Renewable Hydrogen for the Pacific

Lecture 1: Intro to Hydrogen and Hydrogen Production Methods

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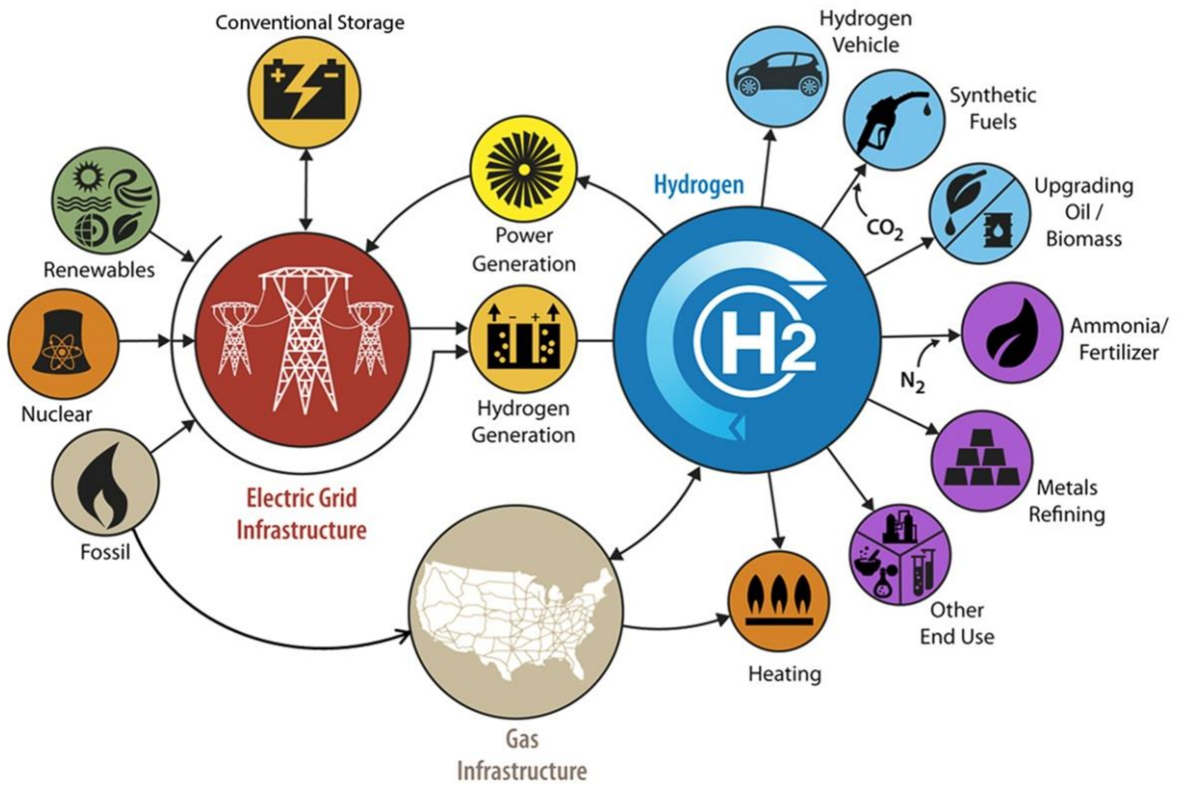
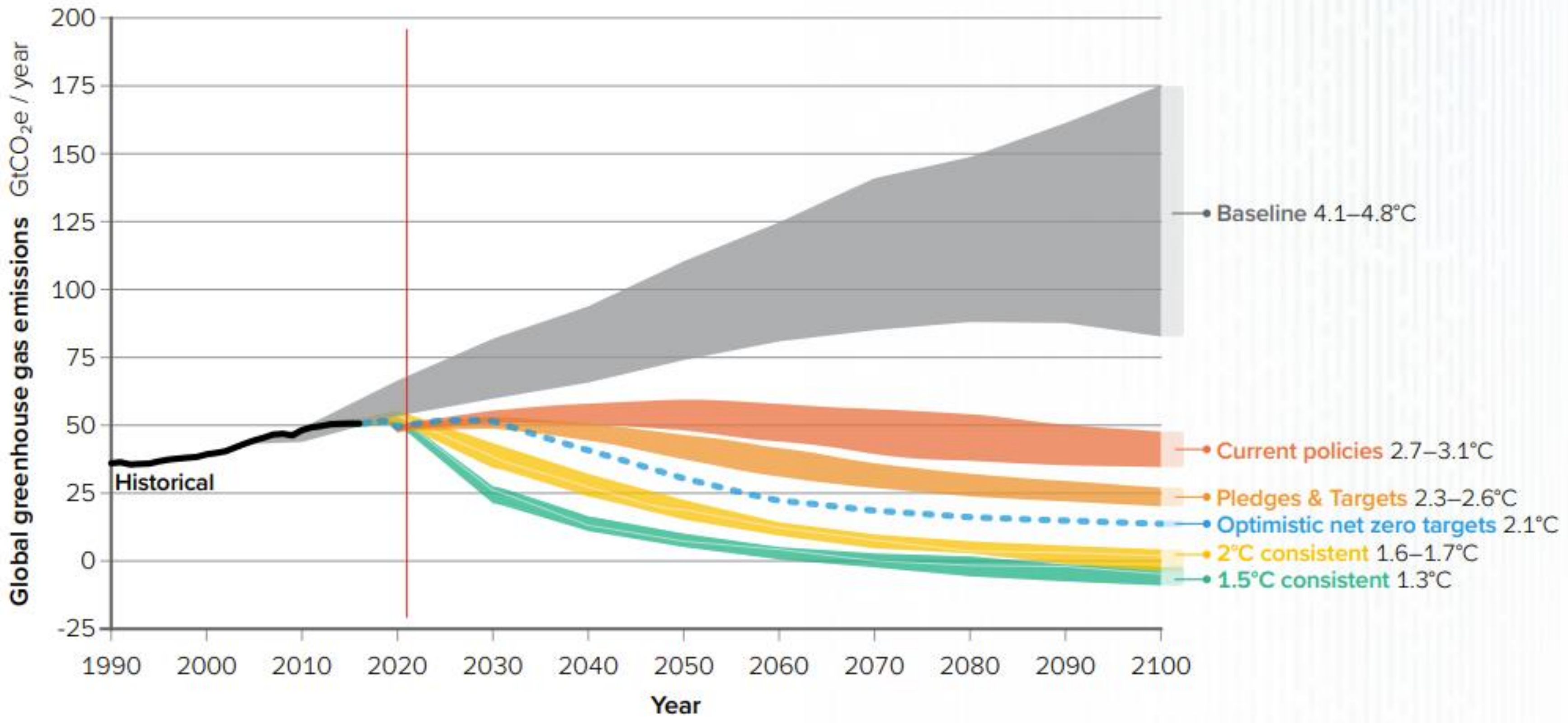
Agenda

- Hydrogen for Net Zero
- Concepts of renewable energy and Power-to-Hydrogen
- Hydrogen Production Pathways
  - ✓ From fossil fuel: natural gas and coal
  - ✓ Electrolysis of water
  - ✓ Biomass



Carbon Footprint and Current Targets for Reduction



Projected warming by 2100 under various scenarios from top to bottom (Climate Action Tracker 2020; Revill and Harris 2017): 'Baseline' models assume no action on reducing GHG emissions while 'current polices' are based on current commitments and policies made by the international community. 'Optimistic polices' include additional pledges that governments have made as of December 2019. 'Pledges and Targets' are conditional and have not yet been implemented. Pathways for '1.5°C' and '2°C' are scenarios based on models run for IPCC Special Report on 1.5°C (IPCC 2018). Temperatures of each scenario are shown as a range arising from different climate models.

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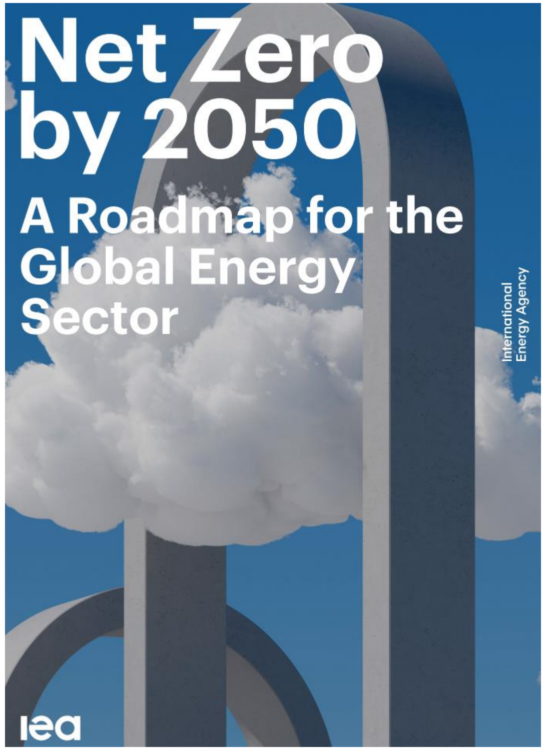
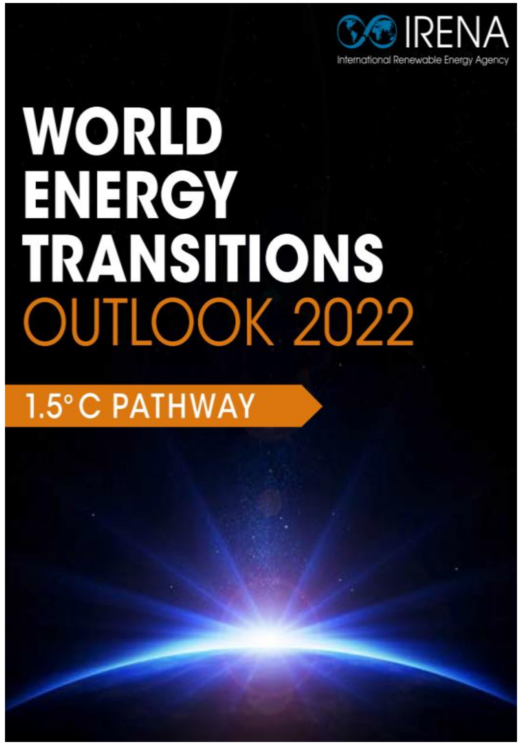
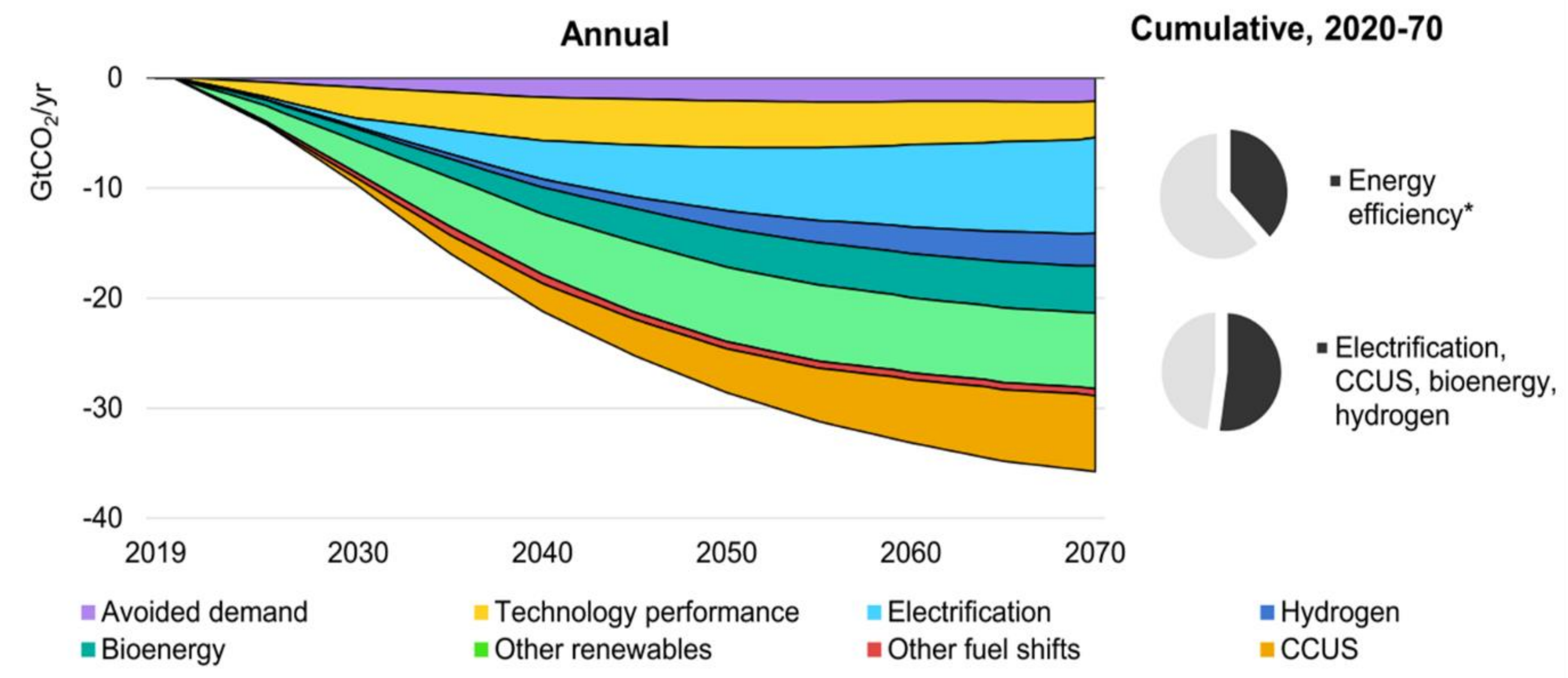
There is a plan… lots of them





Pathways towards Net-Zero

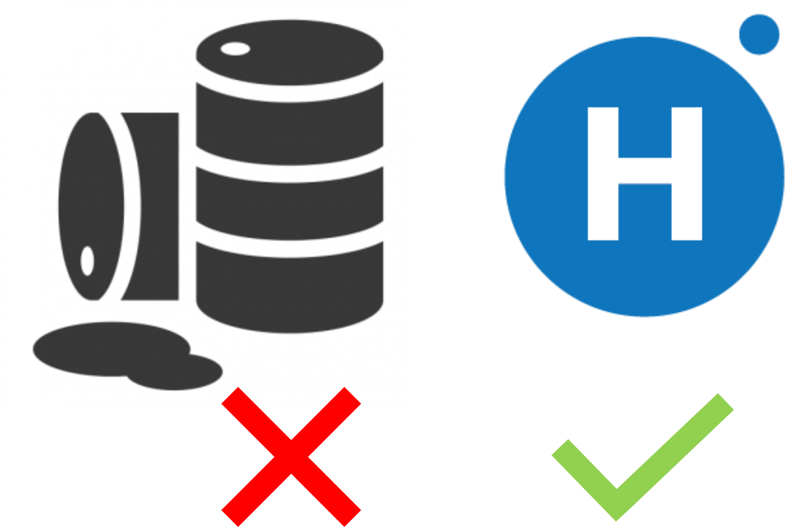


Electrification, bioenergy and hydrogen (and derivative) will play a key role in attaining Net-Zero (source IEA)

Hydrogen and Climate Change

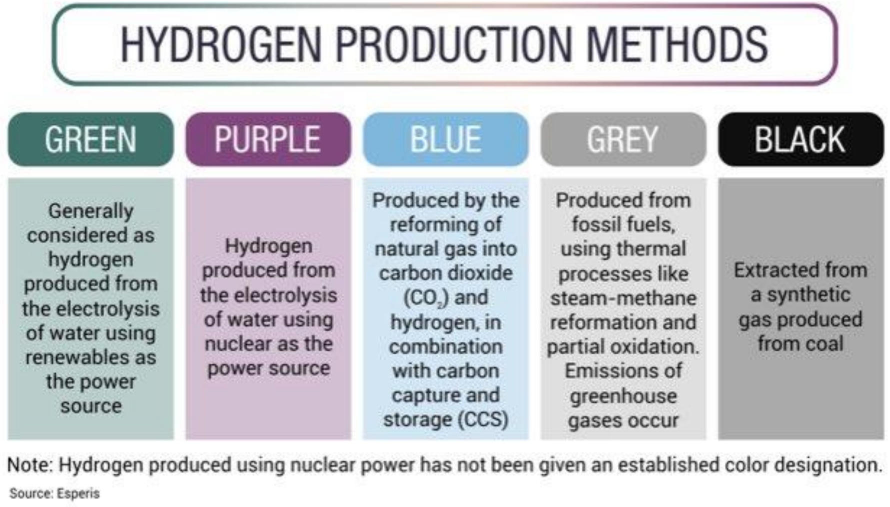
- Hydrogen can therefore tackle climate change if:
  - It is used in place of fossil fuels as an energy source (for example, as an energy carrier of renewable electricity)
  - It is produced through methods that do not release CO_2
- Using hydrogen produced from fossil fuels does not assist in mitigating CO_2 emissions
- However, only 4% of hydrogen is produced using renewable energy
- 96% of hydrogen is produced using fossil fuels

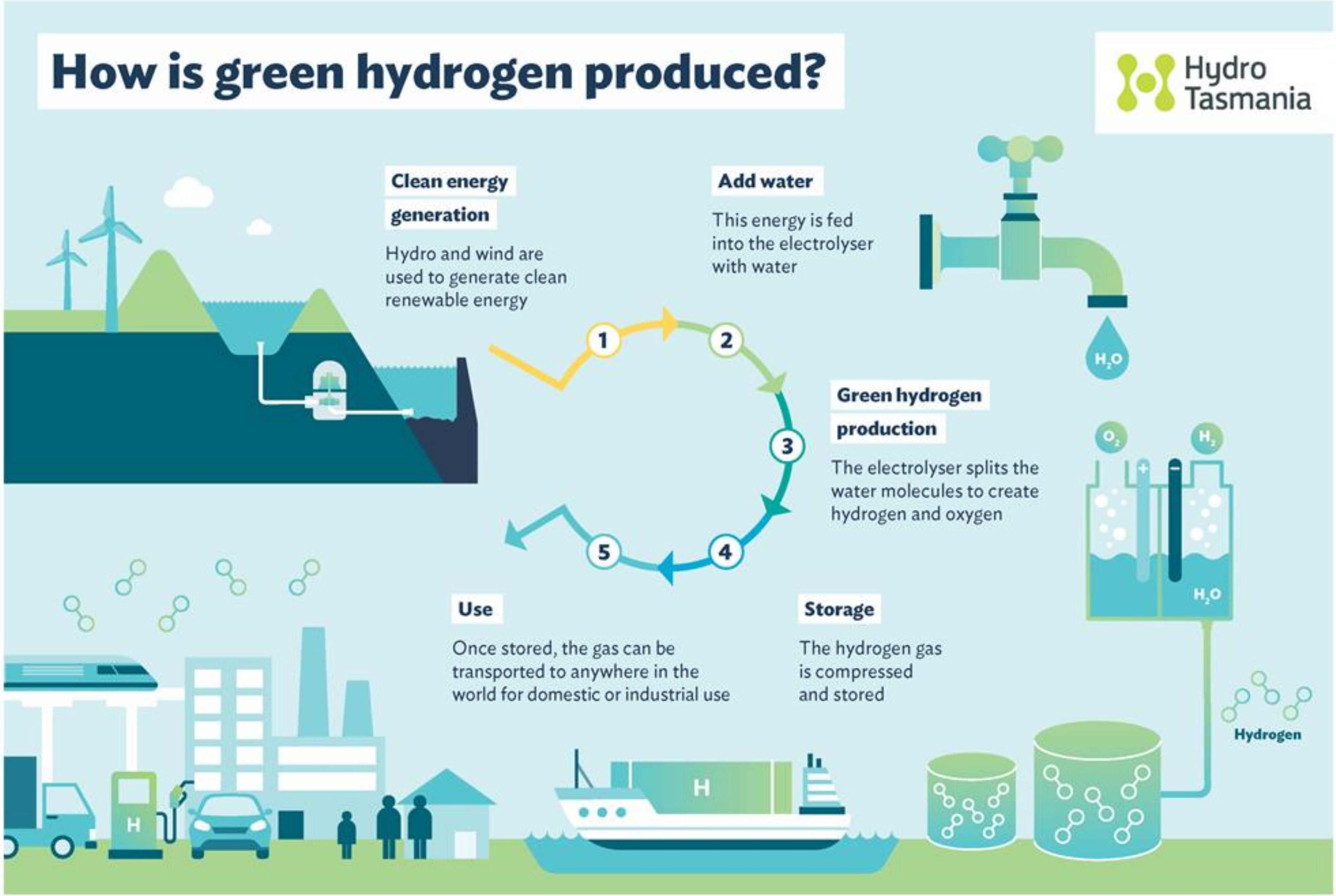
- How do we know that it is produced cleanly?



Hydrogen Production Classification

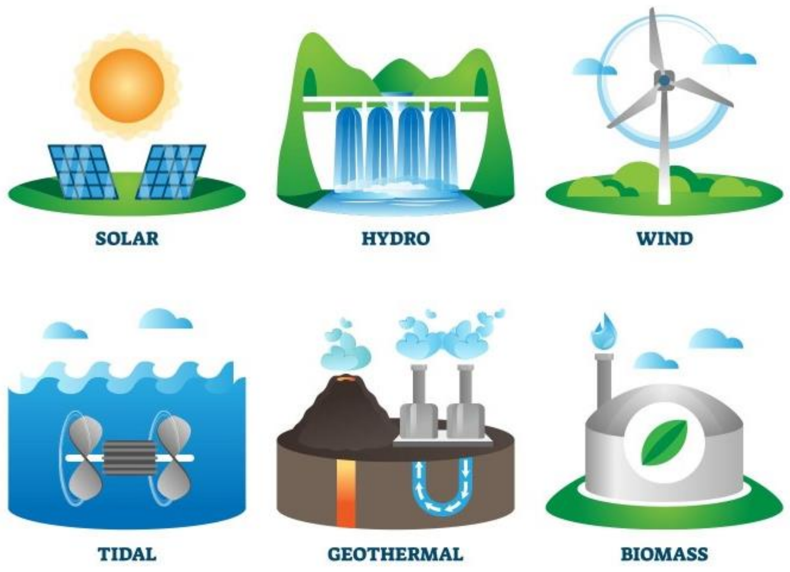
- Hydrogen is classified based on its method of production:
  - Green H_2 is generated through electrolysis powered by renewable electricity
  - Blue H_2 is generated via fossil fuels but with CO_2 emissions captured
  - Grey H_2 is generated via fossil fuels with no emissions captured
  - Black H_2 is made using coal
  - Brown H_2 is made using brown coal (or lignite)
  - Turquoise H_2 and solid carbon is generated by methane pyrolysis
- Other methods also exist




How is green hydrogen produced?
Hydro Tasmania
Clean energy generation
Hydro and wind are used to generate clean renewable energy
Add water
This energy is fed into the electrolyser with water
H_2O
Green hydrogen production
The electrolyser splits the water molecules to create hydrogen and oxygen
O_2
H_2
H_2O
1
2
3
4
5
Storage
The hydrogen gas is compressed and stored
Hydrogen
Use
Once stored, the gas can be transported to anywhere in the world for domestic or industrial use
H
H

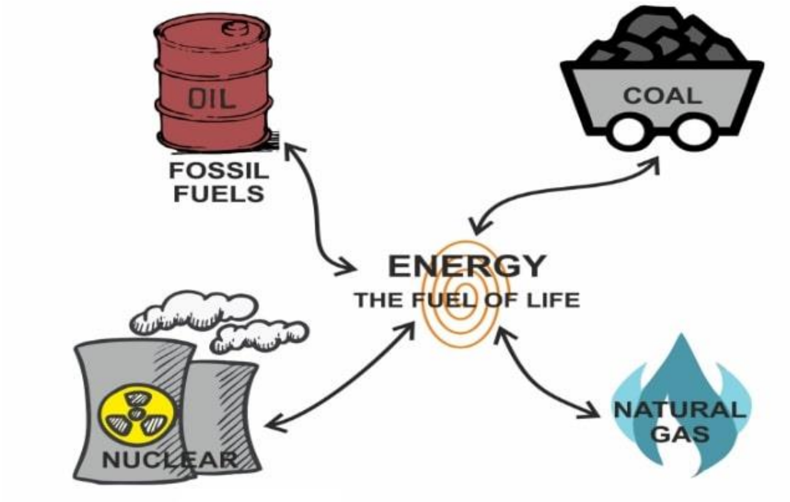
Renewable Energy

- Renewable energy → produced using natural resources that are constantly replaced and never runs out (in theory)
- This definition is extended to energy sources, that for practical purposes, are virtually limitless within human existence
  - Solar Energy (limited to the death of the sun)
  - Wind Energy (requires heating of the Earth by the sun)
  - Biomass (stored chemical energy from the sun)
  - Tidal Energy (limited to the interaction between the Earth and Moon)
  - Geothermal Energy (limited to Earth’s core temperature)



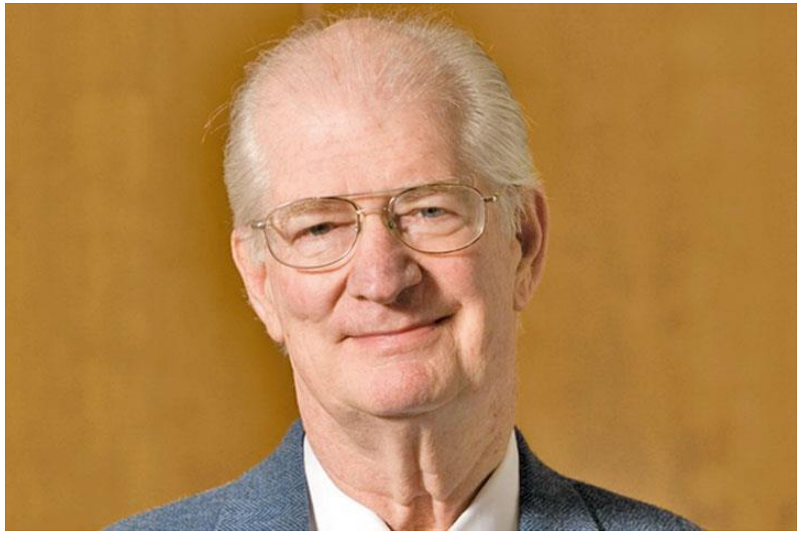
Non-Renewable Energy

- Non-renewable energy → a source of energy that cannot replenish itself
  - Fossil fuels (oil, coal, natural gas) are formed from dead plants and animals over millions of years by pressure and heat. Their original energy comes from the sun via photosynthesis
  - They are non-renewable as we are using them far faster than they can regenerate
  - Nuclear energy comes from radioactive elements (such as Uranium), which is extracted from mined ore and then refined into fuel



What is Sustainability?

- To be truly sustainable is to sustain meeting human needs for the indefinite future
- Herman Daly’s rules for sustainability:
  - Renewable resources must be used no faster than the rate at which they regenerate
  - Non-renewable resources must be used no faster than renewable substitutes for them can be put into place
  - Pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless



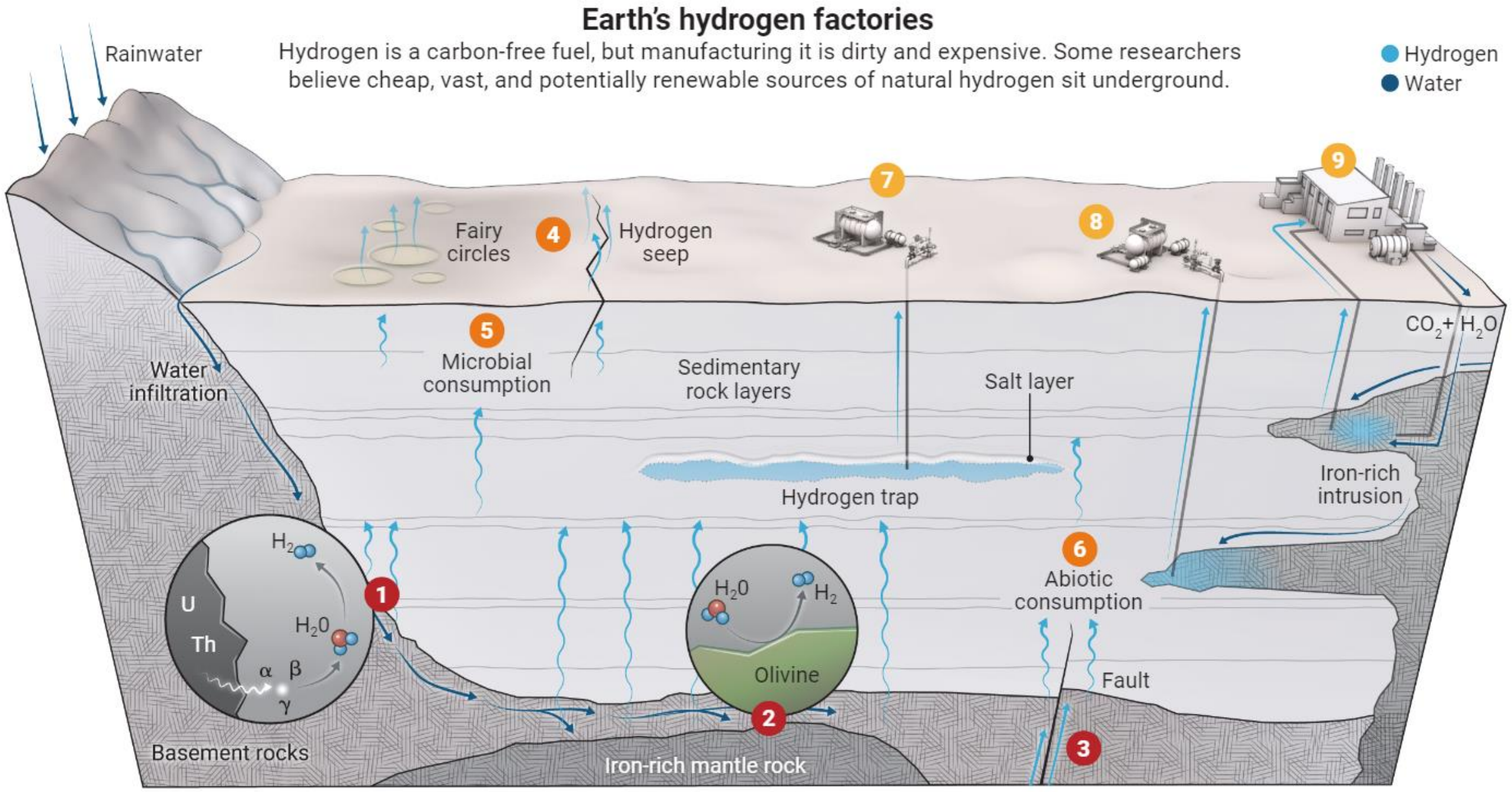
Herman Daly, dubbed as the ‘*father of environmental economics*’

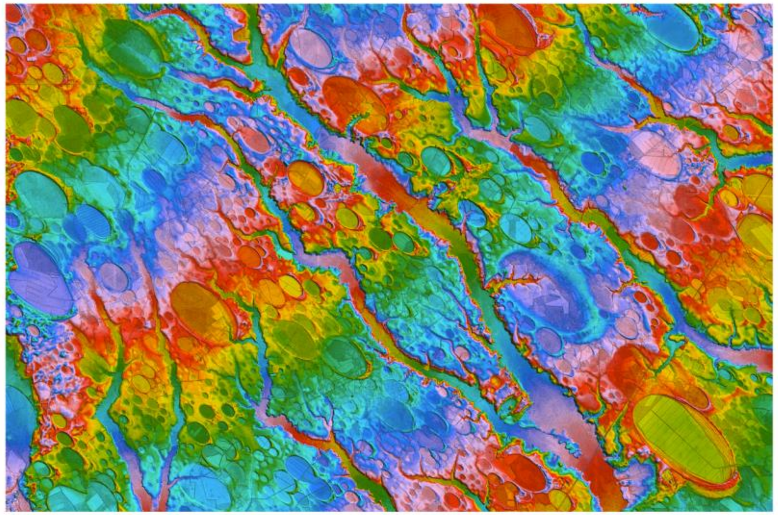
Relation to Hydrogen

- Humans are dependent on non-renewable energy sources
- Not only does burning these fuels release CO_2, but they exist in a finite supply
- We must transition to renewable energy sources before we have exhausted non-renewable sources
- Hydrogen produced through renewable methods can assist in this

Current Methods of Generating Hydrogen

Can you mine Hydrogen?





Hydrogen seepages might explain mysterious depressions often called fairy circles. Some are more than 1 kilometer wide in this lidar image of coastal North Carolina. VIACHESLAV ZGONNIK

Some reports of pure hydrogen gas escaping from oil and gas reserves, reported in former USSR and now in US.

Non-Renewable Hydrogen

- Brown, black, grey, blue, turquoise, and pink hydrogen is produced through non-renewable methods
- Examples of production methods include:
  - Natural gas reforming
  - Oil/naphtha reforming
  - Coal gasification

Steam-Methane Reforming (SMR)

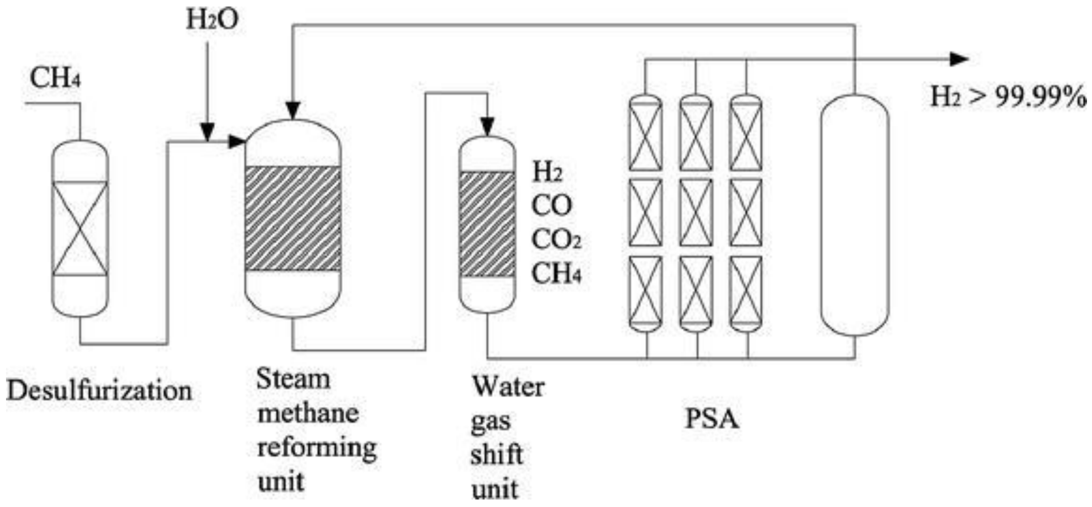
- Natural gas contains methane (CH_4), which can be used to create hydrogen
- Currently the major industrial process for hydrogen production
- Methane reacts with steam to produce hydrogen, carbon monoxide, and small amounts of carbon dioxide:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

- The H_2:CO ratio can be increased through the water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

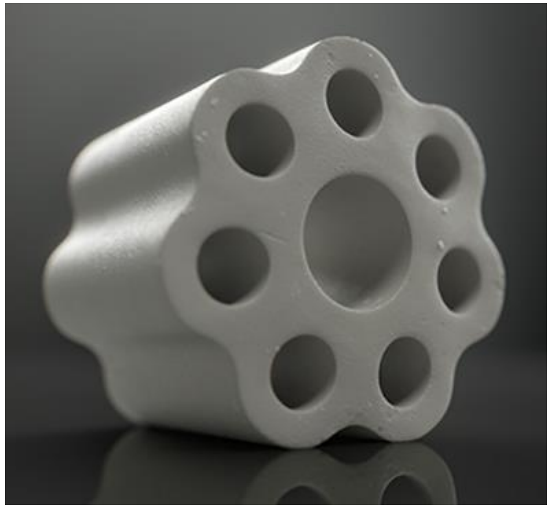
- Pressure-swing adsorption removes CO_2 and other impurities, yielding high-purity hydrogen



If coupled with carbon capture and storage technologies, SMR hydrogen can be considered as blue hydrogen

Steam-Methane Reforming Conditions

- High temperatures (700-1000°C) are required
- Pressures of 3-25 bar are required
  - Note: 1 bar is approximately equal to atmospheric pressure
- A nickel-based catalyst is used. Catalysts are often shaped like spoked wheels, gear wheels, or rings with holes
- The hydrogen produced is classified as blue hydrogen or grey hydrogen depending on whether the CO_2 is captured or not



Partial Oxidation (POX)

- Any hydrocarbon feedstock (e.g. natural gas, residual oils, naphtha) is reacted with a limited amount of oxygen (typically from air) that is not enough to completely oxidize the hydrocarbons to carbon dioxide and water
- For example, the partial oxidation of methane can generate syngas:

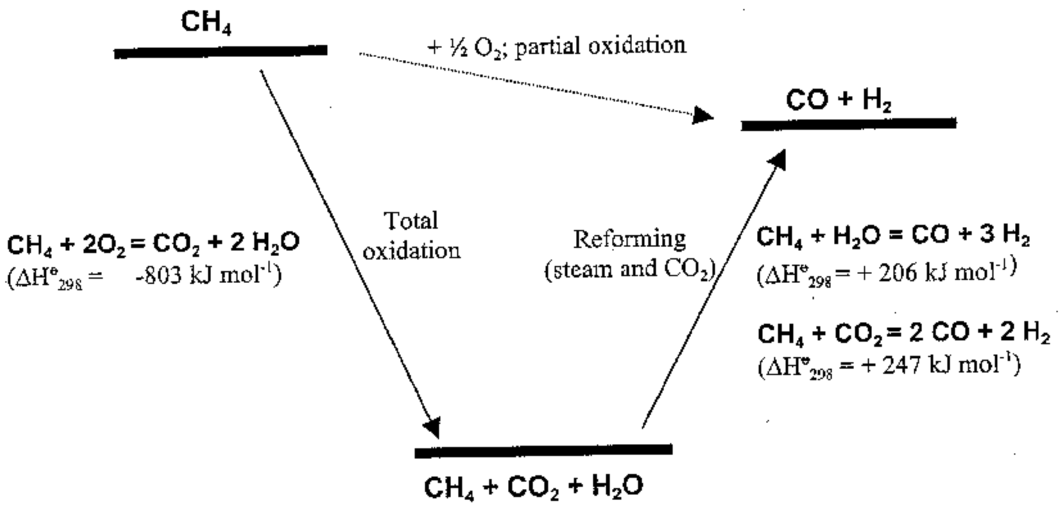
$$\mathbf{CH_4 + ½O_2 \rightarrow CO + 2H_2}$$

- In the water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen:

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2}$$

Partial Oxidation Conditions

- Partial oxidation is exothermic (it gives off heat)
- Ru or Ni based catalysts can be used to reduce the operating temperature from ~1400°C to ~850°C
- Pressures of 30–80 bar are required
- The reaction is much faster than steam reforming and requires a smaller reactor vessel
- Partial oxidation initially produces less hydrogen per unit of the input fuel than is obtained by steam reforming



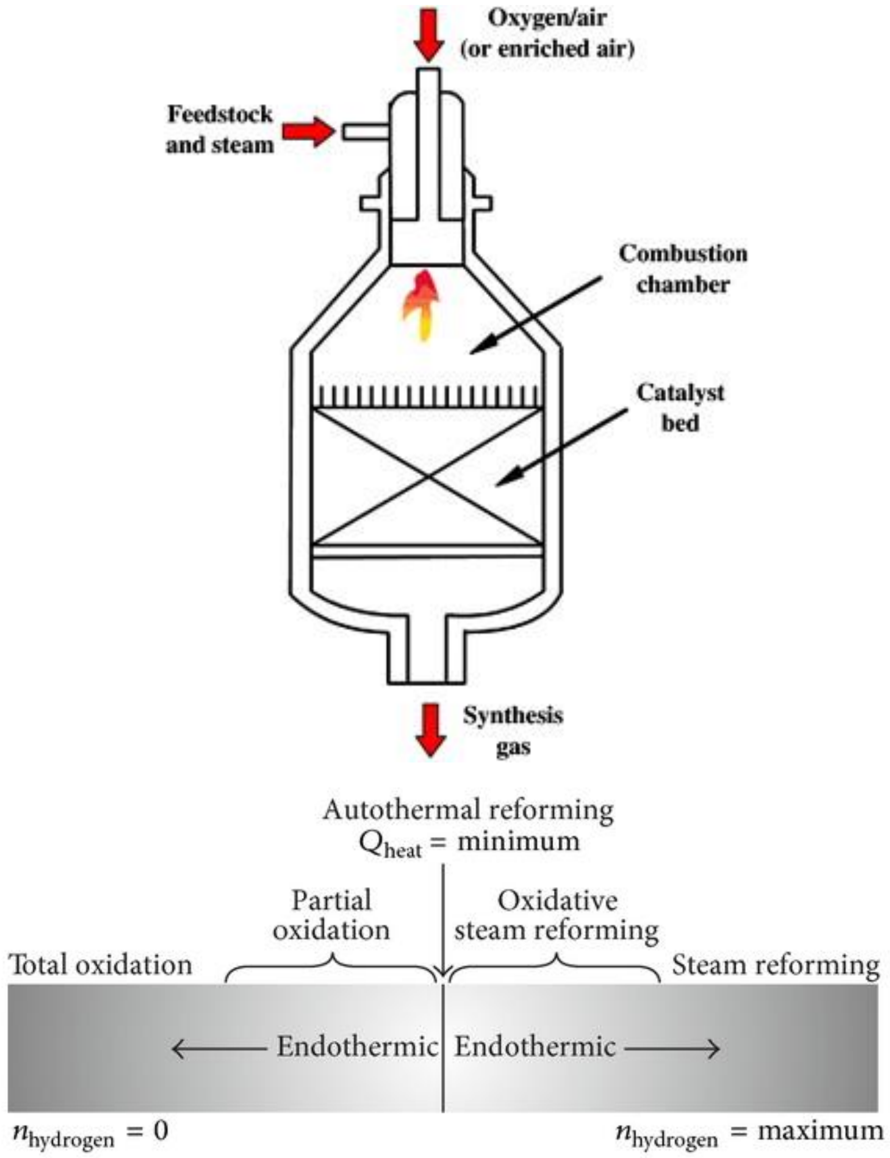
Autothermal Reforming (ATR)

- ATR is a combination of POX and SMR (i.e. reaction with both oxygen and steam)
- In principle, the heat required for the endothermic SMR reaction is provided by the exothermic POX reaction
- **ATR is popular for smaller scale hydrogen generation**, providing higher H_2 production than POX and faster start-up and response times than SMR
- For example, methane is reacted with both oxygen and steam in a single chamber:

$$\mathbf{CH_4 + \tfrac{1}{2}H_2O + \tfrac{1}{4}O_2 \rightarrow CO + 5H_2}$$

- The water-gas shift reaction can then be used to produce more hydrogen:

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2}$$



Autothermal Reforming Conditions

- Temperatures of 900-1150°C are used
- Reformer pressures of between 1-80 bar can be used
- The oxygen may be provided in pure form (O_2), or as air (20% O_2)
- The choice of catalyst depends on the fuel type. For example:
  - Lighter hydrocarbons can use copper-based catalysts
  - Longer chain molecules may use Pt, Rh and Ru based catalysts

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Coal and Biomass Gasification

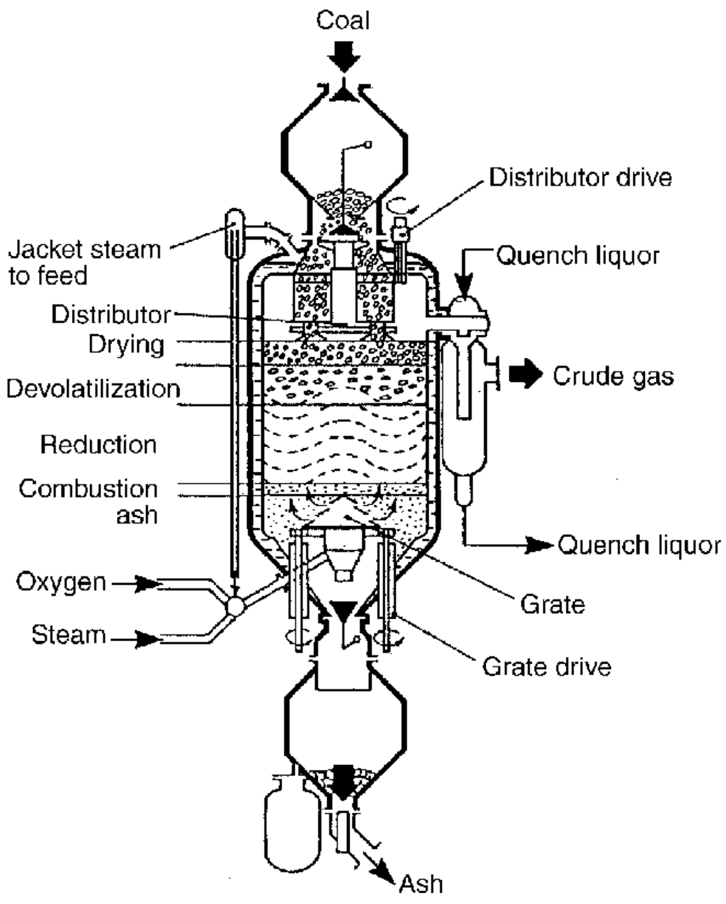
- Coal or biomass gasification works by reaction with oxygen and steam under high pressures and temperatures to form synthesis gas, a mixture consisting of carbon monoxide and hydrogen
- For example, gasification of coal:

$$3C + O_2 + H_2O \rightarrow H_2 + 3CO$$

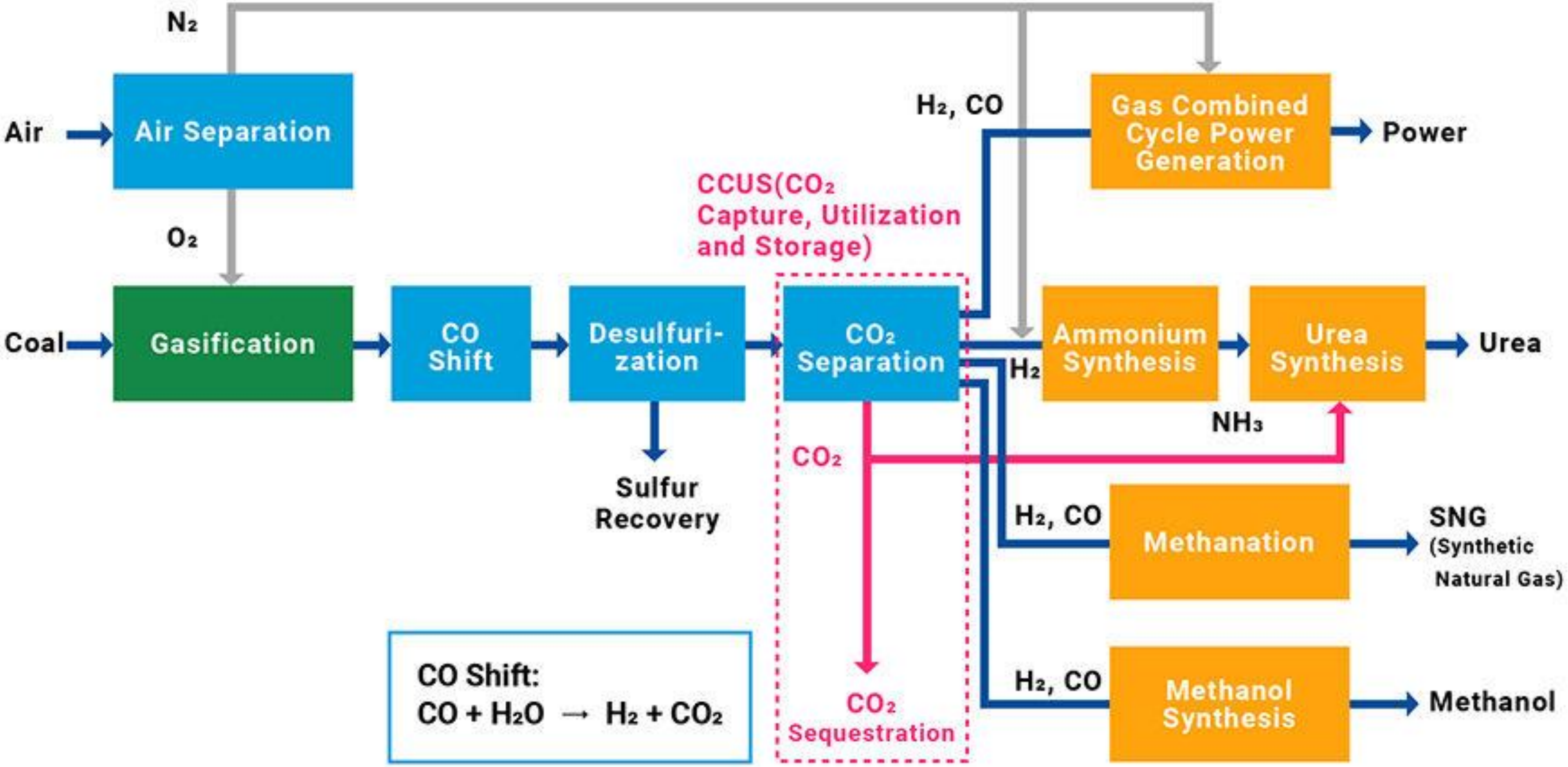
- The produced "coal gas" can then be reacted with water vapour through the water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

- In the case that "low grade" coals such as brown coals (containing water) are used, no steam is required during reaction

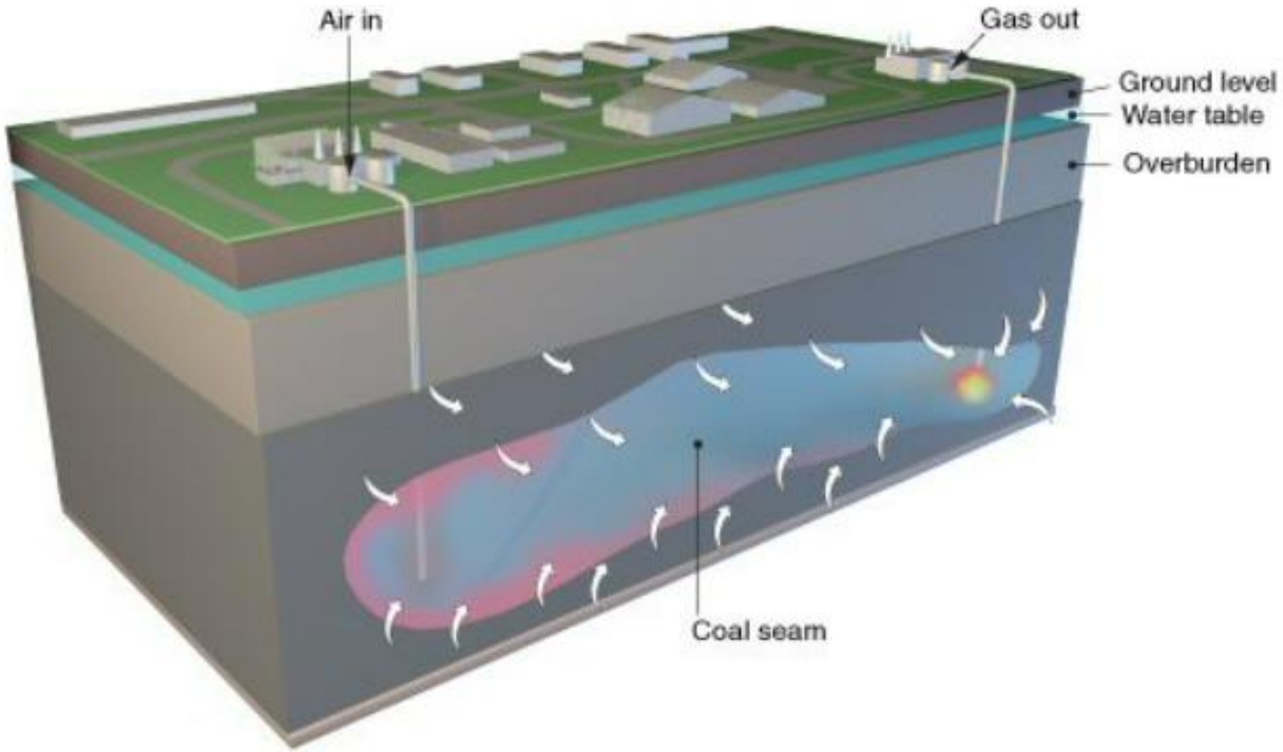


Coal Gasification

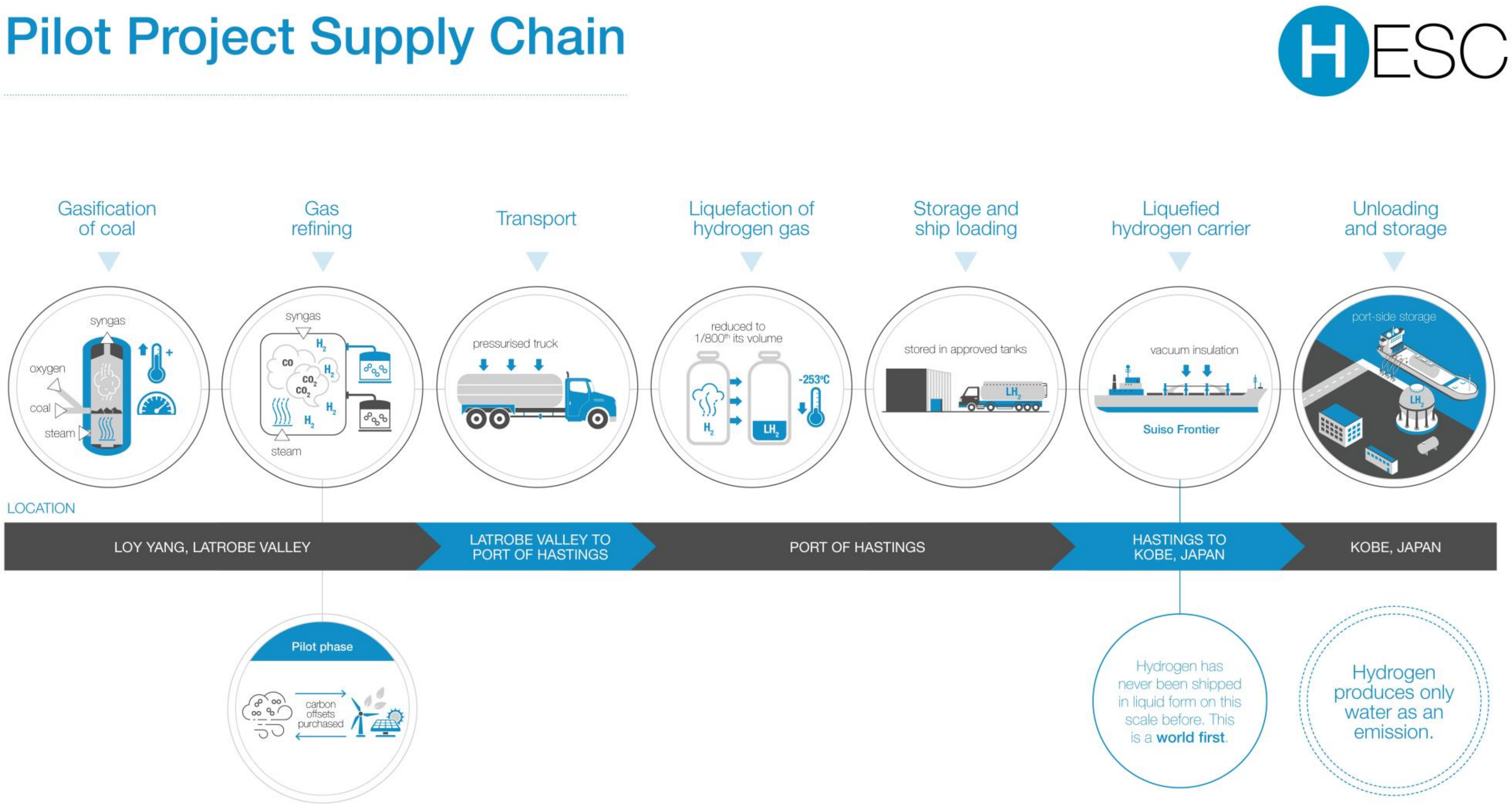


Underground Coal Gasification

- In underground coal gasification, the underground coal seam itself becomes the reactor, so that the gasification takes place underground instead of in a manufactured gasification vessel at the surface
- Injection wells are drilled into an unmined coal seam, and either air or oxygen is injected into the seam along with water
- The coal face is ignited (1200°C), and the high temperatures and limited oxygen causes nearby coal to partially oxidize into hydrogen, carbon monoxide, and carbon dioxide
- These products flow to the surface through one or more production wells

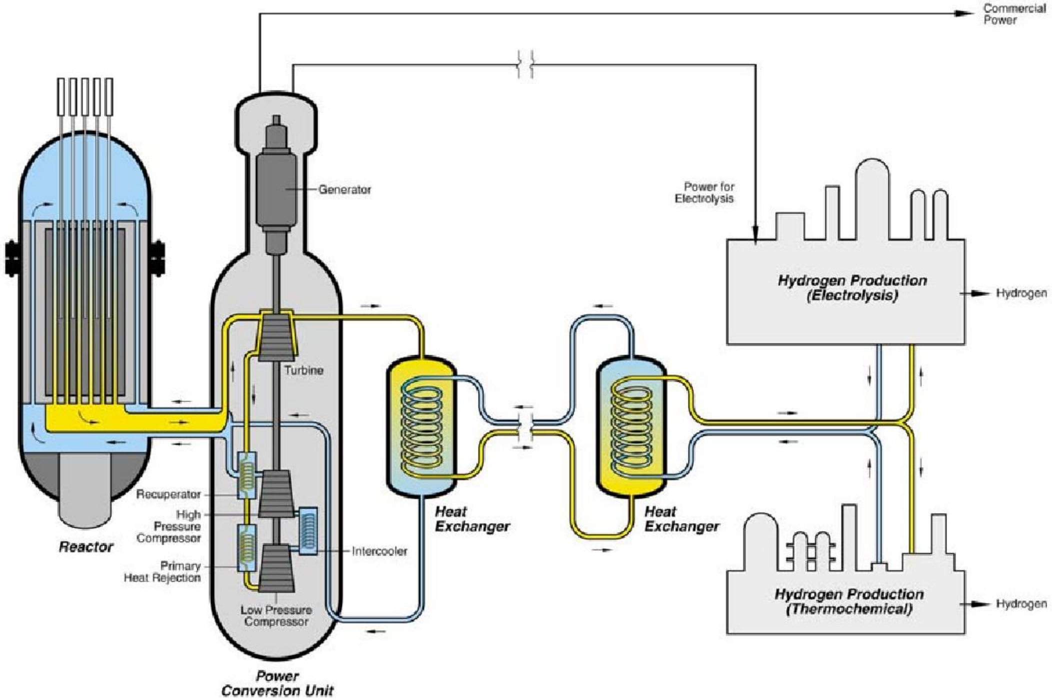


Blue Hydrogen From Coal



Nuclear Hydrogen Production?

- Whilst nuclear energy is usually considered non-renewable, it does not emit carbon dioxide
- However, extraction and enrichment of ores such as Uranium require an energy input
- Nuclear energy may assist in hydrogen production in several ways:
    - Low-temperature steam electrolysis, using heat and electricity from nuclear reactors
    - High-temperature steam electrolysis, using heat and electricity from nuclear reactors
    - High-temperature thermochemical production using nuclear heat
    - Use of nuclear heat to assist steam reforming of natural gas, lowering fossil fuel energy requirements



Pink/Purple Hydrogen

Renewable Hydrogen Production

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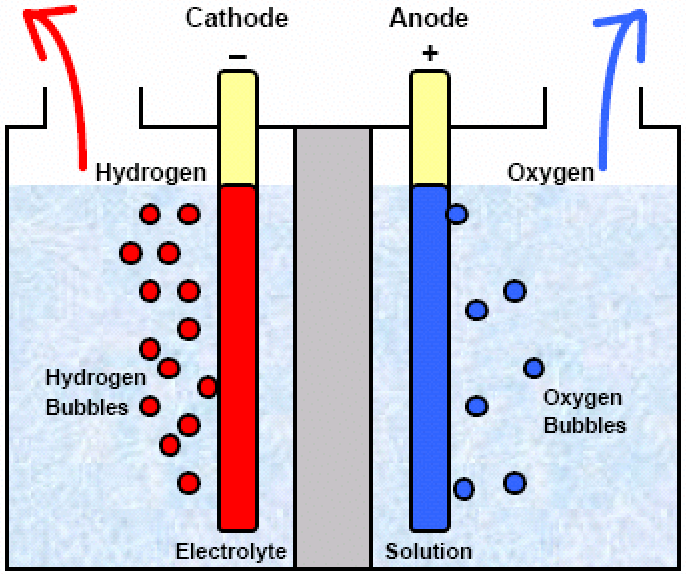
Renewable Hydrogen

Concept: Artificial Photosynthesis

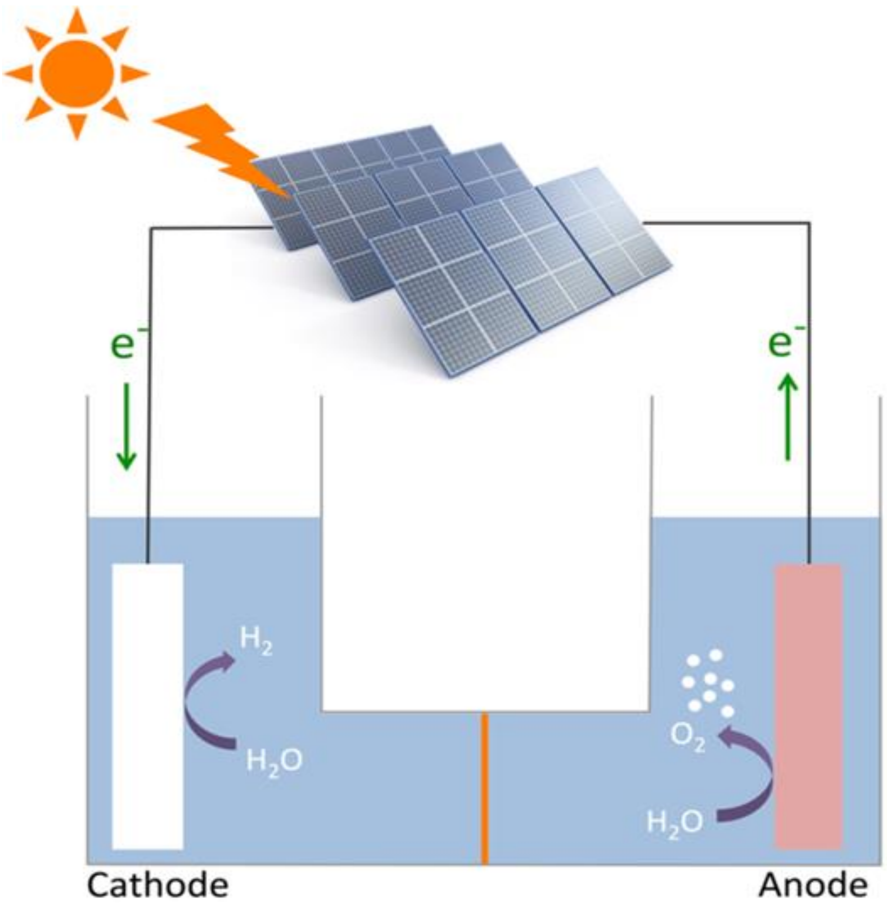
- Green hydrogen is produced through renewable methods
- Electrolysis of water can be powered by a source of renewable energy to separate water into hydrogen and oxygen
- Note that breaking water into H_2 and O_2 requires energy. When we combust H_2 with O_2 the reaction releases energy and forms water
- The main electrolyser types are:
  - Alkaline
  - Polymer electrolyte membrane (PEM)
  - Solid-oxide electrolyser cell (SOEC)

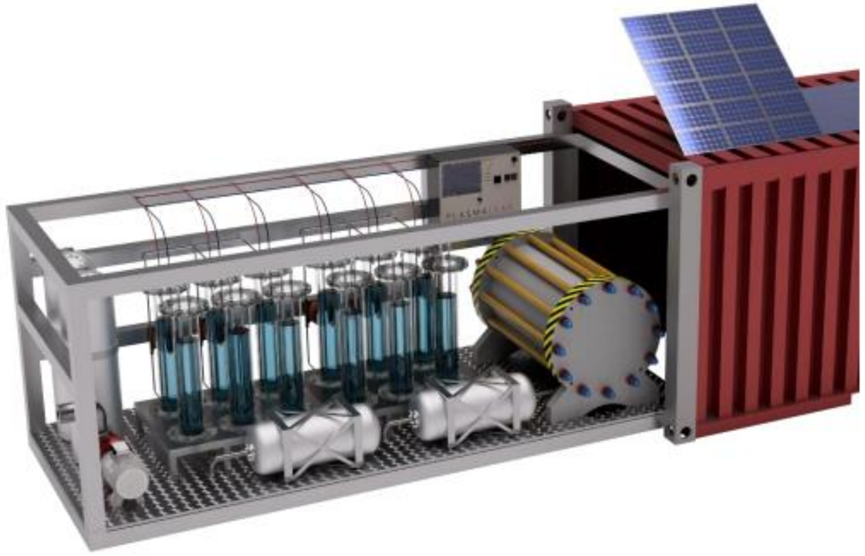


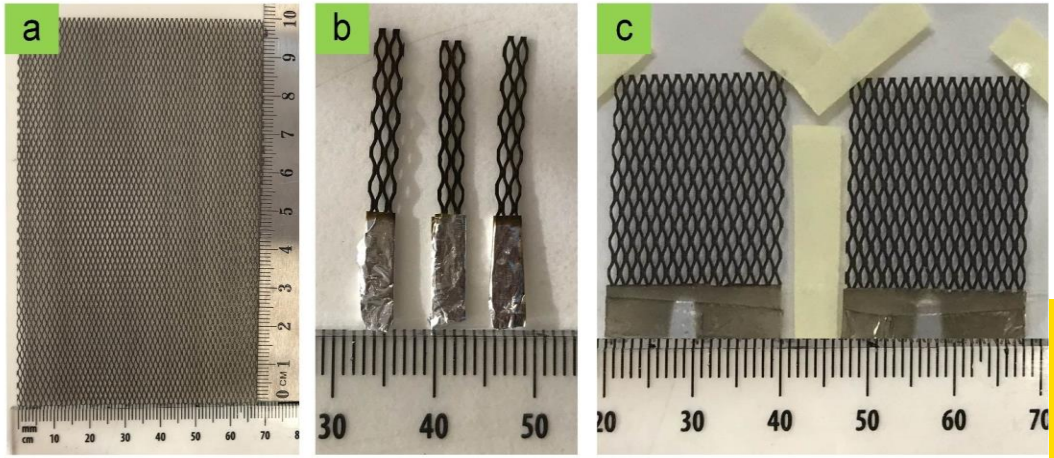
Standard Electrolysis

Electrolysis

- Electrolysis is a technique that uses electricity to drive an otherwise non-spontaneous chemical reaction (i.e. it will not occur without an external input)
- It is undertaken in a cell known as an electrolyser
- An electrolyser cell consists of an anode (positively charged) and cathode (negatively charged) chamber separated by a membrane and immersed in an electrolyte solution





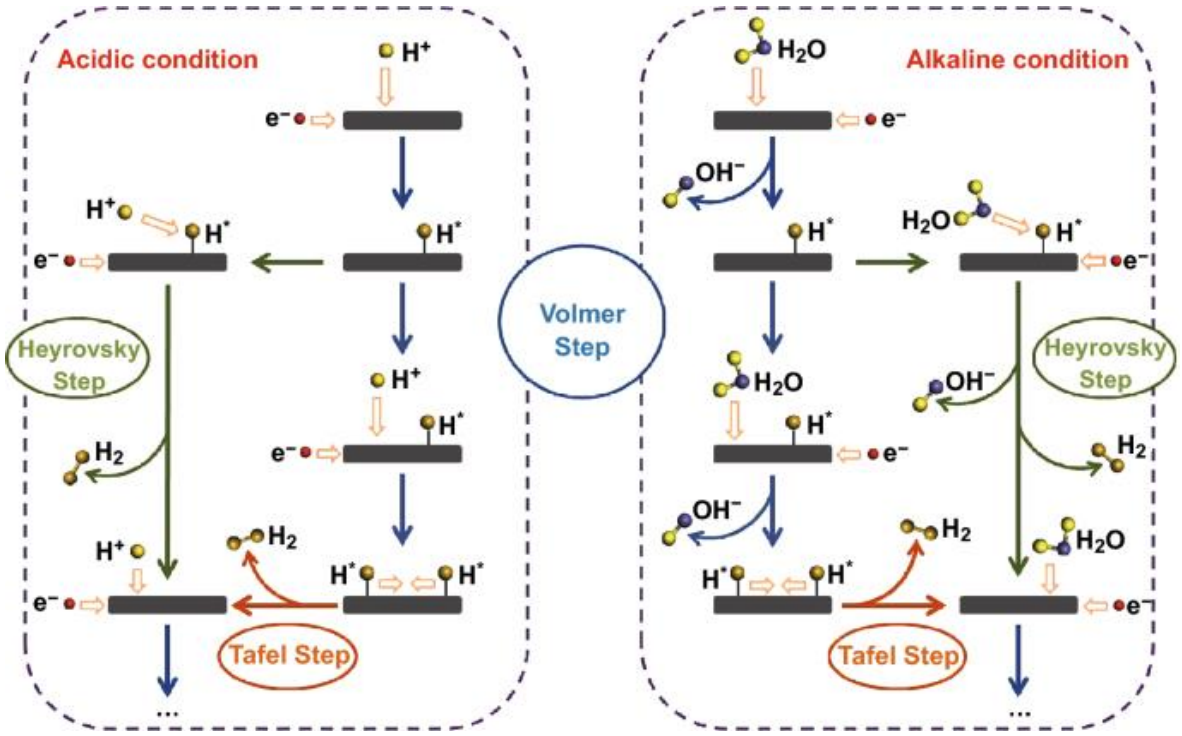


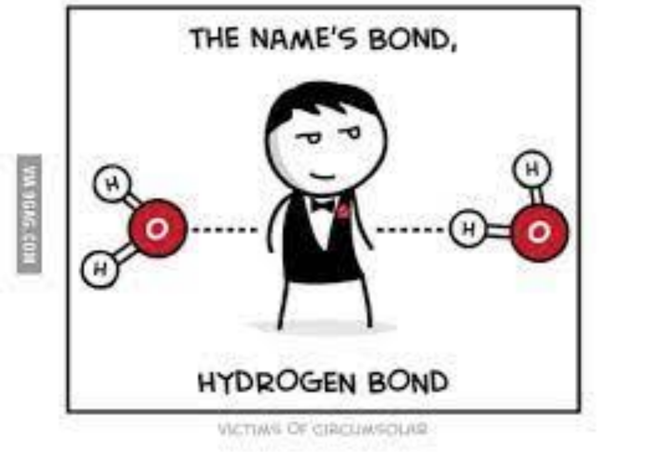
Fundamentals

- Hydrogen is produced at the cathode via the hydrogen evolution reaction (HER)
- Oxygen is produced at the anode via the oxygen evolution reaction (OER)
- The theoretical potential at which this reaction should occur is 1.23 V

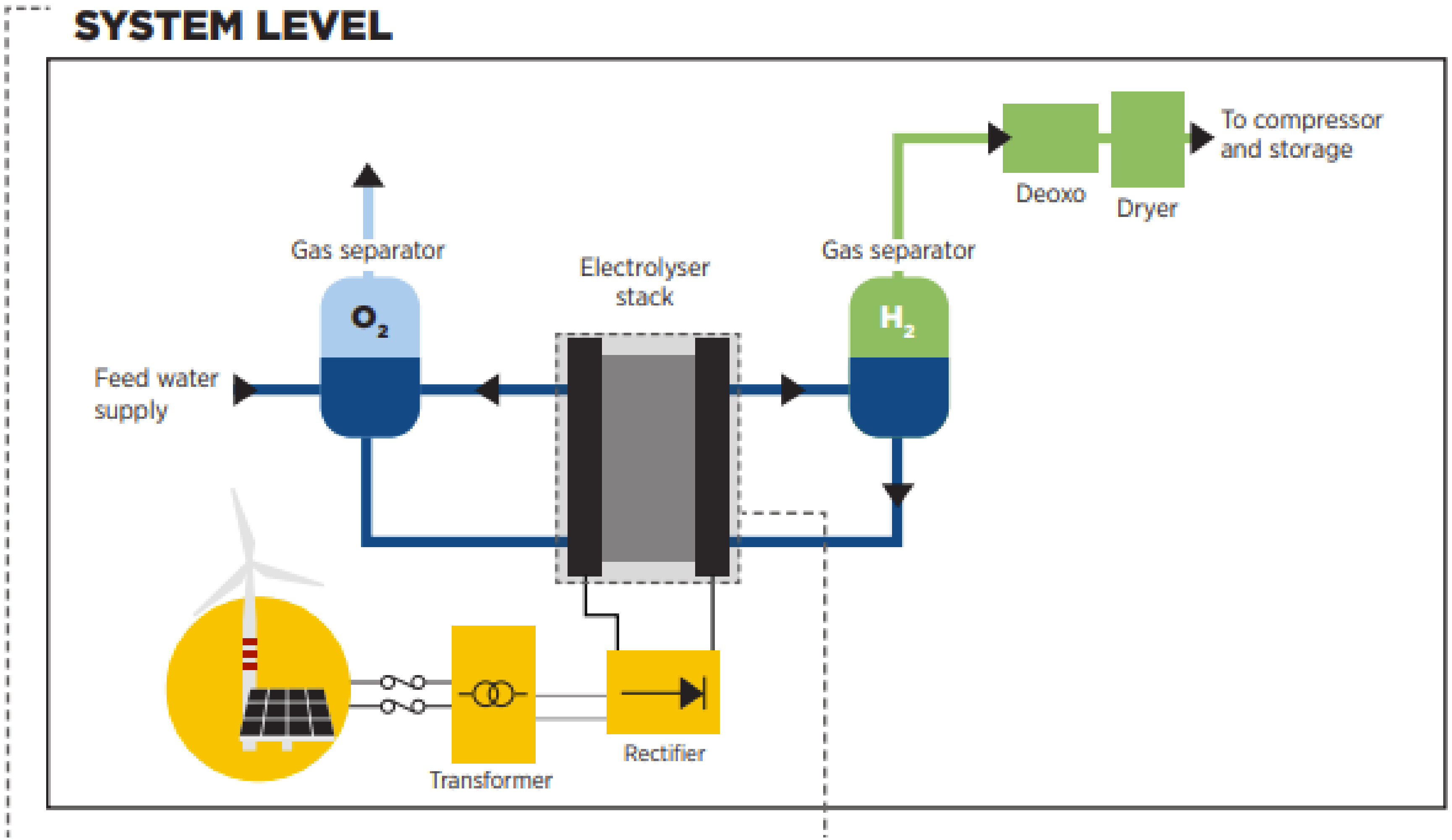
$$2H_2O \rightarrow O_2 + 2H_2 \qquad E^{\circ} = -1.23\ V$$

- Due to the sluggish reaction kinetics of the HER and OER, the input potential for practical applications within electrolysers exceeds 1.23 V
- Significant research is focused on developing catalysts that can reduce this “overpotential”

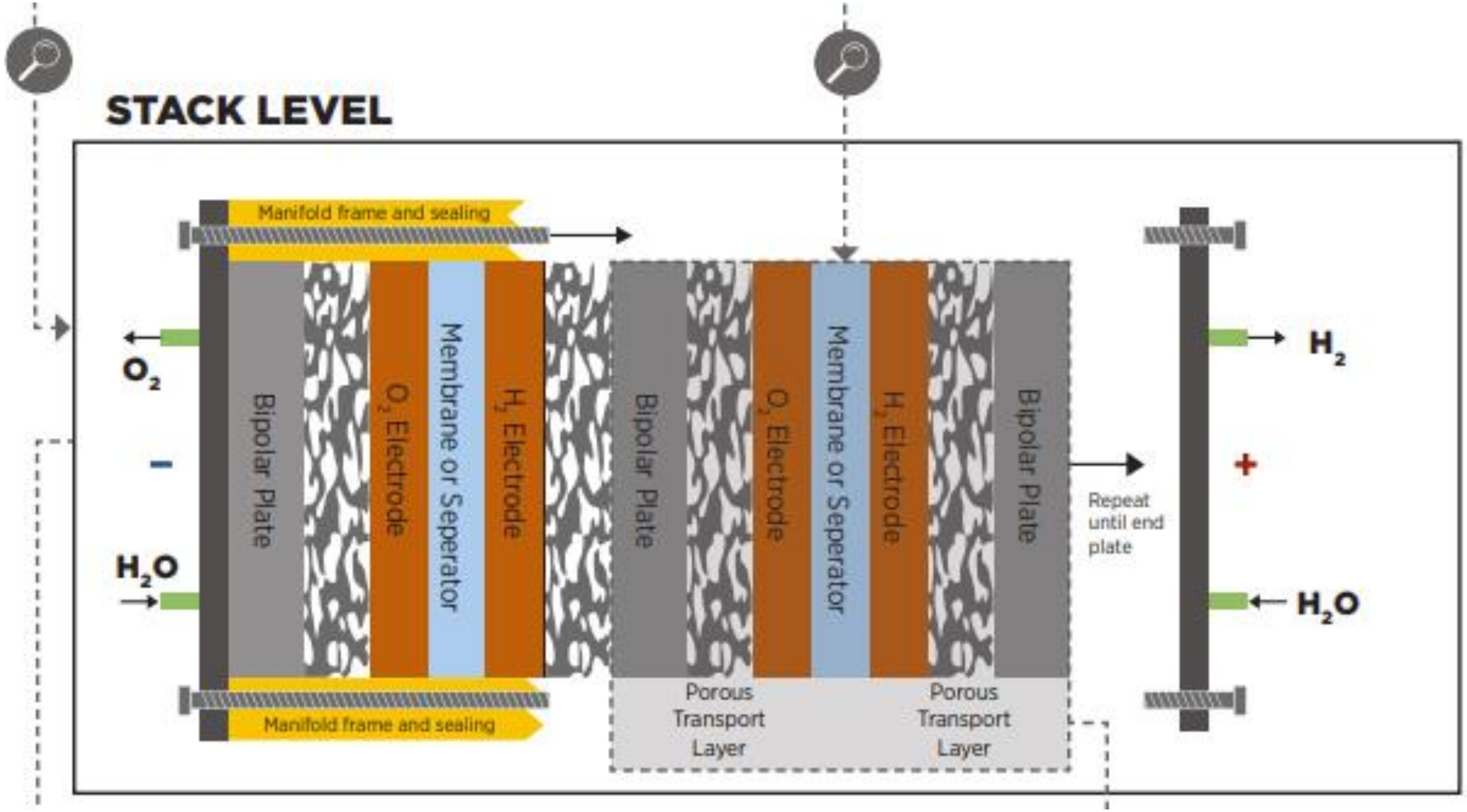




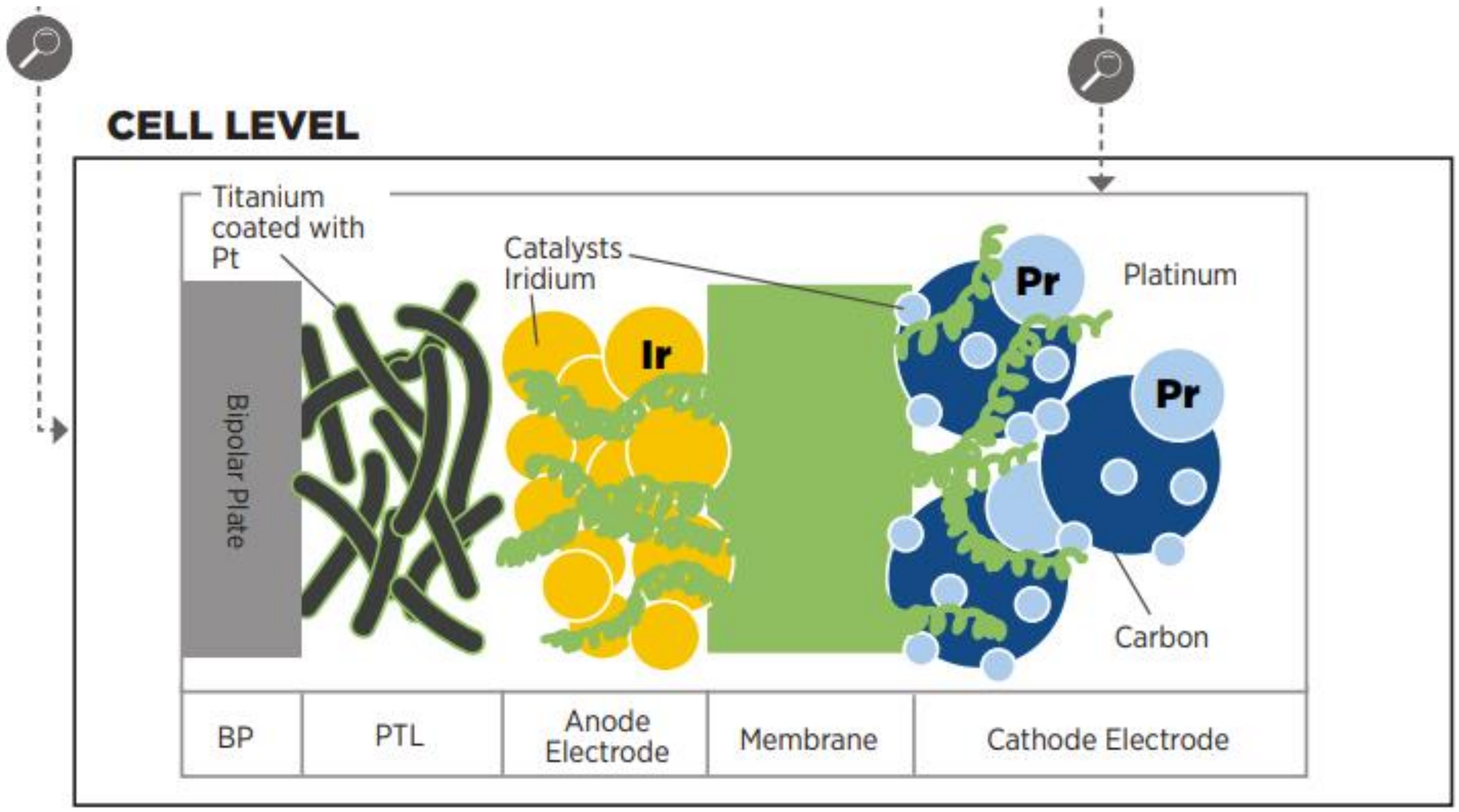
Electrolyser Overview



Electrolyser Overview



Electrolyser Overview



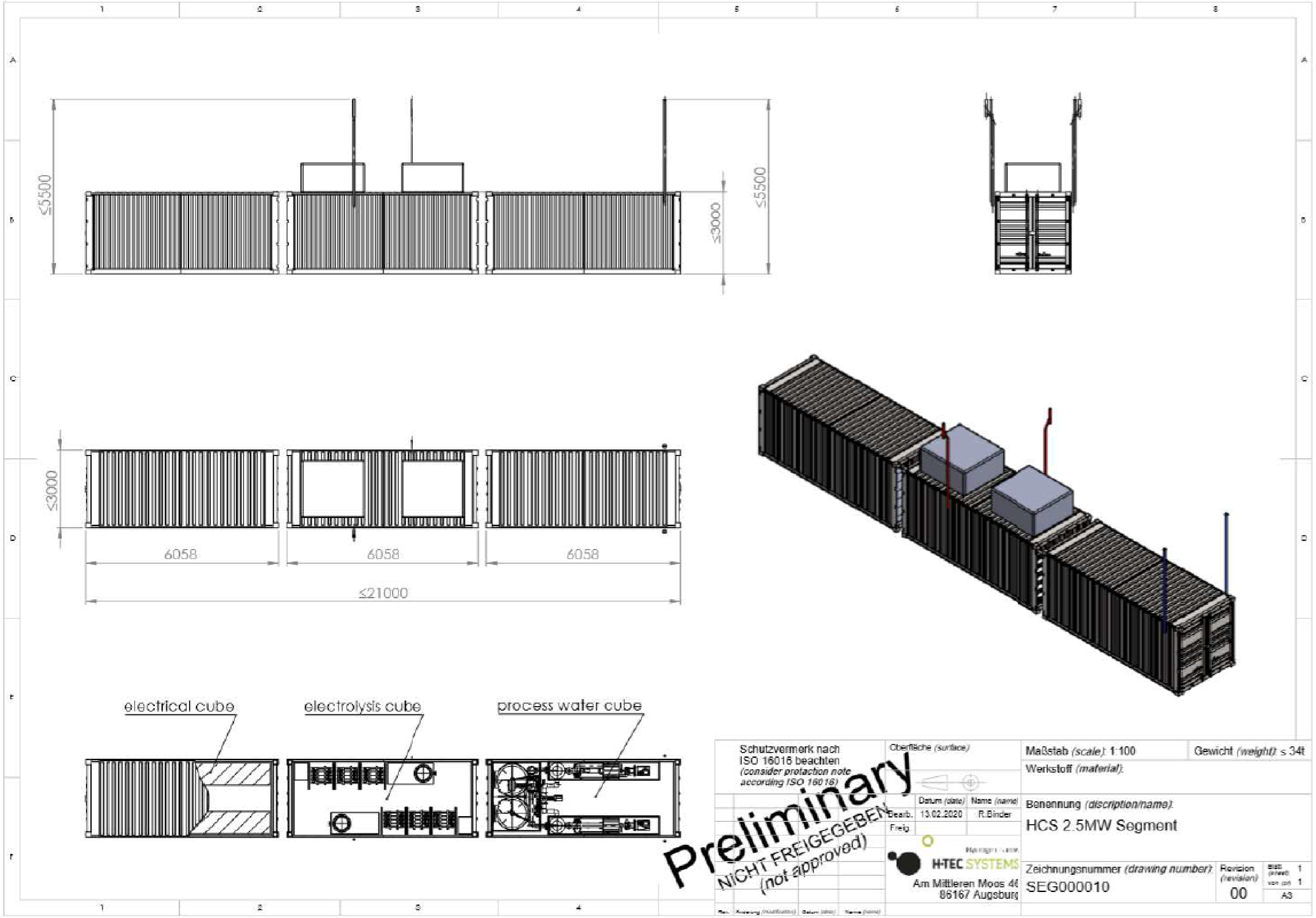

≤5500
≤3000
≤5500
≤3000
6058
6058
6058
≤21000
electrical cube
electrolysis cube
process water cube
Schutzvermerk nach ISO 16016 beachten
(consider protection note according ISO 16016)
Oberfläche (surface)
Maßstab (scale): 1:100
Gewicht (weight): ≤ 34t
Werkstoff (material):
Datum (date)
Name (name)
Bearb.
13.02.2020
R.Binder
Freig.
Benennung (discription/name):
HCS 2.5MW Segment
Preliminary
NICHT FREIGEGEBEN
(not approved)
H-TEC SYSTEMS
Am Mittleren Moos 46
86167 Augsburg
Zeichnungsnummer (drawing number):
SEG000010
Revision (revision)
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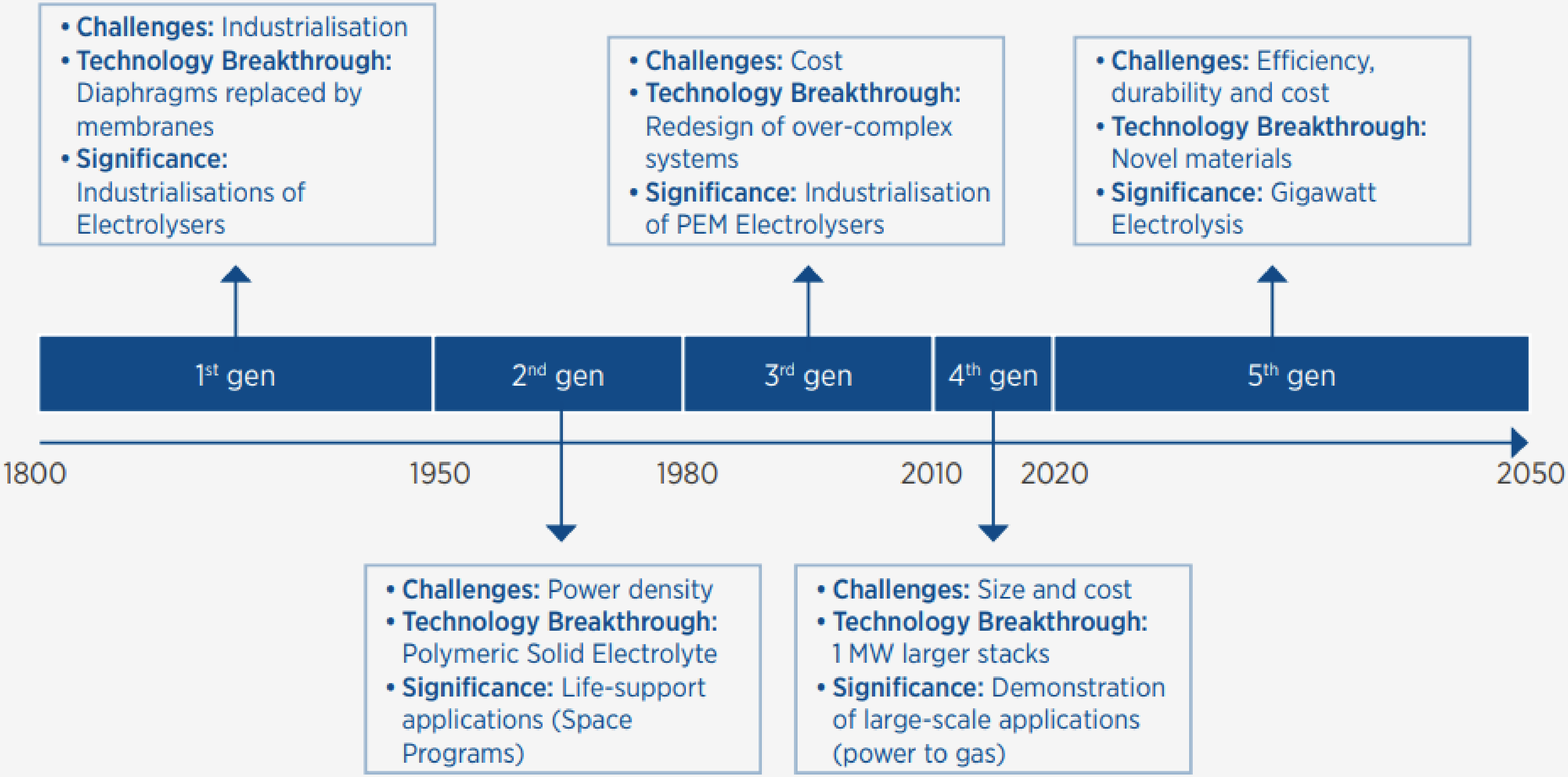
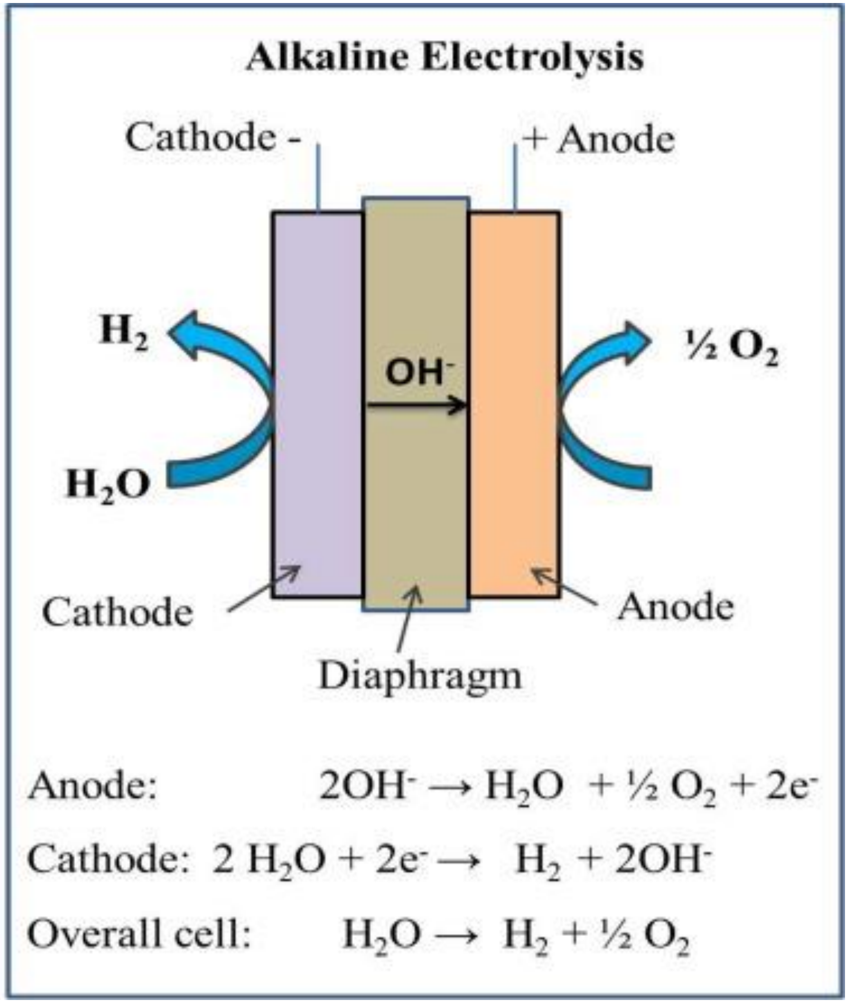
Figure 5. Challenges and technological breakthroughs for each of the generation of electrolysers.



Based on IRENA analysis.

Alkaline Electrolysers

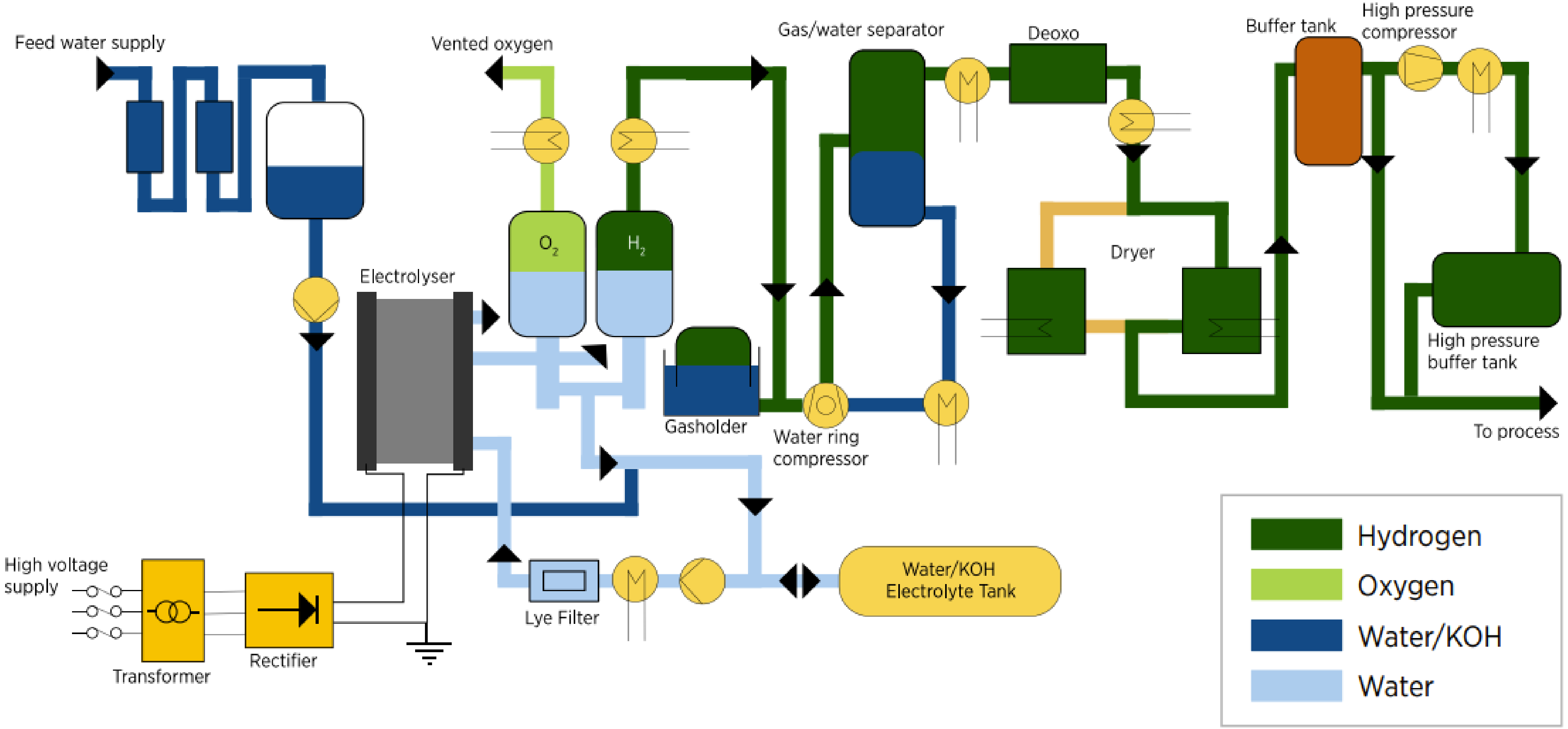
- Alkaline water electrolysis is a well-established technology
- An alkaline solution of aqueous KOH or NaOH is used
- Hydrogen and hydroxide ions (OH^-) are produced at the cathode
- Driven by the applied voltage, hydroxide ions are transferred through a diaphragm or membrane
- Oxidation then occurs at the cathode, forming oxygen and water



Alkaline Electrolyser Operation

- Typical operating temperatures are 60-90°C
- Typical operating pressures are 10-30 bar
- The electrolyte consists of ~30 wt.% KOH
- A typical cathode consists of Ni or Ni,Mo alloys
- A typical anode consists of Ni or Ni,Co alloys
- The cell efficiency is approximately 60-80%
- Cells may be connected in parallel or series to form an "electrolyser stack"

Alkaline Electrolyser System



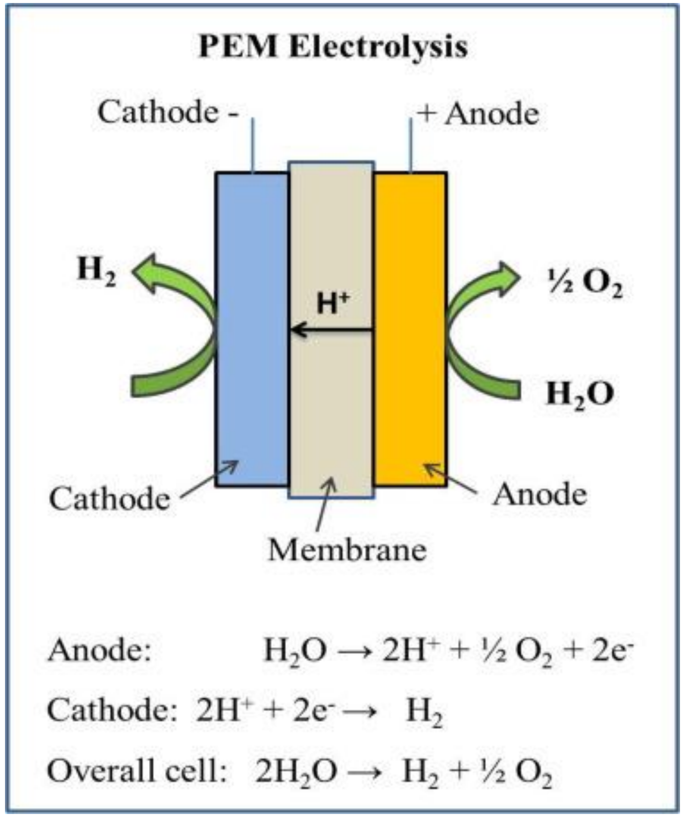
Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Alkaline Electrolyser Advantages and Disadvantages

Advantages	Disadvantages
• Commercially mature technology • Low-cost and abundant metals used for cathode and anode catalysts • Long term stability (stack lifetimes of up to 90,000 hours) • Low capital expenditure compared to alternatives	• Gas crossover can reduce product purity • Corrosive alkaline electrolytes • Lower current densities, lower operational pressures and higher footprint compared to alternatives

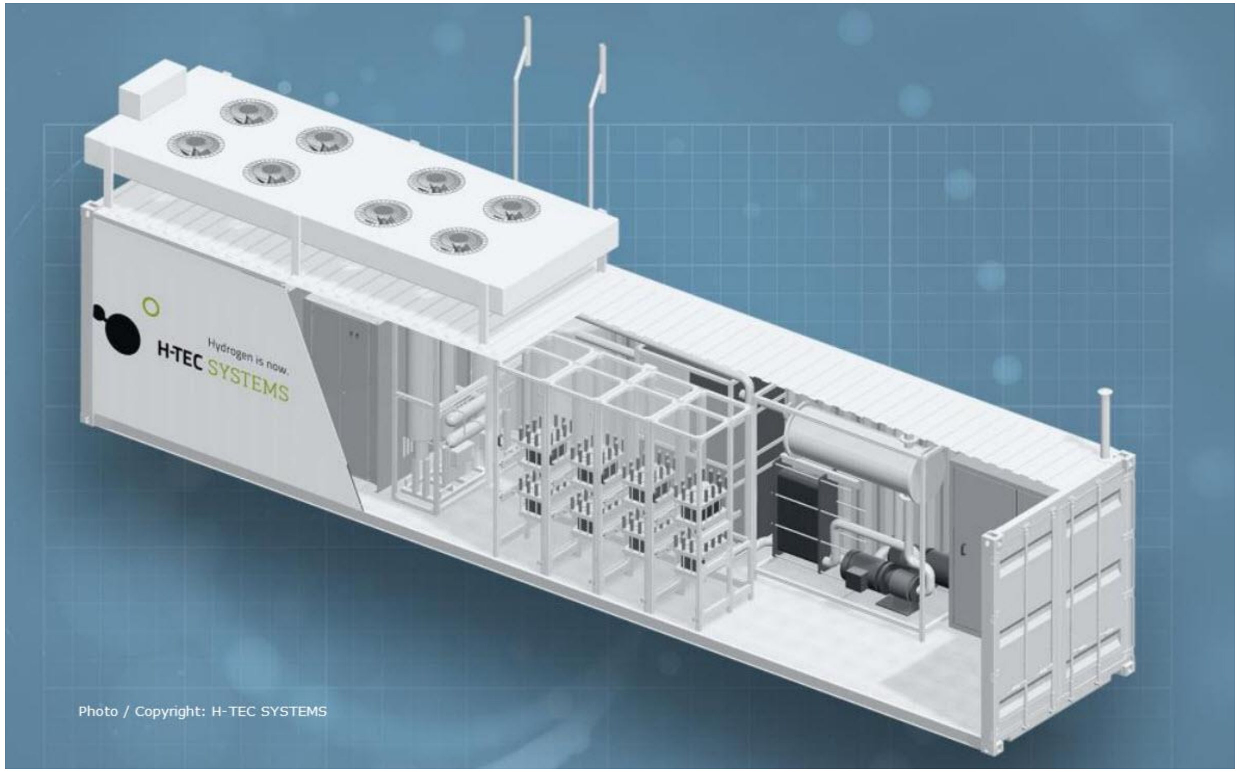
Polymer Electrolyte Membrane Electrolysers

- Also known as proton exchange membrane electrolysers
- PEM electrolysers are also a well-established technology
- A proton exchange membrane separates the two half-cells, with electrodes directly mounted on the membrane to form the membrane electrode assembly (MEA)
- At the anode, water is reduced, with the proton permeating through the proton exchange membrane
- At the cathode, the proton gains an electron to form hydrogen

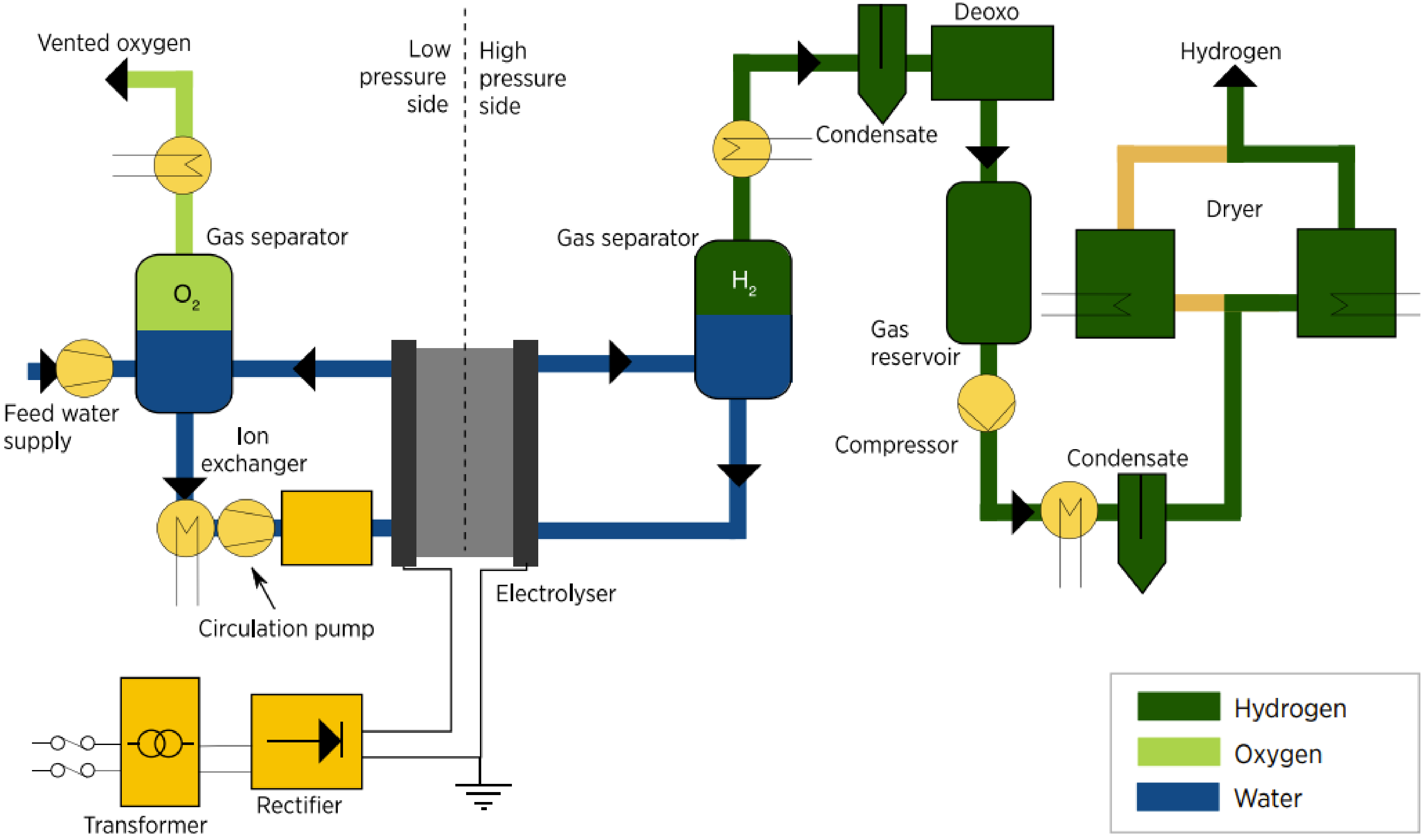


Polymer Electrolyte Membrane Electrolyser Operation

- Typical operating temperatures of 50-80°C
- Typical operating pressures of 20-50 bar
- Due to the acidic environment, expensive noble metals are used as catalysts
  - Ir, Ru at the anode
  - Pt, Pd at the cathode
- The cell efficiency is approximately 70-80%



PEM Electrolyser System



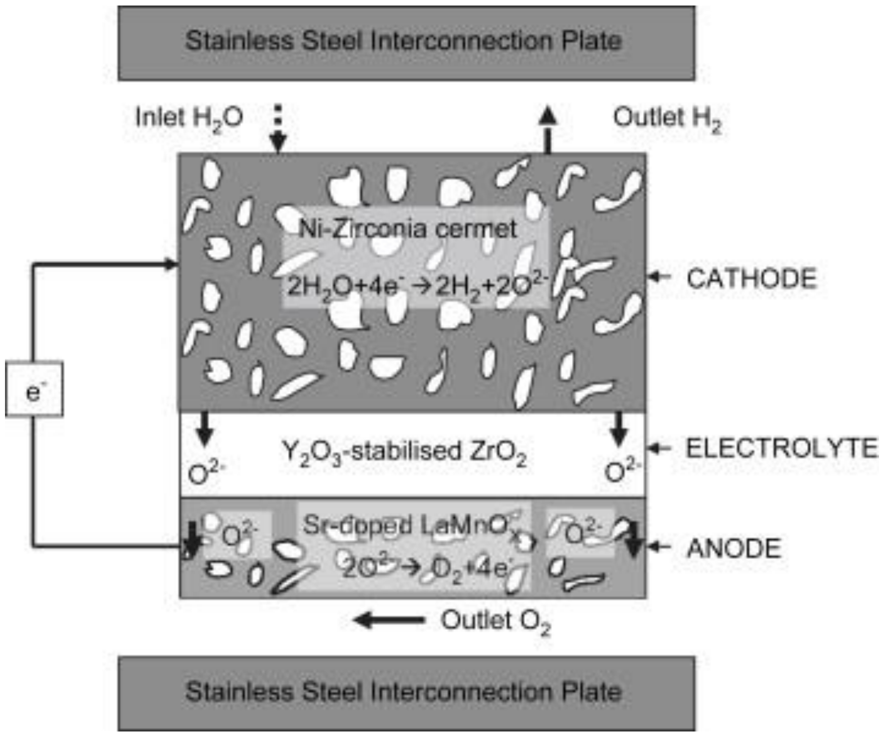
Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Polymer Electrolyte Membrane Electrolyser Advantages and Disadvantages

Advantages	Disadvantages
• Commercially mature technology • Shorter start-up time and higher load flexibility compared to alkaline electrolyzers • High gas product purity • High voltage efficiency	• Shorter lifetime (up to 60,000 hours) and higher maintenance costs compared to alkaline electrolyzers • Corrosive acidic environment • More expensive noble metal-based catalysts

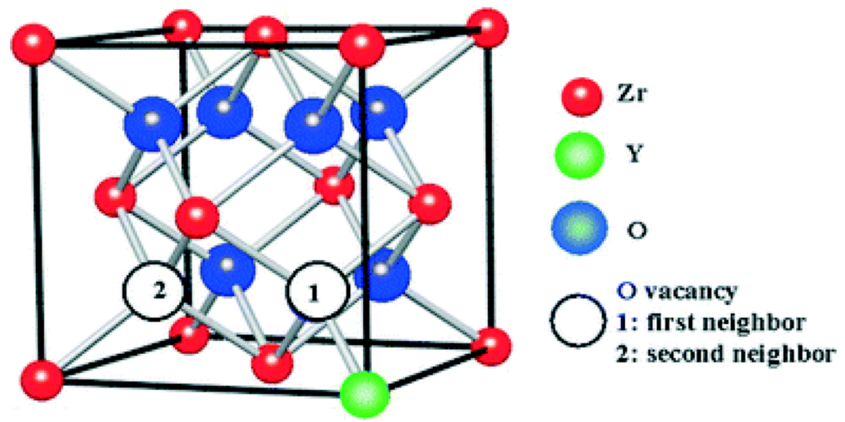
Solid-Oxide Electrolyser Cells

- SOECs are less mature than alkaline and PEM electrolysers
- SOECs typically consist of an yttria-stabilised (Y_2O_3) zirconia (YSZ) electrolyte, strontium-doped lanthanum Manganite (LSM)/YSZ O_2 electrode and a Ni/YSZ H_2 electrode
- Water (or steam at high temperatures) flows into the cathode chamber, where it is reduced to hydrogen and oxide ions, which pass through the YSZ electrolyte, forming oxygen at the anode

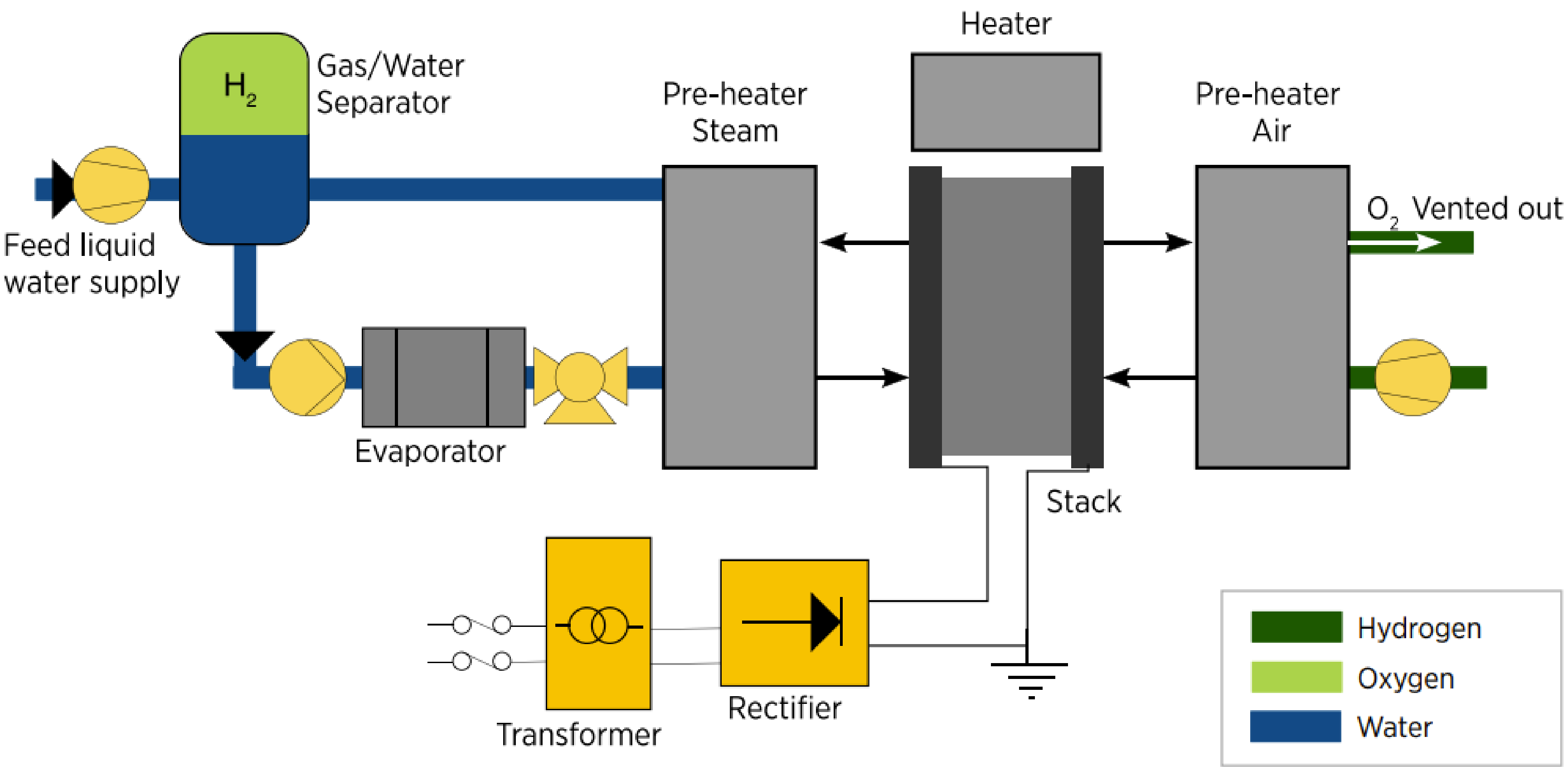


Solid-Oxide Electrolyser Cell Operation

- Typical operating temperatures are 650-1000°C
- Typical operating pressures are 1-15 bar
- The electrolyte is Yttria stabilised Zirconia (YSZ)
- A typical cathode consists of Ni/YSZ
- A typical anode consists of Lanthanum Strontium Manganese (LSM)/YSZ
- The cell efficiency is up to 100%



SOFC System



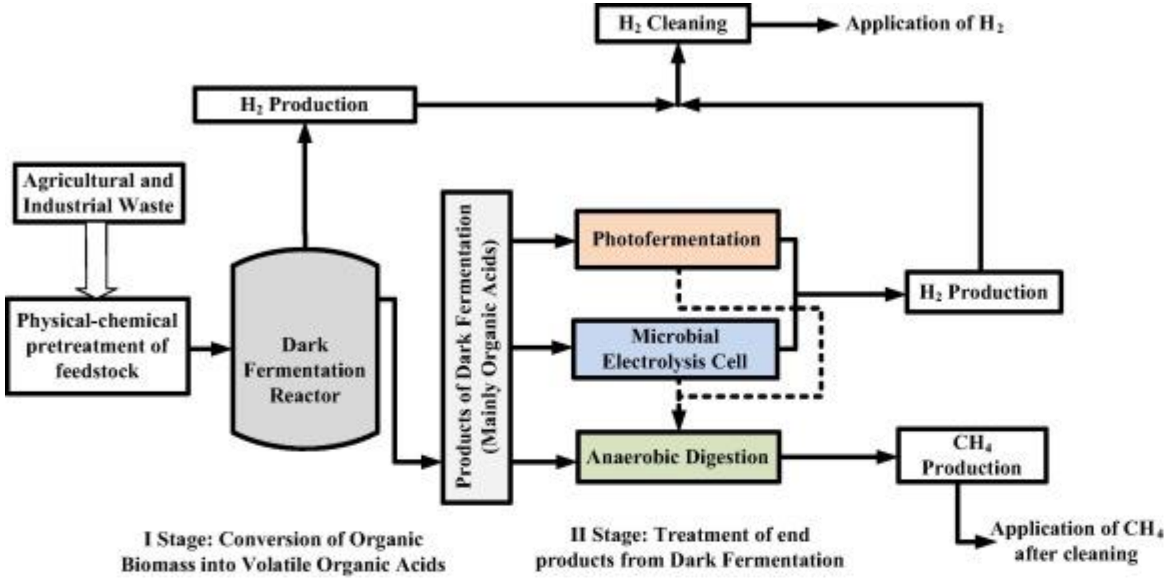
Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Solid-Oxide Electrolyser Cell Advantages and Disadvantages

Advantages	Disadvantages
• Lower specific electrical energy consumption compared to alkaline and PEM electrolysers • Higher cell efficiency than alkaline and PEM electrolysers • Non noble metal-based catalysts	• Laboratory stage of development • Poor long-term durability

Other Renewable Processes (Research Stage)

- More atypical and possible future processes:
- Biological hydrogen production
  - Hydrogen-producing bacteria
  - Carbon neutral, or can even consume CO_2
  - Inputs of organic feedstock and water
- Solar electric
  - Use of semiconductors to absorb solar light to drive the water redox reaction
- Solar thermal
  - Direct concentrated solar heat for water splitting



10 MW Wave Energy Plant in Tonga

- Swedish wave energy company Seabased has signed a memorandum of understanding for the development of a 10 MW wave energy plant offshore in Tonga.
- The initial park in Tonga will be 2 MW and is projected to displace 2 million liters of fuel, reduce carbon emissions by roughly 5.6 kilotons and generate enough power for 2,800 homes.
- The second phase will include additional 8 MW, and save up to 42 million liters of fuel, with the start of operations planned in two years after signing the PPA, according to Seabased.
- Laurent Albert, CEO of Seabased noted that wave energy can also be used for things like desalination of drinking water and for the production of **green hydrogen.**

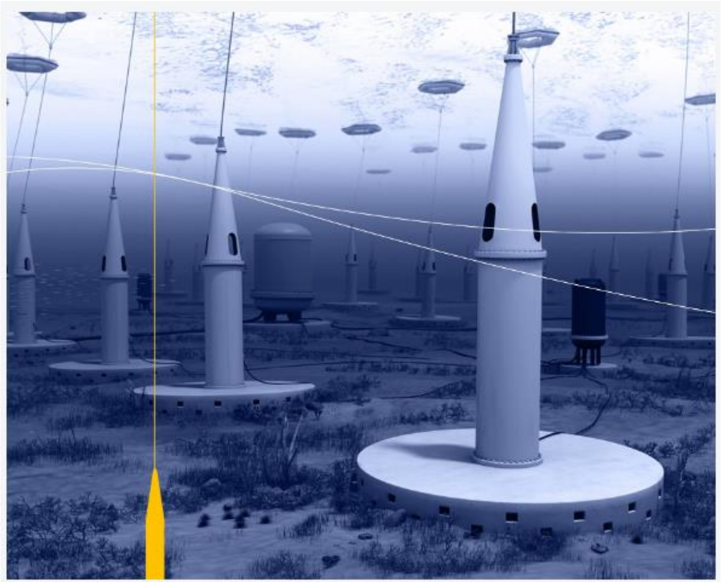


Figure: The Seabased wave energy system.

Reference: https://www.offshore-energy.biz/seabased-shakes-hands-for-10mw-wave-energy-plant-in-tonga/

Hydrogen Production in Papua New Guinea

- Two agreements between Fortescue Future Industries and Papua New Guinea signed in 2020 and 2021 enabled feasibility studies on up to 18 hydropower and geothermal projects in the country, including a hydro project along the Purari River on the nation's southern coast.
- These projects would provide renewable hydrogen to TotalEnergies' Papua LNG project.
- However, Fortescue has not provided any updates on the projects since December 2021 when it said a pre-feasibility study was well advanced.

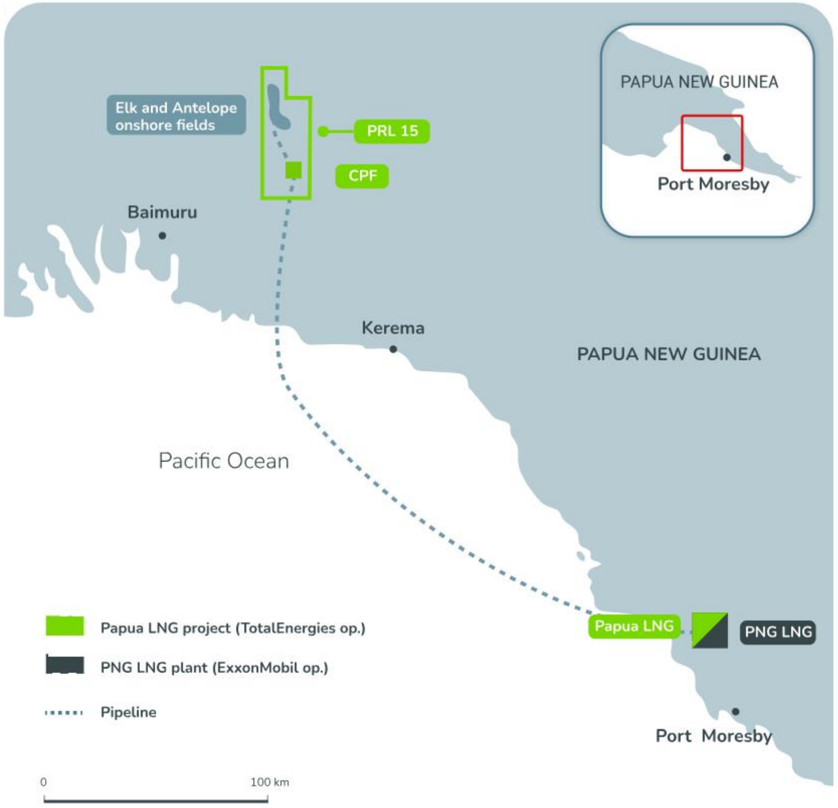


Figure: The Papua LNG project.

Reference: https://www.reuters.com/business/energy/totalenergies-may-buy-green-power-fortescue-papua-new-guinea-regulator-2022-12-08/

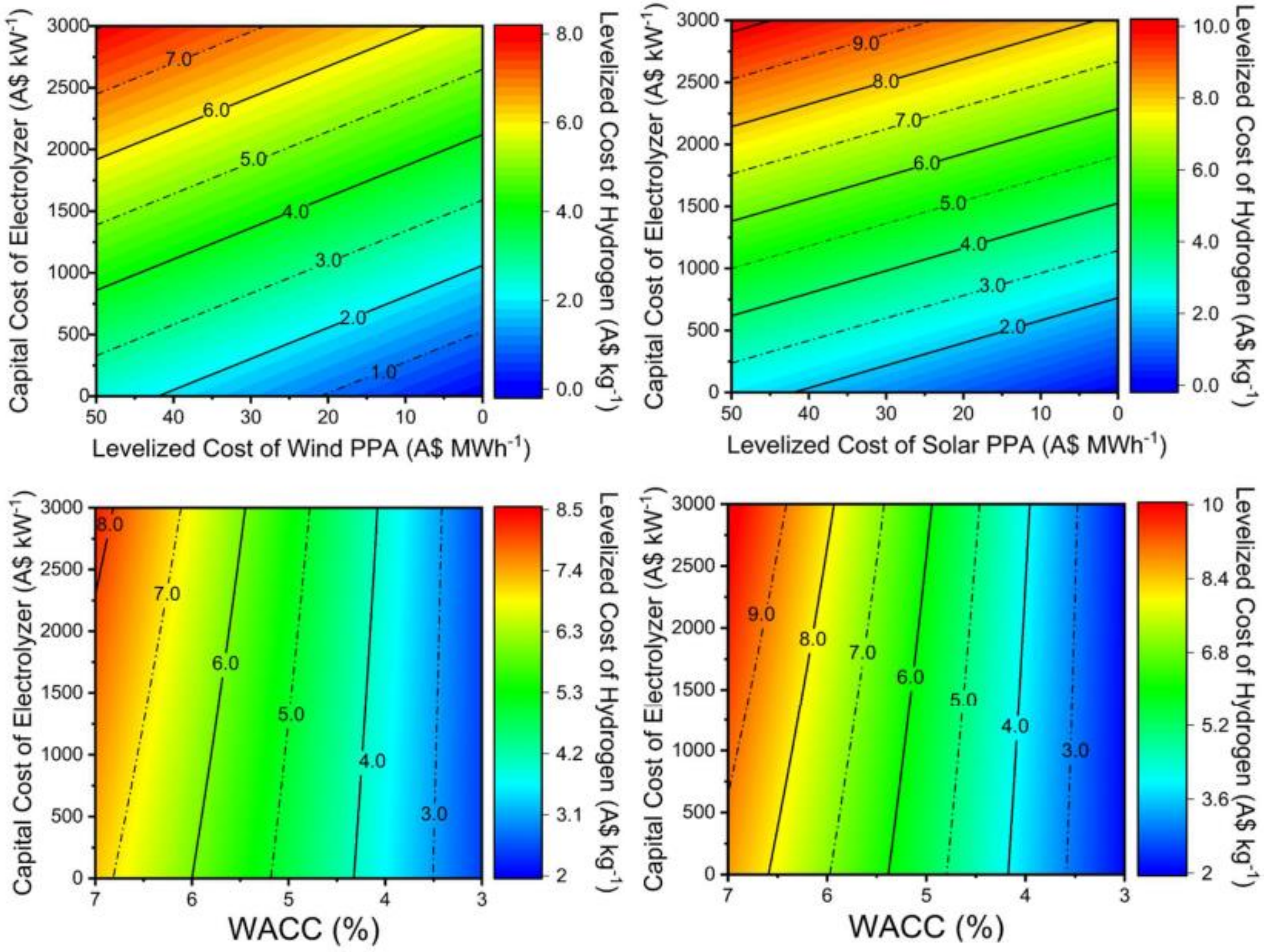
Green H_2 Production Costs

Location matters

Cost reductions needed

- Renewables costs down, CF up
- Electrolysers costs down, efficiency up
- Improved integration (CF optimisation)
- Low cost (de-risked) finance

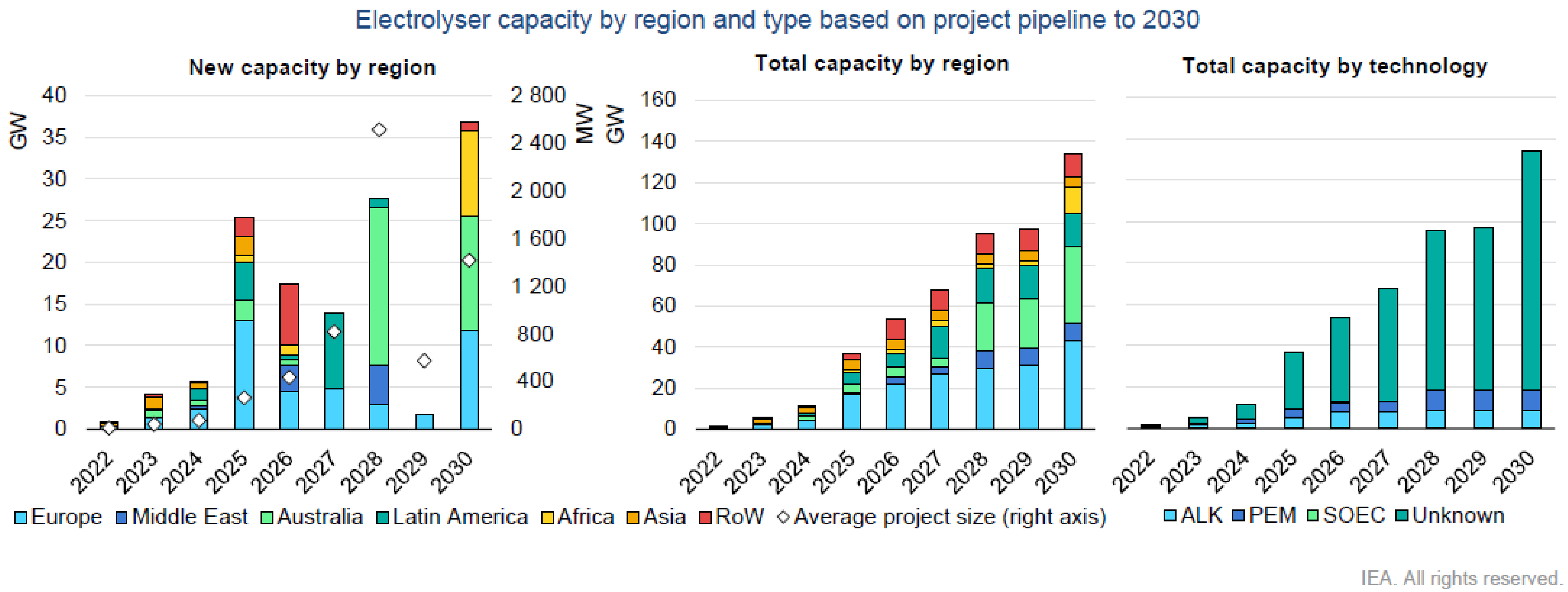
Proponent	Target/projection /Scenario	Price range/kg_{H2}	Adjusted to A$/$kg_{H2}$	Price year	References
Australian Government	Stretch target		A$2	Not indicated	Low Emissions Technology Roadmap,2020[87]
Hydrogen Council	Projection	US $1.40 – 2.30 (U$1.40 in optimal locations)	A$1.89 – 3.11	2030	Hydrogen insights, 2021[12]
EU	Target	Euro 1.1 – 2.4	A$1.77 – 3.87	2030	Hydrogen strategy, 2020[120]
IEA	Net Zero Emissions scenario	US $1.50 – 3.50	A$2.03 – 4.73	2030	Net Zero by 2050, 2021[19]
IRENA	Scenarios	US $1.40 – 2	A$1.89 – 2.70	2030	Low RE cost scenarios in Green Hydrogen cost reduction, 2020[22]
IEA	Renewables connected scenario	US $2 – 4	A$2.70 – 5.40	2030	Future of Hydrogen, 2019[10]
IRENA	Projection	US $1.80 – 3.30	A$2.60 – 4.78	2030	Hydrogen: A Renewable Energy Perspective, 2019[116]
Bloomberg	Projections	US $1.20 – 2.7	A$1.62 – 3.65	2030	BNEF: Hydrogen Economy Outlook, 2020[13]



Global Electrolyser State of Play

Status of Electrolyser Market

Share of Global Electrolyser Demand



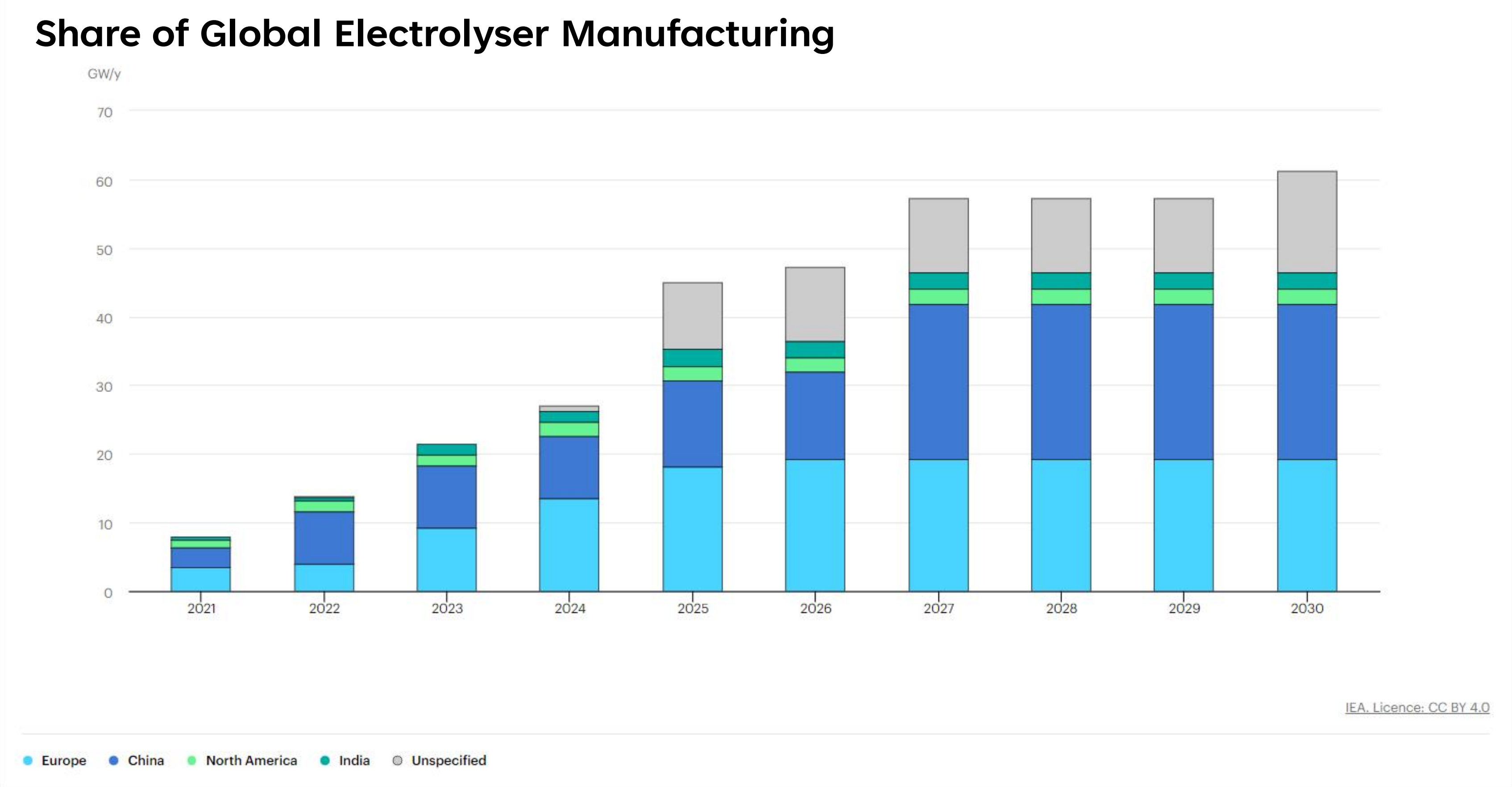
Notes: RoW = rest of world; ALK = alkaline electrolyser; PEM = proton exchange membrane electrolyser; SOEC = solid oxide electrolyser. Only projects with a disclosed start year for operation are included. Projects at very early stages of development, such as those in which only a co-operation agreement among stakeholders has been announced, are not included
Source: IEA Hydrogen Projects Database (2022).

Key Message

The demand for electrolysers in this decade is expected to be dominated by Europe, Middle East, Australia, Africa and Latin America

Reference: https://www.iea.org/reports/global-hydrogen-review-2022

Status of Electrolyser Market



Key Message

China and Europe are the biggest producers of electrolysers.

China is expected to become the dominant manufacturer by the decade’s end.

Diversification of supply is expected by mid-decade, with the US, India and other global players emerging and taking large shares of the market.

Reference: https://www.iea.org/data-and-statistics/charts/global-hydrogen-production-by-technology-in-the-net-zero-scenario-2019-2030

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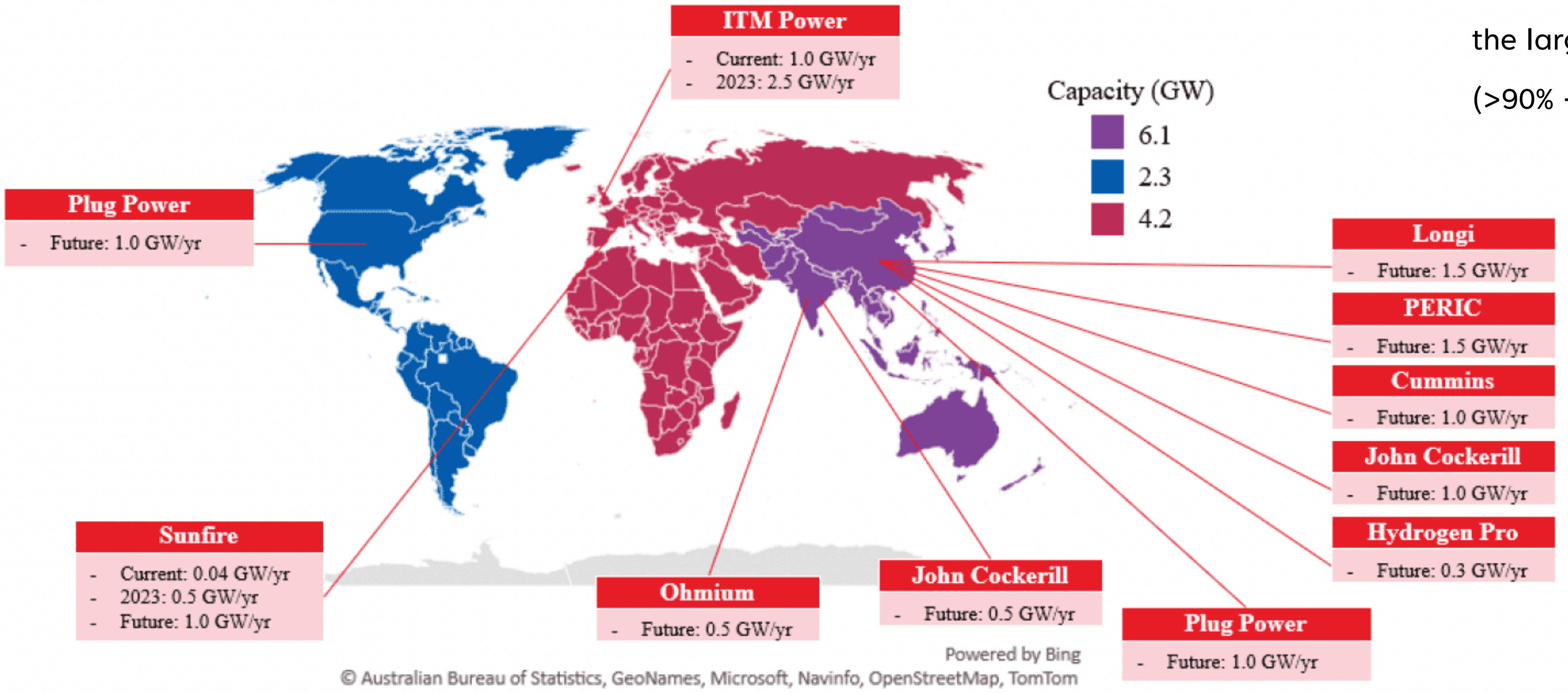
Status of Electrolyser Market

Share of Global Electrolyser Manufacturing



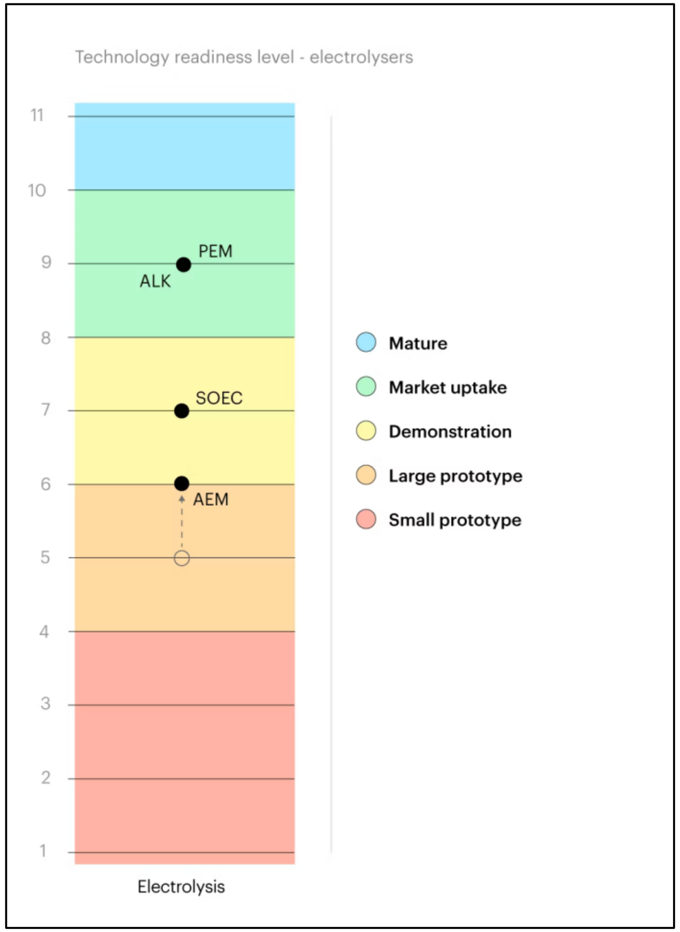
Key Message

- Presently – 12.6 GW/yr electrolyser production capacity
- China and Europe has the largest capacity (>90% - 10.3 GW/yr)

Reference: Bloomberg Analysis – adopted from: https://www.gov.scot/publications/assessment-electrolysers-report/pages/4/

Status of Electrolyser Market

Technology Readiness of Electrolyser Systems



TECHNOLOGICAL BETS OF SOME OF THE WORLD'S LEADING ELECTROLYSER MANUFACTURERS (CIC energiGUNE)

COMPANY	COUNTRY	TECHNOLOGY: ALKALINE	TECHNOLOGY: PEM
McPhy	France	●	
Air Liquide	France		●
SIEMENS energy	Germany		●
Cummins	USA	●	
ITM POWER	UK		●
nel	Norway	●	●
sunfire	Germany	●	
TELEDYNE TECHNOLOGIES INCORPORATED	USA	●	●
Tianjin Mainland Hydrogen Equipment Co., Ltd.	China	●	
PLUG POWER	USA		●
elogen	France		●
AsahiKASEI	Japan	●	
H-TEC SYSTEMS	Germany		●
GREEN HYDROGEN SYSTEMS	Italy	●	●
thyssenkrupp	Germany	●	

Source: Own elaboration based on public available information (only some leading manufacturers within alkaline and PEM technologies are included)

COMPARISON OF MOST DEVELOPED ELECTROLYSIS TECHNOLOGIES by CIC energiGUNE

	ALKALINE	PEM
DEVELOPMENT STATUS	COMMERCIAL (MW)	COMMERCIAL (kW - MW)
EFFICIENCY	★★	★★★
DURABILITY	★★★★★	★★★
FLEXIBILITY	★★	★★★★
LIFE TIME	20-30 YEARS	10-20 YEARS
COST	€€	€€€
TEMPERATURE	50 - 80ºC	ROOM TEMPERATURE - 90ºC
H2 OUTLET PRESSURE	< 30 BAR	< 200 BAR
H2 PURITY	99.5 - 99.9998%	99.9 - 99.9999%
WATER QUALITY	★★	★

*Source: Basque Energy Cluster & Own elaboration

Reference: https://www.iea.org/reports/electrolysers
https://cicenergigune.com/en/blog/electrolyzers-manufacturing-industry-everyone-lead

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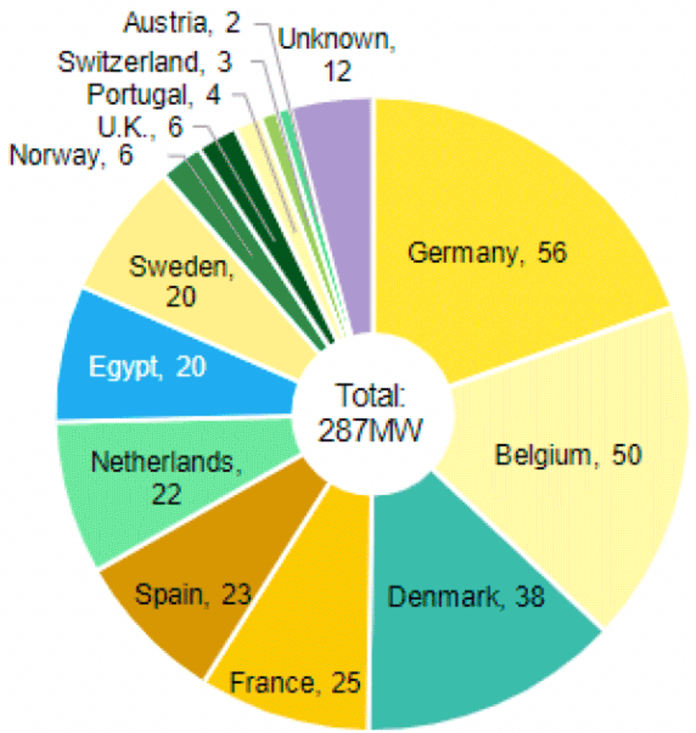
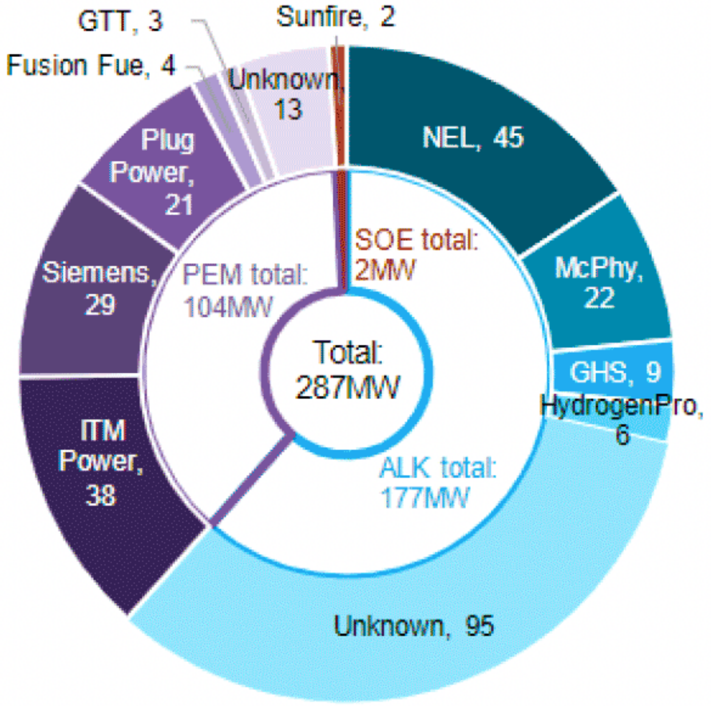
Status of Electrolyser Market

Share of European Manufacturing Capacity – Forecasted Electrolyser Shipments in 2022



Source: BloombergNEF. The 'unknown' slice refers to a 12MW contract to ITM Power, which we estimate in Europe.



Source: BloombergNEF. GHS = Green Hydrogen Systems. GTT = Gaztransport & Technigaz. SOE = Solid Oxide Electrolysis.

Key Message

- **For PEM:** Plug Power, Siemens, and ITM Power are the most prominent manufacturers and suppliers.
- **For AE:** NEL and McPhy are leading manufacturers and suppliers
- **For SOEC:** Sunfire are the dominant manufactures in Europe and globally

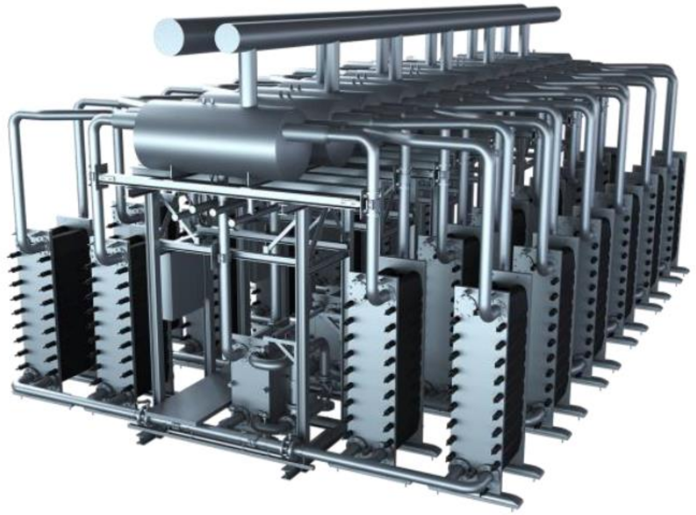
Reference: Bloomberg Analysis – adopted from: https://www.gov.scot/publications/assessment-electrolysers-report/pages/4/

Siemens – PEM Electrolysers

Silyzer 300
Fact Sheet

SIEMENS energy

Hydrogen production	335 kg/h
Plant efficiency (HHV[1])	>75.5%
Power demand	17.5 MW
Start-up time	<1 min, enabled for PFRS[2]
Dynamics in range	10%/s in 0 – 100%
Minimal load	20% single module
Dimension full Mod. Array	15.0 x 7.5 x 3.5 m
Array lifetime	>20 a (Module ≈10 a)
Plant availability	~95%
Demin water consumption	10 l/kg H_2
Dry gas quality[3]	99,9999%
Delivery pressure	Customized



Silyzer 300

The Silyzer 300 PEM system is Siemens's latest generation electrolyser and the largest, most efficient module offering.

References:
https://www.siemens-energy.com/global/en/offerings/renewable-energy/hydrogen-solutions.html
https://www.energyforum.in/fileadmin/user_upload/india/media_elements/Presentations/20210714_h2_large/Siemens_Energy.pdf

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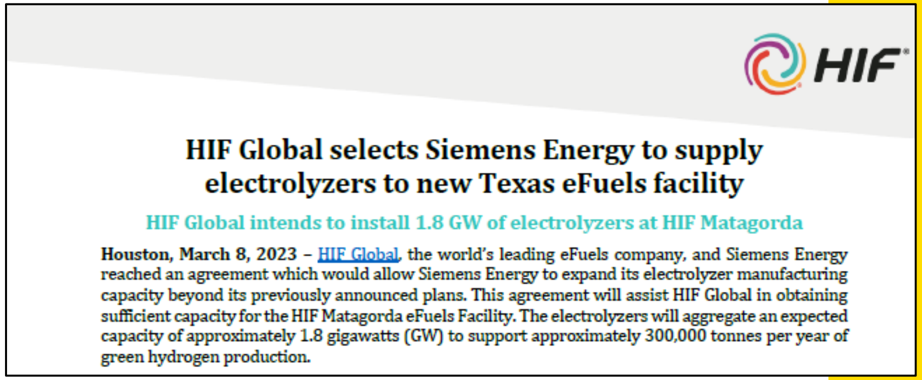
Siemens – PEM Electrolysers

Largest Operating Facility

The largest Silyzer 300 Unit is installed at the Voestalpine Steel Manufacturing plant in Linz, Australia, which aims to generate low-carbon steel.



HIF

HIF Global selects Siemens Energy to supply electrolyzers to new Texas eFuels facility

HIF Global intends to install 1.8 GW of electrolyzers at HIF Matagorda

Houston, March 8, 2023 – HIF Global, the world's leading eFuels company, and Siemens Energy reached an agreement which would allow Siemens Energy to expand its electrolyzer manufacturing capacity beyond its previously announced plans. This agreement will assist HIF Global in obtaining sufficient capacity for the HIF Matagorda eFuels Facility. The electrolyzers will aggregate an expected capacity of approximately 1.8 gigawatts (GW) to support approximately 300,000 tonnes per year of green hydrogen production.

Recent Order

HIF Global has recently placed one of the largest orders for 1.8 GW capacity PEM systems for their project in Texas, US. The plant will produce 0.3 MTPA of H_2 for subsequent e-fuel generation.

Reference:

https://www.siemens-energy.com/global/en/news/magazine/2020/h2future-voestalpine-linz.html

https://hifglobal.com/wp-content/uploads/2023/03/PR-2023.03.08-HIF-and-Siemens-Energy-Electrolyzer-Agreement.pdf

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Plug Power – PEM Electrolyser

EX-4250D System Specifications

The Plug EX-4250D provides up to 4,250 kg/day of high-quality on-site hydrogen.

Instant Load Following
Hydrogen production rate adjusts as electric capacity is available, making this a perfect product for use with grid or renewable energy resources.

Flexible
Operation range covers sub-MW to 10MW.

Scalable
Modular building blocks enable custom-sizing to meet any demand from megawatts to gigawatts.

Corporate Headquarters
968 Albany Shaker Rd,
Latham, NY 12110
518.782.4004

Input	
Stack Power Consumption	Up to 10MW
Voltage & Frequency	4.1 to 34.5kVAC 60HZ (USA) 11 to 33kVAC 50HZ (EU)
Water Consumption	13 liters per kg of H2 produced
Output (Hydrogen Gas)	
Volume	2,000 Nm^3 / hour
Mass	4,250 kg / day
Purity	Up to 99.999%
Pressure	40 barg / 580 psig (w/o compressor)
Operational	
Start Up Time	30 sec warm / < 5 min cold
Average Stack Efficiency	49.9 kWh / kg
Load Following	Instantaneous
Physical / Environment	
Installed Footprint	117.2m^2 / 1,280 ft^2
Ambient Temperature	-20°C to +40°C (wider temperature range optional)
Other	
Compliance / Certifications	ISO 22734, NFPA 2, CE

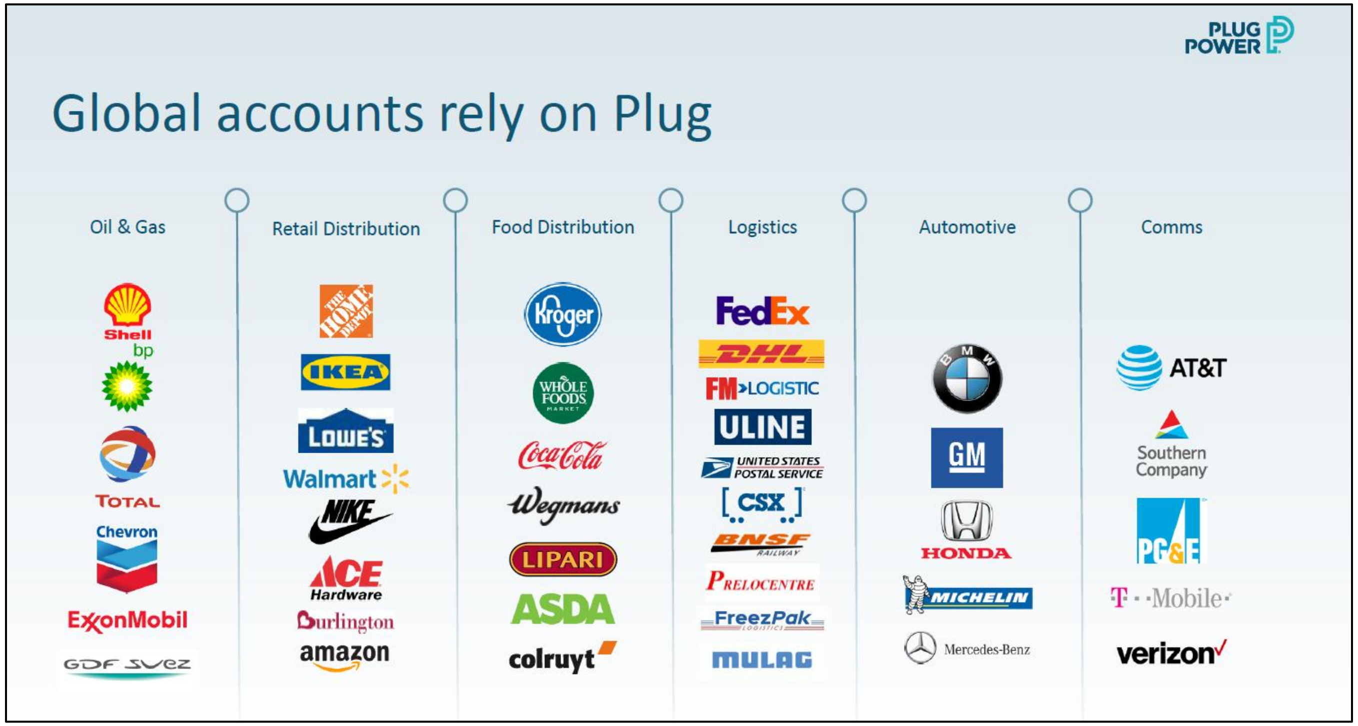
EX-4250D PEM Systems

The EX-4250D is NEL's largest available PEM module.

Plug Power has supplied these units to Amazon, NASA and Boeing.

Reference: https://www.plugpower.com/hydrogen/electrolyzer-hydrogen/

Plug Power – PEM Electrolyser



Plug Power has supplied electrolysers as part of their turnkey fuel cell packages for mobility applications

Plug Power has built a Gigafactory in N.Y. state of the US to supply its fuel cells and electrolyser globally. The facility is expected to have a 2.5 GW/yr capacity once fully operational.

Reference:

https://www.energy.gov/sites/default/files/2022-04/4-H2-AMP%20Workshop-Plug%20Power.pdf
https://www.ir.plugpower.com/press-releases/news-details/2021/Plug-Power-Hosts-Grand-Opening-of-Hydrogen-and-Fuel-Cell-Innovation-Center-Gigafactory-in-Monroe-County-2021-11-12/default.aspx

ITM – PEM Electrolyser

HGAS3SP PEM Electrolyser

Electrolyser technology	PEM
Number of stacks	3
System packaging and size	1x 40ft & 1x 30ft ISO containers and external cooling equipment
Power supply	11kV AC, 3-phase, 50Hz (Standard)
Control	PLC
Hydrogen generation pressure (barg)	30
Hydrogen purity	<5 ppm H_2O & <5 ppm O_2 in the Hydrogen Stream
Maximum hydrogen production approx. (kg/h)	36
Input power at maximum approx. (kW)	2070
Water consumption approx. (litres/kg of hydrogen)	25
Ambient Temperature Range (°C)	-20 to +40

HGAS3SP PEM Systems

The HGAS3SP is ITM's largest available PEM module.

Reference: https://itm-power.com/products/hgas3sp

ITM – PEM Electrolyser

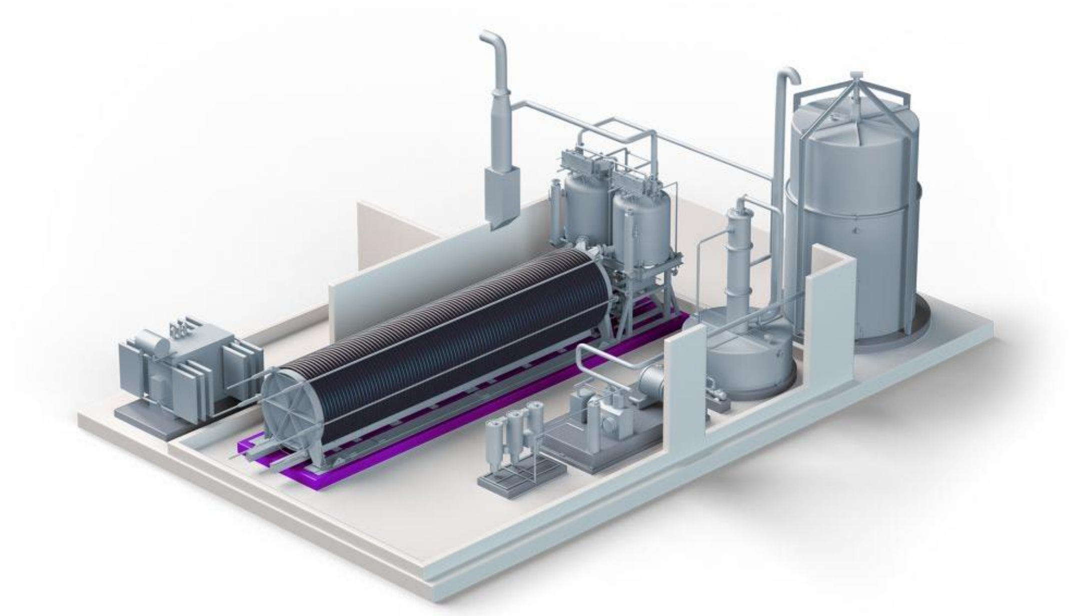
Shell's Energy and Chemicals Park Rheinland

ITM has developed the current 10 PEM electrolyser at the Rheinland Refinery to provide green hydrogen for the refinery process. This facility when the facility became operational in 2021.

Overtime, Shell has expressed interest in collaborating further with ITM to expand the capacity from 10 MW to 100 MW.

Reference: https://www.shell.de/ueber-uns/standorte/rheinland.html

NEL – AE Electrolysers



NEL A Series Electrolyser

The A Series Electrolysers are NEL's latest generation system available in several specs.

Specifications	A150	A300	A485	A1000	A3880
Net Production Rate					
Nm^3/h @ 0°C, 1 bar	50-150 Nm^3/h	150-300 Nm^3/h	300-485 Nm^3/h	600-970 Nm^3/h	2400-3880 Nm^3/h
kg/24 h	108-324 kg/24 h	324-647 kg/24 h	647-1,046 kg/24 h	1,295-2,094 kg/24 h	5,180-8,374 kg/24 h
Production Capacity Dynamic Range	15-100% of flow range	15-100% of flow range	15-100% of flow range	15-100% of flow range	15-100% of flow range
Power Consumption at Stack	3.8-4.4 kWh/Nm^3	3.8-4.4 kWh/Nm^3	3.8-4.4 kWh/Nm^3	3.8-4.4 kWh/Nm^3	3.8-4.4 kWh/Nm^3
H_2 Purity	99.9 ffl 0.1 %	99.9 ffl 0.1 %	99.9 ffl 0.1 %	99.9 ffl 0.1 %	99.9 ffl 0.1 %
H_2 Purity (with Optional Purification)	99.99-99.999 %	99.99-99.999 %	99.99-99.999 %	99.99-99.999 %	99.99-99.999 %
O_2-Content in H_2	< 2 ppm v	< 2 ppm v	< 2 ppm v	< 2 ppm v	< 2 ppm v
H_2O-Content in H_2	< 2 ppm v	< 2 ppm v	< 2 ppm v	< 2 ppm v	< 2 ppm v
O_2 Purity	99.5 ffl 0.2 %	99.5 ffl 0.2 %	99.5 ffl 0.2 %	99.5 ffl 0.2 %	99.5 ffl 0.2 %
Delivery Pressure	1–200 barg	1–200 barg	1–200 barg	1–200 barg	1–200 barg
Dimensions	~150m²	~200m²	~225m²	~350m²	~770m²
Ambient Temperature	5-35° C (41-95° F)	5-35° C (41-95° F)	5-35° C (41-95° F)	5-35° C (41-95° F)	5-35° C (41-95° F)
Electrolyte	25% KOH Aqueous Solution	25% KOH Aqueous Solution	25% KOH Aqueous Solution	25% KOH Aqueous Solution	25% KOH Aqueous Solution

Reference: https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/

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NEL – AE Electrolyser

The NEL electrolyser manufacturing facility in Norway

Systems delivered: **800+**

Production capacity:
500 MW/year → > 2 GW/year

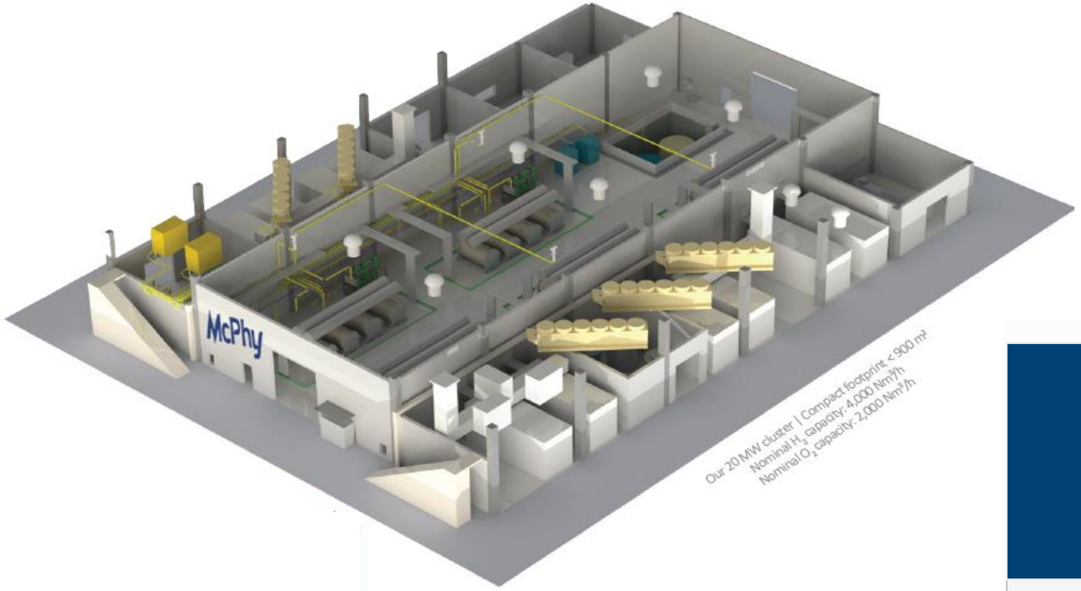
History: **94 years**

NEL's Alkaline electrolyser (4.5 MW) is being used in the HYBIRT Green Steel Project in Sweden.

The plant is still at the demonstration scale and is expected to be fully scaled for commercial operation by 2035.

Reference:
https://nelhydrogen.com/press-release/nel-asa-receives-4-5-mw-electrolyzer-purchase-order-for-fossil-free-steel-production/

McPhy – Alkaline Electrolyser



	Pressure (barg)	Nominal hydrogen flow rate (Nm3/h)	Nominal power (MW)	DC Energy Consumption @ nominal flow rate (kWh/Nm3)
McLyzer 800-30	30	800	ca. 4 MW	4.5

McLyzer AE Systems

The McLyzer System is McPhy's largest available AE Module.

Reference: https://mcphy.com/en/equipment-services/electrolyzers/augmented/

McPhy – AE Electrolyser

GreenH2Atalantic

McPhy will supply a 100 MW Mclyzer unit for 10 KTPA of H_2 at the Sines, Portugal, multi-chemical and fuels facility.

The plant is expected to be constructed in 2024 and operational by 2026 to provide H2 for refinery application and injection into the local gas grid.

Reference: https://mcphy.com/en/achievements/greenh2atlantic/

Longi – Alkaline Electrolyser

Specifications

	LHy-A800	LHy-A1000	LHy-A1500
Net Production Rate (Nm^3/h)	800	1000	1500
Delivery Pressure (barg)	16 (Adjustable)		
DC Power Consumption (kWh/Nm^3)	3.9-4.4		
Rated Power (MW)	4	5	7.5
Production Capacity Dynamic Range	25%-115%		
Purity – with optional purification	99.999%		
O_2-Content in H_2 (ppmv)	<1		
H_2O-Content in H_2 (ppmv)	<1		
Operating Temperature (℃)	90±5		
Lifetime (h)	⩾200,000		
Footprint (m^2)	260	260	280
Ambient Temperature (℃)	5-40		
Electrolyte	30%KOH aqueous solution		

Longi – LHy AE Systems

The LHy AE series is Longi's available AE modules.

Reference: https://itm-power.com/products/hgas3sp

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Sunfire GMBH – SOEC Electrolyser

	HYLINK SOEC
Hydrogen production	
Net production rate	750 Nm³/h
Production capacity dynamic range	5 % ... 100 %
Hot idle ramp time	< 10 min
Delivery pressure	0 bar (g)
Hydrogen purity	max. 99,99 %
Power input and electrical efficiency	
System power rating (AC)	2,680 kW
Specific power consumption at stack level (DC)*	3.3 kWh/Nm³
Specific power consumption at system level (AC)*	3.6 kWh/Nm³
System electrical efficiency**	84 %
Steam input	
Consumption	860 kg/h
Temperature	150 °C ... 200 °C
Pressure	3.5 bar (g) ... 5.5 bar (g)
Other specs	
Footprint***	~ 300 m²
Ambient temperature	-20 °C ... 40 °C

* Power consumption at ambient pressure
** Lower heating value of hydrogen referred to AC power input
*** Average space requirement for a 2.68 MW system comprising all auxiliary systems

HYLINK SOEC

The HYLINK SOEC developed by Sunfire is the world-leading high-temperature electrolysis (one of the only systems with high commercial readiness level)

Reference: https://itm-power.com/products/hgas3sp

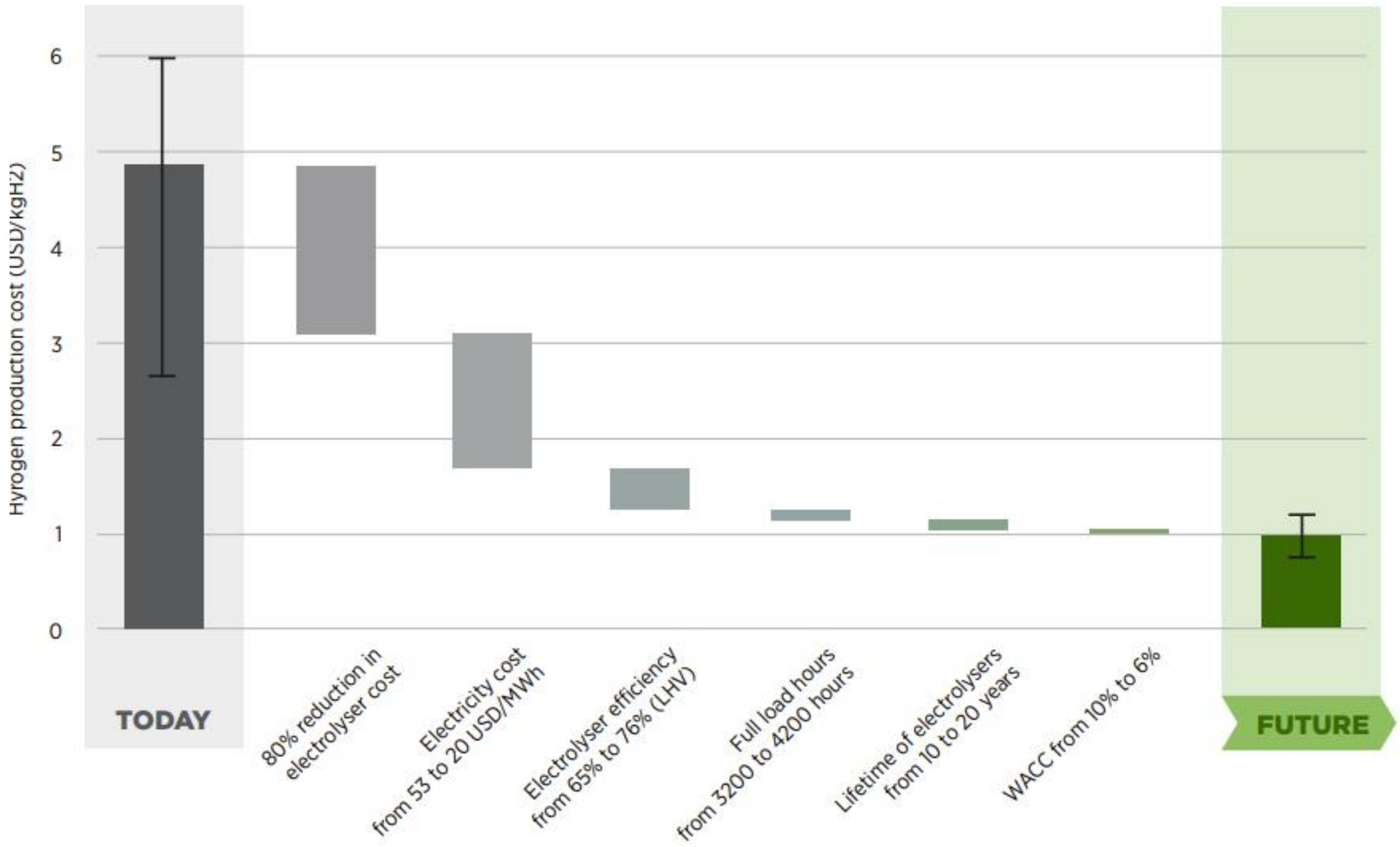
Sunfire GMBH – SOEC Electrolyser

E-CO_2Met – Electricity & CO_2 to Methanol

Sunfire is supplying its SOEC for application in the e-CO2Met project in Germany.

In the project coordinated by TotalEnergies, methanol will be produced by the conversion of green hydrogen and CO2. Fraunhofer CBP and TotalEnergies are planning a pilot plant that will be set up in the new Fraunhofer Hydrogen Lab at the Leuna Chemical Park.

Reference: https://www.igb.fraunhofer.de/content/cbp/en/reference-projects/e-co2met.html



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

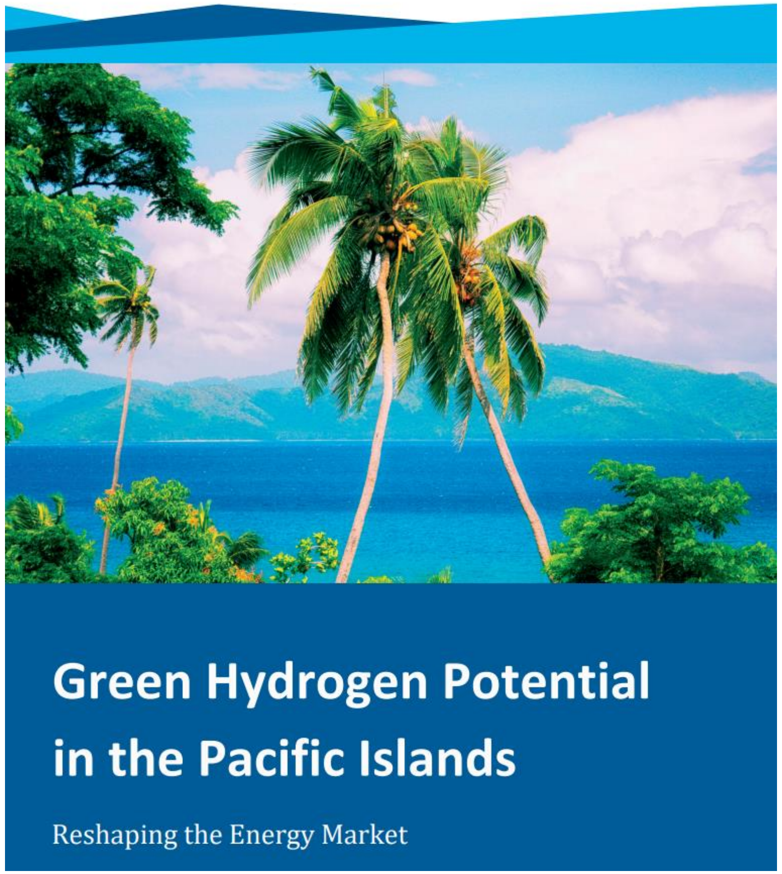
Summary

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or $NaHCO_3$ 1$molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (*e.g.* LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bara]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/KgH_2]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only, > 1 MW) [USD/kW_{el}]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system, >10 MW [USD/kW_{el}]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

Pacific Green Hydrogen Project

- The German New Zealand Chamber of Commerce's (GNZCC) regional responsibility includes seven countries in the Pacific – Fiji, Samoa, Tonga, Cook Islands, Kiribati, Niue, and Tuvalu.
- Roles of the GNZCC include:
  - ➢ Business Intelligence
  - ➢ Consulting Services for Market Entry
  - ➢ Sourcing for Business Partnerships
  - ➢ International Trade Fair Participation
- The Pacific Green Hydrogen Project aims to connect small-to-medium German enterprises that manufacture hydrogen technologies for an off-grid application in the Pacific Islands.
- Excess energy from renewable energy plants is stored in the form of hydrogen and oxygen by electrolysis. This green hydrogen can be used to generate electricity with the help of a fuel cell.



Reference: https://neuseeland.ahk.de/en/services/projects/pacific-green-hydrogen-project

Renewable H_2 to Palau

- Queensland-produced renewable hydrogen will be exported to the Republic of Palau from 2023 as part of a collaboration between Sojitz Corporation, Nippon Engineering Consultants and CS Energy.
- The project will assess the potential of renewable hydrogen for use in fuel cells and marine vessels in Palau to reduce its reliance on fossil fuels and has received subsidies from Japan's Ministry of the Environment.
- Renewable hydrogen for the project will be supplied from CS Energy's Kogan Renewable Hydrogen Demonstration Plant, which will be built on the Western Downs and produce renewable hydrogen from behind-the-meter solar energy.

Figure: Kogan renewable hydrogen plant (1 MW electrolyser, 2 MW solar PV farm).

Reference: https://www.csenergy.com.au/news/queensland-renewable-hydrogen-to-power-pacific-islands-demonstration-project

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HDF Project in Fiji

- The HDF Energy Australia team is currently developing a green hydrogen project on Fiji's Viti Levu island.
- The plant could generate 6 MWe of electricity during the day and evening, and 1.5 MWe throughout the night.
- HDF develops, finances, builds and operates multimegawatt industrial power generation infrastructures.
- HDF marketed the Renewstable® power plants, which capture intermittent renewable energy and store it massively in the form of hydrogen. HDF Energy currently has around ten Renewstable® projects in the advanced development phase in several countries.

Figure: Concept images of the solar PV farm and the hydrogen generation, storage, and fuel cell facilities.

Reference: https://www.hydrogenpower-fiji.com/

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Hydrogen Use in New Caledonia

- New Caledonia is targeting the use of hydrogen in transport and industry. New Caledonia is hoping to attract public-private partnerships, French and EU subsidies, and an €7m grant from France Hydrogen.
- The Caledonian Energy Agency (ACE) is studying how to develop a domestic hydrogen sector and is supporting economically viable pilot projects.
- The ACE estimates there are sufficient solar and water assets to allow this production.
- Prony Resources, Engie NC and Gazpac all have hydrogen projects in the works.

Figure: The Helio Boulouparis 2 Solar Park (16 MW, 10 MWh ESS).

Reference: https://www.mfat.govt.nz/en/trade/mfat-market-reports/new-caledonia-moves-towards-renewable-energy-september-2022/