Evolving Technologies for Green Hydrogen

12/05/2023

Agenda

- About Plug
- Why Green Hydrogen
- Production Technologies,Types of Electrolysers
- Global Electrolyser Market – Existing capacity, Capacity estimates and Cost Curve
- Hydrogen Storage and Transportation
- Hydrogen in Energy Systems and End Applications

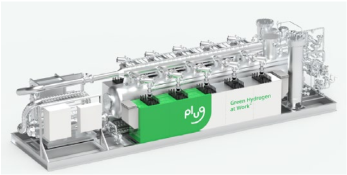
Plug's Ecosystem of Products

Production → Transport and Storage → End Uses

Production

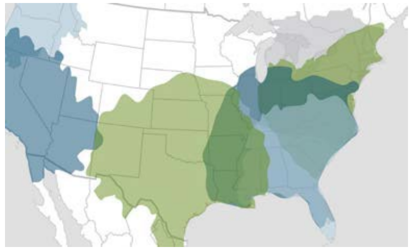
Electrolyzers & Liquefaction

- < 1 MW up to 200 MW architectures
- Hardware or BOO solutions available
- Installation included upon request, in house EPC
- In-house liquefaction OEM and EPC



Green Hydrogen Production Network

- Construction underway across North America, offtake volumes available 2022/23
- 500 TPD green hydrogen by 2025



Transport and Storage

Green Hydrogen Delivery & Storage

- Green hydrogen supply from own resilient network - zero and low CI options
- No complicated long-term contracts
- Liquid or high-pressure gas deliveries
- Large volume H2 storage (liquid and gas) options

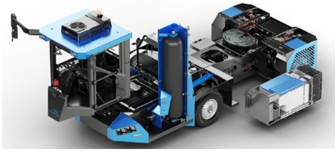
Hydrogen Fueling Stations

- 350 & 700 bar fueling stations
- Up to 3 tons per day of H2 dispensing
- Full turnkey services (EPC, service, and IoT)

End Uses

FCEVs in Mobility

- Class 1-3 material handling
- Terminal tractor, cargo tractors, container mover, tow tractors
- City buses
- Class 4-8 vehicles
- Aviation for regional air-craft
- Mining equipment



Stationary Fuel Cells

- < 1 MW up to 200 MW architectures
- Millisecond response grid stabilization (peak, backup, and baseload power)
- Installation included upon request
- Hardware and PPA solutions available
- Clean, quiet, and secure!

Service and Maintenance

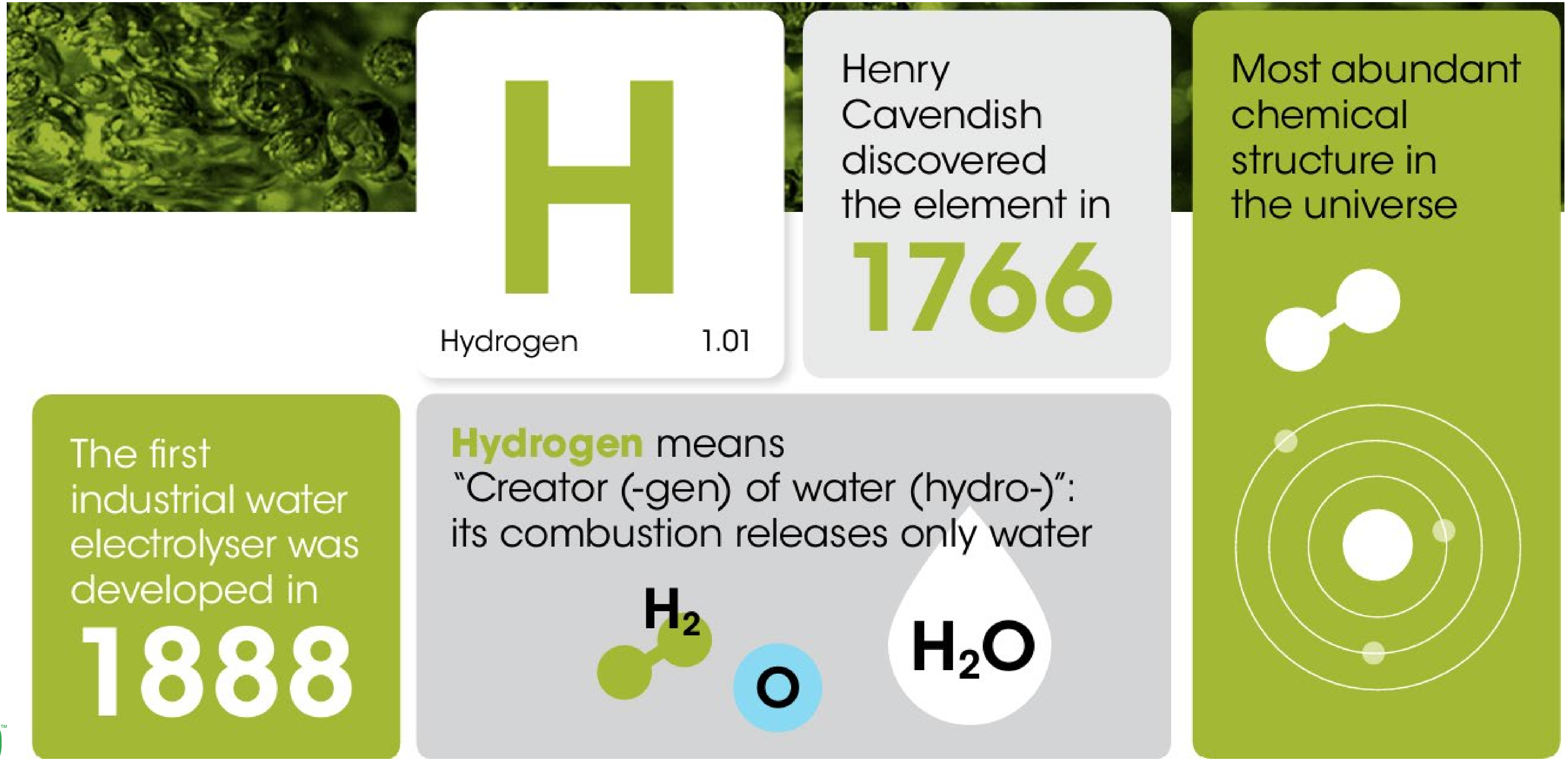
- Uptime and reliability guarantees available
- Over 500 highly skilled technicians
- Remote monitoring and 24x7 technical assistance

Private Ecosystem

- Ask how we can build you your own ecosystem (pipelines or delivery)
- We offer custom built networks of hydrogen generation, delivery, storage, dispensing, and FC apps
- This can be across the entire US or regional in scale

Why Green hydrogen

Hydrogen



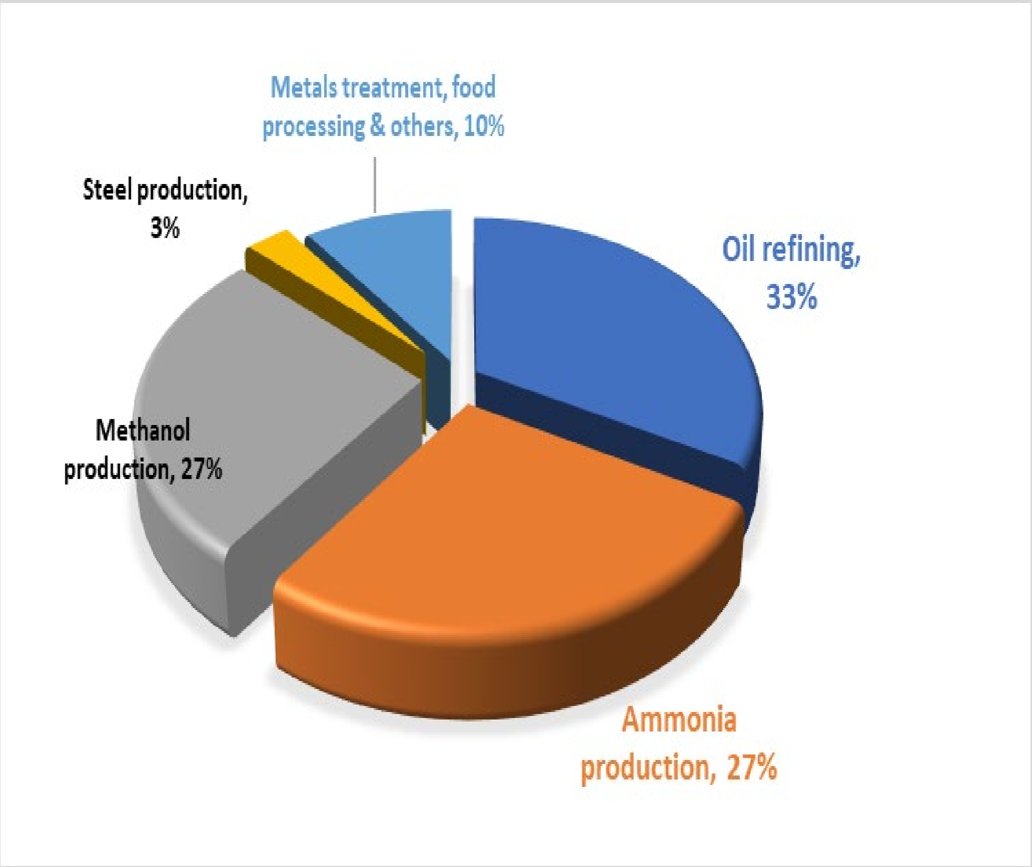
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

Where is Hydrogen used today?

- Hydrogen is currently used mainly for industrial processes
  - Oil refining ~33%,
  - Ammonia production ~27%,
  - Methanol production ~27%, and
  - Steel production ~3% globally
  - 10% is used for treating metals, processing foods, and other applications

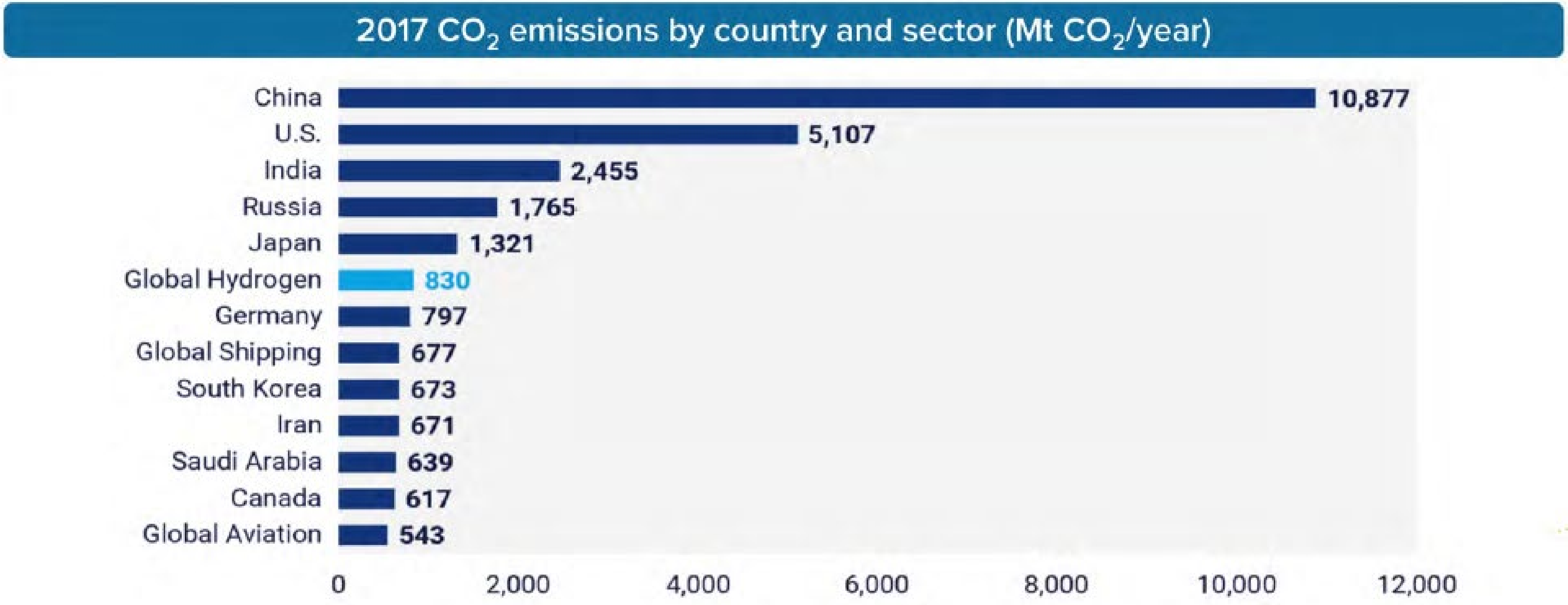
- Hydrogen can be used as a fuel for electricity production, transport, and building heating.

- Such use is limited now but has a potential to lower global carbon emissions



Source: IEA 2019

Global hydrogen production accounts for 832 Mt CO2/year...more than the emissions of Germany



Source: Wood Mackenzie, 2019. "CO_2 and other Greenhouse Gas Emissions"

Colors of Hydrogen

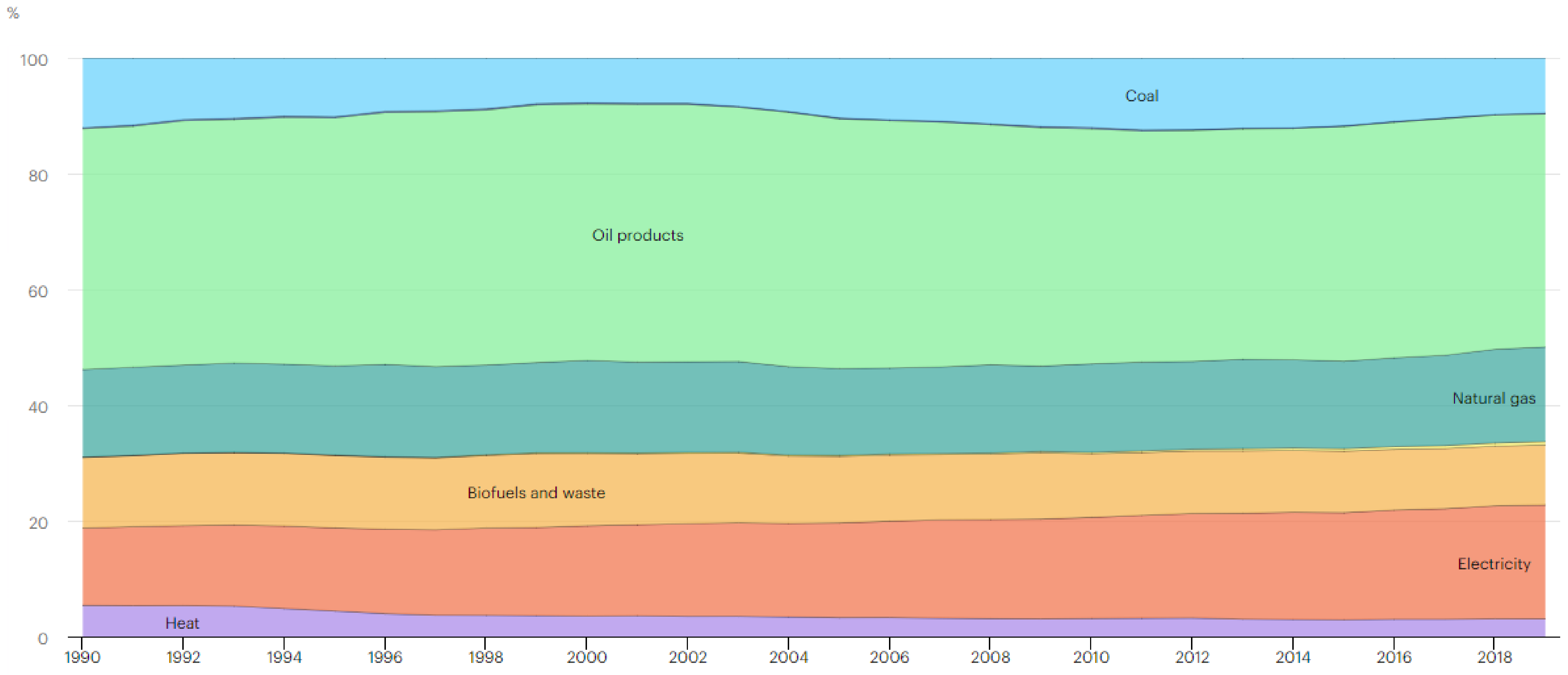
Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Note: SMR = steam methane reforming.

** Turquoise hydrogen is an emerging decarbonisation option.*

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

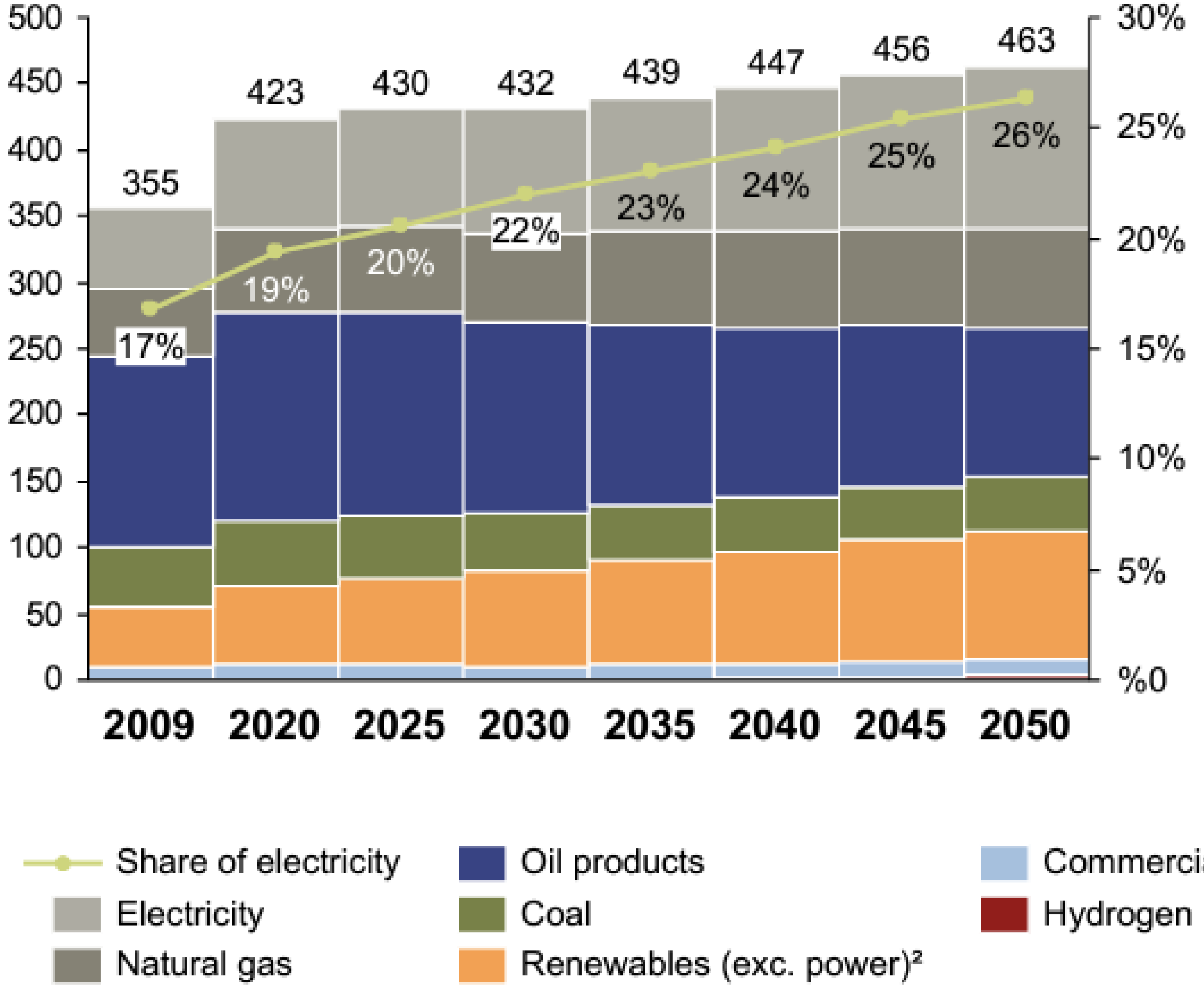
Total final consumption (TFC) by source, World 1990-2019

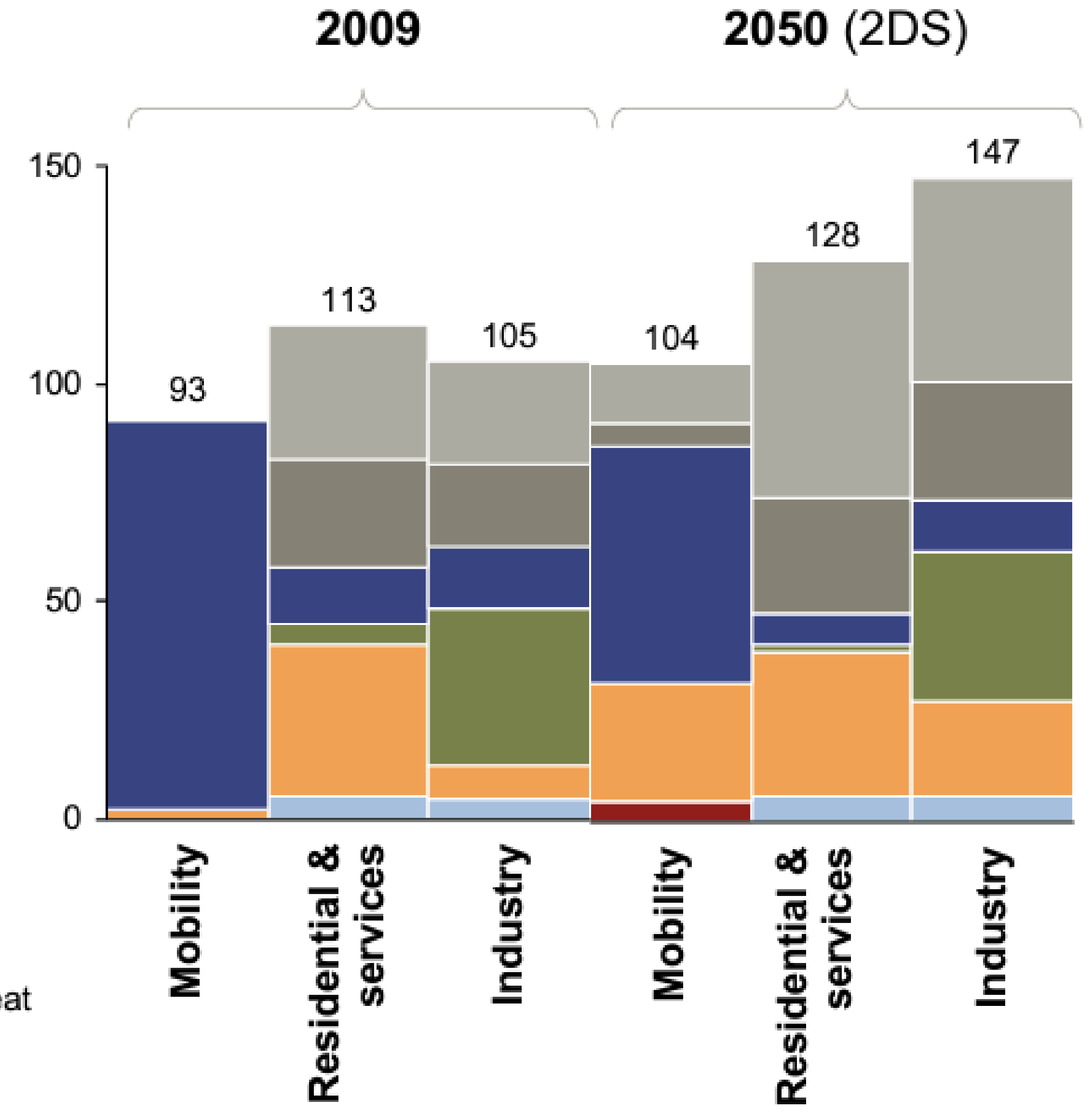


Energy carrier distribution by end-use, 2009 and 2050

(IEA's 2DS scenario[1]) ExaJoules

Electricity is only a limited part of the game





Note: 1The 2DS scenario is the IEA most ambitious decarbonization scenario and corresponds to a scenario that would limit global warming to 2°C by 2050; 2Renewables excluding power correspond mainly to biomass & waste, biofuels and solar thermal.
Source: A.T. Kearney Energy Transition Institute analysis; IEA (2012a).

Total final energy consumption1.5ºC Scenario for 2050

Energy transition is driven by:

- Low-cost renewable power
- Innovation
- Decarbonisation of energy sectors
- Security of energy supply and affordability

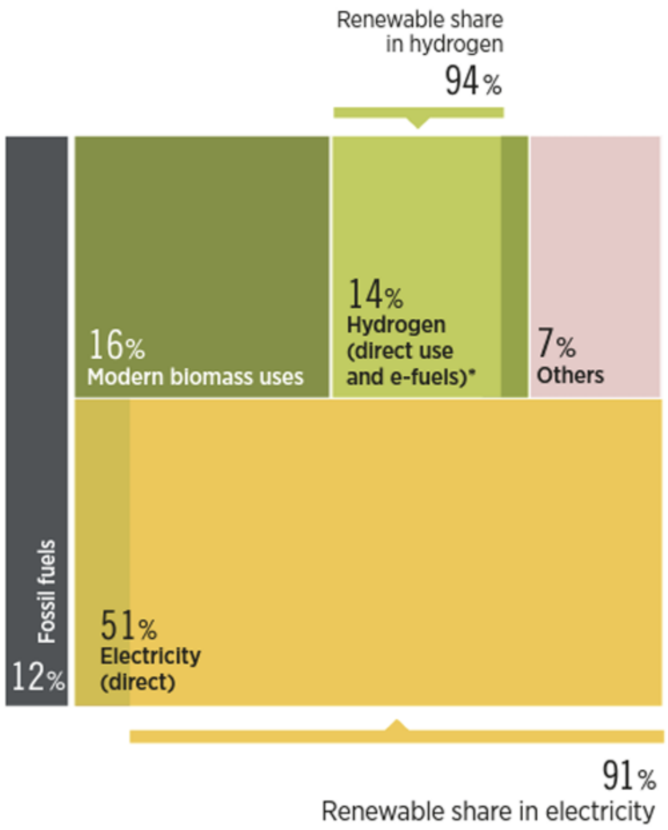
In 2050, 1.5 Scenario sees:

51% of TFEC – Direct electrification

14% of TFEC – Indirect electrification

11 times RE generation compared with 2020

Total final energy consumption(TFEC)
1.5ºC Scenario for 2050



Source: IRENA Innovation Week 2023 edition

As per IEA, Net Zero Emissions by 2050 (NZE) Scenario requires installed electrolysis capacity to reach more than 550 GW by 2050

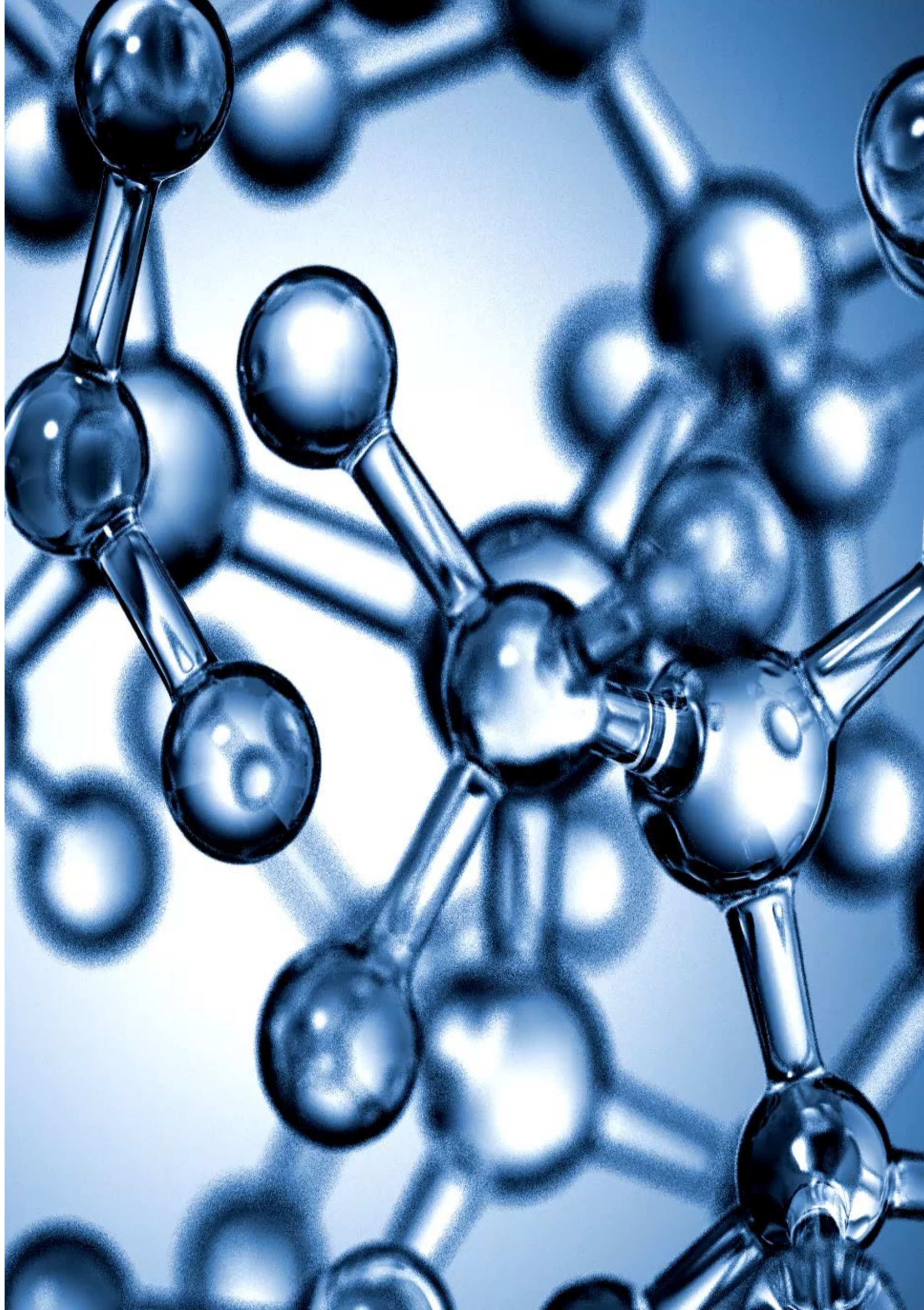
Production Technologies

Hydrogen Production Technologies

Technologies for Hydrogen production:

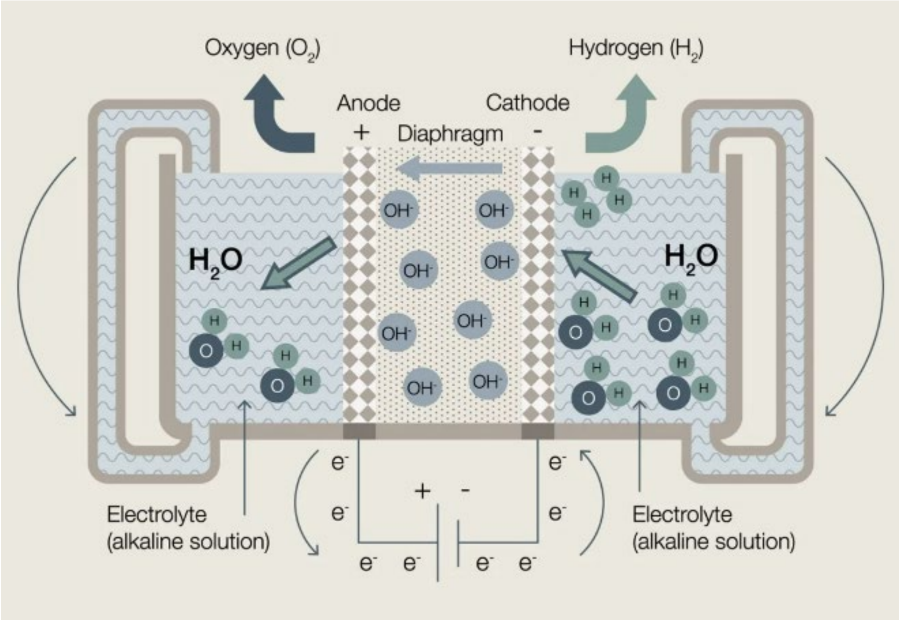
- Thermal Processes such as reforming, gasification, and pyrolysis
- Biological Processes use microbes or fungi in fermentation reactions
- Thermochemical Processes use heat in combination with a closed chemical cycle to produce H2
- Electrolytic Processes
- Photolytic Processes: These processes use light energy to split water into H_2 and O_2

Electrolysis is attracting most attention and investments considering its **scalability, cost reduction potential, maturity and complementarity with Electricity**

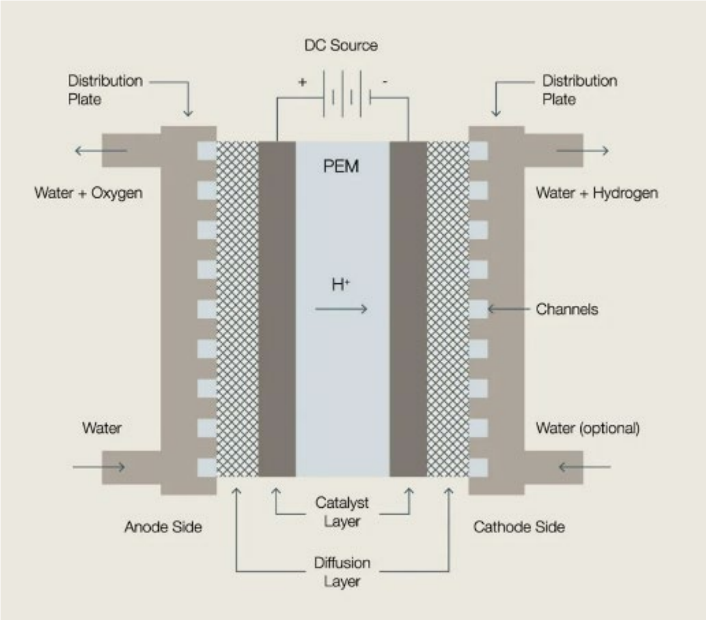


Source: https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/technologies-hydrogen

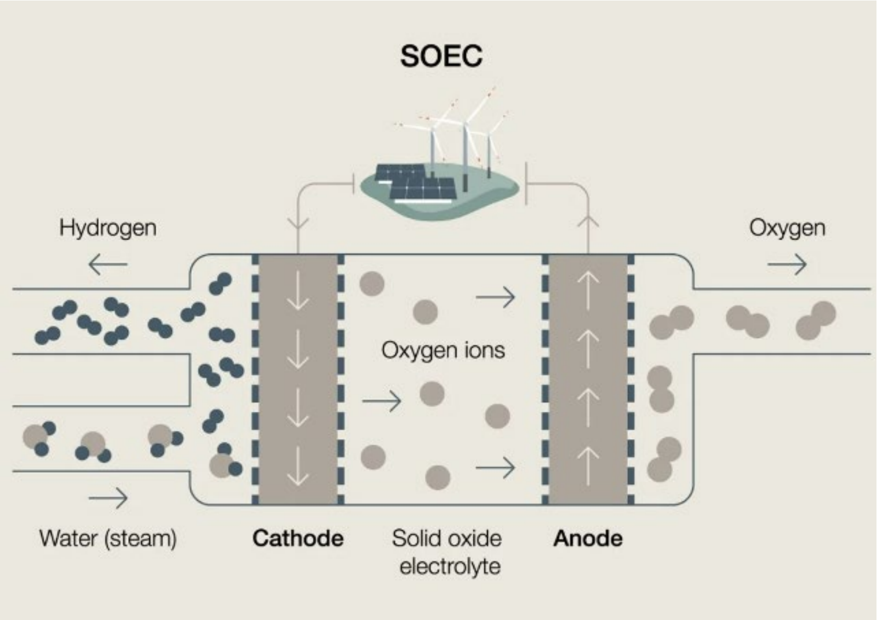
Types of Electrolyzers



Alkaline Electrolyzer



PEM Electrolyzer

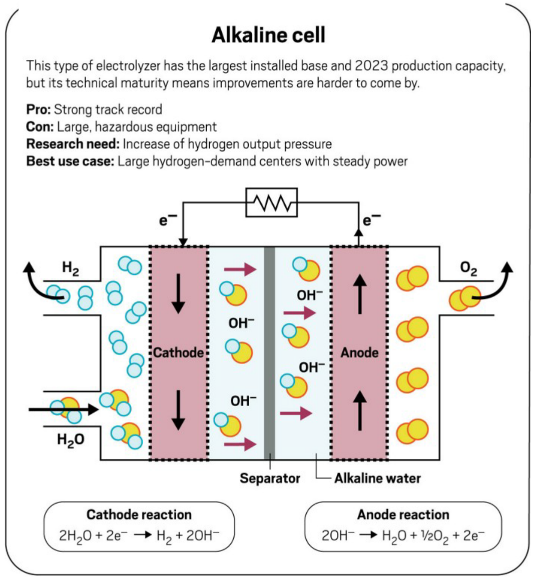


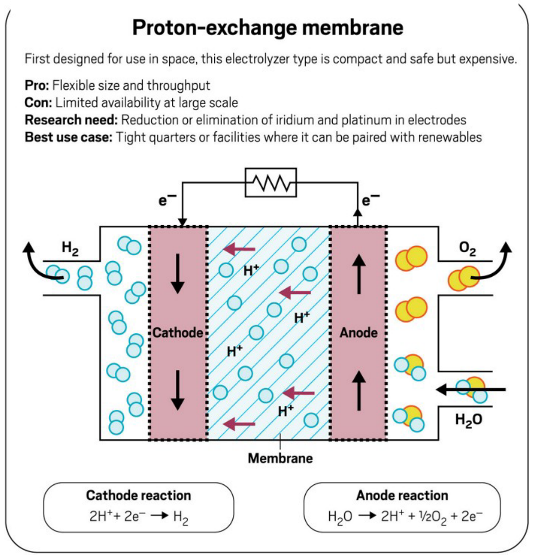
Solid Oxide Electrolyzer

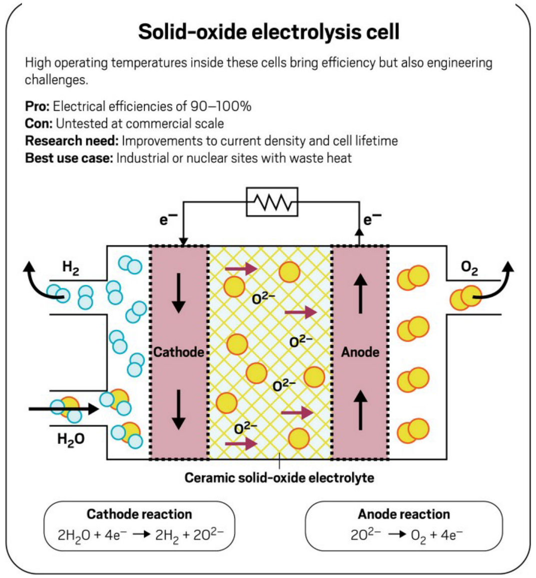
Source: https://www.cowi.com/insights/electrolysis-the-backbone-of-the-green-transition

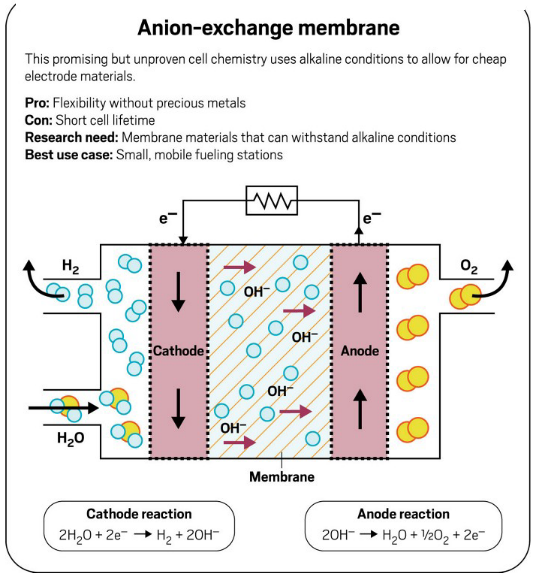
Types of Electrolyzers

- *Water Electrolysis* literally means splitting water using electricity
- Chemical reaction is the same across technologies, $H_2O \rightarrow H_2 + \frac{1}{2}O_2$
- Voltage always pulls electrons out of the anode and through an external circuit and pushes them into the cathode
- Difference lies in how chemicals and materials inside the cell balance electron flow by passing charge carriers—ions—between the electrodes









Types of Electrolyzers

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Alkaline cell

This type of electrolyzer has the largest installed base and 2023 production capacity, but its technical maturity means improvements are harder to come by.

Pro: Strong track record
Con: Large, hazardous equipment
Research need: Increase of hydrogen output pressure
Best use case: Large hydrogen-demand centers with steady power

Cathode reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode reaction: $2OH^- \rightarrow H_2O + ½O_2 + 2e^-$

Proton-exchange membrane

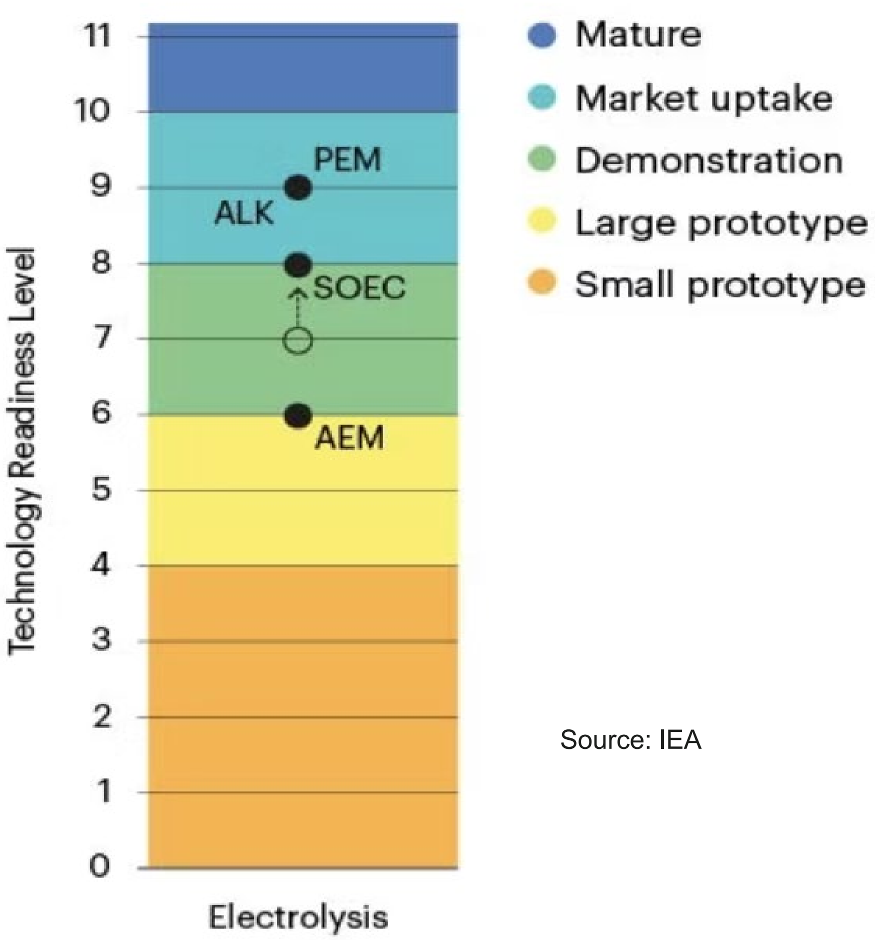
First designed for use in space, this electrolyzer type is compact and safe but expensive.

Pro: Flexible size and throughput
Con: Limited availability at large scale
Research need: Reduction or elimination of iridium and platinum in electrodes
Best use case: Tight quarters or facilities where it can be paired with renewables

Cathode reaction: $2H^+ + 2e^- \rightarrow H_2$

Anode reaction: $H_2O \rightarrow 2H^+ + ½O_2 + 2e^-$

High operating … challenges.
Pro: Electrical …
Con: Untested …
Research need …
Best use case: …

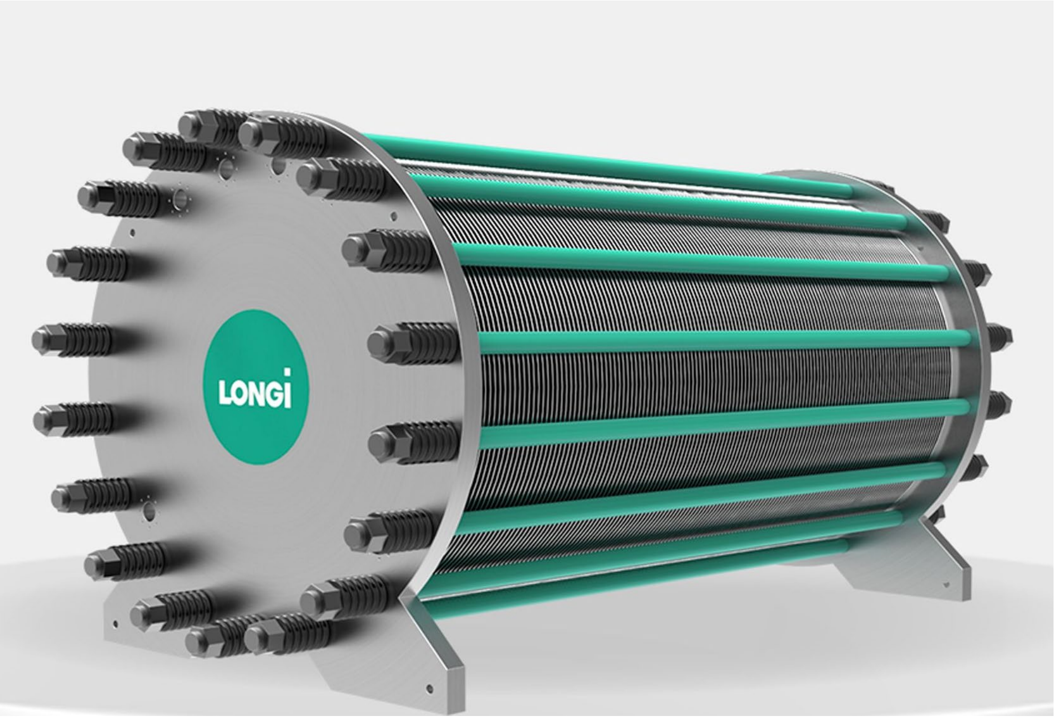


Source: IEA

Alkaline electrolyzer

For

- Oldest and most mature technology
- Stacks in MW scale
- Lower capital cost
- No precious metals



Against

- Low current density, higher footprint
- Corrosive electrolyte, hazardous operating conditions
- Limited partial load range and limited dynamic response
- Lower purity and risk of crossover
- Maintenance concerns at RE collocated remote locations

Picture Source: Longi

PEM electrolyzer

For

- Mature technology, has been around for decades
- MW scale stacks becoming available
- 5x to 6x current density compared to Alkaline, compact footprint
- Excellent partial load range and dynamic response
- High gas purity

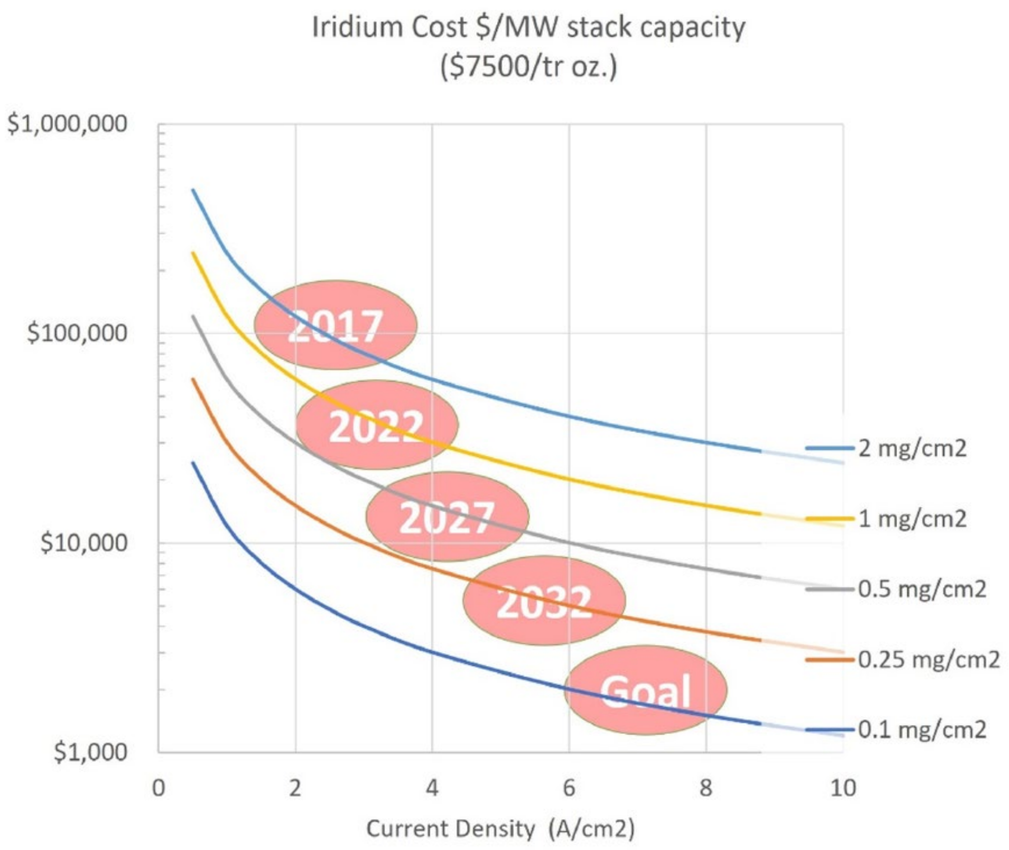
All electrolyzer stacks contain oppositely charged electrodes — cathodes and anodes — as well as an electrolyte. The Plug Power electrolyzer stacks shown here use a technology called "proton exchange membrane" or PEM, which features a solid electrolyte. *Photographer: Adam Glanzman/Bloomberg*

Against

- Concerns about precious metals
- Higher cost than Alkaline
- Requires high purity water
- Commercialization in progress

plug™

Precious Metals – Concern or Overblown Concern?



- Current loading of Ir is 1.5 mg/cm^2 i.e. about 0.4 kg/MW of Electrolyzer
- Future requirement of Ir kg/MW will continue to decrease:
  - Increase in current density
  - Amount of Ir per cm^2 will decrease
- Recycling will reduce Ir demand significantly
- 95% recovery expected with 10 years stack life
- Impact of precious metals is overblown. Ir just adds 0.06/kg of Hydrogen produced and is expected to down to $0.01/kg of H_2 by 2050

Source: Ir Strangelove, or How to Learn to Stop Worrying and Love the PEM Water Electrolysis, Cortney Mittelsteadt,* Esben Sorensen, and Qingying Jia
https://pubs.acs.org/action/showCitFormats?doi=10.1021/acs.energyfuels.3c01524&ref=pdf
https://pubs.acs.org/doi/10.1021/acs.energyfuels.3c01524?ref=pdf

Plug Electrolyzer

Plug 1MW PEM Electrolyzer Stack

Competitive Landscape

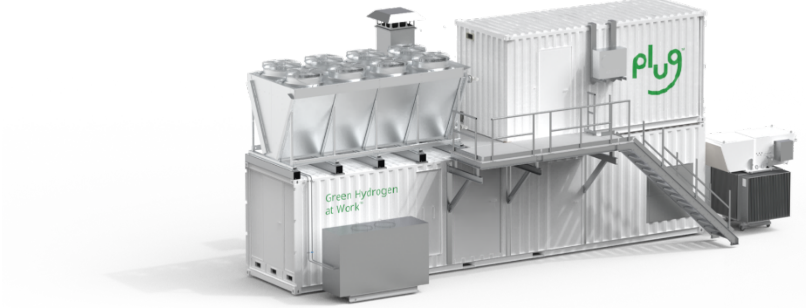
	Alkaline Electrolyzer Competitors	PEM Electrolyzer Competitors	plug
High Current Density Operation	X	X	✓
Small Footprint	X	✓	✓
High Efficiency	✓	✓	✓
High Gas Purity	X	✓	✓
Operating Pressure	X	✓	✓
Differential Operating Pressure	X	X	✓
System Response/Ramp Time	X	✓	✓
Cold Start	X	✓	✓
Stand By	X	✓	✓
High Temperature Pressure	✓	X	✓

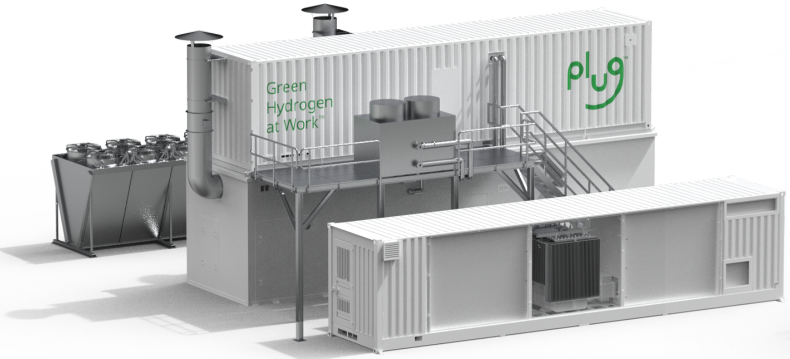
- PEM electrolyzer technology from Giner ELX acquisition
  - Giner has 30+ years of experience working with the DoD and NASA to develop industry leading PEM technology
- First PEM Gigafactory to scale production
- Technology road map will increase output of each stack up to 100%, while lowering precious metal usage by 75%+
  - Allowing capital cost per MW to drop ~60% in next 5 years

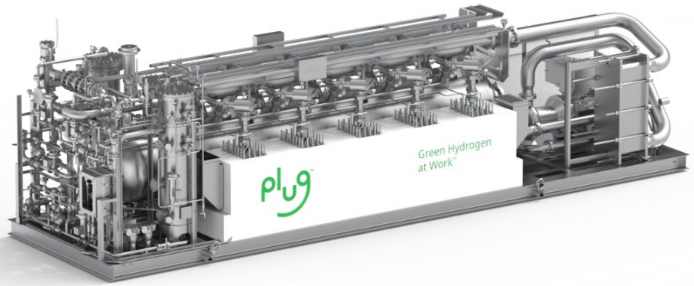
plug

Plug Electrolyzer

Building blocks





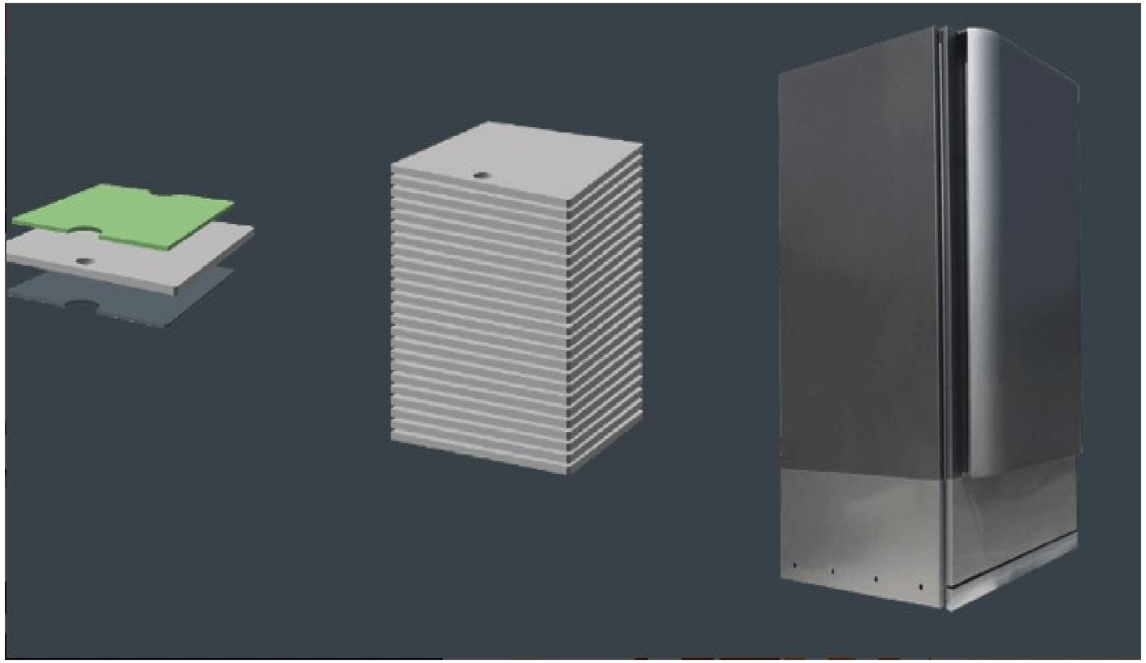


425 kg per day Container	2 Ton per Day System	4 Ton per Day Array
Up to **1 MW** input	Up to **5 MW** input	Up to **10 MW** input
Fully containerized solution (standard 40 ft. / 12.2 m ISO container)	Includes full BoP for turnkey simplicity	BoP custom-engineered to meet customer requirements
Scalable drop-and-play convenience	Containerized solution for high demand applications	Efficient, scalable solution for high volume H_2 plants

Solid Oxide Electrolyzer

For

- High electrical efficiency by using external heat source as additional input
- Can operate in reverse mode
- Can produce syngas
- No precious metals



Against

- Longer startup times
- Thermal integration challenges
- Concerns about life and suitability to fluctuating conditions
- Suffer even worse than Alkaline from on-off cycling

Picture Source: Bloom Energy

Global Electrolyser Market

Green Hydrogen Leaders

Electrolyzer Leaders

- Siemens
- Thyssenkrupp
- Plug Power
- Cummins
- Nel
- ITM Power
- Hydrogenics
- LONGi
- Peric
- HydrogenPro
- Steisdal
- H TEC Systems
- HyAxiom
- Shanghai Electric
- Bloom Energy
- Sunfire
- Denso

Electrolyzer Start-ups

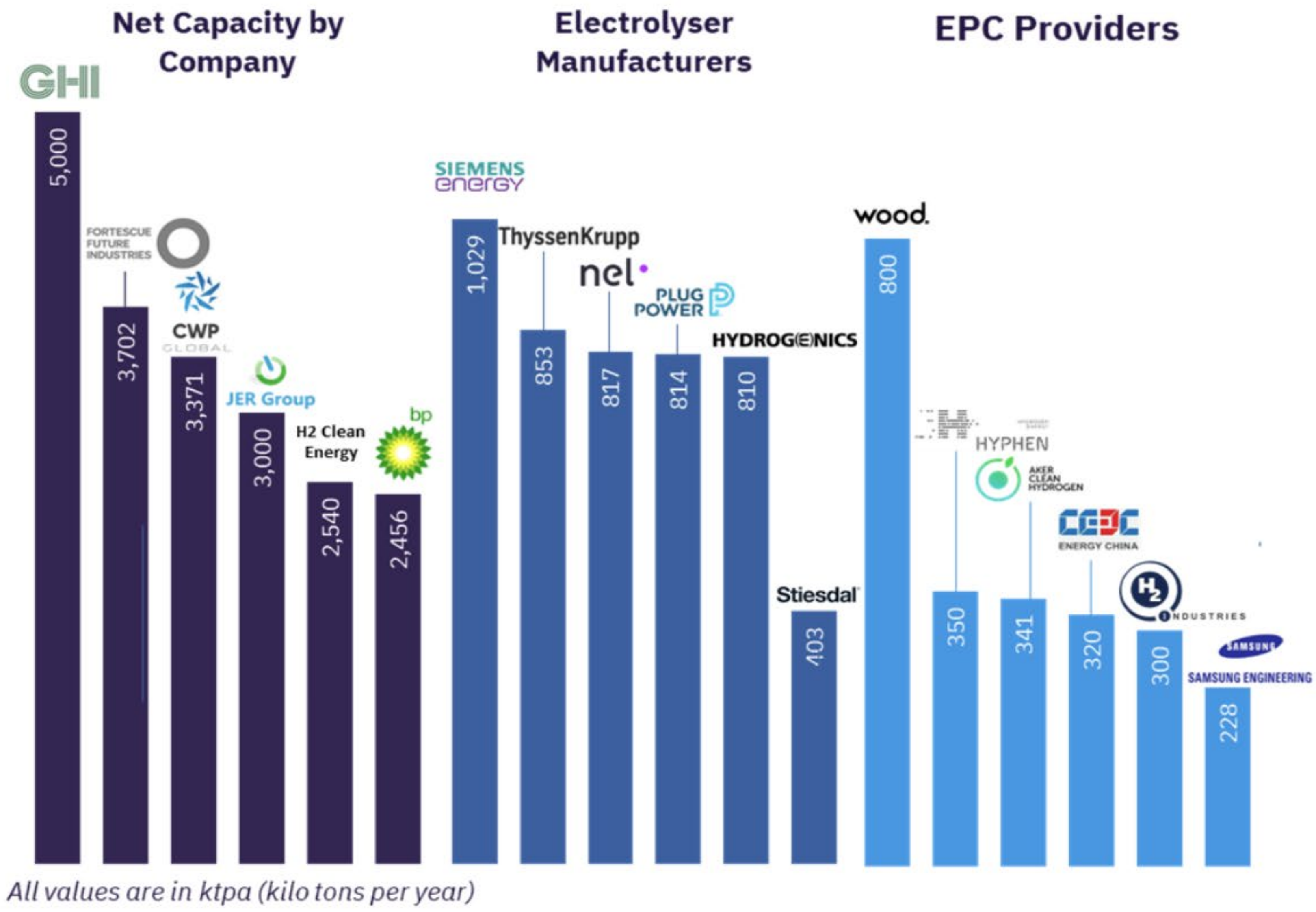
- Ohmium International
- Electric Hydrogen
- Hydrogen Optimized
- Hysata
- Enapter
- Green Hydrogen Systems
- Next Hydrogen
- Beijing Swift New Energy
- Elcogen
- Verdagy

Alternative Hydrogen Technologies

- Lummus Technology and Biohydrogen Technologies
- GH Power
- 8rivers
- SunGas
- Yosemite Clean Energy

Source: Delphi Data Labs GmbH. https://assets-global.website-files.com/62a855b4e6456347b75a24c7/652536c68945881be434017c_ddl-quarterly-review_October-2023.pdf

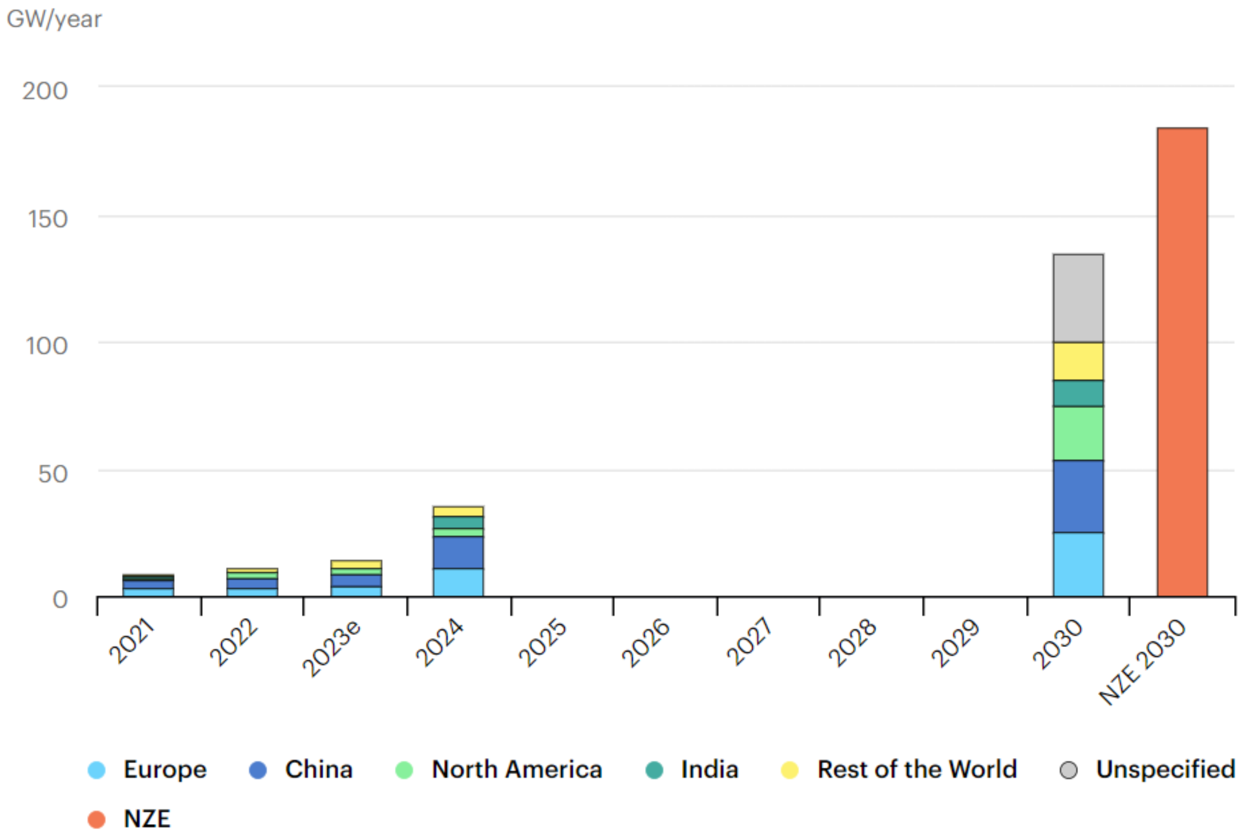
Announced Electrolyser Manufacturing Capacity



Source: GlobalData

Announced Electrolyser manufacturing capacity and capacity needed in the Net Zero Scenario, 2021-2030, IEA

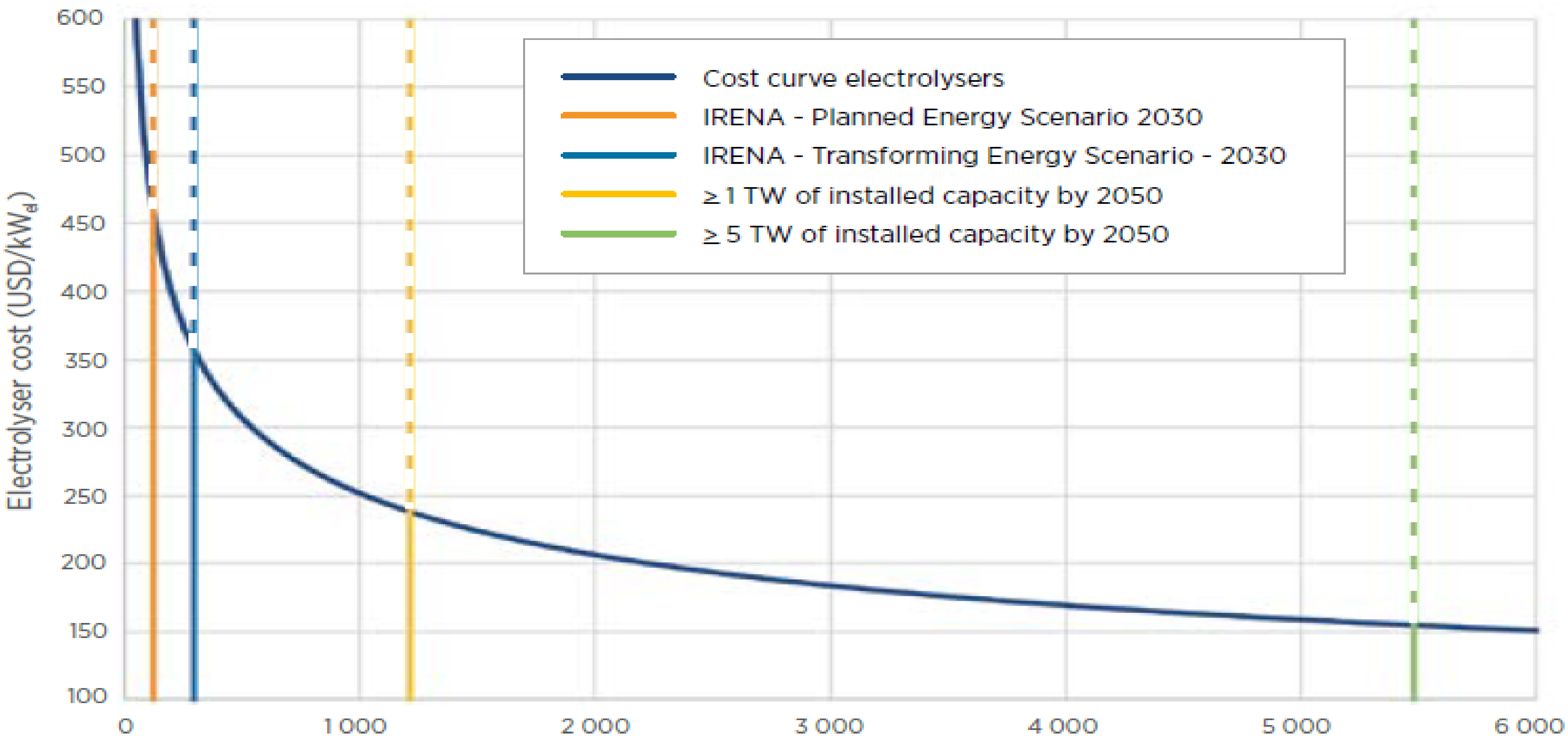
- Global manufacturing capacity reached almost 11 GW per year in 2022
- Europe and China account for two-thirds of global manufacturing capacity
- Global manufacturing capacity for electrolysers could reach more than 130 GW per year by 2030
- Of all the plans by 2030, less than 10% have reached a final investment decision (FID), and 25% have been announced with an unspecified location



Source: IEA

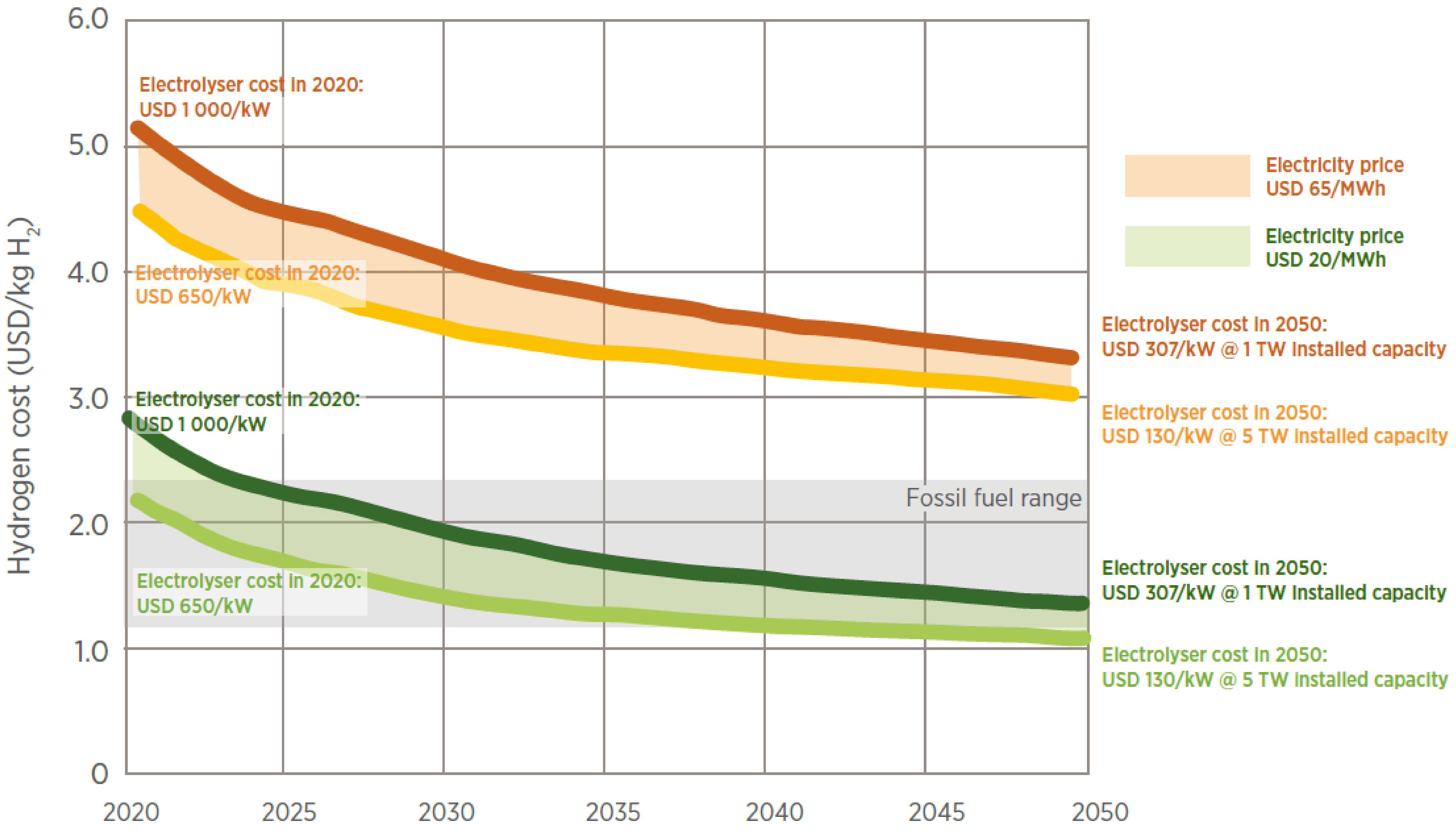
Electrolyzer Parameters and cost reduction opportunities

Energy Consumption per kg	Stack Lifetime	Module and Stack size	Operating range
Use of scarce materials	Start-up Time	Scale of Production	Average Stack Cost



Notes: 1 TW of installed capacity by 2050 is about 1.2 TW of cumulative capacity due to lifetime and replacement. Similarly, 5 TW by 2050 is equivalent to 5.48 TW of cumulative capacity deployed.

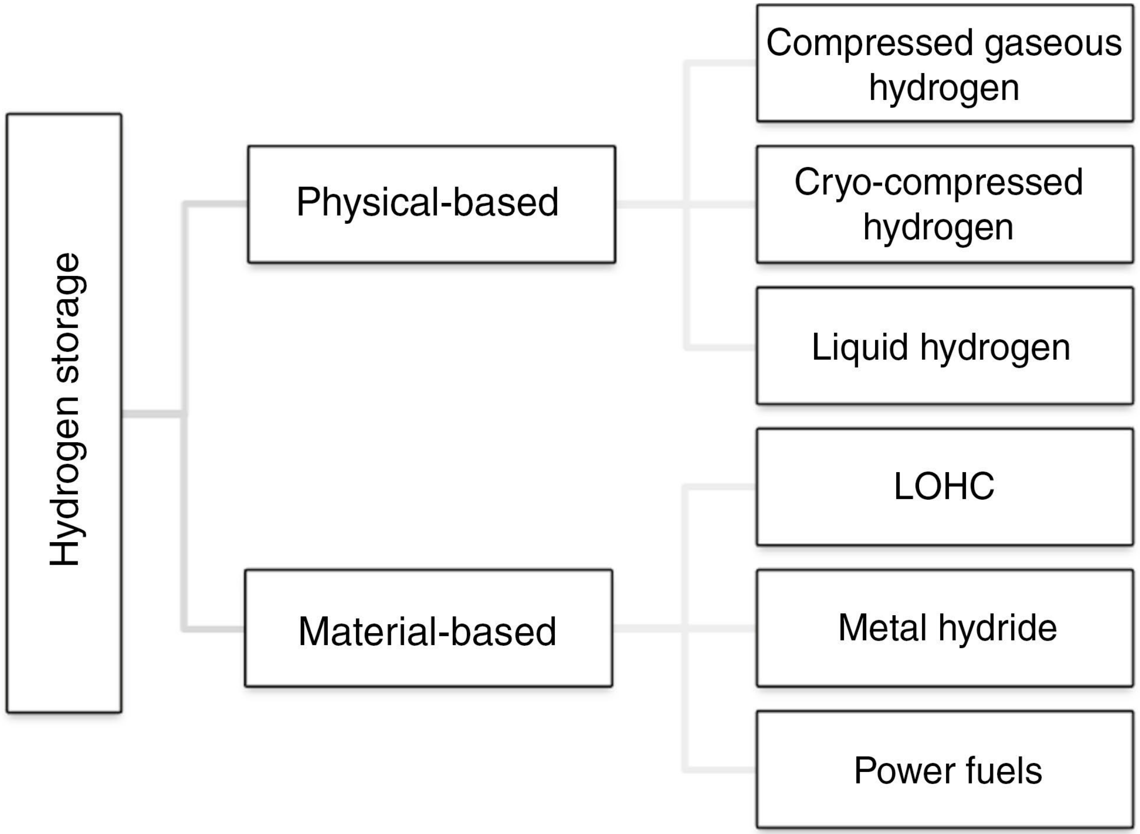
Based on IRENA analysis.

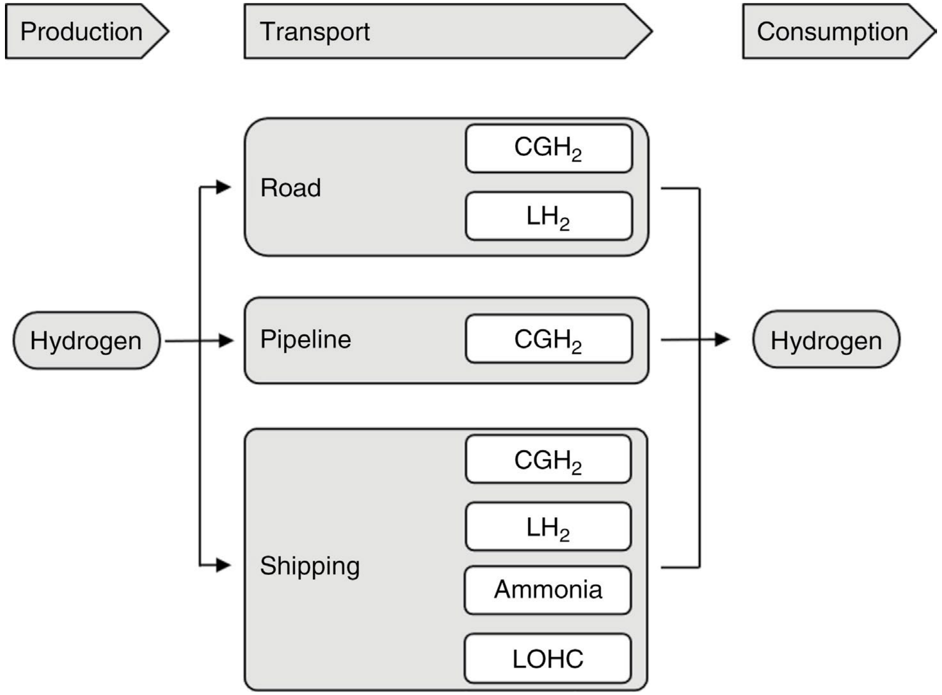


Source: IRENA

Hydrogen Storage and Transportation

Hydrogen Storage and Transport





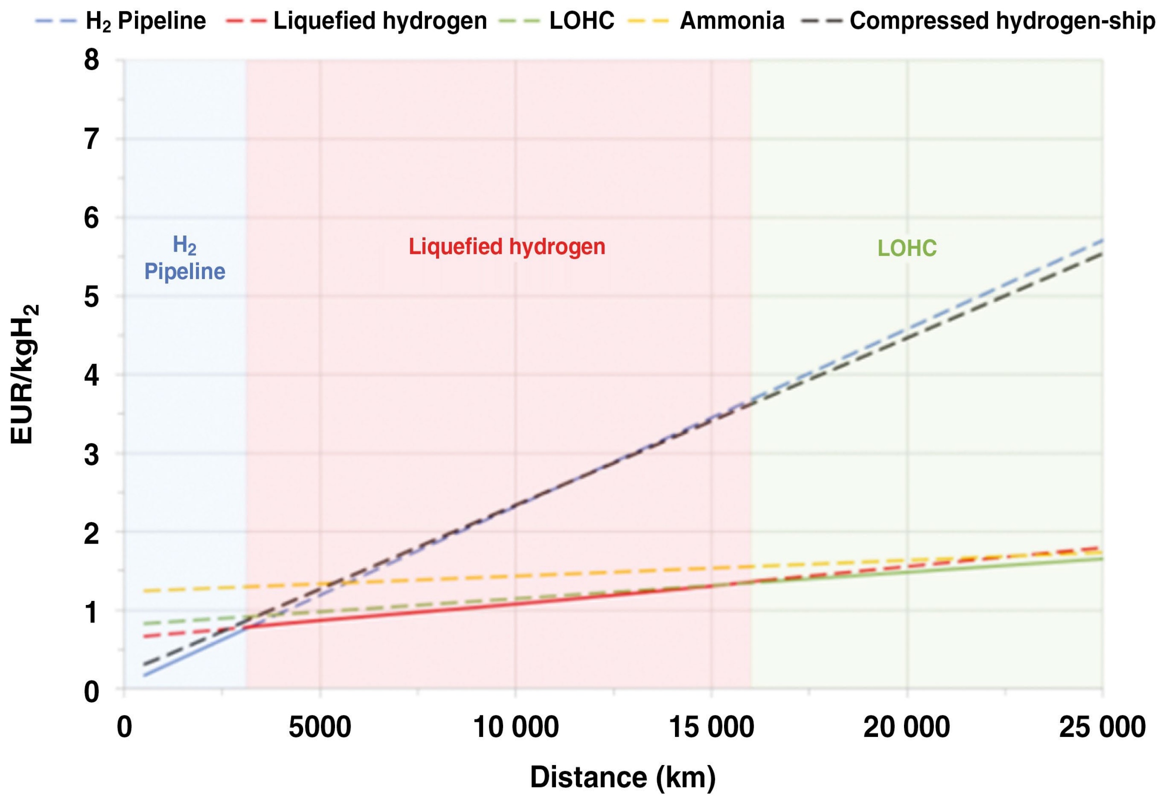
Transport		Appropriate distance
Land transportation	**CG trucks**	Short-distance transport → up to 100 km
	LH_2 trucks	Medium-distance transport → over 500 km
	Pipeline	Long-distance transport → up to 1000 km
Overseas transportation	**LH_2 ship**	Long-distance transport → over 1000 km

urce: *Clean En*, Volume 7, Issue 1, February 2023, Pages 190–216, https://doi.org/10.1093/ce/zkad021

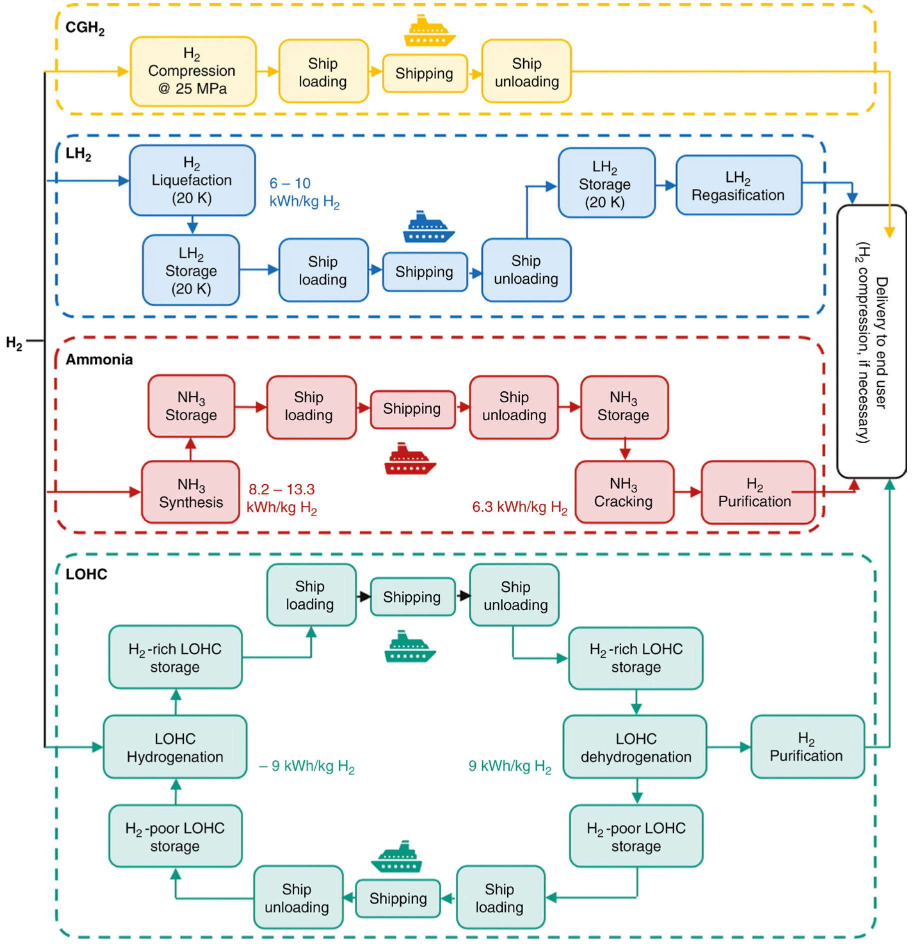
Transporting Hydrogen

- Pipelines
  - Pipelines are the most efficient and least costly way to transport hydrogen up to a distance of 2500 to 3000 km, for capacities around 200 kt per year
  - About 2 600 km of hydrogen pipelines are in operation in the United States and 2 000 km in Europe
  - The European Hydrogen Backbone initiative brings 32 gas infrastructure operators together aiming to establish pan-European hydrogen infrastructure
  - Staying on track with the NZE Scenario would require around 15 000 km of hydrogen pipelines (including new and repurposed pipes) by 2030
- Ships – Ammonia, Methanol, LOHC
  - For long distances, shipping hydrogen and hydrogen carriers are more cost-competitive than hydrogen pipelines
  - Growing number of projects are considering the possibility of transporting ammonia
  - In the NZE Scenario, more than 15 Mt of low-emission hydrogen (in the form of hydrogen or hydrogen-based fuels) are shipped globally by 2030
- Liquid Hydrogen
  - Improves volumetric density of Hydrogen by cooling to 253 deg C and transported in insulated and double hulled tanks on-road
  - Well established technology, simple conversion and reconversion, already in use
  - Key use case: Central production and distribution within regional geography for distributed applications such as mobility and backup power
- Compressed Gaseous Hydrogen
  - Mainly used in on-site applications to reduce volumetric storage requirements
- Carbon Certification balancing
  - Alternative to actual transportation of Hydrogen molecule, settlement through commercial arrangements, under exploration in Aviation market

Transporting Hydrogen



Hydrogen delivery costs for a simple (point-to-point) transport route, for 1 Mt of H_2 and a low and a low electricity cost scenario 2050



Clean En, Volume 7, Issue 1, February 2023, Pages 190–216, https://doi.org/10.1093/ce/zkad021

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Hydrogen in Energy Systems and End Applications

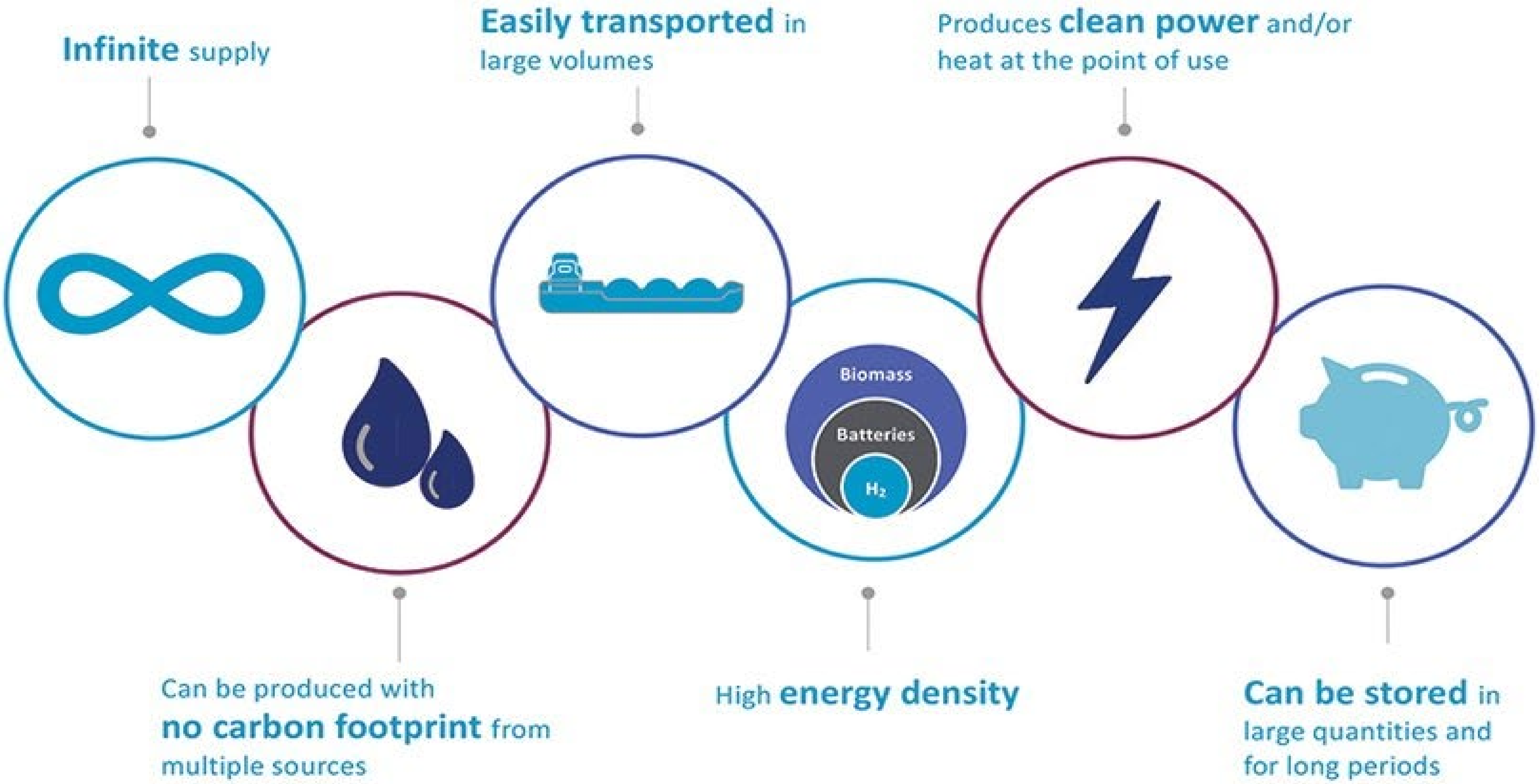
Fossil Fuels vs RE and Hydrogen

Fossil Fuels

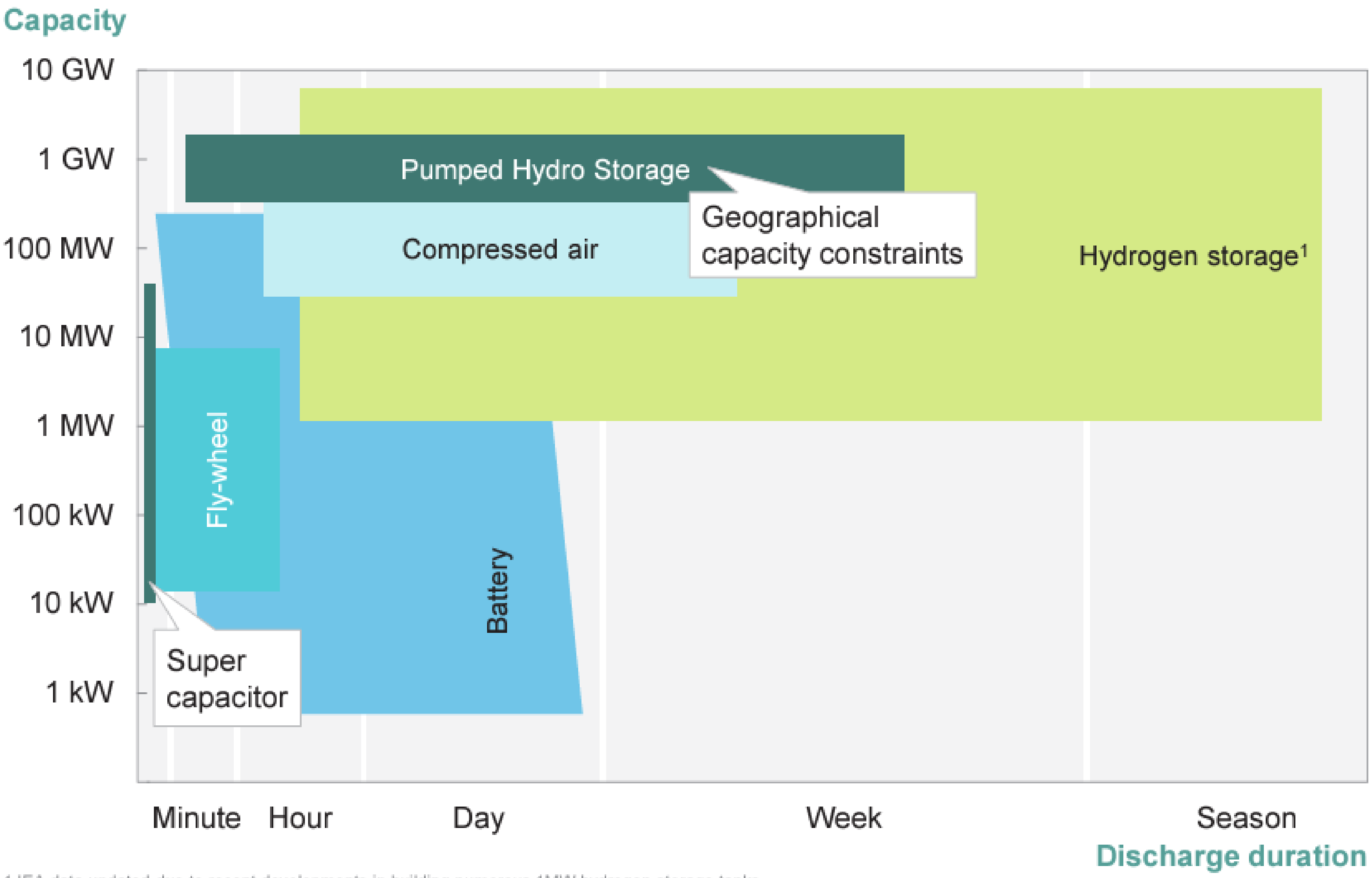
Renewables & Green Hydrogen

Why hydrogen?

A versatile, zero-emission, efficient energy carrier



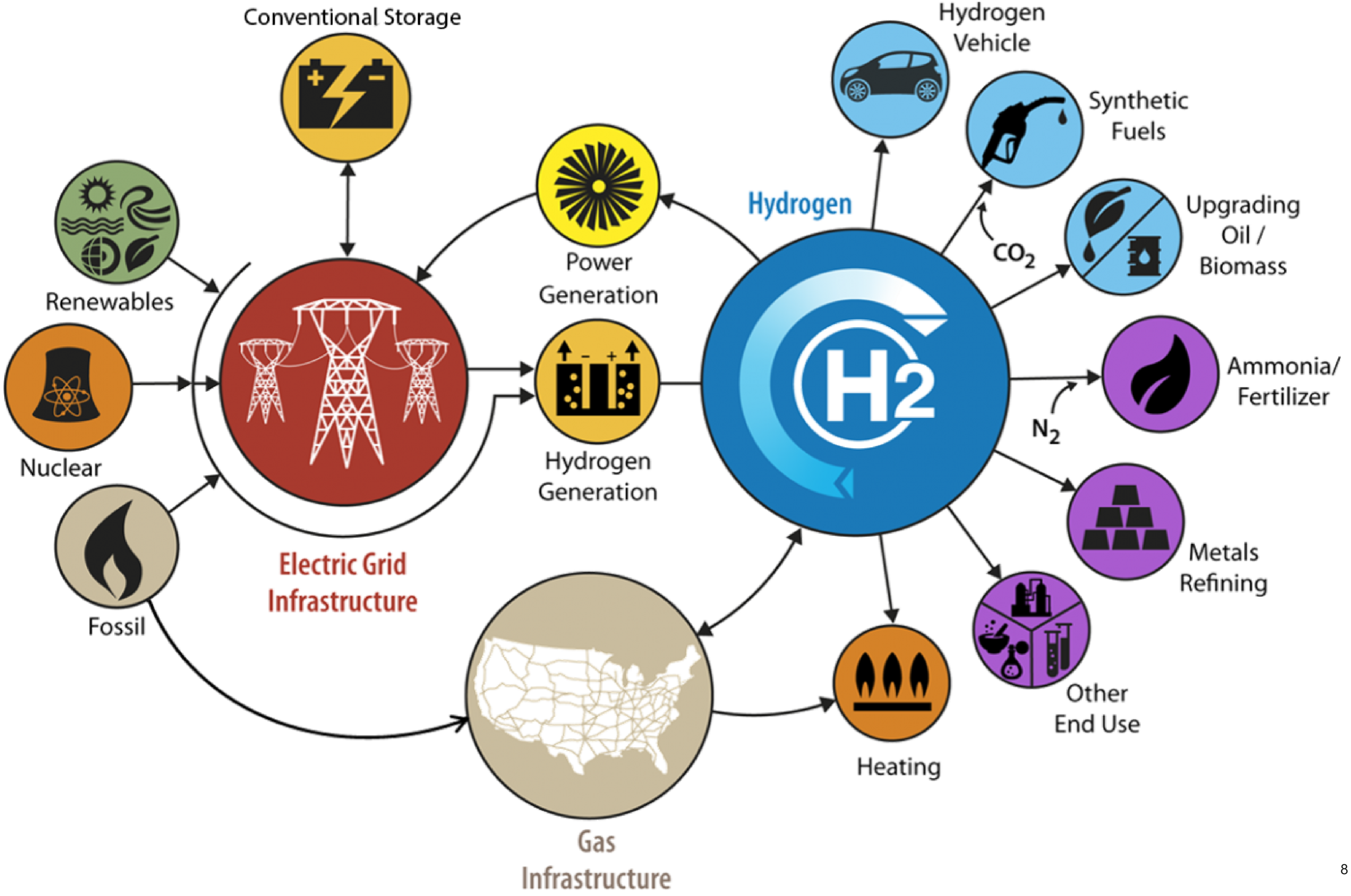
Source: https://m.miningweekly.com/article/south-africas-potential-to-export-green-hydrogen-boosted-2020-05-26



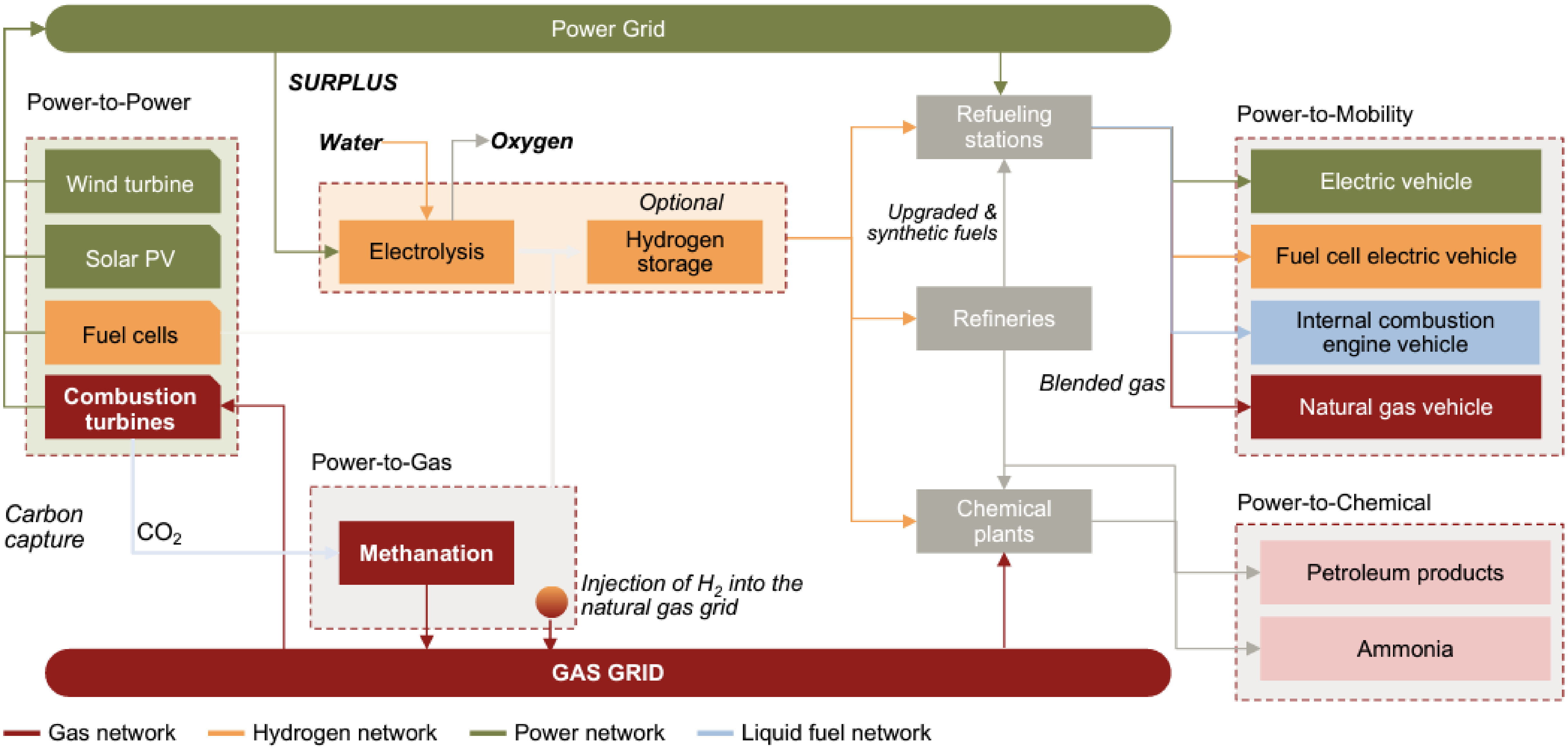
1 IEA data updated due to recent developments in building numerous 1MW hydrogen storage tanks

Source: IEA Energy Technology Roadmap Hydrogen and Fuel Cells, JRC Scientific and Policy Report 2013

Opportunities for hydrogen in energy systems

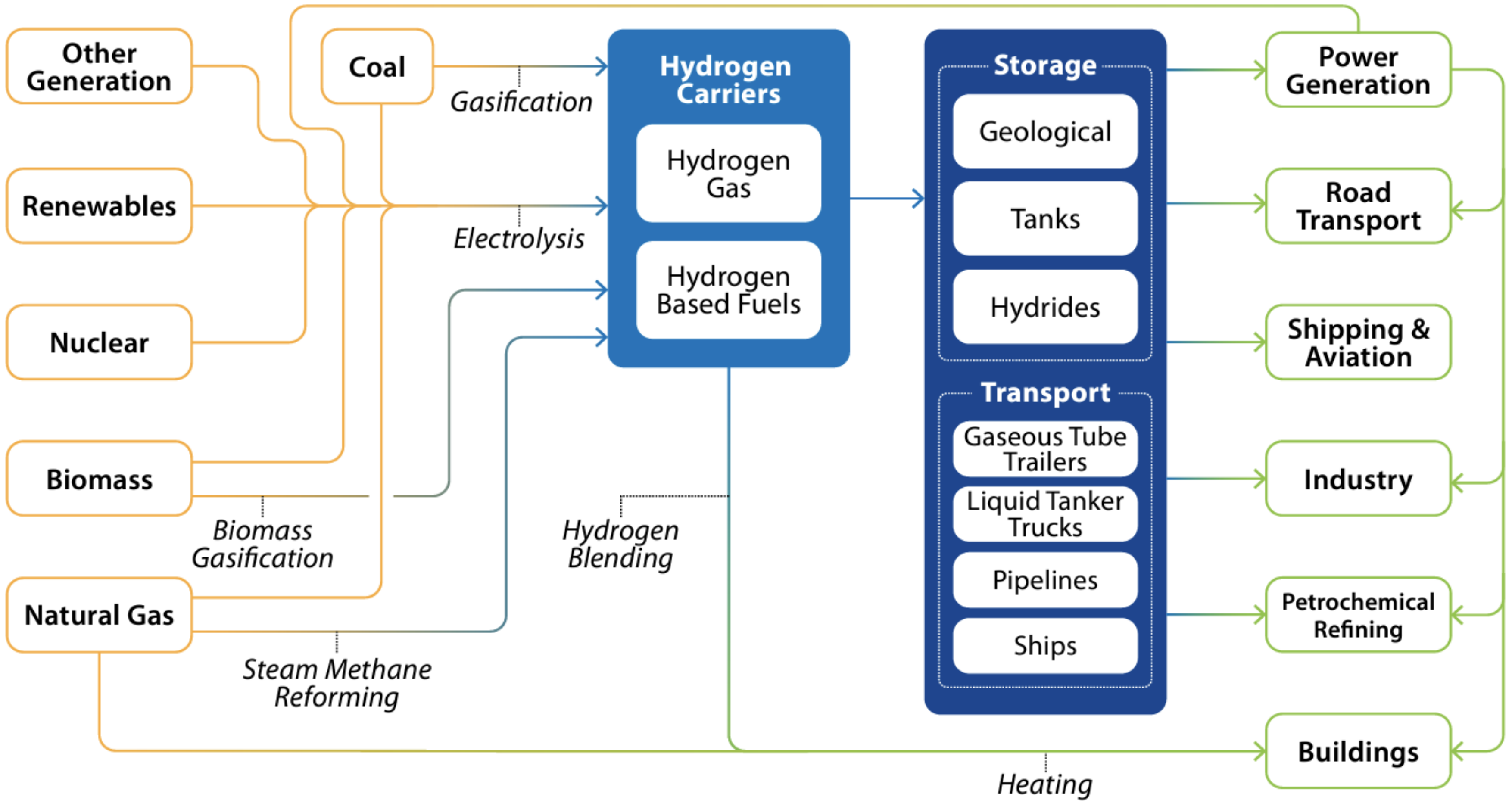


Simplified value chain of hydrogen-based energy conversion solutions[1]

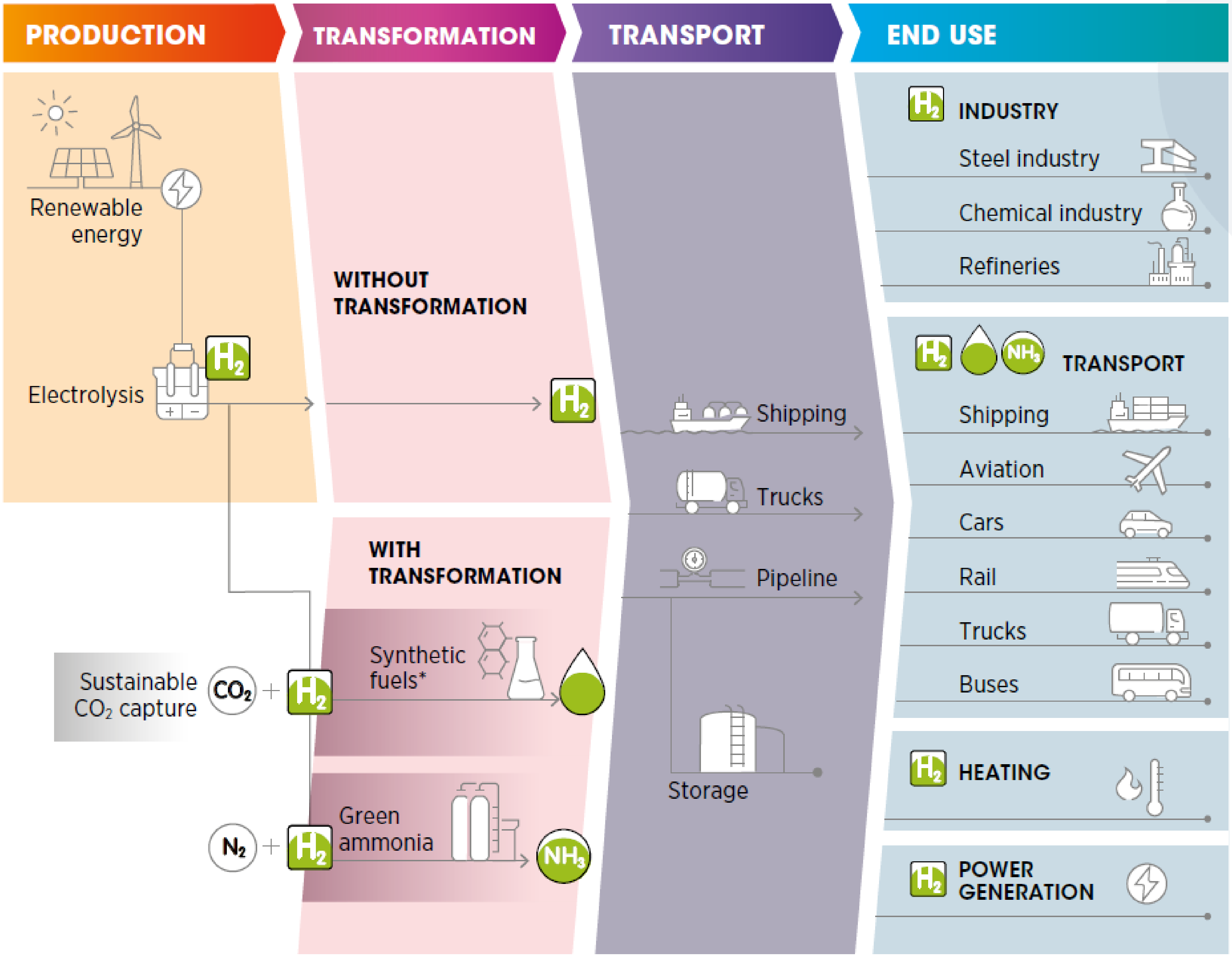


1. Simplified value chain. End uses are non-exhaustive. For more information on the technologies mentioned in this diagram, please refer to next chapter or to the Hydrogen FactBook.
Source: A.T. Kearney Energy Transition Institute analysis.

Energy Process Chain of Hydrogen



Source: NREL, https://www.nrel.gov/docs/fy22osti/82554.pdf



Source: IRENA (2020f).

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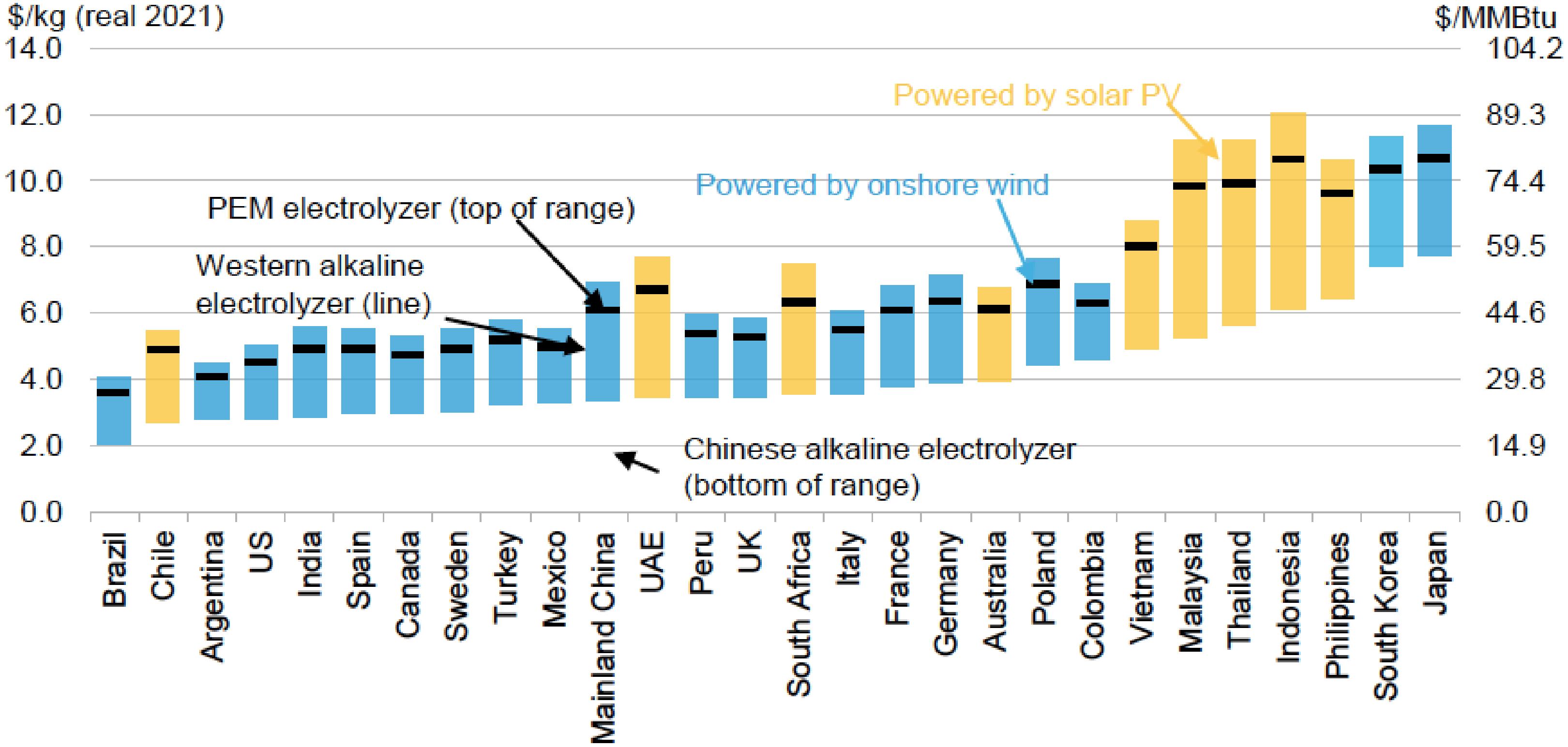
Green Hydrogen at Work™

Hydrogen from renewables remains expensive, but costs vary widely by market

Levelized cost of hydrogen from cheapest available renewable power in 28 markets, 2022



Natural resources are the key to producing low-cost hydrogen with renewable power.

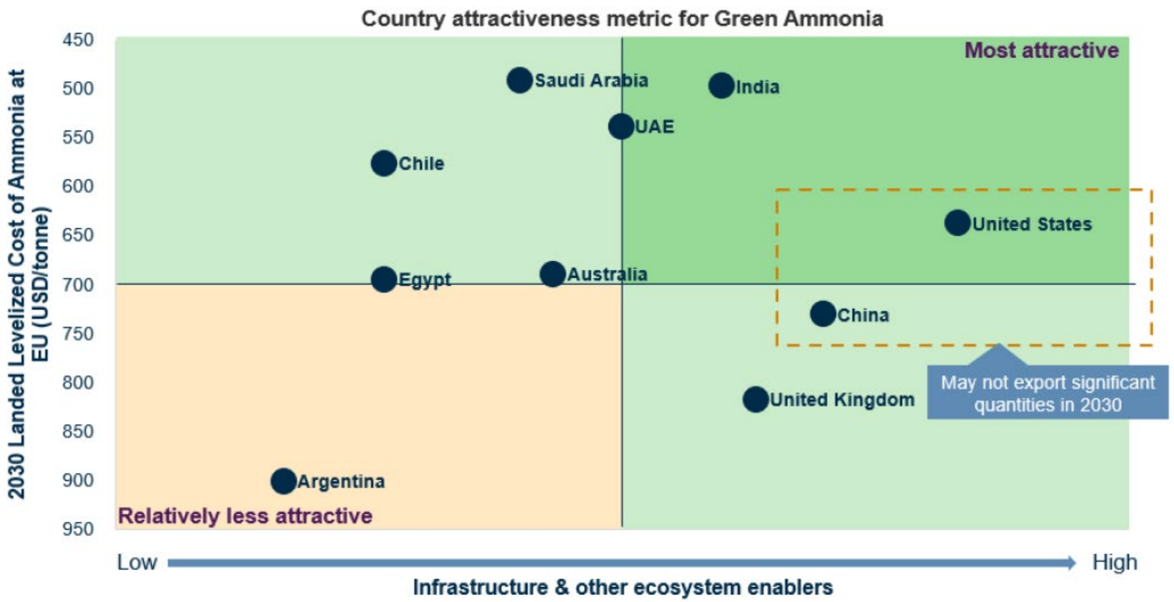
Brazil operates onshore wind projects with some of the highest capacity factors in the world. Partly as a result, it has the world's lowest potential levelized cost for zero-carbon hydrogen at $2.01-4.05/kg. Chile, thanks to its exceptionally sunny conditions in some areas, also has the potential to produce hydrogen at relatively low cost ($2.77-$5.48 /kg).

The cost of the equipment used to produce hydrogen – *electrolyzers* – is critical in the final levelized cost of producing the fuel.

Alkaline electrolyzers manufactured in mainland China tend to have the lowest cost, while proton-exchange membrane (PEM) electrolyzers tend to be the most expensive. Equipment costs are declining, however. India has the potential to be among the lower-cost producers of zero-carbon H2.

Source: BloombergNEF. Values at the bottom show cheapest hydrogen using a Chinese alkaline electrolyzer, values atop the range show cheapest values using a proton exchange membrane electrolyzer, and black lines show cheapest values using a Western alkaline electrolyzer. Electricity source is either solar or wind, whichever is cheaper. MMBtu is million British thermal units.

Green Ammonia Country Attractiveness



Source: Alvarez and Marsal analysis

Table 3: Infrastructure and other ecosystem enablers scoring

	Renewable energy ecosystem	Size of power grid (including transmission)	Current H2 Usage	Manufacturing ecosystem	Petrochemicals and Gas consumption	Port Infrastructure	Ease of doing Business	Trade Relationships (with EU and Japan)	Final score
United States	High	High	High	High	High	High	High	High	3
China	High	High	High	High	High	Medium	Medium	Medium	2.6
United Kingdom	Medium	Medium	High	Medium	Medium	High	High	Medium	2.4
India	High	High	High	Medium	Medium	Medium	Medium	Medium	2.3
UAE	Low	Low	Low	Medium	Medium	High	High	Medium	2.0
Australia	Medium	Medium	Low	Low	Low	Medium	High	Medium	1.8
Saudi Arabia	Low	Medium	Medium	Low	Medium	Medium	Medium	Medium	1.7
Chile	Low	Low	Low	Low	Low	Medium	Medium	Low	1.3
Egypt	Low	Medium	Medium	Low	Low	Medium	Low	Low	1.3
Argentina	Low	Low	Low	Low	Low	Low	Low	Low	1

Source: Alvarez and Marsal analysis

Estimated Market Size by 2030 based on current state of Industry:

Hydrogen Production

- Around 135 projects with 6.8 GW Electrolyzer installation by 2030 estimated producing 1 MMTPA of GH_2
- Estimated Capex of $9.1Bn

Equipment Export and Services

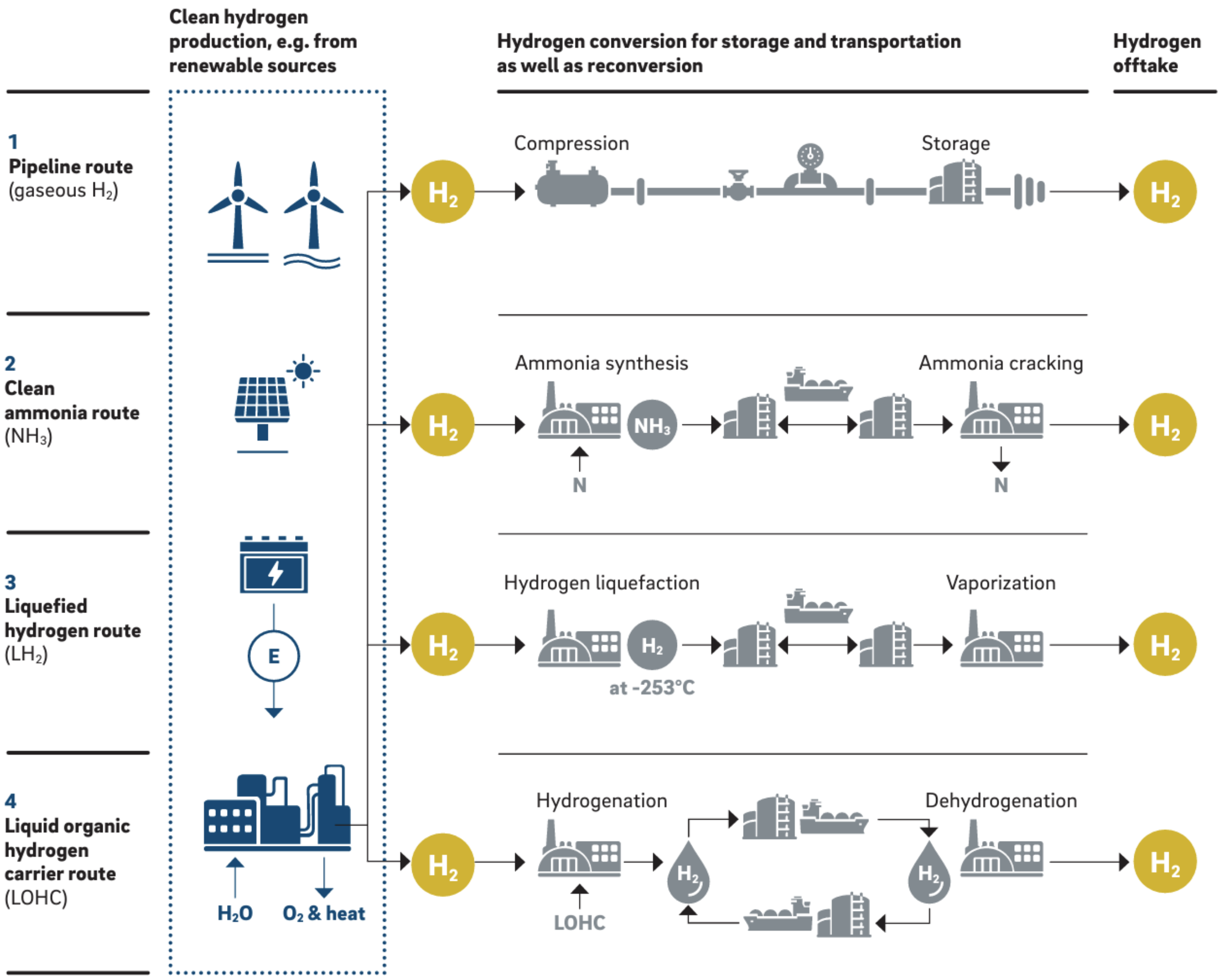
- $34Bn equipment export potential
- $2.1Bn Engineering Services

Total ~$45Bn Equipment & Services opportunity

Source: IH2A

Source: Country Strategy documents, IEA project database, applying an 80% factor for actual realization of announced projects

Transporting Hydrogen



Source: Roland Berger