

# Hydrogen Technologies for Industrial Efficiency

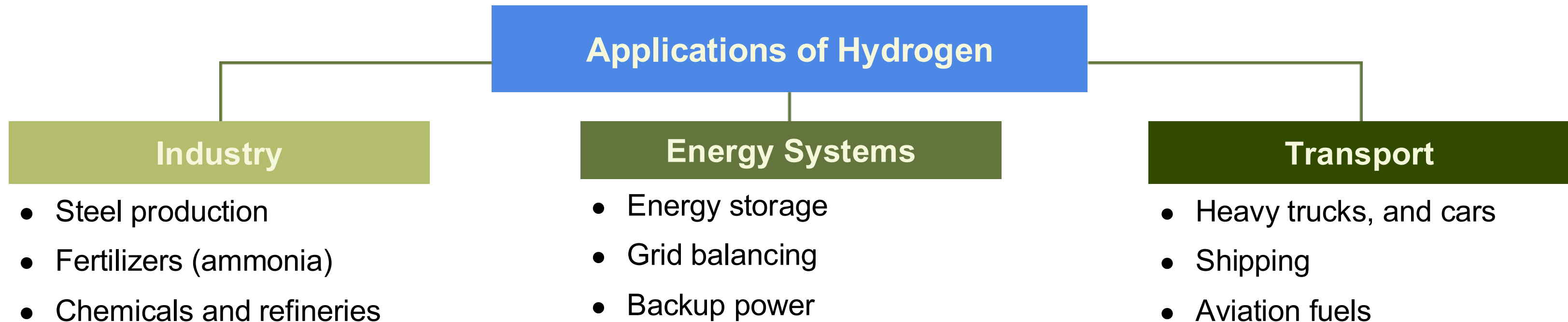


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# Motivation for Advancing Hydrogen Technologies

## Why H<sub>2</sub> Technologies Matter

- Hydrogen is a versatile carrier and enables industrial efficiency.
- Hydrogen production involves the effective utilization of diverse energy resources including coal, gas, and all renewables.
- Hydrogen storage improves grid reliability by offering flexibility to the grid.



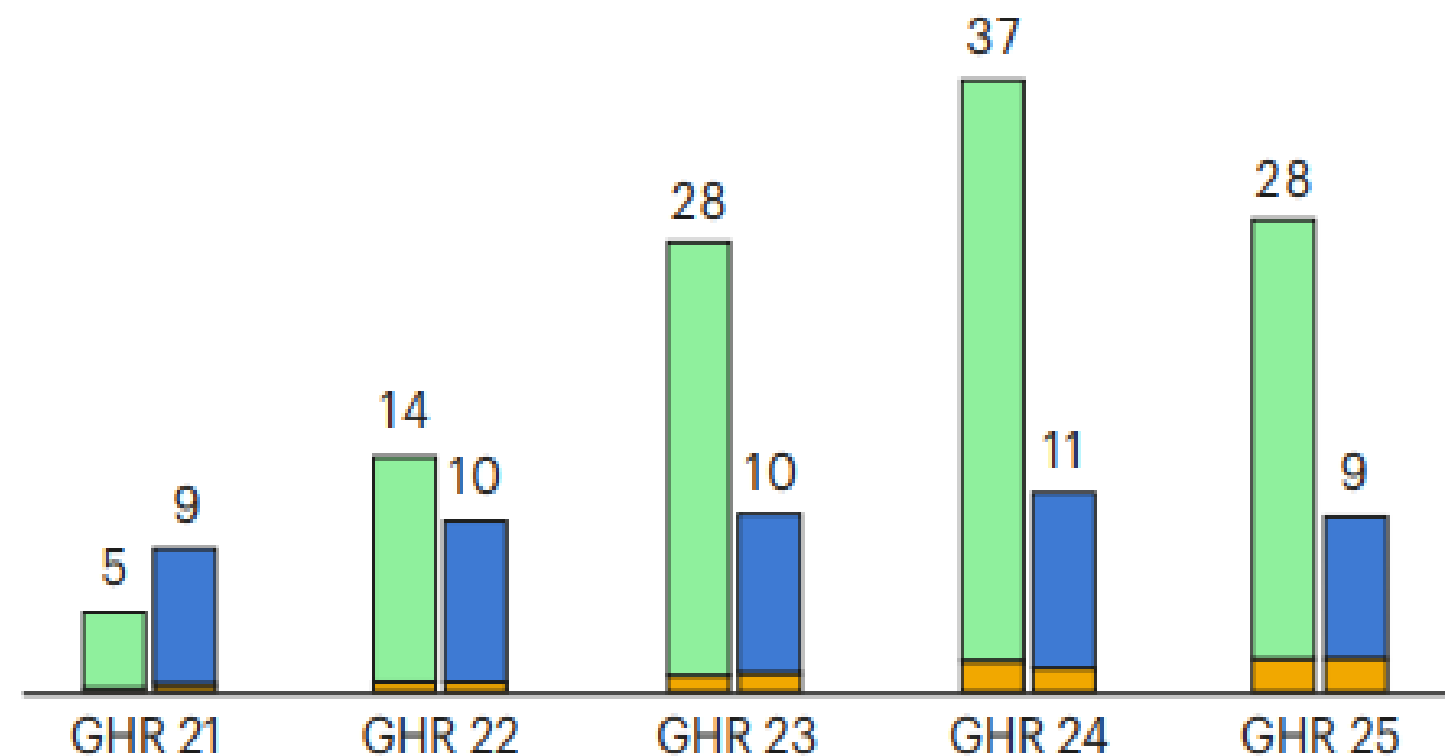
# Hydrogen from Natural Gas

Natural gas-based hydrogen production accounts for about 90–95 million tonnes of hydrogen produced annually, representing roughly 95% of global production.

## Low-emissions hydrogen production from announced projects by 2030

Mtpa

● Renewables ● Fossil fuels with CCUS ● FID



Source: IEA 2025 Hydrogen Review

## Technology

Steam methane reforming (SMR) uses high-pressure steam to extract hydrogen from natural gas.

## Maturity

H<sub>2</sub> from natural gas is the most commercially mature hydrogen pathway, with decades of operational history and a Technology Readiness Level (TRL) of 9.

## Scalability

It is highly scalable and can meet large industrial demands using existing global infrastructure.

## Cost of Production

H<sub>2</sub> from natural gas is currently the lowest-cost hydrogen production option, typically ranging from \$1.0–\$2.0 per kg depending on natural gas prices.

# Hydrogen from Natural Gas Integrated with Carbon Capture, Utilization and Storage (CCUS) Technology

- Hydrogen gas produced from natural gas, with the carbon emissions captured and stored underground is emerging as a viable technology.
- A world-class blue hydrogen plant with integrated CCUS costs between approximately \$500M–\$1.5B to build.

**Technology**

- Requires retrofitting existing H<sub>2</sub> plants get CCUS attached
- Infrastructure, supply chains, and engineering already exist
- CCS captures 85–95% of CO<sub>2</sub>, not 100% ("clean" is relative)

**Scalability**

- Leverages existing gas pipelines, LNG terminals, and industrial infrastructure
- Geographically constrained: needs gas access *and* geologic formations for reliable CO<sub>2</sub> storage

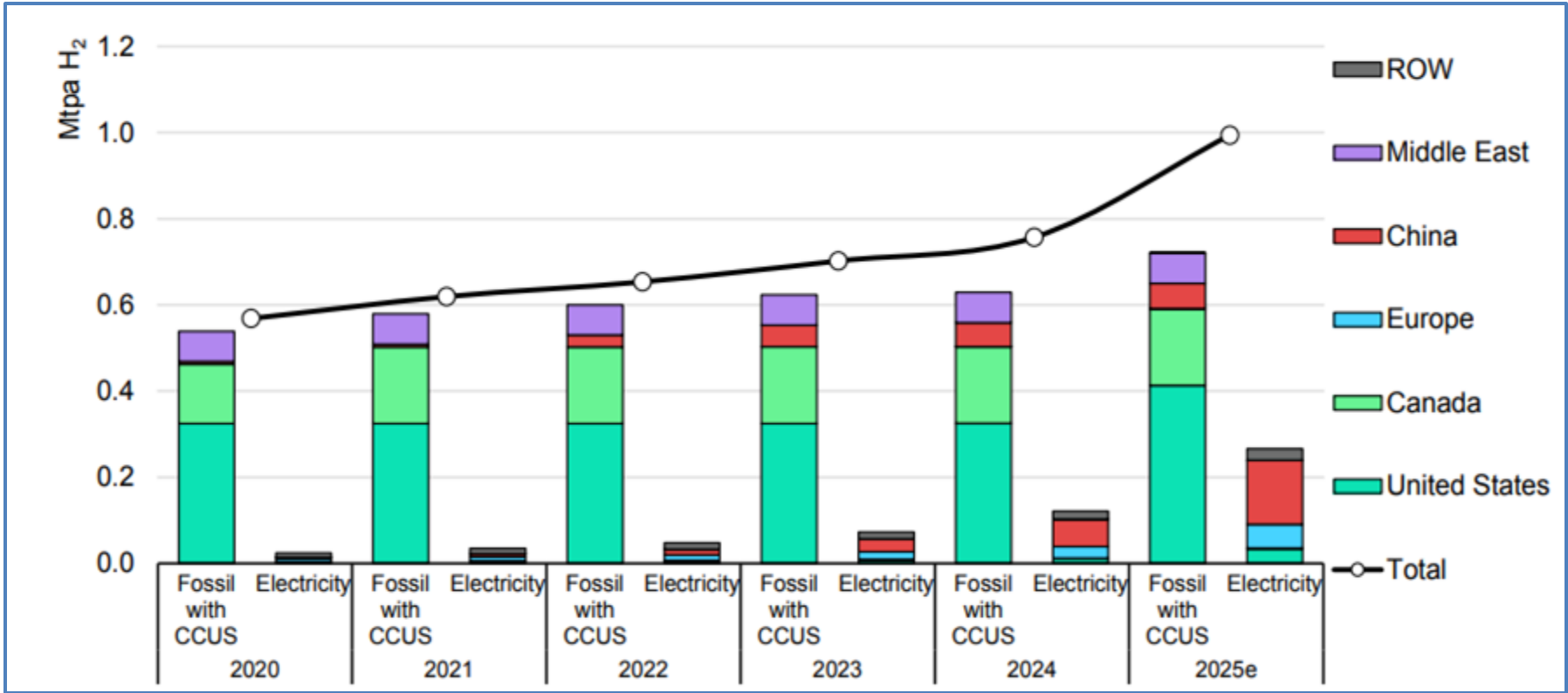
**Maturity**

- **TRL 9** — reforming is fully commercialized
- **CCS at TRL 7–8** — proven pilots but not yet at scale
- Integrated SMR+CCS has few large-scale references

**Cost of Production**

- **Production: \$1.5–3.0/kg** — varies by gas access and CCS maturity
- **High CapEx** — needs long-term **offtake to finance**
- Sits between grey (cheaper) and green (cleaner)
- Exposed to gas price **volatility and geopolitics**

Low-emissions hydrogen production, 2020-2025e



Source: IEA 2025 Hydrogen Review

Acronyms Defined:  
 CCUS: Carbon Capture, Utilization, and Storage  
 SMR: Steam Methane Reforming

# Hydrogen Production via Water Electrolysis

- **Green hydrogen** is hydrogen fuel produced with **very low or near-zero carbon emissions** by using renewable electricity (Brandt et al., 2024).
- The main production method is water electrolysis powered by renewable electricity:  $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$

## Technology

- Alkaline, and Proton Exchange Membrane electrolyzers are mature and commercialized (TRL 9).
- SOEC (Solid Oxide Electrolysis Cells) are approaching commercialization (IEA, 2023).

## Scalability

- **Electrolyser manufacturing capacity** — global capacity is ~41 GW/yr in 2024, heavily concentrated in **China (~60%)**
- **Water availability** — electrolysis needs purified water.
- **Grid access** through dedicated renewable supply.

## Maturity

- Maturity depends on scaling of renewable energy technologies and per unit cost of energy.
- It ranges from fully commercial (alkaline) to early demonstration (SOEC/AEM) depending on which electrolyser technology.

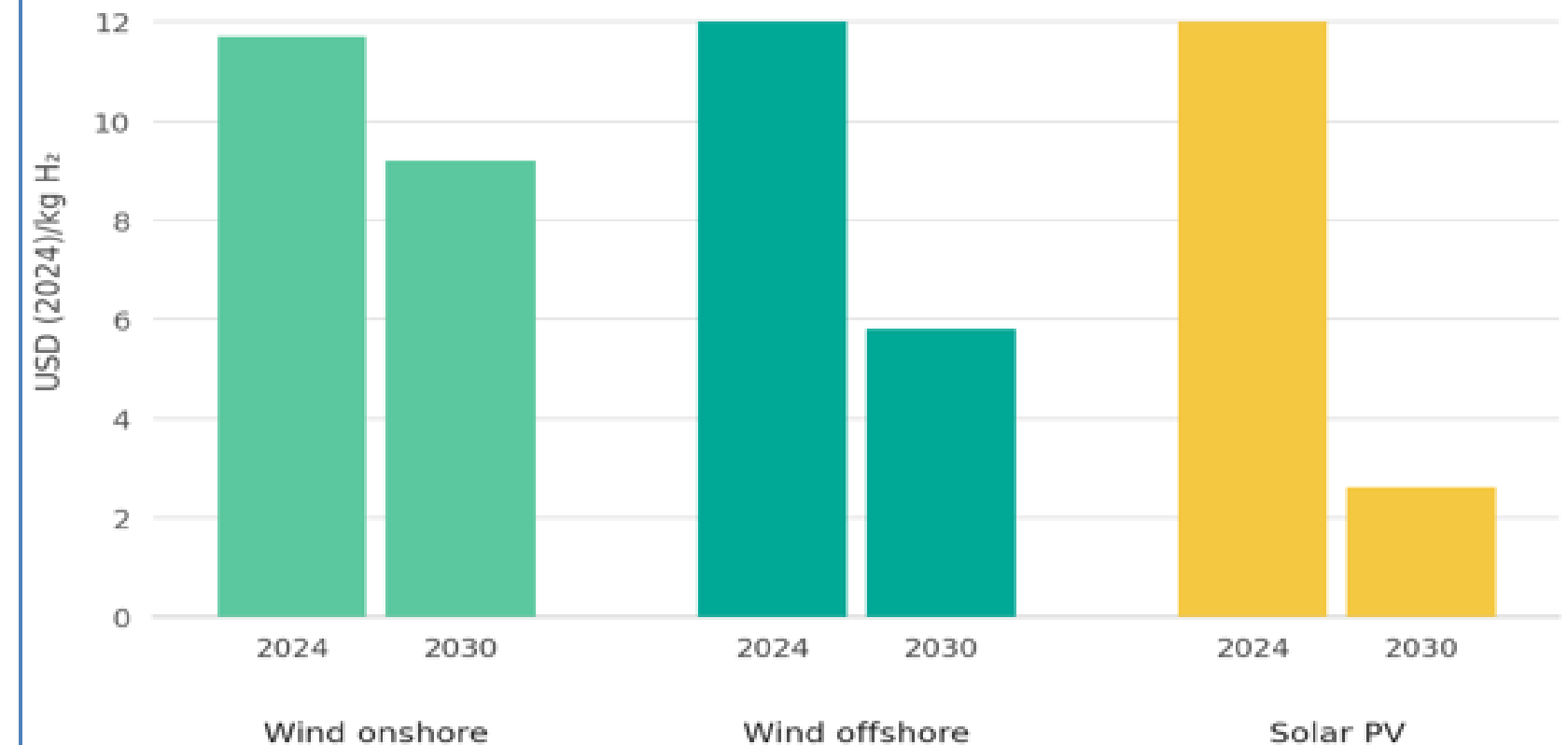
## Cost of Production

- About \$3–6/kg (Curcio, 2025); Costs are falling faster but needs subsidies in current state.
- Significant policy tailwinds affecting the large-scale H<sub>2</sub> development.

## Biggest Cost Drivers

- Renewable electricity price
- Electrolyser capital cost (CAPEX)
- Utilization rate
- Storage and transport infrastructure (Basoulou & Kosmopoulos, 2026)

## Green Hydrogen Production by Source



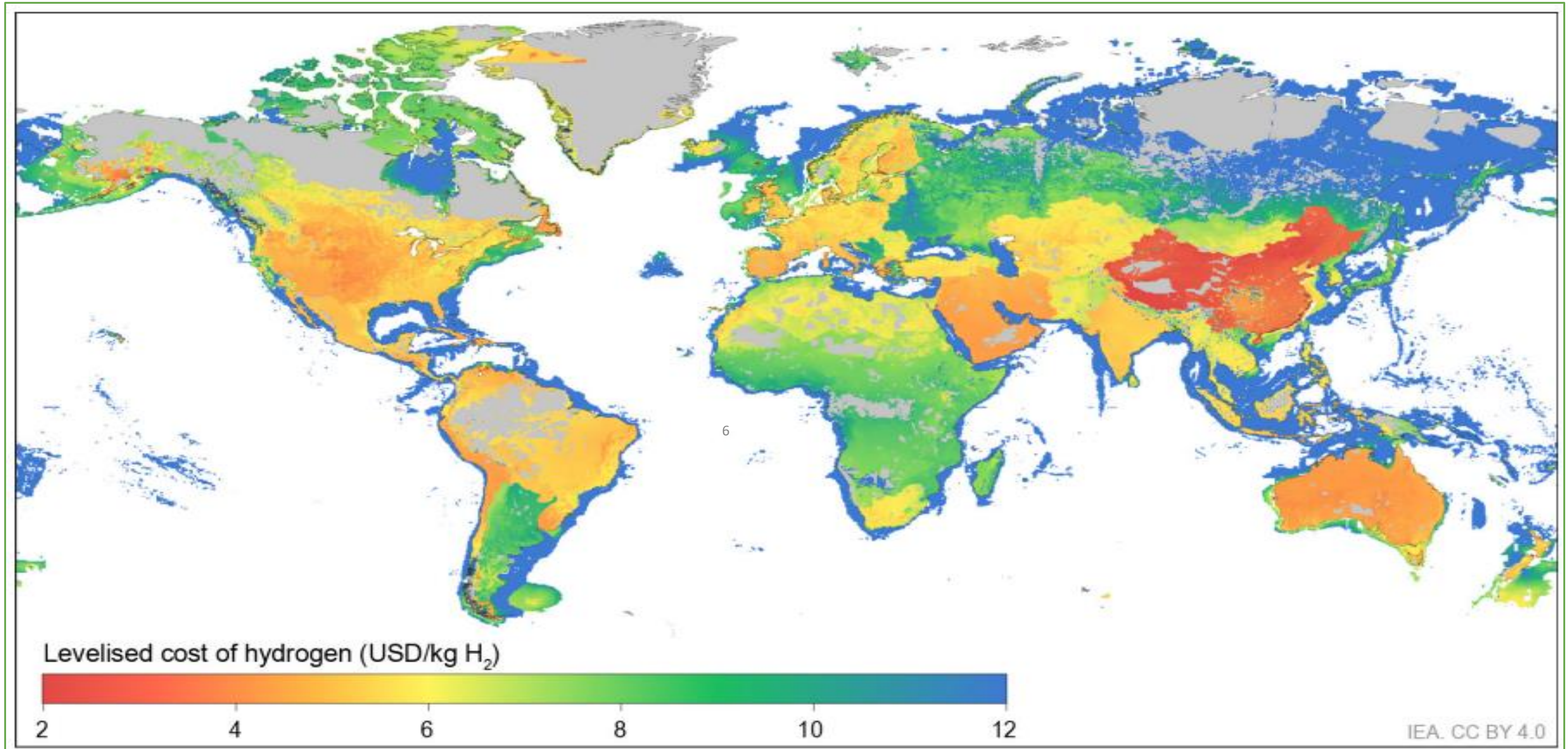
Source: Brandt et al. (2024), *Nature Energy*.  
 Source: International Energy Agency (2023), *Electrolysers*. IEA  
 Source: Basoulou & Kosmopoulos (2026), *Energies*.

Source: Curcio (2025), *International Journal of Hydrogen Energy*.  
 Source: Basoulou & Kosmopoulos (2026), *Energies*.

Figure: Green Hydrogen Production Cost by source  
 Source: IEA 2025 Hydrogen Review

# Green Hydrogen: Production Costs & Global Potential

Hydrogen production cost from electrolysis using hybrid solar PV and onshore wind, and from offshore wind (2030 STEPS scenario)



# Hydrogen from Nuclear Energy

- Natural gas-based hydrogen is currently the most mature hydrogen pathway globally and may serve as a transition fuel as countries move beyond coal toward lower-carbon energy systems.
- About 95% of all hydrogen produced globally is grey. Around **90–95 million tonnes per year** — and almost all of it is grey.

## Technology

- Nuclear electrolysis uses power to drive alkaline or PEM electrolyzers.
- Advanced SMRs and High-Temperature Gas Reactors can supply process heat for thermochemical H<sub>2</sub>.

## Scalability

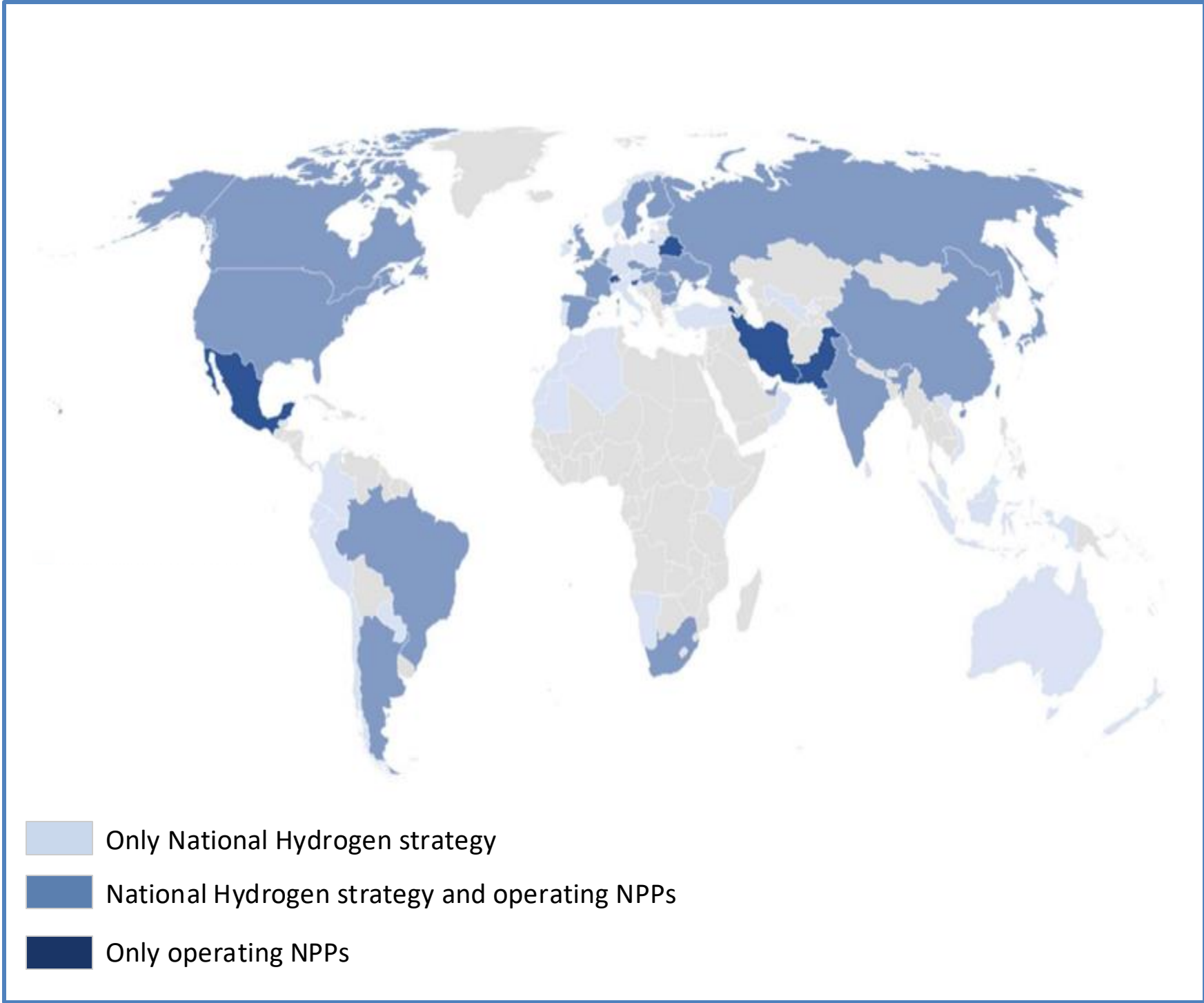
- Constrained by nuclear build timelines: takes 10–15 years
- SMRs promise 3–5 year deployment but remain unproven.
- Geographically flexible with no sun/wind dependency
- Electrolysers achieve ~90% utilization.

## Maturity

- Nuclear power generation: TRL 9 (fully commercial).
- Nuclear-coupled electrolysis: TRL 6–7, only a handful<sup>7</sup> of pilot projects
- Thermochemical splitting via HTGR: Still at demonstration stage
- SMR technology: First commercial plants expected post-2030

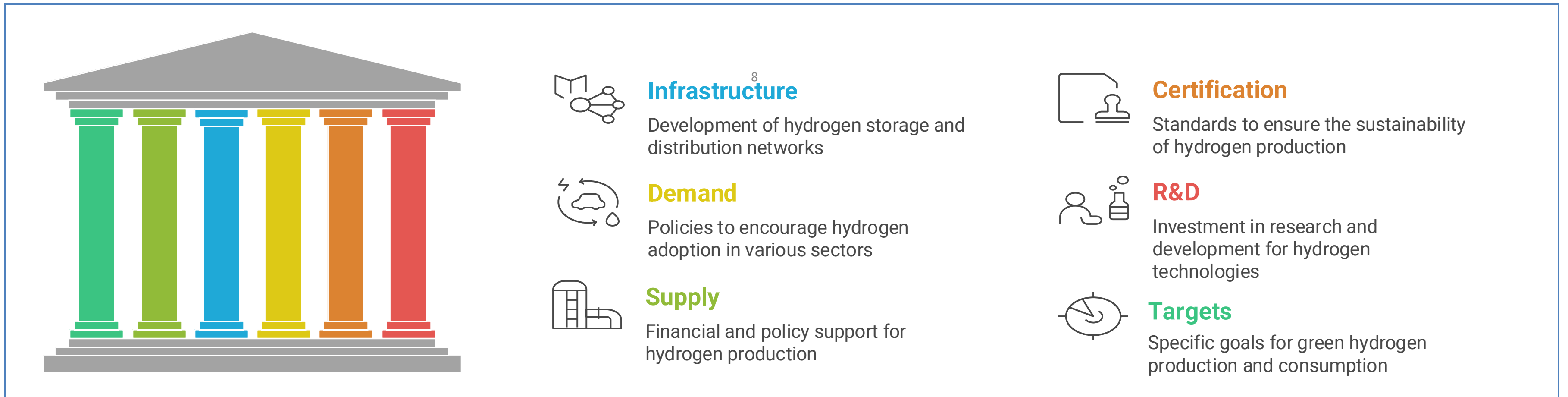
## Cost of Production

- Current cost ~\$4–7/kg H<sub>2</sub>; high nuclear capex is the dominant cost driver.
- Nuclear electricity costs \$80–150/MWh vs solar/wind at \$20–50/MWh. SMR cost targets of \$40–60/MWh could bring pink H<sub>2</sub> down to \$2–4/kg by 2035–2040, making it competitive in land or resource-constrained markets.



Source: International Atomic Energy Agency (IAEA): Hydrogen Production with Operating Nuclear Power Plants

# Navigating the Global Hydrogen Landscape



## CCUS - Shell (Alberta Canada)

<b>Capacity</b>	<ul style="list-style-type: none"> <li>• Captures and stores up to 1.2 million tonnes of CO<sub>2</sub> per year</li> <li>• Supports 3 hydrogen manufacturing units at the Scotford</li> <li>• By end of 2023, Quest had cumulatively captured and stored more than 8.8 Mt of CO<sub>2</sub> since commissioning.</li> </ul>
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<b>Importance</b>	<ul style="list-style-type: none"> <li>• Demonstrates integrated SMR+CCS operating reliably (10+ years)</li> <li>• Closest possible proof-of-concept for CCUS at industrial scale</li> <li>• Reduces direct emissions by 35%</li> <li>• Funds: PPP between Shell and the Canadian governments</li> </ul>
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Source: Shell Website. Link: [here](#)

## Green Hydrogen Project — Xinjiang, China

<b>Capacity</b>	<ul style="list-style-type: none"> <li>• 260 MW of electrolyzers powered by solar energy, targeting 20,000 tonnes of production/year</li> <li>• Storage capacity 210,000 cubic metres and pipeline throughput of 28,000 cubic metres/hour</li> </ul>
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<b>Importance</b>	<ul style="list-style-type: none"> <li>• Commissioned August 2023 — world's largest solar-to-hydrogen project</li> <li>• China's first fully integrated PV green hydrogen production demonstration at industrial scale</li> <li>• Benchmark project for utility-scale green hydrogen</li> </ul>
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Source: Hydrogen Insights. Link: [here](#)



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