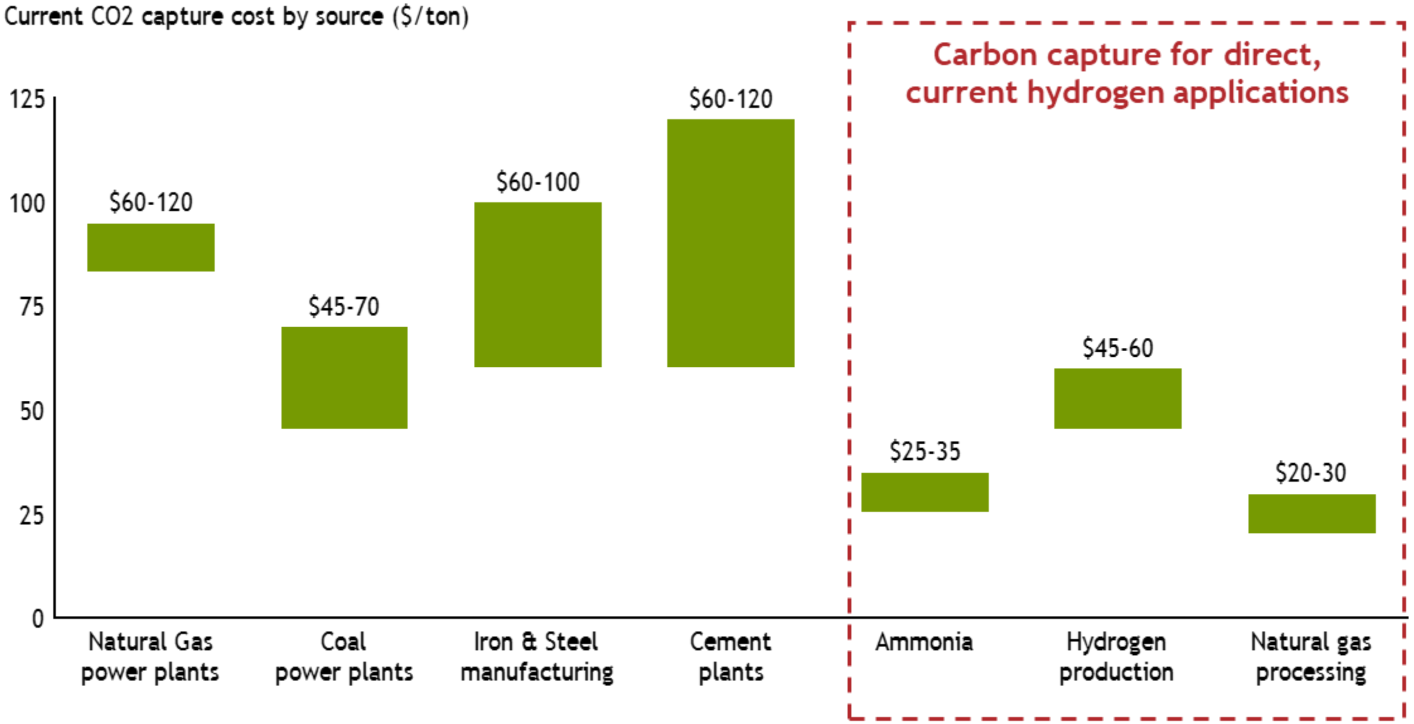
Commentary

- Hydrogen producers **expect improvements in technological effectiveness** of carbon capture for production of blue hydrogen by 2030
  - Low capture rates with current technologies (highest efficacy scale plant still <70%) suggest continued advances in CCUS technology will be necessary for this to occur
- More than **50% of business leaders surveyed have low or no confidence** in CCUS technology becoming cost competitive by 2030
  - Additional R&D required to increase capture rates would likely also **increase the cost of CCUS technology**
  - Current levelized cost of retrofitting Hydrogen production facilities with CCUS tech is less than 50% of electrolysis-based production

Source: Bain / WMBC Global Stocktake Survey (N = 215); Institute for Energy Economics and Financial Analysis

Though carbon capture cost varies by application, hydrogen applications (with high concentrations of CO_2 at the point of capture) are the most advantaged

Cost of carbon capture depends on CO_2 concentration at the point of capture



Concentration of fume gas	~4%	12-14%	21-27%	15-30%	95-100%	30-100%	95-100%

Commentary

- **High concentration of gas** in existing hydrogen production facilities **reduces required complexity** and scale of carbon capture systems to be effective
  - Production in other sectors (e.g., steel) requires CCUS systems to provide coverage of **multiple point sources** of emissions, increasing system complexity
- From a cost perspective carbon capture on existing hydrogen facilities is the optimal place for deploying **employing CCUS retrofits** - this would also avoid stranded costs
  - But cost competitiveness will **depend on the specific policy mechanisms available as well as on regional gas prices**

*"It can also be more cost-effective to retrofit CCUS to existing facilities than building new capacity with alternative technologies… **CCUS is currently the cheapest option** for reducing emissions in the production of some important **chemicals such as ammonia**, which is widely used in fertilizers."* - International Energy Agency, 2021

Source: IEA 'Is Carbon Capture too Expensive?' (2021), IEA 'CCUS in Clean Energy Transition' (2020), NPC: Meeting the dual challenge (2019), IEA: Future of Hydrogen (2019); 'A Process for Capturing CO2 from the Atmosphere' Keith, (2018)

Many governments also view blue hydrogen as a bridge to the green hydrogen market transition

Germany

- Unlike Germany's 2020 hydrogen strategy, the updated 2023 edition **explicitly foresees the use and public funding of fossil-derived blue** hydrogen
- **Renewable energy supply cannot be ramped up fast enough** to produce enough green hydrogen, so the idea is that **blue hydrogen might be needed in transition -** though some experts argue **this risk locking in the continue use of fossil fuels.**
- There are **various projects already** in the pipeline
  - Projects to import blue hydrogen and its derivatives are already in the planning, for example with both Norway and the UAE
  - In March 2022, several projects to deliver blue ammonia from the UAE to Germany were agreed upon - first delivery from Abu Dhabi National Oil Company arrived in Hamburg in October 2022
  - In 2023, blue hydrogen delivery agreed upon from Norway to Germany – to be transported by a pipeline constructed by RWE and Equinor with planned CO_2 storage under Norwegian seabed

Netherlands

- In March 2020, the Dutch government announced the **Dutch national hydrogen strategy (DNHS),** which included policies incentivizing blue hydrogen
- While focus is still green hydrogen, blue hydrogen is seen as an "optimal contribution to **developing broader hydrogen system** without impeding on green hydrogen growth"
- 'The Northern Netherlands Hydrogen Investment Plan' announced **10 long-term projects** to expand capacity to 100PJ per annum by 2030 **- 25% to be in blue hydrogen**
  - Expected to secure ~66,000 existing jobs and create up to 41,000 new jobs by 2050
- **H-vision** is an example of **cross- industry partnership large-scale project** focused on blue hydrogen production
  - CO2 released by businesses in the port of Rottendam to be captured and transported to empty gas fields under the North Sea
  - While currently still in the planning phase, impact is estimated to contribute up to 2.7Mton CO_2 per year to national and regional abatement targets

US

- IRA created production tax credits **of up to $3/kg hydrogen**, scaling with emissions, which can support blue hydrogen
  - Blue producers can claim 1) Expanded 45Q: Credit for CO2 capture of up to $85/tonnes (most attractive) or 2) 45V: 10-year credit dependent on CO2 intensity and meeting wage, hour, and apprenticeship requirements (more attractive only for lowest CO2 intensity levels)
- **Policies will likely become clearer by the end of 2023** when the Department of Energy is expected award billion-dollar subsidies for demonstration projects and Treasury Department issues guidance on claiming IRA tax credits
- **30+ additional blue projects** involving hydrogen and carbon capture systems are **in the planning phase**
  - Blue hydrogen plant in Texas has been up and running since it won DOE loans to demonstrate carbon capture in 2009-10, advantaged by cheaper-than-national-average natural gas
  - Forecasts indicate that Texas will likely be able to export ~10M tonnes per annum (MTPA) of hydrogen by 2050

Source: National Hydrogen Strategy, Germany, H-vision Rotterdam, National Hydrogen Strategy Netherlands, International Energy Agency, Lit search

Limited commercial viability of key technologies for low-carbon hydrogen production hampers ability to scale supply

Green hydrogen

- CapEx costs are falling. **Recent policy trends favoring electrolysis-based ‘green’ hydrogen** accelerating this cost trend as more investment in R&D is required to mature technologies and facilitate broad diffusion
- **Uncertainty over optimal electrolysis technology pathways** (i.e., alkaline vs. PEM vs. solid oxide) may be delaying final investment decisions and deployments of capital
- Existing electrolyzer technologies **requires access to scarce inputs** including renewable electricity sources and critical minerals (e.g., iridium), as well as PFAS, which are at risk from potential bans

“More and more people are interested in green hydrogen… So, I'm sure that there will be customers … it will also depend on how fast we can scale production. We are trying. We are looking at all the possibilities, making sure that it's commercially viable, and then we'll invest in it.”

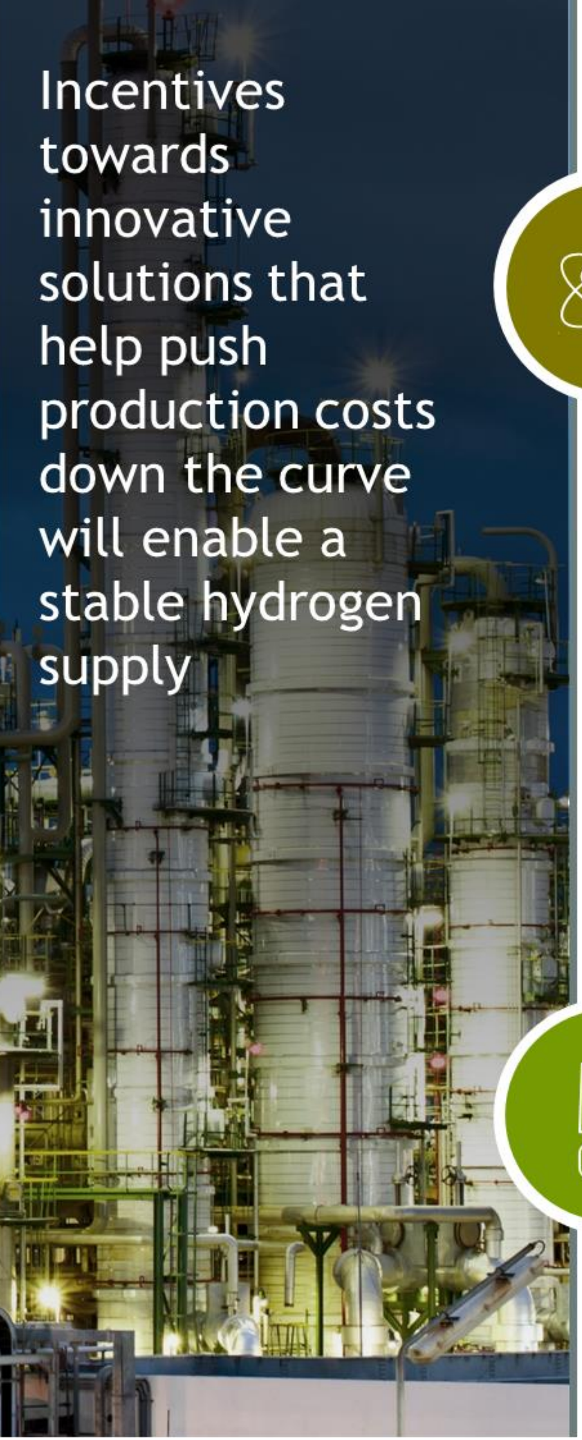
Head of Group Sustainability, Utility company #2

Blue hydrogen

- Existing hydrogen producers (i.e., ammonia fertilizer, methanol, oil refining) almost exclusively use **on-site steam methane reforming**, meaning “path of least resistance” involves retrofitting production with carbon capture technology to produce low-carbon (“blue”) hydrogen as a transitional technology option
- Shifting existing production to electrolysis in the near-term would create **operational disruption to existing production facilities**, stranded assets (i.e., methane reformers), and would require reconfiguration of production facilities
- Retrofitting existing plants with carbon capture technology is the alternative though **more investment in R&D is required to reduce costs and facilitate improvement of capture rates** at scale (existing scale plants target ~85%+ capture rates but are still below 70% at best-in class Shell Quest facility in Canada)

~55% of business leaders express low confidence that CCUS technology will be low enough in cost to be applied to a significant share of their organization’s hydrogen production by 2030

“The focus right now should be on subsidizing the asset owners, i.e., the ones producing the molecule“ -



Incentives towards innovative solutions that help push production costs down the curve will enable a stable hydrogen supply

Incentivize innovative solutions to drive down costs

- Supply-side policy is critical for kick-starting production and bringing technology down learning curves; in the US, tax incentives in IRA and BIL as well as clean energy funding programs by the DoE have been effective - to reduce government exposure, **sliding fiscal incentives can be implemented**
- Incentives aimed at ramping up manufacturing capabilities and building novel IP (e.g., grants, equities in startups) can push businesses to **build innovative solutions** like **alternative pathways** (e.g., Alkaline, solid oxide) or **reduced requirement of iridium** per PEM electrolyzer
- Governments also play an important role in encouraging R&D. For example, multilateral research initiatives can help in **determining technology advancement targets** (e.g., the optimal electrolysis technology pathways) for given regions
- For the long-term viability of green hydrogen projects, **flexibility and expansion of the grid** should be prioritized, and in some cases power market liberalization could be critical for enabling green hydrogen to compete

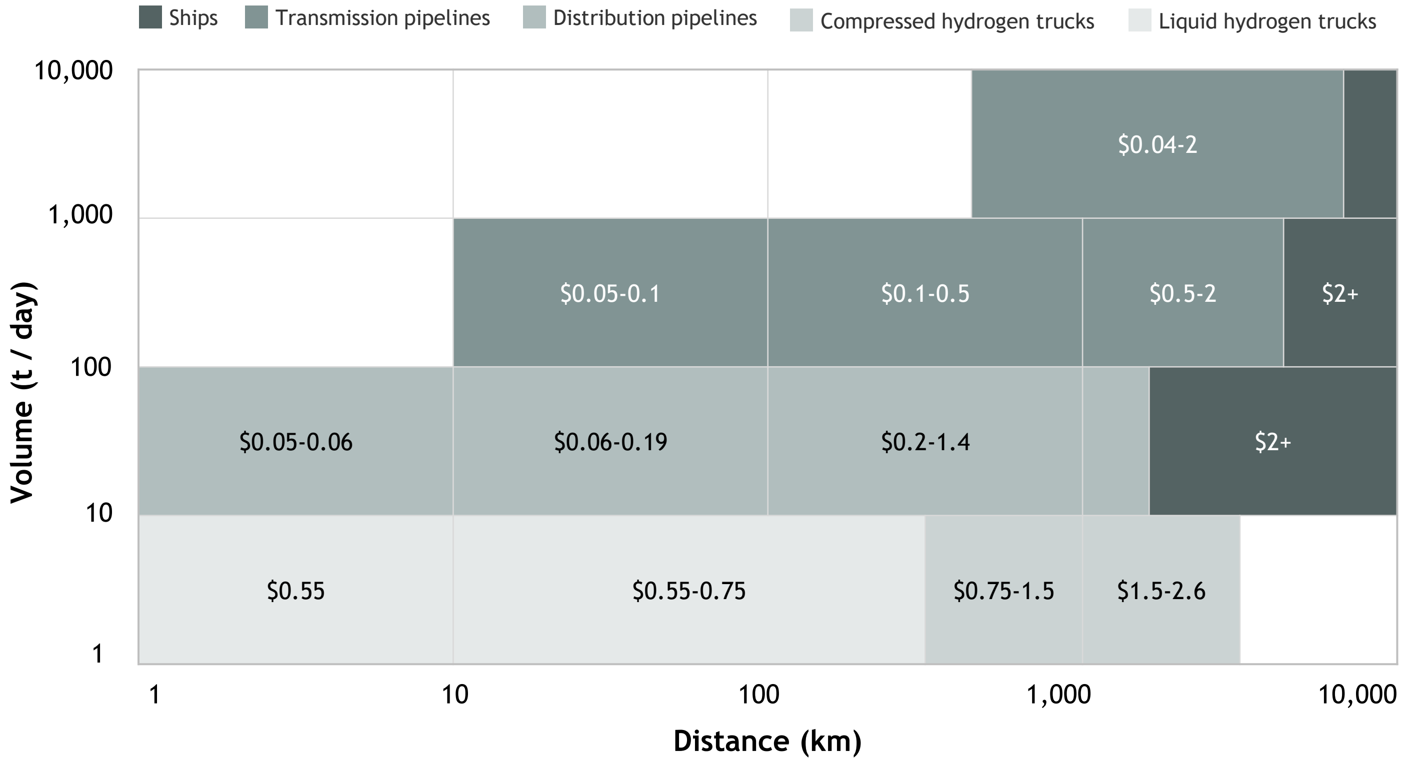
Blue hydrogen as a bridge to decarbonization

- While kickstarting the green hydrogen economy remains a priority for policymakers, **in the short term there is a solid case for retrofitting existing hydrogen infrastructure with CCUS,** which will require clear economic incentives particularly in the context of policy environments like the EU who are directionally favoring green hydrogen

Hydrogen: Table of Contents

Transportation costs for hydrogen will depend on distance, volume, and existing infrastructure - creating headwinds for short-term export markets

Pipelines are the most cost-effective long-range transport option in the near-term[1]



*"We see green ammonia being developed **close to where energy is cheap and then transported**; **hydrogen will be developed where it is used**"* - CEO Carbon Technologies, Utility company #5

Note: 1 – costs in $ / kg; * may require blending with natural gas
Source: IRENA (2022)

Description of transport methods

	Method	Description
Trucking	Liquid H_2 trucks	• H_2 gas is **cooled into a liquid** that is stored in cryogenic tanks carried by trucks • **Limited cost viability** due to liquification and re-conversion costs; likely used when **volumes are too low** for pipeline usage
Trucking	Compressed H_2 trucks	• H_2 gas is **compressed to high pressures** and stored in sealed tanks carried by trucks • Similar **low volume option** capable of longer-distance transport; **compression costs** still typically in excess of pipelines
Pipelines	Distribution pipelines*	• **Large-diameter pipelines** that compress H_2 gas to pressures between 800-1200 psi • **Low-cost option** for **moderate volumes** across **most distances**
Pipelines	Transmission pipelines*	• **Smaller-diameter pipelines** that compress H_2 gas to pressures between 100-500 psi • **Most economically efficient option** for **highest volumes** across **most transport distances**
	Ships	• **Highest cost option** due to liquification or ammonia **conversion / reconversion costs**, will likely only be leveraged for **longest distance** transport

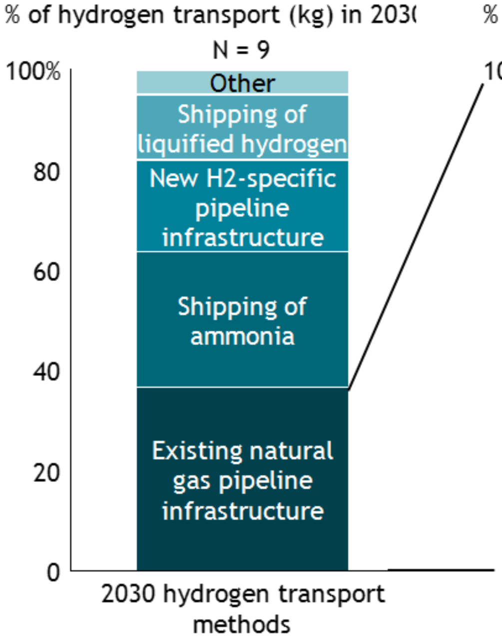
Business leaders lack alignment on anticipated transportation methods for hydrogen, with significant splits across pipelines, shipping, and more

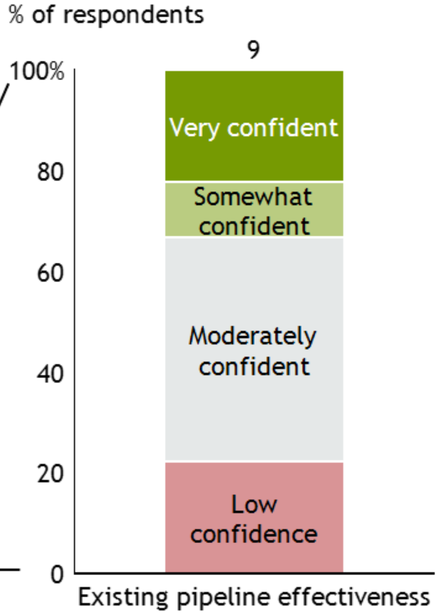
Transport expected across pipelines and ships..

By 2030, how do you expect the share of hydrogen transported to break down across the following methods

… though confidence in existing infrastructure is low

*How confident are you that **existing natural gas pipeline infrastructure can be used to transport significant quantities** of H2 absent material investment in pipeline retrofitting?*





Commentary

- **Existing natural gas pipeline infrastructure** is expected to be the **most prevalent** hydrogen transportation method by 2030, comprising ~**35% of expected transport** volumes
  - However, only **20% of business leaders** are somewhat or very confident that existing pipeline infrastructure can be leveraged **without significant retrofitting** investments
  - Retrofits necessary to prevent leakage, weakened pipes, and accidental ignition due to unique properties of H2 gas
- Investments in **Ammonia** are in an **earlier investment phase** compared to **Liquified H2**, but **both are viewed as viable options** by industry leaders
  - First large-scale demonstration for liquified H2 - 'Hydrogen Energy Supply Chain project' - was set up from Australia to Japan in 2022, and a few projects are in the pipeline. But low density and low liquification temperature are concerns
  - Thus, investments in ammonia as an alternative are increasing, but all projects except one (NEOM project in 2023) are in very early stages. IEA estimates that it's likely to be cheaper in comparison by 2030. But this depends on technological readiness and scale
- **Significant distribution** of anticipated transport across **these distinct methods** risks uncertainty over optimal technology pathways
  - **May chill investment** as infrastructure operators **fear development of duplicative/obsolete** transporting methods

*"We are considering whether **the transport type** will be hydrogen or ammonia - the debate is not over"* - Pascal Chalvon, Chief Sustainability Officer, Solvay

*"**Pipelines are the best and cheapest way** of transporting [..] In the **longer term**, we think **ammonia** will be the most natural carrier"* - Head, CO2 reporting, Renewable power producer #5

Note: 'Other' responses included compressed hydrogen trucking and shipping of methanol
Source: Bain / WMBC Global Stocktake Survey (N = 215); IEA

Emergence of innovative investments demonstrate the role of ammonia for hydrogen transport in the long term

Nutrien Case Study: Nutrien

Overview

- **Description:** World's largest provider of crop inputs, services, and solutions whose business activities include the production and distribution of potash, nitrogen and phosphate products
- **Founded:** 2018
- **Headquarters:** Saskatoon, Canada
- **Ownership:** Public (NYSE: NTR)
- **Revenue (2022):** $81.5B USD

Targets

2025

- Develop a low-carbon, ammonia-powered shipping vessel

2027

- World's largest clean ammonia plant expected to come online

2030

- 30% reduction in GHG emissions per metric ton of products produced compared to 2018
- Invest and pursue transition to low-carbon fertilizers, including clean ammonia

Activities

Focus on clean and low-carbon ammonia production

- Nutrien has **1M metric tons** of annual **low-carbon ammonia production capacity** across plants
  - According to Nutrien, low-carbon ammonia uses CCUS to reduce GHG emissions by 60-80% compared to conventional production
- Nutrien is partnering with Thyssenkrupp to evaluate the construction of the **world's largest clean ammonia plant** at their existing Geismar, Louisiana site, to open in 2027
  - Nutrien defines clean ammonia as ammonia produced with more than 90% of GHG emissions reduced compared to conventional production
  - The plant will use CCUS and ATR to produce clean ammonia and have the potential to meet net-zero emissions with modifications
  - The facility would cost ~$2B and produce 1.2 Mtpa of ammonia
- Nutrien is one of 15 organizations involved in the DOE-funded REFUEL (Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids) project developing a **1 metric ton / day low and zero-carbon ammonia facility**
  - The facility will be in Morris, Minnesota and will use hybrid wind and solar generation in the fully integrated process

Note: Emission targets refer to Scope 1 emissions which include emissions from sources owned and operated by Nutrien and scope 2 emissions which include emissions from energy Nutrien purchases to operate.
Source: Nutrien, Lit. search

Regulatory clarity is crucial to support the deployment of the necessary hydrogen infrastructure

"There needs to be regulatory clarity around jurisdiction for dedicated ***interstate hydrogen pipelines****, around* ***hydrogen blending*** *in interstate natural gas pipelines, and clarity as to* ***which statue and regulatory authority*** *each of these activities would be regulated."*

- VP Policy, Electrolyzer materials provider #2

Source: Corporate interviews

"We're learning from natural gas retrofitting projects across EU and UK and are waiting to see the potential standards that will materialize"

H-21 North of England (NoE)

- **Suite of gas industry projects to prove that gas network can safely transport hydrogen in the future**[1]
- In 2017, awarded **£9M from Great Britain's energy regulator** - Ofgem (*Office of Gas and Electricity Markets)*
  - Another £1.3M was contributed by the UK Gas Distribution Networks
- H-21's first project examined the gas network in Leeds and produced a feasibility study, which concluded technically feasibility and commercial viability of decarbonizing the **UK's gas distribution networks by converting them** from NG to 100% hydrogen at an acceptable cost to the customer
- In 2018, H-21 NoE presented a **detailed engineering solution** for converting the gas networks across the NoE to hydrogen between 2028 and 2034

European Hydrogen Backbone (EHB)

- Founded in 2020, **EHB is a comprehensive study** funded by the EU's Connecting Europe Facility
- **Aims to identify and map the potential hydrogen infrastructure across Europe**, including the reuse of existing pipelines for hydrogen transportation
- These **flagship maps** demonstrate how a vision of a pan-European hydrogen network is both **technically feasible and affordable**
- The study proposes a pan-European hydrogen infrastructure network of **~53K km by 2040**, more than 60% of which would be repurposed natural gas pipelines
- An estimated **total investment of €80-143B** would be needed for capital costs of building new hydrogen pipelines and repurposing natural gas pipelines

STORE&GO

- Funded under Horizon 2020 (€28M), S&G explores large-scale **power-to-gas storage concepts** (PtG) in the form of 3 pilot projects using different power-to-gas technologies
- Aimed to convert renewable electricity into H_2, **which can then be injected into the NG grid** using existing pipelines with focus on repurposing gas infrastructure for hydrogen blending and storage[3]
- Renewable gas generated by PtG could **gradually replace fossil gas**, specifically in heating and transport applications
  - It also diminishes the need and costs for expanding the grid as **hydrogen can be transported in the existing gas grid**
- It was determined that **systems storing 40-200GW equivalent of renewable gas** could feasibly be integrated with future energy systems as costs comes down

German 2020 roadmap on H2 infrastructure

- Plans for the development of **an 1800 km network of pipelines** (800 km will be new and exclusively hydrogen pipelines , remaining **1000 km by converting already existing NG pipelines into hydrogen pipelines**)[4]
- National hydrogen network company to be founded, which would acquire existing hydrogen and NG pipelines
- Focus on linking four major industries - chemicals, refineries, steel, and heavy transport (especially maritime and aviation) **through a network of hydroducts** to achieve reduced CO_2 emissions

*"I think the whole world was a **bit too optimistic**. You could probably blend quite quickly, but if you want to use existing gas pipelines fully for hydrogen, it is **more complicated** than what we may have thought two years ago" - Head, CO2 Reporting, Renewable power producer #5*

Note: Title quote from Head of the Just Transition Office, Renewable power producer #4
Sources: 1) H21 NoE 2) European Hydrogen Backbone 3) Store&GO 4) Germany's Hydrogen Infrastructure

Storage costs will also limit cost competitiveness of non-co-located hydrogen production due to geographic and volume constraints for cheapest storage options

Gaseous storage options are cheaper but face geographic availability constraints

	Gaseous state			Liquid state		
	Salt Caverns	Depleted Oil & Gas Fields	Aquifers	Liquid Hydrogen	Ammonia	Liquid Organic Hydrogen Carriers
						
Main usage *(volume and cycling)*	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks
Working capacity	300-10,000 tons/cavern	300-100,000 tons/field	300-2,500 tons/cavern	0.2-200 tons	1-10,000 tons	0.18-4,500 tons/tank
Current LCOS *($ / kg H_2)*	$1.6-2.5	$1.2-1.3	$1.3-3.3	$4.57	$2.83	$4.50
Potential LCOS decline *(%)*	50-55%	40-45%	65-70%	75-80%	65-70%	55-60%
Geographic availability	Limited	Limited	Limited	Not limited	Not limited	Not limited

Note: Gaseous LCOS ranges show variance between estimates provided in Chen et al. and Muhammed et al.; liquid state LCOS estimates per BNEF; potential LCOS decline (%) based on % change in BNEF 'benchmark case' and 'potential LCOS' case
Source: "Capacity assessment and cost analysis of geologic storage of hydrogen…" (Chen et al., 2023), "Hydrogen storage in depleted gas reservoirs…" (Muhammed et al., 2023), BNEF (2020)

"There is a need for investment in exporting and importing hubs to use hydrogen in a meaningful way"

Hydrogen hubs

- A hydrogen hub is a centralized location that **produces, stores, and distributes hydrogen**
  - The exact **size and scope of a hydrogen hub can vary** depending on the needs of the region it serves
- Hubs are strategically located in areas that enable large-scale production, often providing access to **renewable electricity** or existing infrastructure to be leveraged by CCUS
- **Sufficient local offtake** is required to ensure economic viability of the hub
  - Excess hydrogen that cannot be consumed locally will need to be transported to demand centers, therefore increasing costs

Several factors advantage a hydrogen hub approach….

Large-scale production

- Reliable access to low-cost **renewable energy capacity** (e.g., solar, wind, etc.) is a key determinant to providing low-cost green hydrogen
- Significant **economies of scale** can be realized from large production plants
  - Installing a large-scale electrolyzer stack can cut unit costs by 80%, which translates to ~40% unit cost savings for existing green hydrogen production
- Existing expertise and infrastructure allow **scaled CCUS for blue hydrogen production** (e.g., Canada, Saudi Arabia)

Sufficient demand

- **Proximity to concentrated demand** for low-carbon hydrogen, such as from chemical and petrochemical industrial clusters, can minimize **efficiency losses from transporting** liquid hydrogen
- Prioritization of **trade agreements** that help facilitate a hydrogen marketplace (e.g., Australia's MOUs with Canada, Germany, Japan, Singapore, etc.)
- **Investments in hydrogen end-use applications** to accelerate adoption and create demand (e.g., fuel cells in Japan and South Korea)

Market conditions

- **Governmental policy** towards decarbonization across sectors accompanied by mandates to encourage hydrogen adoption, government subsidy and direct funding programs (e.g., European Green Deal), and tangible financial measures (e.g., carbon taxes)
- Presence of forward-thinking corporates with the **financial imperative to act** in accordance with consumer demands
- Existing pipeline infrastructure or access to affordable methods of **transporting and storing hydrogen** (e.g., Canada's salt caverns)

Note: Title quote from Head of the Just Transition Office, Renewable power producer #4
Source: IRENA; IRENA (2); Energia; Energy Post; BLG; S&P Global; Clifford Chance; WEF; Reuters; MTI; METI; Fuel Cells Work; Statista; KED Global; World Oil

Australia's AREH demonstrates how governments and industries can work together to develop green hydrogen industry

01 02 03 **04 ENABLING INFRASTRUCTURE**

Project vision

- In 2014 the **Asian Renewable Energy Hub (AREH)** was first proposed to government by InterContinental Energy
  - ICE was formed in 2014 to develop intercontinental renewable energy projects around the world
- In 2015, ICE **formed a joint venture** with CWP, a leading Australian RE developer

Key metrics of proposal:

Power Source
Wind + solar

Plant Size
26 GW

Market
Domestic + export

Land Req.
6,500 Km^2

Location
East Pilbara, Western Australia

Timelines
First exports (2027-2028)

Carbon Abatement
17M metric tons annually[1]

Output Volume
Hydrogen : 1.6M metric tons / yr
Ammonia: 9M metric tons / yr

Private investment

- In 2017, **Vestas and Macquarie** became investors in this joint venture project
- In 2022, **BP acquired a 40.5% stake** and renamed the project to the Australian Renewable Energy Hub reflecting its primary location

Ownership structure:

bp: 40.5%	InterContinental Energy: 26.4%
CWP Global: 17.8%	Macquarie / Green Investment Group: 15.3%

Government support

- In 2017, WA Government acknowledged the project's importance, awarding it **"Lead Agency Services status"**[2]
  - Ensures proponents are guided effectively through **approvals processes and don't fall through the cracks**
- In 2020, 15 GW of the project received environmental approval and AREH was **awarded "Major Project Status"** by the Australian Government[3]
- In 2023, Western Australian government **granted 272 hectares of land** in the Boodarie Industrial Area to be used to develop processing facilities for the project's Hydrogen export vectors

Source:) AREH Environmental Review Document 2) Lead Agency Services status 3) Major Project Status 4) Stakeholders of AREH

Bipartisan Infrastructure Law (BIL) provides $7B in funding to establish up to 10 regional hydrogen hubs across America over the next 8 to 12 years

The **US National Clean Hydrogen Strategy and Roadmap** responds to legislation set forth in the BIL and prioritizes:

1. Targeting strategic, high-impact uses for clean hydrogen
2. Reducing the cost of clean hydrogen
3. **Focusing on regional networks**
   - Investing in and scaling Regional Clean H_2 Hubs will **enable large-scale production close to high priority H_2 users**, allowing the sharing of a critical mass of infrastructure
   - These investments will drive **scale in production, distribution, and storage to facilitate market liftoff**

Policy objectives

- Funds provided by the BIL are meant to **accelerate the growth of the U.S. clean hydrogen market**
- **Projects will aim to demonstrate and develop networks for clean hydrogen** producers, potential consumers, and connective infrastructure for **production, processing, storage, and delivery**
- Data gathered from hubs will be used to **identify optimal approaches to scaling the hydrogen market**

Project structure

- Each hydrogen hub is required to **provide a minimum of 50% non-federal cost share** (for a total project cost of at least $800 million to $2.5 billion), to be **executed over 8-12 years**
- The Department of Energy has defined a **four-phase structure** for the hubs
  - Phase 1 will encompass initial planning and analysis to ensure technological and financial viability
  - Phase 2 will finalize engineering designs and business development - site access, agreements, and community engagement
  - Phase 3 will focus on implementation necessary to begin installation, integration, and construction activities
  - Phase 4 will ramp-up to full operations including data collection to analyze operations, performance, and financial viability

Application status

- Applicants hoping to fund their projects with the Regional Clean Hydrogen Hub grants **submitted their project details in April 2023**
  - Launched **H2 Matchmaker, an online information resource** to assist hydrogen suppliers and users with self-identifying collaborators and opportunities to expand development toward realizing regional hydrogen hubs
  - **20+ groups** from across the US submitted final applications to the Department of Energy (33 hubs received notices of encouragement from DoE)
  - Final **selection notifications are expected in Fall 2023**

Source: US National Clean Hydrogen Strategy Roadmap; 2) Regional Clean Hydrogen Hubs, DoE; 3) H2 Matchmaker; 4) Funding Notice for Regional Hydrogen Hubs, DoE; 5) Applications submitted for Regional H2 Hubs, S&P Global

Current physical infrastructure and regulatory frameworks are insufficient to enable use of hydrogen across end markets at scale

T&D infrastructure

- **Infrastructure to support transportation, storage, and distribution of hydrogen is needed** to enable scaled adoption of zero-carbon green hydrogen production
- Various transport and storage pathways exist, but **costs and technical limitations remain barriers to adoption** while uncertainty over the optimal pathway slows investment for new hydrogen infrastructure
- **Insufficient coordination of infrastructure and incentive policy by regional governments** has slowed development of effective “hydrogen hubs” that could circumvent costs and technological limitations associated with transport and storage

~50% of business leaders consider transport, storage, and distribution infrastructure to be a top barrier to the decarbonization of the hydrogen sector

Only 3 of 9 business leaders surveyed were somewhat or very confident that existing gas pipeline infrastructure could be used to transport hydrogen in the future

Regulatory harmonization

- **There is no consistent framework for conducting carbon accounting of hydrogen**, making it difficult for end-customers to leverage hydrogen in their plans to meet their Scope 1 targets at present
- Inconsistent definitions of “green” vs “blue” hydrogen and corresponding carbon accounting standards across jurisdictions risk **mass confusion in the absence of proactive measures to harmonize standards globally**

“We need to protect our investment, which means what would be nice to have a certificate - green hydrogen or low-carbon hydrogen certificate mechanism to be sure of the origin and the content of carbon” - Chief Sustainability Officer, Electrolyzer materials provider #1

Taking a long-term view by developing clear regulatory frameworks and infrastructure strategies will enable use of hydrogen across end markets at scale

Long-term infrastructure planning

- Long-term infrastructure planning is challenging when business models and market structure for low carbon hydrogen are only just emerging; governments can support industry by publishing **long-term hydrogen plans for specific sectors**
- **Clear and consistent signaling on the development of international trade will be particularly important for infrastructure investors – including long-term policy approaches to imports and exports**
- National governments can also continue to support the **development of innovative hydrogen transport technologies** like the DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) in the US; pumping capital into these efforts is key to its success.
- Tools like capital grants, loan guarantees etc. from development banks can facilitate and **de-risk capital flow** towards build-out planning, network expansion, and the retrofitting of existing infrastructure

Implement regulatory harmonization

- At the top of the priority list is **harmonizing standards for green hydrogen**, including the assessment of associated emissions, to lock in demand and make climate benefits clear; these **definitions must be agreed internationally** to enable cross-border hydrogen trade - while existing policies do intersect on topics like system boundaries, production pathways, emissions intensity etc., the approaches can be inconsistent
- There is also **no clear, comprehensive, regulatory roadmap** to fully assess the legal and regulatory implications of **transporting hydrogen**; creation of a central regulatory scheme through a coordinated effort across agencies can provide more clarity to stakeholders
- Development and implementation of **internationally agreed codes** and standards covering the **safe construction, maintenance and operation of hydrogen facilities** and equipment needs to continue, such as international standardization activities for hydrogen technologies (ISO/TC 197)

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