Masterclass session

Green hydrogen production value chain

Massimiliano A. Cervo, Sr. Consultant

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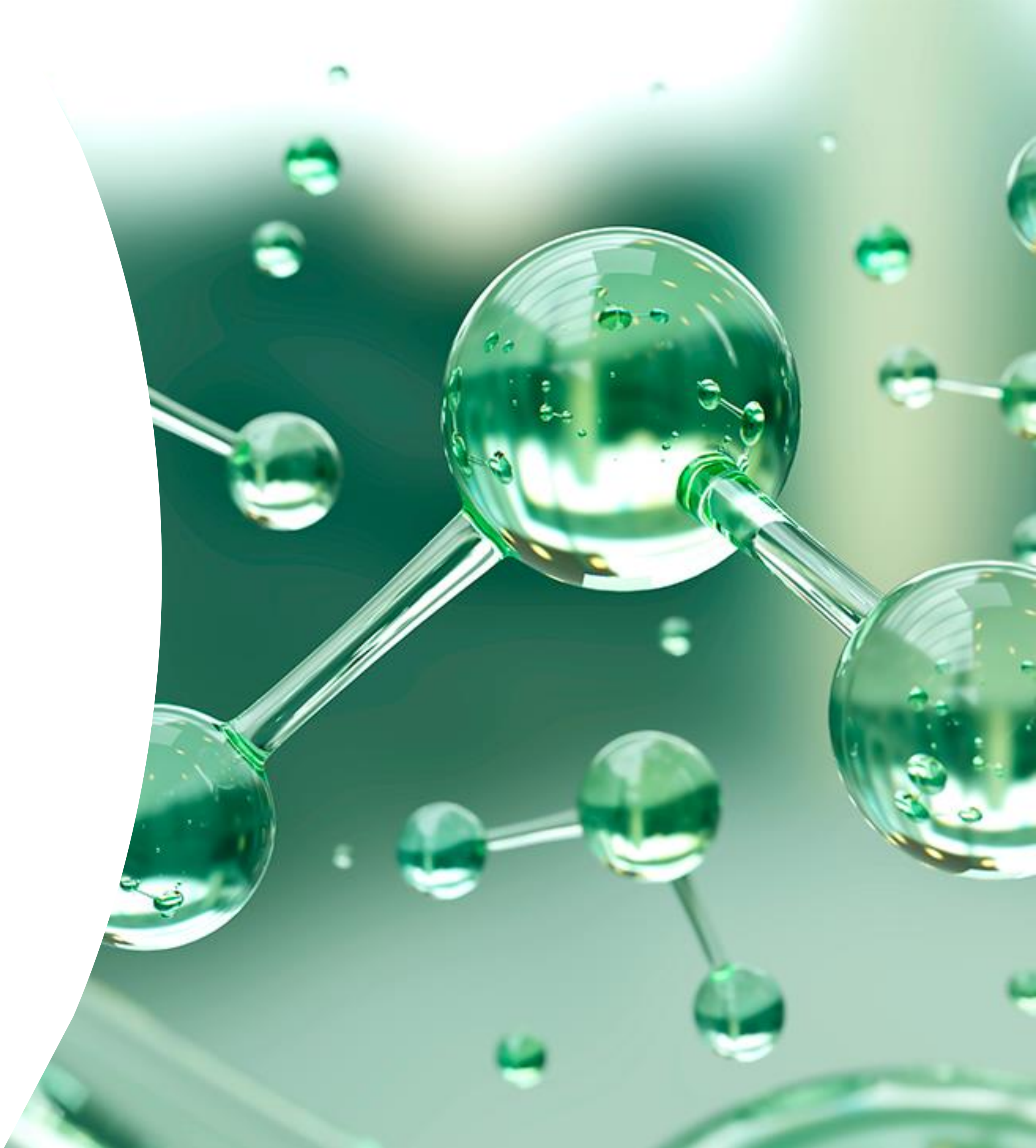
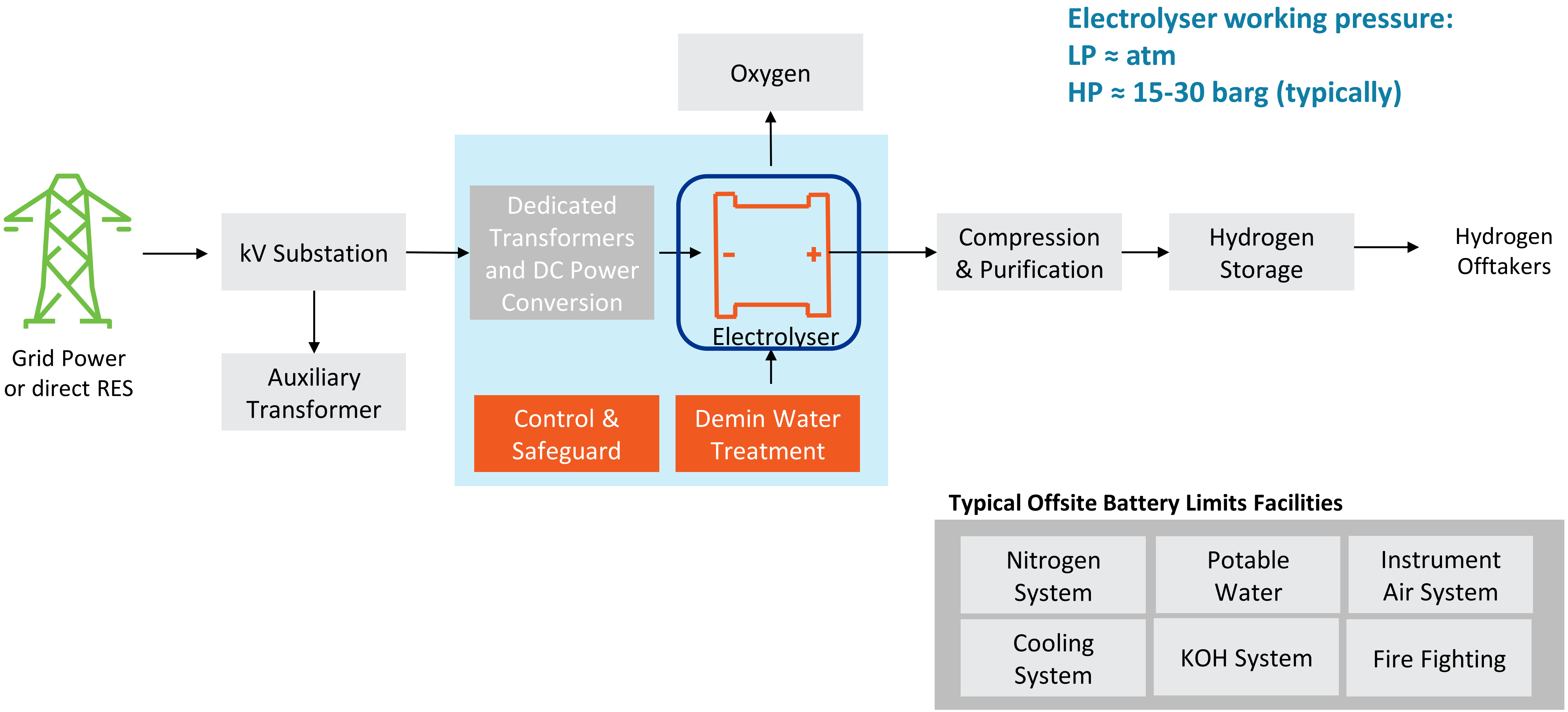


Agenda

1. Introduction of technologies
2. Pros & Cons Alkaline vs PEM
3. Technology readiness level
4. Financial Assessment
5. Manufacturing capacity; future & planned
6. Delivery times
7. Standards and certification

1. Introduction of technologies

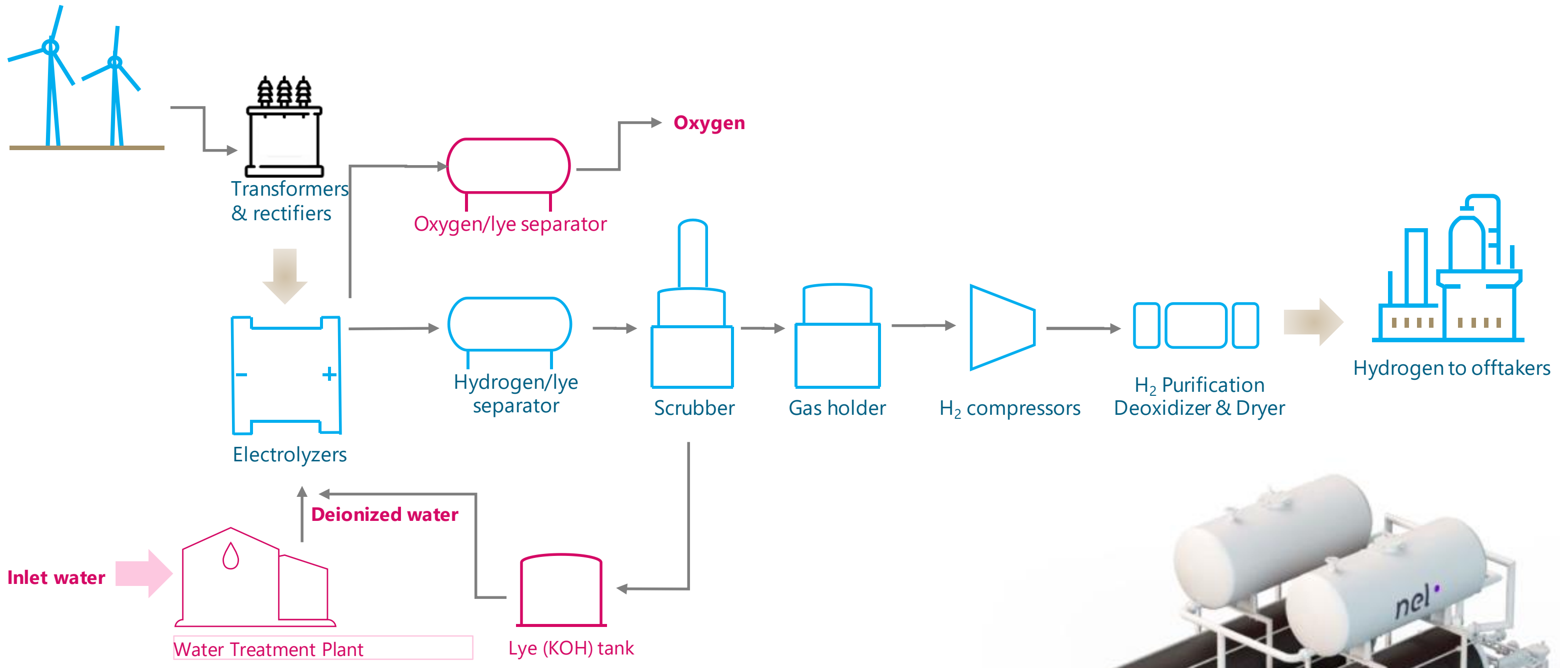
1.1 Main Systems in a Green Hydrogen Production Facility

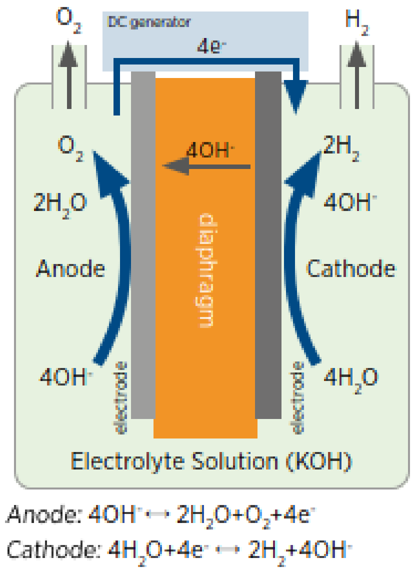


1. Introduction of technologies

1.2 Alkaline Electrolysis Overview

Alkaline electrolyser technology is mature and ready to be deployed at GW scale. It has the ability to adapt to variable available power, but its operation is not as flexible as PEM; it may require a few minutes to go from 10% to 100% load. Currently, this technology is more efficient than PEM. Alkaline technology currently operates with a current density in the range 4-12 kA/m^2.



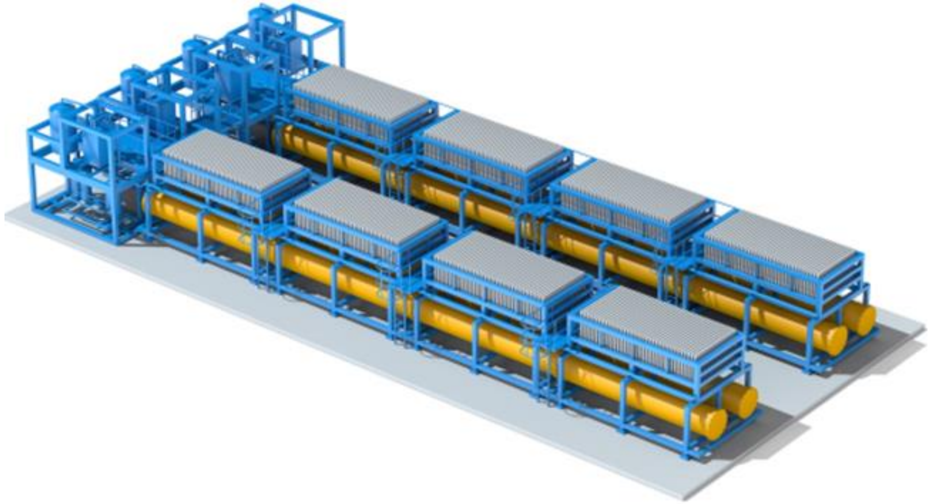


Source: Nel

1. Introduction of technologies

1.3 Alkaline Stack

Typical alkaline cells consist of a separator or membrane, the electrodes, bipolar plates and the structural rings and flanges. The stack is formed by the combination of many cells.

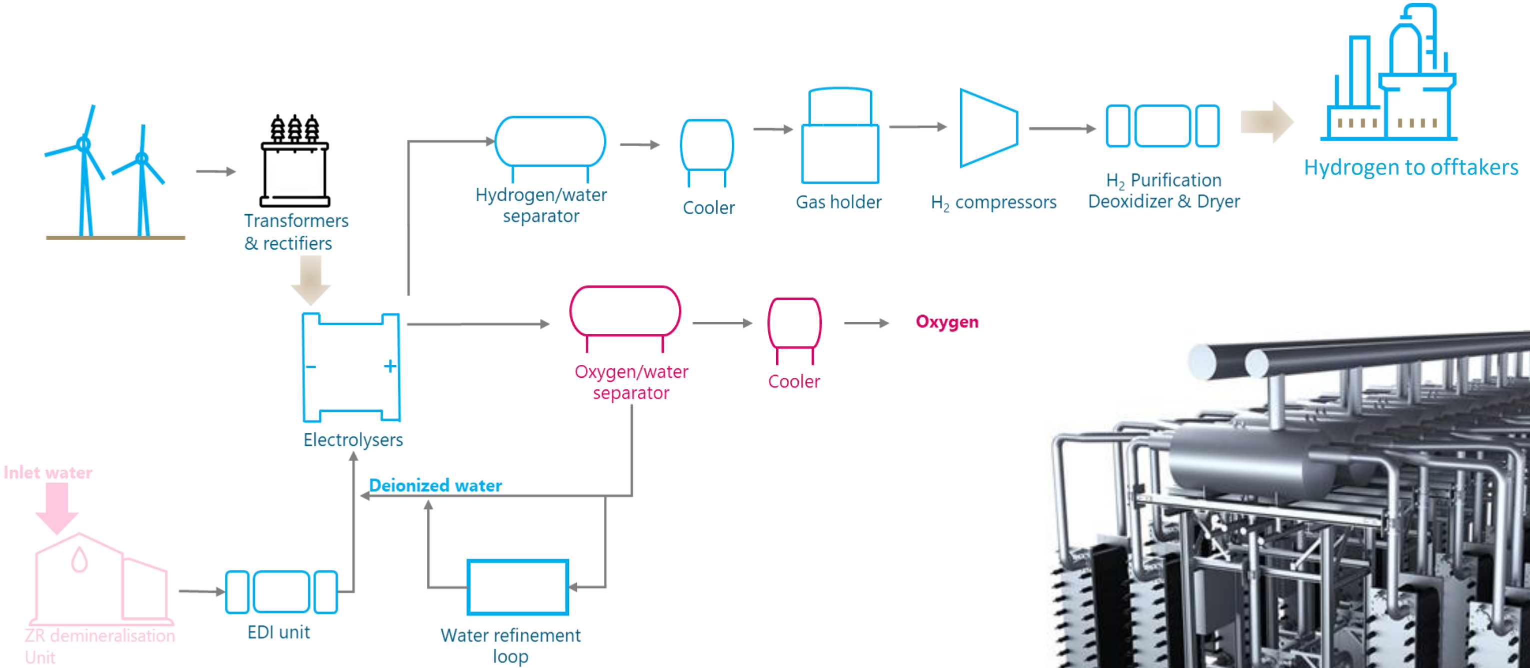


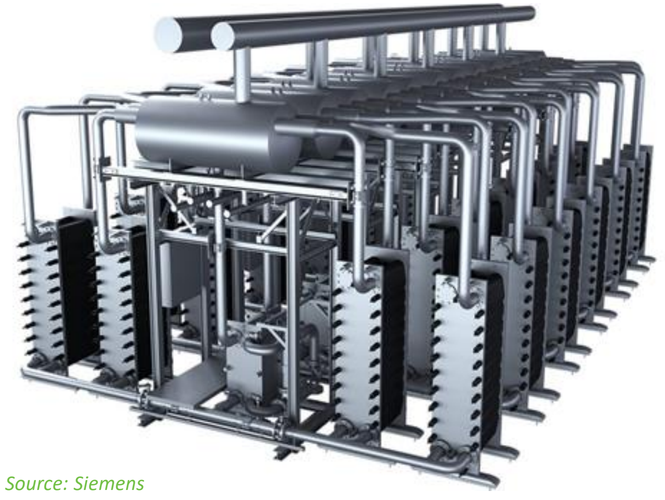
Source: Thyssenkrupp

1. Introduction of technologies

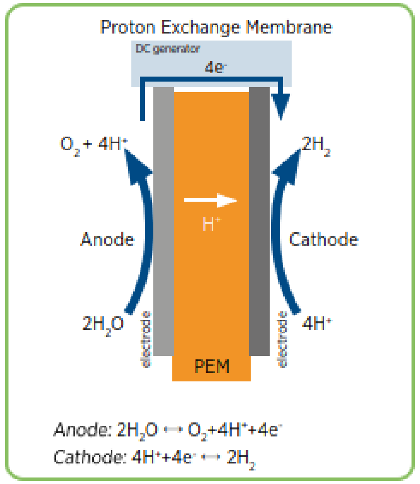
1.4 PEM Electrolysis Overview

Proton-exchange membrane (PEM) electrolyser technology is increasing the matureness level and ready to be deployed at hundreds of MW scale. It has the ability to adapt to variable available power in a flexible way; it may require less than two minutes to go from 10% to 100% load. PEM technology currently operates with a current density in the range 30 kA/m^2.





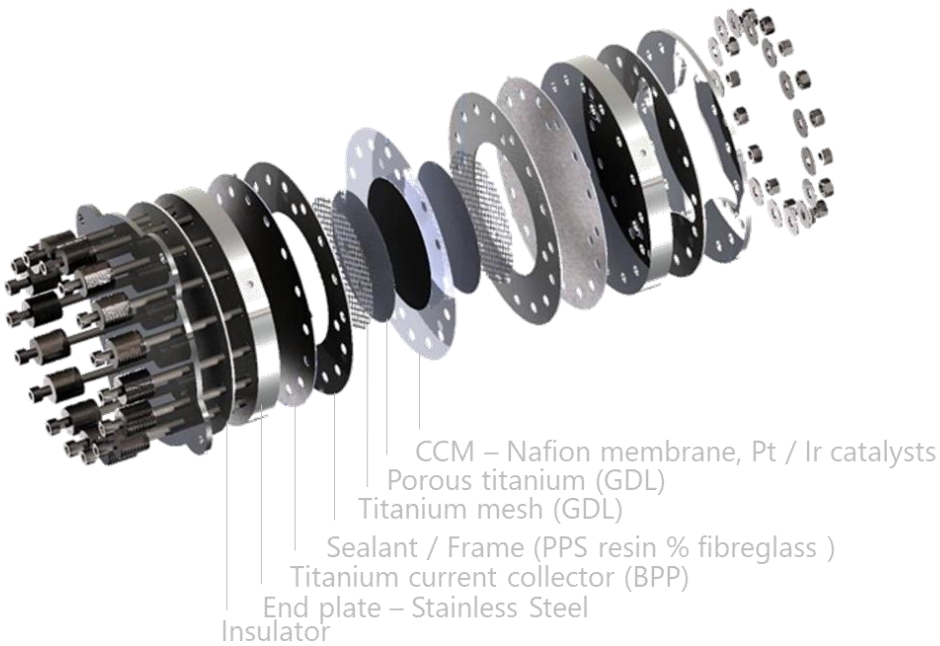
Source: Siemens

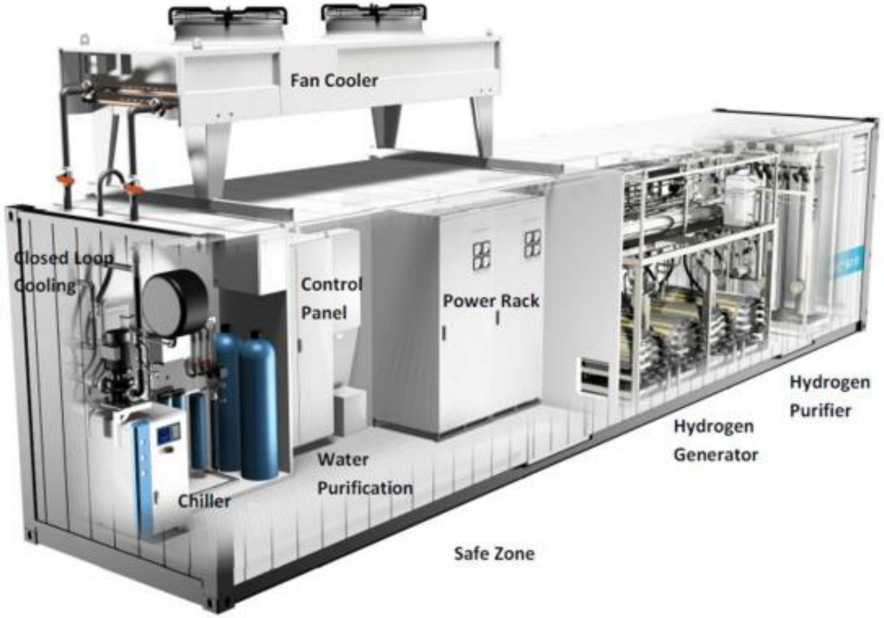


1. Introduction of technologies

1.5 PEM Stack

Typical PEM cells consist of CCM (catalyst coated membrane), gas diffusion layers, bipolar plates and the structural rings and flanges. The stack is formed by the combination of many cells.





Source: Accelera

1. Introduction of technologies

1.6 Pressurised Electrolysis

PROS:

1. Lower cost of water pumping than gas compression → better overall production
2. Pressure decreases bubbles size and thus improves the gases dissolution within electrolyte, reducing ohmic losses.
3. Pressure reduces the water saturated in hydrogen.

CONS:

1. Safety concerns: compliance with DEP requirements and ATEX directive as Hazardous Areas. In the event of a leak vast amounts of hydrogen will be released.
2. Lower technological development, less reliable and higher CapEx (this is improving nowadays).
3. Alkaline tech: pressure increases the gas diffusivity across diaphragm, which reduces gas purity and hence increases deoxo and dryer costs. Additionally, due to this purity decrease, there is a higher risk that oxygen content in hydrogen reaches the flammable range.
4. Pressurised AWE stacks must be returned to OEM to ensure integrity of pressure containment whilst atmospheric AWE maintenance can be performed on site.
5. PEM tech: pressure makes necessary to increase the membrane thickness which reduces the efficiency. Lower efficiency commensurates with higher operating cost, since OpEx is dominated by electricity cost.

2. Pros & Cons Alkaline vs PEM

2.1 Water Electrolysis Technology Comparation

		Alkaline	PEM
Annual Degradation (%/year)		0.5-1.2	1-2
Lifetime (thousand hours)		80	80
Plot space		100%	≈10-30% lower than alkaline*
Electrolyte		KOH (25-30% aq)	Solid polymer membrane
Flexibility of Operation		High	Very High
Required demi water (l/kgH2)		<10	<10
Plant CapEX		100%	≈30% higher than alkaline**
Stack Electrical Efficiency	**(%, HHV)**	73-80	68-75
	(kWh/kg H_2)	48-54	52-58
Advantages		▪ Well-established ▪ Large-scale ▪ Long-term stability ▪ Low CAPEX	▪ High current density ▪ Compact system ▪ Dynamic operation ▪ Significant improvement potential
Disadvantages		▪ Low current density ▪ Corrosive electrolyte ▪ Slow dynamics ▪ Gas permeation ▪ Lye management	▪ High degradation ▪ High membrane & electrode cost ▪ Noble materials ▪ Low efficiency ▪ Iridium

Based on IRENA analysis and Advisian/Worley experience.
**Depending on size.*
***For capacities around 100MW, a 40% higher CapEx in the electrolysis package is expected. This difference can be diluted with the size of the plant, additional configuration as hydrogen storage, etc.*

2. Pros & Cons Alkaline vs PEM

2.2 Functional Specifications Comparison

	Alkaline		PEM	
Part	**Assumptions**	**Notes**	**Assumptions**	**Notes**
Membrane	M-PBI	Cast membrane	Nafion 117 (purchased)	PFSA (PEEK, PBI)
Electrodes	Raney-Nickel	PVD + Leaching to reach porosity	Pt-Price = USD 988 per oz As of 30/11/2022	Anode= 7 g/m2 (Pt) Cathode= 4g/m2 (Pt-Ir)
Porous layer	Pure Nickel sheets Price: USD 0.031 per kg	Corrosion resistance in alkaline solutions	Sintered porous titanium Ti price = USD 9.00 per kg	Porosity = 30%
Frame	PPS-40GF or PEEK	Injection molding	Sceen printed or PEEK seal	Seal is for MEA bonding
Plates	Nickel plates	Surface treatment of high purity sheets	Stainless Steel 316 L	Coated through plasma nitriding

2. Financial Assessment

2.3 Tehnology differences

Polymer Electrolyte Membrane (PEM)

Strengths
- Has very fast response to electricity supply network changes
- May require less than 2 minutes to go from 10% to 100% load

Weaknesses
- Has higher OPEX and CAPEX than AWE (alkaline) electrolysis
- Less mature technology than alkaline

Alkaline Water Electrolysis (AWE)

Strengths
- Demonstrated at large scale
- Overall system CAPEX currently lower than alternatives
- More efficient than PEM

Weaknesses
- Low system efficiency and can be slower to respond to electricity supply variations
- May require a few minutes to go from 10% to 100% load

Solid Oxide Electrolyser (SOCE)

Strengths
- Has potential for greater efficiency if cheap heat is available

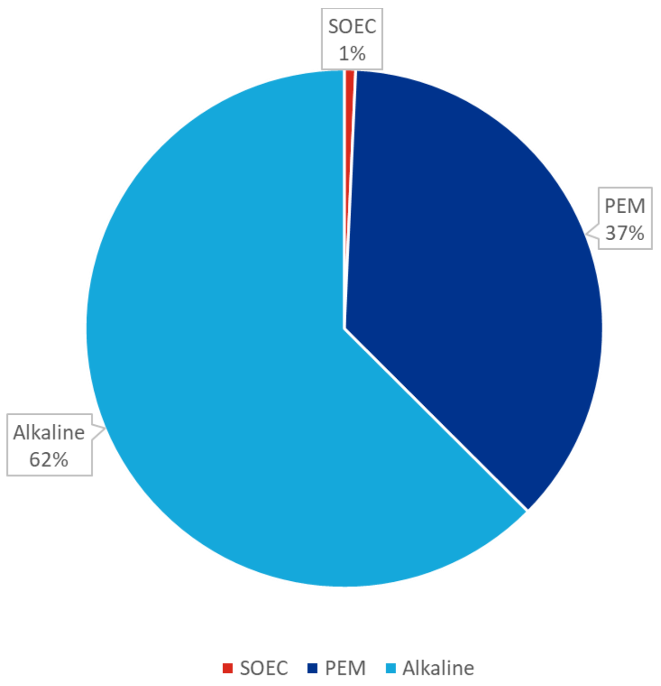
Weaknesses
- Currently not yet developed at commercial scale

Anion Exchange Membrane (AEM)

Strengths
- Can eliminate the need for alkaline solution and not require PGM electrodes

Weaknesses
- Currently not yet developed at commercial scale

Installed capacity share



3. Levels of maturity between Alkaline and PEM technology

3.1 Technology readiness level and costs

Technology	TRL (IEA)	TRL*	CRI*
Atmospheric Alkaline	9	9 (up to 20 MW) 8 (above 20 MW)	4
Atmospheric PEM	9	9 (up to 20 MW) 7 (above 20 MW)	3
Pressurized Alkaline	-	6-7	
Pressurized PEM	-	6	

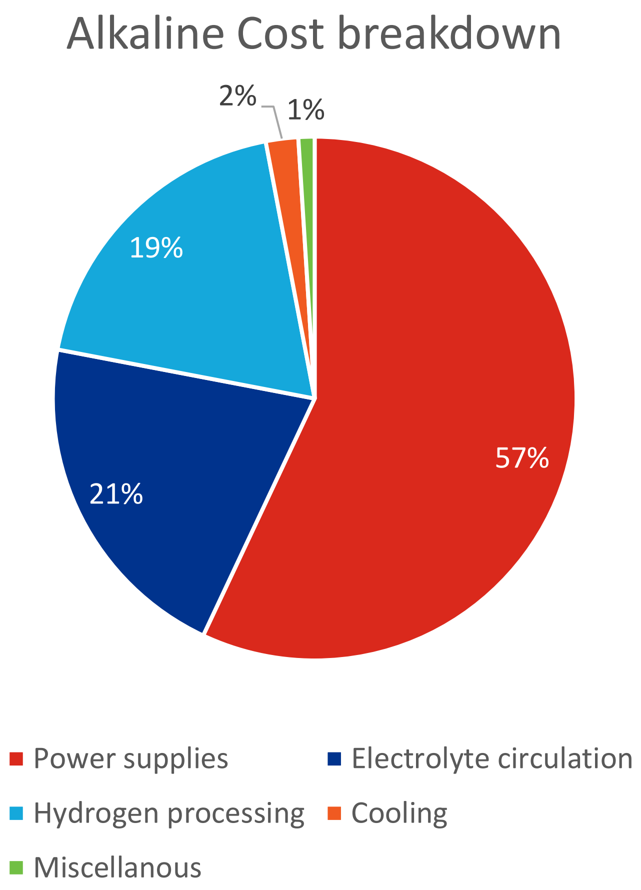
**TRL and CRI values have been assigned according to Worley's experience and criteria obtained by direct participation in several OEM tabulation processes, information gathered from specific vendor and project developer's public data.*

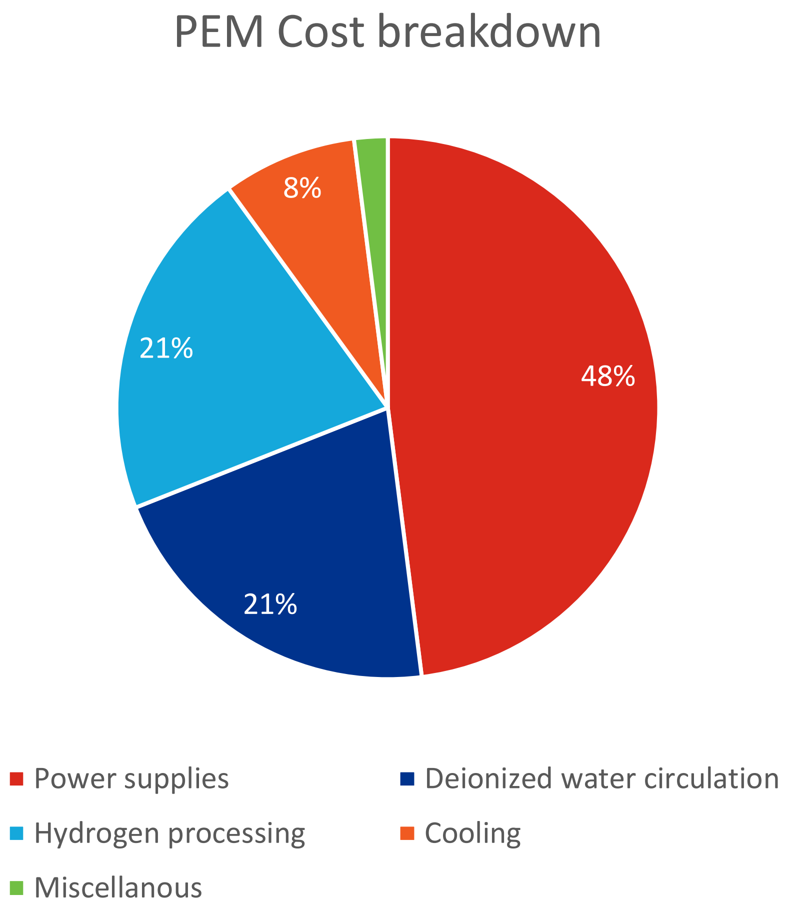
Technology	CapEx (USD/kW)
Electrolysis (Atm. ALK)	550-750
Electrolysis (Atm. PEM)	800-1100
Electrolysis (Press. ALK)	700-900
Electrolysis (Press. PEM)	1,200-1,500

** Based on Worley internal database, 2022*

4. Financial Assessment

4.1 Balance of Plant for Alkaline and PEM

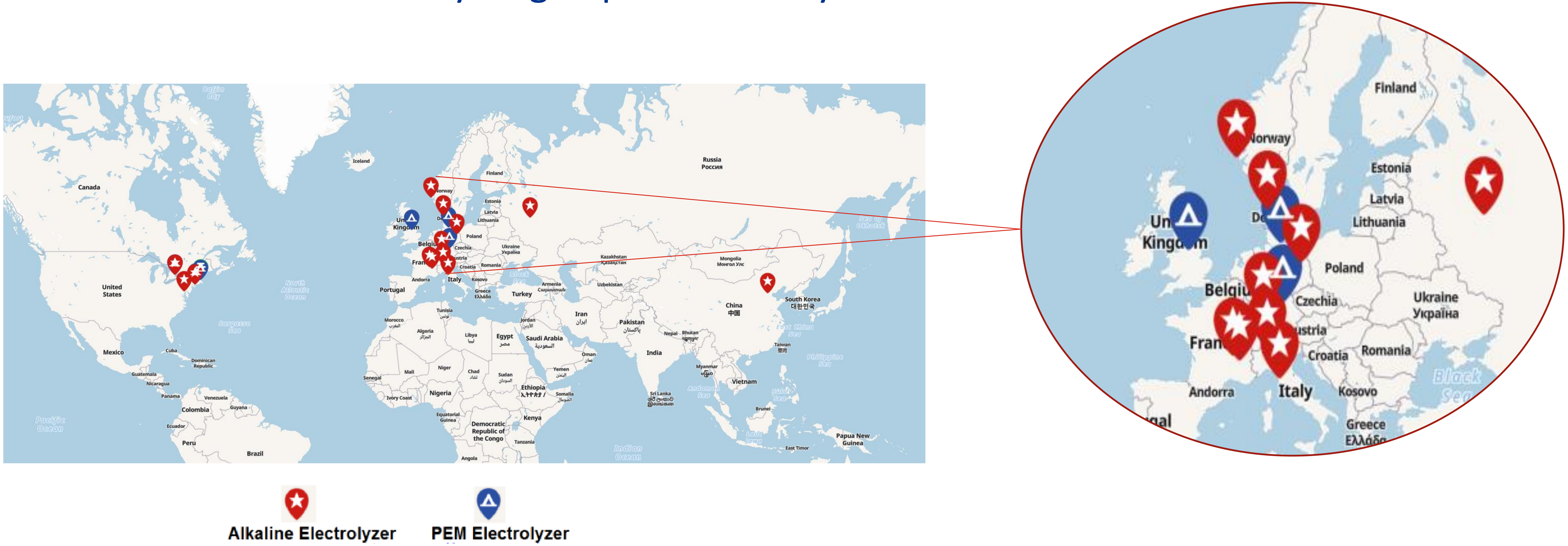




Note: These are BoP costs additional to the electrolyser purchase. Using as a reference quotes for a 100 MWe plant.

5. Manufacturing capacity; future & planned

5.1 Manufacturers of Hydrogen production systems

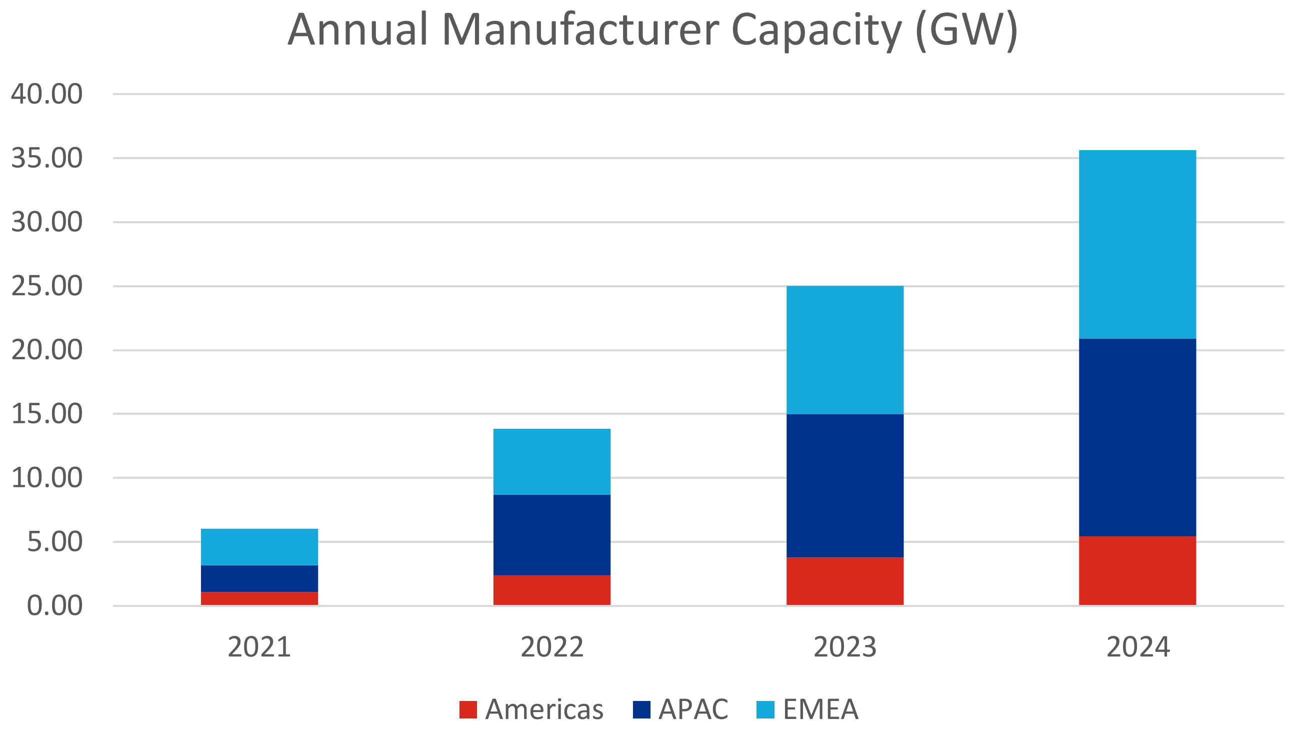


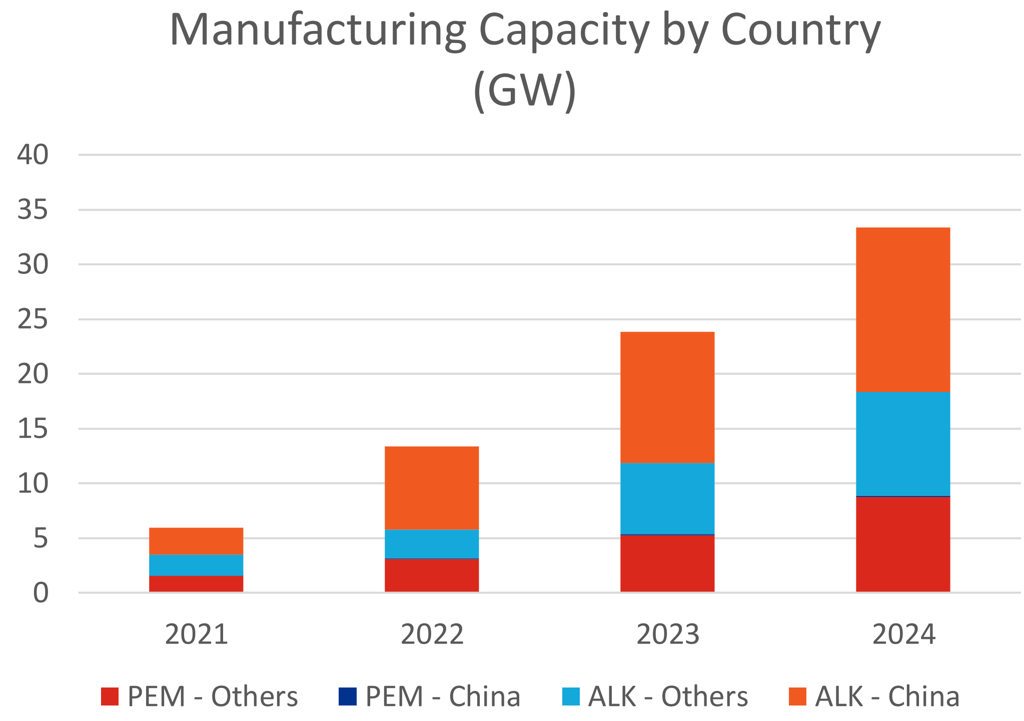
Source: Maphub

Note: Only public available companies are mapped.

5. Manufacturing capacity; future & planned

5.2 Global electrolyser supply chain capability





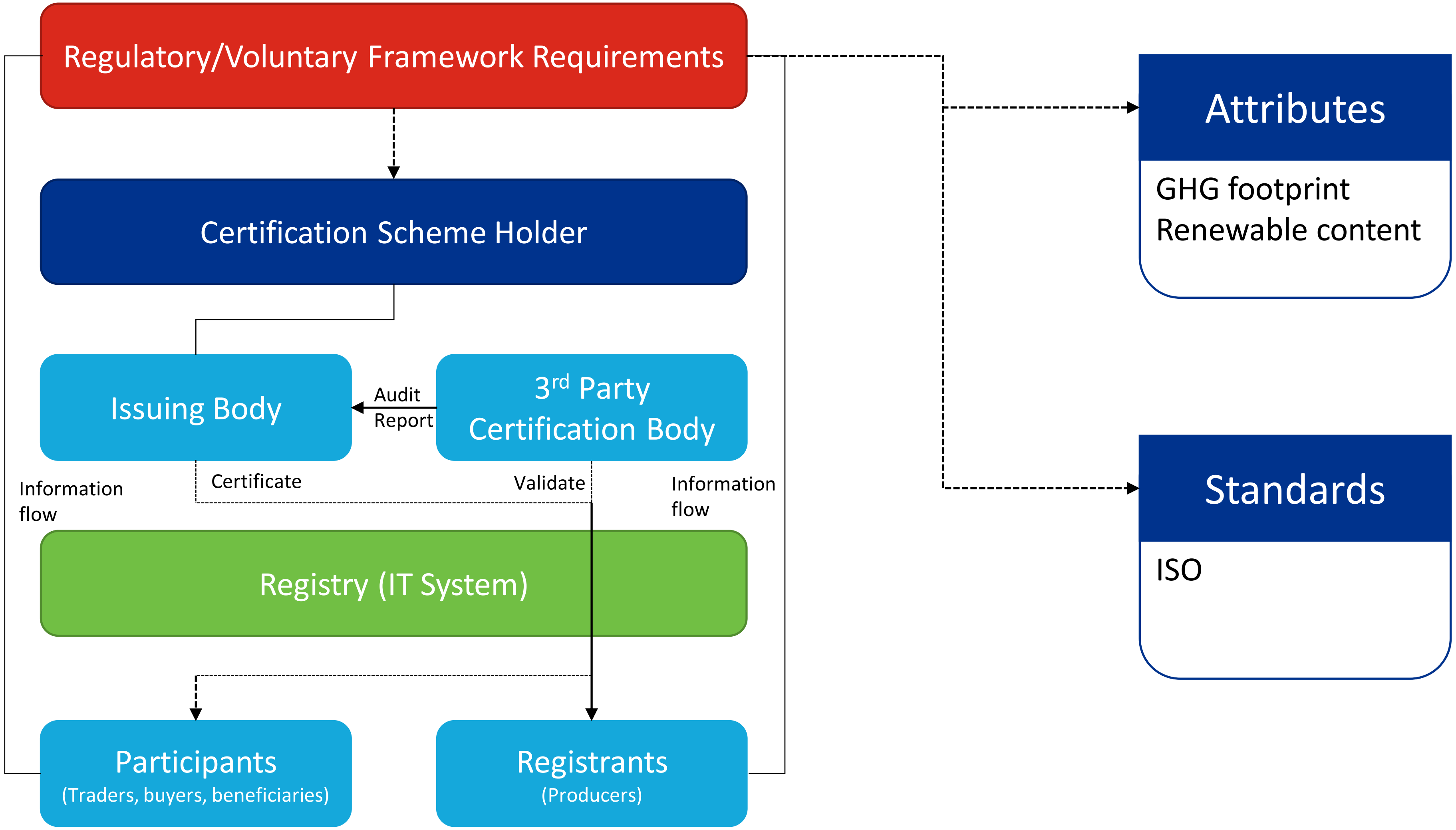
Source: Bloomberg NEF 2022

6. Delivery Times

Total delivery time: above 24-30 months

7. Hydrogen certifications

7.1 Certification process



7. Hydrogen certifications

7.2 Recognized certification systems

	Low carbon fuel standard	CertifHy	TUV SUD
Year of establishment	2011	2019	2011
Public/Private	Public	Private	Private
Geographic scope	USA	Europe, extending internationally	Germany focused, applicable internationally
Objective	Compliance with legal requirements	Consumer disclosure & legal requirements of EU	Consumer disclosure
Governance	California Air Resources Board	Stakeholder platform	TUV SUD
Verification	Third-party for pathways, otherwise carried out by CARB	Certification bodies (TUV SUD recognized so far)	TUV SUD or other certification bodies
Emission quantification	CI standard	Guarantee of origin scheme for green & low-carbon	Green hydrogen standard

7. Hydrogen certifications

7.3 Requirements for implementation in Namibia

1
- Definition
  — Develop comprehensive national standards for hydrogen across supply chain
  — Define and standardize low-carbon definition for green hydrogen and derivatives

2
- Certification
  — Implement guarantees of origin certification scheme and tracking system
  — Certification scheme should be aligned with the country's export targets

3
- Regulations
  — Incentivize the adoption of International Sustainability and Carbon Certification (ISCC)
  — Develop hydrogen certification within Public-Private-Partnerships

4
- Adoption
  — Fiscal incentives could accelerate technology adoption and scale-up of pilot projects, such as tax credits
  — Labelling standards and requirements of hydrogen derivatives will accelerate the implementation of certification schemes

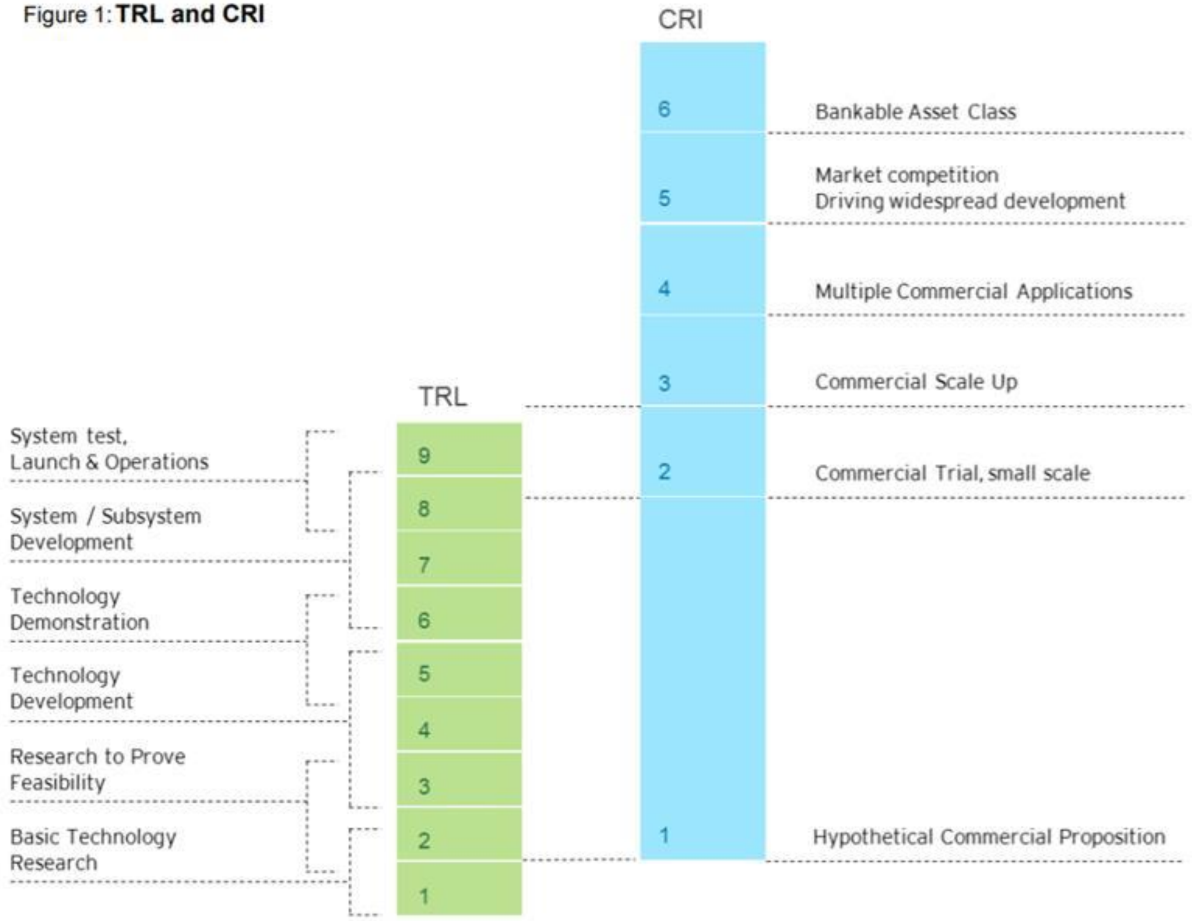
5
- Tracking
  — Develop an auditing figure for the monitoring and guarantee of origin of feedstocks for H2 production
  — Certification mandates will maximize the value of derivatives

Q&A

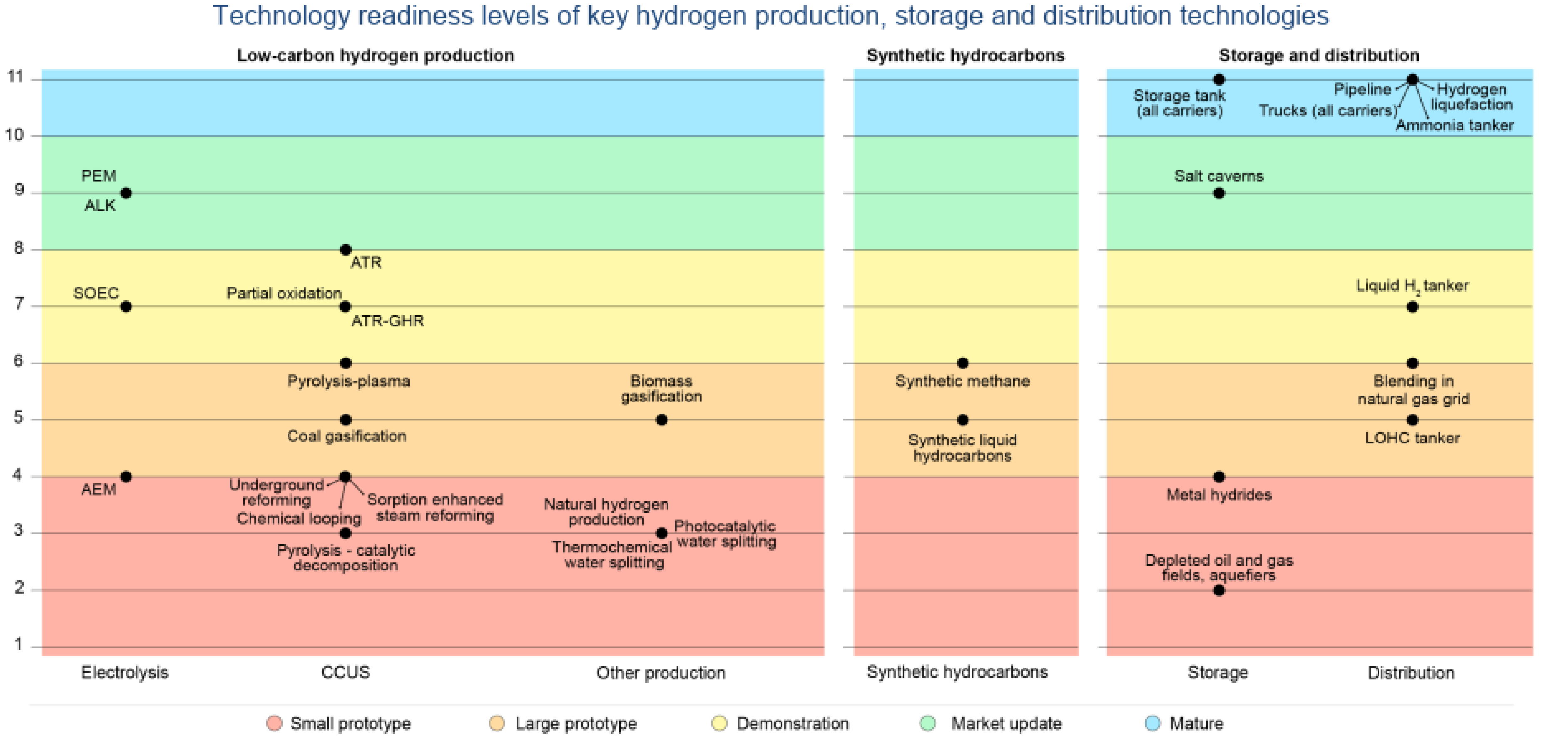
2. Water Electrolysis Technology Assessment

TRL & CRI

Figure 1: **TRL and CRI**



Several hydrogen technologies not yet commercially available



Notes: AEM = anion exchange membrane. ALK = alkaline. ATR = autothermal reformer. CCUS = carbon capture, utilisation and storage. GHR = gas-heated reformer. LOHC = liquid organic hydrogen carrier. PEM = polymer electrolyte membrane. SOEC = solid oxide electrolyser cell. Biomass refers to both biomass and waste. For technologies in the CCUS category, the technology readiness level (TRL) refers to the overall concept of coupling these technologies with CCUS. TRL classification based on Clean Energy Innovation (2020), p. 67.

Source: IEA (2020), ETP Clean Energy Technology Guide.

2. Water Electrolysis Technology Assessment

Comparison of Technologies

Some of the critical parameters that define an electrolysis plant, such as the specific electricity consumption, the CAPEX, an indicative footprint and typical construction times and lifetimes have been listed below.

	Alkaline	PEM	Solid Oxide
Annual Degradation (%/year)	1-1.5	1-2	4-8
Lifetime (years)	30	30	TBD
Stack materials	Zirfon, Nickel	Nafion, Platinum, Iridium	Ceramic materials
Operational parameters: cell temperature, operating pressure, current density	55-90 ºC Atmospheric/30 barg 4-12 kA/m^2	55-90 ºC Atmospheric/30 barg 30 kA/m^2	800 ºC Atmospheric/25 barg 10-30 kA/m^2
Flexibility of Operation	High	Very High	Low

2. Water Electrolysis Technology Assessment

Comparison of Technologies

Some of the critical parameters that define an electrolysis plant, such as the specific electricity consumption, the CAPEX, an indicative footprint and typical construction times and lifetimes have been listed below.

	Alkaline	PEM	Solid Oxide
Minimum Stable Load (%)	10	10	Unknown at large scale
Start-up Time from Cold (minutes)	30-60	5-10	Depends on the steam source
Ramp Up / Down Time **(10-100% and vice versa, minutes)**	2-10	0.5	Depends on the steam source
Demin Water Consumption **(l H2O/kg H2)**	10	10	10
Required demi water quality (µS/cm)	<5	<1	1-5
Oxygen production **(tonne O_2/tonne H_2)**	8	8	8

2. Water Electrolysis Technology Assessment

Comparison of Technologies

Some of the critical parameters that define an electrolysis plant, such as the specific electricity consumption, the CAPEX, an indicative footprint and typical construction times and lifetimes have been listed below.

	Alkaline	PEM	Solid Oxide
CAPEX	Low	30-40% higher than Alkaline	Unknown at large scale
Indicative Footprint **(ha/100MW electrolyser)**	1.5	1	Unknown at large scales
Largest Project **(Power, location, application)**	25 MW, Malaysia, Silicon	20 MW, Canada, Industrial/mobility	kW Range, Testing

2. Water Electrolysis Technology Assessment

Comparison of Technologies

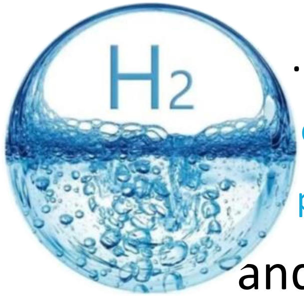
Some of the critical parameters that define an electrolysis plant, such as the specific electricity consumption, the CAPEX, an indicative footprint and typical construction times and lifetimes have been listed below.

	Alkaline	PEM	Solid Oxide
Advantages	Well-stablished Large-scale Long-term stability Low CAPEX	High current density Compact system Dynamic operation Significant improvement potential	Potential higher efficiencies Integration with exothermic processes Non-noble materials
Disadvantages	Low current density Corrosive electrolyte Slow dynamics Gas permeation	High membrane and electrode cost Noble materials Low efficiency	Demo scale Unstable electrodes Brittle ceramics Sealing issues

Performance

Theoretically LP alkaline electrolysers envisage a better stack efficiency and H_2 purity due to:

- Pressure decreases gases bubbles size and, despite slightly reducing the ohmic losses, consequently…



… pressure makes gases being more dissolved in the electrolyte with following implications:

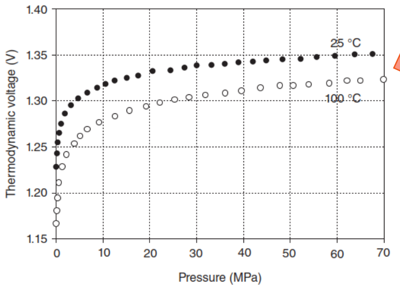
diffusivity/crossover across diaphragm → lower H_2 and O_2 purity

performance of gases/lye separators → electrolyte returns contaminated with gases

and pressure difficulties the bubbles separation when formed in the electrodes → lower efficiency

Nevertheless, pressure decreases the water saturation pressure so hydrogen will exit the electrolysers with a lower moisture content specially beneficial in case of having a HP compression stage.

No conclusions with regard to degradation, OEM dependent.



Overall performance:

Lower cost of water pumping than gas compression (especially at low pressure) → potential better overall performance depending on OEM selected and compression cost impact in TIC according to plant capacity, storage, offtake pressure level, etc.

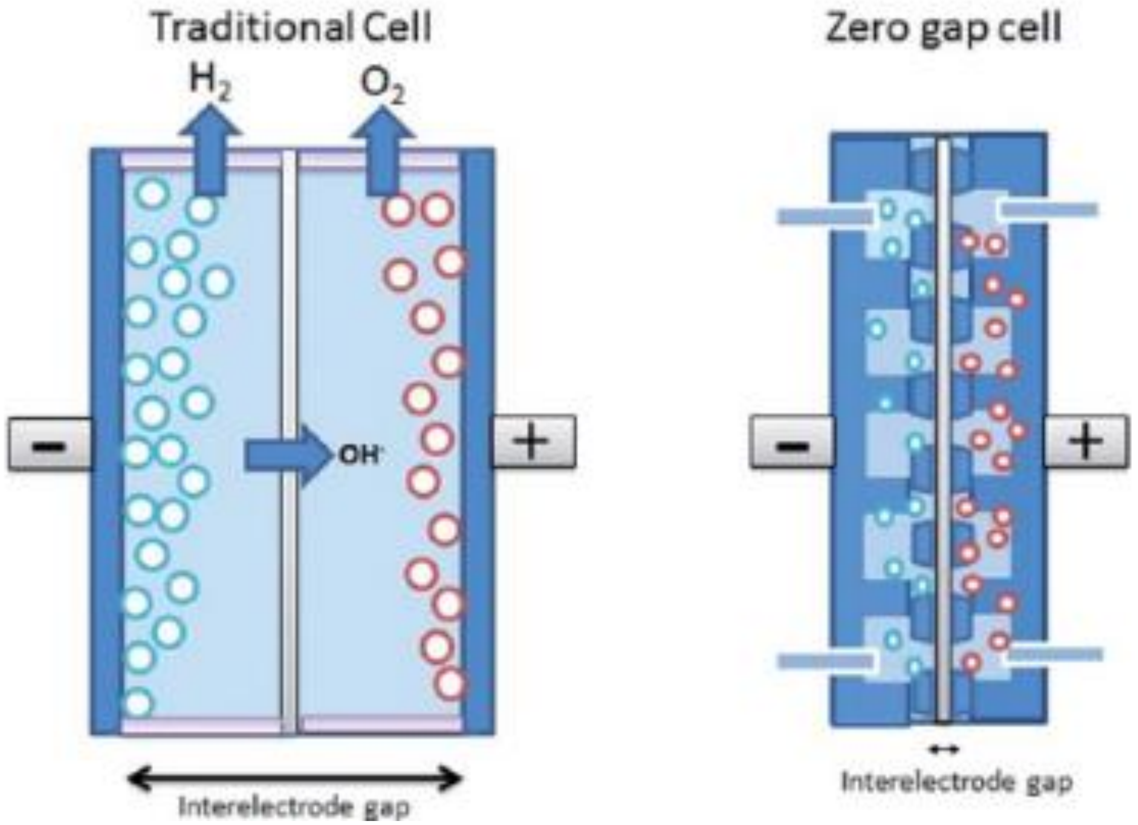
PEM functional Specifications

		PEM Technology suppliers								
	Unit	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Supplier 7	Supplier 8	Supplier 9
Rated stack consumption	kW	7.20	14.40	14.00	28.00	40.00	45.00	160.00	50.00	1,250.00
Hydrogen purity	%			99.9995	99.9995	99.995	99.995		99.3	99.9
System efficiency	kWh/Nm3	6.70	6.70	7.30	7.00	6.80	7.50		6.25	5.56
Net production rate	Nm3/h	1.00	2.00	2.00	4.00	6.00	6.00	30.59	40.00	225.00
Net production rate	kg/day	2.16	4.32	4.31	8.63	12.94	12.95	66.00	86.30	485.46
kW per kg / day	Ratio	3.34	3.34	3.25	3.24	3.09	3.48	2.42	2.90	2.57
Turndown ratio	%	0 to 100%		0 to 100 % - automatic	0 to 100 % - automatic	0 to 100 % - automatic		10 to 00%	10 to 00%	
Output pressure	bar	7.90	7.90				15.00	40.00	12.00	35.00
Fresh water demand	L/Nm3H2	1.00	1.00	1.83	3.66	5.50	5.40		3.40	1.50
Inlet water pressure	bar	0.7 - 6.9	0.7 - 6.9	1.5 - 4	1.5 - 4	1.5 - 4	01-oct			
Cooling strategy	Technology	Air cooled	Air cooled	Liquid cooled	Liquid cooled	Liquid cooled			Air or liquid	Air cooled
Operating temperature	ºC	5 to 40	5 to 40	5 to 40	5 to 40	5 to 40	0 to 46		5 to 35	
Dimensions	mXmXm	0.75 x 0.66 x 1.17	1.30 x 1.00 x 1.25	180 x 81 x 191	180 x 81 x 191	180 x 81 x 191	2.18 x 0.84 x 1.91		0.85 x 1.05 x 1.65	6.3 x 3.10 x 3.00
Weight	kg	250	275	682	750	858	908	900	260	17000

Alkaline functional specs

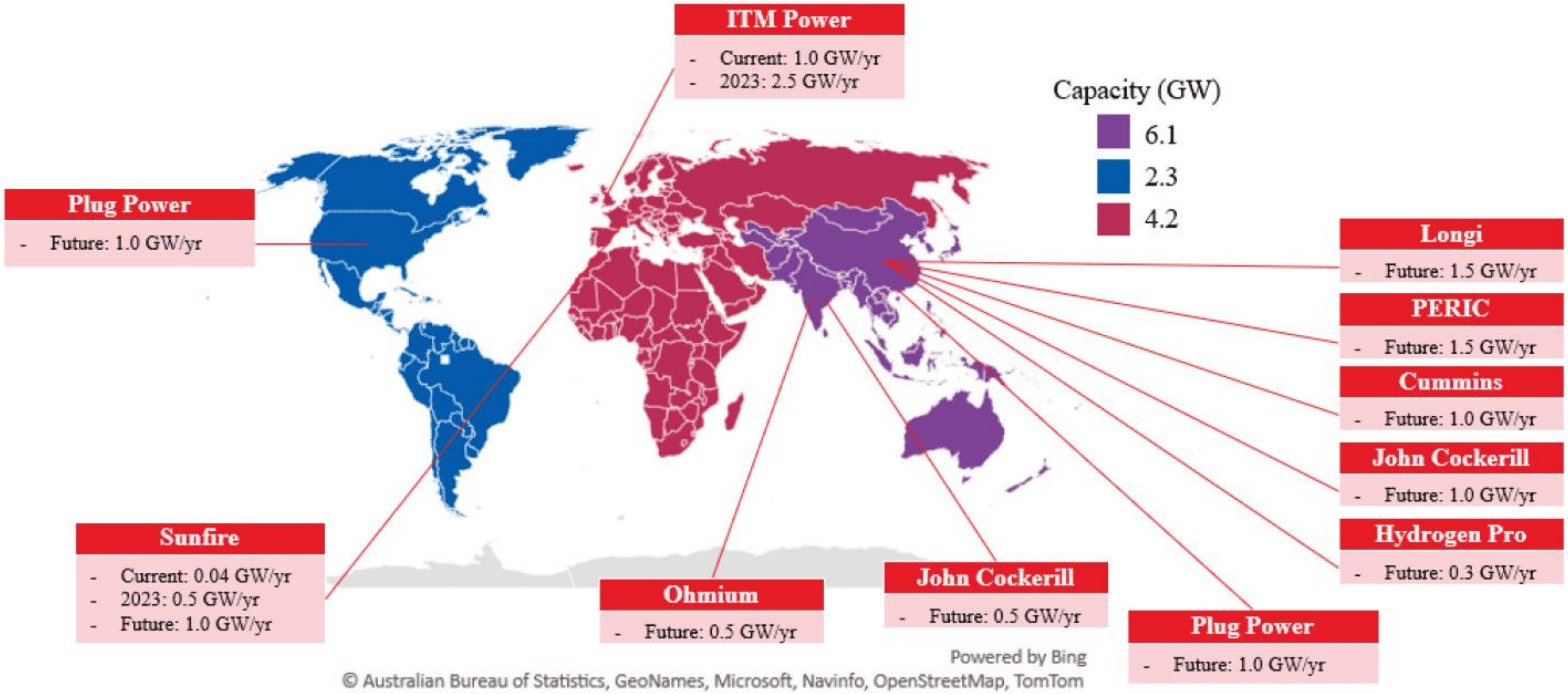
Alkaline Technology suppliers					
	Unit	Supplier 1	Supplier 2	Supplier 3	Supplier 4
Rated stack consumption	kW	22.30	145.00	270.00	515.00
Electrolyte	Type	H20 + 24% NaOH	H20 + 30% KOH	H20 + 30% KOH	H20 + 30% KOH
Hydrogen purity	%	99.80	99.90	99.90	99.90
System efficiency	kWh/Nm3	5.58	4.90	5.20	4.90
Net production rate	kg/day	35.90	227 to 570	456 to 1140	912 to 2280
Consumption	kWh/kgH2	62.08	54.52	57.86	54.52
Turndown ratio	%	10 to 100%	20 to 100%	20 to 100%	20 to 100%
Output pressure	bar	12.00	10.00	10	10
Cooling strategy	Technology	Air cooled	Water cooled	Water cooled	Water cooled

Zero gap cell design

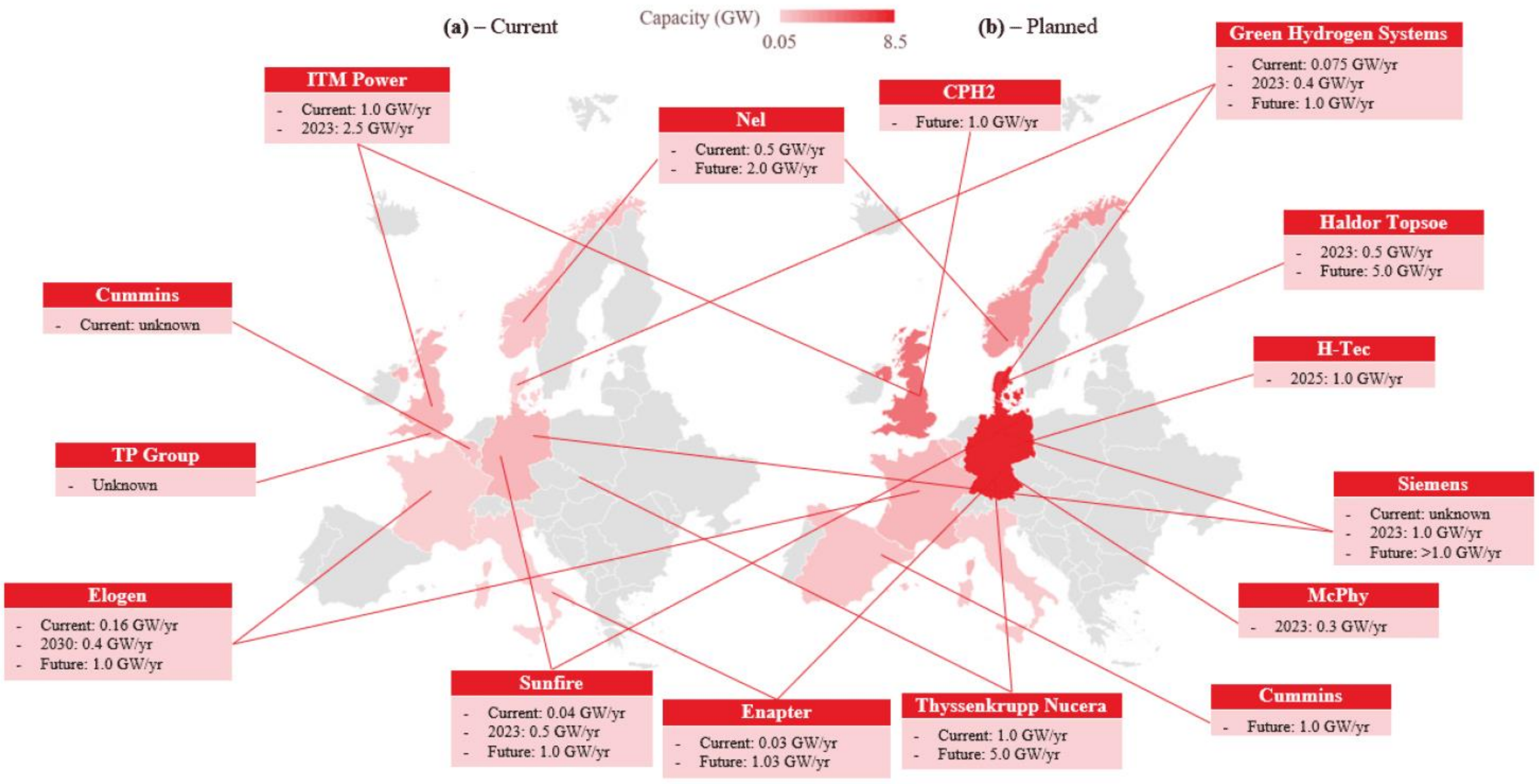


Reduction of inter-electrode gap. Reduces significantly the overall cell resistance, increases the performance, specially at high current density.

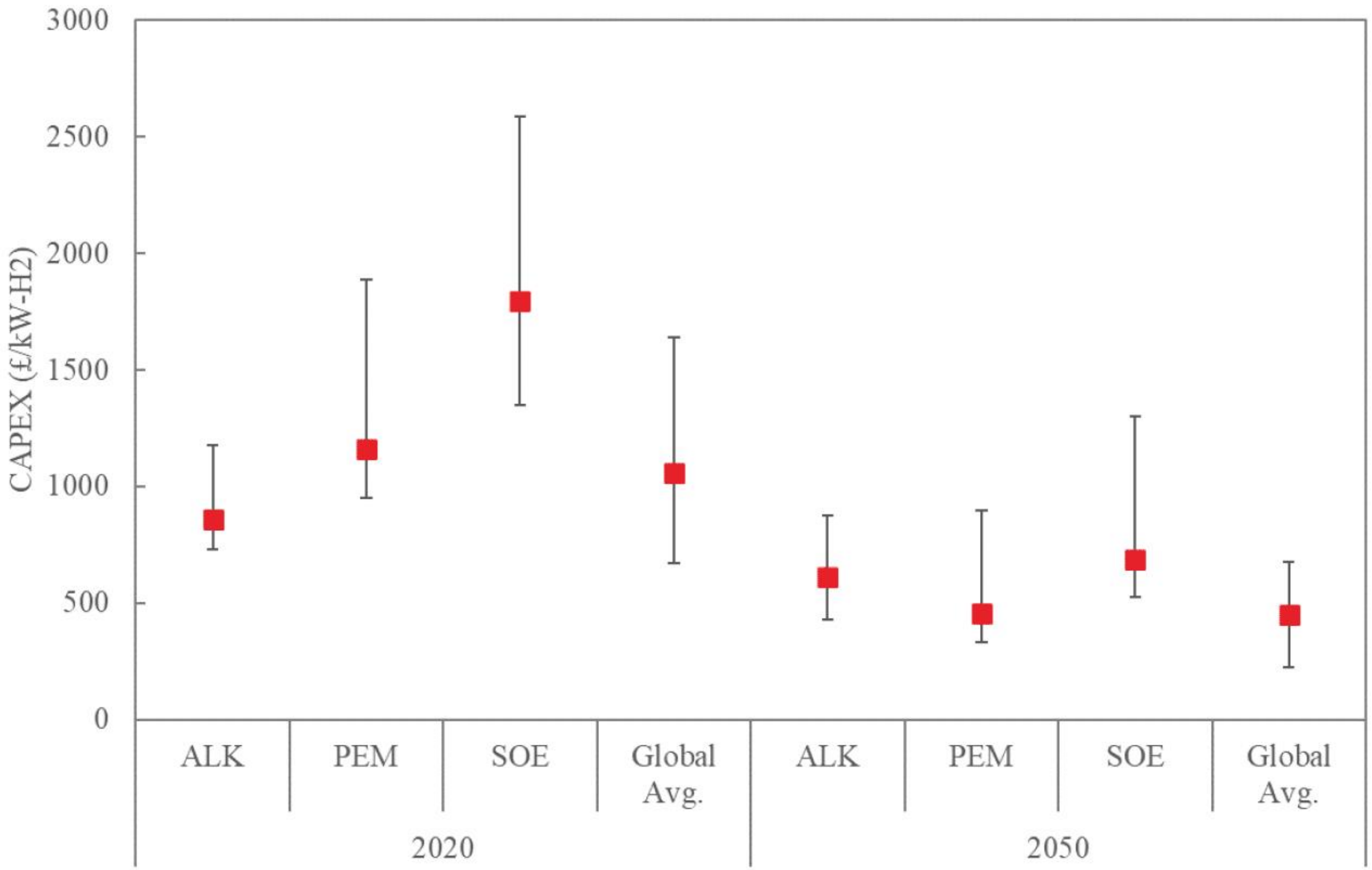
Manufacturing capabilities



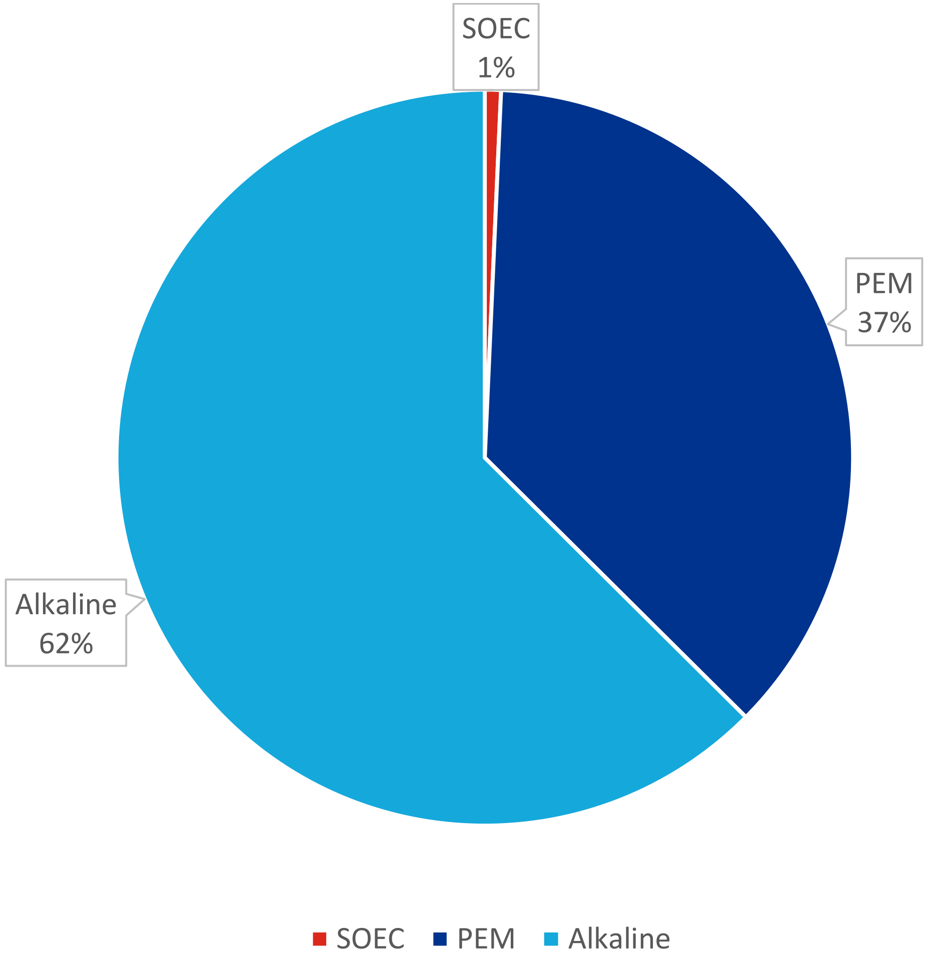
Europe manufacturing capacity



Capital cost of manufacturing



Technology market share



Q&A