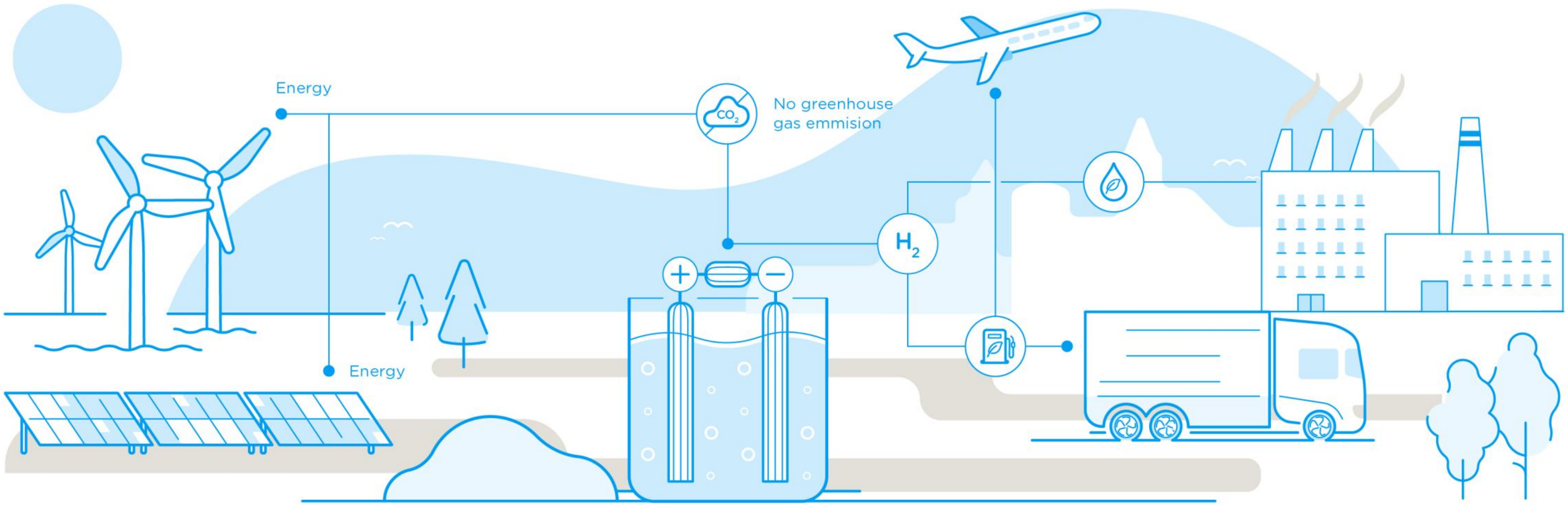


On the path to low Levelized Costs of Hydrogen (LCOH): Electrolysis technology considerations

April, 2023

Carlos Bernuy-Lopez, PhD

Senior Consultant

Hydrogen Tech World Conference 2023

What to expect in next 20 min?

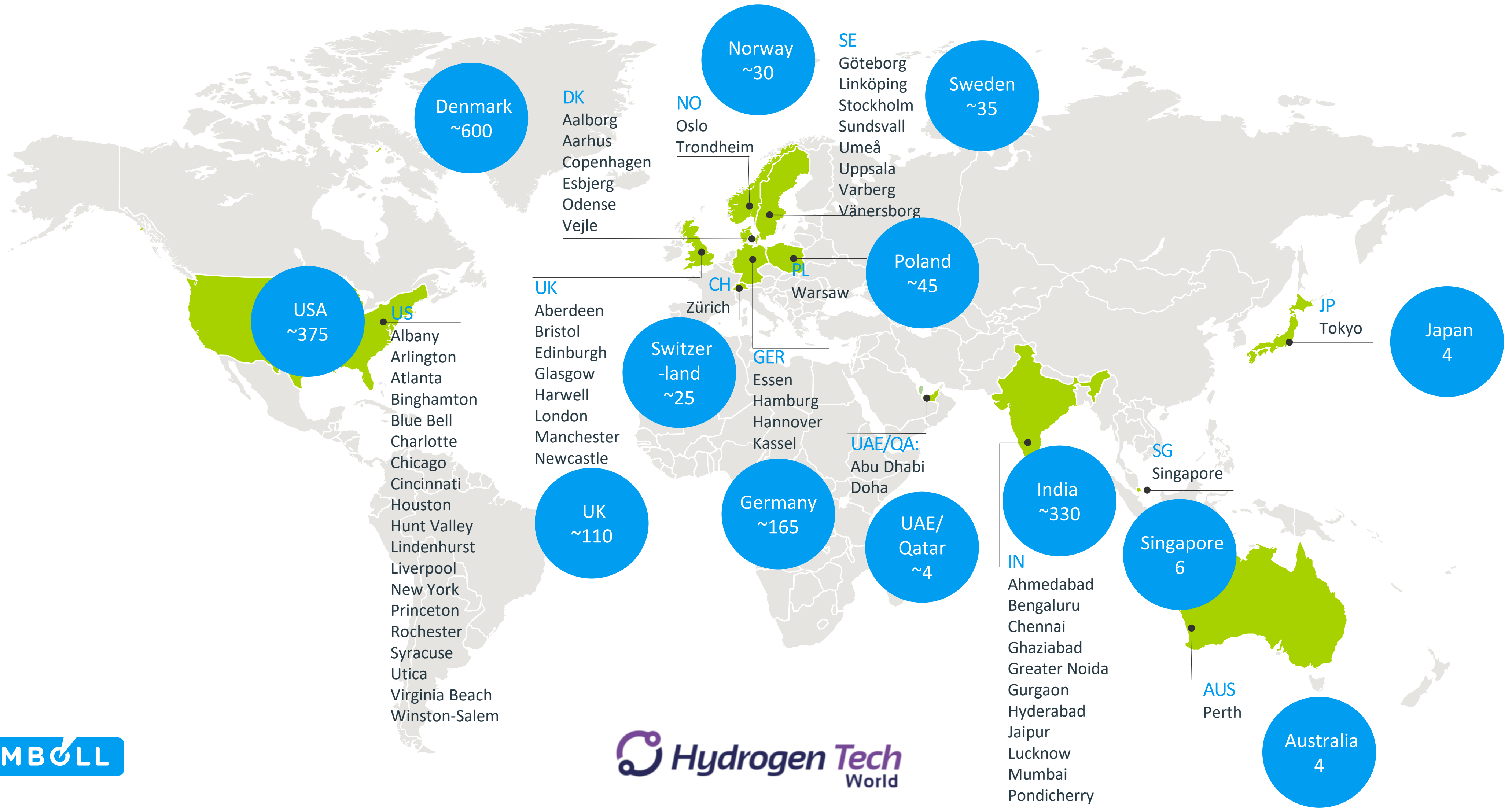
1. Ramboll as partner in your Power to X project
2. Hydrogen plants and importance of electrolyzer technology
3. Relationship between LCOH and electrolysis technologies: watch your OPEX!

Ramboll in brief

- Independent architecture, engineering and consultancy company
- Founded 1945 in Denmark
- 17,500 experts
- Present in 35 countries
- Particularly strong presence in the Nordics, the UK, North America, Continental Europe, and Asia Pacific
- Creating sustainable solutions across Buildings, Transport, Energy, Environment & Health, Water, Management Consulting and Architecture & Landscape.
- EUR 1.8 billion revenue
- Owned by Rambøll Fonden – The Ramboll Foundation

We are a multidisciplinary society consultant

1,750 employees in 15 countries



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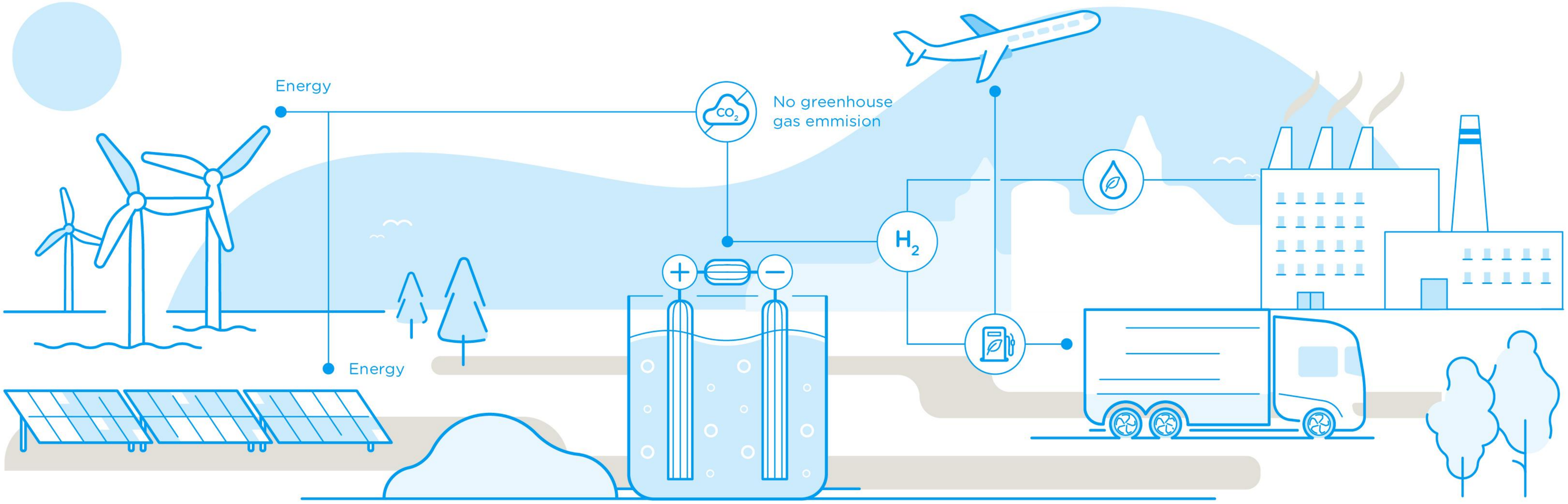
Ramboll Energy - Fields of expertise

- Wind & solar
- Biofuels and Bio-to-X
- **Green hydrogen and Power-to-X**
- Carbon capture, CCUS & BECCS
- Fuel cells
- Datacenters
- Energy infrastructure
- District energy & heating
- Biogas
- Waste-to-energy
- Energy-intensive industries
- Thermal power generation
- Power transmission and distribution

Power-to-X: A pathway to decarbonising sectors that cannot easily be electrified



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Explore with confidence

- World-class technical expertise on Hydrogen and Power-to-X
- 130 successful hydrogen projects in 2020-2023
- Holistic and multi-disciplinary approach
- Excel in integration of complex systems
- Co-create the best solutions with and for our partners

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Recent completed projects

Idea Concept Development Pre-feasibility Study	Funding	Feasibility Study Risk Assessment Permitting	Basic Engineering Planning
			
• Energy Island Vindø (CIP) • Bornholm Bunker Hub • PTX potential on Lolland	• DynAmmonia - project application • Technical Advisor to European Investment Bank	• Power-to-Ammonia (CIP) • Hydrogen Refuelling Stations • Windpark Kremsdorf • PTX in Greenland	• H2 Energy Esbjerg, 1 GW • SSV Energipark (Ørsted) • HySynergy (Everfuel) • Green Hydrogen Hub

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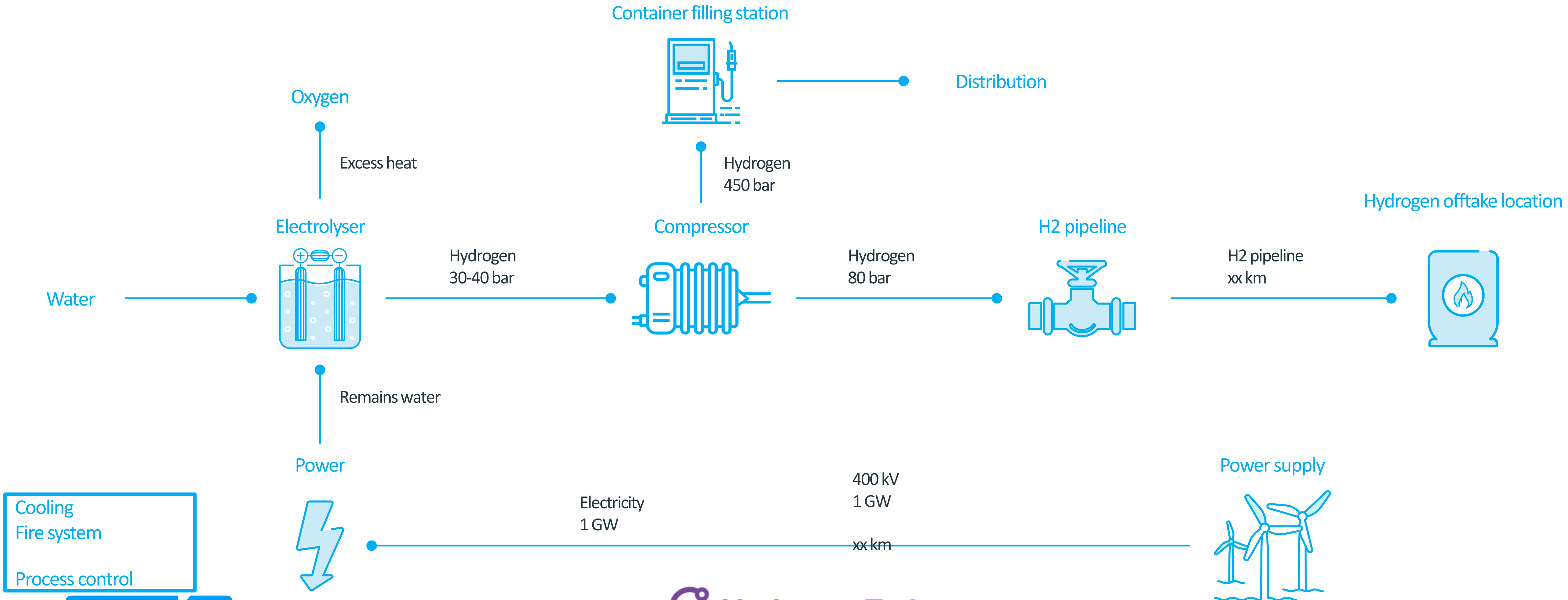
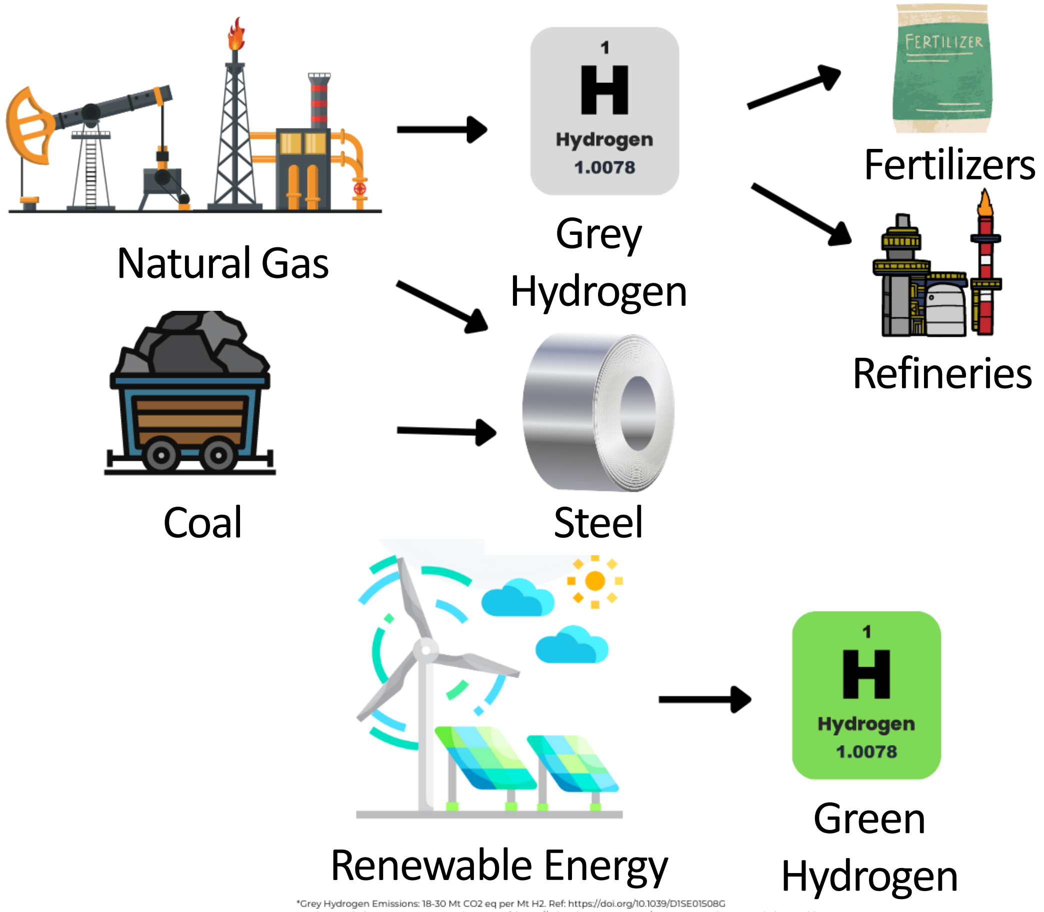
Project example

Key elements of a large-scale H_2 production plant



Role of Green Hydrogen in Decarbonizing EU industry



*Grey Hydrogen Emissions: 18-30 Mt CO2 eq per Mt H2. Ref: https://doi.org/10.1039/D1SE01508G
Total EU emissions: 2700 Mt CO2 eq in 2021 Ref: https://edgar.jrc.ec.europa.eu/report_2022?vis=tot#emissions_table
1 M = 1 000 000

European Union (yearly)

- 8 Mt Grey Hydrogen → 200 Mt CO_2 Emissions (≈ 7 % of EU)* → ≈ 300 000 Jobs
- 160 Mt Steel → 221 Mt CO_2 Emissions (≈ 8 % of EU)* → ≈325 000 Jobs

RePower EU plans for Renewable Hydrogen by 2030

- 10 Mt Internally + 10 Mt Exported
  10 Mt = 70 GW Electrolysers = 150-200 GW New Renewable Energy Generation
- 1 Mt Green Steel = 55 000 t Green Hydrogen

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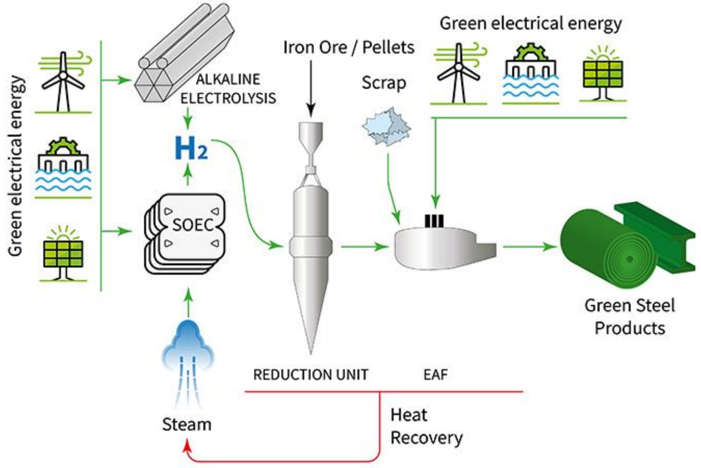
Sweden in the forefront of Green Steel



H_2 Green Steel and Hybrit in Sweden will produce 3.5 Mtonnes with 1.4 GW size electrolysers

1 million tons of steel requires 55 000 tonnes of H_2 annually, i.e. 400 MW size electrolysers

	Steel production	Emissions share	Electrolysers size
World	1900 Mt/year	8 %	760 GW
Europe	160 Mt/year	5 %	64 GW
Sweden	4.7 Mt/year	12 %	1.8 GW

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H_2 Plant: what do you have inside?

H_2 plant

H_2 Plant: what do you have inside?

H_2 plant

n x Electrolyser system

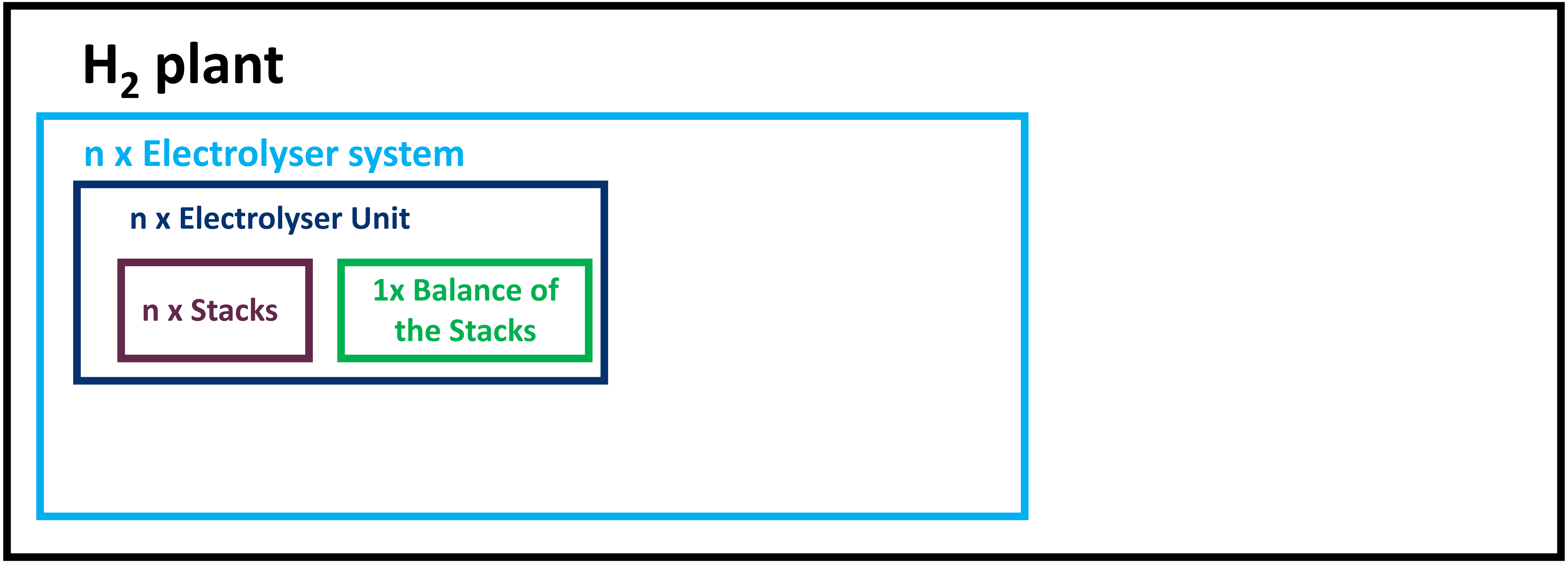
H_2 Plant: what do you have inside?

H_2 plant

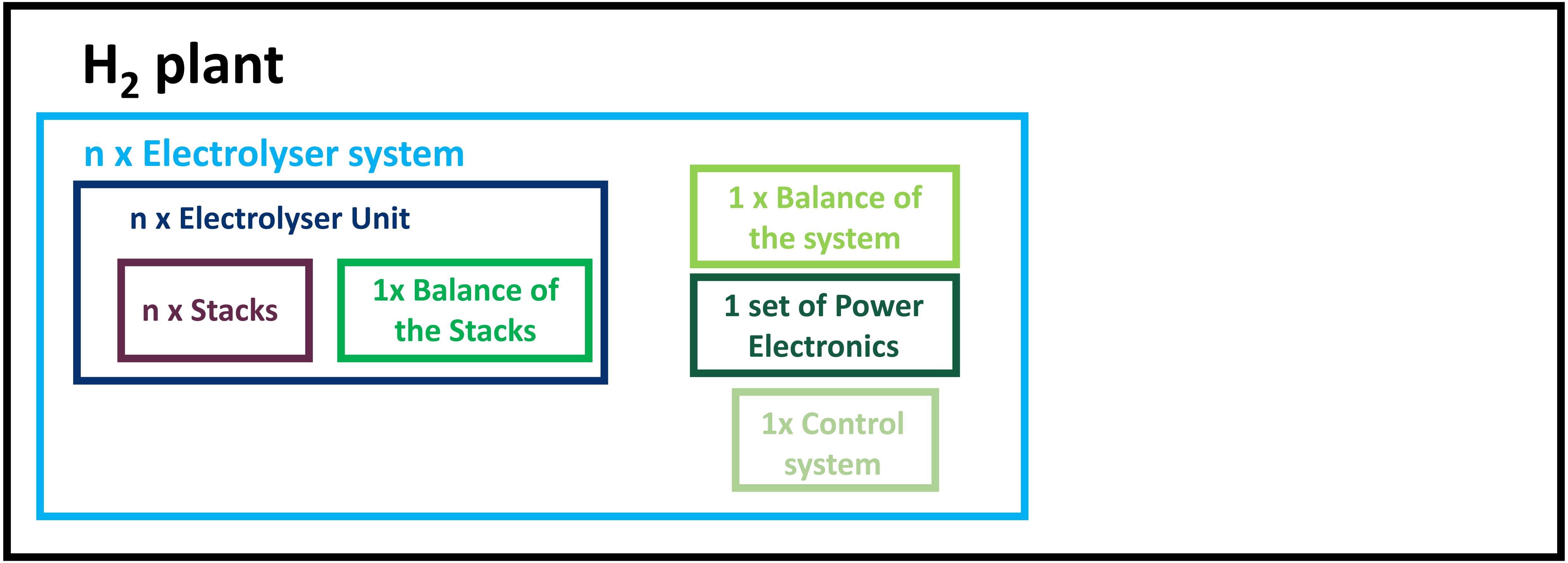
n x Electrolyser system

n x Electrolyser Unit

H_2 Plant: many components!



H_2 Plant: many components!



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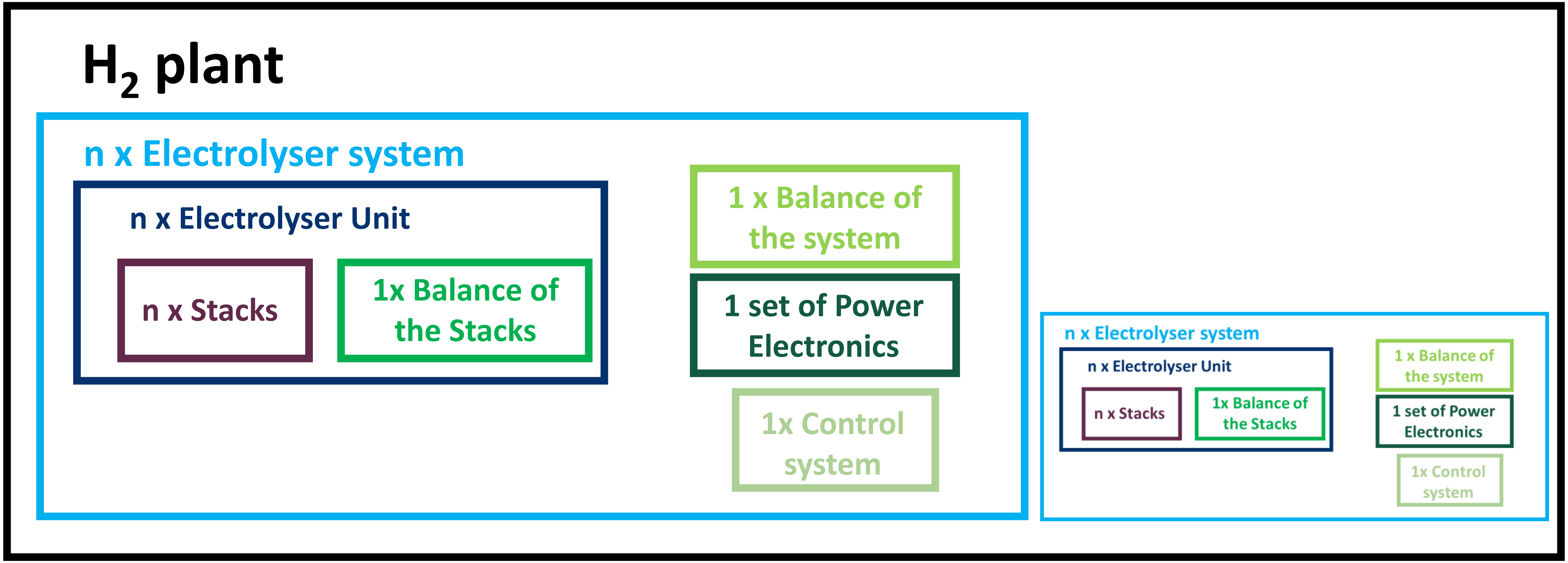
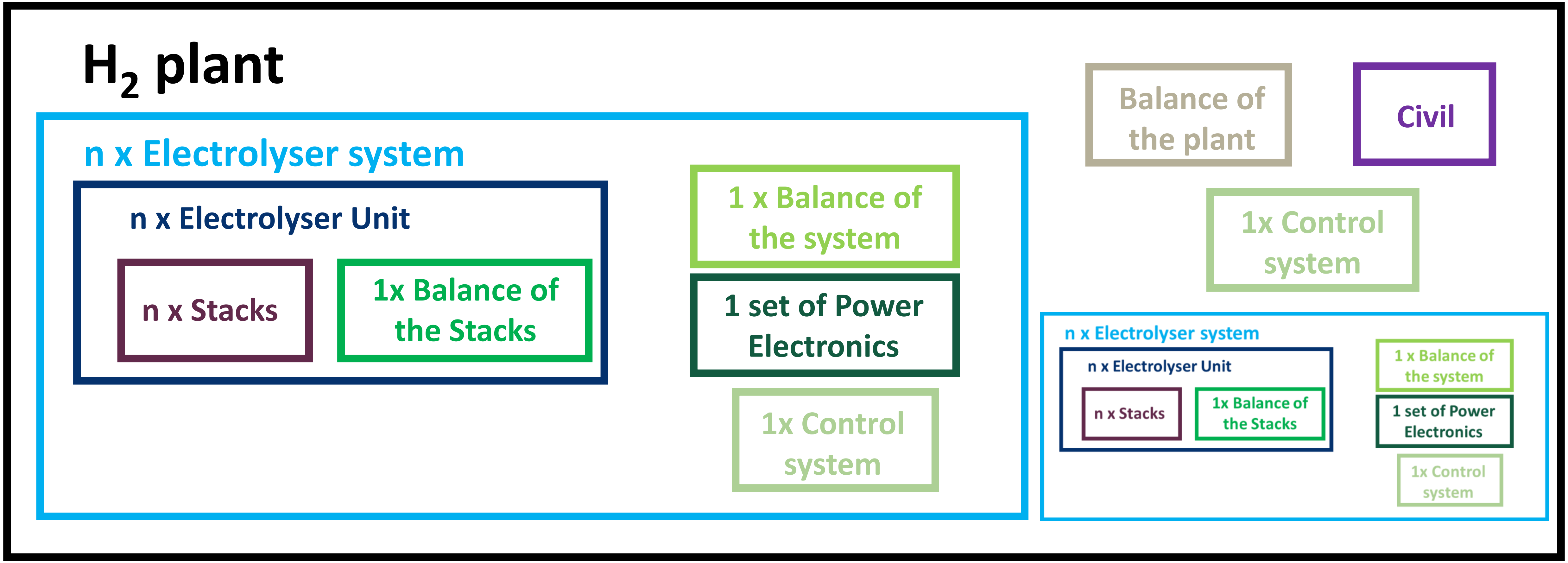
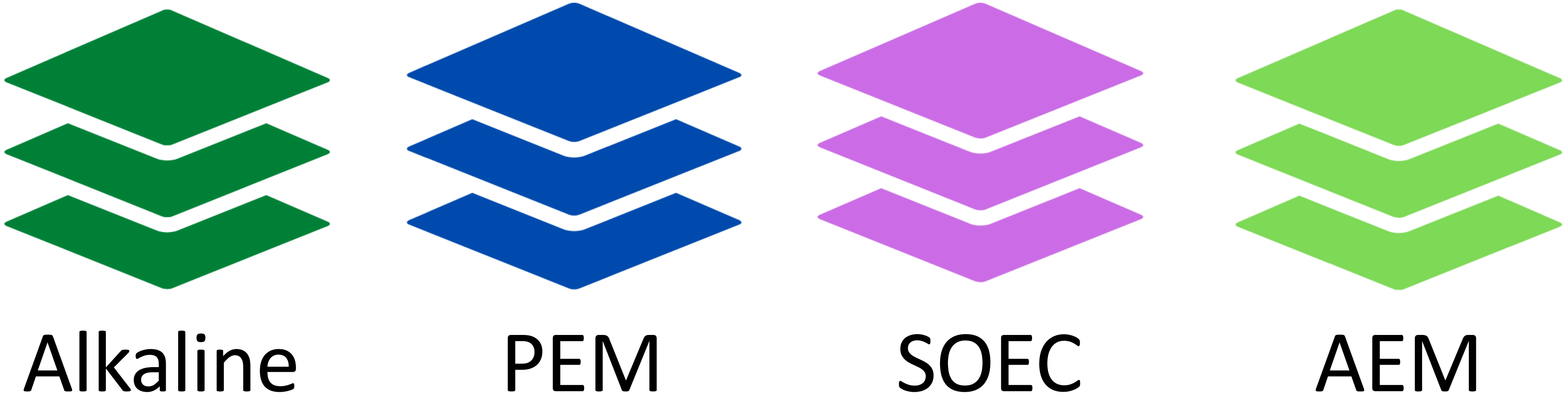
H_2 Plant: example with n electrolysers

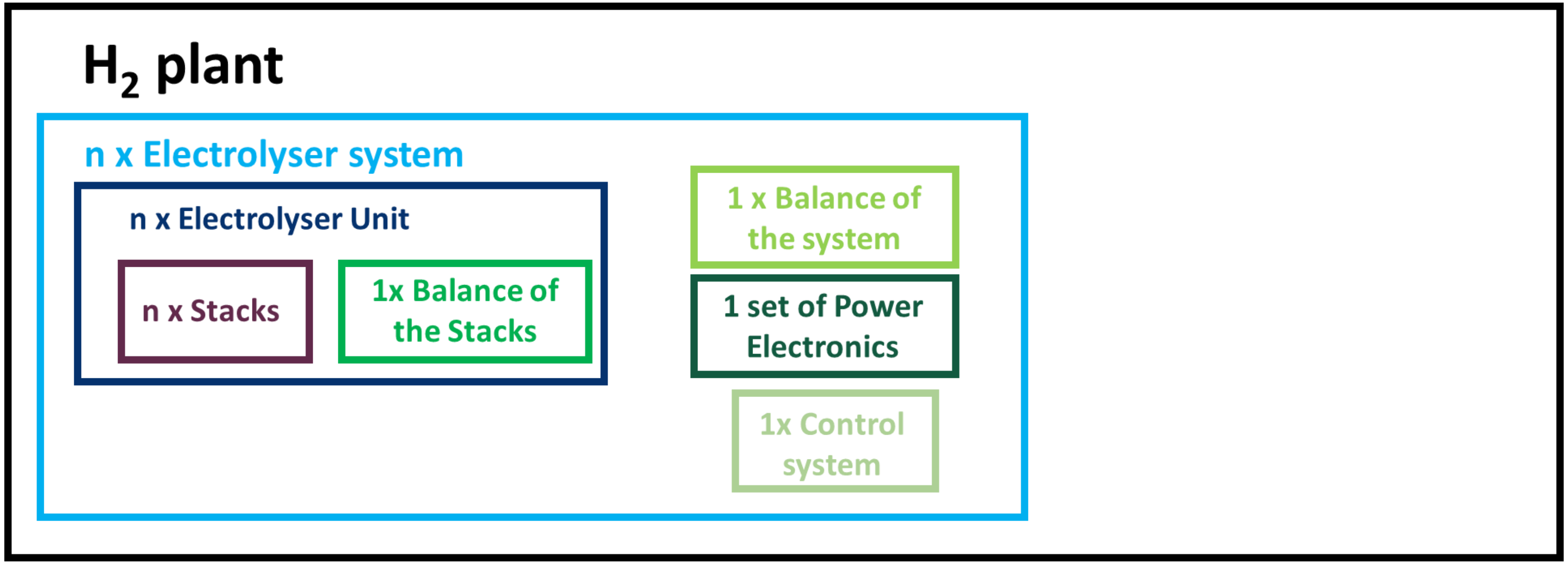


H_2 Plant: needs even more components!

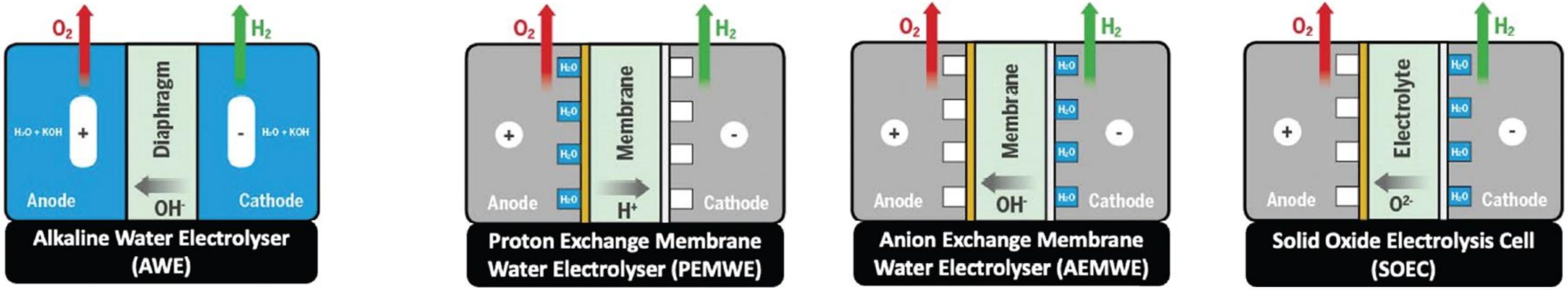


Summary of technologies: stack





Green Hydrogen Production by Water Electrolysis



Type	Low Temperature				High Temperature
	Atmospheric Alkaline (AWE)	Pressurized Alkaline (PAWE)	Proton-Exchange Membrane (PEM)	Anion Exchange Membrane (AEM)	Solid Oxide Electrolysis Cell (SOEC)

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DOI: 10.1039/d0cs01079k

Green Hydrogen Production by Water Electrolysis

Type	Low Temperature				High Temperature
	Atmospheric Alkaline (AWE)	Pressurized Alkaline (PAWE)	Proton-Exchange Membrane (PEM)	Anion Exchange Membrane (AEM)	Solid Oxide Electrolysis Cell (SOEC)
Electrolyte	Liquid (KOH-OH^-)		Solid (NAFION-H^+)	Solid (DVB-OH^-)	Solid (YSZ/CGO-O^{2-})
Pressure	Ambient	Up to 30 bar	Up to 70 bar	Up to 35 bar	Ambient
Temperature	60-80 °C		60-80 °C		600-850 °C
Materials	Ni, carbon steel		Ti, Pt, Ir	Ni, steel	Y, Zr, Ni, Co, Stainlesss steel
Stack size	1-5 MW	5 MW	1-2 MW	1-5 kW	10-50 kW
System size	1 GW	1 GW	1 GW	1 MW	50 MW

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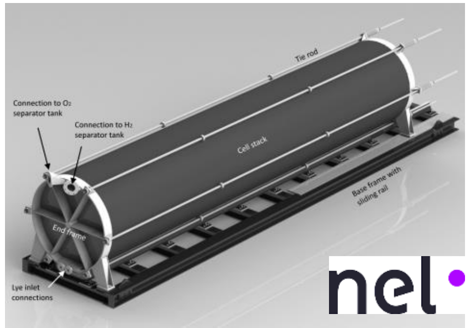
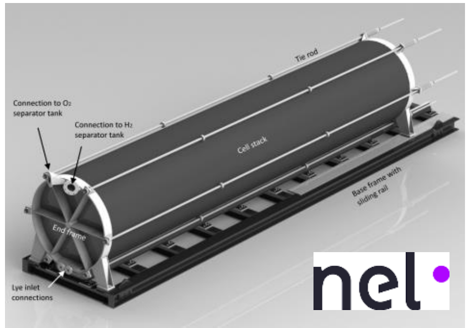
Summary of technologies: stack



	Alkaline	PEM	SOEC
Size	5 MW / 15 m^3	2.5 MW / 2 m^3	0.05 MW / 0.1 m^3
H_2 production	101 kg/h	49 kg/h	1.3 kg/h
Energy consumption	51 kWh/kg (65 %)	52 kWh/kg (64 %)	40 kWh/kg (83 %) – Up to 35 kWh /kg (95 %) with external heat
Life time	80 000 h	60 000 h	20 000 h

Summary of technologies: different electrolyser types



	Alkaline	PEM	SOEC
Advantages	+ Low CAPEX + Mass Manufacture	+ High Flexibility + Small footprint	+ Low energy consumption + Inexpensive materials
Drawbacks	– Large footprint – Energy consumption	– High CAPEX – Energy consumption	– Small volume productions – Durability

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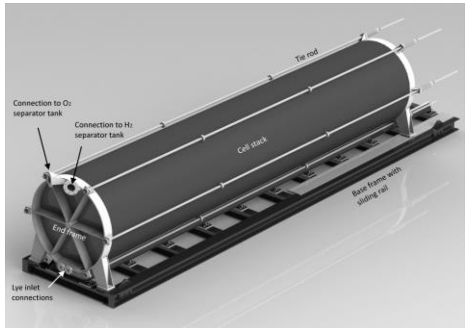
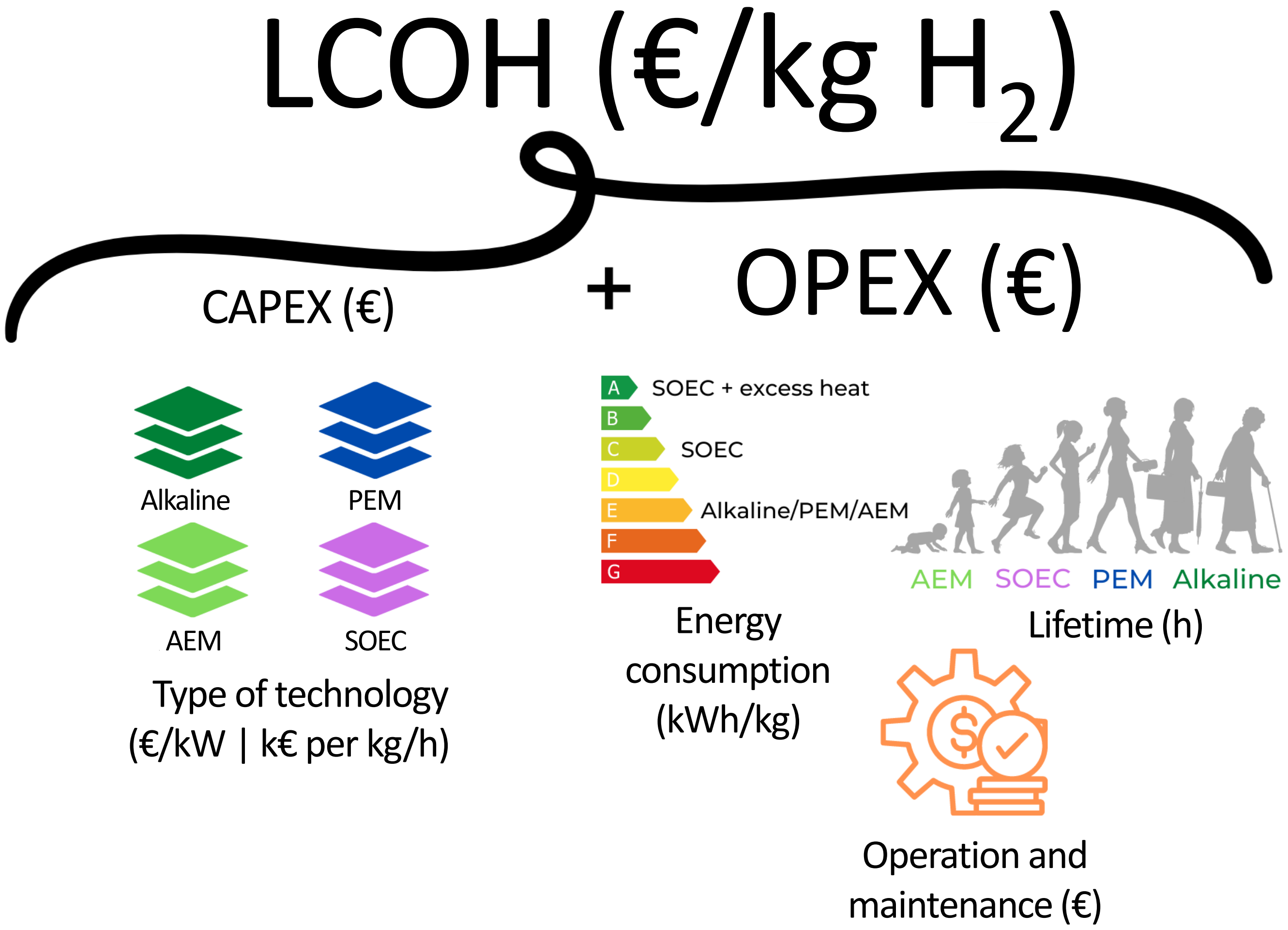
Summary of technologies: 2030 perspective



	Alkaline	PEM	SOEC
R&D efforts	Improved efficiency with better catalyst microstructures	Reduced expensive components such as Ti, Ir, Pt	Increase stack sizes and durability
2030 perspective (if R&D succesful)	Industrial projects with continuous supply of electricity	Projects with limitation of space and variable renewable electricity	Industrial projects with excess heat available

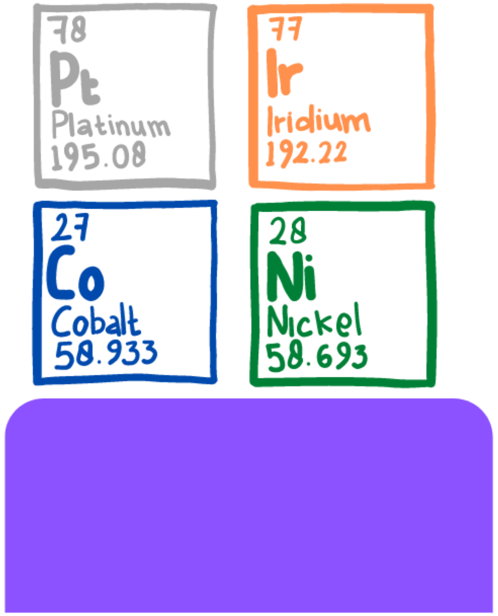
Levelized Cost of Hydrogen (LCOH): Impact of Electrolysis Technology



The importance of addressing OPEX in order to obtain low Levelized Cost of Hydrogen (LCOH)

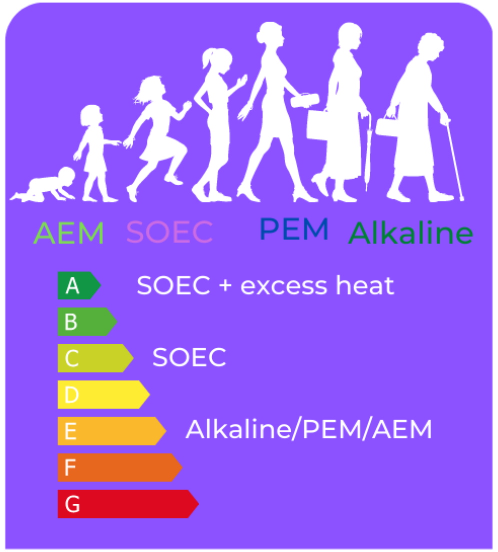
Reduction in LCOH (%)

6.7 % reduction



-50 % CAPEX reduction

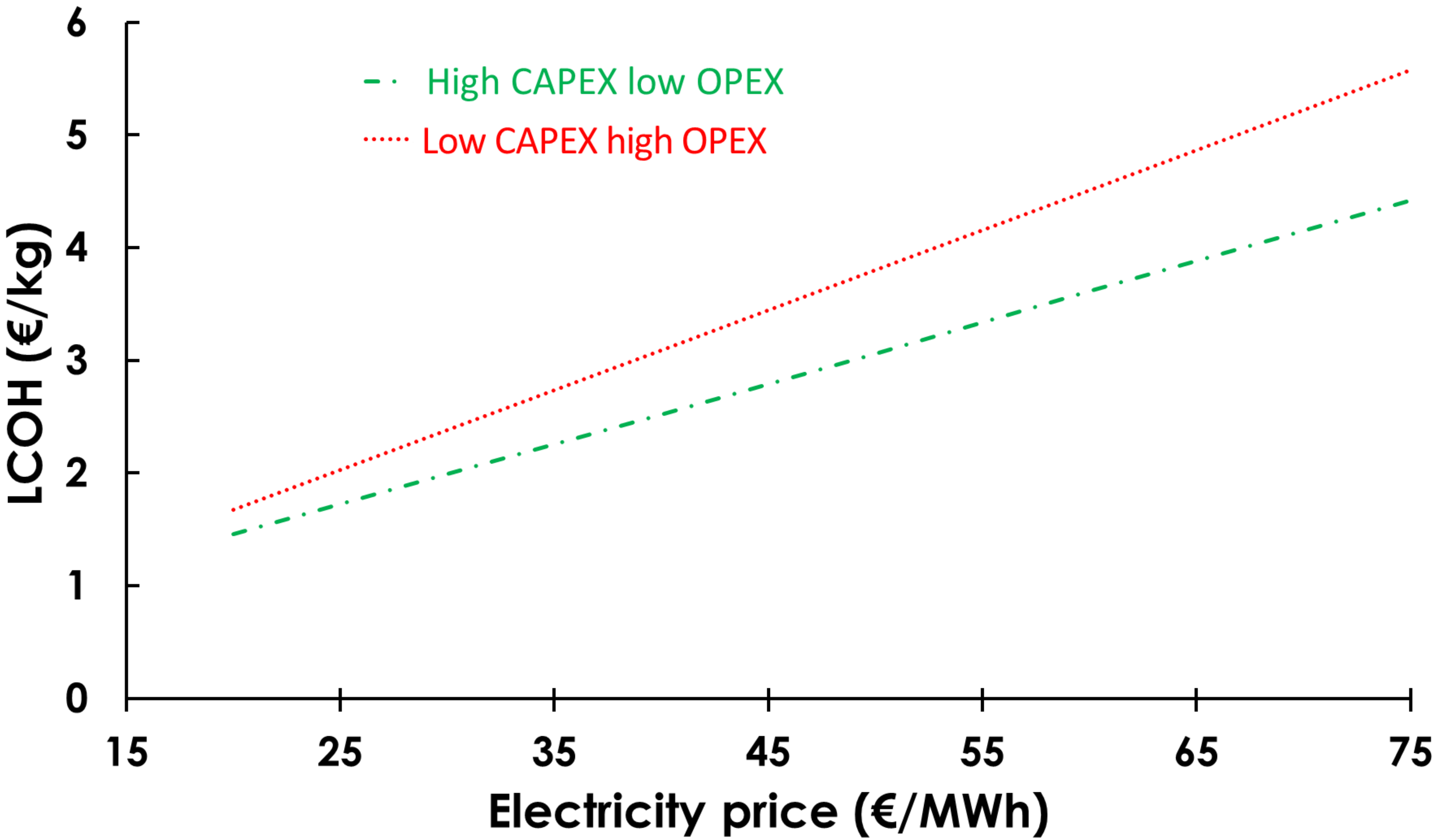
17 % reduction



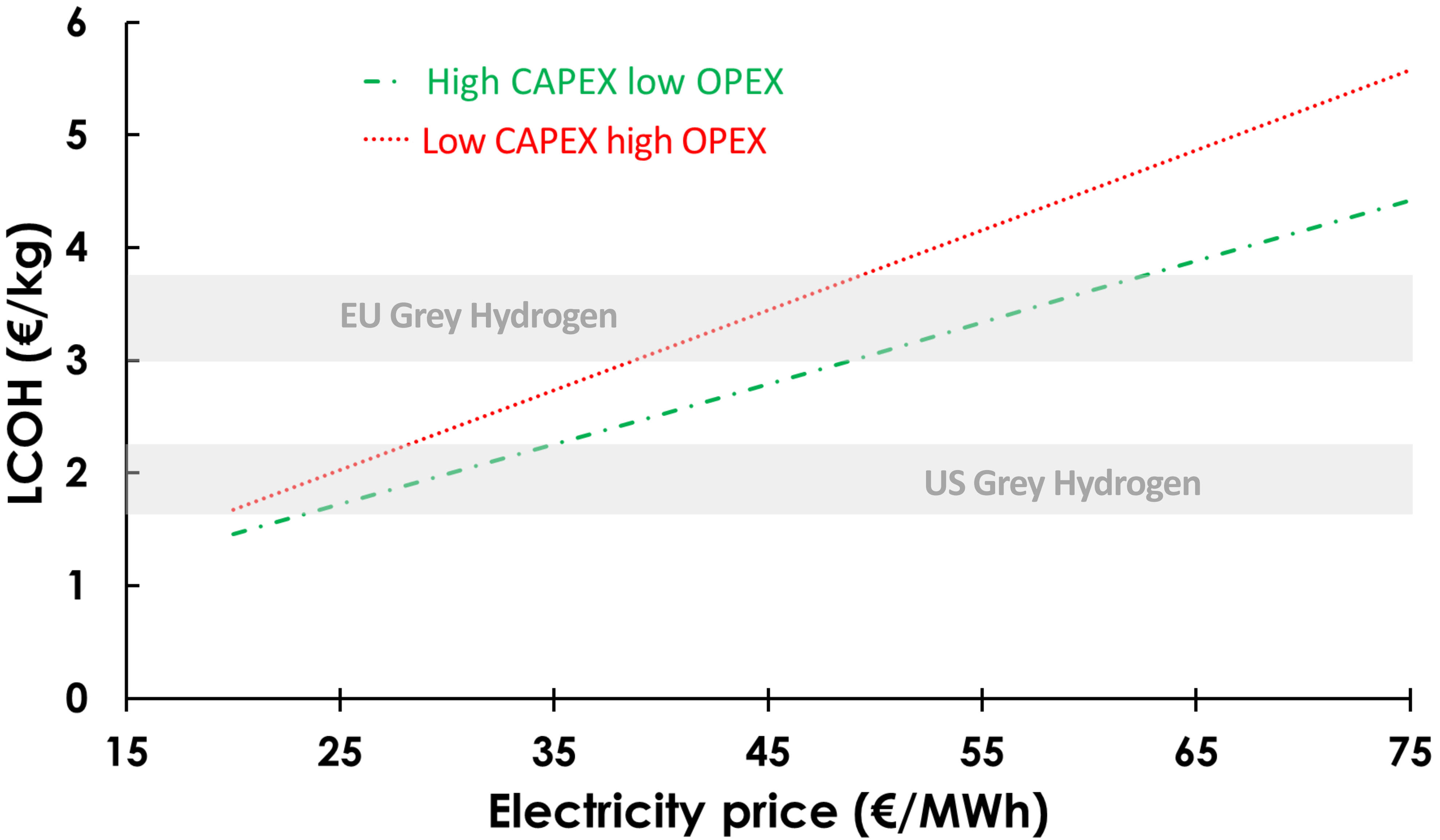
-25 % OPEX reduction

*Electricity price = 40 €/MWh

LCOH vs Electricity Price

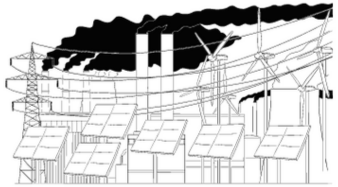


LCOH vs Electricity Price



Electricity Price in Europe





Country	Solar energy €/MWh	Wind energy €/MWh	Electricity average price €/MWh
Spain	30	27	176
Sweden	50	37	111
France	76	43	121
Germany	55	50	151
Netherlands	90	41	133
UK	90	40	210

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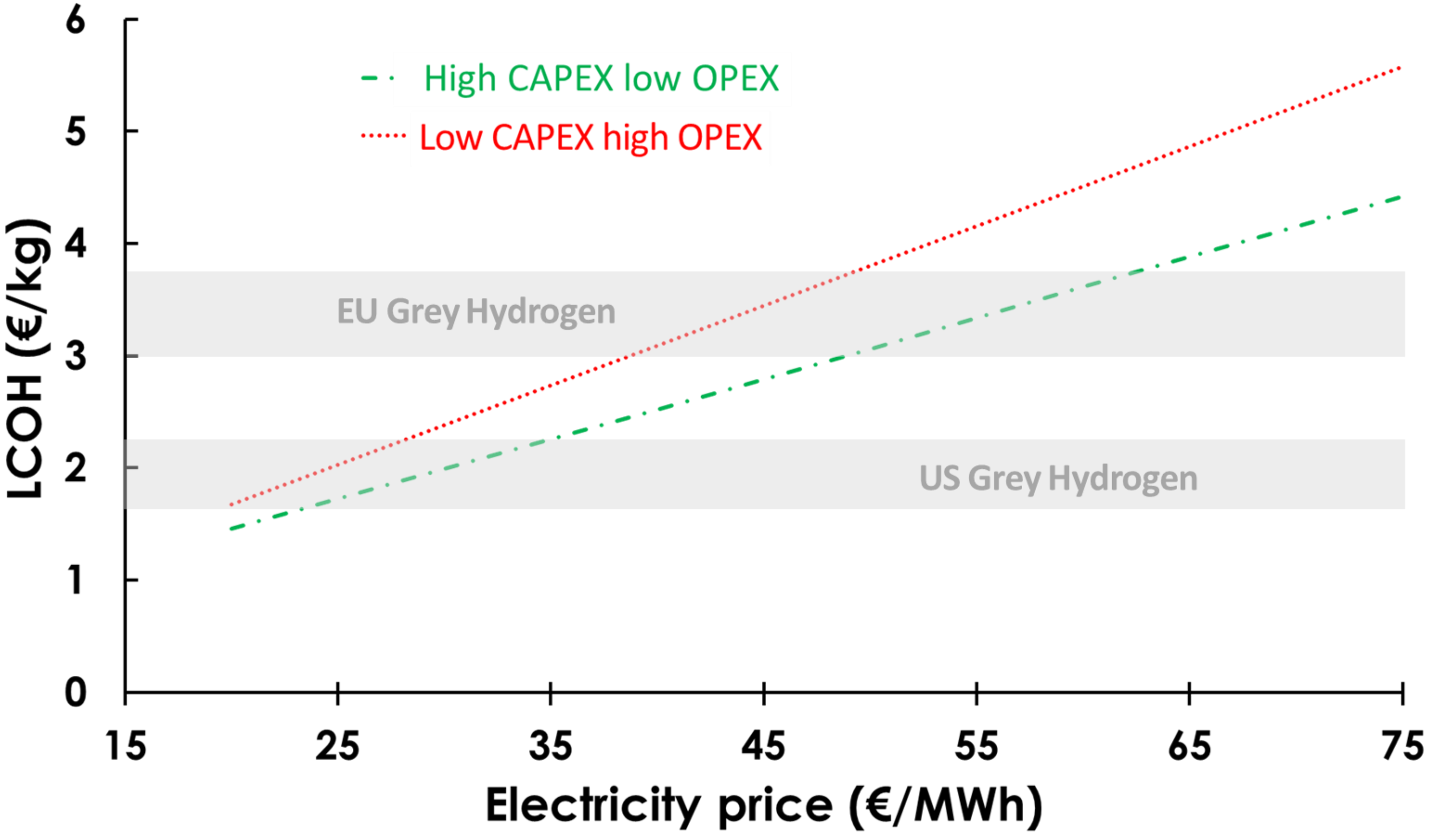
LCOH vs Electricity Price



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Take home messages and perspectives

- Power-to-X : Ramboll capabilities → From Initiation to execution
- H_2 plant: More than electrolysers
- Electrolysis technologies: Pros and Cons with every technology. Think about the specificity of your project
- LCOH: Electricity price is your key parameter → Think of your OPEX!

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Bright ideas. Sustainable change.

Gr

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Thanks!

Danke!

¡Gracias!

Tack!!