innovation for life

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

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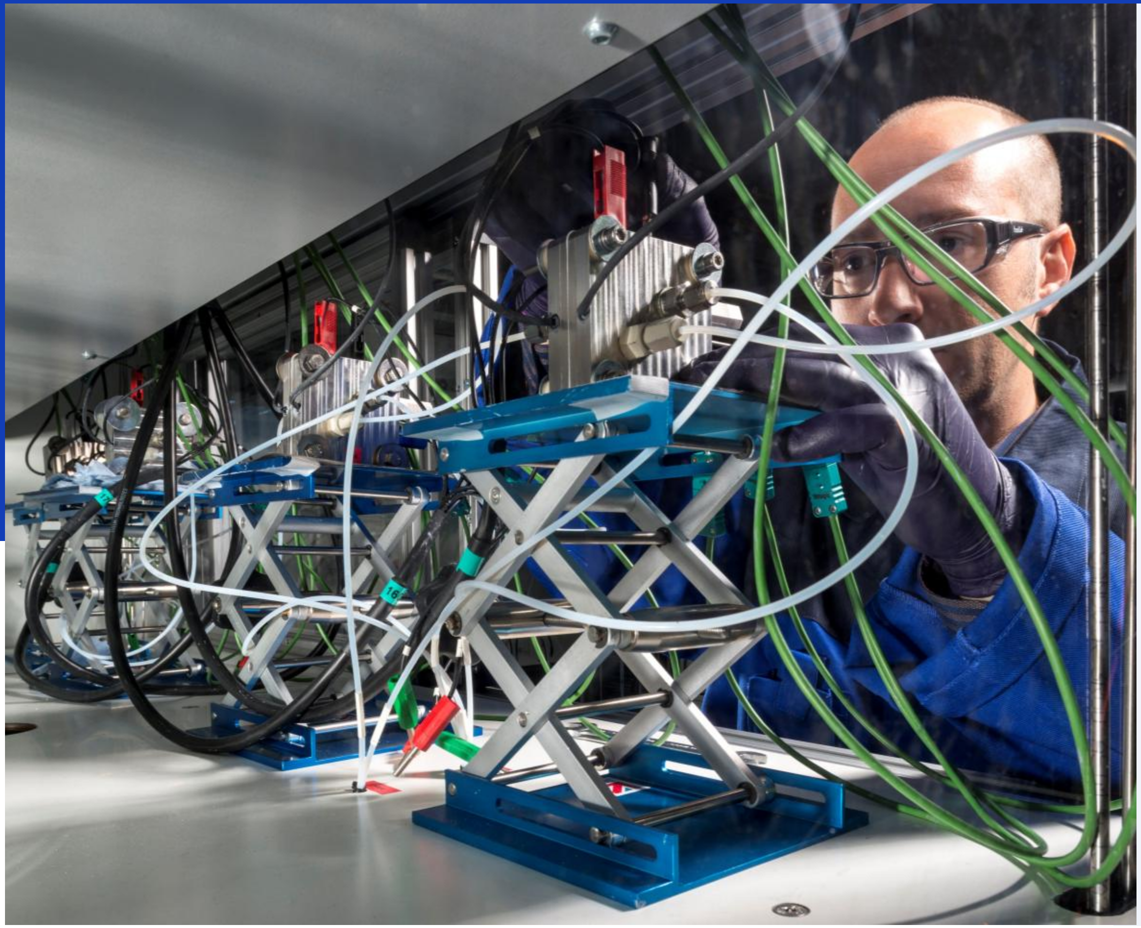
Talk Outline



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**

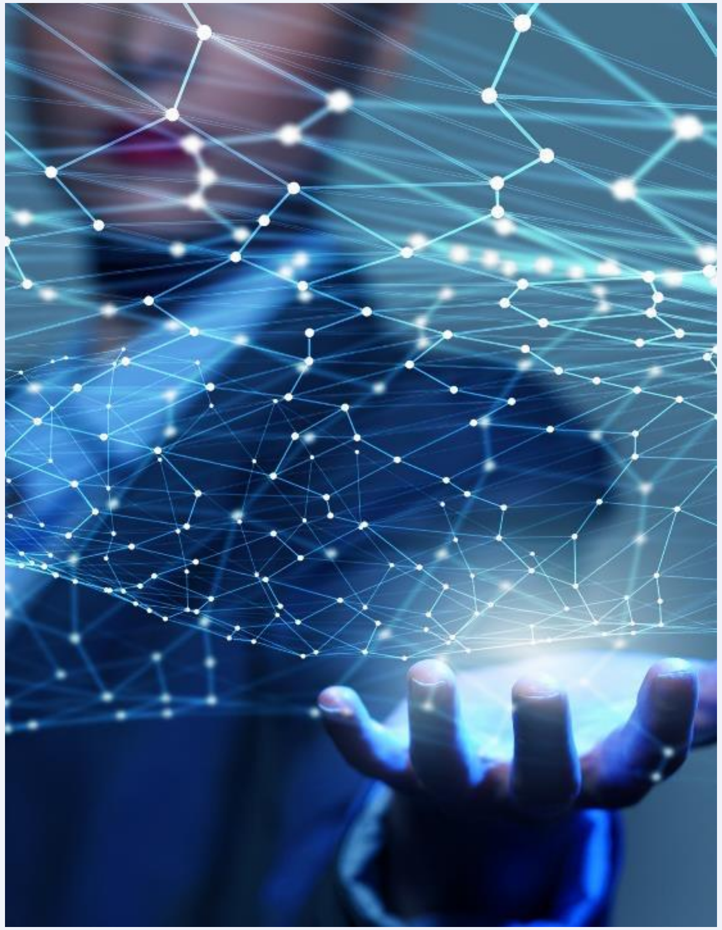
Netherlands Organisation for Applied Scientific Research

Connecting people and knowledge

Creating innovations

Sustainably strengthening business competitiveness

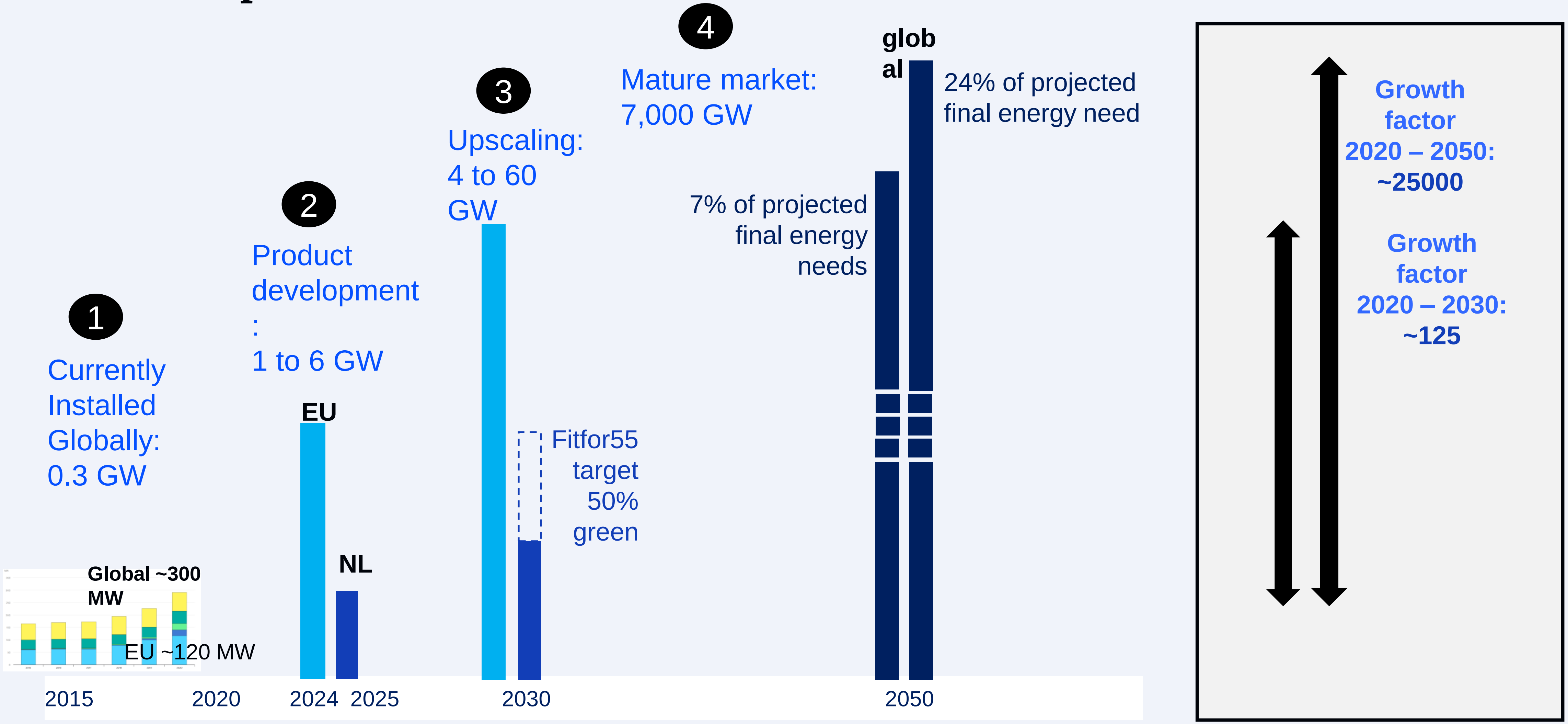
Sustainably strengthening well-being across society



TNO key figures 2022

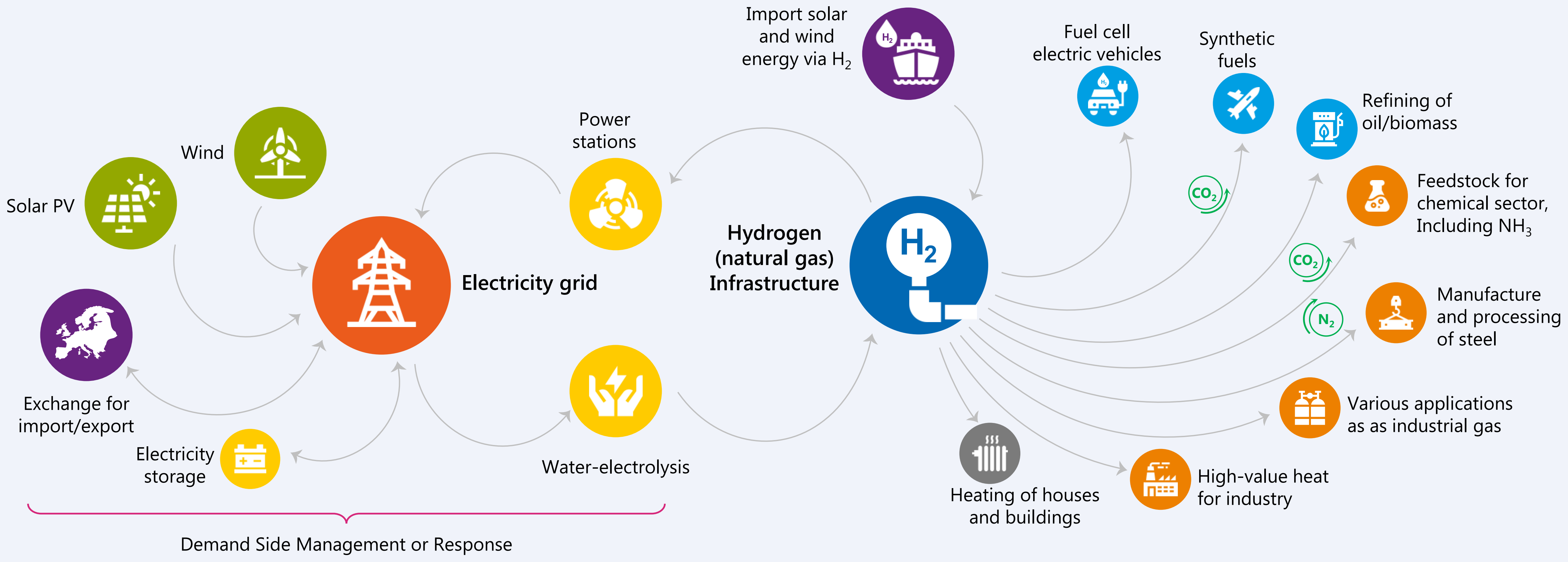
3897	1,000	42	876
Number of employees	Public-private partnerships	Lecturers professors	Patents

Market Development Forecast



Source: IEA (2021), Global installed electrolysis capacity by region , 2015-2020 (link), Bloomberg, Hydrogen Economy Outlook – Key messages, March 2020 (link), adapted by TNO

Integral system perspective on hydrogen



How Does TNO Contribute to Electrolyser Development?

Our Vision on Hydrogen

To reach our climate goals we see green hydrogen as a **key enabler** to:

- **Improve the integration of renewable electricity in our energy system**
- **Decarbonise the carbon emitting sectors** such as aviation, chemical & steel industry
- **Energy security** with underground hydrogen storage and CO_2-free dispatchable power

Our Mission In 2025

We contribute to:

- **Decreased production cost** for green hydrogen by at least 30%
- **Reduced use of scarce materials** (PGM)
- **Success of the electrolyser industry** related to the hydrogen production value chain

TNO's green hydrogen activities aim to

- Deliver technical, social and policy innovations to accelerate the development of hydrogen as a fuel and as an industrial chemical as part of the energy and materials transition
- Promote the emergence of public-private green hydrogen ecosystems such as manufacturing

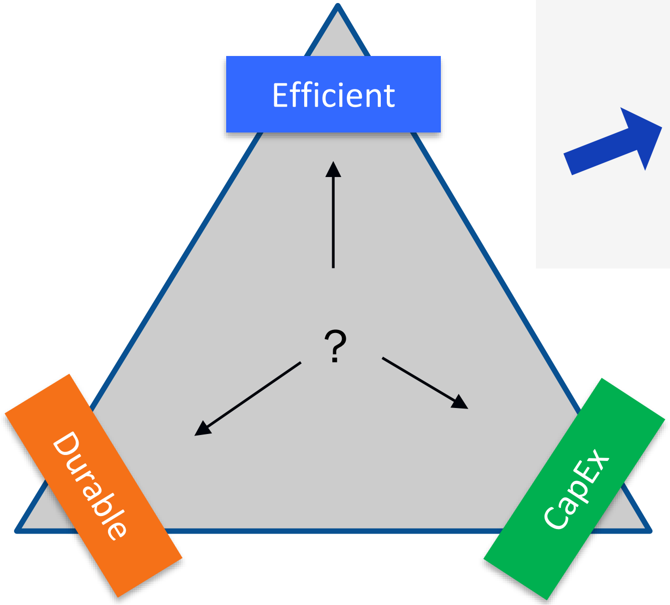
Systemic approach to technology development, technology value chain development, ecosystem and infrastructure, and end-use applications of green hydrogen

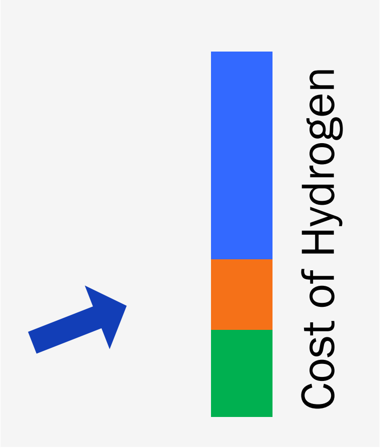
Trade-off between Efficient – Durable – Low cost

› 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

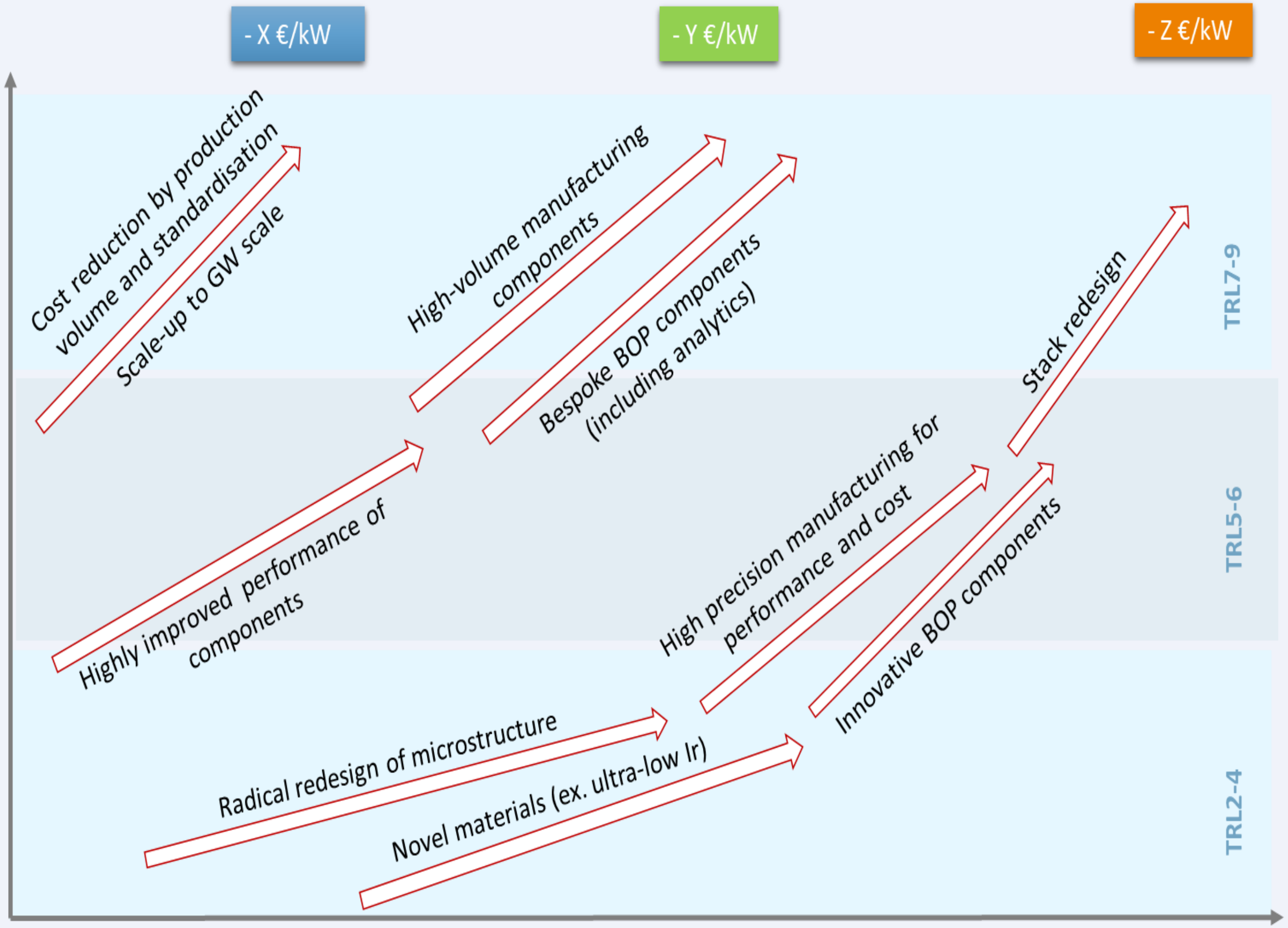
		Efficiency	Capex	Durability (Lifetime)
Cell design	High catalyst loading	+	-	+
	Thick membrane	-	-	+
Operating conditions	High temperature	+	+	-
	High current	-	+	-





Concept of electrolyser generations

- Our view on innovations & role of TNO



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

TNO Role

Integration support

Accelerate innovation

Create new Inventions

BOP: Balance of Plant

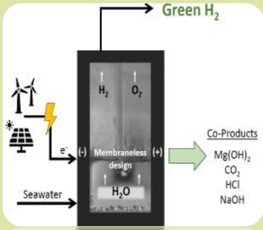
Snapshot Different companies and there are more to come

Electrolyser technologies

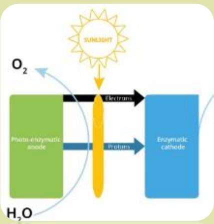
Integrated concepts

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

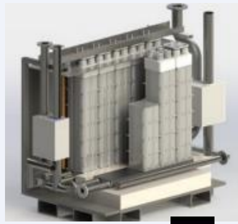
Cummins

Plug power

NEL

SOE (high temp)

Haldor Topsoe



Sunfire

Elcogen

AEM

Enapter

Hydrolite

Alchemr

New electrolyser concepts

H2Pro

Battolyser

Hystar

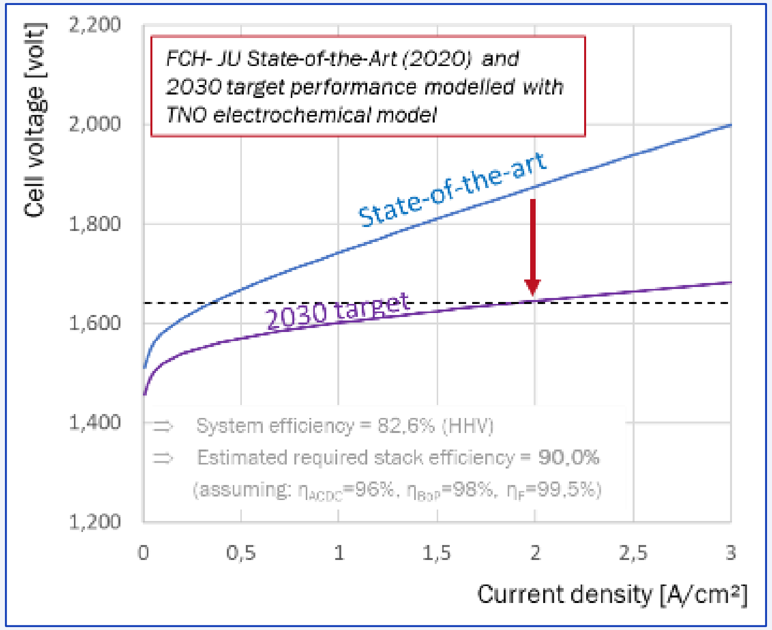
Not an extensive list, but it includes the current main players for each technology. Multiple technology developers and start-ups working on new generation technology especially in PEM and AEM

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

PEM Electrolysers **Key challenges**

Scale + durability @ high performance, (scarce) material use, cost…

No	Parameter	Unit	SoA 2020	Targets 2024	Targets 2030
1	Electricity consumption @ nominal capacity	kWh/kg	55	[illegible]	48
2	Capital cost	€/(kg/d) €/kW	2,100 900	[illegible] 700	1,000 500
3	O&M cost	€/(kg/d)/y	41	30	21
4	Hot idle ramp time	sec	2	1	1
5	Cold start ramp time	sec	30	10	10
6	Degradation	%/1,000h	0.19	[illegible]	0.12
7	Current density	A/cm²	2.2	2.4	3
8	Use of critical raw materials as catalysts	mg/W	2.5	[illegible]	0.25



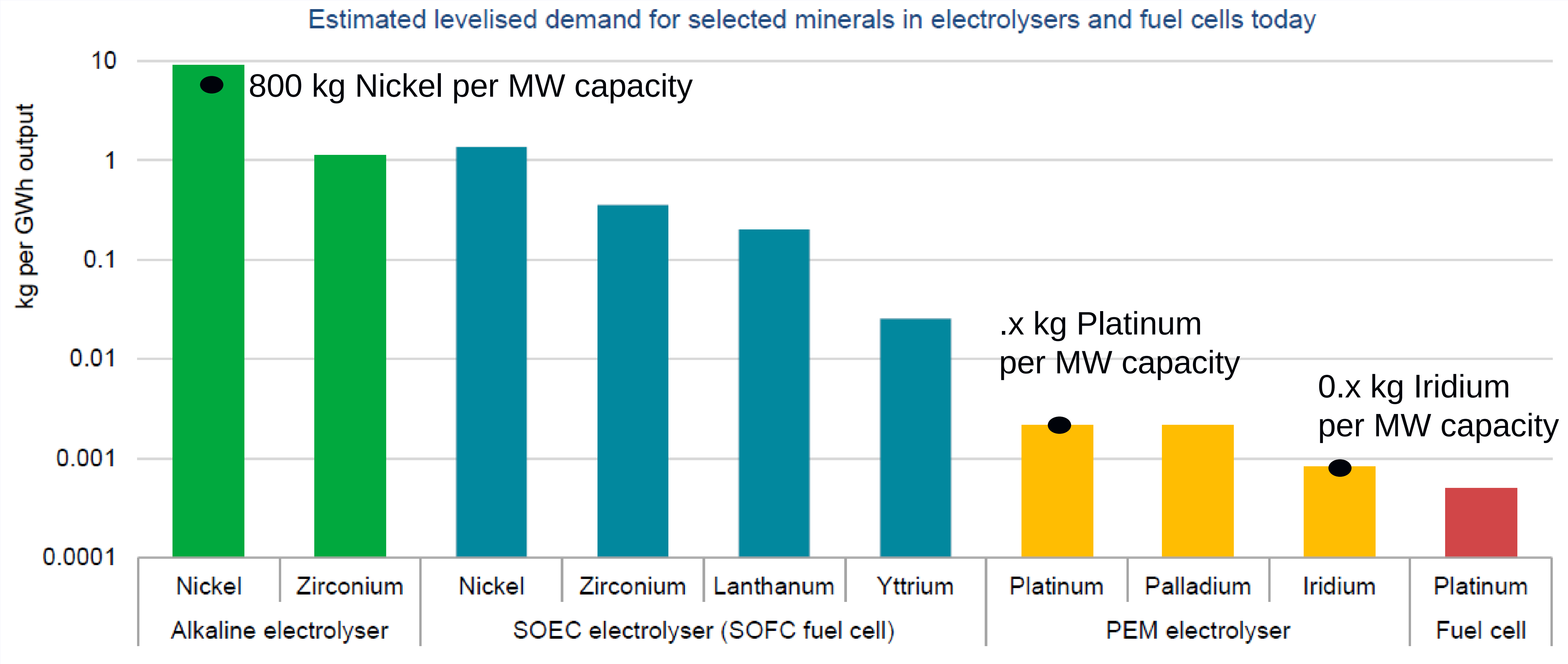
⇒ System efficiency = 72,1% (HHV)

⇒ Estimated required stack efficiency = 78%

(assuming: η_{ACDC}=95%, η_{BoP}=97%, η_F=99%)

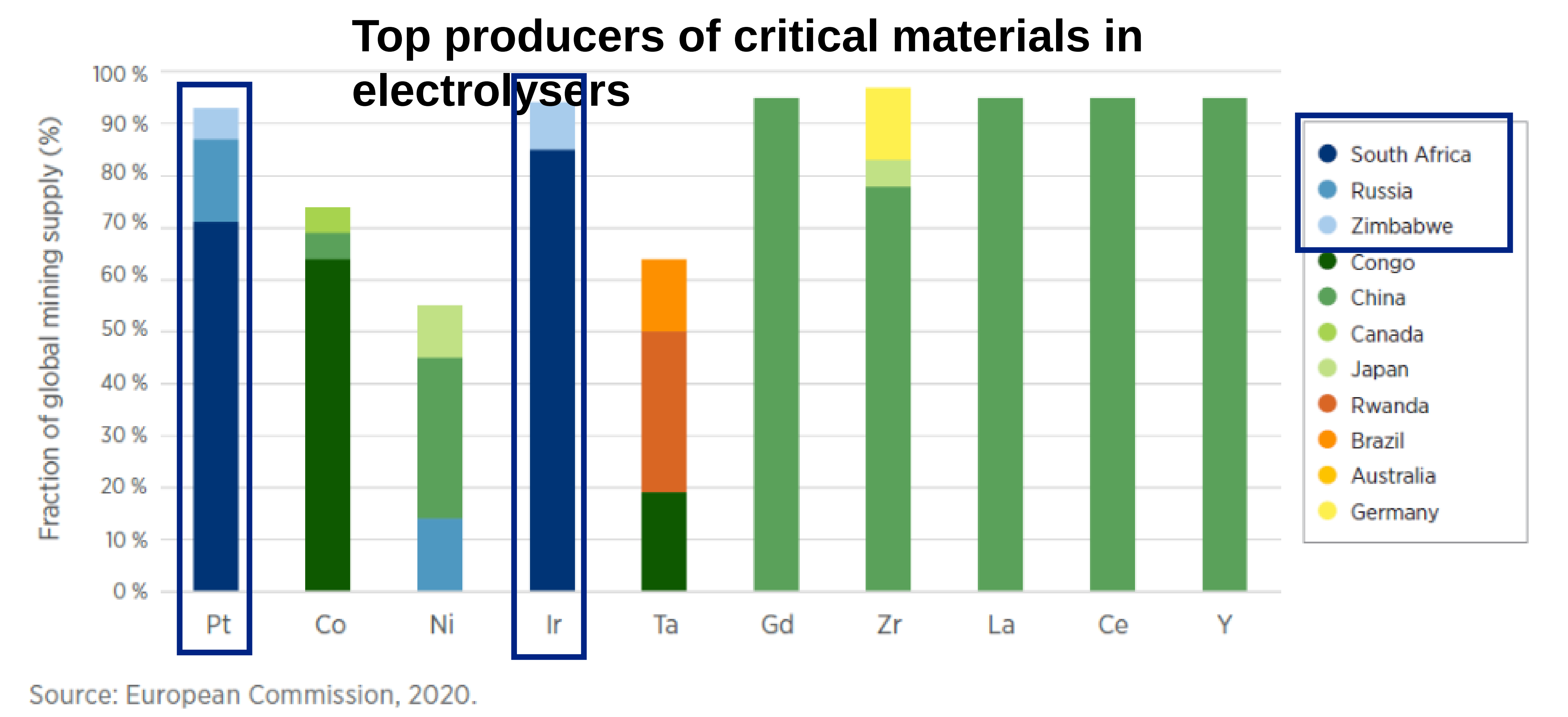
Strategic Research and Innovation Agenda (SRIA)
Clean Hydrogen Joint Undertaking (Clean Hydrogen JU) 2021-2027 Adopted on 25-02-2022
https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en

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**

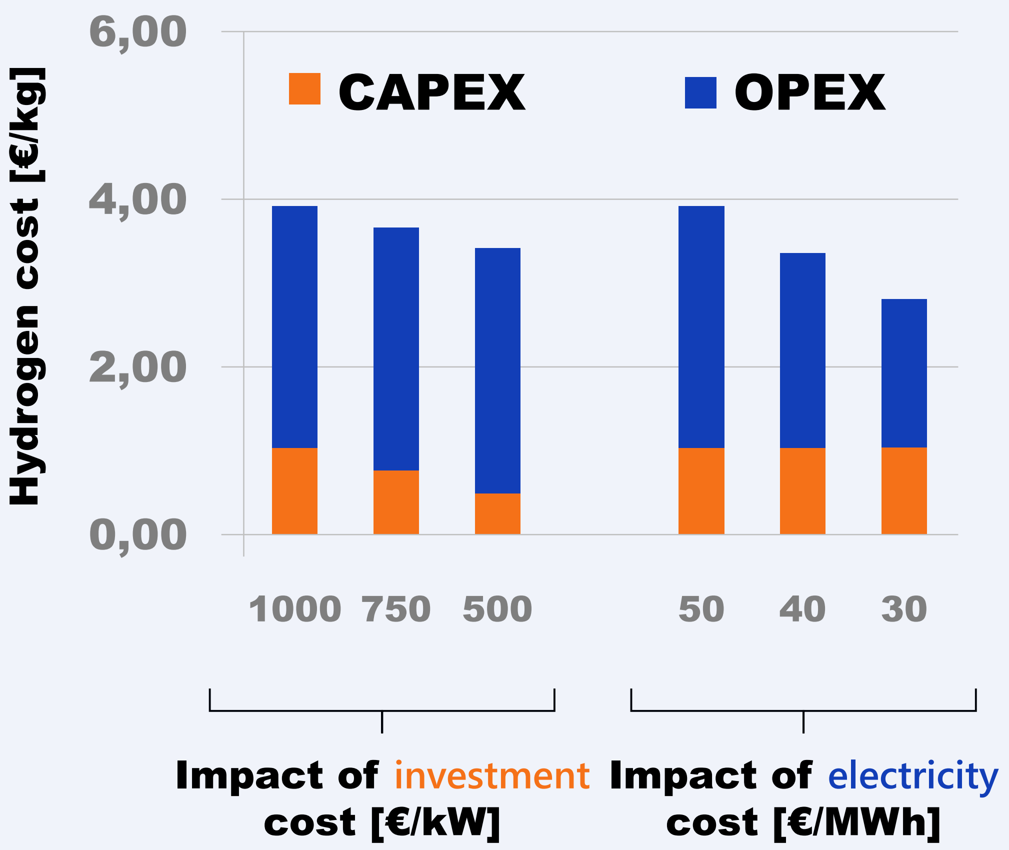
% of CRM global annual supply used as a result of each strategy

	CRM	Base case	Reduction	Substitution	Higher productivity	Extended lifetime	Recycling
PEM	Iridium	122%	6%	122%	81%	91%	122%
AEL	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

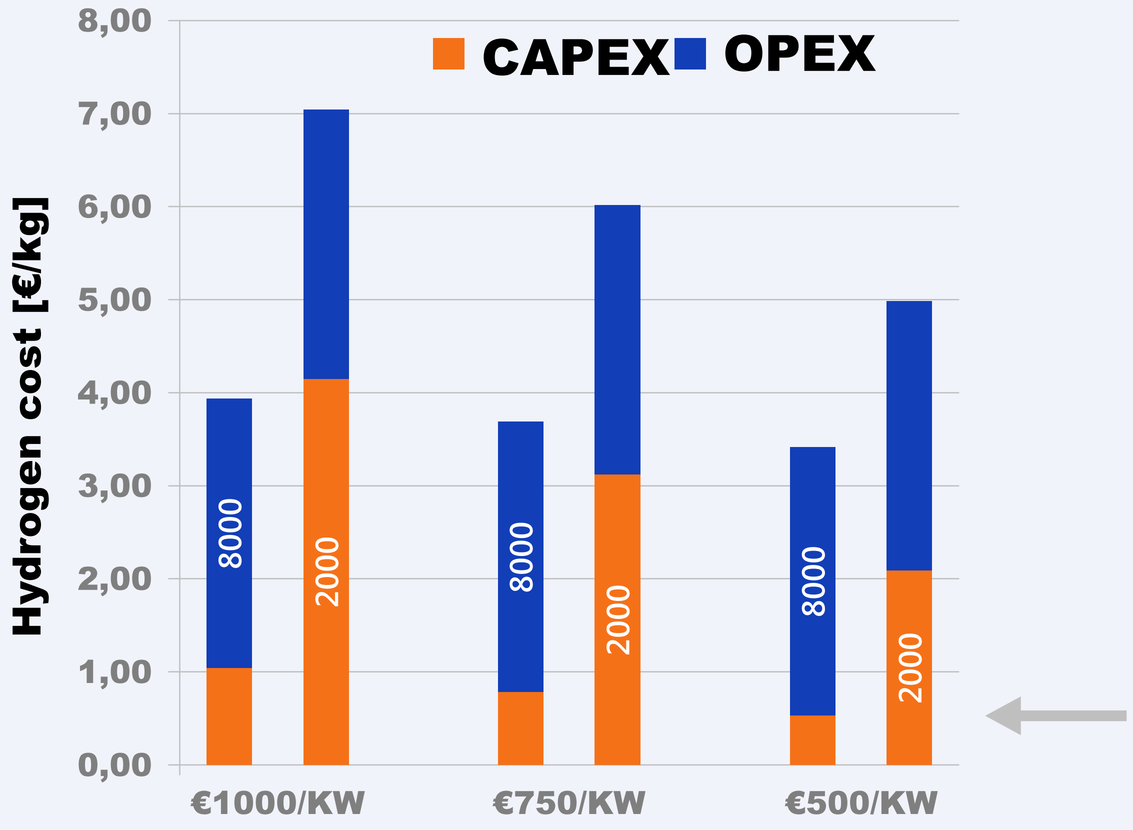


Two major costs:

- **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

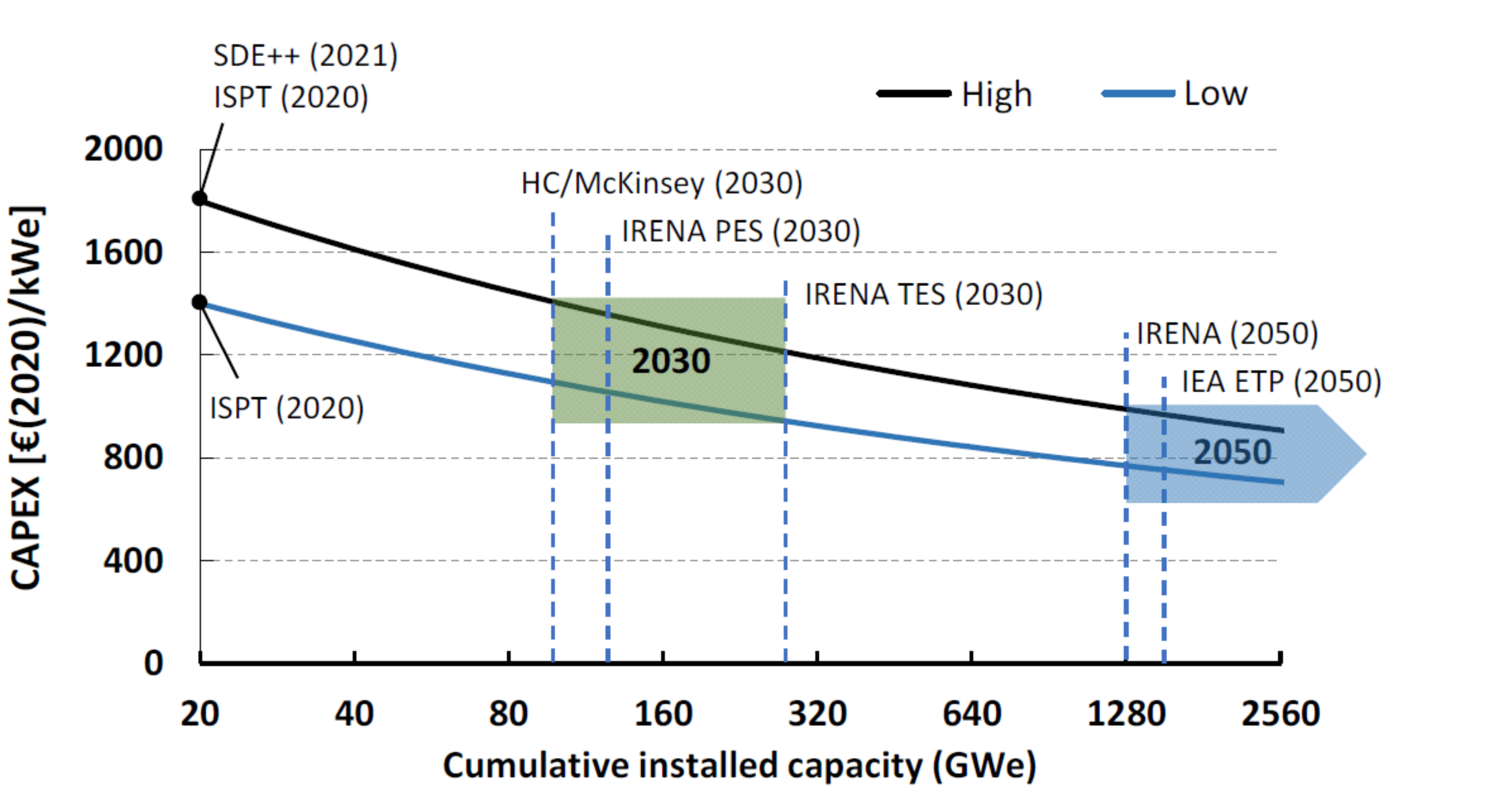
and

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

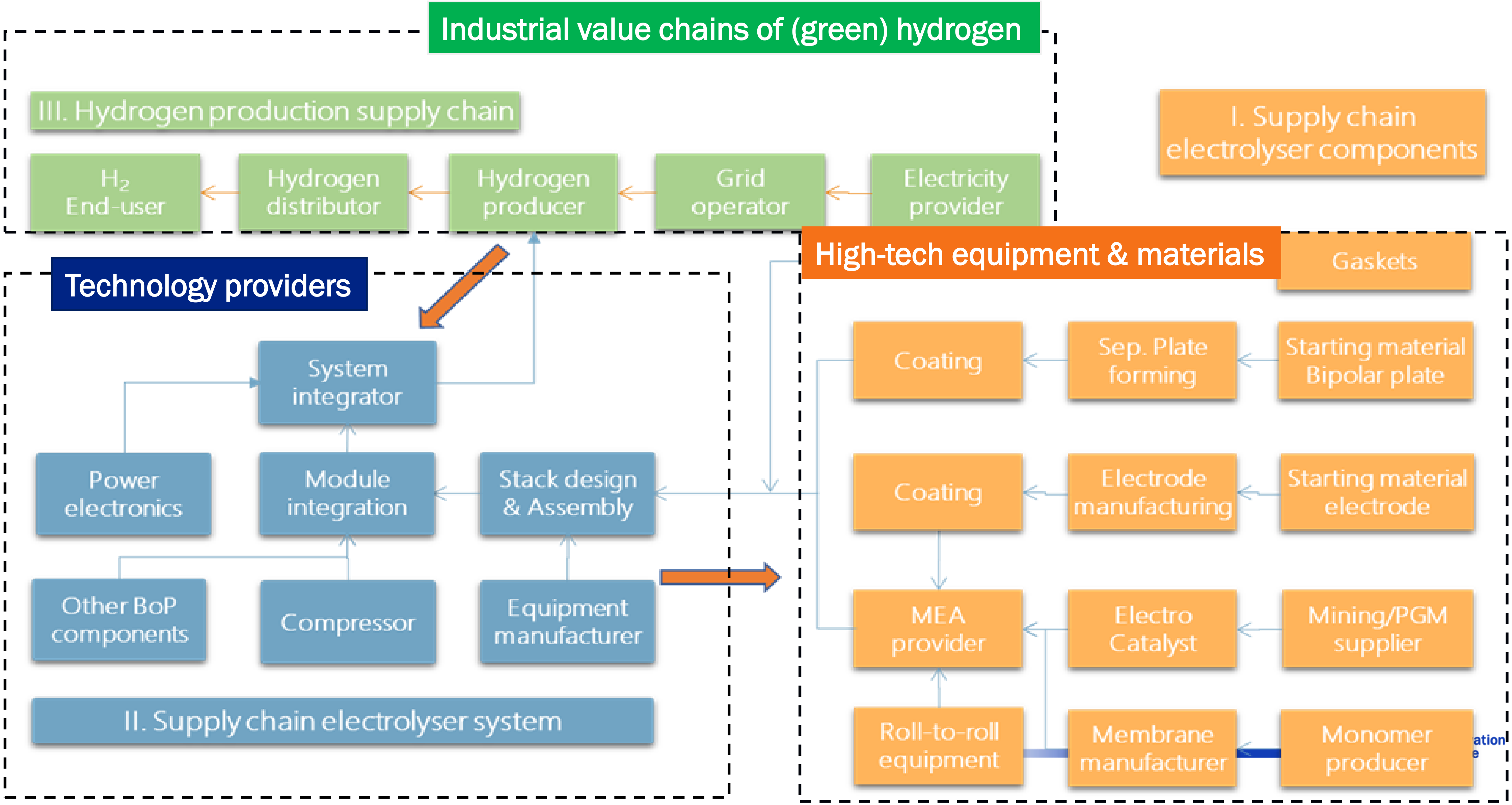


- The **learning rate** of all electrolyser technology varies between 12-20%. However, it will differ between PEM, Alkaline, SOE.
- PEM and SOE can **benefit from fuel cell developments**
- To reach a cumulative installed capacity of 100 GW in 2030, annual installation need to double each year until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

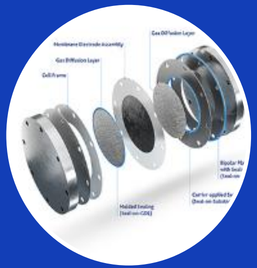
ACCELERATE LEARNING CURVE

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

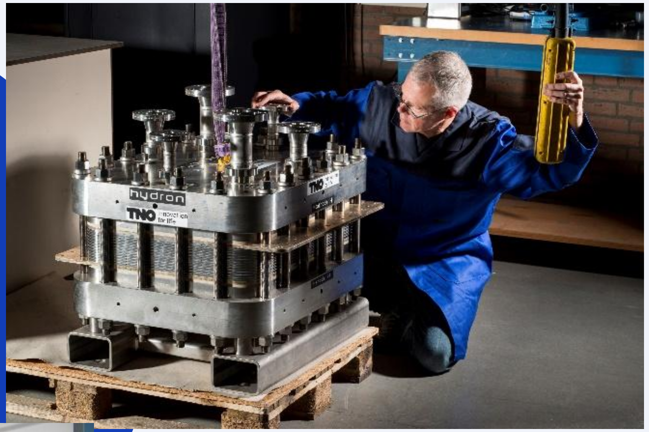
Value from System Engineering: Using feedback/feedforward of knowledge on the entire chain

From PEM cell development towards industrial scale

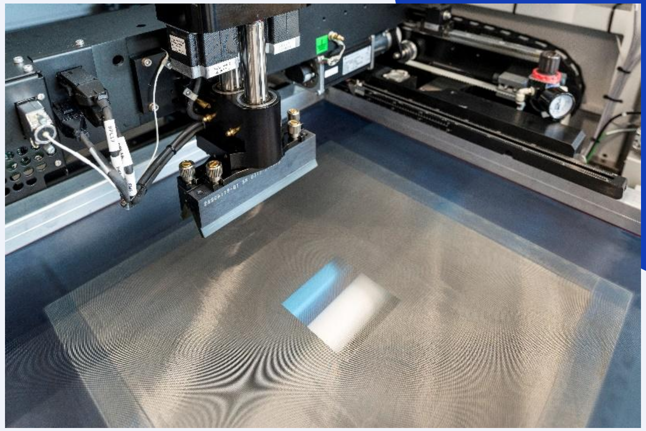
Rapid prototyping

Accelerated life time validation and benchmarking

Industrial scale R&D stack



Cell manufacturing

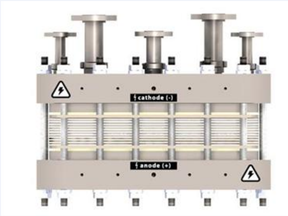


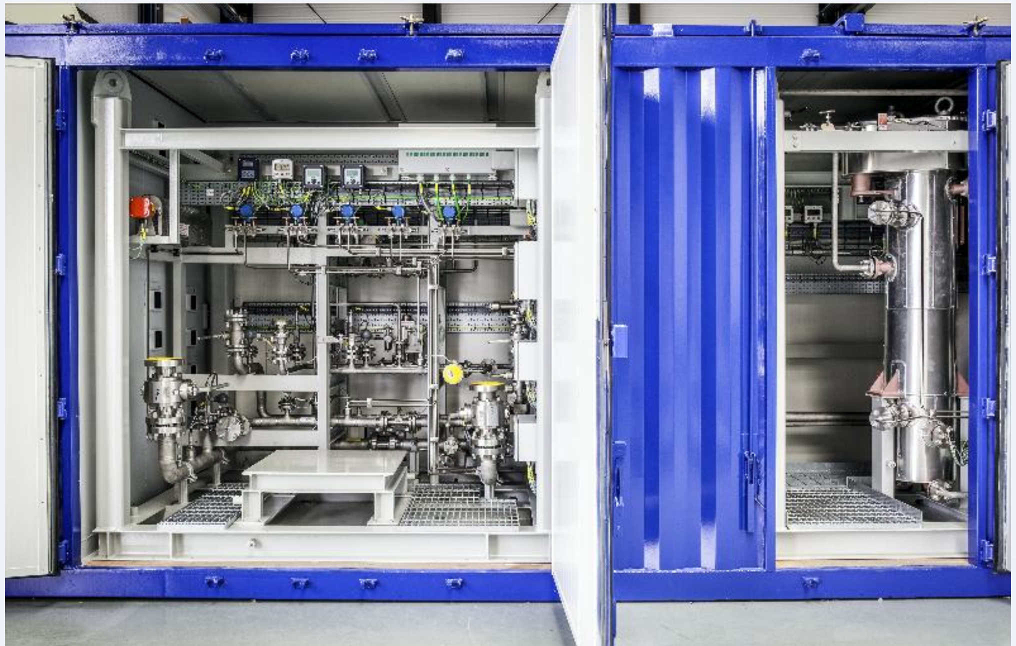
MW-size system

Source: TNO (2022) TNO PEM Electrolyser research facilities in Petten and Groningen (Netherlands)

the 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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