TNO innovation for life

Strategies to accelerate the energy transition using next-generation electrolyser technologies for green hydrogen

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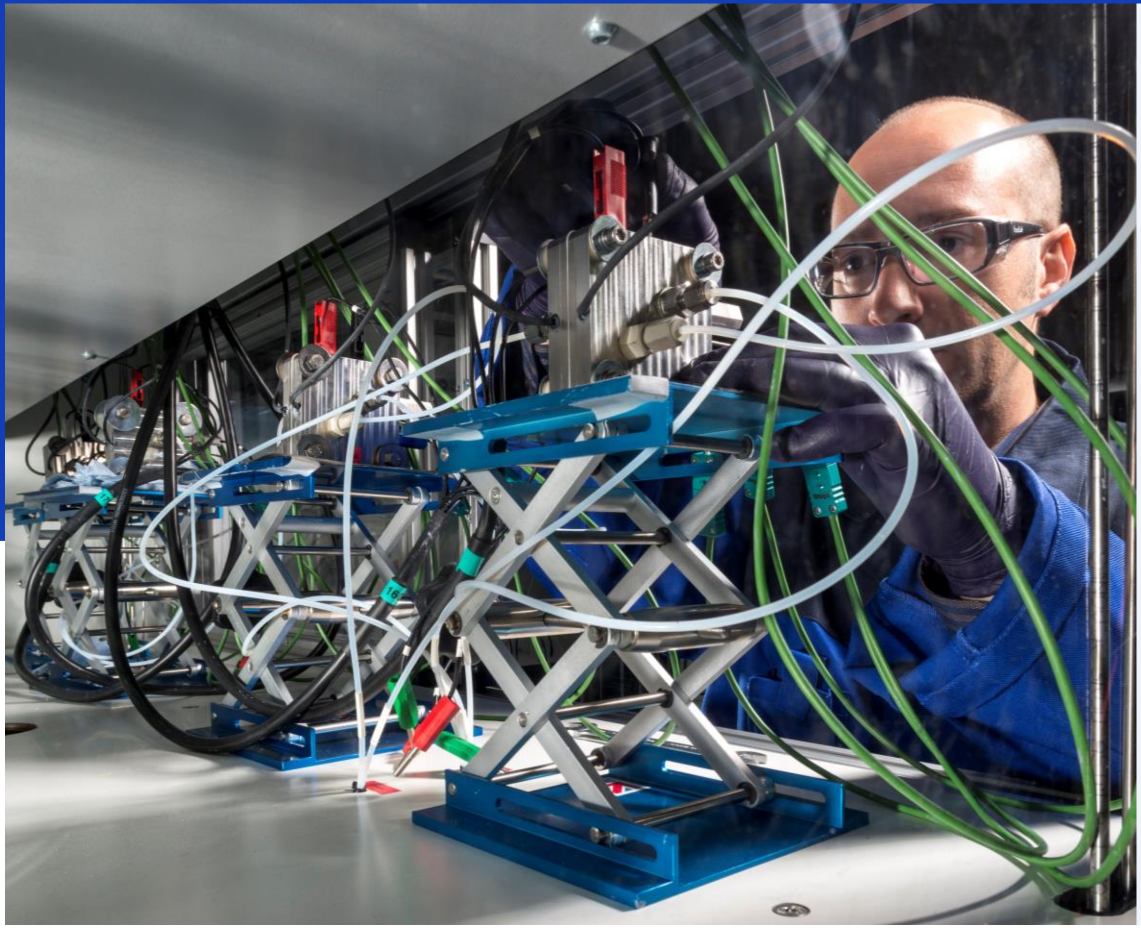
Talk Outline



1. **Introduction** TNO
2. **TNO H_2 program**
3. **Key Research Challenges**
4. **Low Iridium technology** as a promising solution for PEM
5. **Business case** current & future cost of green hydrogen
6. **Accelerating Innovation**
7. **Summary**

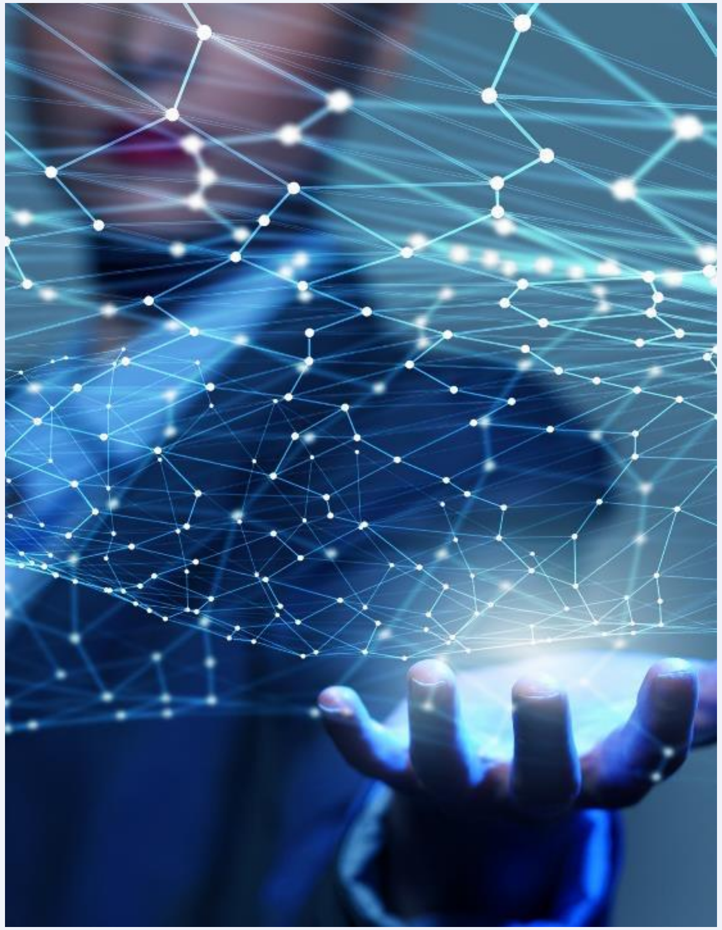
Netherlands Organisation for Applied Scientific Research

Connecting people and knowledge

Creating innovations

Sustainably strengthening business competitiveness

Sustainably strengthening well-being across society



TNO key figures 2023

4316

Number of employees

1,067

Public-private partnerships

62

Lecturers professors

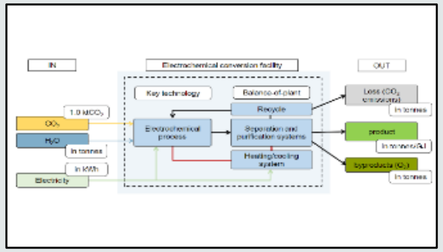
937

Patents

Our value proposition in Hydrogen and Power-2-X

*We help customers from the process industry and equipment supply sector to **select Power-2-X technologies**, **identify the right partners** and **de-risk development by collaborative R&D** on efficiency, durability, scalability and technology integration towards first industrial pilot.*

System Integration



Integrated (collaborative) assessments to better understand opportunities, de-risk investments and facilitate decision making.

Main focus:
- Value chain integration & regulatory assessment
- Multi-criteria technology assessment
- Accelerated scale-up and scale-out approach

Hydrogen Production

Cost reduction and scale up of water electrolysis and integration in industrial processes towards fuels and added value chemicals.

Main focus:
- Next generation PEM water electrolysis
- Next generation AEM water electrolysis
- Next generation Solid Oxide steam electrolysis
- Photochemical hydrogen production

Chemicals Production

Development, testing and implementation of innovative electrosynthesis and plasma technologies the production of chemical building blocks.

Main focus:
- Solid Oxide electrolysis of CO2
- Electro-synthesis from CO2 and bio-feedstock
- Plasma-synthesis from waste gases and CO2
- Photochemical conversion of CO2

Collaboration models

- Business community membership
- Contract R&D and Consultancy
- Sponsored and shared research
- Subsidized research collaboration

Orchestrating unique cross-sector ecosystems

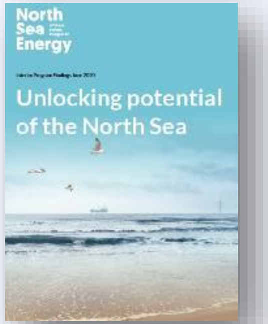
North Sea Energy

Offshore industry, Energy infrastructure & Hydrogen OEM's

In collaboration with:

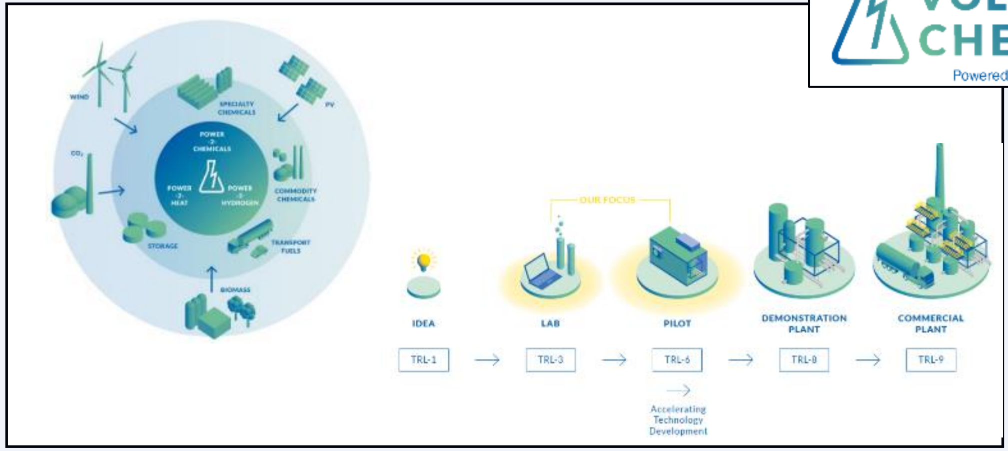
Supported by:

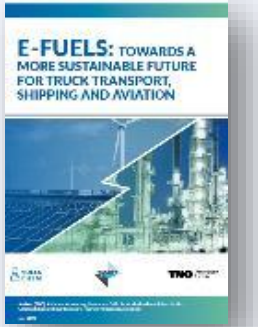
www.north-sea-energy.eu



VoltaChem

Chemical industry, Power-2-X OEM's and high-tech providers



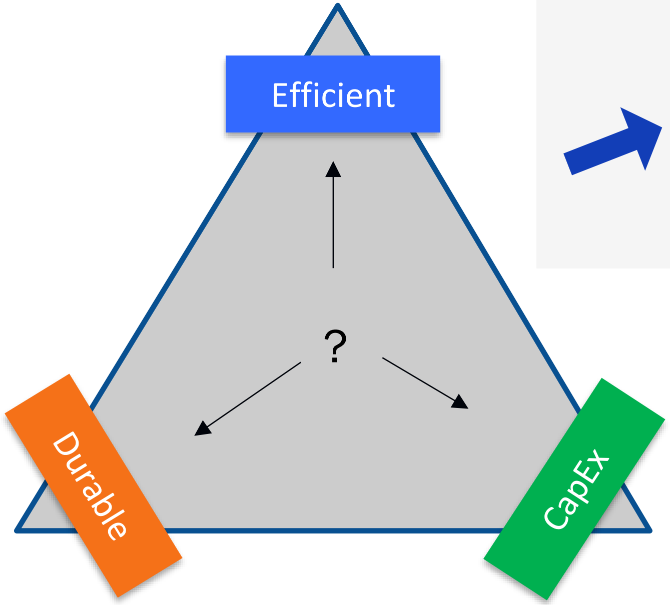


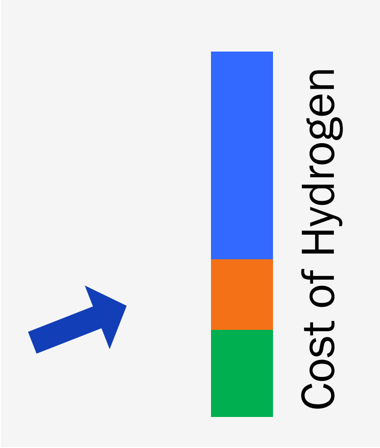
Trade-off between Efficient – Durable – Low cost

- In design and operation of electrolyser systems there are important trade-offs between efficiency, durability and capital expenditure

Table: Example of trade-offs in design & operation

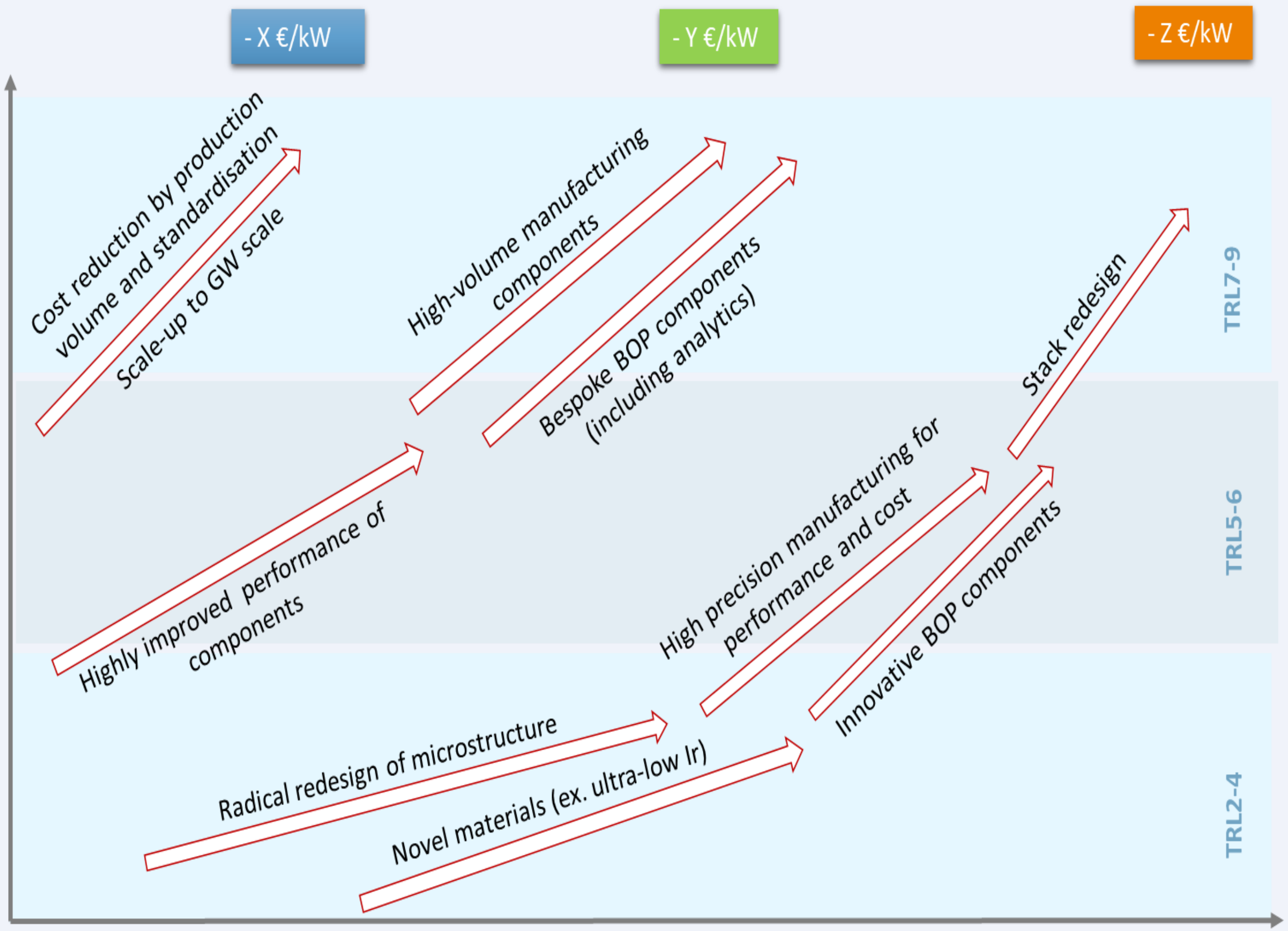
		Efficiency	Capex	Durability (Lifetime)
Cell design	High catalyst loading	+	-	+
	Thick membrane	-	-	+
Operating conditions	High temperature	+	+	-
	High current	-	+	-





Concept of electrolyser generations

- Our view on innovations & role of TNO



	TNO Role
1st generation • Current technology used by OEM's. Substantial cost reduction possible by simply scaling-up	Integration support
2nd generation • Development of improved components (membranes, electrodes, coatings) including high volume manufacturing	Accelerate innovation
3rd generation • Radically new architecture of cell and stack, leading to breakthrough in performance and use of scarce materials	Create new Inventions

BOP: Balance of Plant

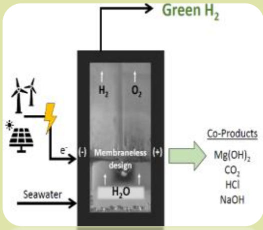
Snapshot Different companies and there are more to come

Electrolyser technologies

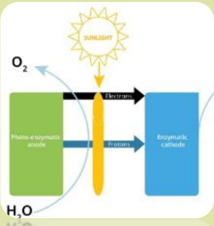
Integrated concepts

Hygro

SolHyd



sHYp



H2Win

Atmospheric alkaline

Thyssenkrupp

AKC (Asahi Kasei Corp)

NEL

Pressurized alkaline

McPhy

PERIC

John Cockerill

Hydrogen-Pro

Green Hydrogen systems

Sunfire

PEM (atmospheric and pressurized)

Siemens

Elogen

ITM

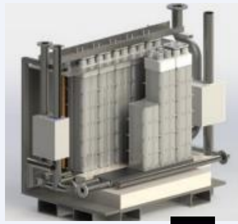
Cummins

Plug power

NEL

SOE (high temp)

Haldor Topsoe



Sunfire

Elcogen

AEM

Enapter

Hydrolite

Alchemr

New electrolyser concepts

H2Pro

Battolyser

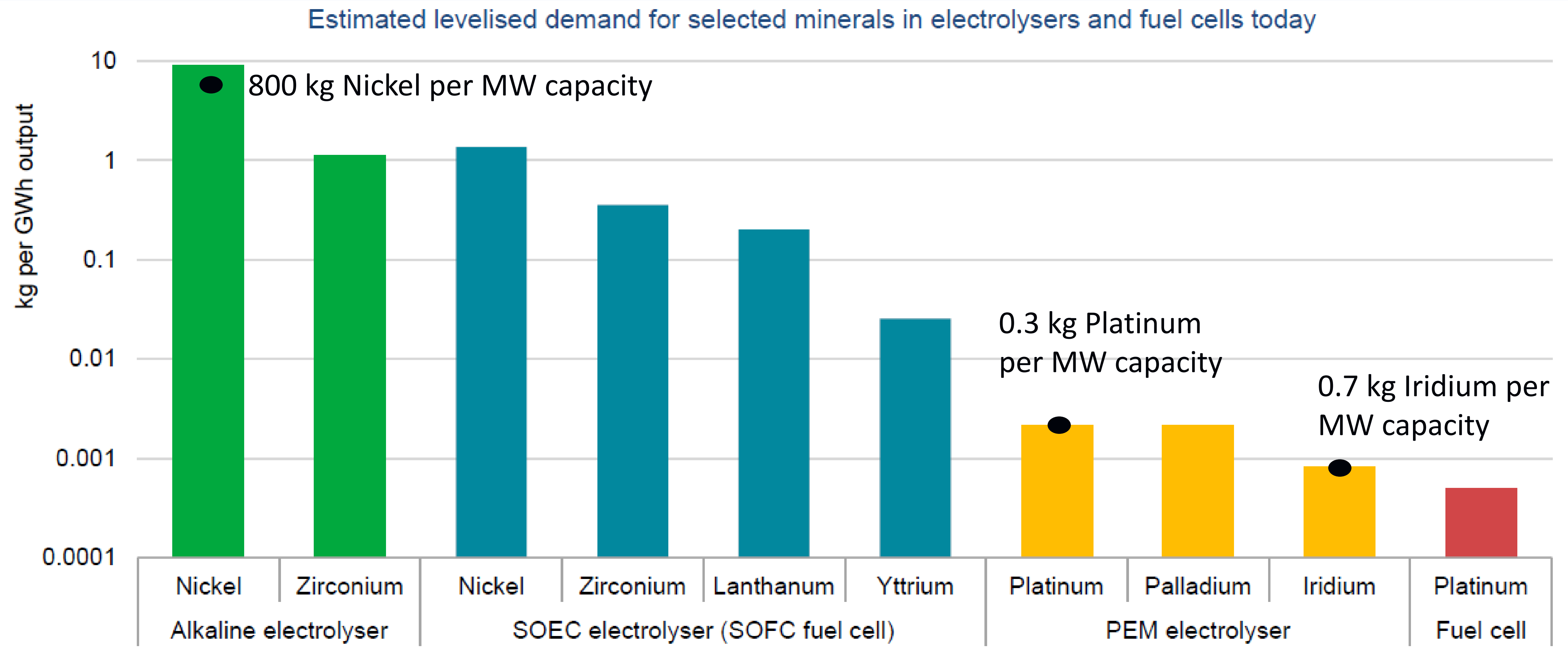
Hystar

Not an extensive list, but it includes the current main players for each technology. Multiple technology developers and start-ups working on new generation technology especially in PEM and AEM

TNO innovation for life

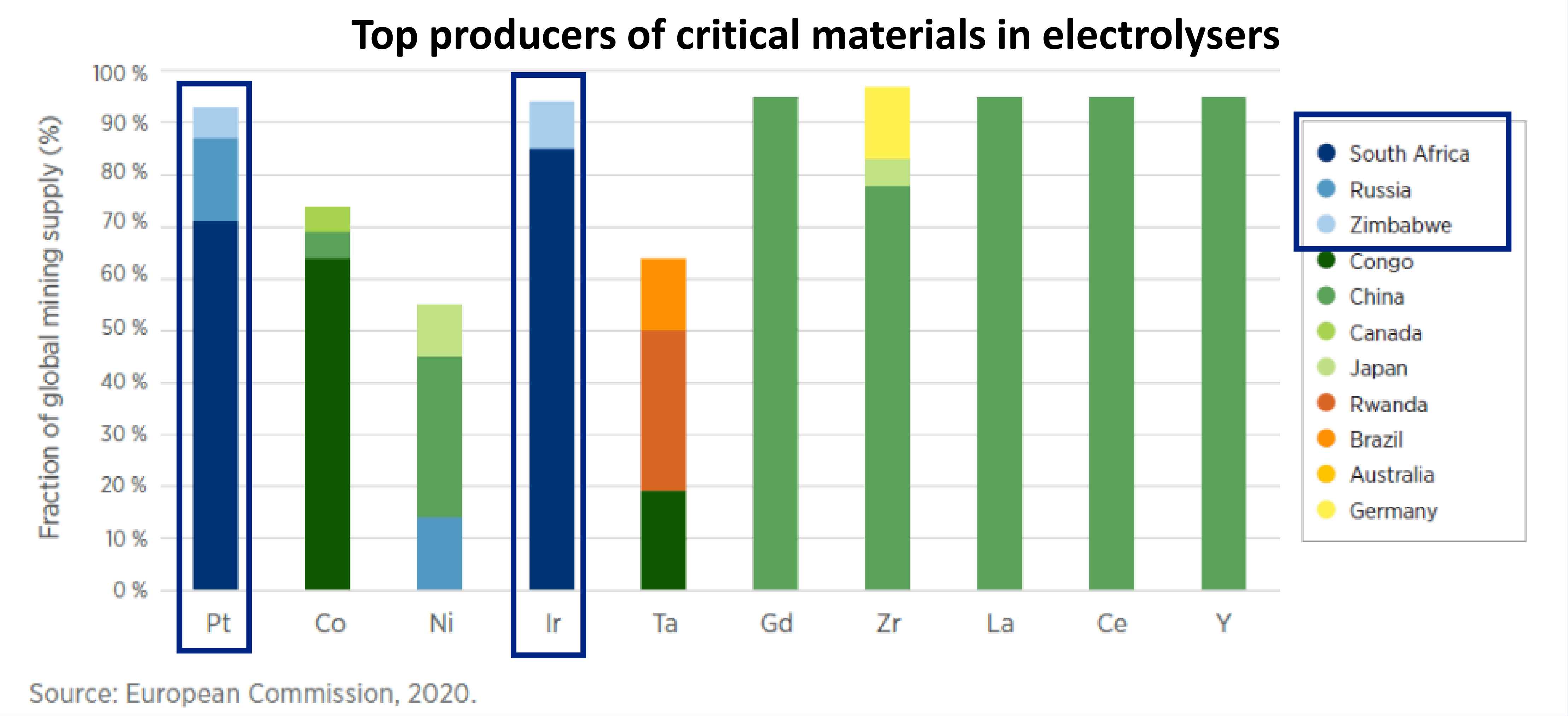
Source: HyCC, Thijs de Groot (2022); adapted by TNO; different electrolyser suppliers

Electrolysers drive up the Demand for Nickel, Platinum and other minerals



Source: IEA (2021), The Role of Critical Minerals in Clean Energy Transitions (link)

Critical materials in electrolysers: a show stopper?



Irena (2020) Green hydrogen cost reduction: scaling up electrolysers to meet the 1,5 C Climate goal (link)

Lower use of scarce materials

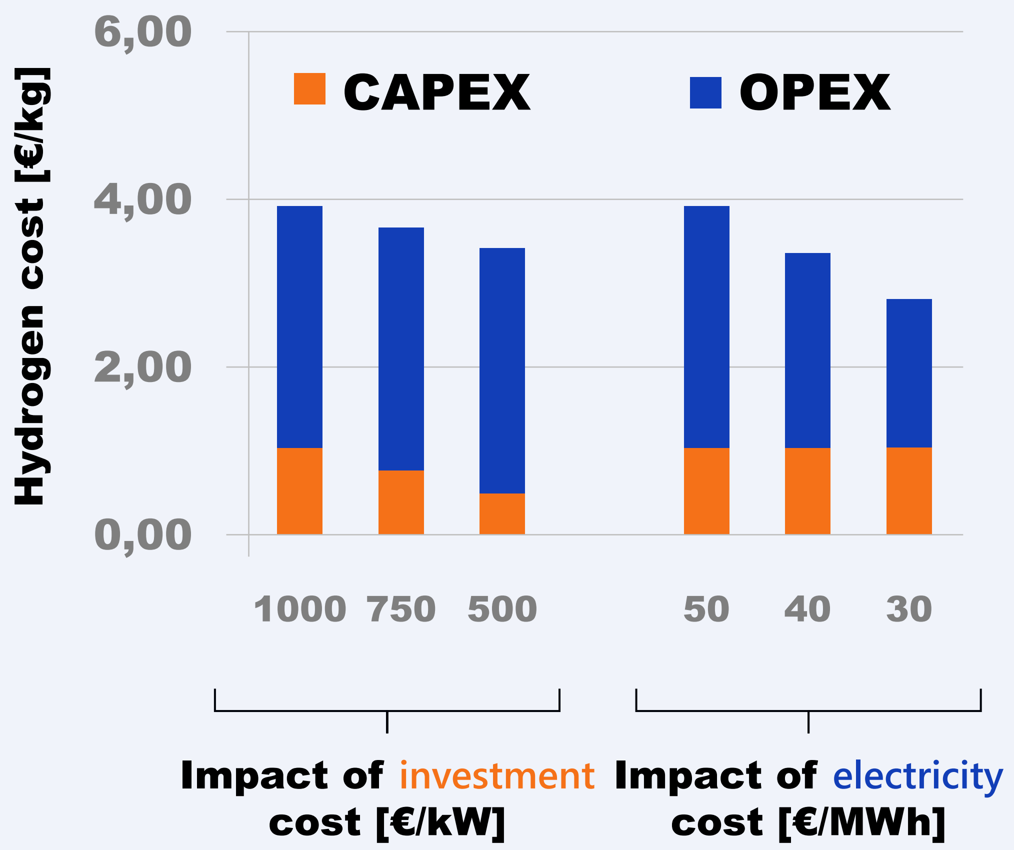
- **Different strategies to reduction**

% of CRM global annual supply used as a result of each strategy							
	CRM	**Base case**	**Reduction**	**Substitution**	**Higher productivity**	**Extended lifetime**	**Recycling**
PEM	Iridium	122%	6%	122%	81%	91%	122%
PEM	Platinum	25%	0.1%	0%	1%	21%	24%
AEL	Raney-Ni	0.4%	0%	0.8%	0.1%	0.3%	0.0%
AEL	Nickel (class 1)	2%	2%	2%	0.6%	2%	2%
AEL	Cobalt	0.1%	0.1%	0%	0%	0%	0.1%

Strategy with most potential

Source: TNO (2021), Part 1 - How raw materials scarcity can hinder our ambitions for green hydrogen and the energy transition as a whole (link), Part 2 - How we can prevent the scarcity of raw materials and achieve our ambitions for green hydrogen (link)

Electricity price is determining the hydrogen cost

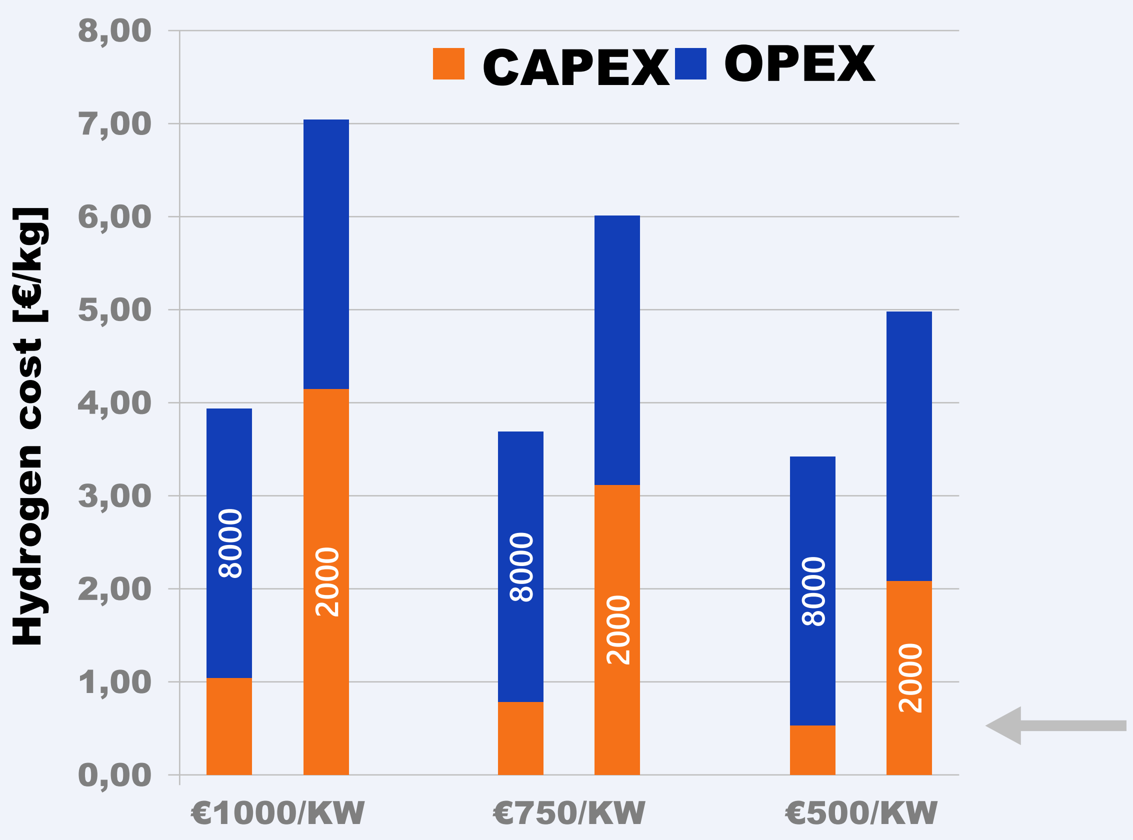


Two major costs:

- **Electrolyser costs (CAPEX)**
- **Electricity costs (OPEX)**

Base case (BC)	
Investment cost	1000 €/kW
Depreciation	15% /year
O&M	2% /year
Electricity price	50 Euro/MWh
Operating hours	8000 hours
Efficiency	60%

When operating flexible, capex becomes dominant



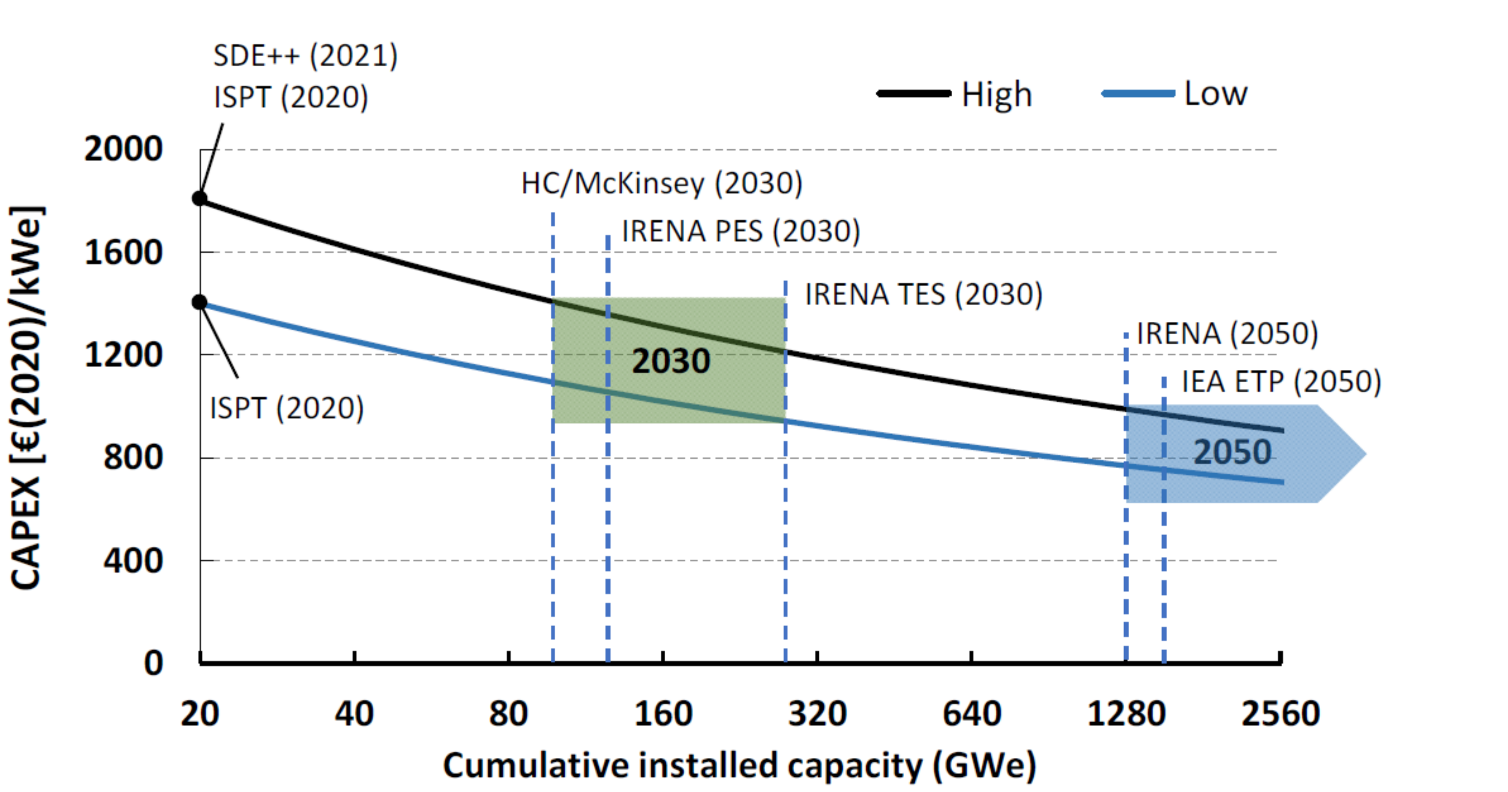
Cost reduction
- Stack
- Balance of plant and system
- Smart contracts with offshore wind

and

Increase profit
- Multiple H_2 markets
- Reference cost grey hydrogen increases
- Value of flexibility
- Value of oxygen
- Value of heat

Operational hours per year

Projected Learning Curve | Electrolyzer Investment Costs

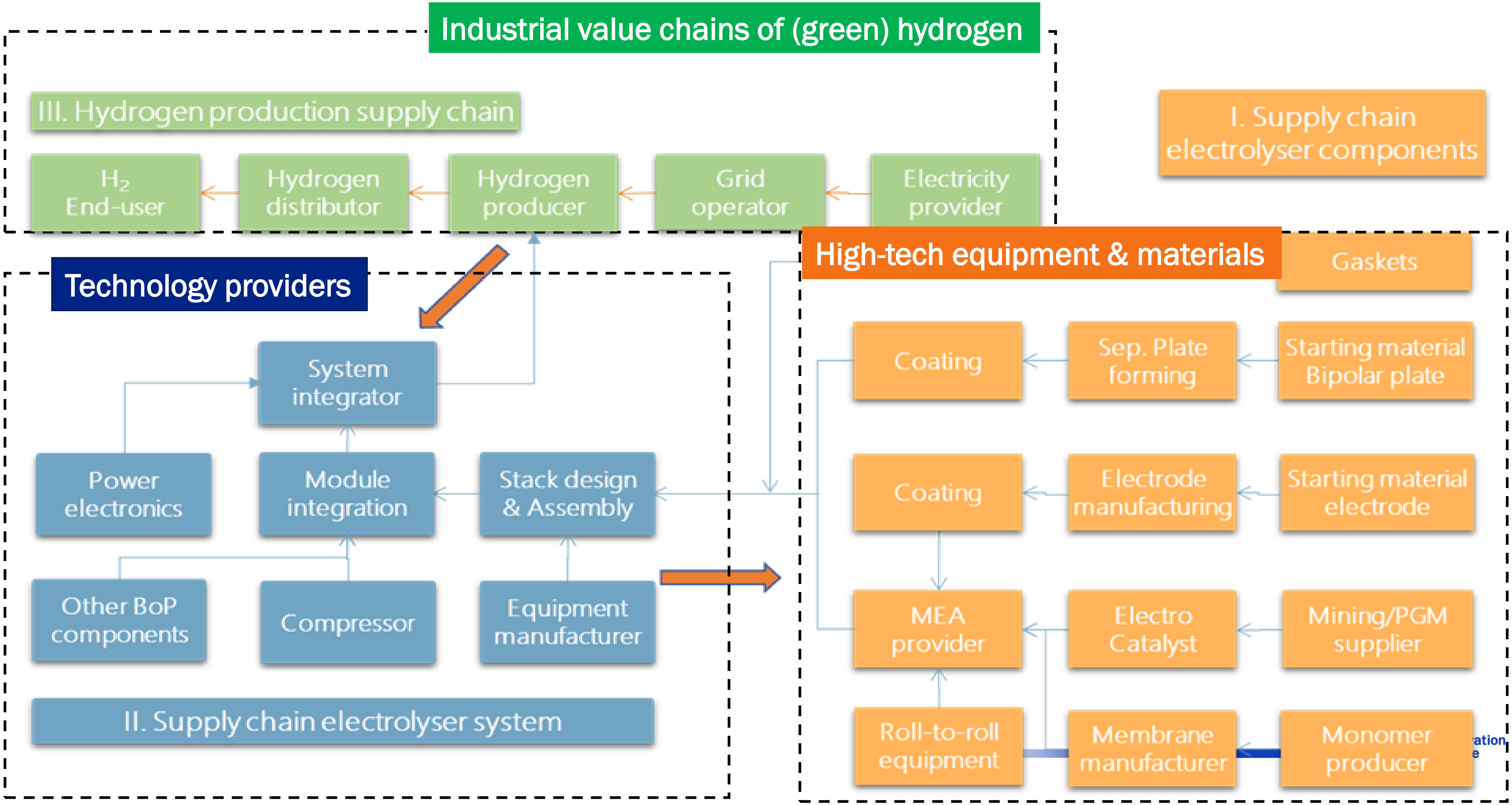


- The **learning rate** of all electrolyser technology varies between 12-20%. However, it will differ between PEM, Alkaline, SOE.
- PEM and SOE can **benefit from fuel cell developments**
- To reach a cumulative installed capacity of 100 GW in 2030, annual installation need to double each year until 2030

2030
High: 1100 – 1350 (Euro/kWe)
Low: 650 – 850 (Euro/kWe)

Source: TNO (2022) Projections of electrolyzer investment cost reduction through learning curve analysis ([link]),

Developing the electrolyser supply chain



How to accelerate the technology development?

- Get out of the Lab faster into industrial Demo’s

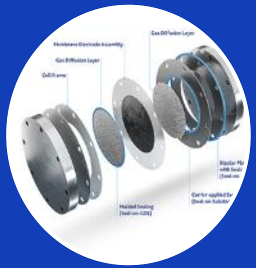
TNO facilities	Industrial electrification	Water electrolysis	*Offshore H2 production*
Lab scale Up to 50 KW TRL 2-5			
Industrial Scale 0.1- 1 MW TRL 5-6			
Demonstration Multi MW TRL 6-7	*In progress*	*In progress*	*In progress*

Introduction

5 pillars of the TNO electrolysis program 'Clean Hydrogen Production'

Our Added Value in the Electrolyser Value Chain





SYSTEM INTEGRATION

Developing models

Sensors & state-of-health

Monitoring & Control solutions

Use cases

Offshore electrolysis

ACCELERATE LEARNING CURVE

State-of-art facilities

Protocols for fabrication & testing of components, cells & stacks

Validation & benchmarking

Accelerated testing

NEXT GENERATION PEM TECHNOLOGY

Novel materials & components incl. manufacturing

Optimal integration in cells & stacks

2nd & 3rd generation PEM

NEXT GENERATION SOE TECHNOLOGY

Large scale SOE cell development, manufacturing & validation

Cell development

2nd generation SOE

BREAKTHROUGH TECHNOLOGY

Developing new & disruptive game changing electrolyser concepts

Scouting technology

High-Performance AWE

AEM

Focus areas

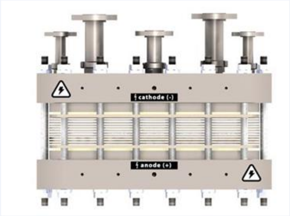
Orchestrating Innovation: Connecting the ecosystem(s) for innovation and implementation

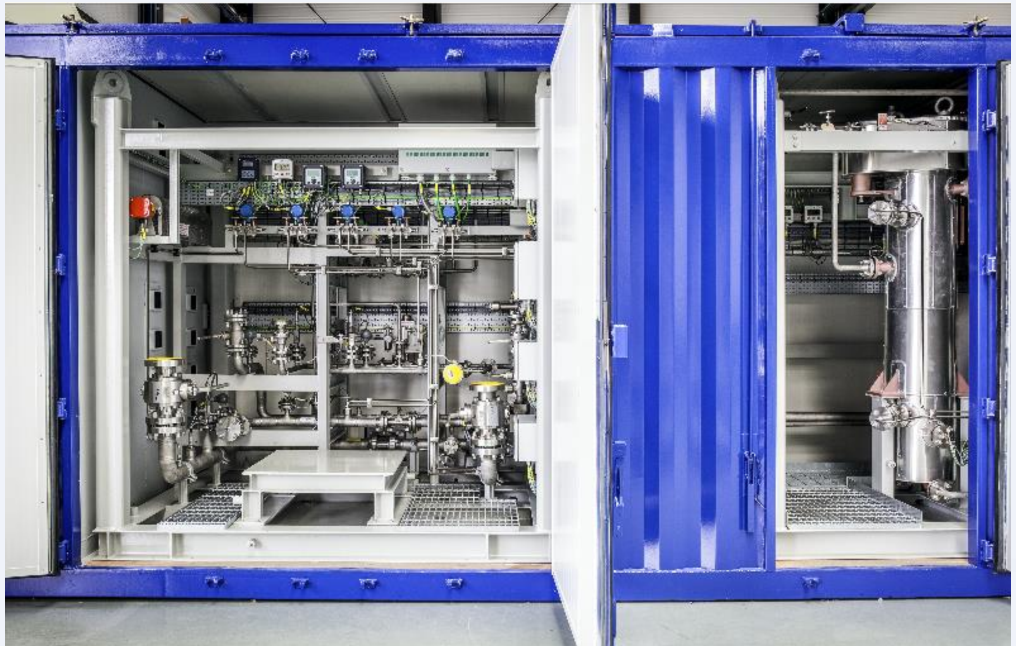
Manufacturing Technology: Component & System Interaction

Value from System Engineering: Using feedback/feedforward of knowledge on the entire chain

World’s largest open electrolyser test centre

- MW Test Center
- **TNO Develop & build 250 kW PEM stack**
- Commission system in Groningen (NL)
- Modelling thermal behaviour of stack
- Static and dynamic operating conditions
- Advanced process control





Summary

Addressing Technical Challenges for Electrolysers

- Scalable, low-cost technology
- Drastic reduction in critical raw materials use
- TNO's ultra-low Iridium concept
  - Performance, reproducibility, and durability improvements at 100x lower Iridium.
- High durability at high performance

Accelerating Innovation

- Parallel development of technology **generations**
- Large initiatives
- Shared programs for accelerating innovation

Want to know more? Please contact us !

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