Columbia Business School
AT THE VERY CENTER OF BUSINESS

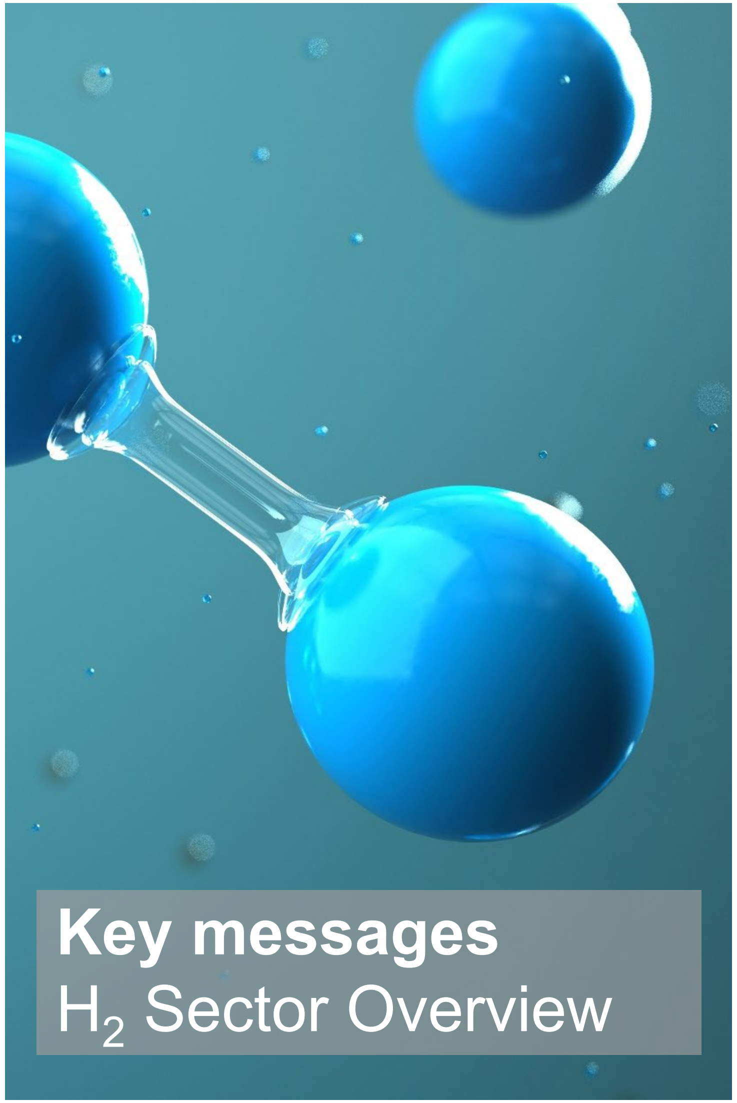
12 December 2024

Greening Hydrogen

Friedrich Sayn-Wittgenstein, Grace Frascati, Hoshi Ogawa, Nadine Palmowski, Ellie Valencia, Linfei Zhang, Hyae Ryung Kim, and Gernot Wagner

Columbia Business School
AT THE VERY CENTER OF BUSINESS

H_2 Sector Overview



Key messages
H_2 Sector Overview

Hydrogen (H_2) is a gaseous energy molecule that functions as a fuel source to produce electricity and heat. It also serves as an input for chemical processes—for example, in refining.

Global H_2 demand today remains low at ~100 Mt in 2022, accounting for less than 1% of the global energy mix. And while there are three types of H_2, most of this demand is met by grey H_2, the most carbon-intensive option.

- **Grey H_2** is produced using natural gas and therefore produces significant greenhouse gas emissions. It accounts for **~98% of current global H_2 production**.
- **Blue H_2** is also generated using natural gas, incorporating carbon capture, utilization, and storage to cut emissions. It consists of **<1% of current global H_2 production**.
- **Green H_2** is produced by electrolysis using water and renewable energy and has the potential to be a zero-carbon fuel. It makes up **<1% of the global H_2 supply**.

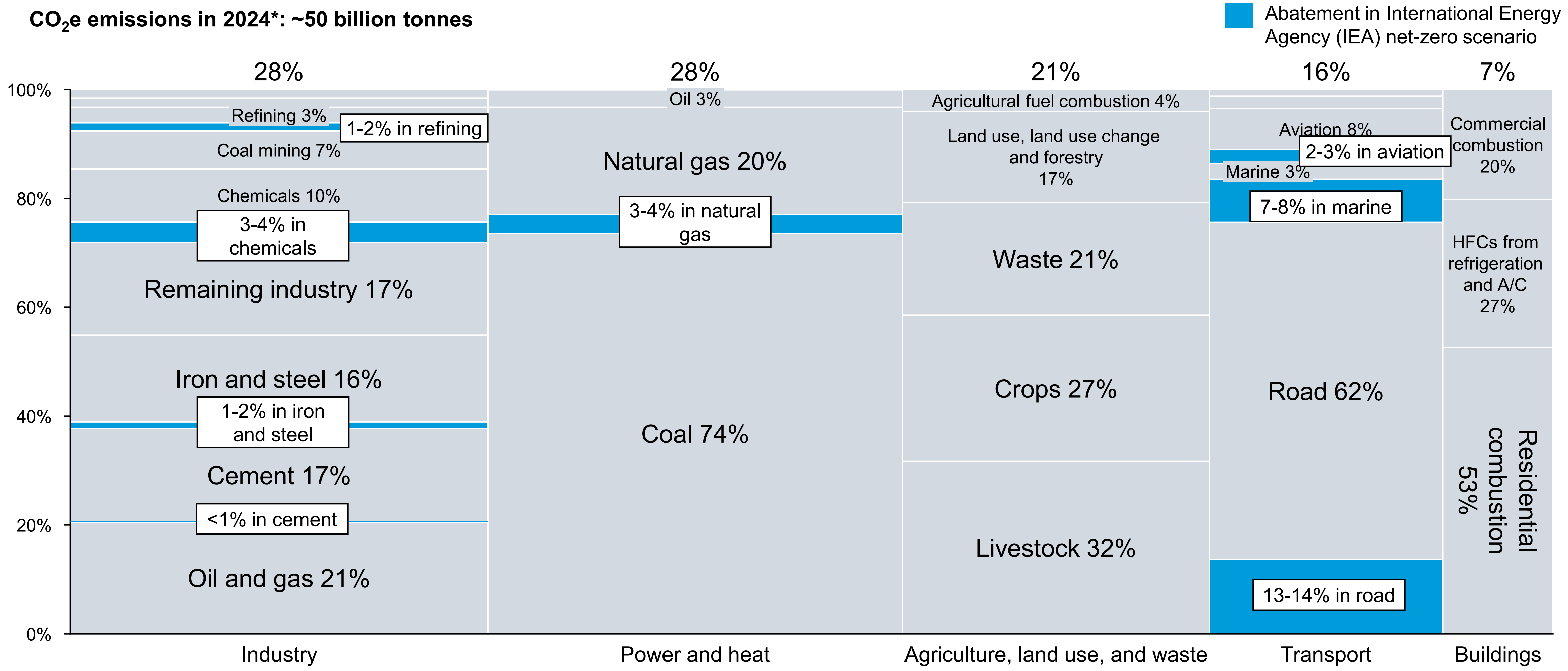
Green hydrogen holds significant potential as a **low-carbon energy source for the heat and power sector** and for **decarbonization of difficult-to-abate sectors**, including steel, cement, chemicals, and potentially transportation.

However, it currently faces **large-scale infrastructure and investment hurdles**.

For hydrogen using renewable energy to be truly green, **electricity generation** needs to be **additional, localized, and time aligned** to effectively reduce emissions.

Green H_2 targets industry, power, and transport with an estimated emission abatement of ~3 billion tonnes by 2050

CO_2e emissions in 2024*: ~50 billion tonnes



Sources: Scope 1 emissions from Rhodium Group ClimateDeck (September 2024); Scope 2 iron and steel estimate from IEA (2023); abatement estimates from IEA Net Zero Roadmap (2023); BNEF Energy Outlook (2024); other industry sources *2024 emissions based on projections

Credit: Theo Moers, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Columbia Business School

Almost all existing H_2 production today uses fossil fuels, leaving green H_2 with <1% market share

Hydrogen 'colors' represent production method and indicate carbon intensity*

	Grey hydrogen	Blue hydrogen	Green hydrogen
Production process	• Produced from natural gas **steam methane reforming** (SMR), where CO_2 emissions generated during the production are released.	• Produced through **SMR of natural gas, but the carbon emissions are captured, utilized, or stored (CCUS)**.	• Produced by **electrolyzing water** (electrolysis) using **electricity generated from renewable energy sources**.
Main inputs	CH_4 + Steam (Methane, Steam)	CH_4 + Steam + CCUS (Methane, Steam, CCUS)	H_2O + Renewable power (Water, Renewable power)
CO_2e per kg of H_2 (Scope 1)	11.0 – 13.7 kg	0.2 – 3.2 kg	~0.0 kg
Energy input per kg of H_2	~ 60 kWh	~ 60 kWh	~ 50 kWh
Current market share	~98% (all fossil fuels)	<1%	<1%
Production cost per kg of H_2	~$1-3/kg	~$2-5/kg	~$4-12/kg (High variation due to early-stage technologies and global differences in cost of renewable energy.)
Observations	• **Demand for grey hydrogen is expected to decline** as demand for green hydrogen becomes cost competitive.	• Some **question the effectiveness of blue hydrogen** for a net-zero economy, as carbon capture does not abate all carbon emissions.	• Potential challenges currently include **high costs, inability to scale**, and large ranges of demand forecasts.

*Other types of hydrogen include pink (electrolysis with nuclear electricity), yellow (electrolysis with mixed electricity, e.g. from grid) and turquoise (produced via pyrolysis of natural gas).

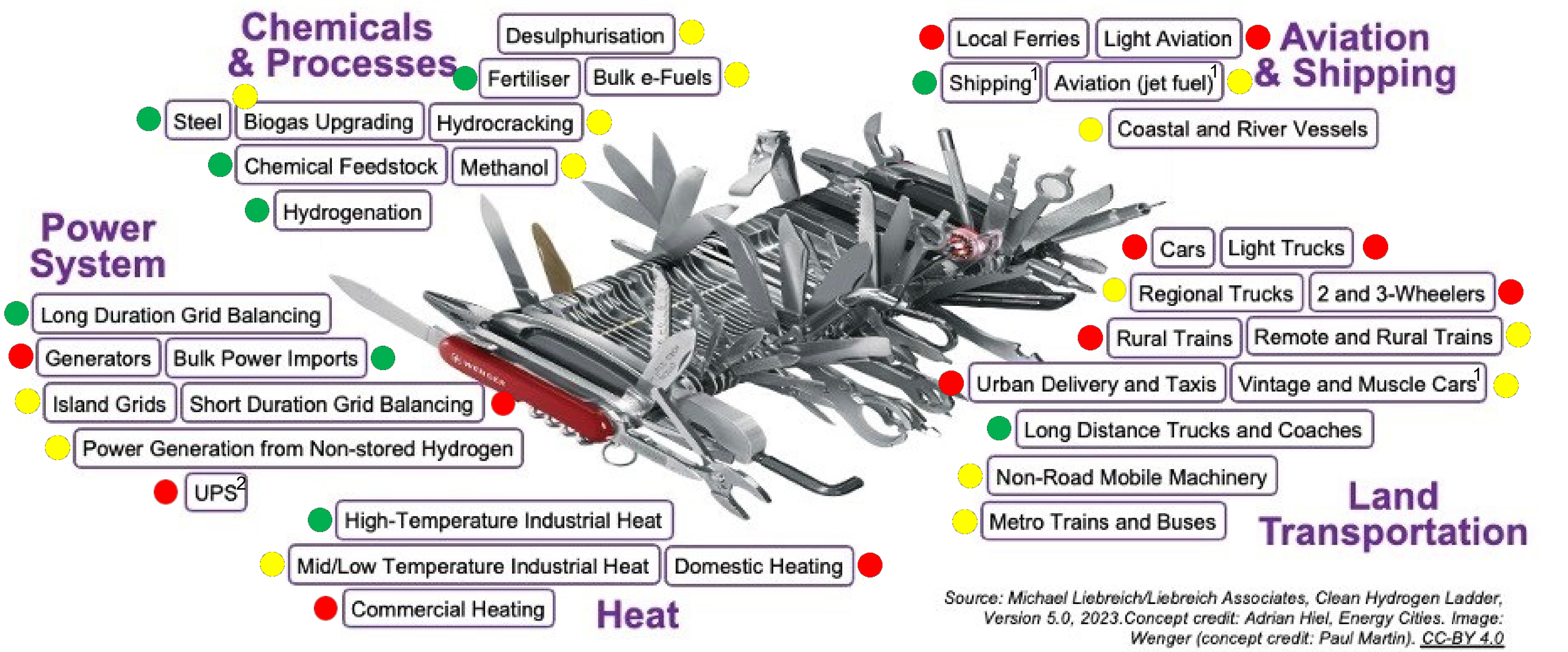
Sources: S&P Global Commodity Insights, Atlas of Energy Transition (2023); World Economic Forum, Grey, blue, green—why are there so many colours of hydrogen? (2021); IEA, Global Hydrogen Review 2022 (2023); McKinsey, Global Energy Perspective 2023: Hydrogen Outlook; various industry sources

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

H_2 dubbed Swiss Army knife of decarbonization, but application potential varies significantly across sectors

Varying levels of technical and economic potential

High application potential (green) · Mid application potential (yellow) · Low application potential (red)



Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023.Concept credit: Adrian Hiel, Energy Cities. Image: Wenger (concept credit: Paul Martin). CC-BY 4.0

Observations

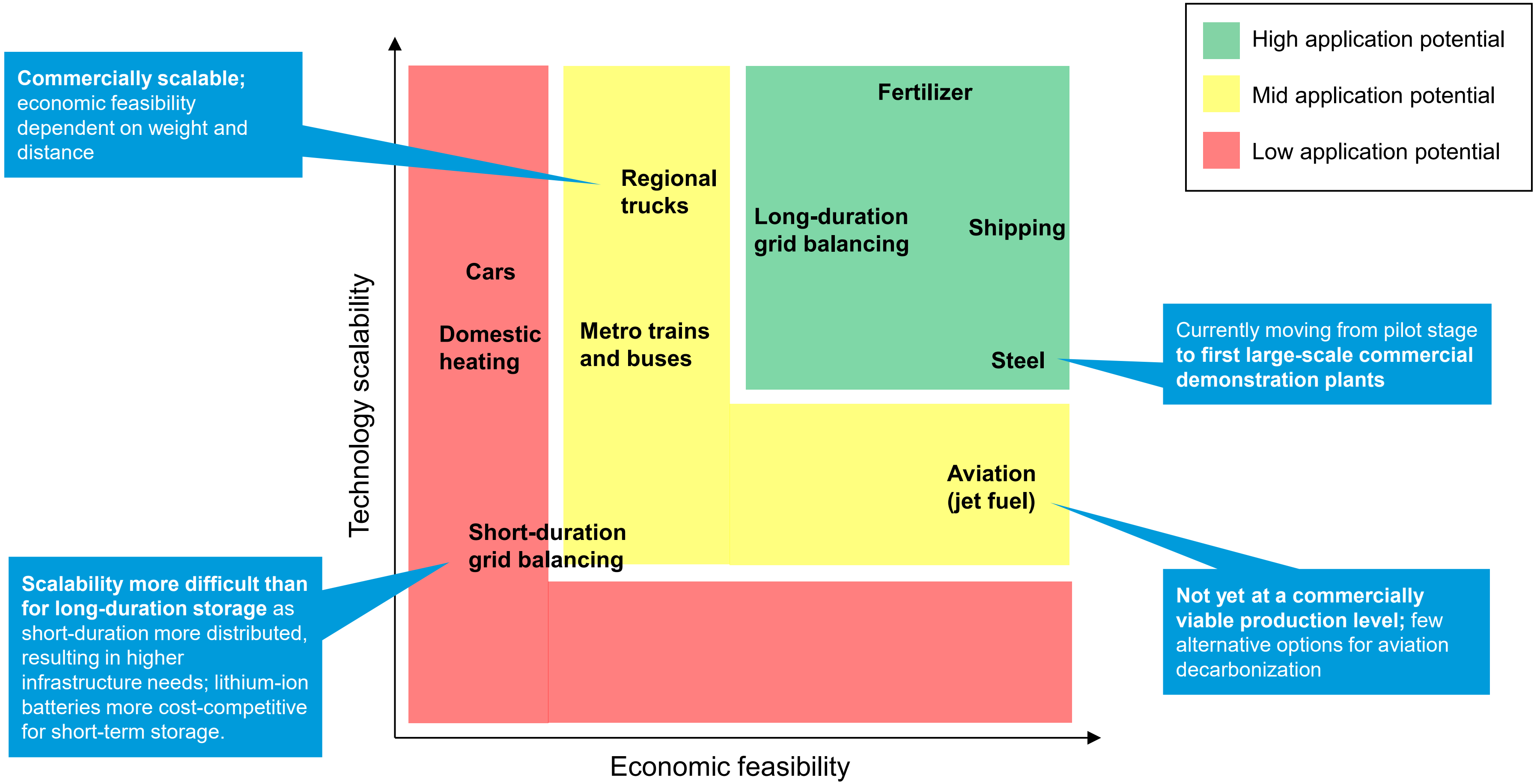
- Some refer to hydrogen as the **Swiss Army knife of decarbonization** for its extensive applications across sectors.
- While the feasibility of theoretical technology has been proved for many H_2 applications, the true **potential varies significantly between sectors**.
  - Some technologies are more in prototype stage and have not yet been tested on large-scale applications.
  - Despite its many theoretical applications, hydrogen **can fall short on cost advantages and efficiency**.
- Hydrogen is **best utilized in hard-to-abate sectors**, e.g., in industry or certain subsectors of transportation, where applications come with a **large potential for future growth**.

[1] Long-haul overseas shipping using ammonia or synthetic e-fuels as a clean energy source; [2] uninterruptible power supply

Sources: Liebreich & Associates (with concept credit to Paul Martin), The Clean Hydrogen Ladder (2021); Redefining Energy, Hydrogen…it's complicated! (2021)

True potential for green and blue H_2 determined by viability of use cases as well as economic feasibility

Evaluation of selected H_2 technology use cases



Observations

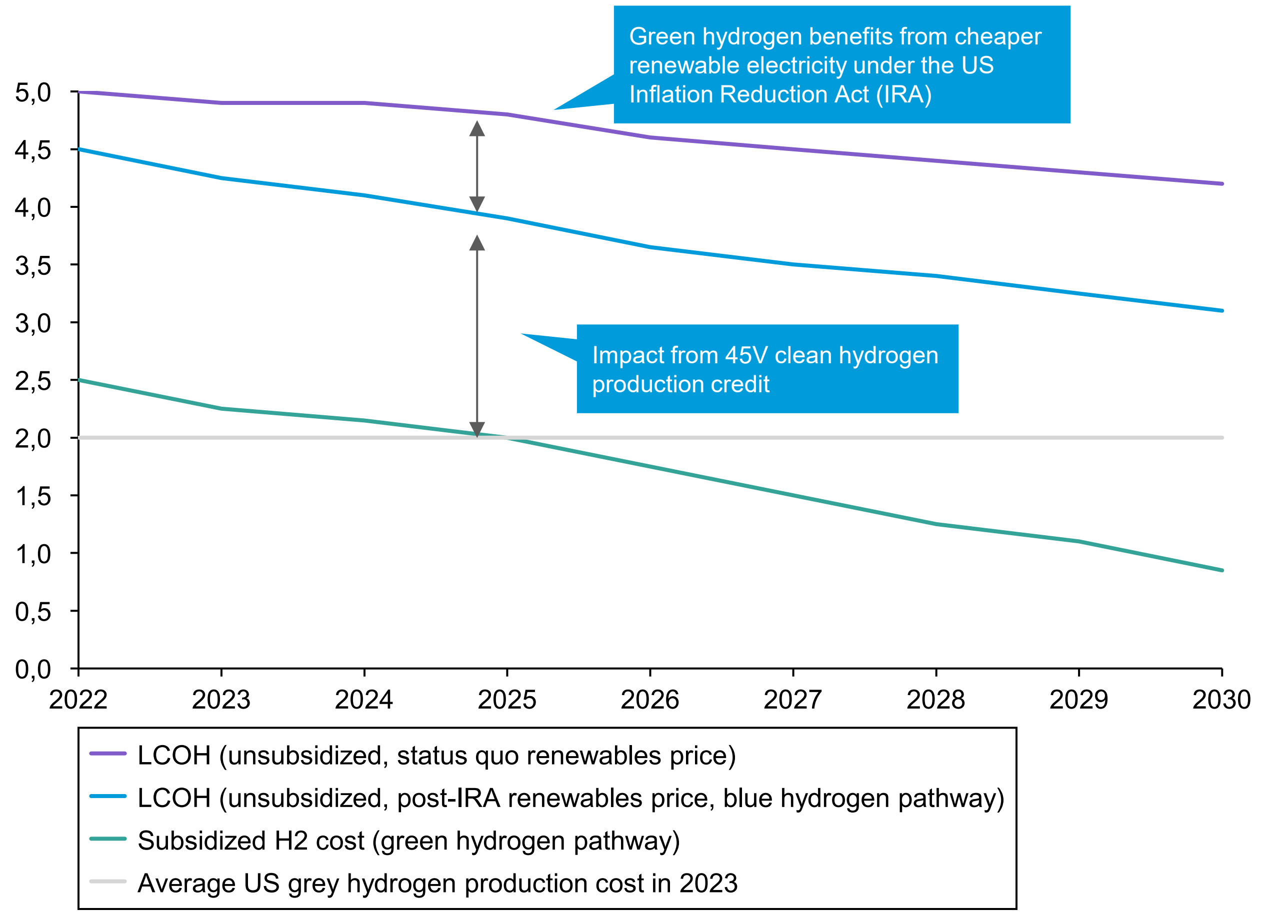
- Beyond theoretical technological feasibility, **two main factors determine** whether blue and green H_2 are a **realistic decarbonization solution** for a specific use case
  - **Technological scalability:** Is the technology sufficiently mature, scalable and viable for commercial application?
  - **Economic feasibility:** Is H_2 the best available decarbonization technology? Are there other technologies that are more (cost-) efficient?
- Evaluation among the two metrics shows how **use case viability is in many cases driven by economic feasibility; i.e., the availability of better or cheaper alternative technologies** (electric vehicles for cars, heat pumps for heating)

Source: IEA, Net Zero Roadmap (2023); Liebreich & Associates (with concept credit to Paul Martin), The Clean Hydrogen Ladder (2021); various industry sources

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Potential of H_2 in technologically viable sectors requires political support to become economically competitive

Expected levelized cost of green hydrogen (USD/kg)



Three requirements for H_2 to be green

Additionality	Localized	Time matching
Renewable electricity must be specifically built for H_2 production. **Diverting power from existing clean plants increases dependence** on conventional power sources and **carbon emissions**.	**Dedicated local clean** energy sources are linked to electrolyzers. The mere buying of "green" certificates is insufficient.	H_2 production is **synchronized with clean electricity procurement**. Some electrolyzer technologies (e.g., PEM) work with intermittent input.

Observations

- **Integrating these production requirements with public support (tax credits, subsidies) enables the scale-up** of green hydrogen in technologically viable sectors.
- Although potentially delaying ramp-up, this **ensures effective allocation of public funds** and **avoids stranded assets** or lock-in of less ideal solutions.

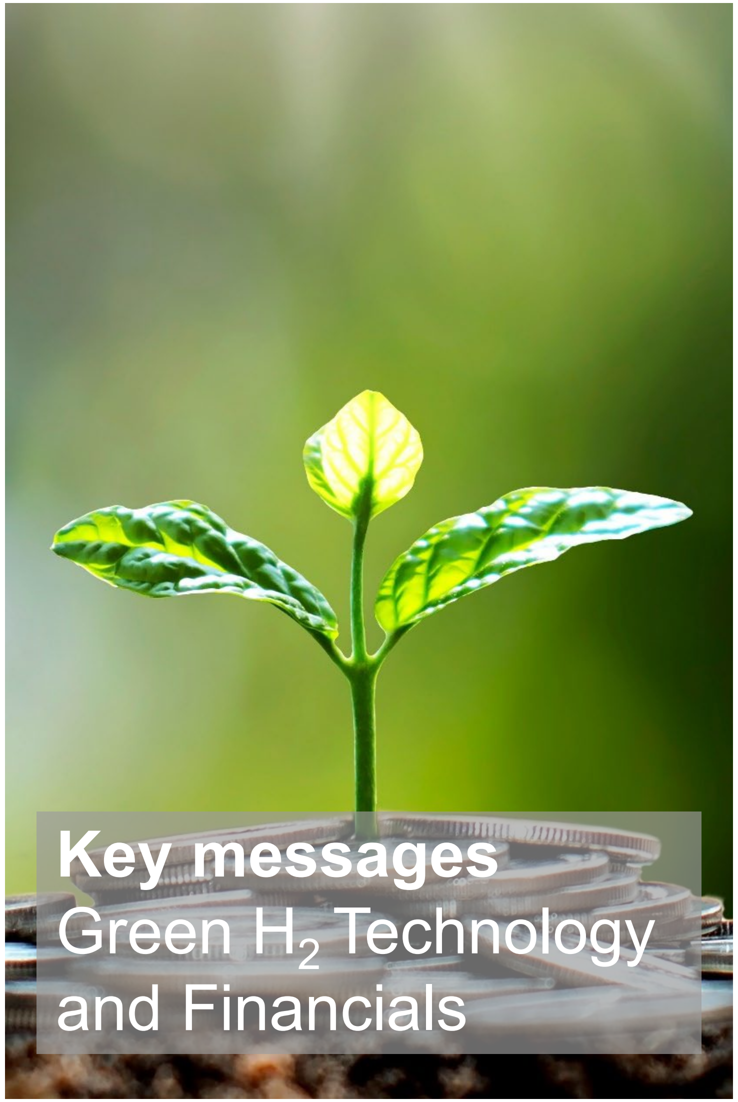
Sources: Roland Berger, Green Hydrogen Report (2023); BNEF, Green Hydrogen to undercut grey sibling by end of decade (2023); Cullenward and Wagner, *The Washington Post* (2023)

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Columbia Business School

Columbia Business School
AT THE VERY CENTER OF BUSINESS

Green H_2
Technology and Financials



Green H_2 production costs remain substantially higher than those of grey and blue H_2, presenting a major barrier to widespread adoption. The H_2 sector faces infrastructure and investment limitations. However, progress is underway through increased subsidy incentives, technological advancement, and expansion of renewable energy production.

- **Grey H_2** costs an average of **$1-3/kg,** driven by the low cost of fossil fuels and natural gas.
- **Blue H_2**, while similarly benefiting from lower fossil fuel prices, incurs additional expenses due to carbon capture, utilization, and storage, raising its cost to **$2-5/kg.**
- **Green H_2**, in contrast, averages between **$4-12/kg**, with the higher costs attributed to the development of electrolyzer technology and reliance on renewable energy sources.

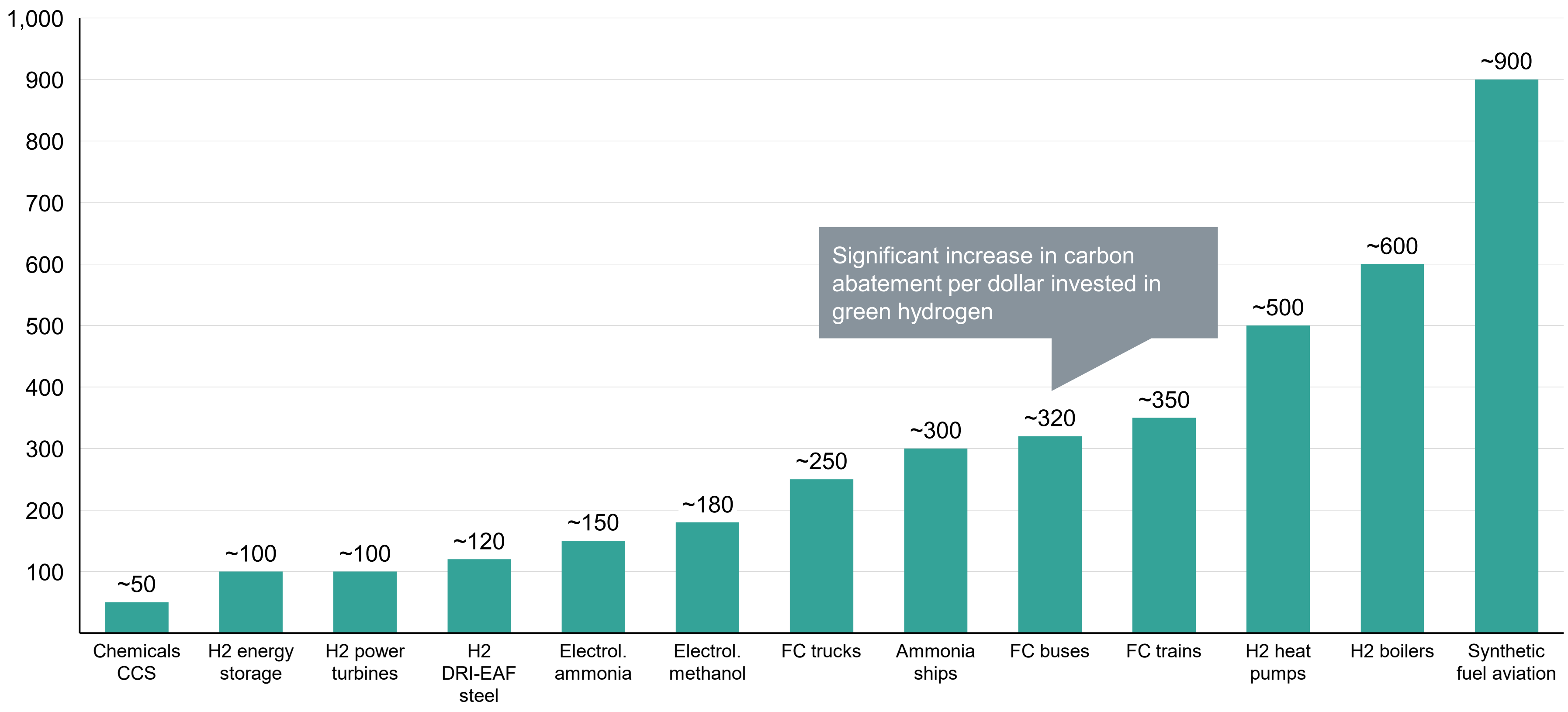
Green H_2 remains significantly more expensive than H_2 from less sustainable sources, with a cost premium of approximately **$2-10/kg** as of 2023. These price variations are influenced by regional factors, levels of private investment, and the extent of government support.

Today, **alkaline water electrolysis (AWE) is the most widely used method for green H_2 production,** primarily due to its low cost. **Proton exchange membrane (PEM) electrolysis, however, is also expected to play a significant role in the future,** as it is better suited to manage the variability of renewable energy inputs.

Research and development in electrolyzer technology could lead to **significant cost reductions and enable specialized applications**. For instance, solid oxide electrolyzers can leverage excess industrial heat for enhanced efficiency, while anion exchange membranes offer a compact solution for space-constrained environments.

Primary challenge for green H_2 is balancing its high production cost with its significant emissions abatement potential

Green hydrogen on a carbon abatement cost curve ($/t CO_2e)



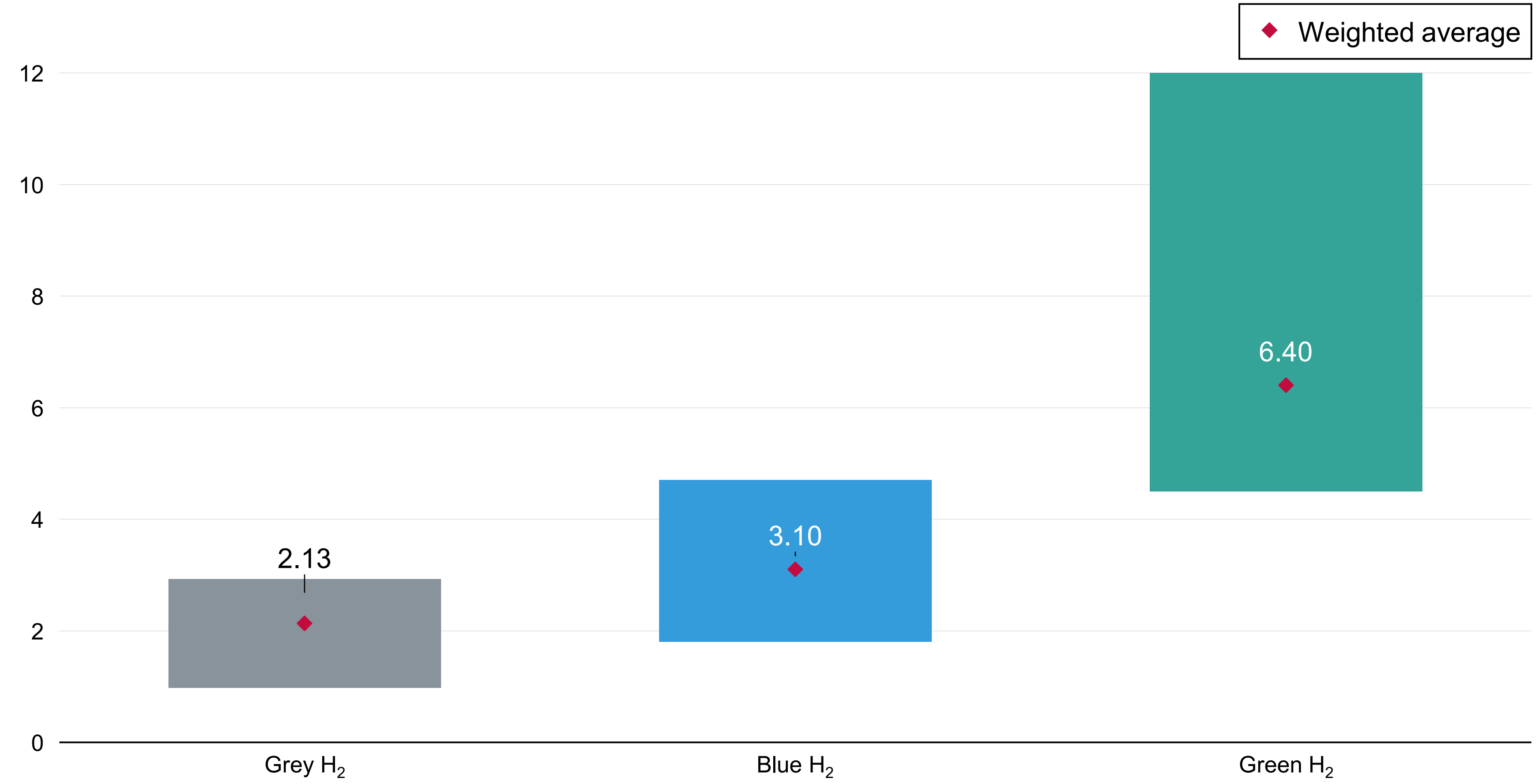
Observations

- The diverse applications for green H_2 provide **decarbonization solutions with varying cost implications**.
  - The use of H_2 for chemical production, energy storage, and power generation is currently cost efficient, with an abatement cost of 100 USD/t CO_2e equivalent.
  - The use of H_2 for producing synthetic aviation fuels represents the highest price point of ~900 USD/t CO_2e.
- **Carbon abatement costs are expected to decrease in the future**, driven by reductions in the costs of electrolyzers and renewable energy.
- The adoption of H_2 applications will be determined not only by the cost per ton of carbon abatement but also by the **competitiveness of alternative decarbonization technologies**.

Source: Goldman Sachs, Carbonomics: The clean hydrogen revolution (2022)

Current production costs of green H_2 carry a substantial price premium over fossil-based alternatives

Average green hydrogen premium more than double that of grey hydrogen in 2023 ($/kg)



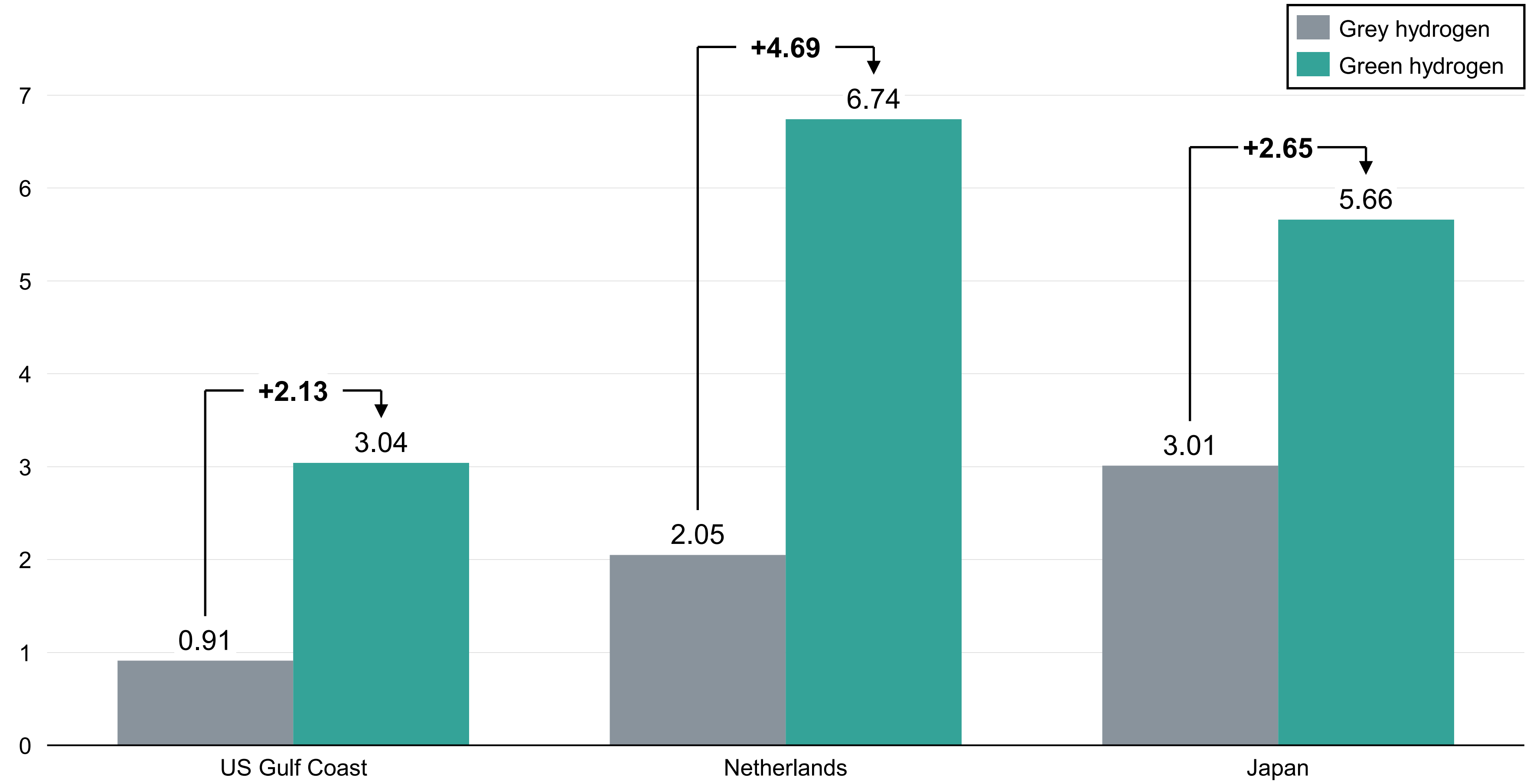
Observations

- In 2023, **green H_2 production costs** ranged from $4.50 to $12.00/kg, **averaging $6.40/kg**.
  - Blue hydrogen costs are lower, ranging from $1.80 to $4.70/kg.
  - Grey hydrogen is the least expensive, varying between $0.98 to $2.93/kg.
- The largest cost drivers for green H_2 are **electrolyzers** and the price of **renewable electricity**.
- Despite its current premium, **green H_2 could achieve cost parity with blue and grey H_2** through economies of scale and advancements in technology.
- To enable hydrogen offtake, **infrastructure, transport, and storage costs must be added to production costs**.

Sources: BNEF, Green Hydrogen to Undercut Gray Sibling by End of Decade (2023); Center on Global Energy Policy, Columbia University, Demystifying Electrolyzer Production Costs (2023)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Relatively small green H_2 premium in US compared to EU and Japan

Green hydrogen premiums vary regionally, ranging from $2-5/kg



Observations

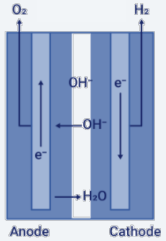
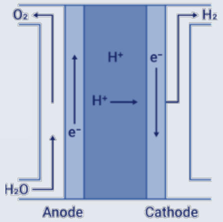
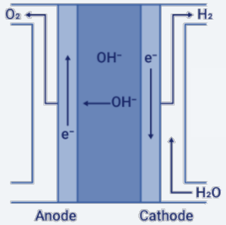
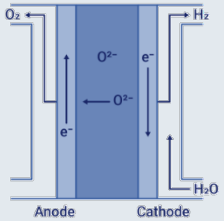
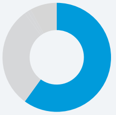
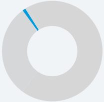
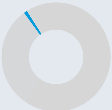
- **Green H_2 premiums** refer to the additional cost of green H_2 compared to more carbon-intensive alternatives, such as grey and blue H_2.
- The **Gulf Coast** reported the lowest average price for green hydrogen among three major regions, reflecting the impact of **significant US government investments aimed at reducing costs**.
  - The US Department of Energy's Hydrogen Shot initiative targets a reduction in clean hydrogen production costs **to $1/kg by 2031**.
- Key efforts to lower green H_2 hydrogen costs include **substantial investments in infrastructure and tax incentives**, such as the 45V tax credit.

Source: S&P, Global Commodity Insights Report (restricted)

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Alkaline water electrolysis now dominant; proton exchange membrane costlier yet suitable for intermittent electricity

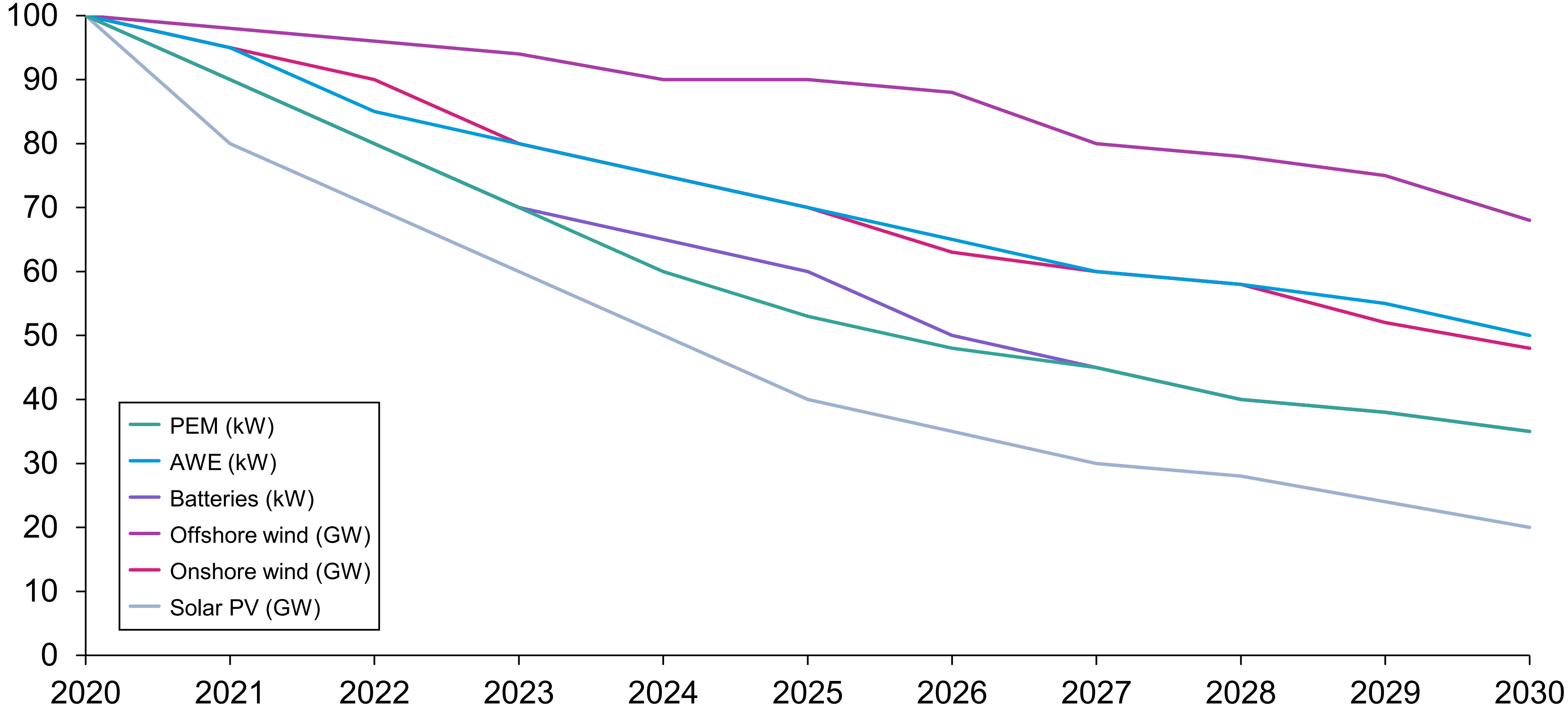
Scalability, cost, temperature, and use cases to shape future technology adoption

	Alkaline water electrolysis (AWE)	Proton exchange membrane (PEM)	Anion/ hydroxyl exchange membrane (AEM/HEM)	Solid oxide electrolyzer (SOEC)
Description and schematic overview	• **Electrolysis of alkaline water** using nickel electrodes 	• **Water electrolysis with solid polymer membrane** and precious metal electrodes 	• **Like PEM design; replaces precious metals** and titanium with nickel and steel 	• **Water steam electrolysis** at high temperature (700-1000°C) via solid oxide or ceramic membrane 
Market share	• **60% market share**, leading technology 	• **30% market share** (higher in Europe and North America) 	• **Small market share**, future growth potential 	• **Small market share**, ideal for high waste-heat use cases 
Advantages	• **Scalability** of manufacturing, **cost**	• **Compact size, controllability** of production allows management of intermittent renewable energy input	• **Compact size, potential cost reduction** because made with more easily obtained materials than PEM	• **More efficient** than AWE and PEM due to lower voltage levels
Limitations	• **Continuous electricity supply needed** for optimal operation	• **Higher cost, potential shortage of rare metals** such as iridium	• **Reduced durability**	• **High capital investment**, high temperatures required
Investment cost	~$600/kW	~$800-1,250/kW	>$930/kW	>$1,850/kW
Big players	LONGi, McPhy	ITM, nel	Enapter, HydroLite, Cipher Neutron	sunfire

Sources: Center on Global Energy Policy, Demystifying Electrolyzer Production Costs (2023); US Department of Energy, Hydrogen Production: Electrolysis (2022); IEA, Electrolyzers (2023); IRENA, Green Hydrogen Cost Reduction (2020); Hydrogen Council, Hydrogen Insights May 2023 (2023); graphics by ID Tech Ex from Alex Holland at EE times; various industry sources
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Both AWE and PEM expected to follow renewables cost reductions and efficiency improvements

Clean tech CapEx for green hydrogen indexed to 2020 levels ($/kW or GW)



Observations

- **The cost of acquiring and operating green hydrogen electrolyzers is expected to decline significantly** over the next decade compared to 2020 levels.
  - Among the various renewable energy sources, **solar PV is projected to experience the fastest cost reductions**, while offshore wind is expected to take longer, to lower its capital expenditures.
  - **Clean H_2 electrolyzers are anticipated to follow a similar trend**, with a projected CAGR of -60% for both PEM and alkaline technologies.
- Green H_2's cost reductions will primarily be driven by **technology advancements, increased productivity** in PEM and alkaline electrolyzers, and **greater capital investments in the sector**.

Sources: Goldman Sachs, Investment Research Carbonomics (2022); McKinsey, Global Energy Perspective 2023: Hydrogen outlook (2023)

Columbia Business School
AT THE VERY CENTER OF BUSINESS

Green H_2 Industry Trends

Global demand for green and blue H_2 is expected to grow substantially, with estimates indicating an **increase from 125 million tonnes per annum in 2030 to 460 Mtpa by 2050**. This growth will be driven by both traditional industrial uses and emerging applications, particularly in commercial transport, which is projected to become the largest new demand driver by 2040.

By 2050, green H_2 is forecasted to dominate global hydrogen production, accounting for 50 to 65% of the total supply.

- Regional demand growth will initially be led by China and North America, while at the sector level, **industry will dominate with offtake agreements**, followed by transport, especially in long-haul shipping.
- **Green and blue H_2 trade is projected to expand fivefold between 2030 and 2050**, with North America emerging as the largest net exporter.
- The US and Canada are expected to lead green and blue H_2 exports, supported by robust policy frameworks. **Long-distance transportation of H_2 will be driven by its use in end products like ammonia and synthetic kerosene**.

Key players in the fossil fuel, energy, and utility sectors are recognizing H_2's potential as a critical energy carrier. They are incorporating H_2 into their strategies, acquiring large-scale hydrogen assets, and increasing investments in green and blue hydrogen projects.

H_2 currently used primarily in industrial processes and petroleum refining, with limited application in heat and power sectors

Large-scale use of grey H_2 in industry and refining, with some early green H_2 in heat and power

	Industry	Refining	Heat and power
Role of H_2	• H_2 is used as feedstock for **synthetic fuels** (e.g., methanol) or **fertilizers** (e.g., ammonia). • Other industries such as steel and cement aim to adopt **H_2 to decarbonize their production processes**.	• The oil refining process uses H_2 for **hydrotreating and hydrocracking**, reducing sulfur content of oil to **produce cleaner fuels like diesel and jet fuel**.	• H_2 can generate electricity through fuel cells or be blended into gas turbines for **power generation in internal combustion engines and heating applications**.
Current market dynamics	• The **industry sector consumed 53 Mt of H_2 in 2022,** with 60% used for ammonia production, 30% for methanol production, and 10% for iron and steel production.	• H_2 use in **refining reached 41 Mt in 2022**, driven to record levels by strong demand in North America and the Middle East.	• As of 2023, H_2 accounted for only **0.2% of the global electricity mix**.
Green H_2 adoption challenges	• Cost reductions are crucial in the green H_2 sector to **compete with low natural gas and grey H_2 prices**.	• Most H_2 used in refining is **produced on-site as a byproduct of catalytic reformers** or ethylene crackers, rather than sourced externally.	• H_2 use in electricity generation faces **compatibility challenges** with existing **infrastructure and combustion systems**.

Sources: EIA, Hydrogen Explained (2023); IEA, Global Hydrogen Review 2023 (2023); Methanol Institute, Renewable Methanol; Wood Mackenzie, Low-carbon hydrogen demand in refining could reach 50 Mtpa by 2050 (2022); Yara, Green fertilizers: everything you need to know

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

While commercial transport applications remain limited today, they are expected to play a bigger role in the future

Green H_2 is expected to play a key role in decarbonizing the commercial transport sector

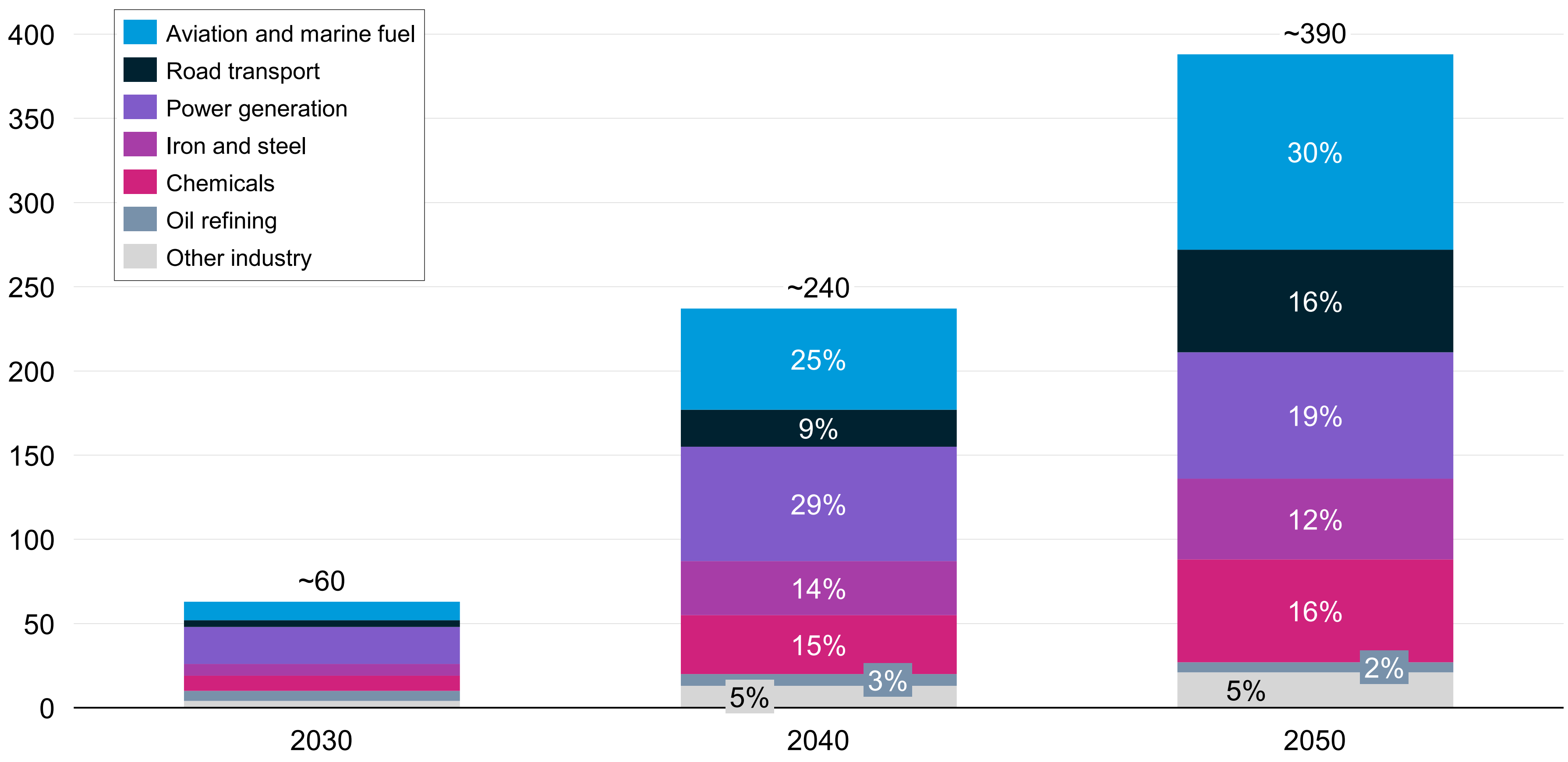
	Road transport	Shipping	Aviation
Role of hydrogen	• H_2 fuel cell electric vehicles (FCEVs) provide **faster refueling, longer ranges, and lighter fuel weight** compared to electric vehicles.	• H_2 **can power vessels either directly** as liquid hydrogen **or through synthetic fuels** like ammonia and methanol.	• **H_2 fuel cells** could power planes for short-haul flights. • **H_2-based sustainable aviation fuel (H_2-SAF)** has the potential to replace traditional jet fuel.
Current market dynamics	• In 2023, **China represented 95% of FCEV trucks globally**, while South Korea accounted for 50% of private FCEV cars.	• In 2023, the **global shipping industry ordered 298 vessels** designed to operate on alternative fuels, including 138 on methanol, 11 on ammonia, and five on H_2.	• In 2022, Rolls Royce and easyJet successfully ran an aircraft engine on H_2.. • **Airbus plans to introduce a H_2-powered aircraft to market by 2035**.
Green hydrogen adoption challenge	• FCEVs face **limitations due to insufficient fueling infrastructure** and **competition with battery electric vehicles** for market share.	• H_2's **lower energy density** compared to alternative marine fuels **makes transport on ships more challenging, necessitating carriers** like ammonia or liquid hydrogen.	• The main challenge for **H_2-SAF** is its high cost. • Sustainable aviation fuel is an **existing drop-in fuel for aircrafts, requiring no retrofitting** of aircrafts or infrastructure.

Sources: Airbus, ZEROe; CSIS, Hydrogen: The Key to Decarbonizing the Global Shipping Industry? (2021); DNV, Maritime decarbonization efforts propelled as orders for alternative-fueled vessels grow (2024); European Maritime Safety Agency, Potential of hydrogen as a fuel for shipping (2023); Global Maritime Forum, Ammonia as a shipping fuel (2023); IEA, Global Hydrogen Review 2023 (2023); International Air Transport Association, Liquid hydrogen as a potential low-carbon fuel for aviation; Rolls Royce, Rolls Royce and easyJet set new world first (2022)

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Under IEA's full decarbonization scenario, demand for green and blue H_2 is expected to increase to ~400 Mt by 2050

Projected demand for green and blue hydrogen by sector (Mtpa)



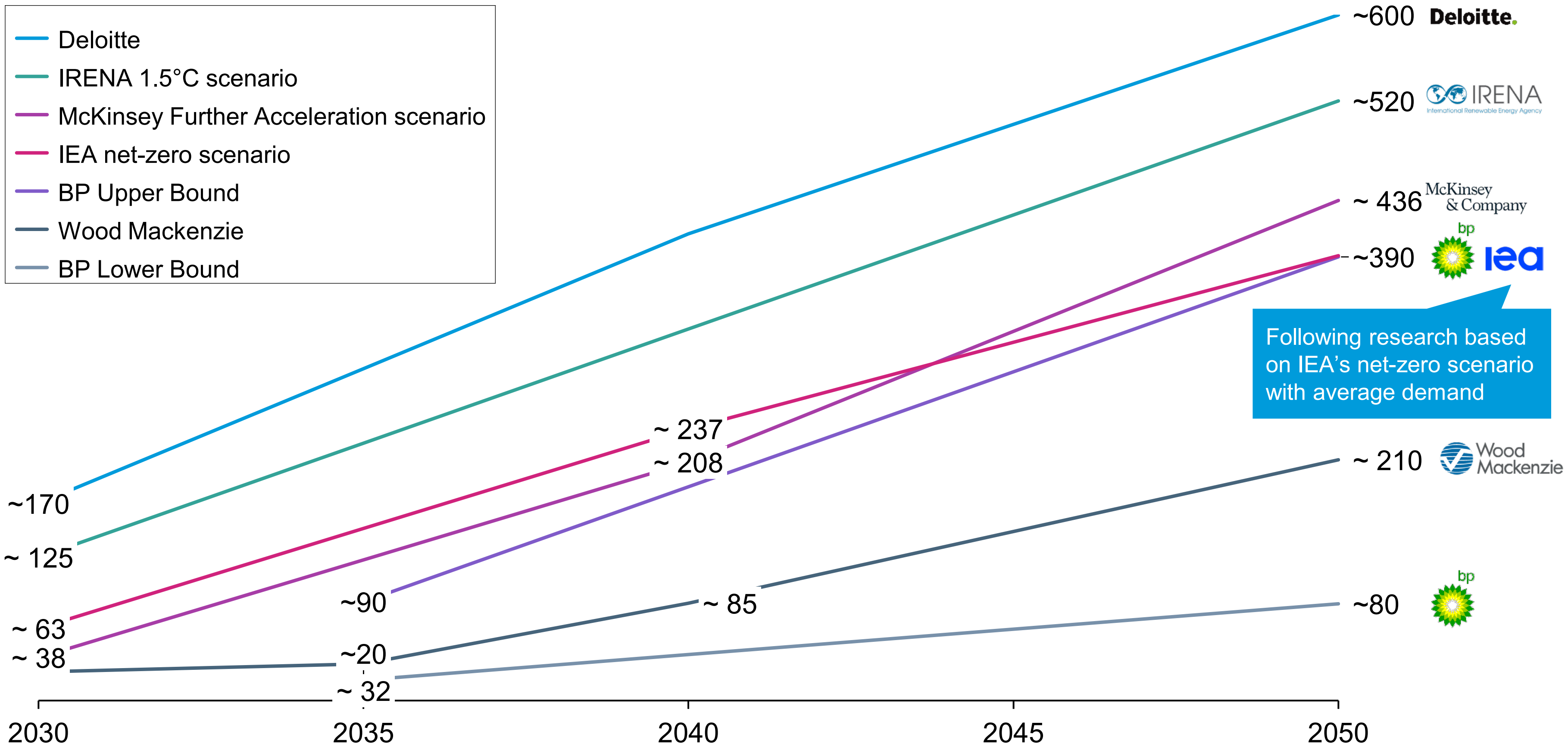
Observations

- **Green and blue H_2** adoption across existing and emerging applications could **drive H_2 demand to ~240 Mt by 2030 and ~390 Mt by 2050**, compared to less than 1 Mt in 2023.
- **The transport sector will be the main driver** of demand, accounting for ~34% in 2040 (across aviation, marine, and road transport) and ~46% of total demand in 2050.
- **Industry** (including chemicals and iron and steel) **and power generation** will also be significant contributors to demand.
  - Industry demand will be driven by both conventional uses (replacing grey H_2 with green and blue H_2) and new applications.
- **Oil refining will continue to have relatively low demand** for green and blue H_2, as grey H_2 is a byproduct of refining and unlikely to be replaced by green or blue H_2 in the near term.

Note: Demand scenarios differ a lot; demand numbers derived from IEA's net-zero scenario
Sources: IEA, Net-zero scenario hydrogen outlook (2023); McKinsey, Global Energy Perspective 2023: Hydrogen outlook (2024)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Green and blue H_2 industry demand projections vary widely around IEA's ~400 Mt per year by 2050

Projected demand for green and hydrogen, 2030-2050 (Mtpa)



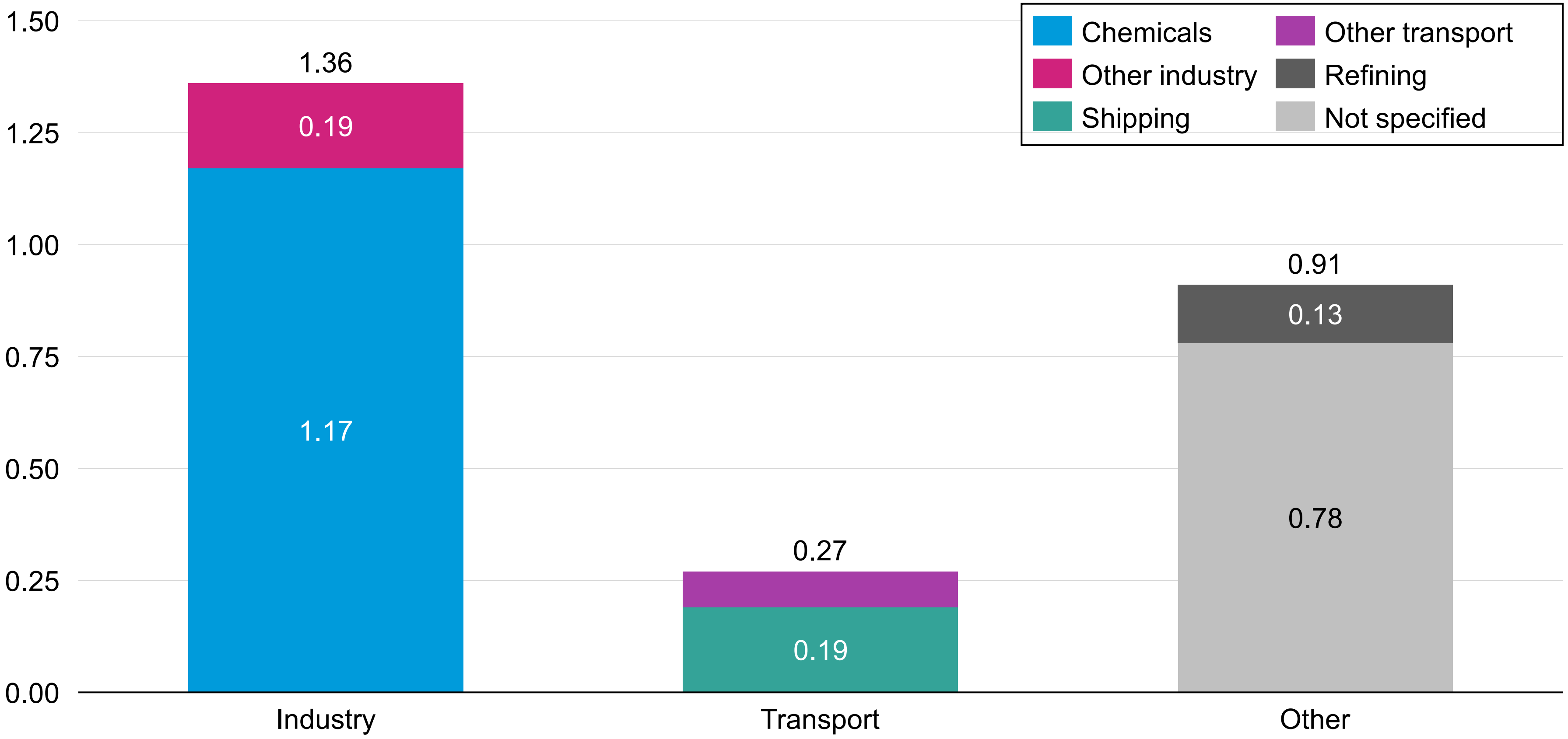
Observations

- In nearly all scenarios, a **substantial increase in demand for green and blue H_2** is expected.
  - Projections suggest total annual volumes **could approach 400 Mt by 2050**.
  - With 50 kWh/kg of green H_2, this would require **~20,000 TWh of green electricity by 2050** (today: ~25,000 TWh).
- **Meeting future demand will require a significant scale-up in production**; in 2022, demand for green and blue H_2 was ~1 Mt.
- At the same time, the IEA estimates the **demand for a 1.5°C pathway will be around ~390 Mt in 2050**, even under its ambitious net-zero scenario**.** This is much lower than several industry projections, such as Deloitte's estimate of ~600 Mt.

Note: Demand and abatement differ due to varying carbon intensities and emission proportions across sector. Clean H_2 includes both blue and green H_2.
Sources: IEA, Net-zero scenario hydrogen outlook (2023), BP, Hydrogen (2023); Deloitte, Green hydrogen: Energizing the path to net zero (2023); McKinsey, Global Energy Perspective 2023: Hydrogen outlook (2023), IEA, Hydrogen (2023), IRENA, World Energy Transition Outlook (2023), Wood Mackenzie, 2050: The Hydrogen Possibility (2024)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Chemicals industry dominates H_2 offtake agreements

Industrial sector expected to dominate hydrogen offtake agreements by 2030 (Mt)



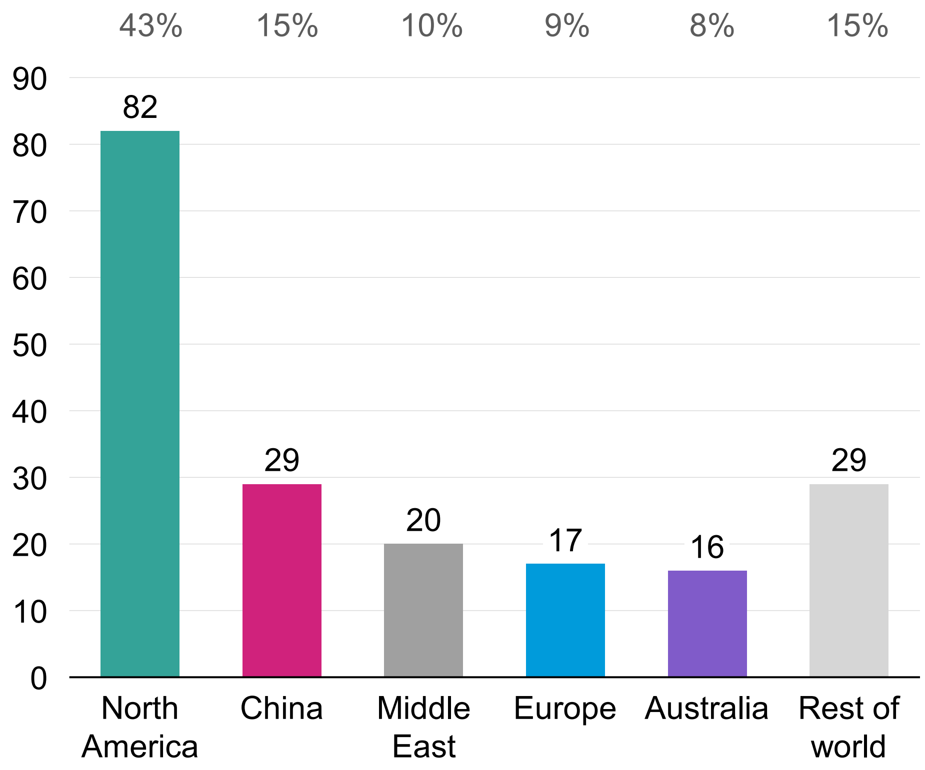
Observations

- The **industrial sector is leading in securing offtake agreements**, with ~1.3 Mt of demand, half of which has already been firmly implemented.
  - Within the industrial sector, the **chemicals** subsector accounts for 85% of the agreed volumes, largely driven by ammonia production.
- While progress in the **transport sector has been slower**, **significant agreements have been made**, particularly in shipping.
  - Major logistics companies have signed agreements for synthetic methanol and synthetic marine diesel.

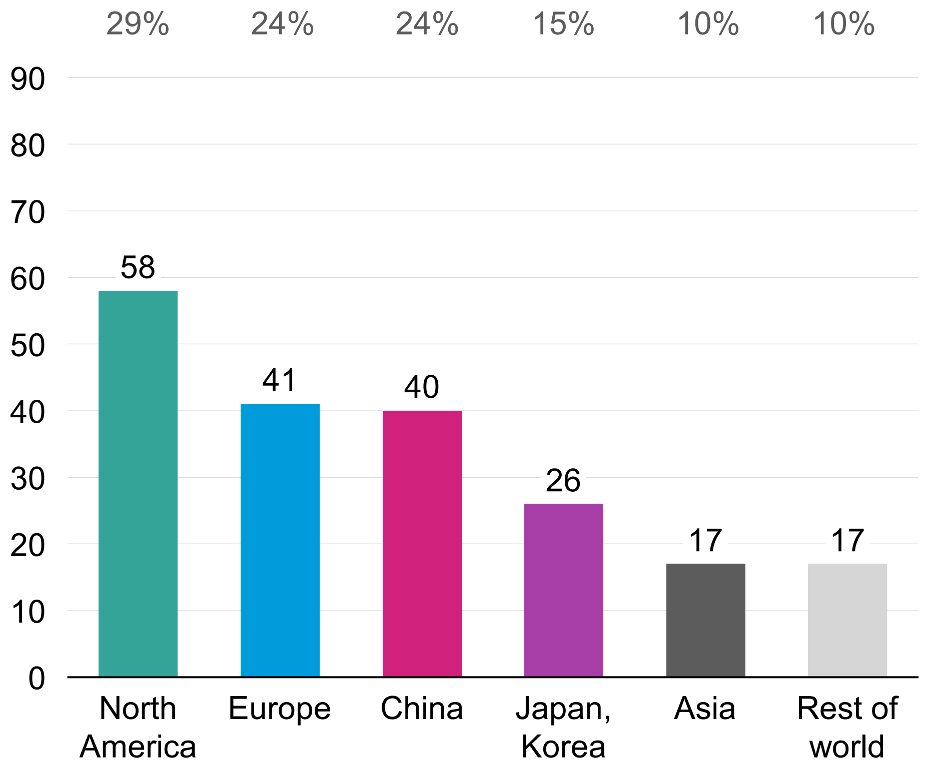
Source: IEA, Global Hydrogen Review 2023 (2023)

North America expected to become the largest green H_2 net exporter, while China and Europe lead as net importers

Long-distance green and blue H_2 supply projections, share by region (Mt, 2050)



Long-distance green and blue H_2 demand projections, share by region (Mt, 2050)



Observations

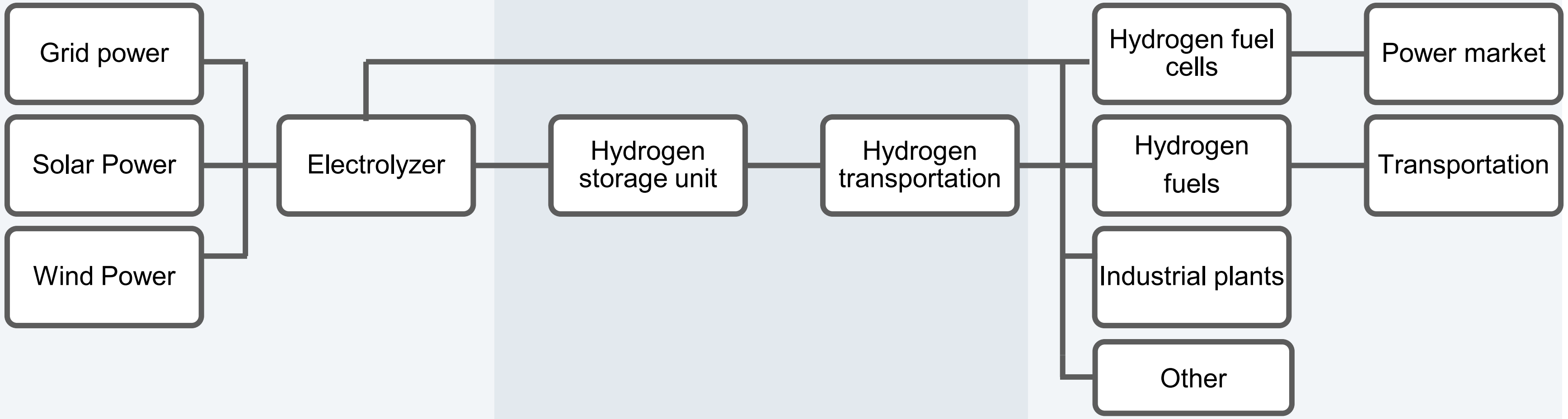
- **North America** is anticipated to **lead in blue and green H_2 production**, driven by supportive policies in the US and Canada.
- By 2050, **North America and China** are projected to contribute **58% of global blue and green hydrogen supply and 53% of demand**.
- **North America is expected to become a net exporter**, with ~30% of its blue and green H_2 supply transported over long distance.
- **Europe and China are projected to be net importers**, relying on importing for ~59% and ~25% of their hydrogen demand, respectively.
- In addition to long-distance trade, **robust inner-continental hydrogen transport** is anticipated, such as from Iberia and the Nordic countries to Central Europe.

Source: Hydrogen Council, Global Hydrogen Flows - 2023 Update (2023)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Green hydrogen value chain is global, with production and end-use applications often separated by significant distances

Green hydrogen value chain spans three main fields

Production	Distribution	Application
• Production will be **concentrated in regions with abundant and low-cost renewable energy**.	• **Depending on the distance, transport occurs via pipelines** or is **shipped long distance,** with storage hubs along the transport route.	• **Location of end-use applications is mainly determined by regional demand**; some use cases might move to places with low-cost renewables.



Observations

- The H_2 value chain from **production to distribution and application** operates globally, as **supply and demand are often geographically distant.**
- **Inner-continental H_2 transport is primarily conducted via pipelines**, with three options:
  - Blending into existing gas pipelines (up to ~5% of the mix can be H_2)
  - Retrofitting old gas pipelines
  - Building new hydrogen-only pipelines
- Long-distance H_2 transport relies on marine shipping **technologies** such as:
  - Liquified hydrogen
  - Ammonia
  - Liquid organic hydrogen carriers
- H_2 **storage is essential at various points** along the value chain, including pre- and post-shipping as well as pre-industry use.

Source: IRENA, Geopolitics of the Energy Transformation (2022)

Three potential H_2 carriers are suitable for marine transport

Shipping technologies face significant adoption challenges at various stages

	Liquified hydrogen (LH_2)	Ammonia (NH_3)	Liquid organic hydrogen carriers (LOHC)
Description	**Produced via extreme cooling**, it can be used directly as fuel or converted back into gas at the destination.	**Synthesized into ammonia for transport**, enabling either direct use as green ammonia or conversion back into H_2 through racking.	**Transported through hydrogenation and post-transport dehydrogenation** by covalently bonding with liquid organic molecules, such as dibenzyl toluene.
Energy density[1]	0.071 kg/L (at -253°C)	0.12 kg/L (at -33°C)	~0.05 kg/L (at 25°C)
Process steps	Green H_2 → Liquefaction → Marine transport, storage → Regasification → Distribution and end use	Green H_2 → NH3 synthesis → Marine transport, storage → NH3-cracking to H2 → Distribution and end use	Green H_2 → Hydrogenation → Marine transport, storage → Dehydrogenation → Distribution and end use
Adoption challenges	**Energy intensive**; liquefaction is expensive	**Energy intensive** and **expensive cracking**; health risks	**Expensive hydrogenation**; **lack of technology readiness** for scale-up
Share of volume of announced projects[2]	~5%	~35%	~10%
Market readiness	Pilot stage, infrastructure not yet widely available	Established shipping, cracking at pilot stage	Pilot projects, infrastructure for some molecules available

Observations

- Marine H2 transport **requires cooling or carriers** due to H_2's low energy density.
- Different H_2 carriers face **bottlenecks related to infrastructure and costs**, with technology choices influenced by specific use cases:
  - Ammonia synthesis is relatively cost efficient but expensive to crack, making it ideal for direct use as green ammonia (e.g., fertilizers).
  - Liquid H_2 liquefaction is expensive but suitable where liquefaction is necessary for end use as fuel.
- **The market's dominant shipping technology is still undecided:**
  - Half of announced shipping projects have yet to decide on a specific technology.
  - Among projects specifying a carrier, ammonia accounts for 35% of volume, followed by LOHC at 10% and liquid hydrogen at 5%.

[1]Energy density of gaseous H_2 at 1 atm. Temperature and pressure is 8.9E-10 kg/l; [2] only 50% of announced projects have already decided on technology.

Sources: Spotalisano et al., Liquefied hydrogen, ammonia and liquid organic hydrogen carriers for harbour-to-harbour hydrogen transport (2024); Hydrogen Council, Global Hydrogen Flows-2023 Update (2023), Hydrogen Council, Hydrogen Insights (2022)

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

As forecasts for clean H_2 demand increase, major oil companies and utilities are positioning themselves to capture market share

Multibillion-dollar investments and equity stakes are becoming increasingly popular

Large-scale investment in M&A for blue H_2

aramco

- **In 2024, Aramco acquired a 50% equity stake** in Blue H_2 Industrial Gases Company.
- **Blue H_2 will be transported by pipeline** through Saudi Arabia's Eastern Province, **with potential for regional exports**.
- The investment aligns with Saudi Arabia's **National Green Hydrogen Strategy, which aims to invest $36 billion** in green and blue hydrogen by 2030.

$36B investment in green and blue H_2 production and export hub

bp

- **In 2022, BP acquired a 40.5% equity stake** worth $36 billion in the Australia Renewable Energy Hub (AREH).
- Upon completion, AREH will produce **1.6 Mt of green H_2** or 9 Mt of green ammonia annually, supported by 26 GW of clean power.
- The H_2 and ammonia produced by AREH will supply both Australia and **regional markets, including Japan and South Korea**.

Allocating significant funds to transition from gas to H_2 in power generation

NEXTera ENERGY

- In 2023, the utility announced a commitment of **$20 billion to decarbonize its operations in the US.**
- A key part of its decarbonization strategy is **converting 16,000 MW** of natural gas power plants **to operate on green hydrogen**
- **Florida Power & Light**, the largest utility in the US, established the Cavendish NextGen Hydrogen Hub to **test hydrogen blends for turbines**.

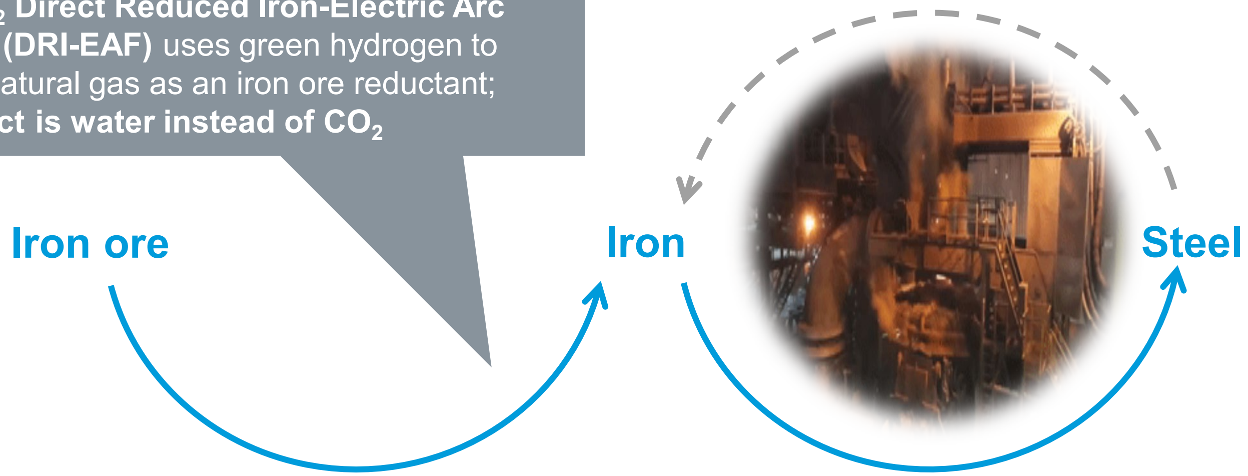
Sources: Air Products, Air Products, Aramco, ACWA Power, and Air Products Qudra Reach Financial Close (2023); Aramco, Aramco to acquire 50% stake in Air Products Qudra's Blue Hydrogen Industrial Gases Company (2024); BP, BP to lead and operate one of the world's largest renewables and green hydrogen energy hubs based in Western Australia; NextEra Energy, Climate Change 2023 (2023); NextEra Energy, Florida Power & Light company announces completion of clean hydrogen hub (2023); NextEra Energy, NextEra Energy sets industry-leading Real Zero goal (2022)

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

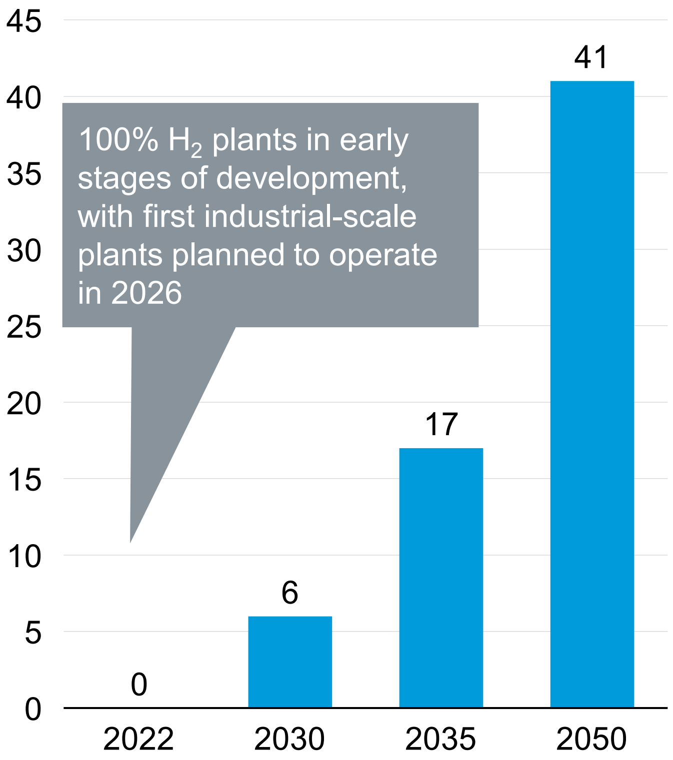
Green steel production possible key driver for green H_2 demand, with each tonne of Green H_2 DRI-EAF steel requiring ~50-60kg H_2

Green H_2 direct reduced iron with decarbonization potential of ~90% compared to now dominant Blast Furnace-Basic Oxygen Furnace (BF-BOF)

Green H_2 Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) uses green hydrogen to replace natural gas as an iron ore reductant; **byproduct is water instead of CO_2**



H_2 demand for steel (Mt)



Sources: Center on Global Energy Policy at Columbia University, Low-Carbon Production of Iron & Steel (2021); IEA, Iron and Steel Technology Roadmap (2020); IEA, Net-zero scenario hydrogen outlook (2023); McKinsey, Decarbonization challenge for steel (2020); BNEF, Scaling Up Hydrogen (2024)

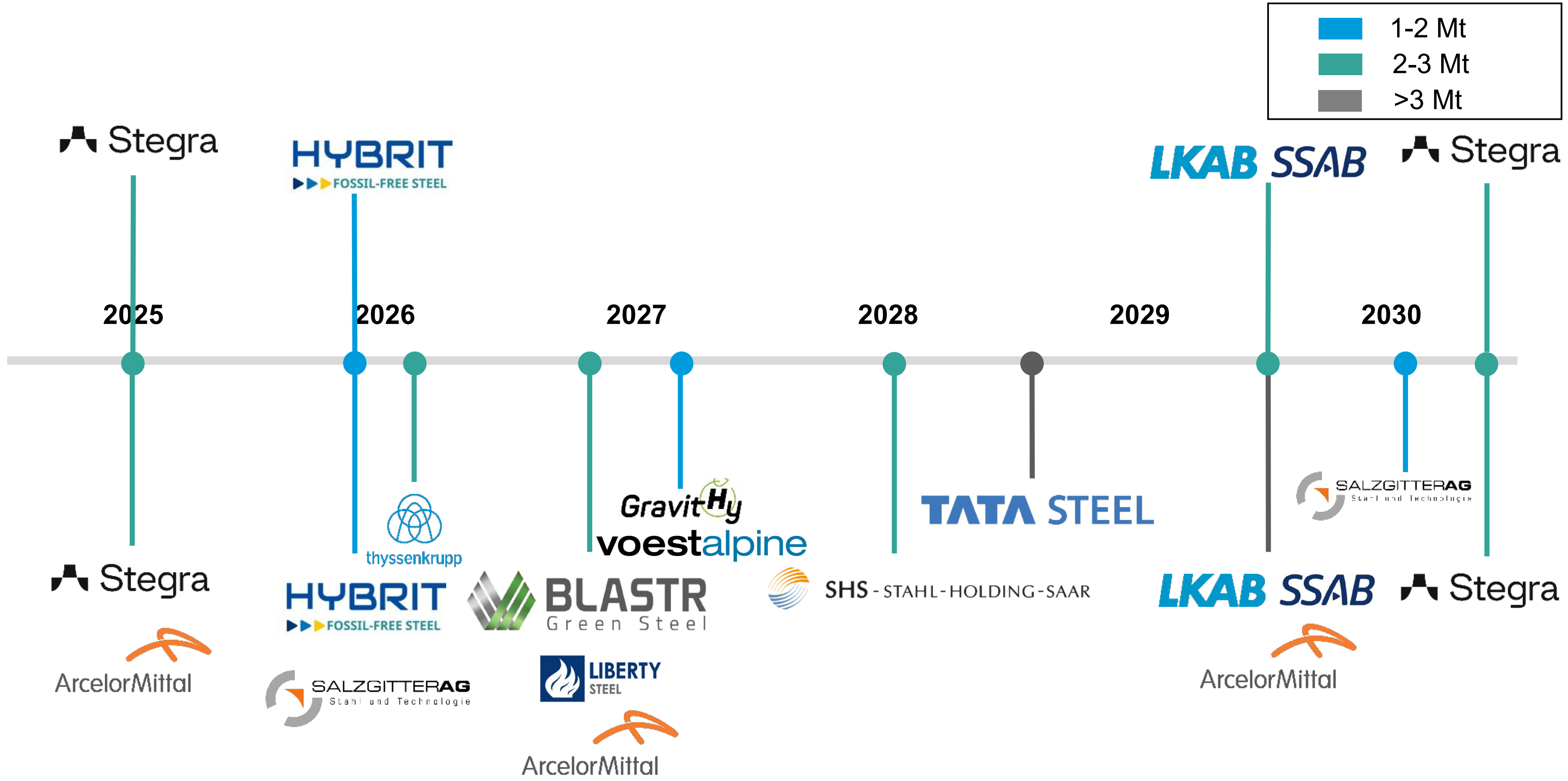
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

~40 Mt of green steel project announced in Europe by 2023, implying 2-2.4 Mt green H_2 demand

As of 2023, ~40 Mt of green steel projects announced in Europe alone

Four green steel plants announced as of 2021

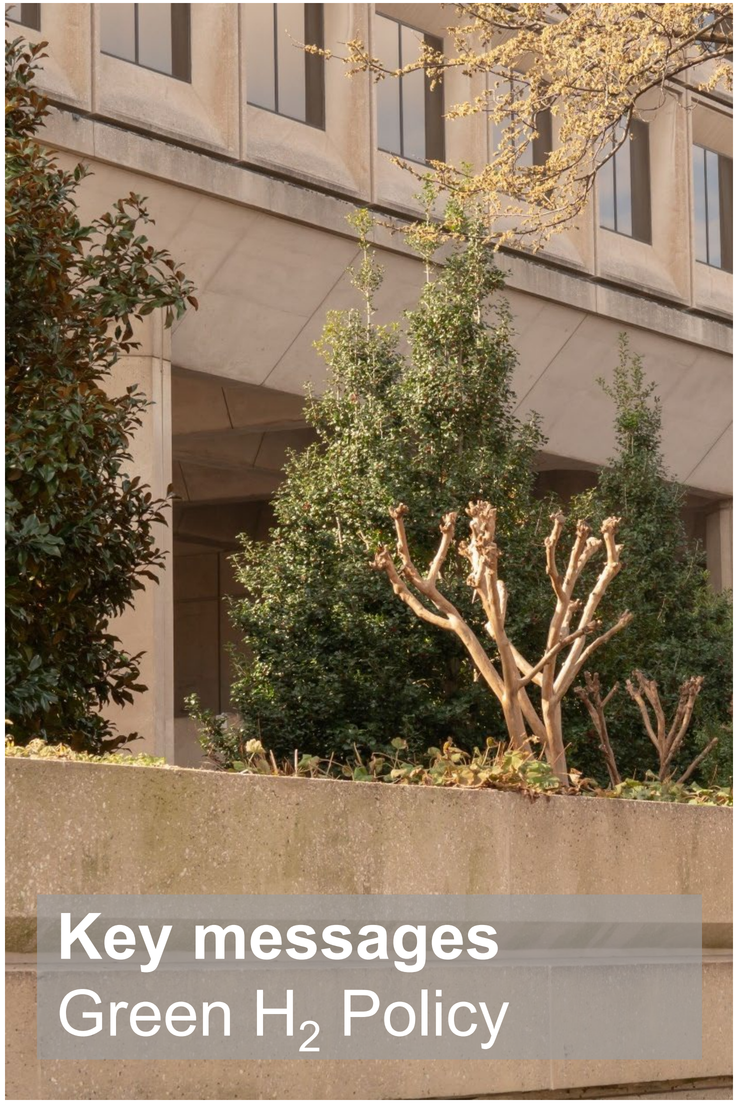
As of 2023, ~40 Mt green steel announced in Europe by 2030



Source: Columbia Business School, H2 Green Steel (2024)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Columbia Business School
AT THE VERY CENTER OF BUSINESS

Green H_2 Policy



Key messages
Green H_2 Policy

Over 30 governments, representing ~80% of energy-related CO_2 emissions, have adopted national green H_2 strategies. The EU and US are at the forefront, supporting research, development, and demonstration projects, while deploying grants and tax incentives to mitigate investment risks and establish standards for large-scale hydrogen initiatives.

Financial incentives have significantly reduced electrolyzer costs and accelerated green hydrogen adoption. However, challenges such as **high initial investments, uncertainty in long-term returns, and the need for infrastructure and storage remain significant**.

Additional **policy frameworks and collaborations** are required to **scale production and build efficient supply chains** despite legal and financial barriers.

– The EU, US, Australia, Japan, and other countries have set **ambitious electrolyzer capacity and hydrogen production goals**. The EU aims for 40 GW of electrolyzers by 2030, while the US aims to achieve a green H_2 price of $1/kg within the next decade.

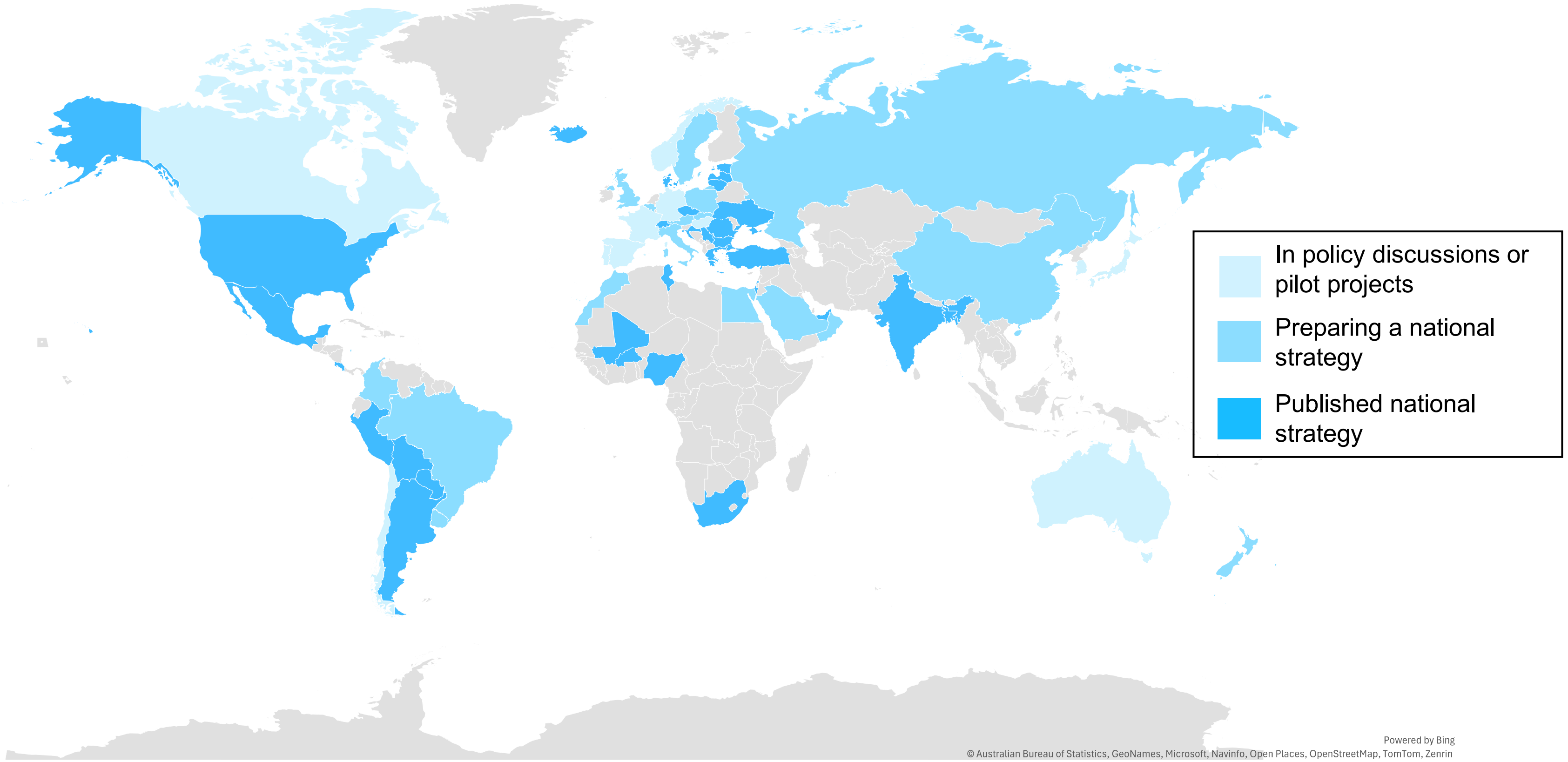
– Research initiatives, such as the **US Department of Energy's $64 million H2@Scale program, are focused on reducing costs and advancing hydrogen technologies**. Infrastructure projects in the US include retrofitting natural gas pipelines and developing new hydrogen storage facilities.

– The **US Bipartisan Infrastructure Law dedicates $8 billion to establish seven Regional Clean Hydrogen Hubs**, targeting emissions reductions of 1 to 9 Mt/year. In addition, the Inflation Reduction Act introduces the Clean Hydrogen Production Tax Credit (45V), offering incentives up to $3/kg for low-carbon-intensity projects.

Government subsidies, tax credits, and financial initiatives are essential for making green H_2 cost competitive with fossil-based grey H_2, driving its adoption in the industrial sector and improving its scalability and economic viability.

Over 30 governments, representing ~80% of energy-related CO_2 emissions, have implemented green H_2 strategies

Global adoption of hydrogen strategies



Observations

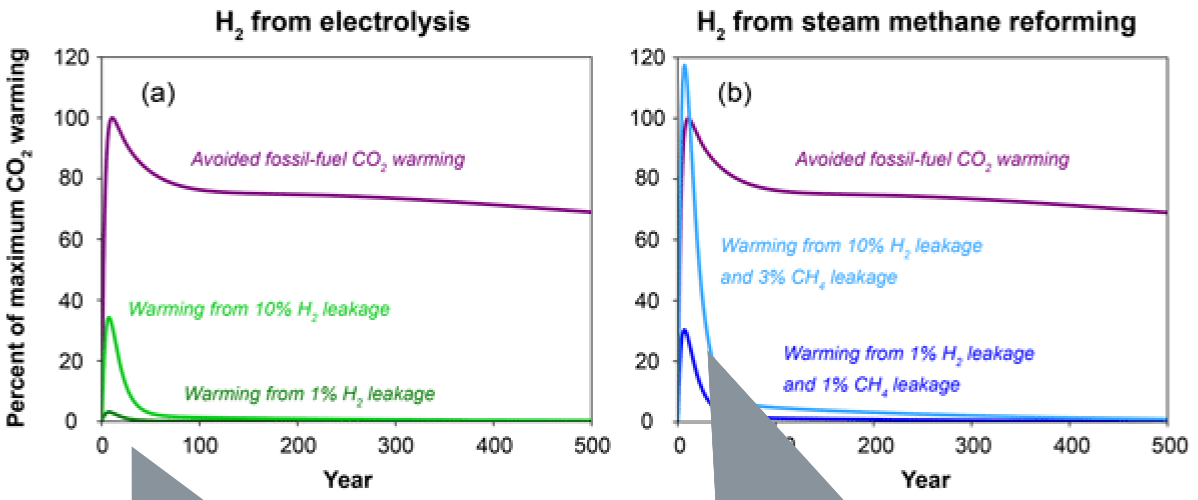
- Around **30 countries have established national H_2 strategies**, with an additional 23 countries in the process of developing their own proposals.
- The **EU and US are leading efforts to support the research, development, and demonstration** of H_2 projects and technologies.
- Governments are introducing mechanisms such as grants, loans, and tax incentives to **mitigate investment risks**, alongside growing efforts to implement **standards and certification schemes for green H_2.**
- Despite growing governmental involvement, **large-scale green H_2 projects remain underdeveloped in many emerging markets**.

Source: IRENA, Green Hydrogen Supply (2023)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Columbia Business School

Methane and H_2 leakage a concern for the production of grey and blue H_2, not for green H_2

Green hydrogen with less warming even with large H_2 leakage



Green H_2 is better than fossil alternative, even with 10% H_2 leakage

Methane (CH_4) leakage is a potential concern with grey or blue H_2 production, not with green H_2

Observations

- While H_2 production and transport play a crucial role in reducing carbon emissions, they can also **contribute to the greenhouse gas effect if not managed properly**.
  - Methane, a greenhouse gas 28x more potent than CO_2, can leak into the atmosphere during blue and grey H_2 production.
  - H_2 itself is an indirect greenhouse gas and can contribute to global warming if significant leakages occur.
- Other potential environmental effects of H_2 production include **water and land use, though these effects appear small compared to the overall benefits in most regions**.
- **Despite these challenges, H_2's potential to significantly reduce carbon emissions far outweighs the global warming impact of its potential leakage.**

Sources: Ocko and Hamburg, Climate Consequences of Hydrogen Emissions (2022), Duan and Caldeira, Comment on “Climate Consequences of Hydrogen Emissions” by Ocko and Hamburg (2022) (2023)

Government incentives play a critical role in accelerating green H_2 adoption, with the EU, US, and other regions leading the charge

Countries are actively exploring various incentives to accelerate the adoption of green and blue H_2

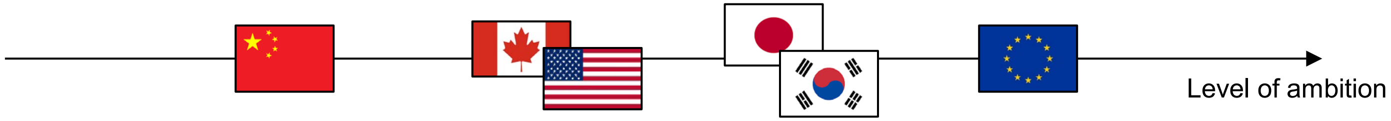
	Description	EU	Australia	Japan	United States
Financial incentives	• **Temporary subsidies can boost green H_2 production** by reducing investment risks and lowering costs. • **Public investment in infrastructure**, such as pipelines and storage, is essential for the **rapid scaling of a H_2 economy**.	• **Infrastructure grants** through the **Important Projects of Common European Interest** support investments in pipelines and storage.	• **Hydrogen Headstart** supports large-scale green and blue H_2 production with $4 billion in grants. • The country provides a $2 **tax incentive** for each kg of clean H_2.	• **Contracts for Difference** program aims to bridge the price gap between clean H_2 (domestic and imported) and fossil fuels.	• The **Inflation Reduction Act and 45V tax incentives** promote the adoption of green and blue H_2 production.
Policy and regulatory frameworks	• **Government targets, strategies, and standards** such as criteria defining green H_2 can build market trust and **accelerate scaling efforts.**	• The EU aims to **roll out 40 GW** of electrolyzer capacity **by 2030**. • EU-wide **CertifHy** certification program is being implemented to standardize green and blue H_2.	• **Australian Renewable Hydrogen Hub** supports development of export routes.	• Country has a **target of 3 Mt green and blue H_2 production** by 2030, increasing to 20 Mt by 2050.	• **Hydrogen Energy Earthshot initiative aims to reduce the cost** of green and blue H_2 to **$1/kg** within a decade.
Education, research, and partnerships	• **Investments in research and pilot projects** can drive technological advancement and facilitate scaling. • **Educational initiatives and international partnerships** can foster public support and global collaboration.	• EU is forming **partnerships with North African countries** to import their green H_2 production.	• H_2 Industry **Workforce Development Roadmap** focuses on upskilling workers for H_2 production and related industries.	• **Significant investments in H_2 technology research** have enabled Japan to account for 24% of global H_2-related patent applications between 2011 and 2020.	• The **Department of Energy's Hydrogen and Fuel Cell Technologies office** focuses on advancing research, education, and project implementation.

Sources: IRENA, Green Hydrogen Supply (2023); EU Clean Hydrogen Partnership (2024); CGEP, Energy Institute, Statistical Review of World Energy (2024); various government sources

Regulatory and economic factors are driving the transition from grey to green H_2

Three scenarios outline potential shift from grey to green and blue H_2 through 2030

	Current scenario	Accelerated trajectory	Ambitious trajectory
Share of grey H_2 converted (% by 2030)	0-20%	30%	50%
Required CO_2 price and policy (USD/ton CO2)	**Low or zero CO_2 cost**	**~50-100 USD/ton CO_2**	**100+ USD/ton CO_2**
	• Industry commitments and consumer demand are key drivers of decarbonization efforts.	• Most cost-optimal use cases convert grey H_2 (e.g., close to carbon storage).	• Policy incentives (e.g., RED[1] and the phase-out of free allowances) further accelerate the transition.
Progress across focused regions			



Observations

- **The phase-out of grey H_2 will depend on carbon pricing and supportive policies such as blending mandates for clean fuels or ammonia.**
- These measures are expected to drive industry commitments and amplify consumer demand for a green H_2 transition.
  - Current scenario: By 2030, around **10% of grey H_2 could shift to renewable or low-carbon alternatives**, primarily driven by industry pressure.
  - Accelerated trajectory: **Carbon costs of $50 to $100 per ton could result in around 30% of grey H_2 transitioning,** particularly in regions with lower green and blue H_2 costs and facilities that can be readily upgraded.
  - Ambitious trajectory: **High carbon pricing and additional incentives could enable a 50% conversion rate**. Examples include EU's RED II/III and California's Low Carbon Fuel Standard.

[1]Renewable Energy Directive

Source: McKinsey, Global Energy Perspective 2023: Hydrogen outlook (2023)

Credit: Friedrich Sayn-Wittgenstein, Nadine Palmowski, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim & Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

While the EU has established ambitious green H_2 targets, implementation efforts have fallen behind schedule

Companies like Air Liquide and Siemens have made significant progress in advancing green hydrogen projects

EU regional overview	
	• By **setting clear objectives, providing financial incentives, and fostering collaboration,** the EU has accelerated **the green H_2 transition**. • However, progress on **deployment of green and blue H_2 projects has not kept pace with these goals**. • Achieving a sustainable hydrogen economy will require continued policy support, effective implementation, and stronger alignment between targets and execution.

	Pre-policy adoption (pre-2020)	Policy adoption phase (2020-2024)	Post-policy impact (as of mid-2024)
EU policy landscape	• H_2 production has mainly relied on **fossil fuels, with fragmented national and regional policies, limited infrastructure**, and **low adoption** of hydrogen technologies.	• EU launches **EU Hydrogen Strategy**, aiming for 6 GW of electrolyzer capacity by 2024 and 40 GW by 2030.	• **Electrolyzer supply has surpassed the targets** outlined in the Net Zero Industry Act. • However, progress **toward 2030 production goals remains slow,** with only 3.6% of 2030 projects having reached the FID* stage.
Air Liquide	• **Operated hydrogen production facilities but invested minimally in H_2 R&D** due to regulatory uncertainty and high production costs.	• **Increased renewable H_2 production, expanded H_2 refueling stations,** and developed optimization tools within its infrastructure across the EU.	• **Became leader in green H_2 production** with established **initial refueling network**. • **Committed to investing €8 billion in low-emission H_2 by 2035** and targeting 3 GW of electrolysis capacity by 2030.
SIEMENS energy	• **Focused on PEM electrolyzers with a few pilot projects,** like Hyflexpower, integrating H_2 into natural gas infrastructure.	• **Expanded its H_2 activities with investment in large-scale projects,** including an 8.75 MW electrolyzer plant in east Germany and a 20 MW electrolyzer in partnership with Air Liquide.	• **Increased production with large-scale projects,** such as Voestalpine in Austria, producing 1,200 cubic meters of green H_2/hour to decarbonize steel production.

*Final Investment Decision

Sources: CGEP, Low-Carbon Production of Iron & Steel (2021); Energy Institute, Statistical Review of World Energy (2024); IEA, Iron and Steel Technology Roadmap (2020); Journal of Cleaner Production, Towards fossil-free steel (2023); The Oxford Institute of Energy Studies, 2024 State of the European Hydrogen Market Report (2024); Air Liquide, Air Liquide Hydrogen (2024); Siemens Energy, Siemens Hydrogen (2024)

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim & Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

In the US, the Inflation Reduction Act provides further support for green and blue H_2 with a production tax credit

Clean Hydrogen Production Tax Credit (45V) provides incentives up to $3/kg

Eligibility for 45V tax credit

Carbon intensity* ($kg\ CO_2/kg\ H_2$)	Hydrogen color	Percentage of full 45V tax credit (%)	Applicable credit value ($/kg H_2)	Additional requirements
< 4.0		20	0.60	• Must start construction before 2034 • Cannot be combined with the Carbon Capture and Sequestration Tax Credit (45Q) • Can be combined with the renewable energy production tax credit and the zero-emission nuclear credit • Must promote well-paying jobs
< 2.5		25	0.75	
< 1.5		33	1.00	
< 0.45		100	3.00	

Observations

- The **Inflation Reduction Act 's Clean Hydrogen Production Tax Credit** (Section 45V**)** is the largest tax credit for green H_2 to date.
  - **Producers can collect a tax credit of up to $3/kg** for projects constructed by 2033.
  - **Both green and blue H_2 are eligible,** with subsidy values determined by greenhouse gas emissions as measured, as defined under the US Clean Air Act.
- Section 45V credit will be key in making the **levelized cost of blue and green H_2 competitive with grey H_2** .
- Additional support includes the **Advanced Energy Project Credit**, offering a 30% tax credit for investments in fuel cells, electrolyzers, or hydrogen infrastructure.

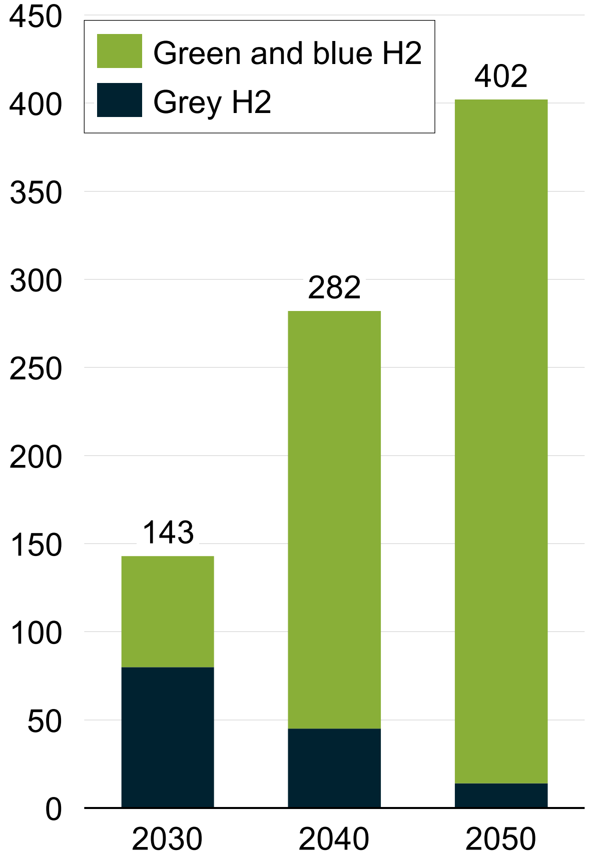
*Scope 1-3 carbon intensity

Sources: PV Magazine, The Hydrogen Stream (2023); US Department of Energy, Financial Incentives for Hydrogen and Fuel Cell Projects; US Department of the Treasury, U.S. Department of the Treasury, IRS Release Guidance on Hydrogen Production Tax Credit to Drive American Innovation and Strengthen Energy Security (2023)

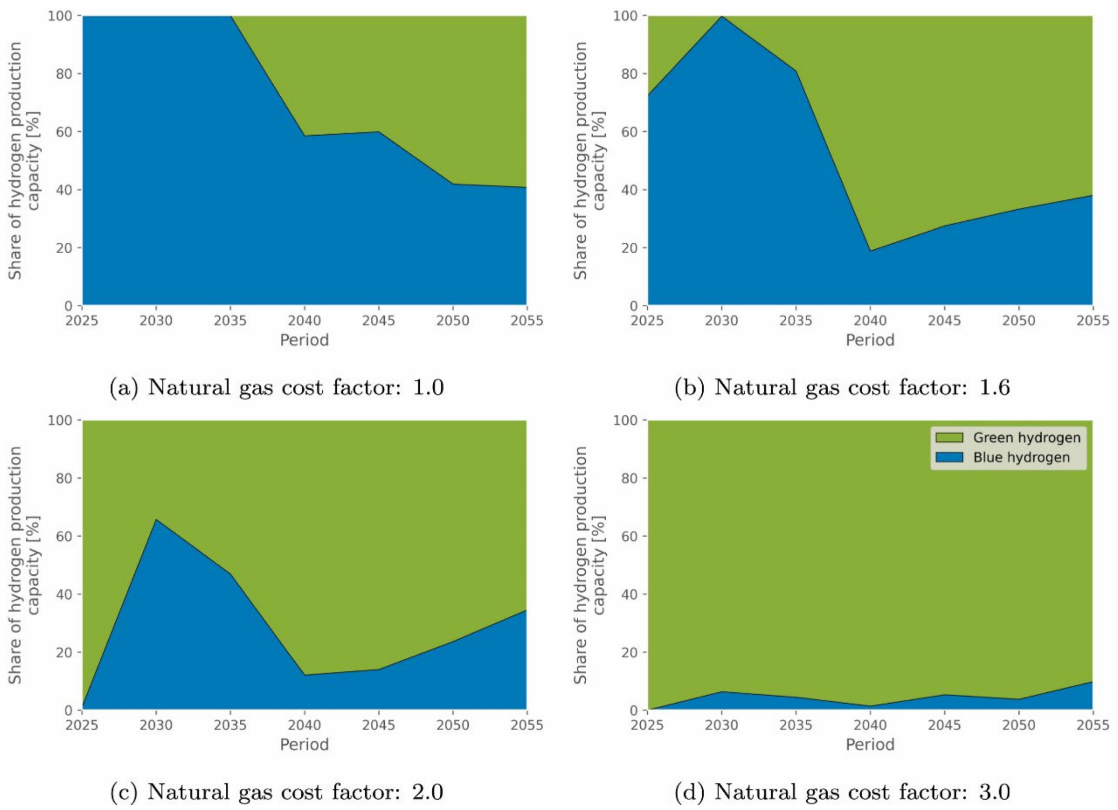
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Policy a key driver for the shift away from grey H_2, while gas prices determine the balance between blue and green H_2

Projected H_2 demand (in Mt)



Green H_2 share depends on cost factors such as gas prices



Observations

- Green and blue H_2 are expected to complement grey H_2 initially but will **almost completely replace it by 2050**.
  - **Government policies and incentives are crucial** for rapidly scaling H_2 production to meet demand.
  - **Economies of scale and declining CapEx** will accelerate the transition to green and blue H_2.
- The future split between green and blue H_2 **is difficult to estimate**.
  - **Green H_2 is expected to become competitive** as renewables and electrolyzer costs decline.
  - The share of blue H_2 **is highly sensitive to natural gas prices** due to its reliance on carbon capture, utilization, and storage.

Note: Natural gas price in base case is 31.3EUR/MWh in 2025-2030 and 39.0 EUR/MWh in 2050-2055 (Durakovic et al., 2023)
Sources: IEA, Net-zero scenario hydrogen outlook (2023); Durakovic et al., Are blue and green hydrogen competitive or complementary? (2023)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

CKI Green H_2 Team

Friedrich Sayn-Wittgenstein

Master of Public Administration in Environmental Science and Policy

Team Lead

Grace Frascati

Bachelor of Science

CKI Fellow

Hoshi Ogawa

Master of Business Administration

CKI Fellow

Nadine Palmowski

Master of Public Administration in Environmental Science and Policy

CKI Fellow

Ellie Valencia

Master of Business Administration

CKI Fellow

Linfei Zhang

Master of Public Administration in Climate, Energy, and Environment

CKI Fellow

Hyae Ryung (Helen) Kim

PhD in Sustainable Development

Senior Research Fellow

hk2901@columbia.edu

Gernot Wagner

Senior Lecturer, Columbia Business School

Faculty Director, Climate Knowledge Initiative

gwagner@columbia.edu

Columbia Business School
AT THE VERY CENTER OF BUSINESS

Appendix

Glossary

AWE	Alkaline water electrolysis
BOS	Balance of system
CAPEX	Capital expenditure(s)
CAGR	Compound annual growth rate
CCUS	Carbon capture, utilization, and storage
CH_4	Natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO2 equivalent, using global warming potential as conversion factor
DOE	Department of Energy
DRI-EAF	Direct Reduced Iron-Electric Arc Furnace production process
ETS	Emissions Trading System
Fe	Iron
FeO_2	Iron oxide
FCEV	Fuel cell electric vehicle
FID	Final Investment Decision
GHG	Greenhouse gas
Gt	Gigatonne, equal to 1 billion metric tonnes
H_2	Hydrogen
IRA	Inflation Reduction Act
kWh	Kilowatt-hour
LCOH	Levelized cost of hydrogen
LH_2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
Mt	Million metric tonnes
Mtpa	Million metric tonnes per annum
MWh	Megawatt-hour
NH_3	Ammonia
PEM	Proton exchange membrane
PGM	Platinum group metals
PPM	Parts per million
R&D	Research and development
ROI	Return on Investment
SAF	Sustainable aviation fuel
SOEC	Solid oxide electrolyzer cell
Tonne	Metric ton
TWh	Terawatt-hour