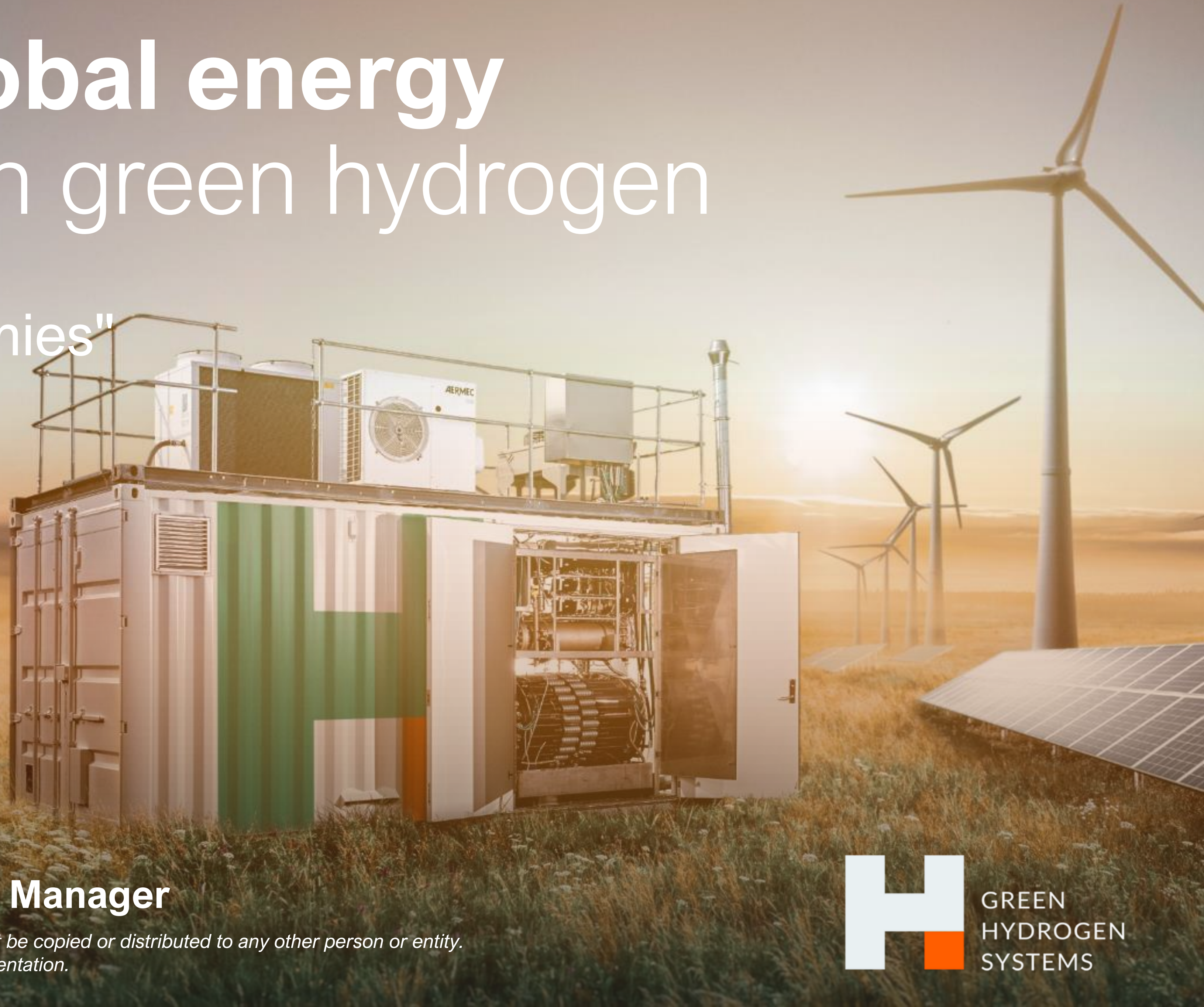
# Driving the **global energy transition** with green hydrogen

## Electrolyzers for "dummies"




**September 7th, 2023**

**Christian Buhl Sørensen, R&D Manager**

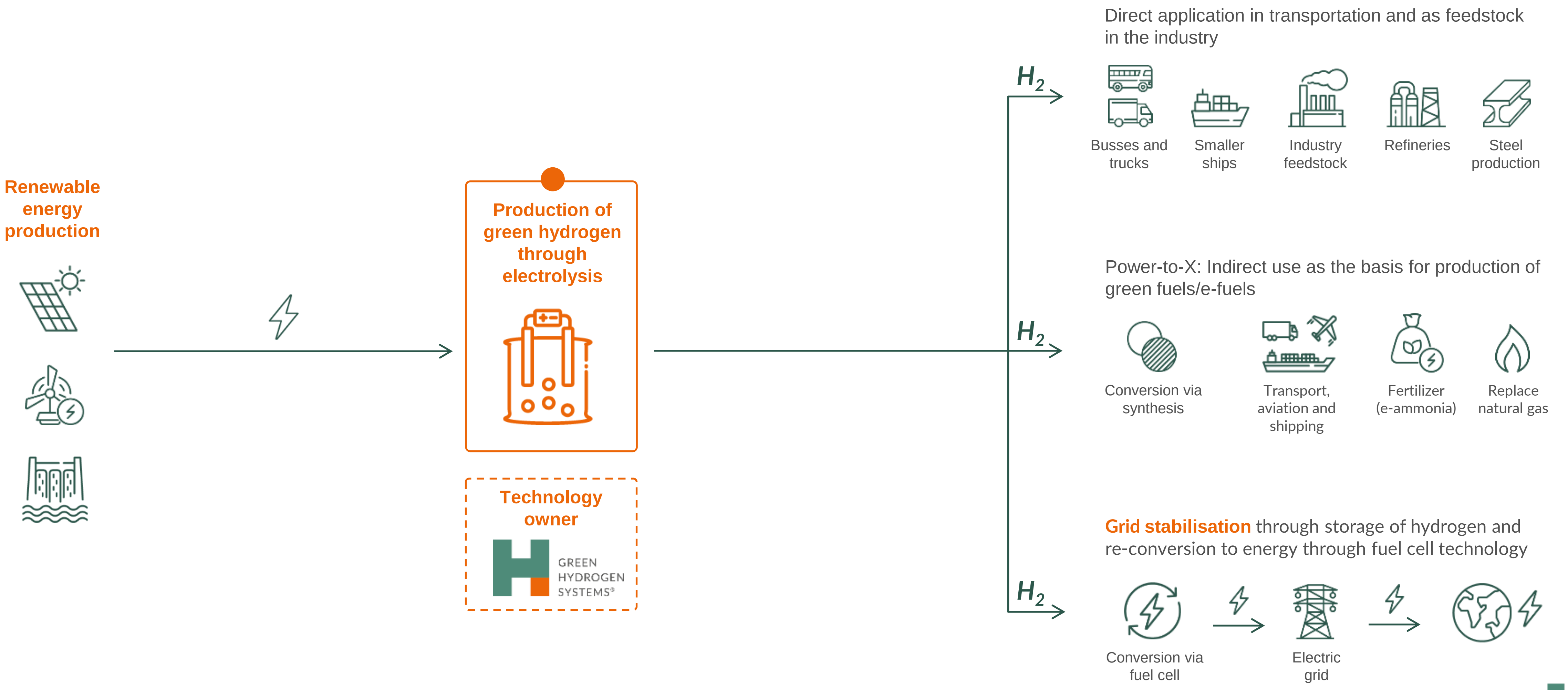


GREEN HYDROGEN SYSTEMS

# Introduction

## The why

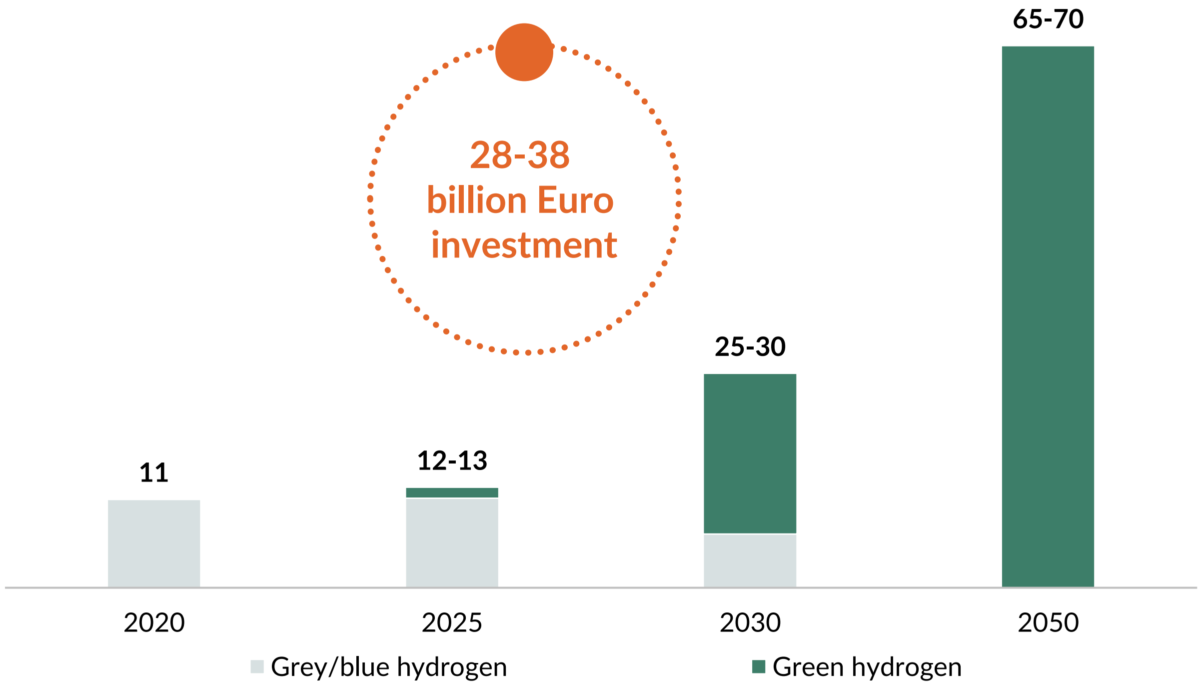
# Green hydrogen's role in the future energy system



# Increased electrolyser demand

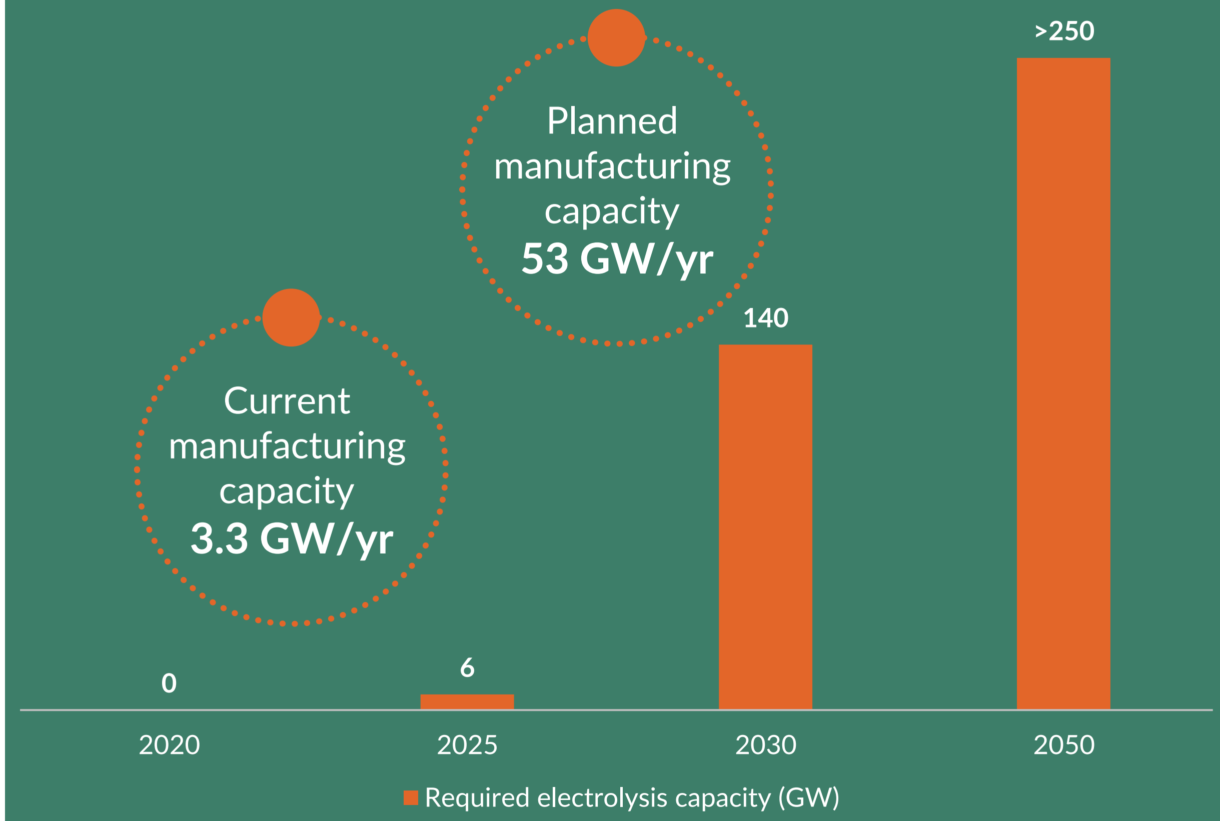
## Estimated future demand for hydrogen in the EU

From Dansk Energi. Hydrogen demand in million tonnes H2 2021;
Clean Hydrogen Monitor 2022, Hydrogen Europe; REPowerEU, EU 2022




**Demand for hydrogen in Europe is expected to grow significantly**

## Required electrolysis capacity to meet EU demand




**To meet demand, manufacturing capacity must increase considerably**

# Levelized Cost of Hydrogen

- Cost contributors example*

  - CAPEX 15-25%
  - Efficiency 60-80%
  - OPEX 5-15%

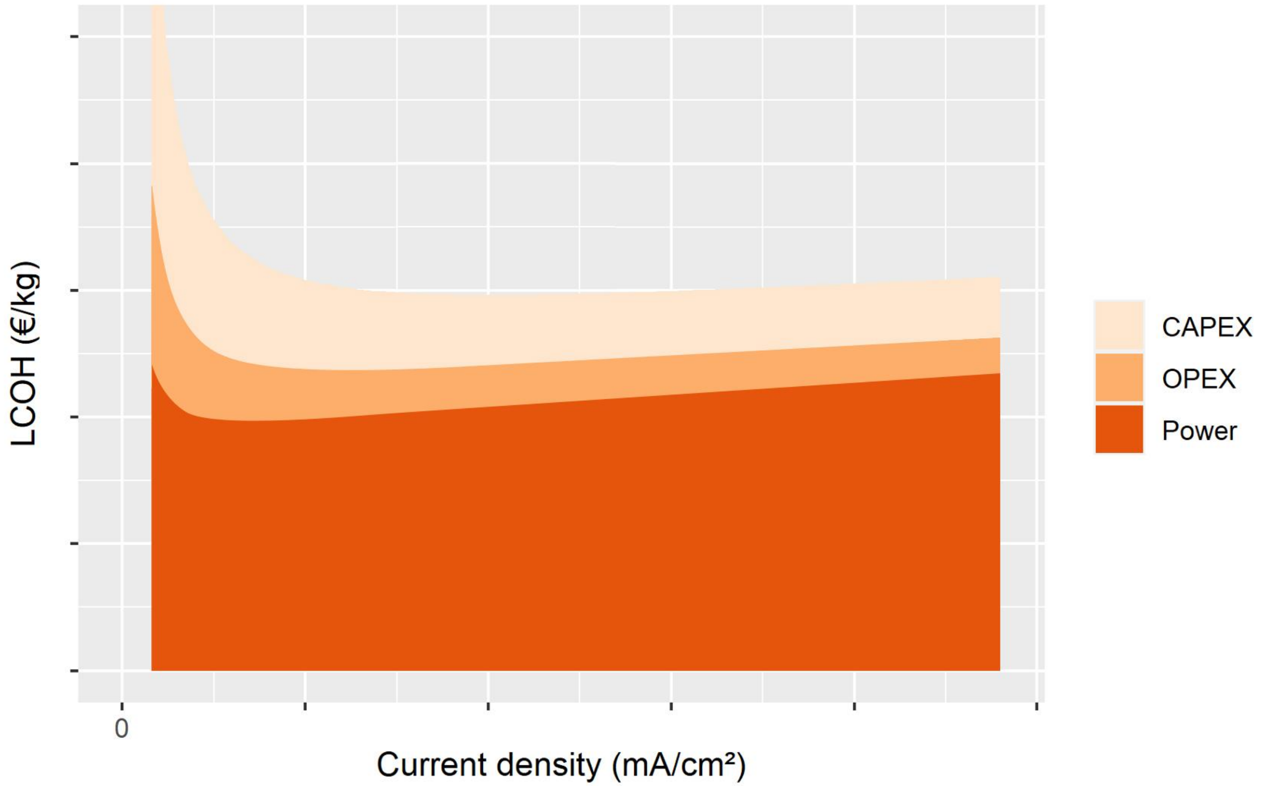
$$LCOH = \frac{Costs}{H_2 \text{ production}}$$

* Electricity spot prices from Denmark's electricity grid in 2023, 75% utilization

# Levelized Cost of Hydrogenn

- Cost contributors example*
  - CAPEX 15-25%
  - Efficiency 60-80%
  - OPEX 5-15%
- LCOH insights give strategy to lower LCOH
- LCOH insights can be counter-intuitive
- Note: added value from increased pressure not included in LCOH

$$\text{LCOH} = \frac{\text{Costs}}{H_2 \text{ production}}$$




* Electricity spot prices from Denmark's electricity grid in 2023, 75% utilization

# Levelized Cost of Hydrogen

- Improving the picture: using several value streams
- Hydrogen
- Oxygen
- Waste heat

$$LCOH = \frac{Costs}{H_2 \text{ production}}$$

$$LCOH = \frac{Costs}{H_2 \text{ production} + O_2 \text{ production} + \text{waste heat}}$$

* Electricity spot prices from Denmark's electricity grid in 2023, 75% utilization

# HyProvide® A–Series

A modular, containerized, plug-and-play electrolysis solution

## Current offering

- **Two product variants**: A180 (900kW)
- **Hydrogen production:** 180 Nm³/hr – (16 kg)
- **Hydrogen gas purity:** 99.998 %
- **Cell stack:** 53 kWh/kg
- **Cell stack + Stack Power Supply (SPS):** 57 kWh/kg $H_2$
- **Hydrogen outlet pressure:** 30 barg.

**0.9 MW**

**A180, two stacks of 450kW each, in a 40 foot container**

(includes auxiliary systems)

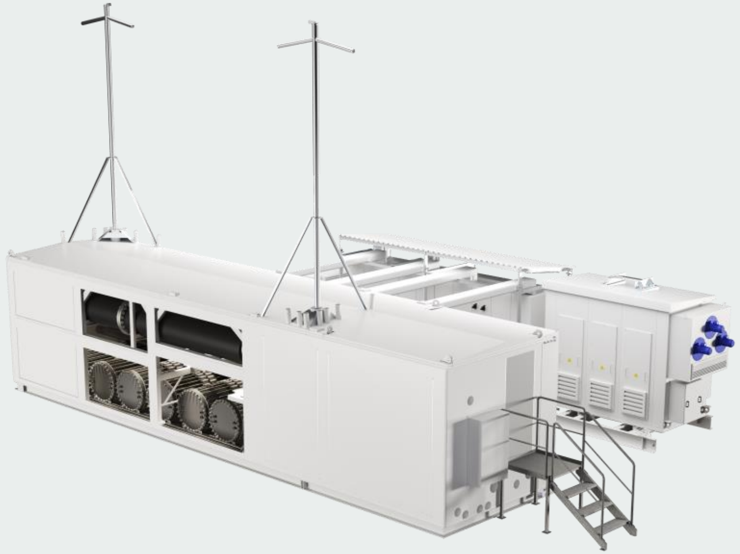
# HyProvide® X–Series

A modular, scalable electrolysis solution in enclosure

## Under commisioning

- **One product variant:** X1200 (6 MW)
- **Hydrogen production:** 1,200 Nm³/hr (107 kg)
- **Hydrogen gas purity**: 99.998 % (with GTO)
- **Cell stack**: 53 kWh/kg $H_2$
- **Cell stack + Stack Power Supply (SPS):** 57 kWh/kg $H_2$
- **Hydrogen outlet pressure**: 35 barg.

**6 MW**

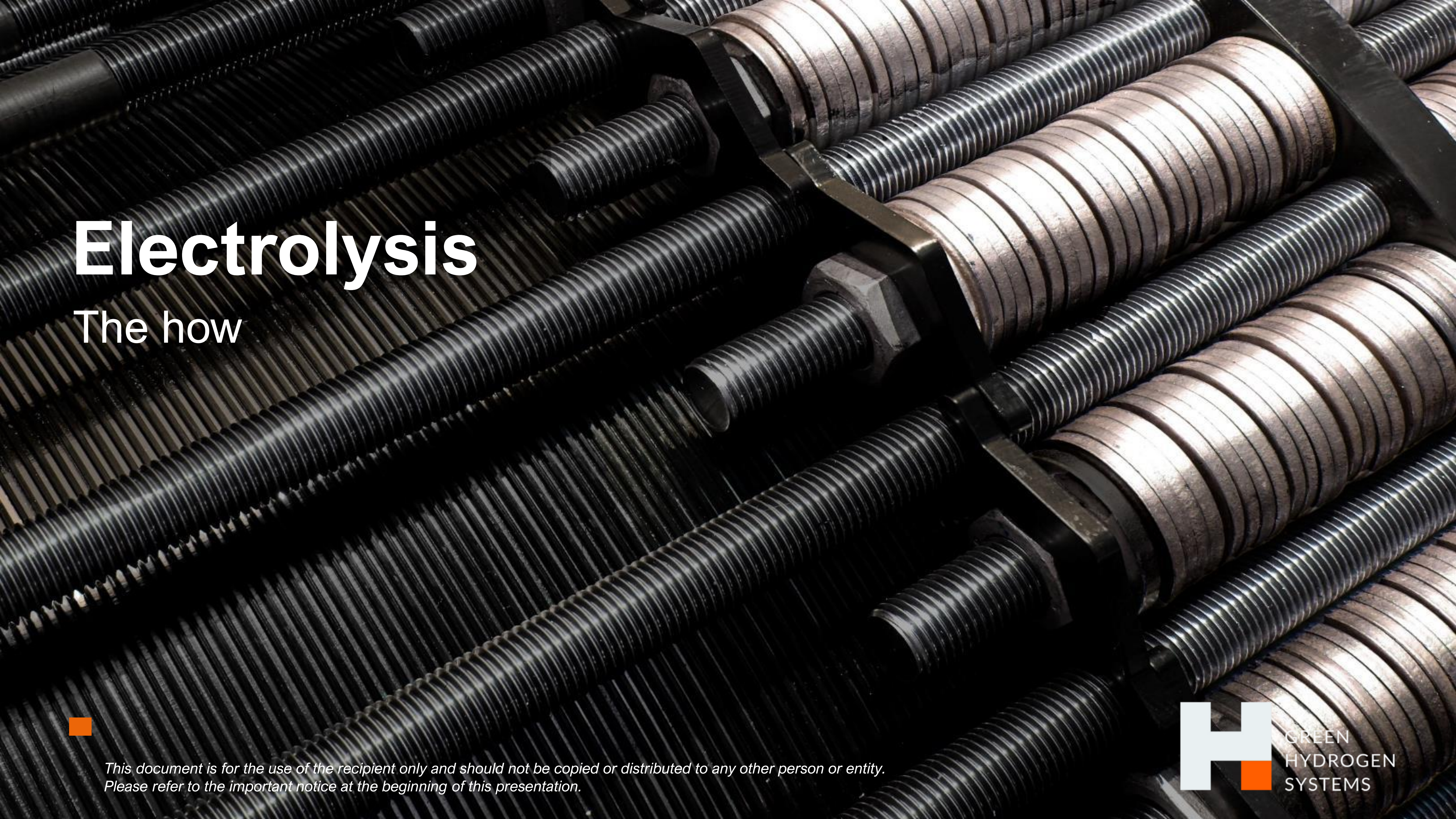


**Enclosure comprising 1x X1200 unit**

(auxiliary systems incl.  Deoxo, Dryer and Dry cooler are optional)



GREEN HYDROGEN SYSTEMS



# Electrolysis

## The how



GREEN
HYDROGEN
SYSTEMS

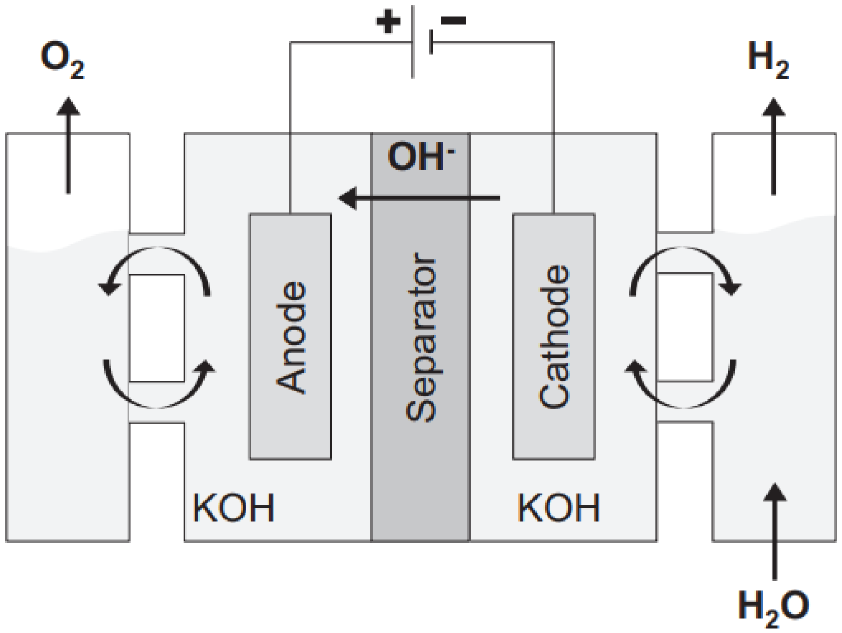
# How to choose between electrolyser technologies

## Specific customer requirements will lead to different choices

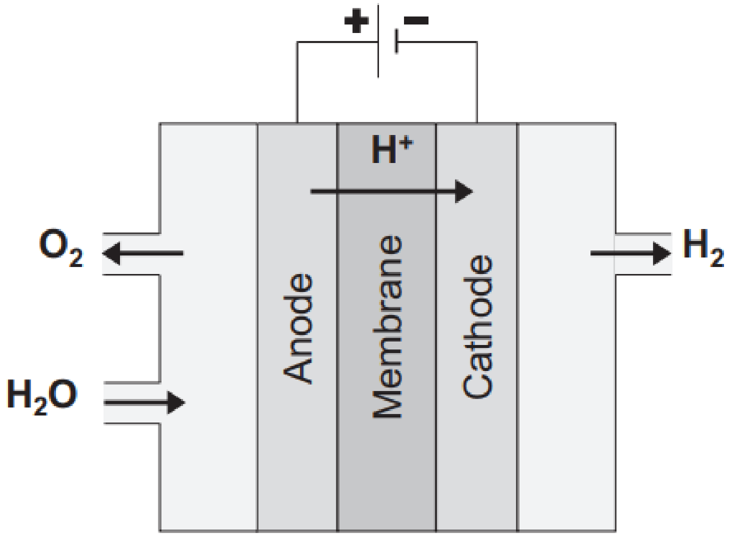
- Project size (MW)
- Footprint
- Material use
- Hydrogen quality
- TCO / business case
- Hydrogen pressure
- Dynamic response

# Technologies

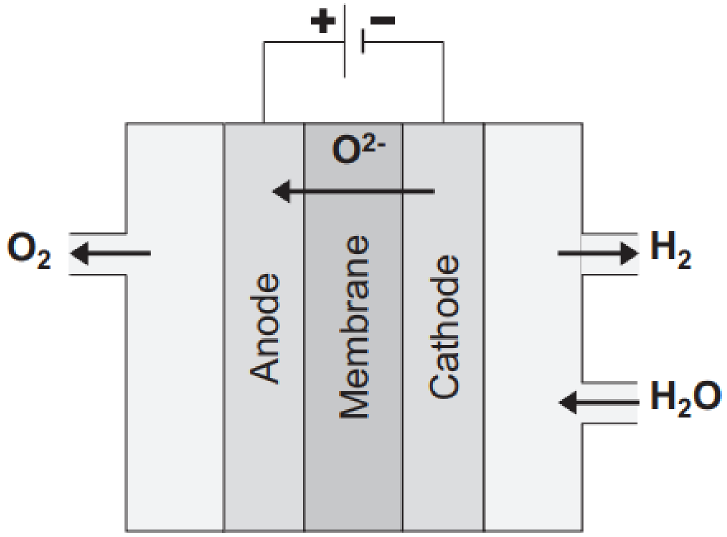
**AEC**




**PEMEC**




**SOEC**




Anode: $2OH^- \rightarrow H_2O + \frac{1}{2} O_2 + 2e^-$

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

Overall cell: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

Anode: $H_2O \rightarrow 2H^+ + \frac{1}{2} O_2 + 2e^-$

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

Overall cell: $2H_2O \rightarrow H_2 + \frac{1}{2} O_2$

Anode: $O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$

Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$

Overall cell: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

# Detailed Technology Comparison

**Table 1 – Main characteristics of AEC, PEMEC and SOEC systems.**

| | AEC | PEMEC | SOEC |
|---|---|---|---|
| Electrolyte | Aq. potassium hydroxide (20–40 wt% KOH) [9,32,33] | Polymer membrane (e.g. Nafion) [33,34] | Yttria stabilised Zirconia (YSZ) [37,38] |
| Cathode | Ni, Ni-Mo alloys [9,32,33] | Pt, Pt-Pd [34] | Ni/YSZ [37,38] |
| Anode | Ni, Ni-Co alloys [9,32,33] | $RuO_2$, $IrO_2$ [34] | LSM[b]/YSZ [37,38] |
| Current density (A $cm^{-2}$) | 0.2–0.4 [34] | 0.6–2.0 [34] | 0.3–2.0 [9,38] |
| Cell voltage (V) | 1.8–2.4 [34] | 1.8–2.2 [34] | 0.7–1.5 [38] |
| Voltage efficiency ($\%_{HHV}$) | 62–82 [34] | 67–82 [34] | <110 [33] |
| Cell area ($m^2$) | <4 [33] | <0.3 [33] | <0.01 [33] |
| Operating Temp. (°C) | 60–80 [34] | 50–80 [34] | 650–1000 [37,38] |
| Operating Pressure (bar) | <30 [33] | <200 [33] | <25 [33] |
| Production Rate[c] ($m^3_{H2}$ $h^{-1}$) | <760 [33] | <40 [33] | <40 [33] |
| Stack energy[c] ($kWh_{el}$ $m^{-1}_{H2}$) | 4.2–5.9 [34] | 4.2–5.5 [34] | >3.2 [33] |
| System energy[c] ($kWh_{el}$ $m^{-1}_{H2}$) | 4.5–6.6 [16] | 4.2–6.6 [16] | >3.7 (>4.7)$_{kWh\_energy}$[a] |
| Gas purity (%) | >99.5 [32] | 99.99 [33] | 99.9[a] |
| Lower dynamic range[d] (%) | 10 – 40 [33,34] | 0 – 10 [34] | >30[a] |
| System Response | Seconds [33] | Milliseconds [33] | Seconds[a] |
| Cold-start time (min.) | <60 [16] | <20 [16] | <60[a] |
| Stack Lifetime (h) | 60,000–90,000 [16] | 20,000–60,000 [16] | <10,000[a] |
| Maturity | Mature | Commercial | Demonstration[a] |
| Capital Cost (€ $kW^{-1}_{el}$) | 1000–1200 [16] | 1860–2320 [16] | >2000 [16] |

[a] Where no reference is provided, data were derived during expert elicitations.
[b] Perovskite-type lanthanum strontium manganese ($La_{0.8}Sr_{0.2}MnO_3$).
[c] Refers to norm cubic meter of hydrogen (at standard conditions) and respective electrical energy consumption ($kWh_{el}$) if applicable.
[d] Minimum operable hydrogen production rate relative to maximum specified production rate.

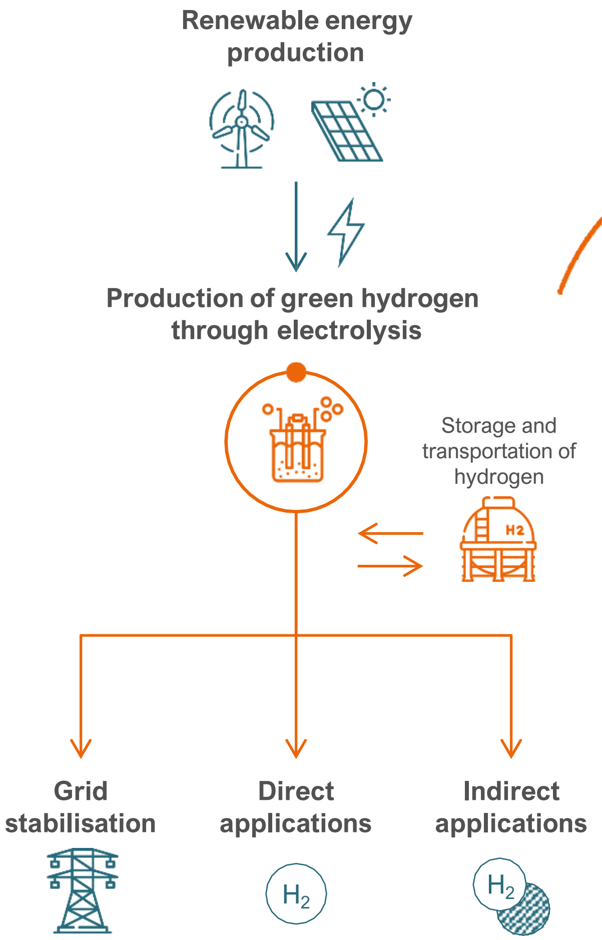
Schmidt **2017**, Future cost and performance of water electrolysis: An expert elicitation study



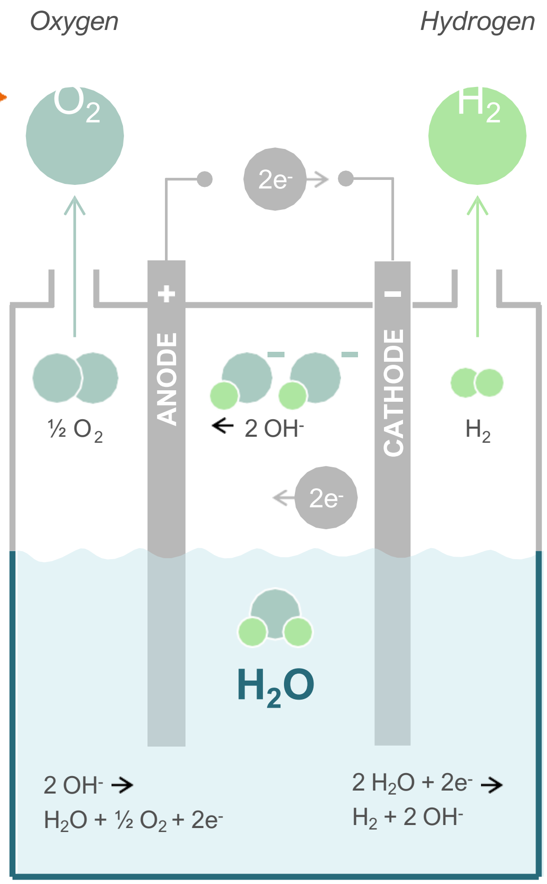
GREEN HYDROGEN SYSTEMS

# Pressurized Alkaline Electrolysis

## Splits water into hydrogen and oxygen




### Hydrogen electrolysis process




Hydrogen electrolysis is a process that splits water into hydrogen and oxygen using electricity.

Hydrogen generated from renewable electricity sources is considered **green hydrogen**.

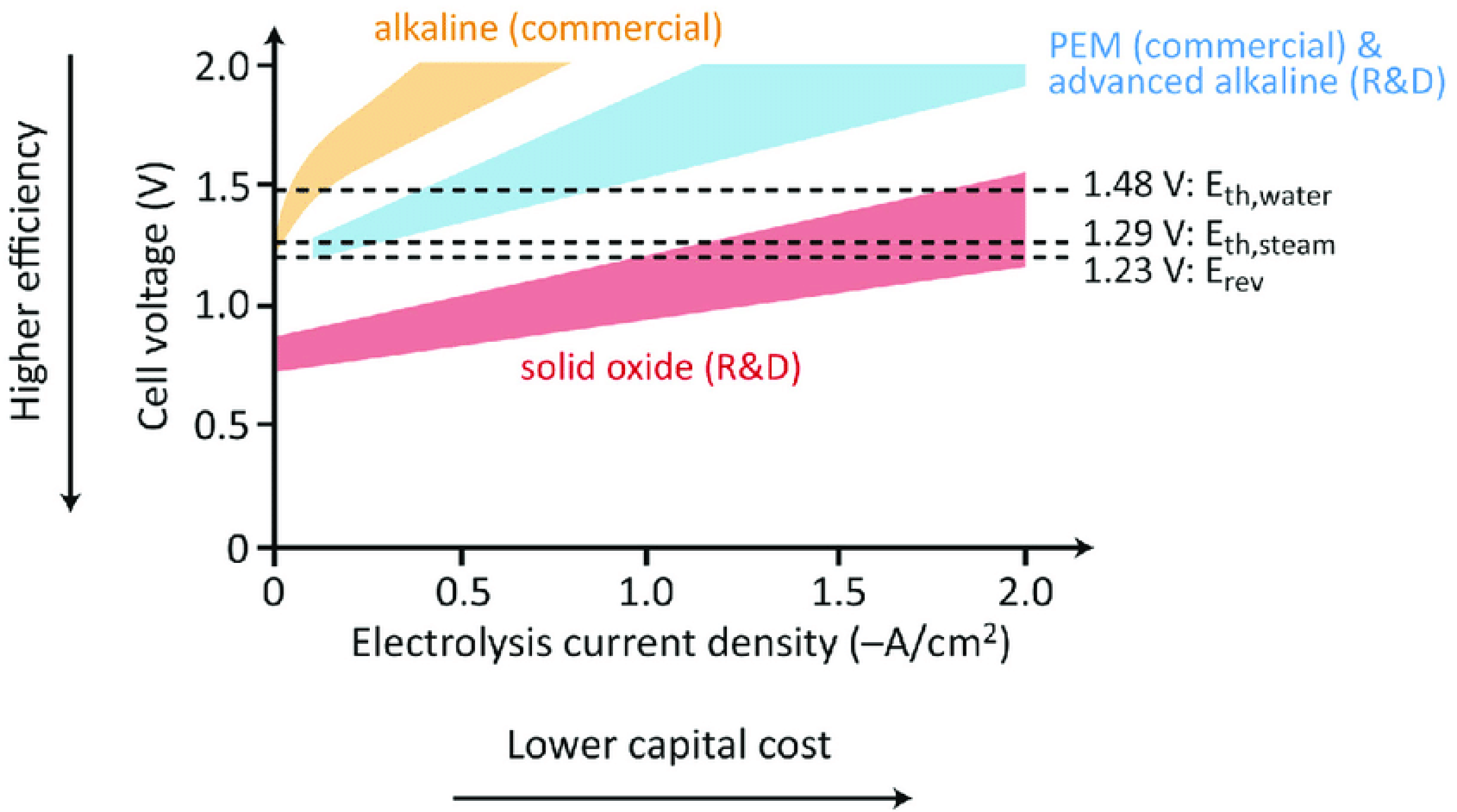
The process of green hydrogen electrolysis is completely fossil-free, as the only by-product is oxygen and the power used in electrolysis is generated from renewable sources.



GREEN HYDROGEN SYSTEMS

# Pressurized Electrolysis

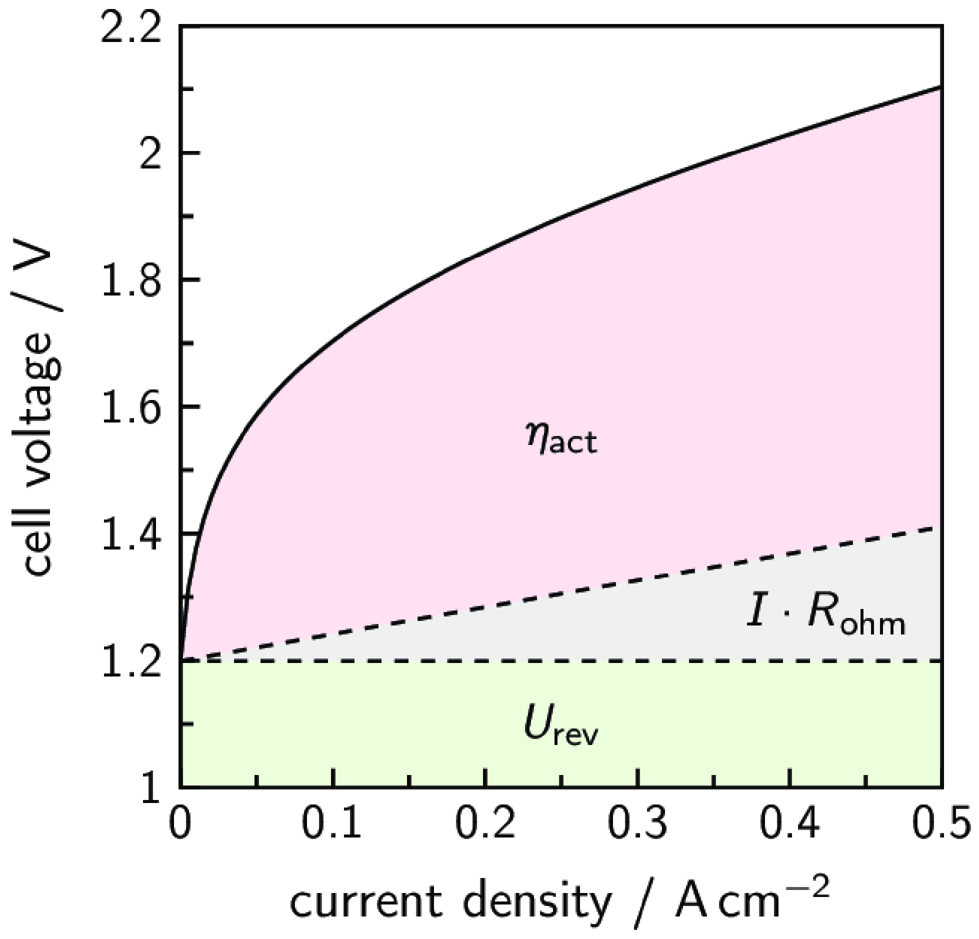
## Splits water into hydrogen and oxygen




Rozzi, Elena & Minuto, Francesco Demetrio & Lanzini, Andrea & Leone, Pierluigi. (2020). Green Synthetic Fuels: Renewable Routes for the Conversion of Non-Fossil Feedstocks into Gaseous Fuels and Their End Uses. Energies. 10.3390/en13020420.

# Pressurized Alkaline Electrolysis

## Splits water into hydrogen and oxygen

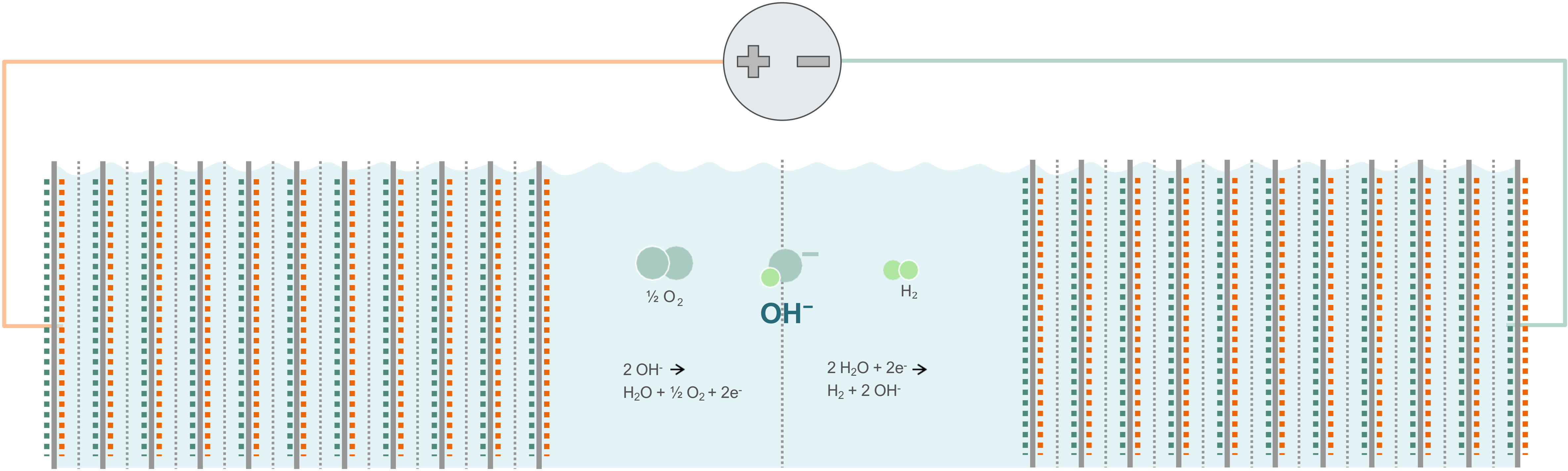



- Activation losses (improvement possible from higher T and catalyst on anode/cathode)
- Resistive losses (diaphragm, circuit, bubbles, electrolyte etc)
- Reversible cell voltage (1.23 V, electrolysis of vapour H2O)
- Not shown: starting from liquid water (U_"rev" from 1.48 V)

Brauns, Jörn & Turek, Thomas. (2020). Alkaline Water Electrolysis Powered by Renewable Energy: A Review. Processes. 8. 248. 10.3390/pr8020248.

GREEN HYDROGEN SYSTEMS

# Pressurised (Alkaline) Electrolysis




**Zero-gap** design – combines numerous electrochemical cells into a stack of cells.

All cells are wetted with electrolyte (pH > 14), which is in turn saturated with hydrogen and oxygen. Electrolyte circulated through system.

Resulting in

- High area with small design
- Few electrical connections
- Higher voltage with the same current

Challenges

- Highly corrosive environment
- Conducting electrolyte will draw stray currents

GREEN HYDROGEN SYSTEMS

GREEN HYDROGEN SYSTEMS

# Pressurized (Alkaline) Electrolysis

### Electrolyser as pressure vessel

Using the electrochemical reactions to pressurize the system

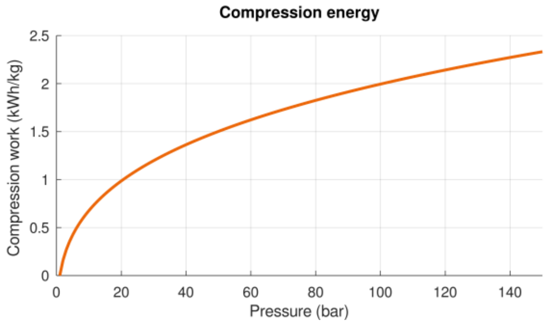

Anode (+) $2OH^- \rightarrow H_2O + ½\ O_2 + 2e^-$

Cathode (-) $2H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

Overall reaction: $H_2O \rightarrow H_2 + ½\ O2$

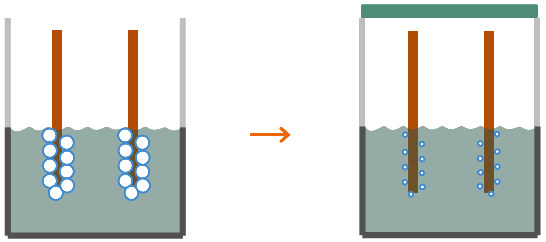
### System efficiency

The overall energy demand for producing pressurized hydrogen can be reduced by utilizing the nature of the electrolyser.




### Reduced gas volume

- Dynamic behaviour: Fast ramp rates enable coupling to RE sources.
- Footprint: Greatly reduced by in-creasing gas density.



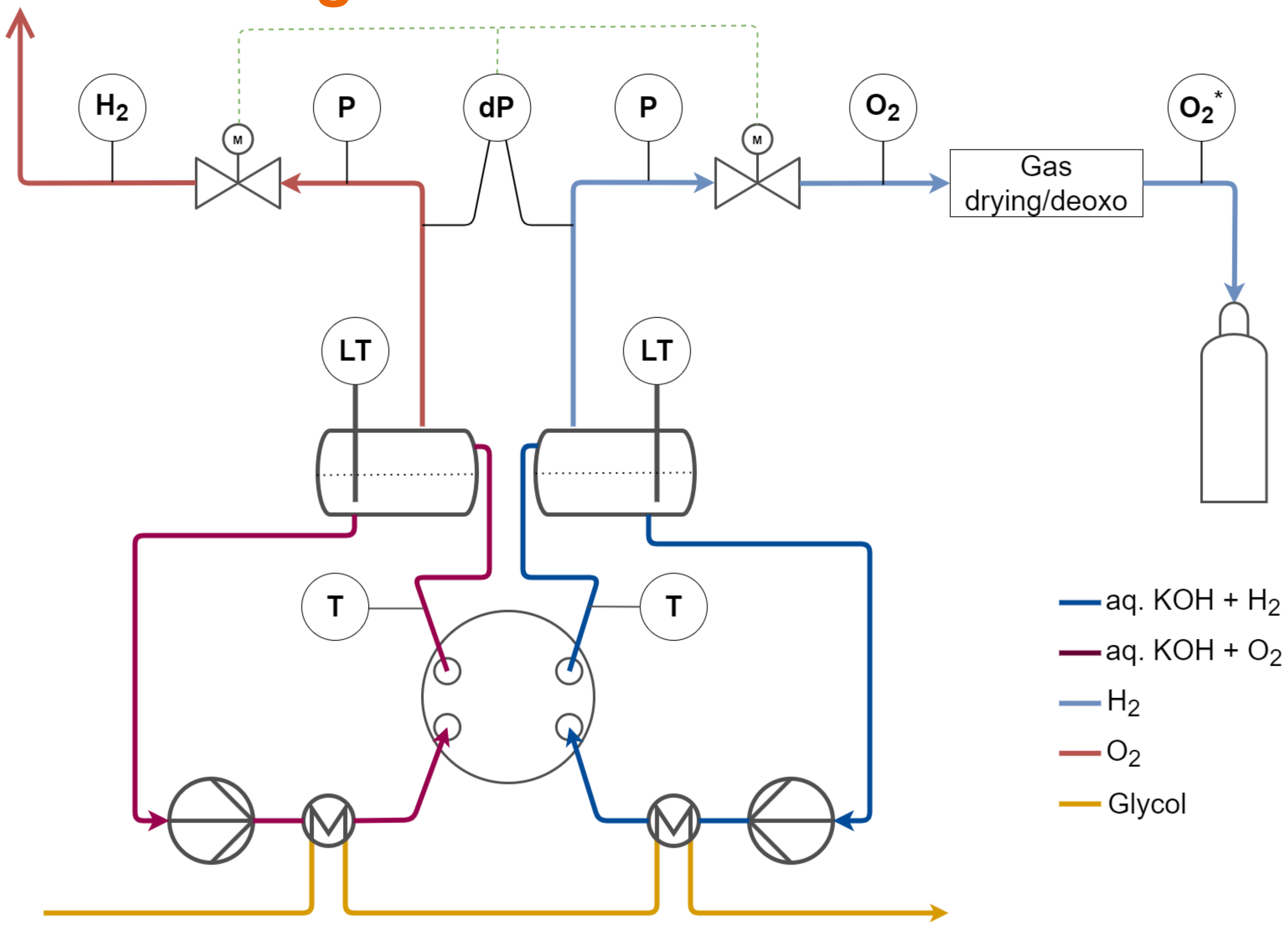
<53 kWh /kg $H_2$ (Stack energy requirement)

# Instrumentation and operation



GREEN HYDROGEN SYSTEMS

# MinWP Process diagram




GREEN HYDROGEN SYSTEMS

# Instrument requirements

| Gas system | (P)AWE system | (P)PEM system |
| --- | --- | --- |
| $H_2$ or $O_2$ compatible | 35% aq. KOH + dissolved $O_2/H_2$ | Water + dissolved $O_2/H_2$ |
| AISI 316 or similar | Ni or F | Pt, Ir (316L) |
| 35-50 bar(g) | 35-50 bar(g) | 35+ bar(g) |

Zone 2, Hydrogen,

GREEN HYDROGEN SYSTEMS

# Conclusion

## The what (technology)

*This document is for the use of the recipient only and should not be copied or distributed to any other person or entity.*
*Please refer to the important notice at the beginning of this presentation.*

GREEN
HYDROGEN
SYSTEMS

# Recap of technologies

| Competitive dimension | Pressurised alkaline | PEM | Atmospheric alkaline |
|---|---|---|---|
| **Flexibility**<br>Capacity to operate dynamically at variable load rates | ✓ | ✓ | ✗ |
| *Key for utilisation of renewable energy sources – across potential applications and minimisation of energy lost* | | | |
| **Reliability**<br>System uptime and durability | ✓ | ✓ | ✓ |
| **Efficiency**<br>Competitive energy to hydrogen conversion | ✓ | ✓ | ✓ |
| **Footprint**<br>Minimal footprint compared to other electrolyser technologies | ✓ | ✓ | ✗ |
| **Independency of scarce resources**<br>Noble metals not an input in process | ✓ | ✗ | ✓ |
| **Water purity**<br>Lower water purity required in process | ✓ | ✗ | ✓ |
| **Independency of lye**<br>The chemical lye is not contained in the electrolyser | ✗ | ✓ | ✗ |

Technological viability has the potential to be a key competitive differentiator, as CAPEX costs between technologies are expected to converge in the long-run

Long term market differentiators could be centered around flexibility, reliability, efficiency (main OPEX driver) and footprint

**Pressurised alkaline is well-positioned across competitive dimensions**

# Thank you

GREEN
HYDROGEN
SYSTEMS

GREEN
HYDROGEN
SYSTEMS