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Greening hydrogen, the promise beyond the hype

4 May 2023

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Welcome!

Do you have any questions?

Send them in via the Q&A tab. We aim to answer as many as we can today!

You can also let us know of any tech problems there.

We are recording this webinar today.

We‘ll let you know by email where to find it and the slide deck, so you can re-watch it at your convenience.

A new geopolitics of hydrogen?

Yana Zabanova, RIFS Potsdam

„Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy“ Project

4 May 2023, pv magazine Webinar | Greening hydrogen, the promise beyond the hype

“…the Russian invasion of Ukraine has put an end to the globalization we have experienced over the last three decades.”

Larry Fink, CEO of Blackrock, on 24 March 2022

Hydrogen for energy security

"We must become independent from Russian oil, coal and gas (…). The quicker we switch to renewables and hydrogen…the quicker we will be truly independent and master our energy system."

EU Commission President Ursula von der Leyen presenting the REPowerEU plan, 18 May 2022, Brussels

Caixa Research: by 2030, green hydrogen could replace up to **17.4%** of the 155 bcm of Russian gas imported by the EU in 2021

A new geopolitical and geoeconomic order?

- **Liberal international order**: interdependence as an asset and the „glue" of globalization
- Today: interdependence increasingly viewed as a security risk
  - **„Weaponized interdependence":** States with political authority over central economic nodes "can weaponize networks to gather information or choke off economic and information flows, discover and exploit vulnerabilities, compel policy change, and deter unwanted actions." (Drezner 2021)
  - **Strategic autonomy** and **resilience** are prominent motivations
  - Friendshoring/ allyshoring
- **Potential tradeoffs**:
  - technological fragmentation
  - higher barriers to investment
  - costly supply chain reconfiguration
  - efficiency losses

A global green (subsidy) race?

Policy priorities:

- Promoting green manufacturing and technology leadership
- Securing access to clean energy to preserve industrial competitiveness in the future

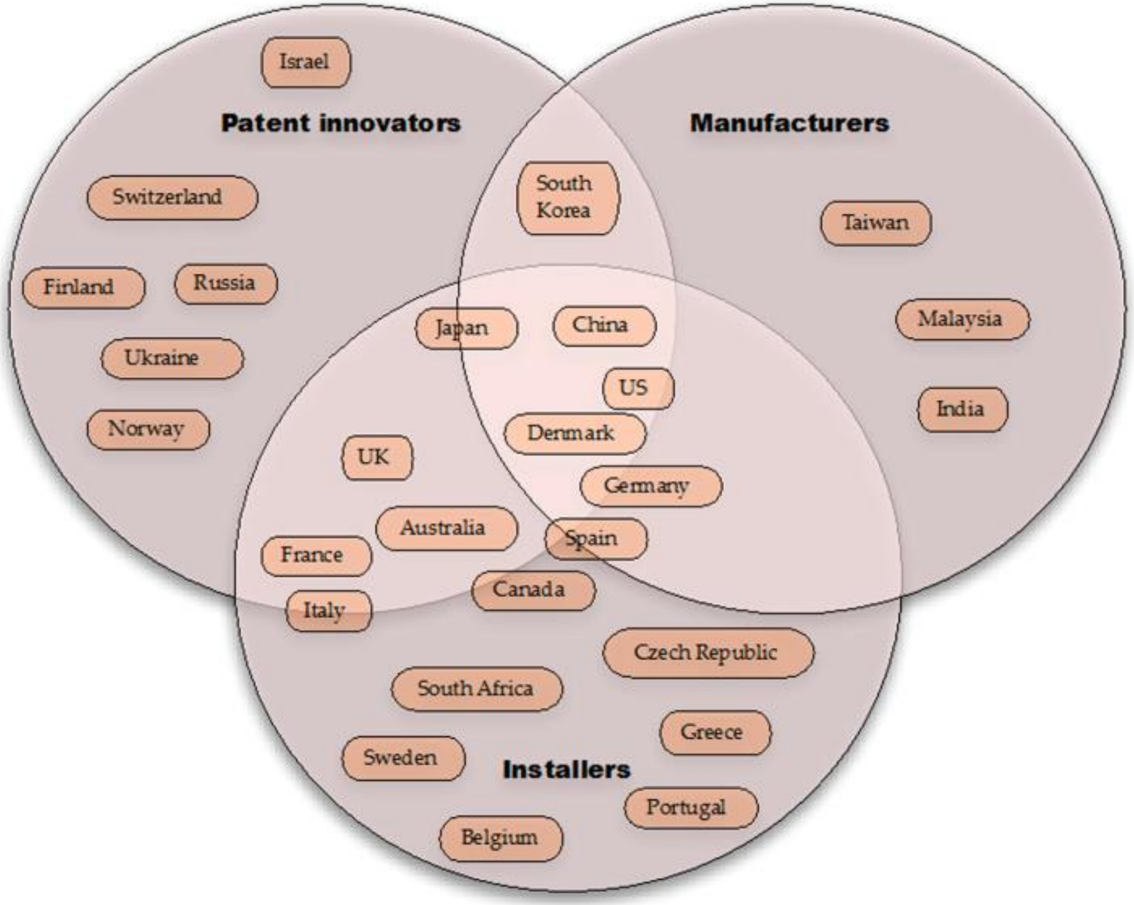
USA: **Inflation Reduction Act** (2022), 369 billion USD, including 270 bn USD in tax incentives

  - Hydrogen tax credit of up to **3 USD/kg**
  - Domestic content requirements

EU: **Green Deal Investment Plan** (incl. Net Zero Industry Act), 2023

  - Electrolyzer manufacturing capacity target: 50% of renewable and fossil-free hydrogen annual deployment needs
  - European Hydrogen Bank: 3 bn EUR budget; 800 mln EUR for the first auction (2023), fixed premium subsidy up to **4 EUR/kg**
  - **But:** institutional and legal obstacles, lack of unity among Member States

Global green division of labour: what about H2?

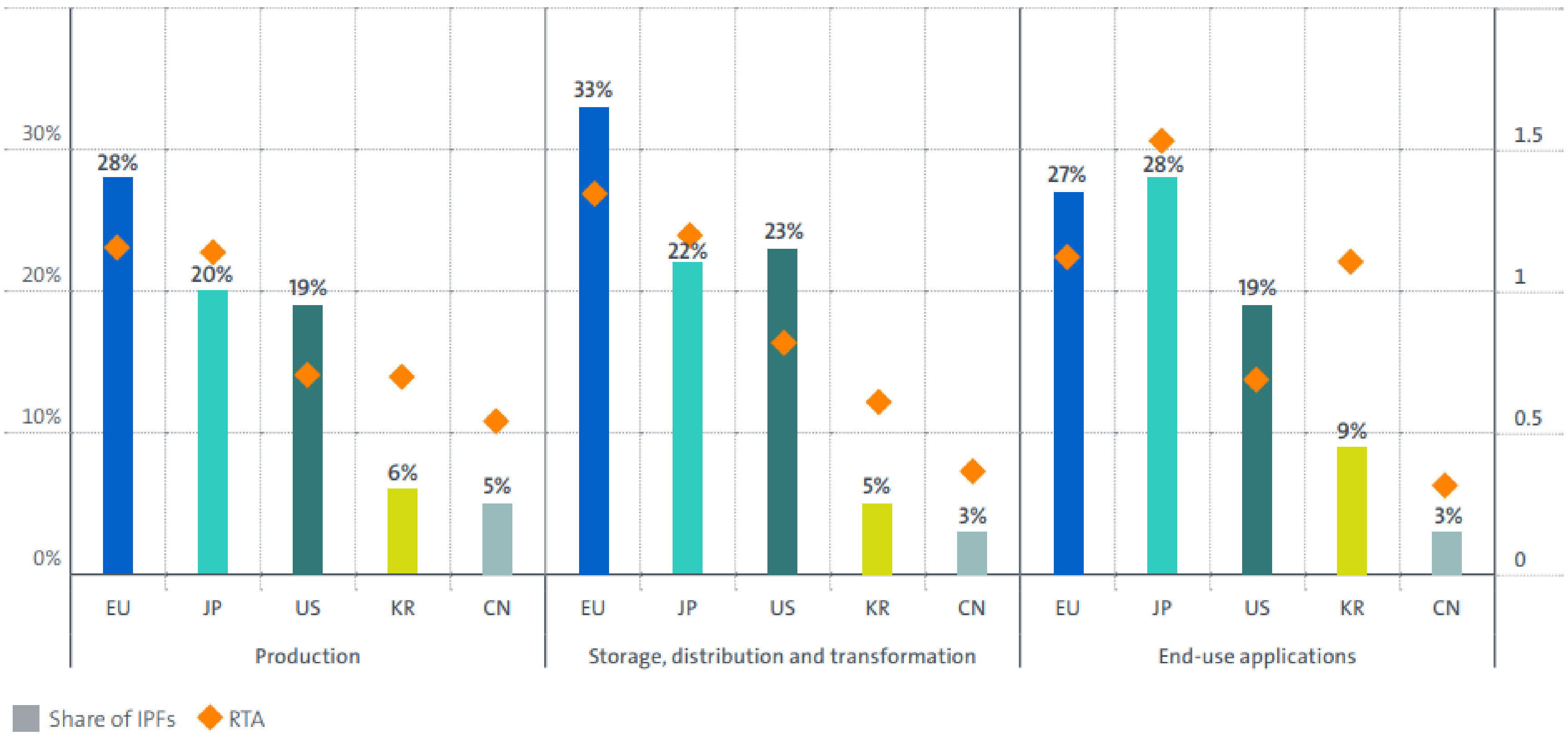


Source: Lachapelle et al (2017)

The clean energy global division of labour

Patent innovators

Share of international patenting and revealed technology advantage by main world regions and value chain segments (IPFs, 2011–2020)

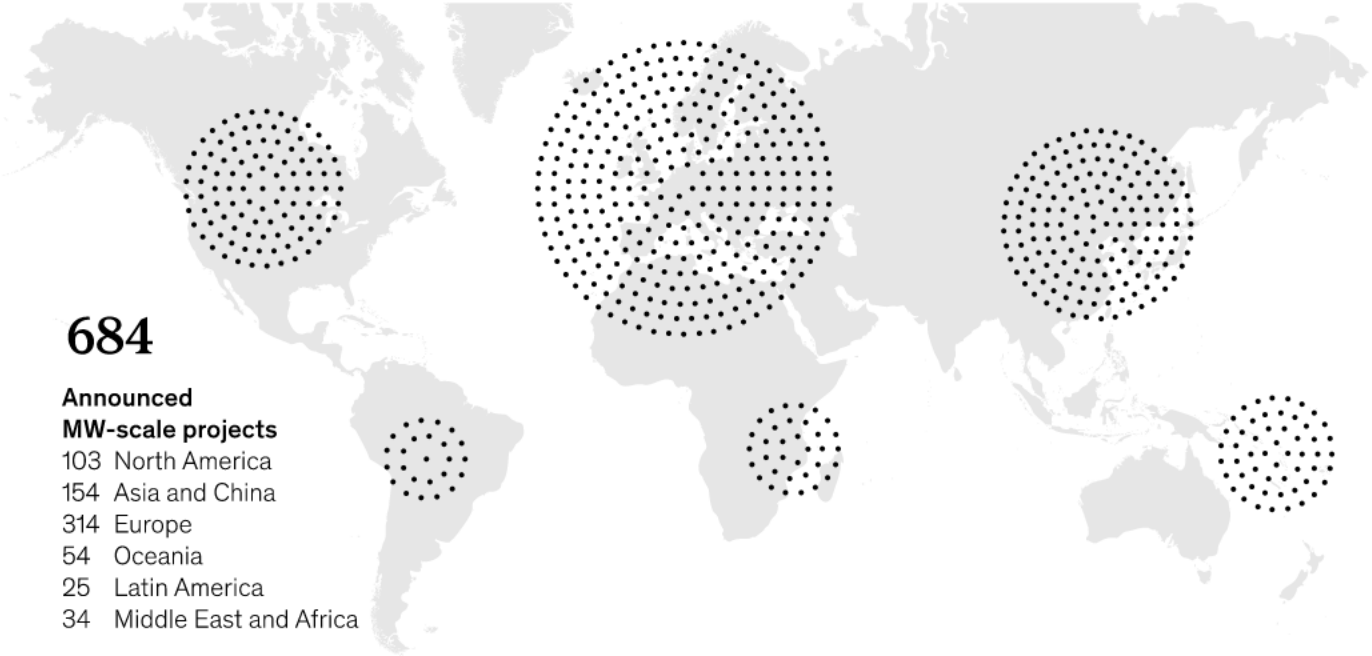


Source: IEA: Hydrogen Patents for a Clean Energy Future, 2023

Installers

More than 680 large-scale hydrogen projects have been announced globally, with a focus on production, industrial usage, transport, and infrastructure.

684 announced megawatt-scale projects[1]



Source: McKinsey (2022), data as of May 2022

April 2023:

Total electrolyser projects in development:
1,125 GW

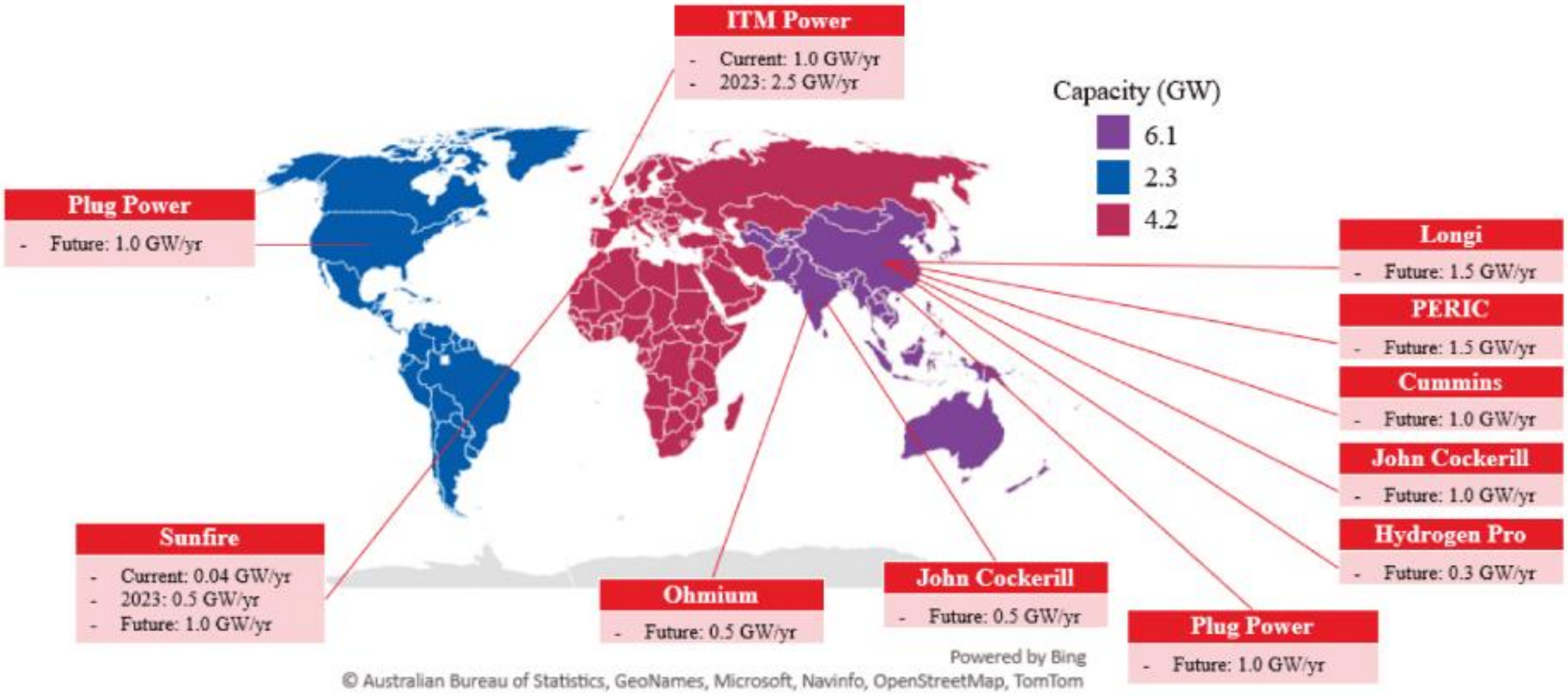
Europe`s share: declined to 56% from 64% in October 2022

Largest project pipeline capacity increase: North America

… but only **1%** of projects currently in construction!

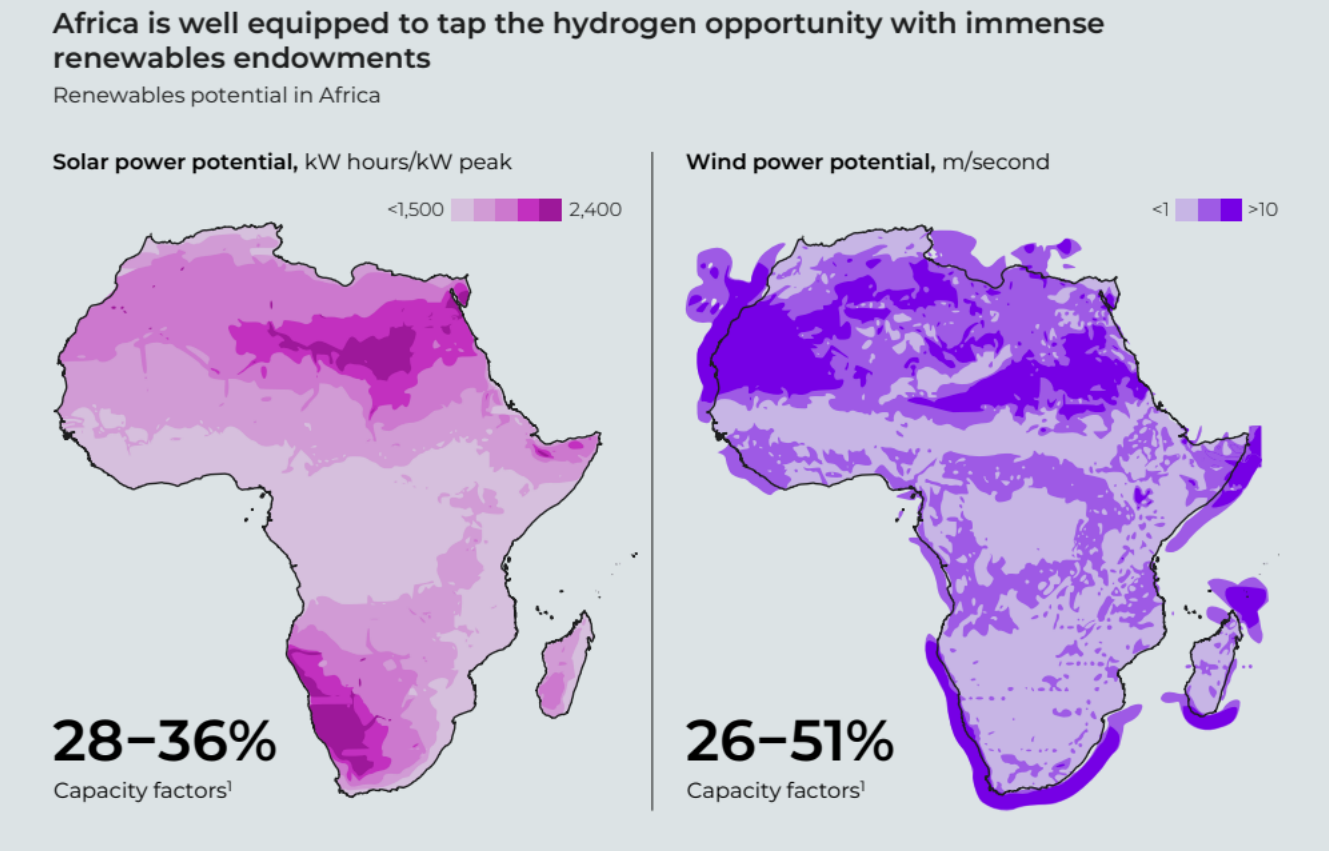
Source: Aurora Energy Research (2023)

Manufacturers: Electrolyser manufacturing capacities by region



Source: Scottish Government; data from Bloomberg NEF and featured manufacturers

Future hydrogen partnerships: exports vs. domestic value capturing



Source: Africa’s Green Hydrogen Potential (data taken from Global Solar Atlas; Global Wind Atlas; McKinsey Hydrogen Cost Optimization Model)

South Africa: producing direct reduced iron (DRI); domestic manufacturing of H2 technologies using PGM („Platinum Valley“ industrial cluster)

Morocco: green fertilizer from domestically produced ammonia

Thank you!

PV Magazine Webinar: Greening Hydrogen, the Promise Beyond the Hype

George Touloupas

Senior Director, Technology and Quality

May 4th , 2023

Company Snapshot

Clean Energy Associates is a technical advisory company that provides unrivaled insight into the solar PV, energy storage and hydrogen manufacturing industries to ensure the success of solar PV, storage and electrolyzer projects worldwide.

1,000+
Years of industry experience

200+
Professionals

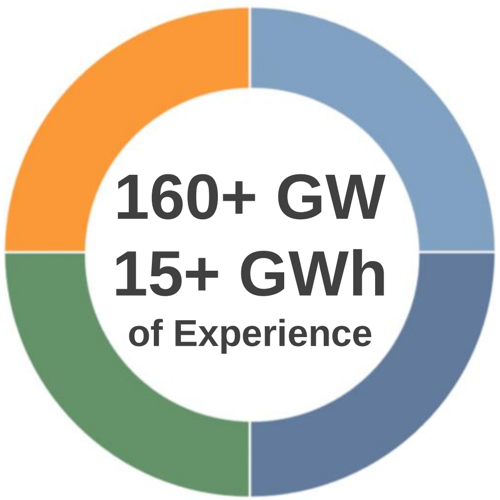
135+
Engineers

13
Year track record

13
Countries with a physical presence

Supply Chain Management

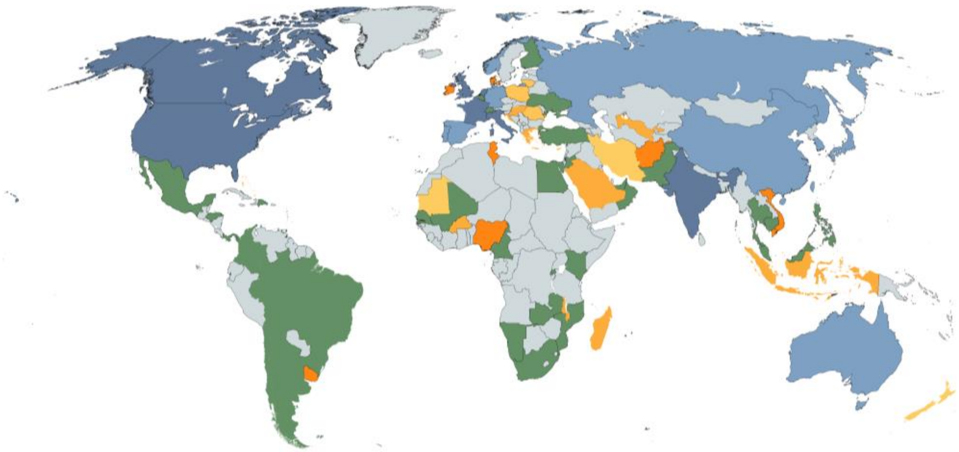
Market Intelligence



Engineering Services

Quality Assurance

Client engagements in **70+** countries



Engagements in **350+** solar and storage factories worldwide

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Topics

1. Supply and demand
2. Scaling up
3. Levelized Cost of Hydrogen (LCOH)
4. Q&A

1. Supply and demand

Production methods and potential use cases for green hydrogen

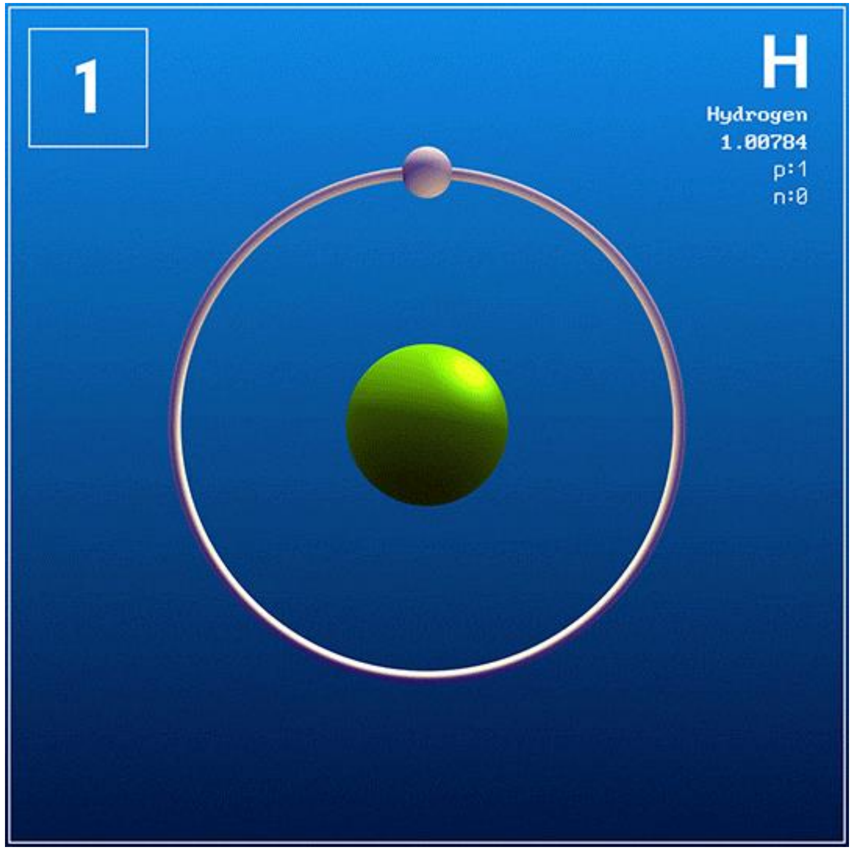
Hydrogen: the Element

Hydrogen is the lightest, simplest and most abundant element in the universe: ~75% of visible matter).

It is mostly found in chemical compounds, and, notably, water: 1 liter of water contains 111 g of H_2

Hydrogen is an energy carrier. Combined with oxygen, it releases a lot of energy and no carbon dioxide.

Hydrogen has a wide flammability, 4%-74% in air, 4%-94% in oxygen, and special precautions are needed to handle it.



Electrolysis: $2H_2O$ + energy --> $2H_2 + O_2$

Oxidation: $2H_2 + O_2$ --> $2H_2O$ + energy

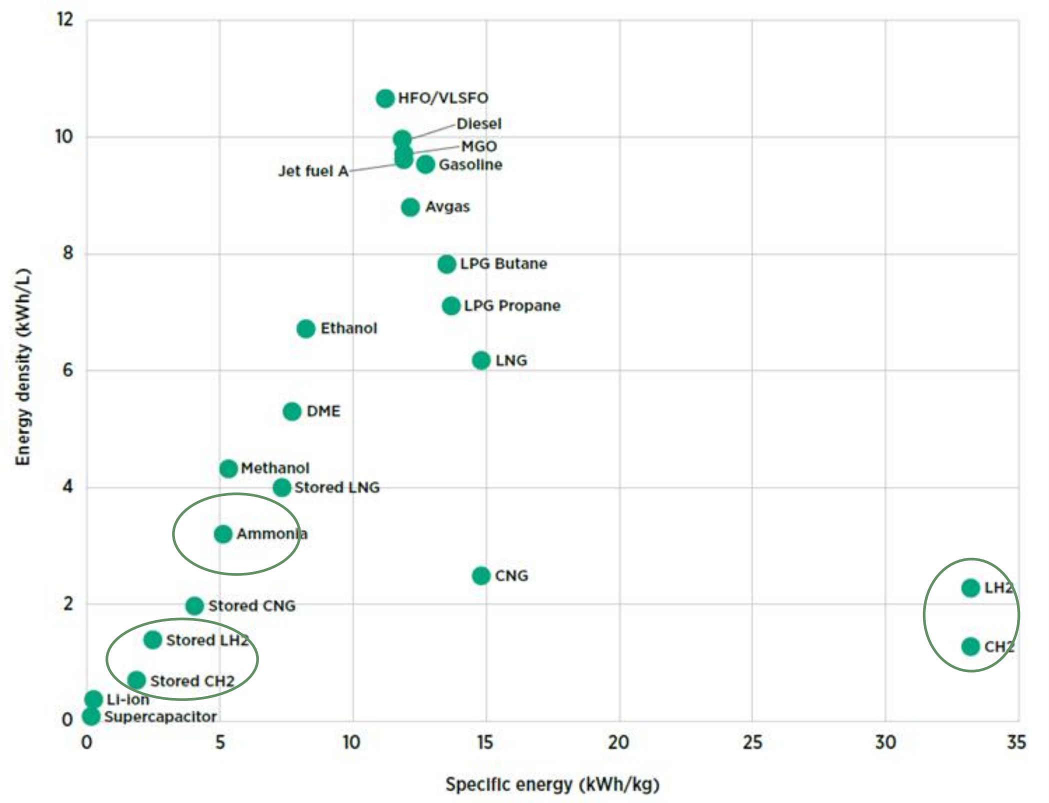
Hydrogen as Energy Carrier

Hydrogen is very energy dense by weight: 33.3 kWh/kg*, compared to gasoline's 12.9 kWh/kg.

However, hydrogen has **very low volumetric density**: only 1.25 kWh/L (compressed at 700 bar) vs 9.5 kWh/L for gasoline.

Hydrogen can be liquified at low temperatures (-253 °C), and reach 2.35 kWh/L, or 25% of gasoline's volumetric density, but this has high energy cost (~-30%) and storage cost.

Ammonia is another potential hydrogen carrier, it has fair density, but relatively high energy cost: ~-40% to make it and ~-30% to convert it back to hydrogen.



Notes: Avgas = aviation gasoline; CH2 = hydrogen compressed at 70 MPa; CNG = natural gas compressed at 25 MPa; DME = dimethyl ether; HFO/VLSFO = heavy fuel oil/very low sulphur fuel oil; LH2 = liquefied hydrogen; Li-ion = lithium-ion battery; LNG = liquefied natural gas; LPG = liquefied petroleum gas; Stored CNG = Type IV tank at 250 bar; Stored CH2 = best available CH2 tanks at 70 MPa; Stored LH2 = current small-scale LH2 on-board tanks; Stored LNG = small-scale storage at cryogenic conditions; MGO = maritime gasoil. Numbers are expressed on a lower heating value (LHV) basis. Weight of the storage equipment is included.

Source: IRENA

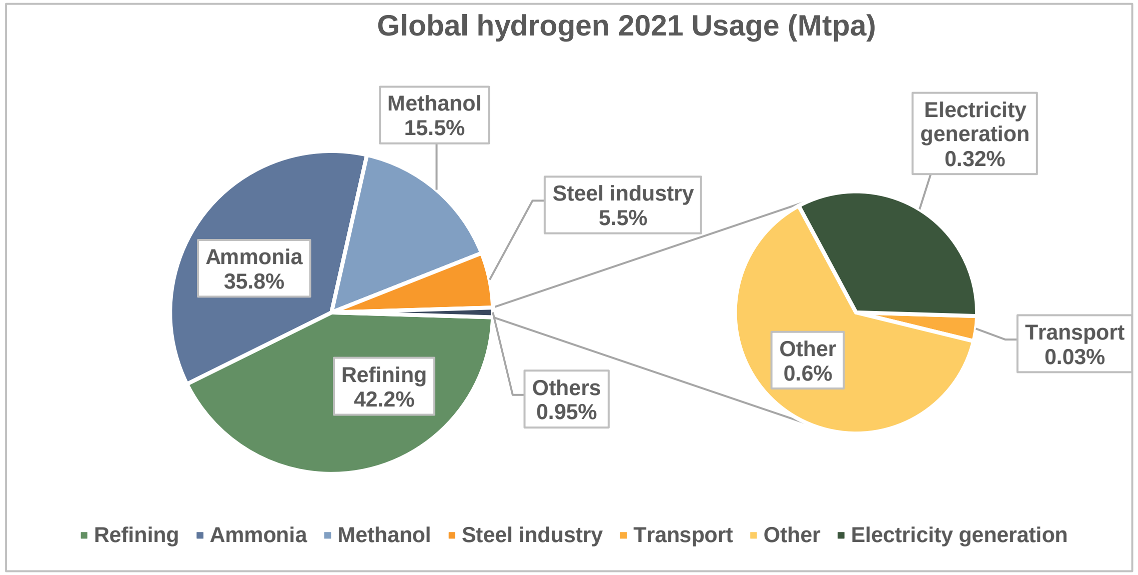
*LHV (Low Heating Value)

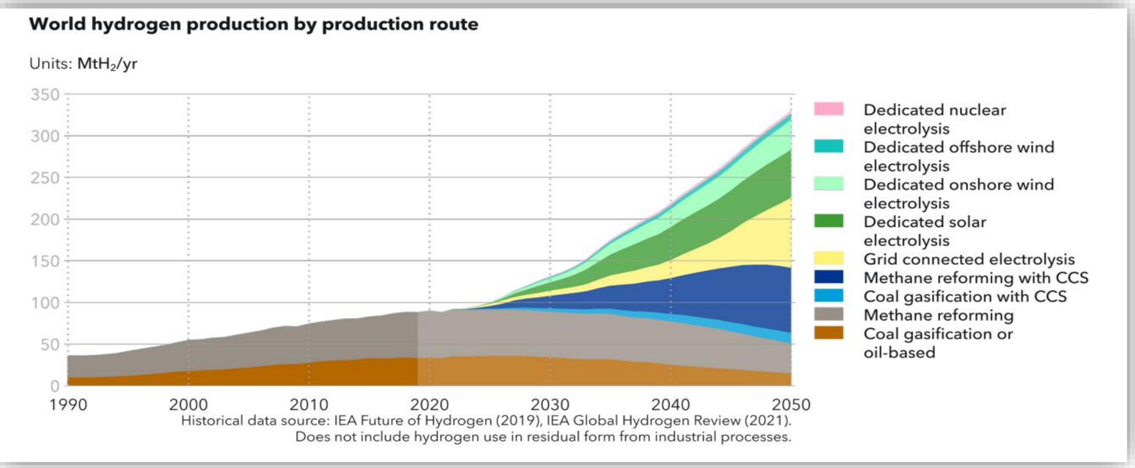
Supply and Demand Pathways

94 Mtpa of H_2 were produced in 2021, almost all coming from fossil fuel based chemical processes, to be used in oil refining, ammonia, chemicals and iron production.

About 10 kg of CO_2 is emitted for every 1 kg of hydrogen produced from natural gas, and hydrogen production from fossil fuels directly contributed to ~ 2.5% of total global CO_2 emissions in 2022.

IEA's Announced Pledges scenario, predicts 130 Mtpa of hydrogen in 2030, with ~15% coming from water electrolysis.





*Mtpa = million tons per annum

Data source: IEA

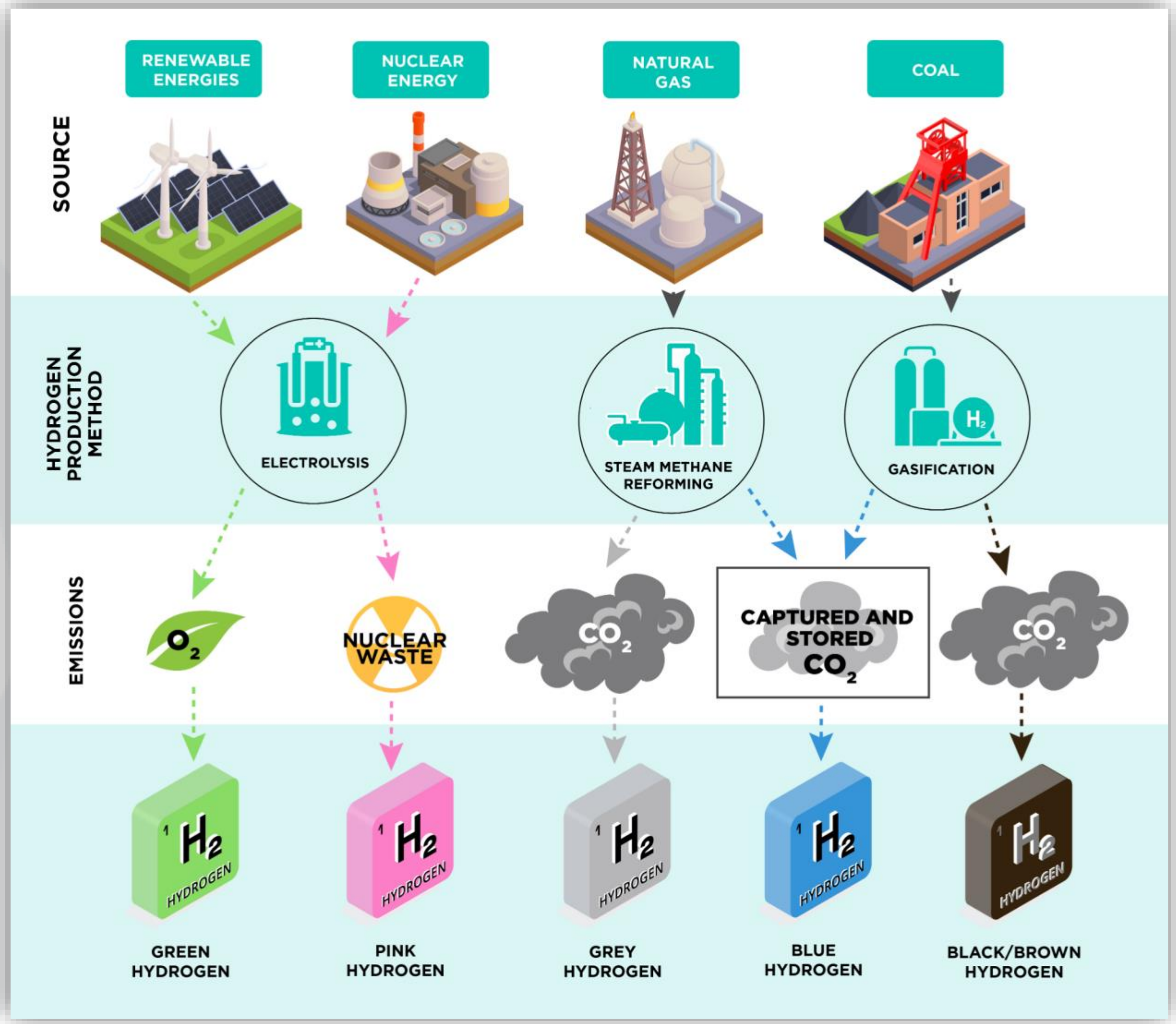
Hydrogen Colors

To be clean, Hydrogen needs to be produced by processes that do not use fossil fuels.

Electrolysis used to be the main hydrogen production process until the sixties, then the natural gas reforming process matured and gradually achieved the lowest cost, currently at $1-1.8/kg.

With the advent of very low-cost renewable electricity, renewable (green) hydrogen can look up at achieving similar or lower costs than fossil fuel based hydrogen in the next 3 decades.

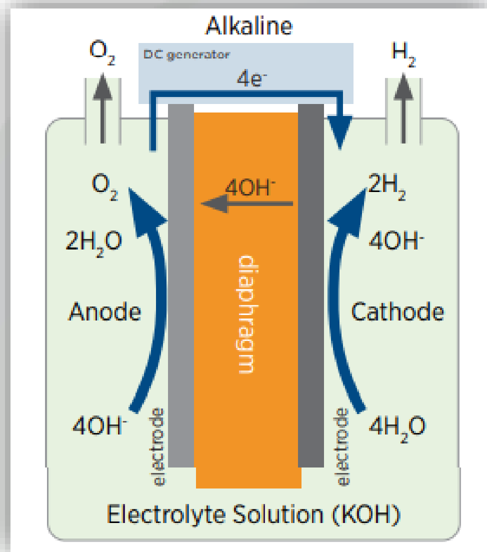
Blue hydrogen, which is fossil fuel derived with carbon capture, is heavily promoted by the oil and gas industry, however, carbon capture and storage technologies are not mature yet and methane leaks could further reduce its effective capacity to overall mitigate greenhouse gases.



Source: CIC energiGUNE

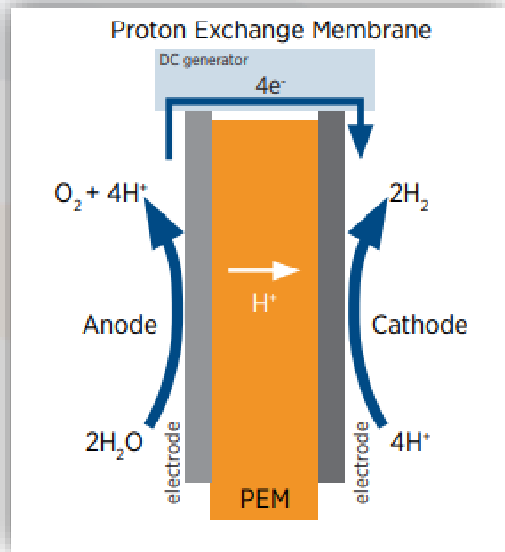
Quick Primer: The Electrolyzer Technologies

Alkaline



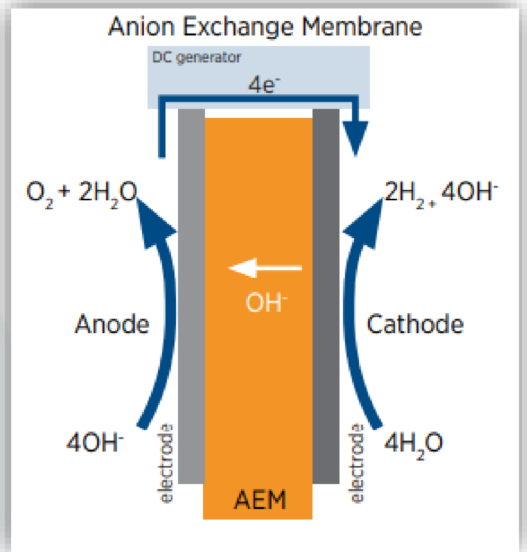
- **Mature**
- Lowest cost
- Easy to scale up
- Abundant raw materials

PEM



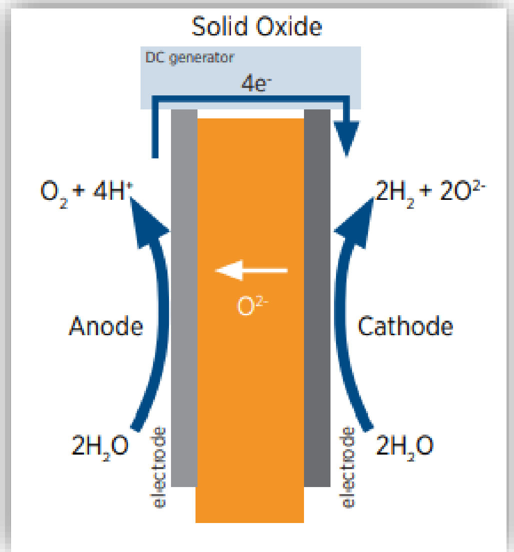
- **Mature**
- High cost
- Easy to scale up
- Scarce raw materials

AEM



- Not commercial
- Potential for low cost
- Abundant raw materials

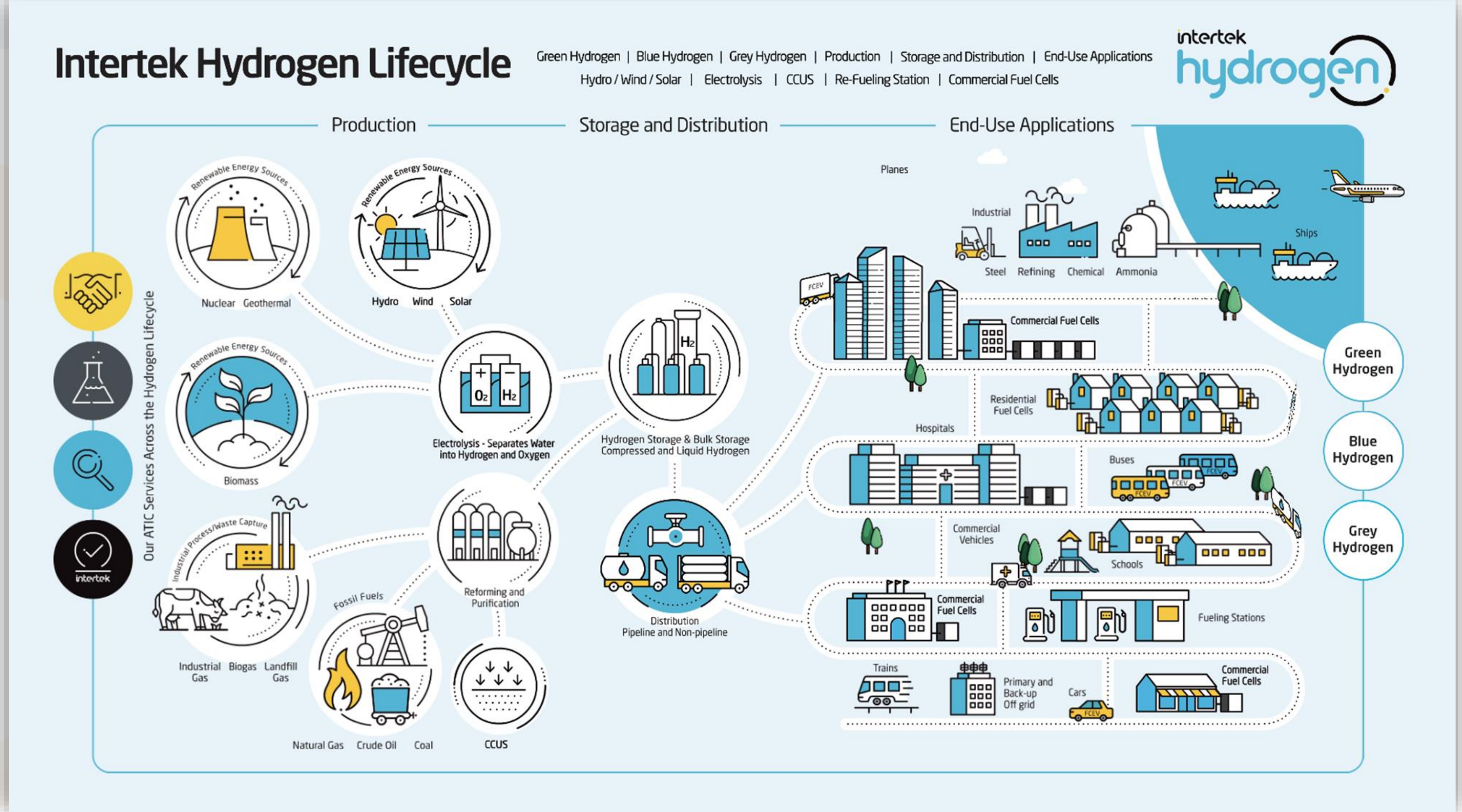
SOEC



- Not commercial
- Highest efficiency
- Must run continuously

The Many Potential Uses of Hydrogen

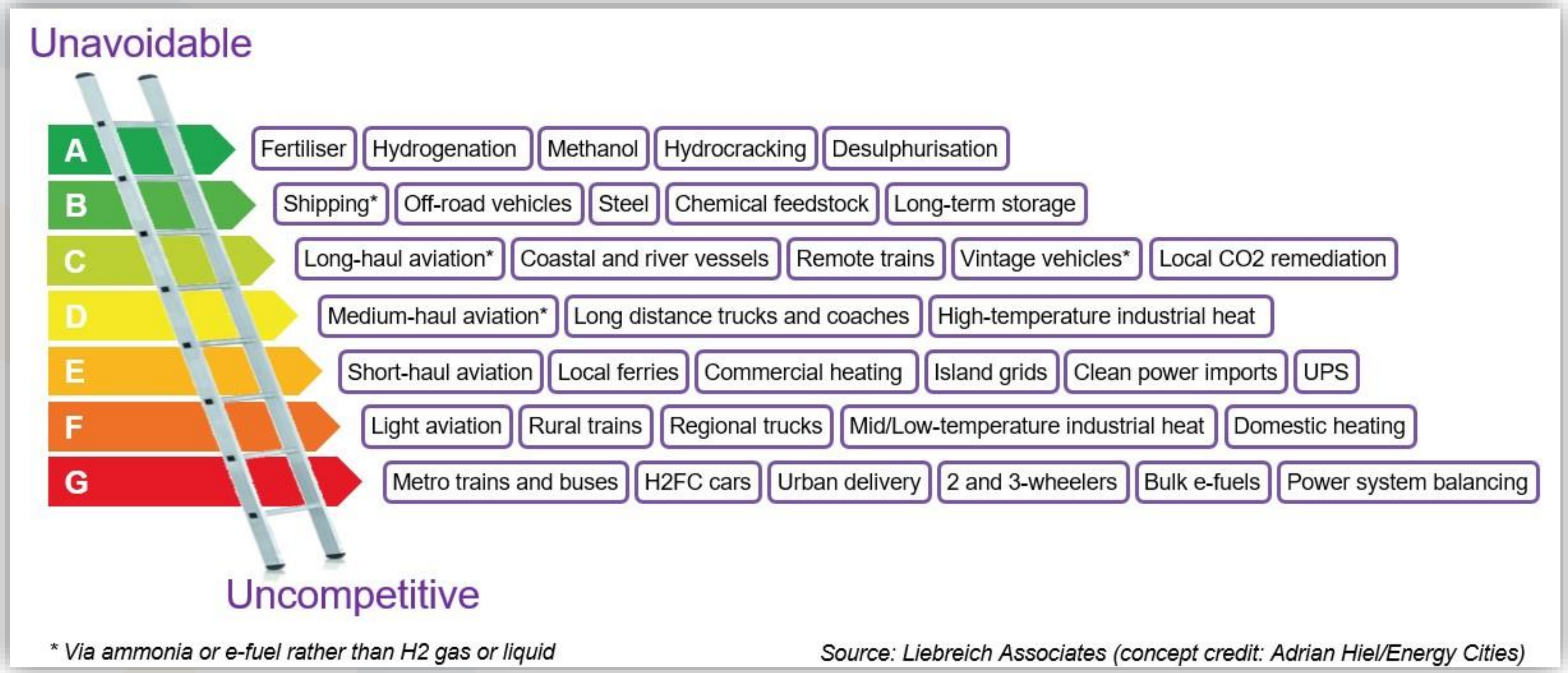
The applications of hydrogen are many: from chemical feedstock, to cleaning the steel industry, re-purposing natural gas infrastructure and power stations, powering ships, aviation and transportation and even making green synthetic fuels.



The Sensible Uses of Hydrogen

However, not all applications are economical, feasible, or even mature, and there is a lot of speculation (“hype”) regarding the volumes to be needed in the future.

Michael Liebreich' s hydrogen ladder is a nice visualization of how its uses should be prioritized.



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2. Scaling up

Can electrolyzer suppliers meet current and future market expectations?

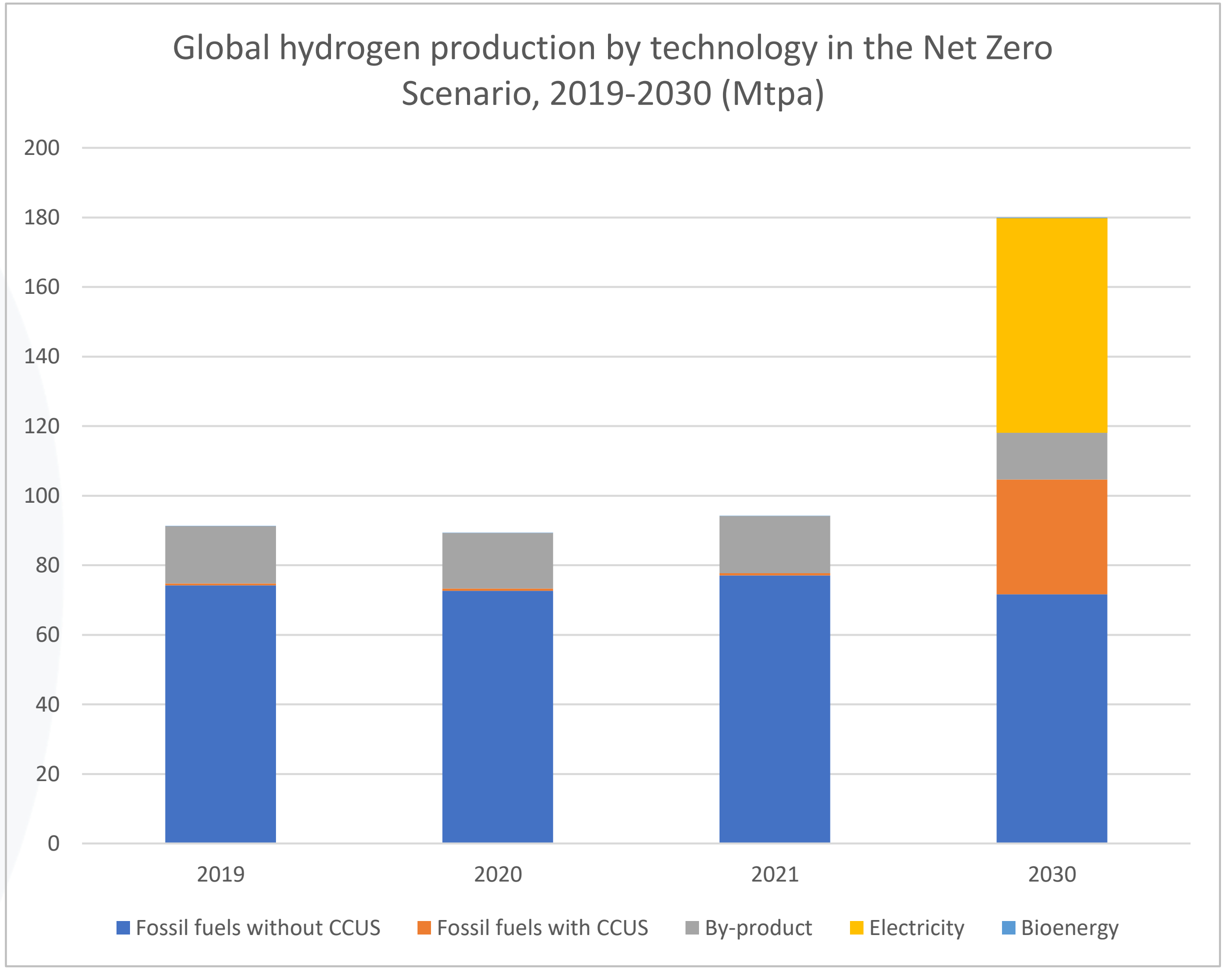
Electrolyzer manufacturing and economics

Global Needs for Green Hydrogen: Can we Meet Them?

According to IEA's Net Zero Scenario, by 2030 hydrogen production should reach around 180 Mtpa, with nearly half of that demand coming from new applications, particularly in heavy industry, power generation and the production of hydrogen-based fuels.

In the Net Zero Scenario, low-emission hydrogen production accounts for ~95 Mtpa, more than half of global hydrogen production by 2030. Around two-thirds of this production is based on electrolysis, whereas another third is hydrogen produced from fossil fuels with CCUS*. This will require an installed capacity of more than 700 GW of electrolyzers (50% capacity factor, with coupling of wind and solar energy).

CEA's capacity data show that by 2030, the cumulative electrolyzer capacity will be ~270 GW, therefore the global hydrogen quantity produced by water electrolysis will be only about 22 Mtpa (50% CF & coupling of wind and solar energy), which accounts for just one third of the global green hydrogen production target of about 62 Mtpa.

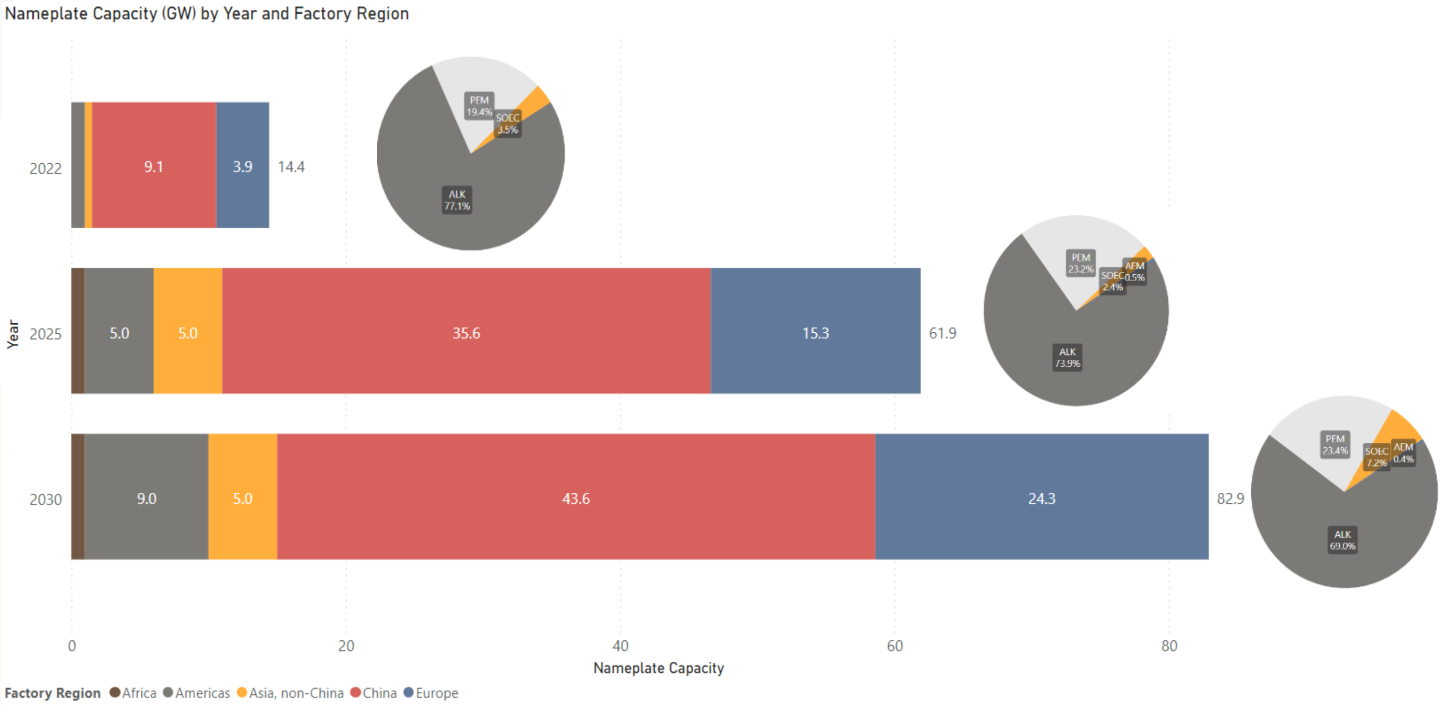


Data source: IEA

*CCUS: Carbon capture, utilization and storage

Global Manufacturing Capacity

- China, Europe, and US will be leading the capacity expansion race, contributing to over 90% of the total electrolyzer manufacturing capacity by 2030.
- CEA's Forecasted Capacity applies 60% discount over the announced nameplate capacity expansion plans for China, Europe, and Asia (non-China) based manufacturers, due to on-going and foreseen policy and demand uncertainties.
- No capacity discount is applied for US based manufacturers, with IRA being the most aggressive and executable clean hydrogen incentive program so far. However, US's PEM focused supply chain may face bottlenecks coming from potential catalyst metal shortage and more urgent cost reduction targets compared with alkaline systems.



Source: CEA data, compiled from nameplate capacity, current and announced

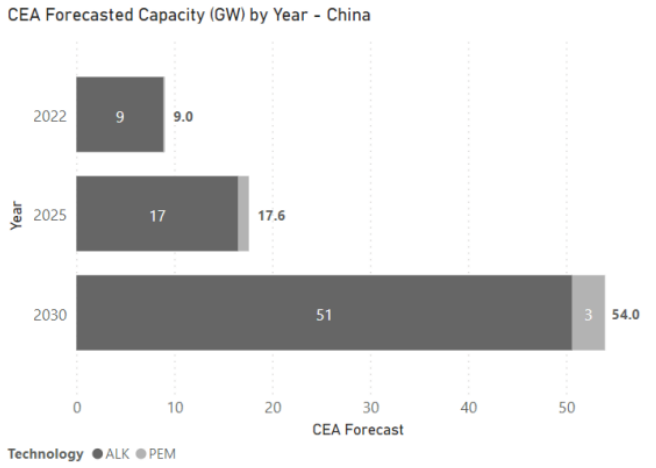
IRA: Inflation Reduction Act

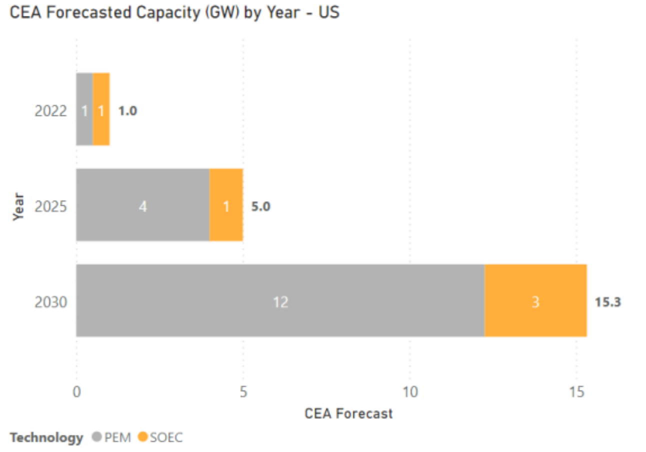
Note: As most announced capacity expansion plans are short-term and don't go beyond 2025, we applied a growth factor between 2025-2030, based on what PV experienced in 2015-2020.

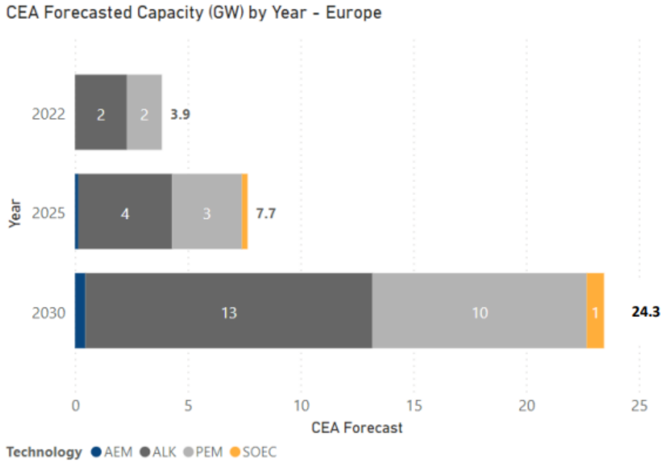
Global Manufacturing Capacity

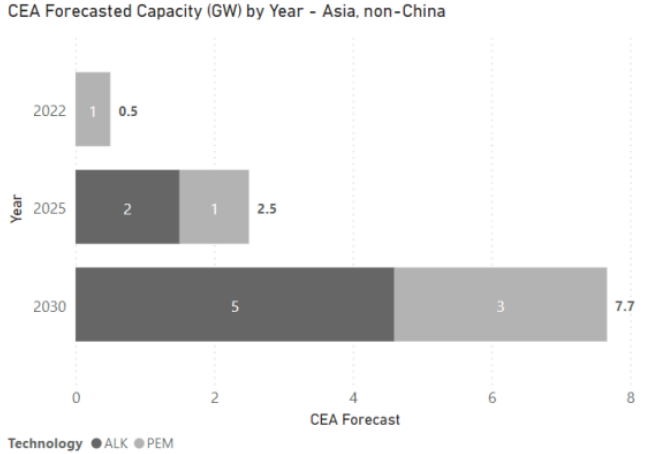
Looking at technology approaches we can see that:

- China is heavily focused on alkaline technology, with only a small part dedicated to PEM. China has not adequately invested in PEM R&D in the past, and costs are expected to remain very high.
- Europe has an almost equal blend of alkaline and PEM, due to strong players in both technologies.
- The US seems to be strongly focused on PEM and some SOEC, due to strong local players.
- Rest of Asia is split between alkaline and PEM.





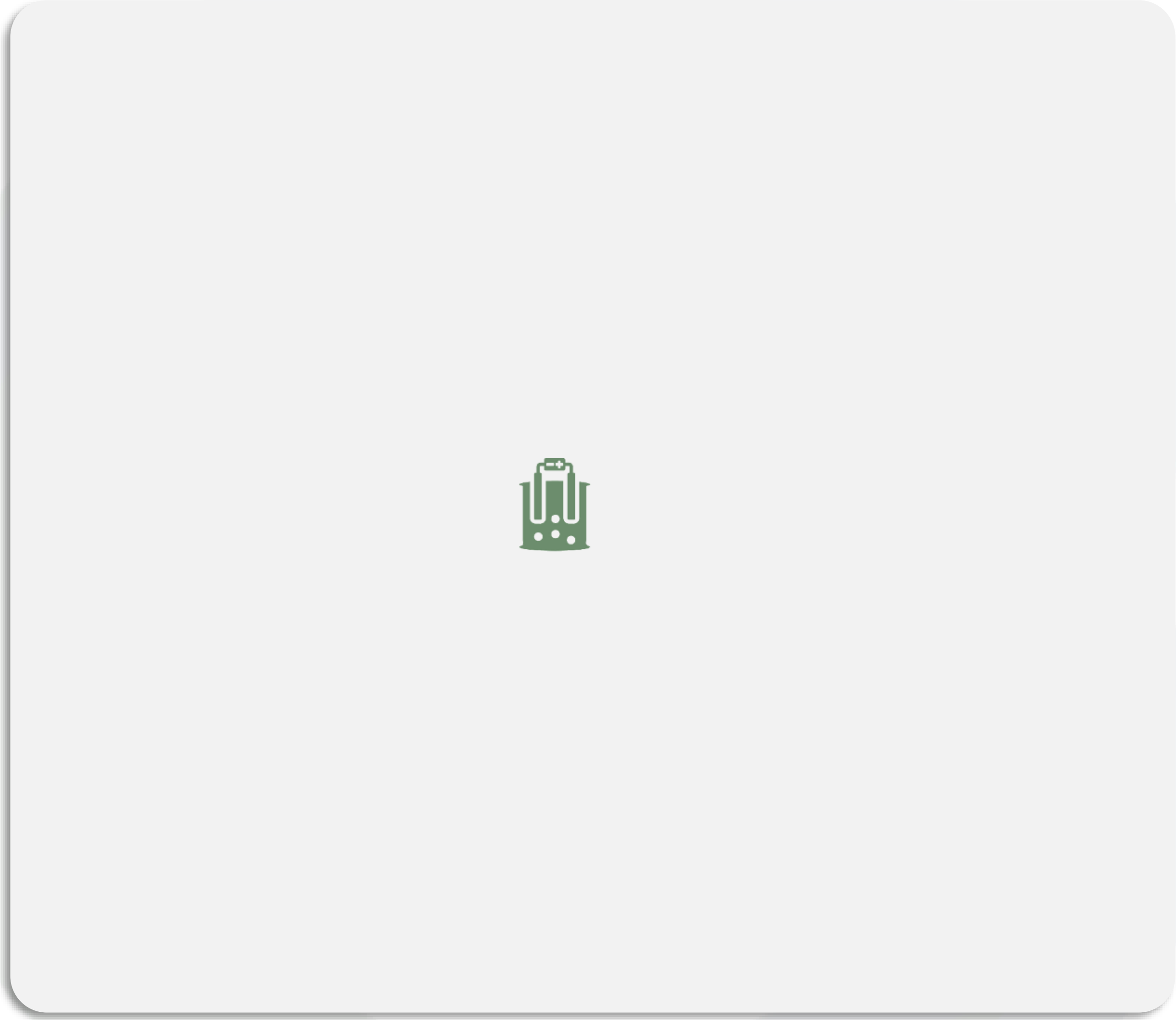




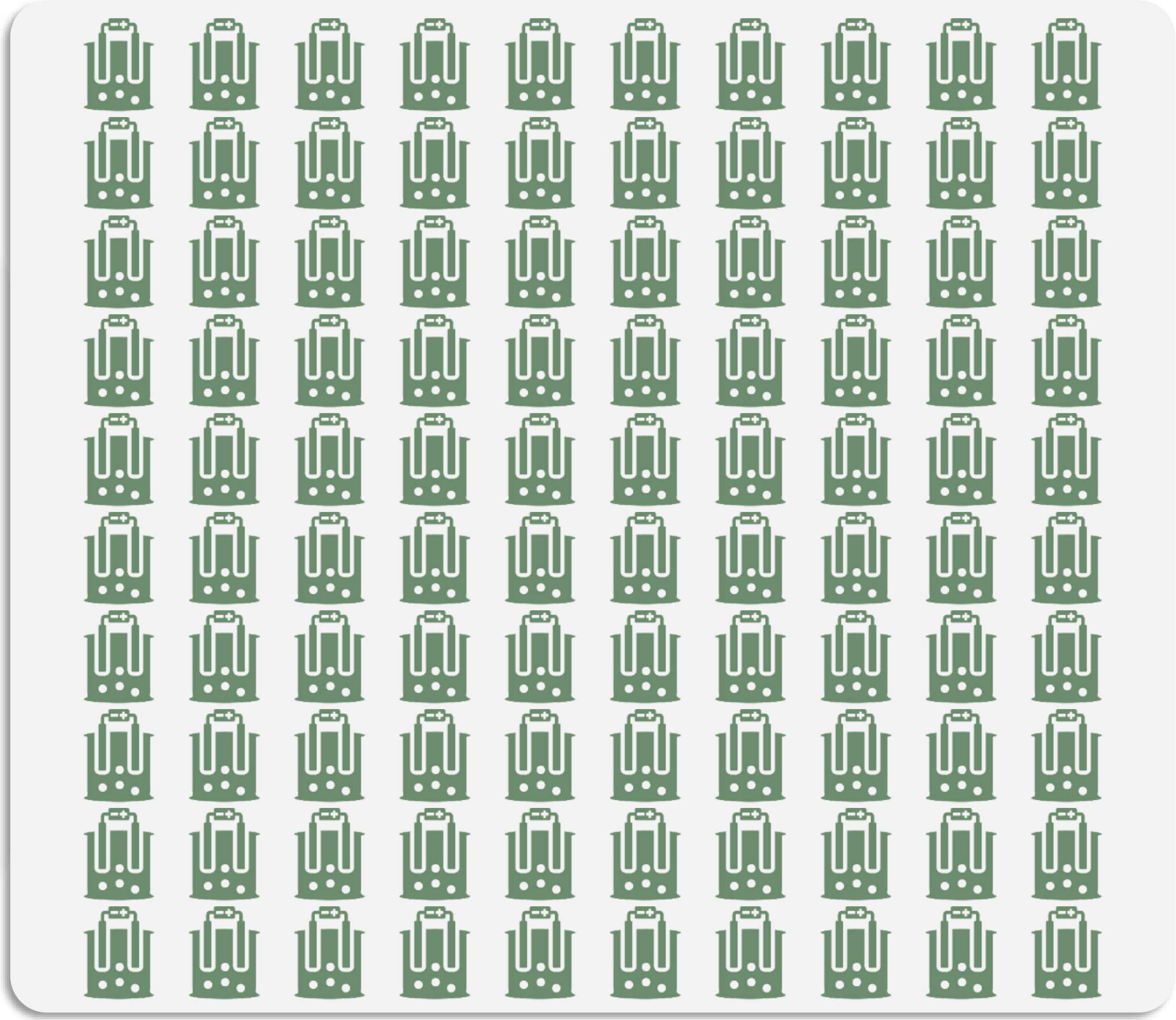
Source: CEA data, compiled from nameplate capacity, current and announced

The Scaling up Challenge:
Annual Shipments Of Electrolyzers Must Increase ~100X by 2030

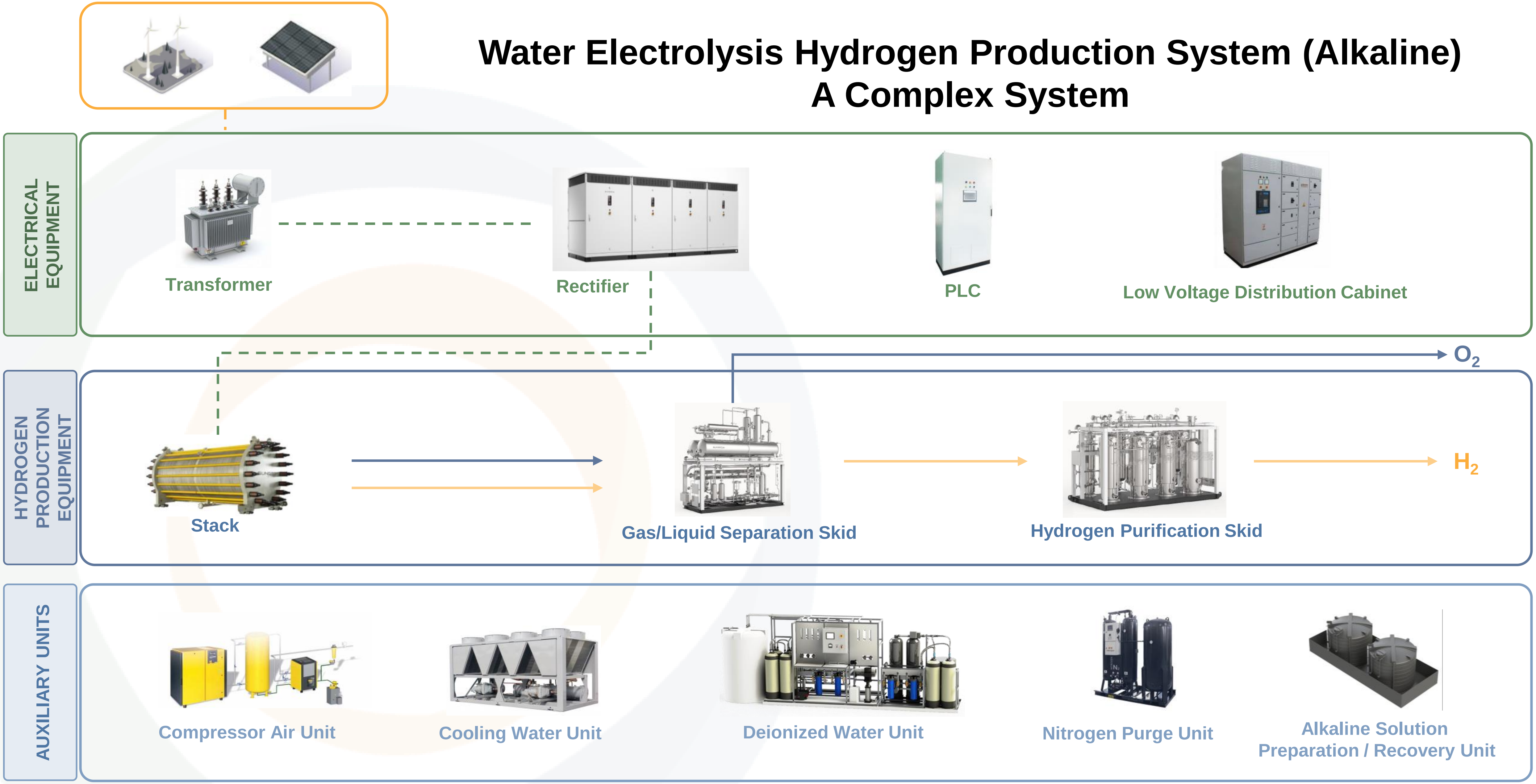
2022 (~1 GW)



2030 (close to 100 GW)



Water Electrolysis Hydrogen Production System (Alkaline)
A Complex System

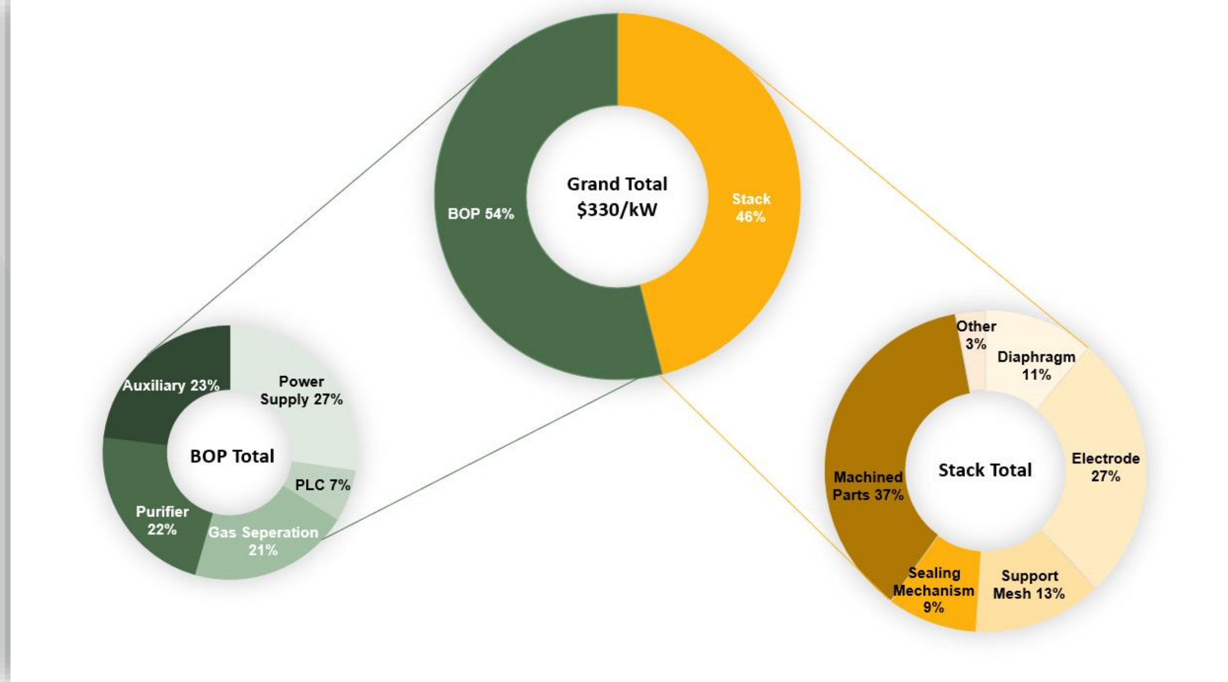


Alkaline Technology Costs (China)

For alkaline systems, the stack contributes to 46% of the system cost, with machined parts and electrodes being the most cost-intensive components.

Machined parts include electrode frames, end plates, and bipolar plates, which are mainly composed of nickel-plated carbon steel. In addition to the cost of raw materials, the cost of steel processing and nickel plating are also included.

Alkaline systems' BOP is slightly more complex than PEM systems due to the use of strong corrosive alkaline, which necessitates additional alkaline stripping tanks and the alkaline solution recirculation system.



Source: CEA data and cost models

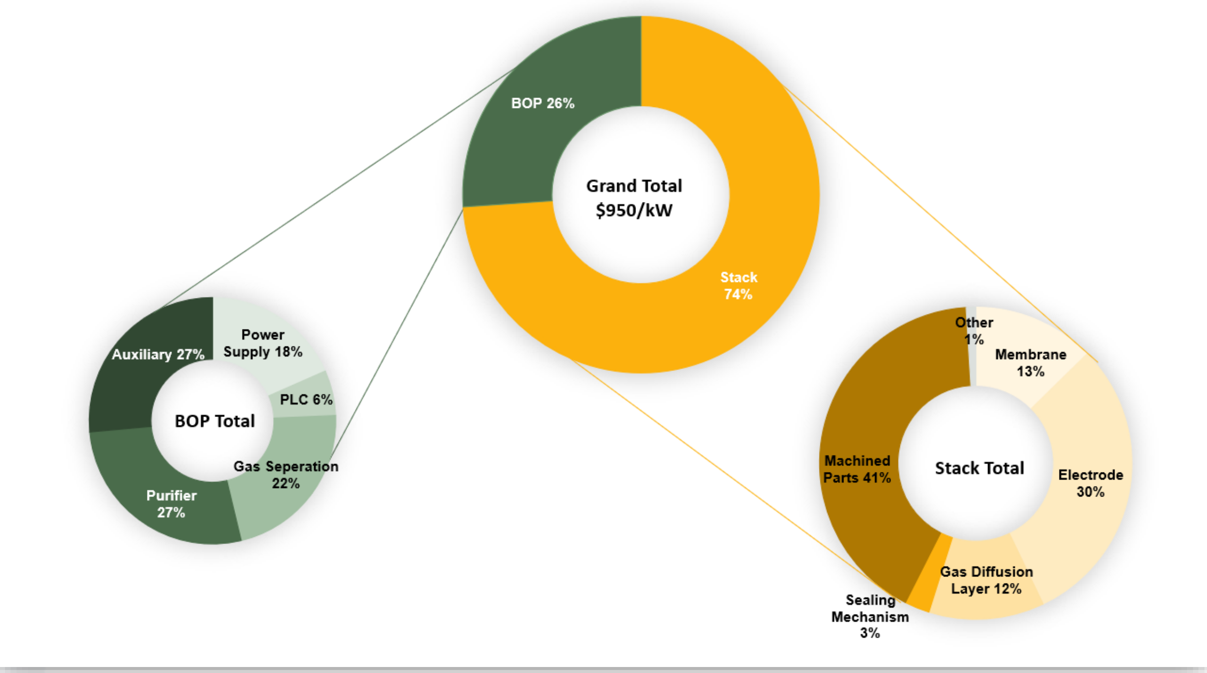
Balance of Plant (BOP): everything else apart from the electrolyzer stack

PEM Technology Costs (China)

For PEM systems, the stack contributes to a large percentage of the system cost. The use of costly catalysts and more complicated flow channels on the bipolar plate adds to the cost of stack significantly.

The high cost of electrodes in PEM electrolyzer stacks is mainly from the iridium and platinum catalysts in the MEA (Membrane Electrode Assembly), and the titanium used in bipolar plates and anode gas diffusion layers.

More complex stack interconnection and higher pressure from PEM differentiates its BOP compared to alkaline systems.



Source: CEA data and cost models

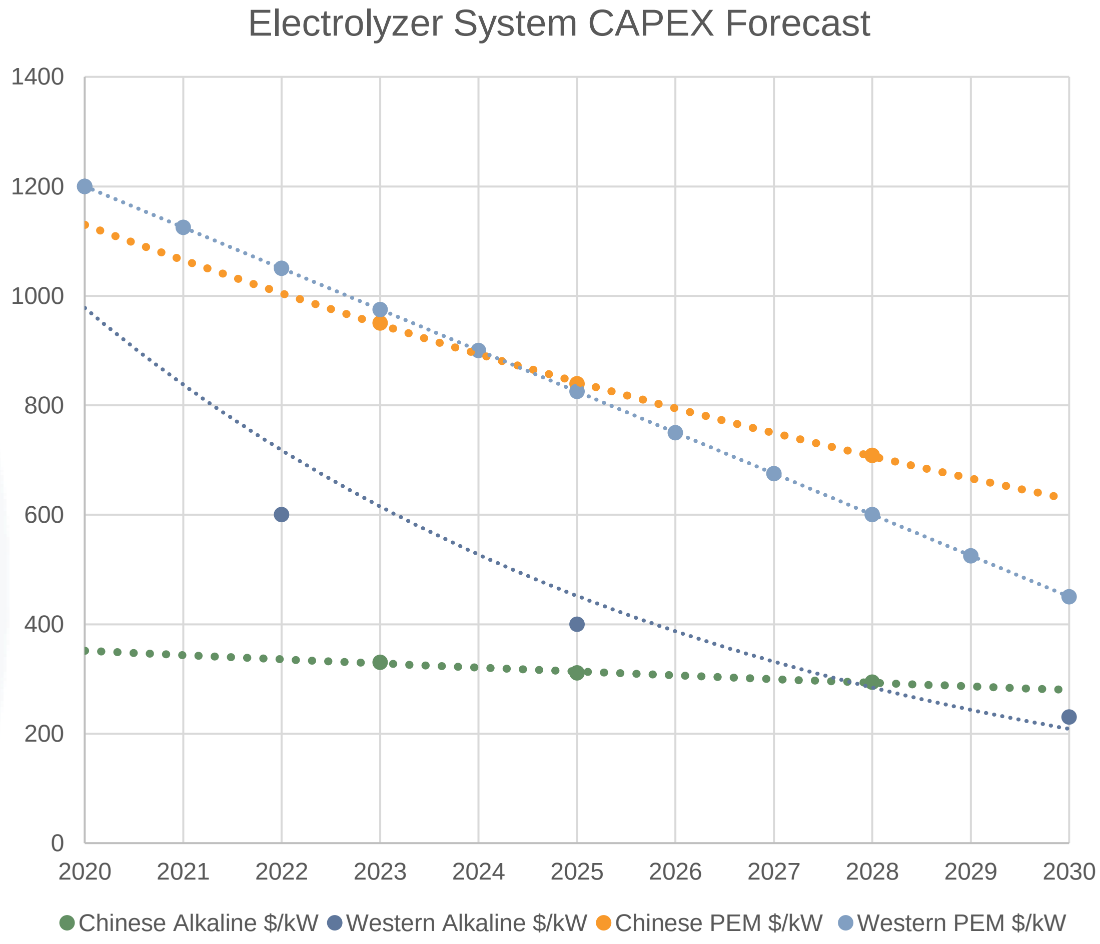
Economics and Competitiveness: CAPEX

Currently, global electrolyzer shipments are only a few hundred MW per year, with the great majority being alkaline and the 10 top suppliers supply 90% of the volume.

Chinese manufacturers have focused on alkaline technology and achieved very low costs, due to high factory utilization and mature supply chain.

Scaling up of production may see western and Chinese costs converge by 2030.

PEM has a long way to go to reach alkaline costs.



Sources: Chinese electrolyzer CAPEX from CEA data and cost models
Western electrolyzer CAPEX from BNEF and others
Note: CAPEX includes stack and balance of plant

3. Levelized Cost of Hydrogen (LCOH)

Drivers: LCOE, utilization and Capex

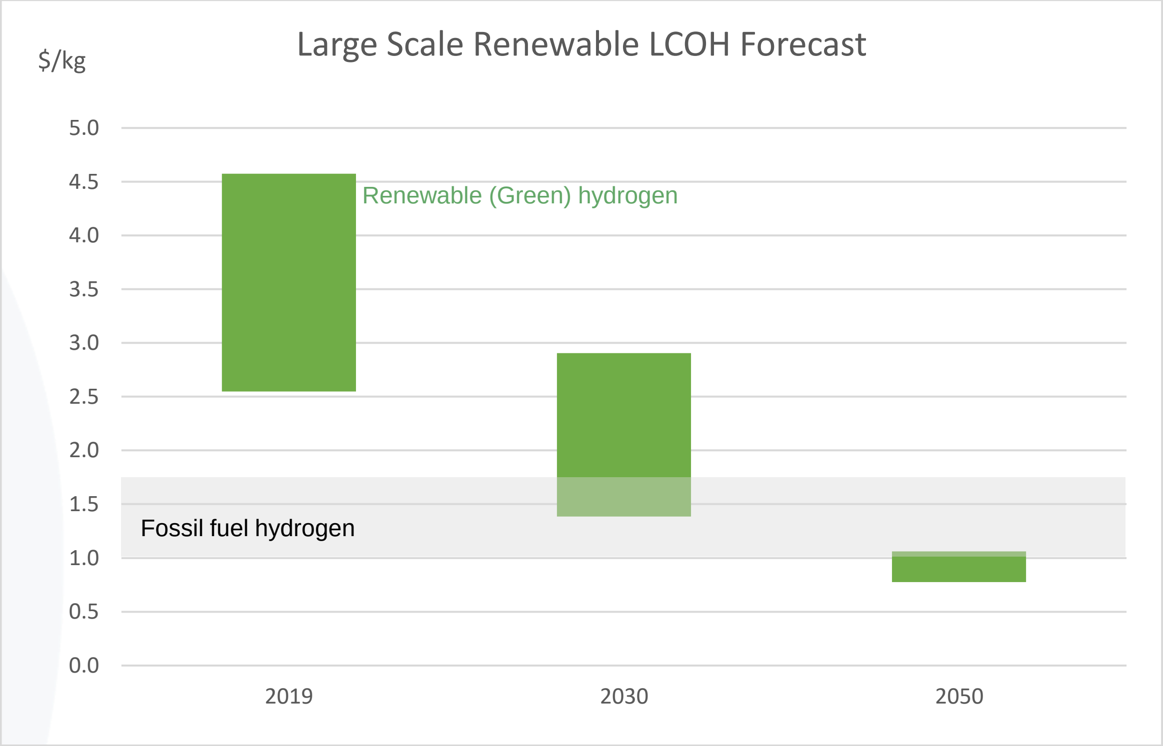
How renewable energy couples with electrolyzers in cost effective ways

Economics and Competitiveness: LCOH (Levelized Cost of Hydrogen)

Current LCOH levels favor fossil fuel (Grey/Brown) hydrogen. The volatility of natural gas prices has driven the LCOH much higher recently, however, in the long term, fossil-derived hydrogen will remain low cost, unless it gets carbon-taxed.

Green hydrogen must get competitive to quickly gain market share. PV and wind have proved that state support can help at early stages.

A combination of subsidies and regulation are needed in the first years, so that electrolytic hydrogen produced with low, or zero carbon, low cost electricity becomes competitive.



Source: BNEF and others
LCOH: Levelized Cost of Hydrogen

Economics and Competitiveness: LCOH (Levelized Cost of Hydrogen)

Major factors affecting LCOH are:

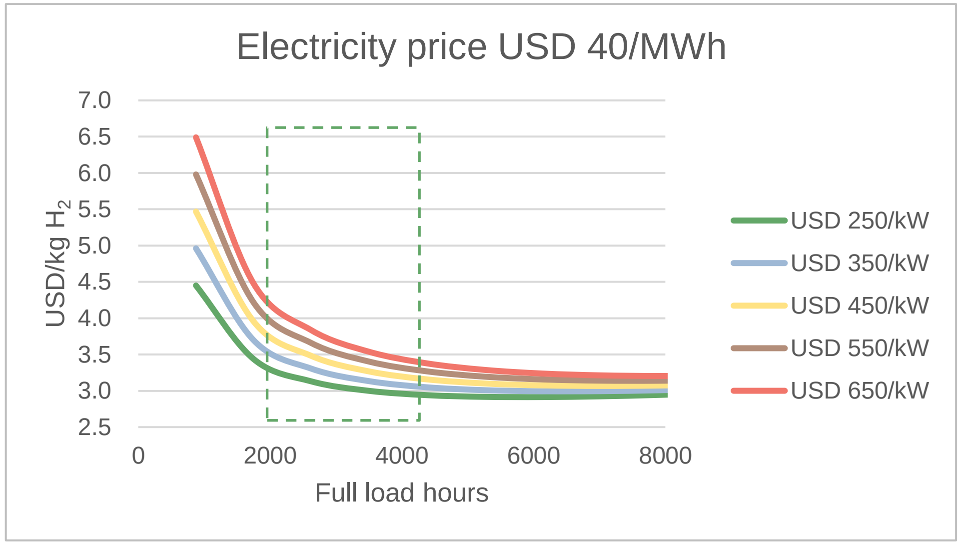
- CAPEX
- Electricity cost (LCOE)
- Utilization rate aka Capacity Factor (number of full load hours / 8,760)

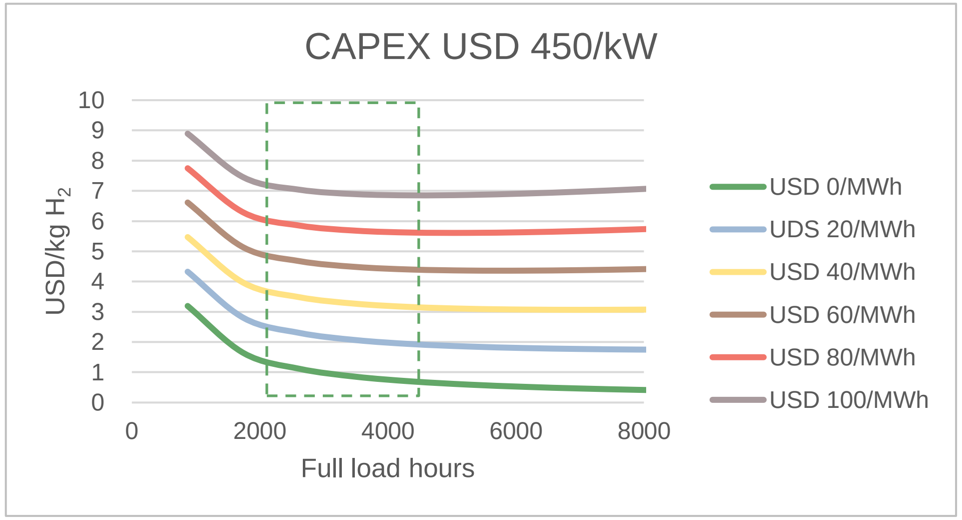
At high utilization, CAPEX plays a lesser role

However, at **mid-and low range utilization**, which are a better fit for renewables, CAPEX becomes very important.

LCOE prices below $25/MWh are needed for breakthroughs.

Even at $0/kWh (free energy), at 20% utilization, LCOH is $1.6/kg.





Source: CEA data, based on electrolyzer efficiency at 74% (LHV), 25-year asset life, 0.25% degradation rate per 1000 hours, 6% WACC

LCOE: Levelized Cost of Electricity

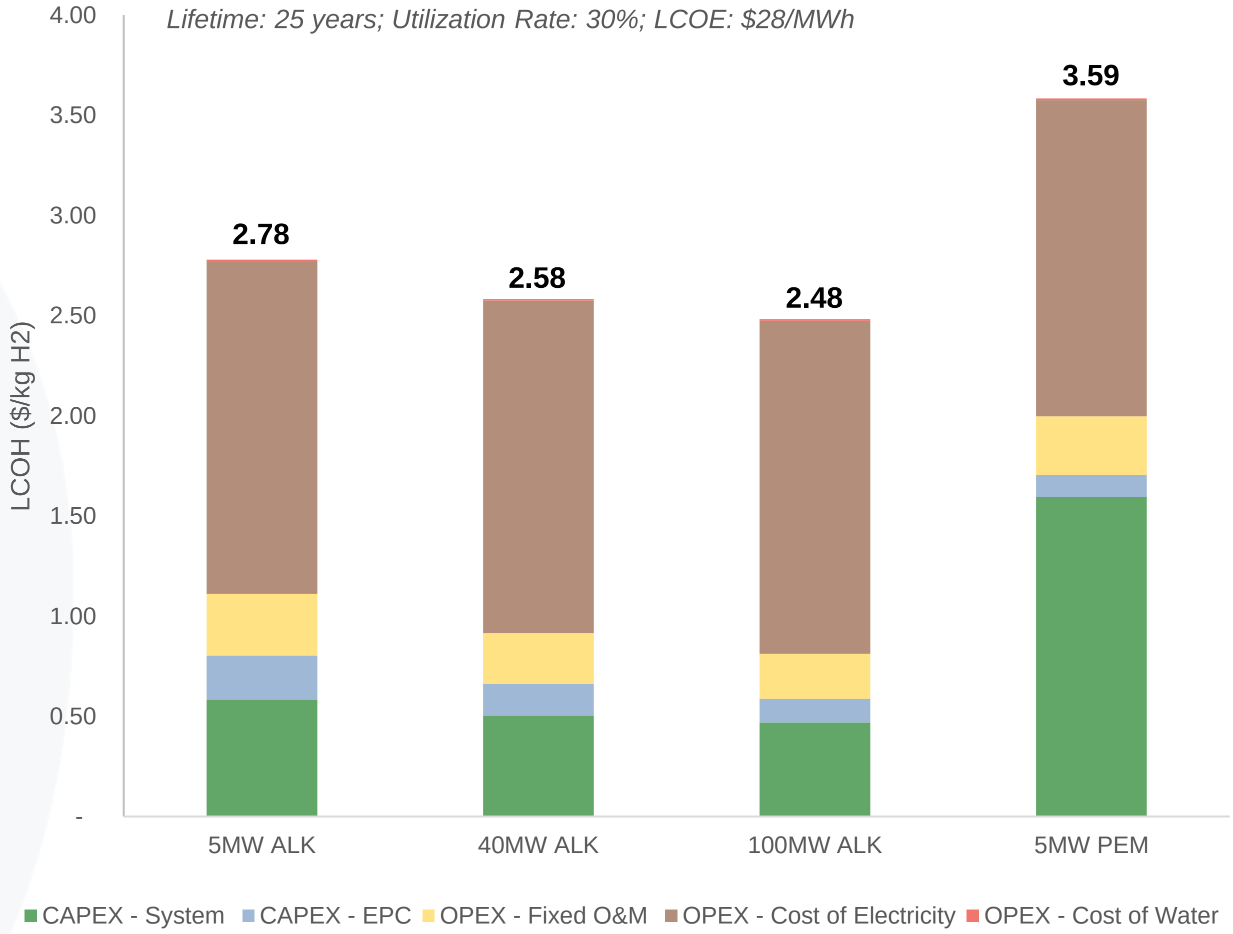
LCOH: Alkaline vs. PEM

Electricity cost accounts for more than 60% of the LCOH share for alkaline systems and more than 40% for PEM.

The scale effect shows a decreasing trend for both CAPEX and O&M items. About 10% LCOH reduction is achieved from scaling an alkaline system from 5 MW to 100 MW.

For a 5 MW PEM system, the LCOH over 25-year life span is about **30% higher** than an alkaline counterpart because the high CAPEX for PEM system.

As the existing projects of PEM remains in the single digit MW-level, it's hard to estimate the scale effect for PEM systems quantitatively.



Source: CEA data and cost models

LCOH: Utilization Rate and LCOE

Utilization rate is decided by the power supply conditions and directly impacts the operating time of the electrolyzer system.

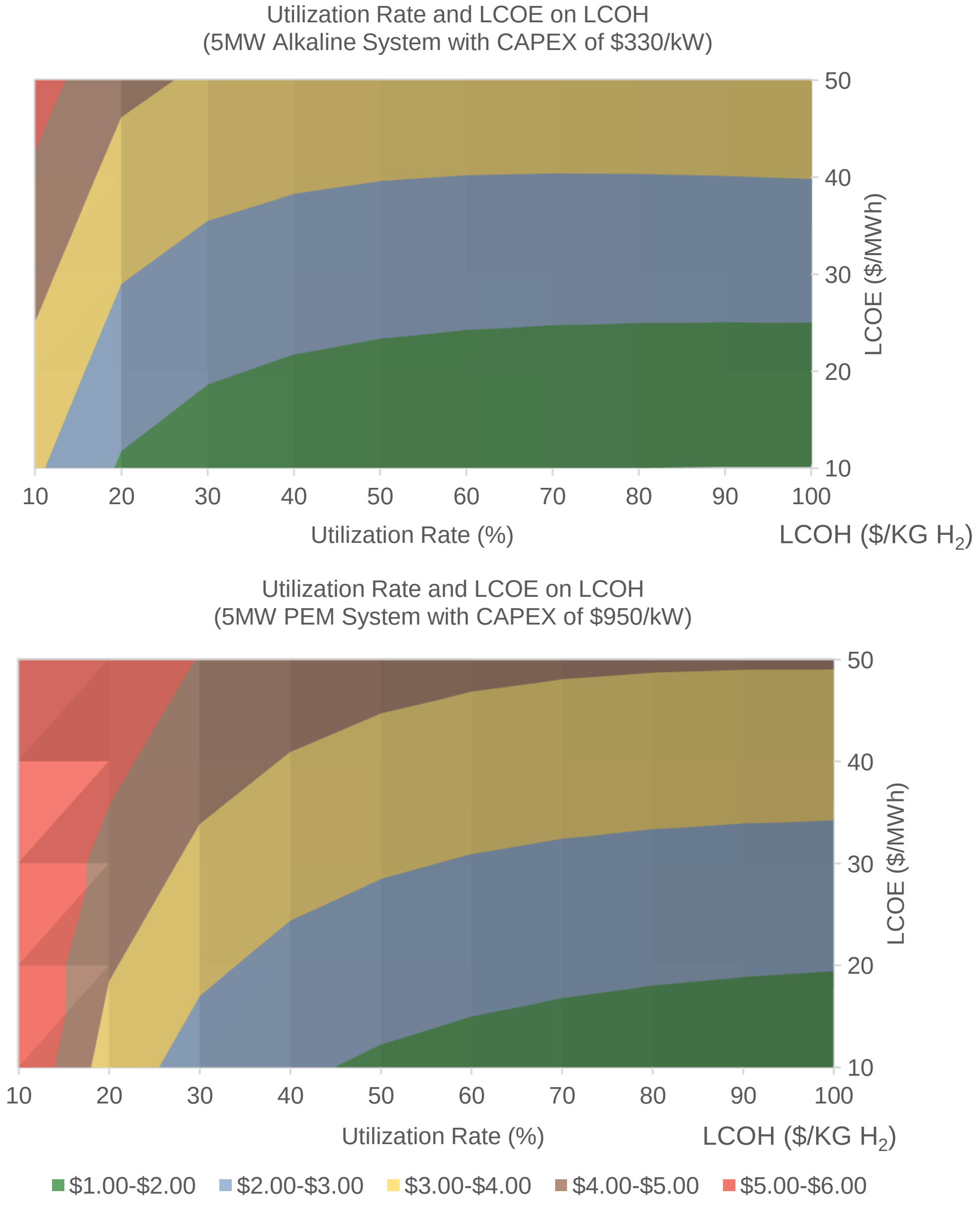
LCOE plays a dominant role in deciding LCOH at higher capacity factors.

Alkaline electrolyzer with lower CAPEX shows better economies than PEM in a wide range for utilization rate and LCOE.

Designing for minimized LCOH is not always possible.

Physical limitations: water and power supply constraints.

Commercial limitations: electricity PPAs and hydrogen offtake agreements.



Q&A

Thank You

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Website: www.cea3.com

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Greening hydrogen, the promise beyond the hype

Q&A

4 May 2023

5:00 pm – 6:00 pm | CEST, Berlin, Paris, Madrid
11:00 am – 12:00 pm | EDT, New York City
8:00 am – 9:00 am | PDT, Los Angeles

Jonathan Gifford
Editor in chief
pv magazine

Sergio Matalucci
Hydrogen editor
pv magazine

George Touloupas
Senior Director, Technology and Quality
Clean Energy Associates

Yana Zabanova
Research Associate
Research Institute for Sustainability

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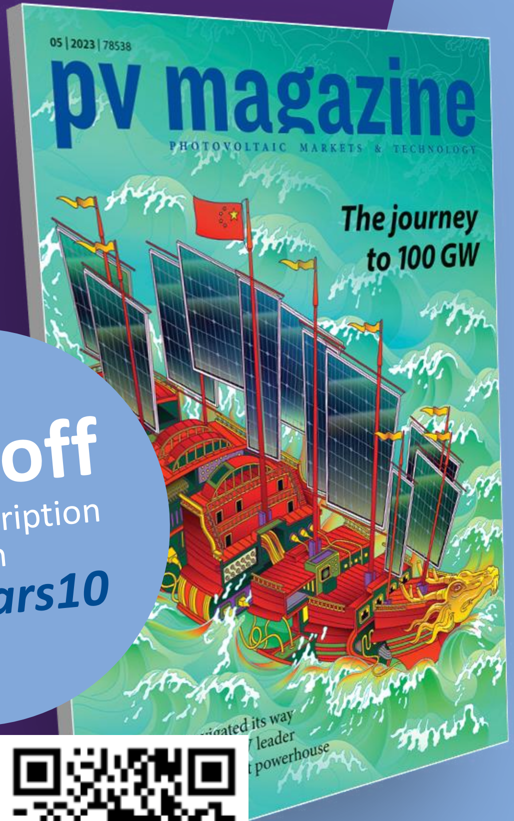

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10 – 11 May 2023
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Barcelona, Spain

Solar + Storage España

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Thank you for joining today!