How to accelerate hydrogen development?

Waterstof Industry Cluster meeting

Lennart van der Burg, Cluster Manager Hydrogen TNO

19 September 2024, Eindhoven

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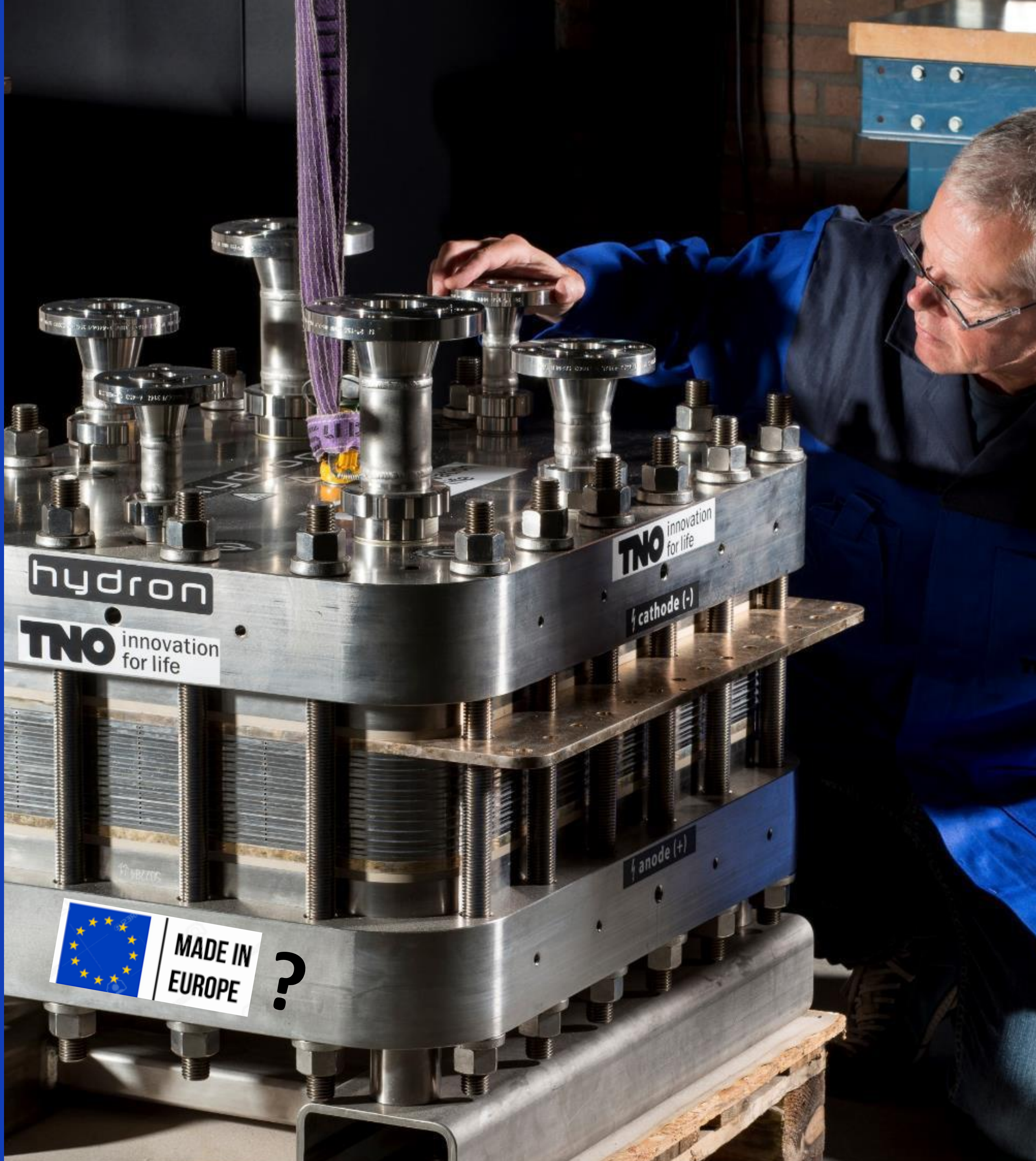
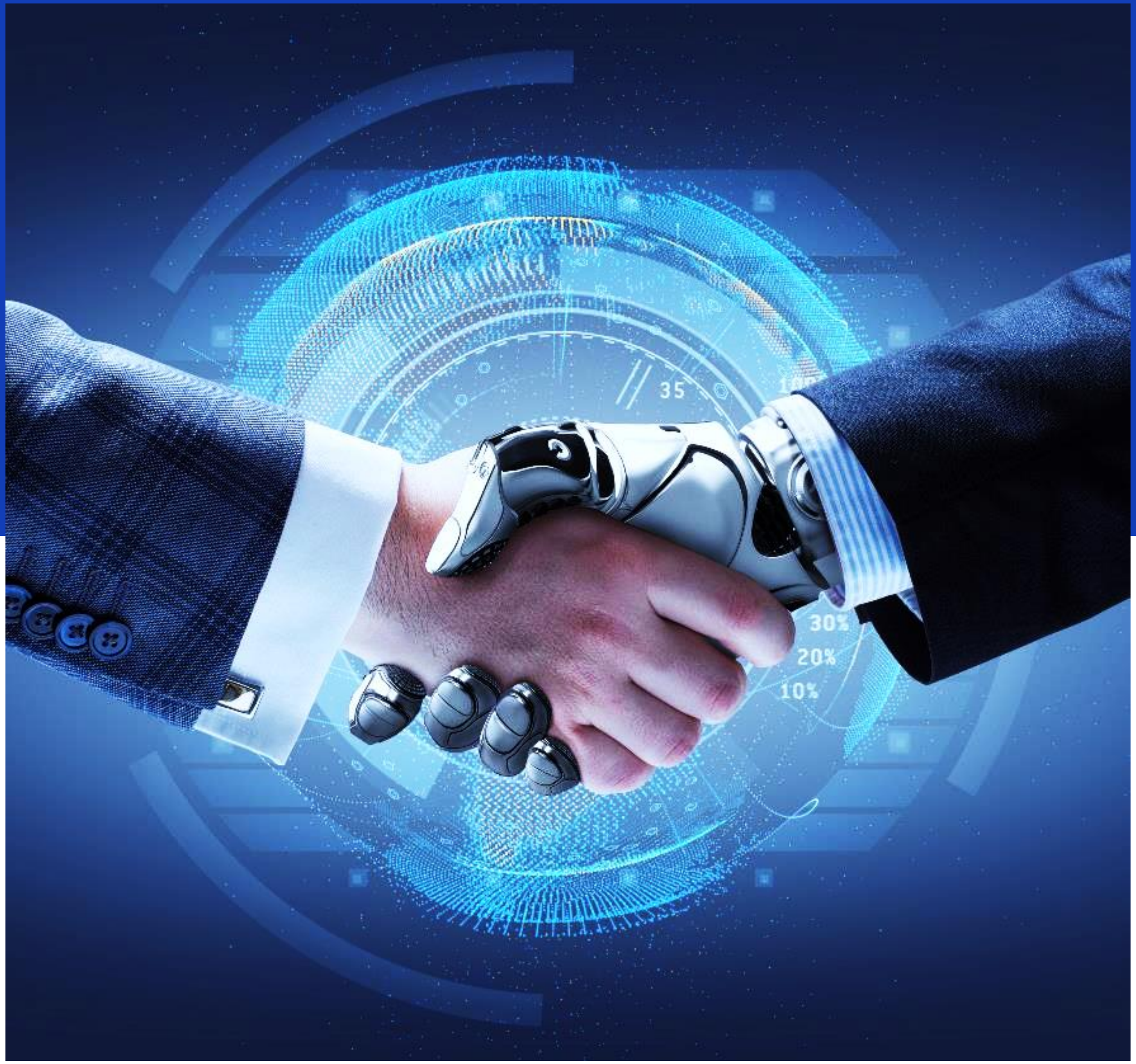
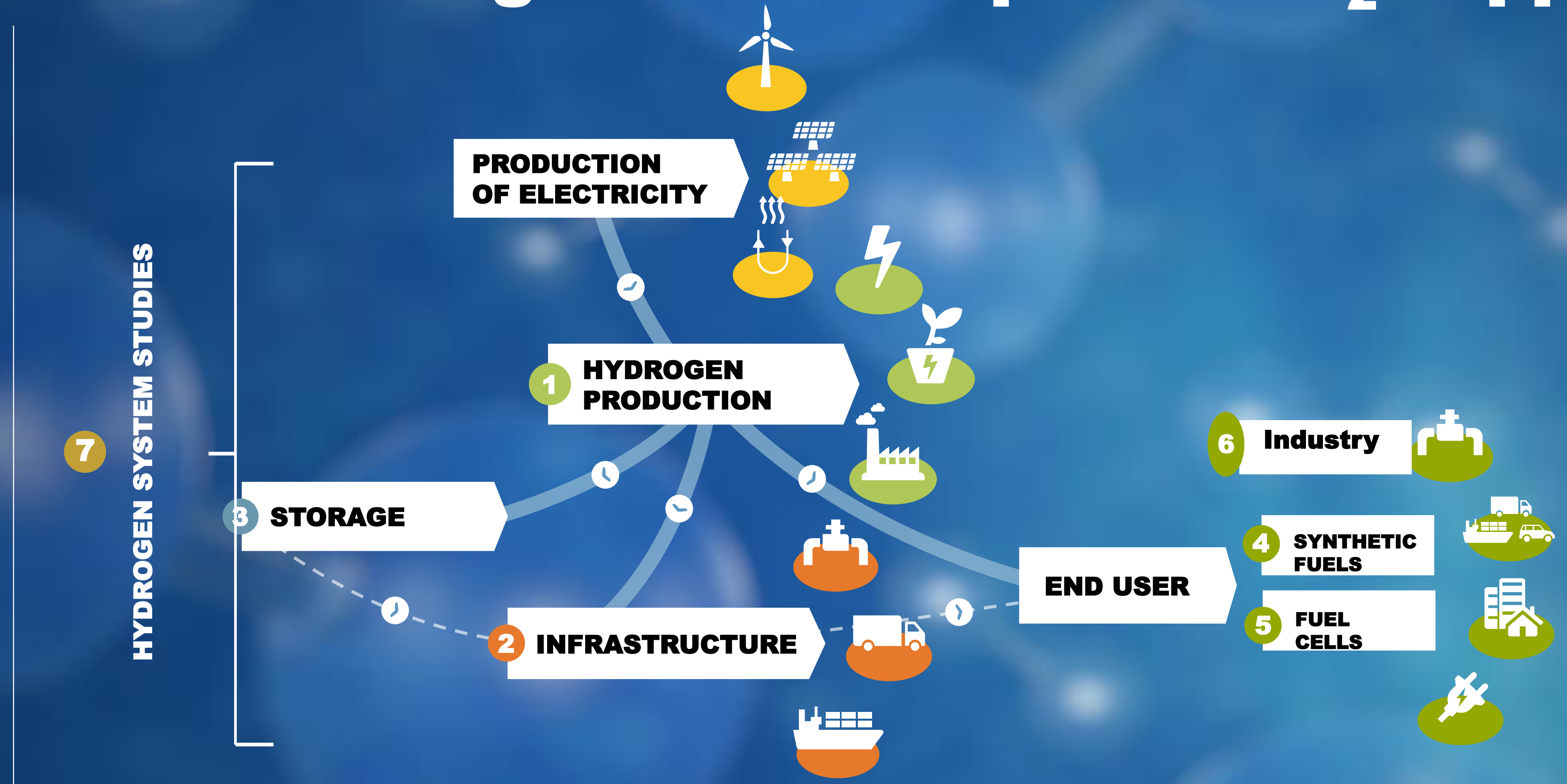


Inhoud



TNO working on each step in the H_2 supply chain



Located in the Netherlands > International focus

Hydrogen related highlighted:

- Faraday Lab (Petten)
- Hydrohub (Groningen)
- Holst Centre (Eindhoven)
- Materials Solutions (Eindhoven)
- Power trains (Helmond)
- CO_2 electrolysis (Rijswijk)
- Fieldlabs Switch (lelystad), Poshydon (Noordzee), Flie (Rotterdam)

TNO impact publications Q2-Q3 2024

1. An analysis of the **main cost factors** for green hydrogen production (LCOH) based on input of 11 hydrogen project developers in the Netherlands (link)
2. TNO executed a study together with the Hague Centre of Strategic Studies on the opportunities and threats of the **upcoming Chinese electrolysers** (link)
3. The position paper on the effect of the **PFAS legislation** on the PEM fuel cell and electrolyser markets (link)
4. State of Art in **Offshore Hydrogen** Production (link)
5. The **public perception** of green hydrogen in the Netherlands (link)
6. The **critical raw materials** needed for electrolyser development and some key solution (link)
7. A study on the opportunities for **reusing waste heat** from electrolysers *(to be published)*
8. A report on how to **accelerate the learning** in green hydrogen projects (*to be published)*
9. **Safety strategies** for electrolysers in operation (*to be published*)
10. …

Opportunities and threats Chinese electrolysers

Conclusions

- China is rapidly becoming more dominant
- They will likely achieving a key position in global offshore wind and electrolyser value chains
- Excluding Chinese players may decrease the speed and increase intermediate cost of the energy transition

Recommendations

- Fair level playing field is important & require restrictions
- Include non financial requirements in public procurement
- Protect and expand the EU industry

Upcoming PFAS regulation electrolysers and Fuel cells

Fraunhofer | RI. SE Research Institutes of Sweden | tecnalia | TNO innovation for life | VTT

Joint Statement on PFAS

Executive summary

We recognize that a restriction on Per- and Polyfluoroalkyl Substances (PFAS) is necessary due to their adverse environmental and health effects, and we therefore support and welcome the regulatory development. However, we would like to highlight the challenges associated with a restriction, particularly in the context of the green transition and the role PFAS play in a wide range of crucial industries. As Research and Technology Organizations (RTOs), we are in a unique position to accompany the legislative process: by assessing the environmental risks of exposure, researching material substitutes and developing sustainable solutions. While we do advocate for PFAS restrictions, we emphasize the need for a nuanced risk assessment that also takes into consideration that in some industrial production processes suitable substitutes do not yet exist. We recommend strategic investments into substitutes, closed-loop methodologies and a systematic assessment of the feasibility of interventions. We support a balanced approach that integrates the responsibility of the industry, regulatory support and the urgent need for independent research to obtain sustainable alternatives, thus ensuring both, the twin transition and the considerate phase-out of PFAS to protect society in the short and the long term.

Our positions in summary

- **We welcome a restriction on PFAS** because the environmental and toxicological hazards posed by many PFAS are undisputed. Restrictions need to be assessed and implemented in a differentiated approach that considers the hazards, the availability and the (economic) viability of substitutions in the respective use cases. Well-considered restrictions will stimulate research and development on alternatives and, if well implemented, can thereby provide EU-based companies with competitive edge.
- **Indiscriminate restrictions of PFAS** compounds **without mitigating measures** and available **substitutes threaten to disrupt a green transition**, European industrial competitiveness and European technological sovereignty. In a wide range of industrial use cases substitutes for PFAS can be identified. However, there are still essential use cases for PFAS for which a viable alternative does not yet exist on a commercial scale.
- **Europe's RTOs stand ready to support regulators** with independent advice or verification. We emphasize the urgent **need for the research and development** of alternative materials, processes and products.
- **Innovation must be facilitated and accelerated** through **consistent policies, appropriate regulation** and other (financial) mechanisms that provide incentives for the fast development of suitable alternatives.
- In cases where viable alternatives do not yet exist, **the industry must provide evidence** prior to any regulatory exception that no risks are associated with the production, use and recycling of PFAS materials.

- We welcome a restriction on PFAS
- Mitigating measures and available substitutes are crucial
- Urgent need for the research and development of alternative materials, processes and products.
- Consistent policies, appropriate regulation and other (financial) mechanisms needed
- Provide evidence prior to any regulatory exception

Offshore Hydrogen Production

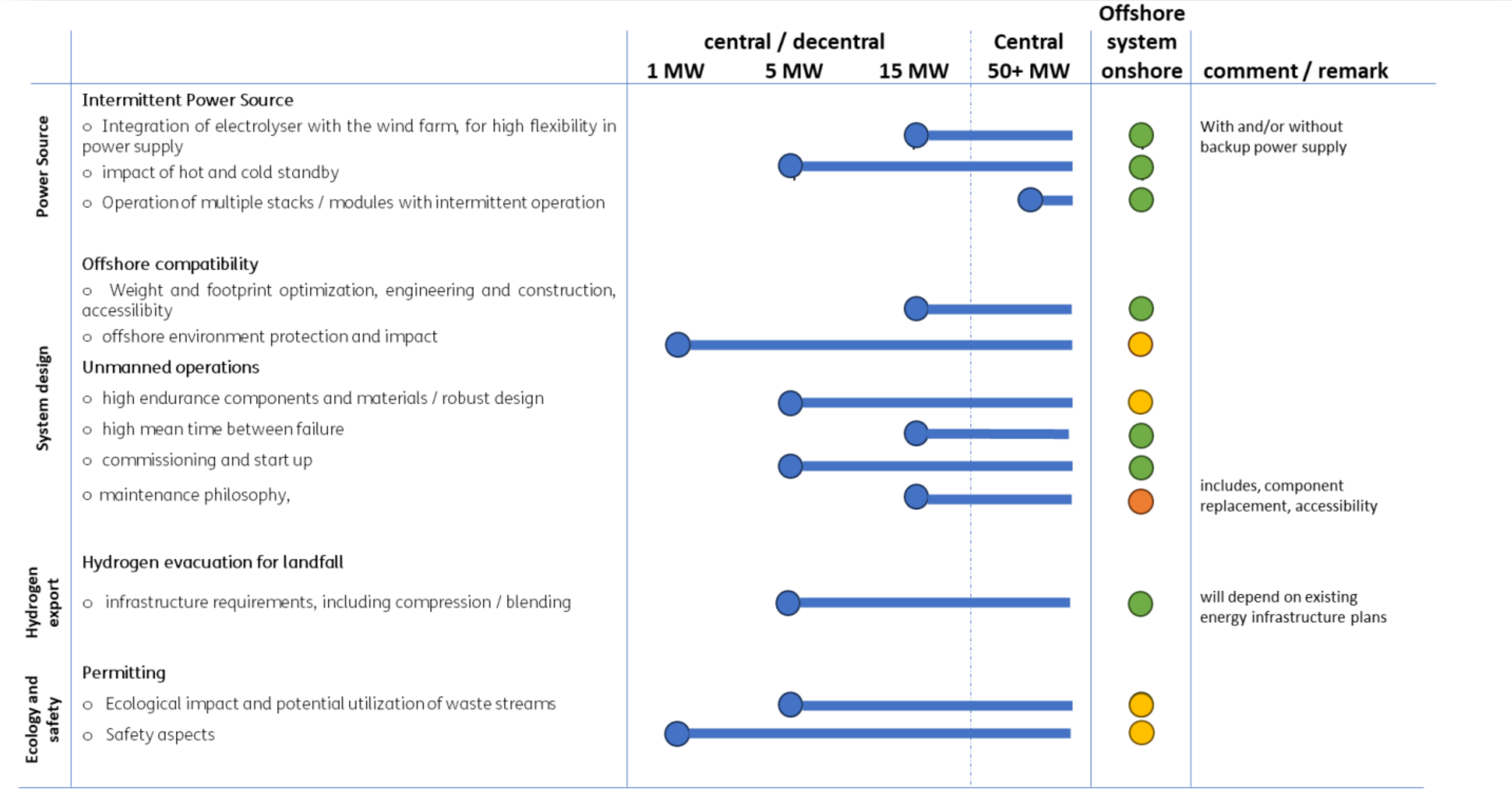
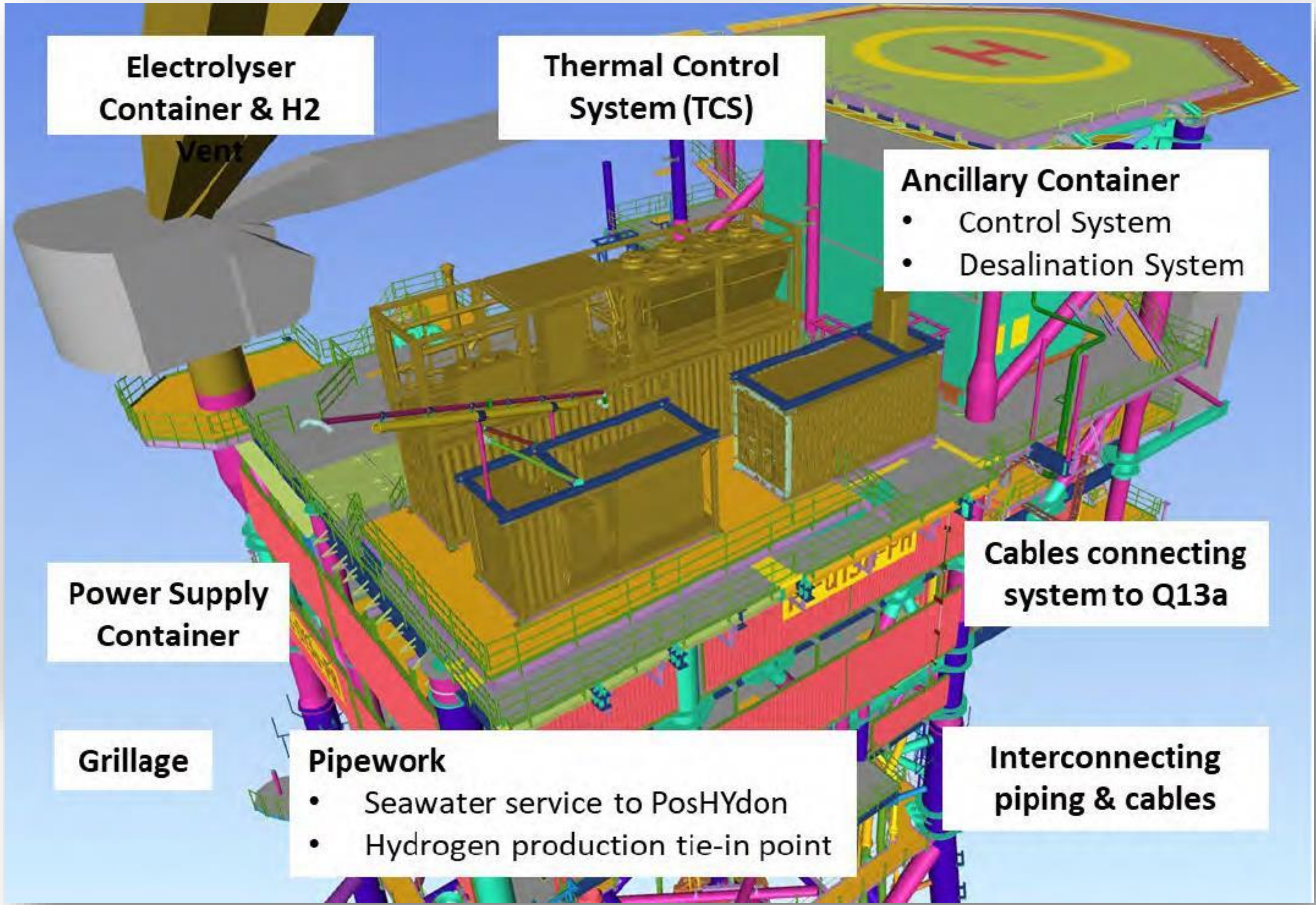


Figure 6.1: Knowledge roadmap for offshore hydrogen production

Offshore Hydrogen Production



Public perception hydrogen

>1.500 People consulted (national)
500 in port of Rotterdam (regional)


TNO innovation for life

The public perception of green hydrogen in the Netherlands

Report HyScaling project task 6.2

TNO Public | TNO 2024 R10988
28 June 2024

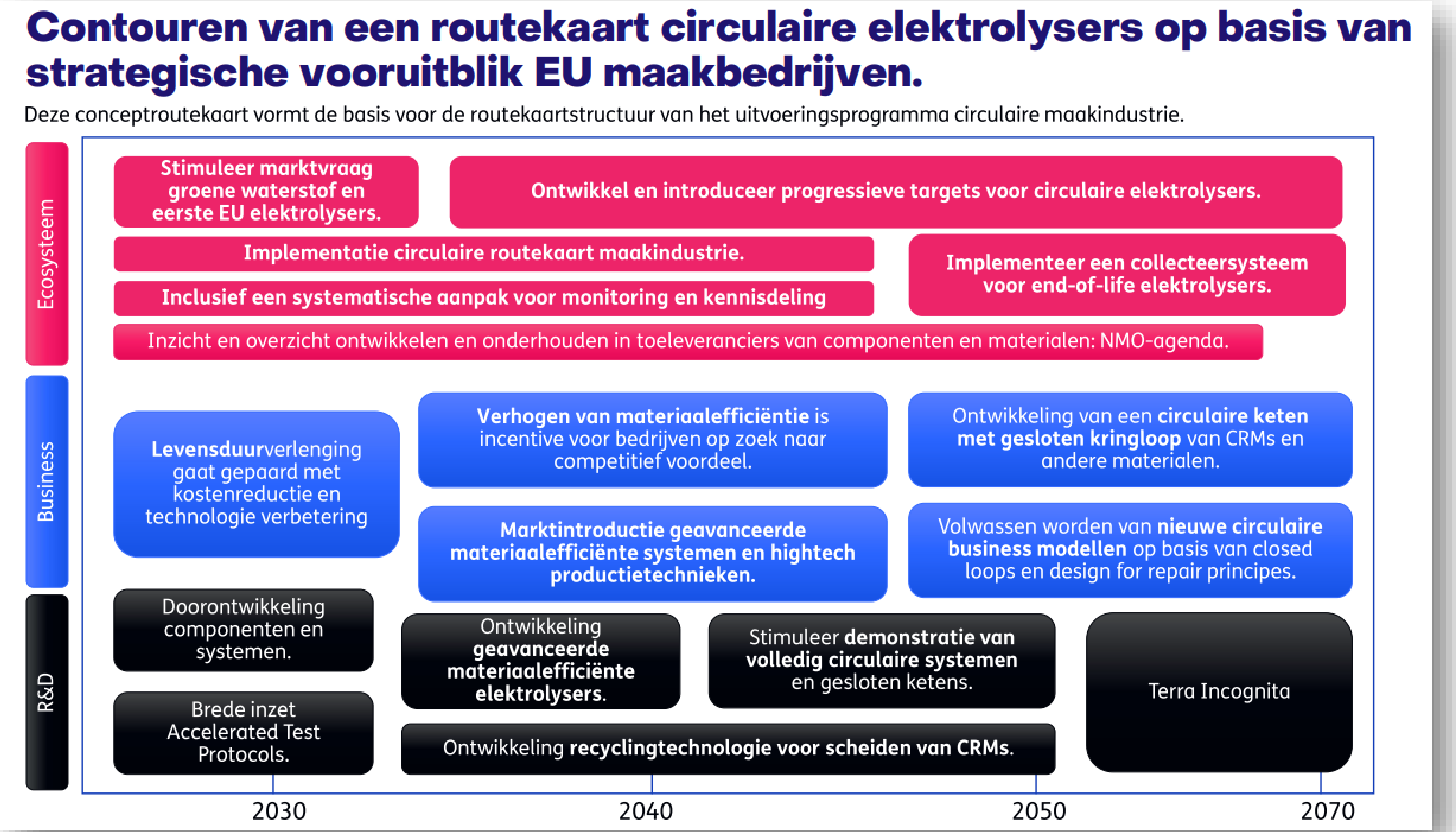
Research questions:

- How do people perceive green hydrogen in general, specific aspects and what characteristics can explain the general perception of green hydrogen?

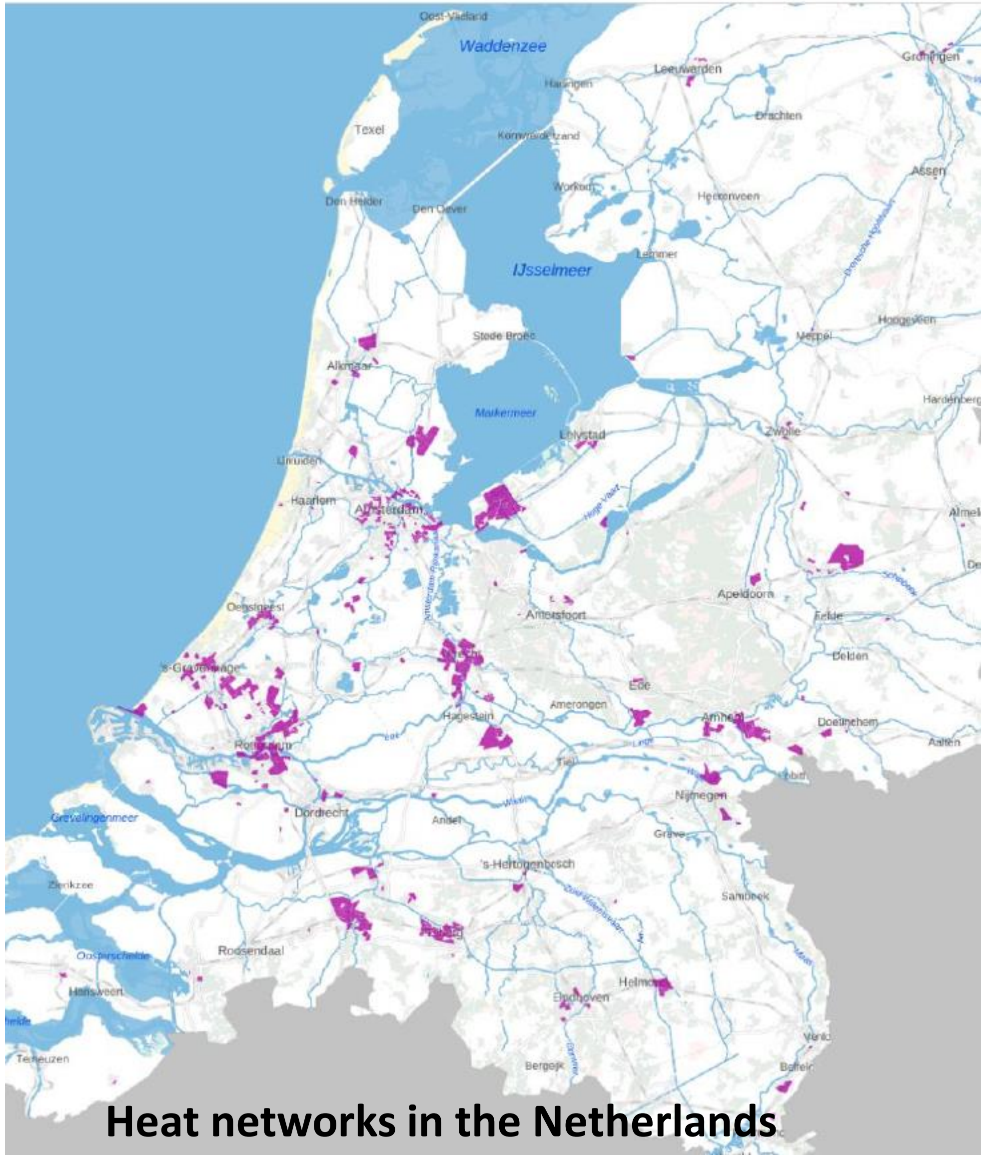
Conclusions:

- In general quite positive
- Trust in organizations that produce, transport, store and use hydrogen is one of the most important explanatory factors
- Perception of risks and benefits is context-dependent
- Future potential role of green H2 and future societal cost has an impact on perception

Route towards circular electrolysers



Reusing waste heat from electrolysers



Heat networks in the Netherlands

Research questions:

- Can we use the waste heat of electrolysers?
- Is this economical, spatial, organisational, legal, financial feasible?
- Should the government set additional requirements for electrolyser projects to use this waste heat efficiently ?

Conclusions:

- It is desirable to make the project and design ‘heat use ready’
- The future available waste heat is substantial
- High level of uncertainty if the heat can be used
- Feasibility to be defined case-by-case

How can we learn more from the first H2 projects?

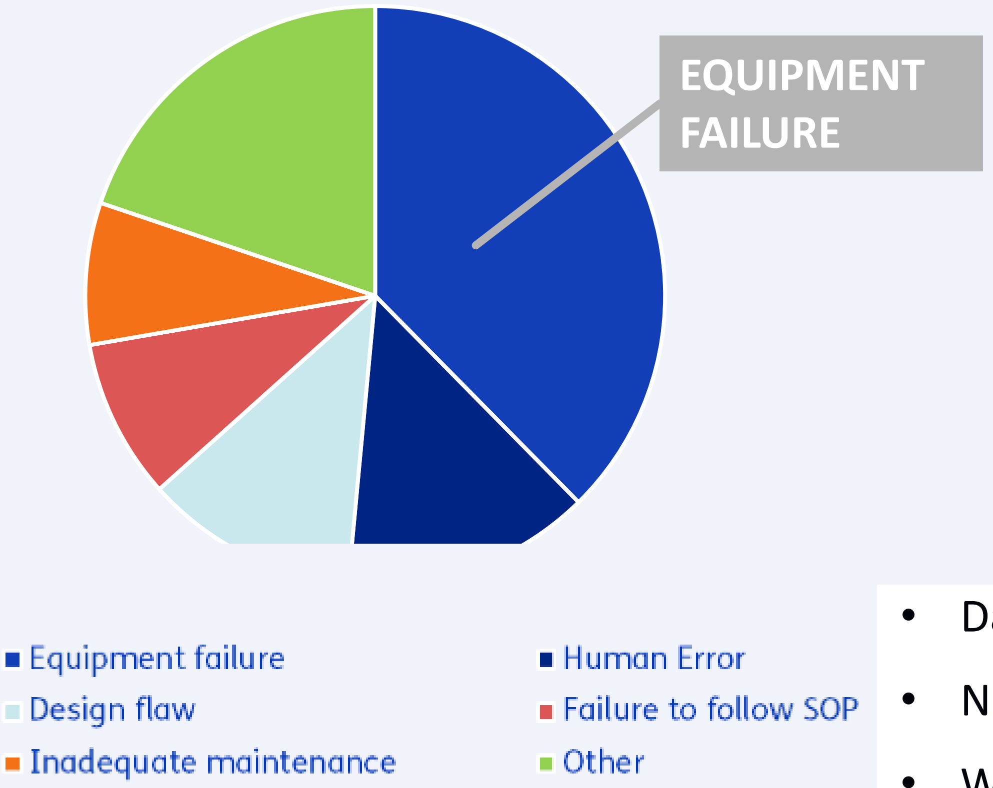
Situation:

- Current green hydrogen projects are (and will be) heavily supported by the Dutch government (7,500 million euro public investment in hydrogen projects proposed for the next 7 years (2024-2030)
- Up to now limited new players are active in the large green hydrogen production projects
- It is unclear what data and knowledge will be shared in the (first) pilot and demo projects (KPI's in IPCEI not shared)
- There is a lack of independent validated and verified data on large scale electrolysers in operation which is needed i.e. for safety analysis

Can we…

- learn more, faster and with a broader group of companies?
  - to better **position the Dutch and European High-Tech manufacturing industry** to increase our earning power
  - to **accelerate the learnings** in the first pilot projects to further develop the technology leading to i.e. lower cost and safer electrolyser plants
- … by
  - **making (structured) data sharing mandatory** in the subsidised pilot projects (IPCEI, DEI, SDE++, ..)
  - **Professionalizing the data collection**, analysing and dissemination by using AI and machine learning

Learn from incidents



- Blockage of electrolyte
- Piping rupture
- Valve failure (h2tools)
- Ventilation system
- Pressure release devices
- Heating equipment (ARIA #25777)
- Safety systems (HIAD #950)
- Electrical systems (HIAD #950)
- Design flaws (HIAD #1002)

The main incidents-prone environments are*:

- Laboratories (36%)
- Fuelling stations (11%)
- Commercial facilities (9%)

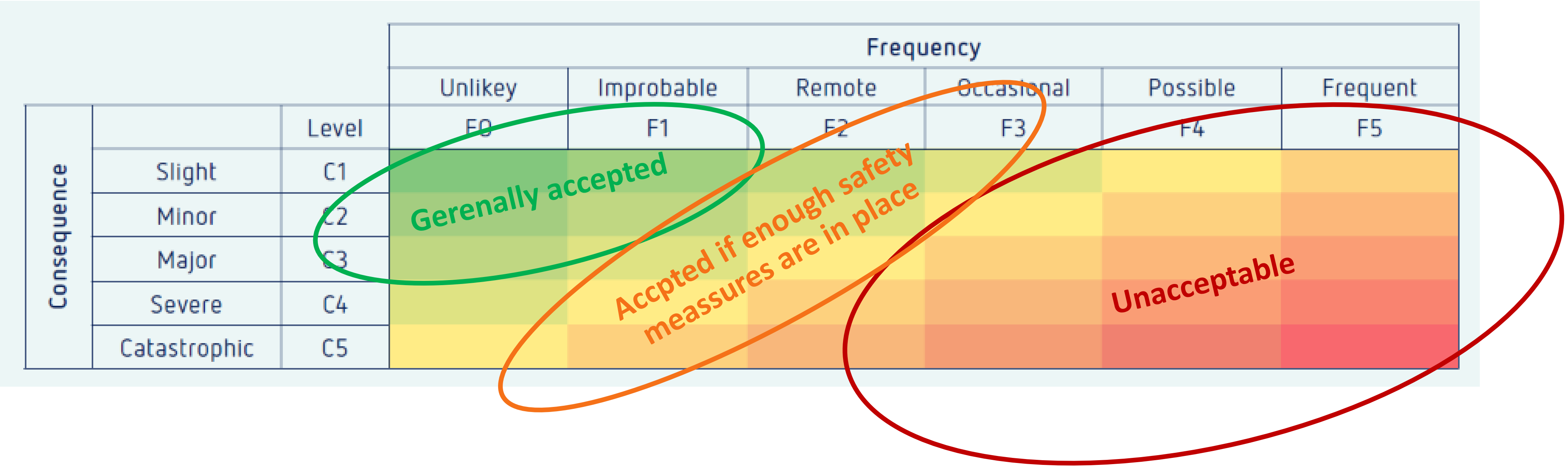
- Databases on incidents still limited
- No report obligations on incidents (except EU projects)
- We can also learn form incidents in the lab

Safety analysis are often based on static data, limited open data is available from the field

*Based on Yang, F., et al., 2021.

How to make a good decision?

- There is no national safety matrix. Companies are making there own decisions
- We should work towards an “inherent safer design approach” to mitigate certain risk
- Install safety measures when “inherent safe’ is not possible



Industry sector standard are crucial also to prevent a ‘race-to-the-bottom’

Source: ISPT, Safety Aspects of Green Hydrogen Production on Industrial Scale (November 2023) (link)

Projects are under pressure …

Many H2 projects in the pipeline, we are still waiting on FID

'World's largest' blue hydrogen-based ammonia project shelved due to increased costs and lack of market

Fertiliser giant Nutrien has put the plant in Geismar, Louisiana, on hold after announcing it

Three green hydrogen projects drop out of first UK production subsidy round ahead of negotiations

The government plans to award operational support to 250MW by end of year, but 262MW i still in the running

Engie delays 4GW green hydrogen target by five years, due to slower-than-expected industry progress

French energy company admits market for H2 and its derivatives is emerging more slowly than it had forecast

French hydrogen firm McPhy saw electrolyser orders halve in 2023, but massive factory expansion will continue

Company saw revenue growth in 2023 as it worked through shrinking backlog of orders

HydrogenPro puts 500MW Texas factory on hold amid clean hydrogen tax credit uncertainty

First manufacturing site outside of Ch ...yser manufacturer prepares f ...tion at Tianjin factory

Also large wind projects are under pressure

NIEUWS

Vattenfall zet streep do... windpark

Vattenfall zet een streep door de bouw van ... offshorewindpark in het Verenigd Koninkr... energiebedrijf kampt met te hoge kosten, ...

NIEUWS

Grote aanbesteding voor wind op zee flopt in Groot-Brittannië

Een grote aanbesteding voor hernieuwbare energie in Groot-Brittannië is vrijdag geflopt. Geen enkel bedrijf bracht een bod uit om een groot windpark in zee te bouwen. Voor de Deense windturbinebouwer Vestas is de flop aanleiding om uitbreiding van productiecapaciteit in het VK te heroverwegen. Voor Nederland, dat later dit jaar ook weer een grote veiling begint, lijken de effecten vooralsnog beperkt.

NIEUWS

Koers Ørsted hard omlaag na miljardenafschrijving op windparken

De aandelenkoers van Ørsted is woensdag met ruim 20% gekelderd, nadat het Deense energiebedrijf waarschuwde mogelijk ruim $2 mrd te moeten afschrijven op een aantal Amerikaanse windparken. Die afboeking is nodig, omdat de hoge rente en haperingen in de levering van onderdelen kunnen leiden tot oplopende kosten en vertraging van de bouw.

Key reasons

1. **Higher Cost** of capital
2. Parties more **focus on higher return** on investment / short term fossil profits (esp.Oil & Gas)
3. **International competition** of first H_2 projects in other regions outside EU (US, India, China, Middle East)
4. **Increase cost of materials** and electricity price volatility
5. **Delay in execution** due to permitting, available materials, technologies and experienced people
6. **Delay in policies** i.e. subsidies and regulation (i.e. hourly matching)
7. **More technical challenges** lead to higher risk margins → suppliers are over-promising
8. 1st large projects, **many learnings** not shared unfortunately

Source: HydrogenInsight (link), (link), (link), (link), (link), (link) Energeia (link), (link), (link) ; TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link)

…despite huge public hydrogen investment in the Netherlands

- **Elektrolyse onshore: € 5,2**
  - 2023: € 0,25
  - 2024: € 1
  - >2025: € 3,9
- **Elektrolyse offshore: € 1,9**
- **Infrastructuur: € 1**
  - Backbone land: € 0,75
  - Backbone sea: € 0,05
  - Storrage : € 0,25
- **EU (IPCEI): € 1,6**
- **Import: € 0,3**

- **R&D Electrolysis growth funds: € 0,05**

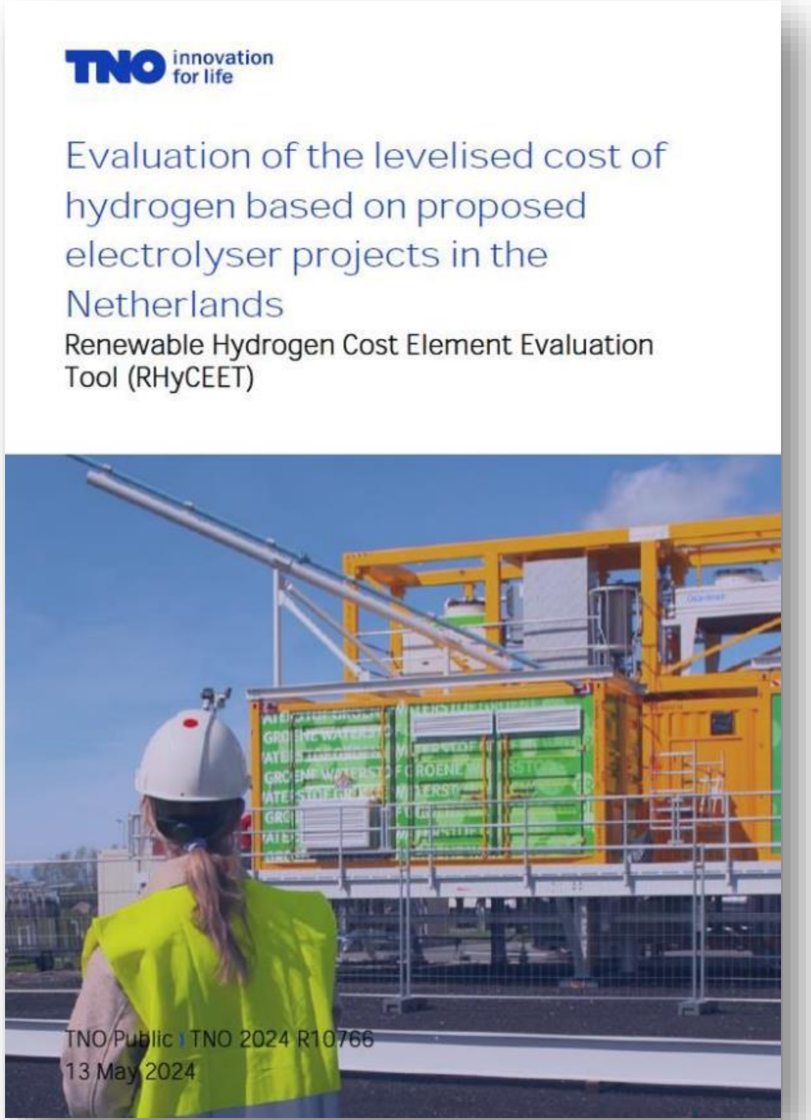
Approx 10 billion euro public investment (excl. SDE++) in hydrogen projects allocated for the next 7 years (2024-2030) from the climate fund

No direct effects on CO_2 reduction in 2030

- 1,2 billion euro
(reduction in climate fund by new Dutch coalition)

Source: Government of the Netherlands (2023) Tabel Klimaatpakket voorjaarsbesluitvorming –(In Dutch) (link) and letters to parliament (link); Ontwerp Meerjarenprogramma Klimaatfonds 2024 (link) , Growthfund NextGen High-tech (link), Growthund Groenvermogen NL (link); Consultatie regeling maakindustrie (link)

What are todays cost to produce 1 KG of green hydrogen in the Netherlands?



Objective study:

- Determine important cost components LCOH
- Provide a common basis for further cost analysis
- Input for effective policy support & strategies

Disclaimer

The companies that contributed to this project provided data and suggestions for analysis and visualisation of results. TNO is responsible for the calculations and analyses carried out in the context of this project, and for the content of the report. However, TNO is not responsible for the quality of the data supplied by the companies.

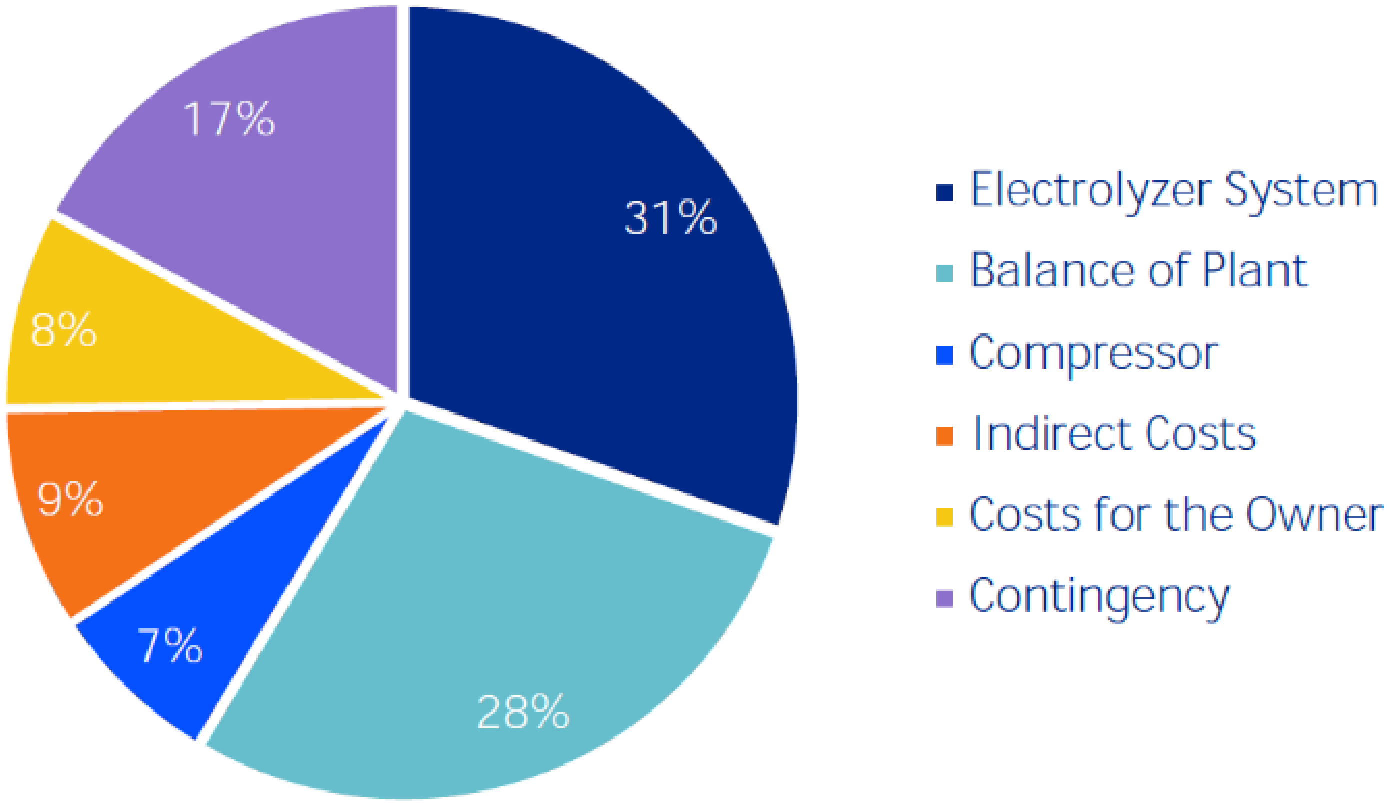
TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link)

Cost parameters as supplied by industry – 14 H2 projects in NL

Parameter	Unit	This study	SDE++
Unit Capital Cost (UCC)	€/kW_e	3,050.-[4]	2,200.-
Operation and Maintenance (O&M)	€/kW_e/yr	75.34[4]	88.-
TSO (TenneT) EHS electricity grid tariff	€/kW_e/yr	143.57[5]	144.30
HNS hydrogen network tariff (entry fee)	€/kW_e/yr	21.13[6]	-
Total electricity consumption	kWh_e/kg_{H2}	56[7]	58
Electricity consumption electrolyser system	kWh_e/kg_{H2}	51	-
Unit cost of electricity (Offshore wind)	€/MWh_e	75.-	58.30
Degradation rate	%/1000 hrs	0.18	0.39[8]
Stack replacement cost	% of UCC	10[5]	10[9]
Weighted average cost of capital (WACC)	%	9.5	7.5
Full-load Hours (FLH)	hrs	4,800	5,150[10]

TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link)

Breakdown Unit Capital Cost: 3 mln. per MW



TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link)

Costs are increasing instead of decreasing

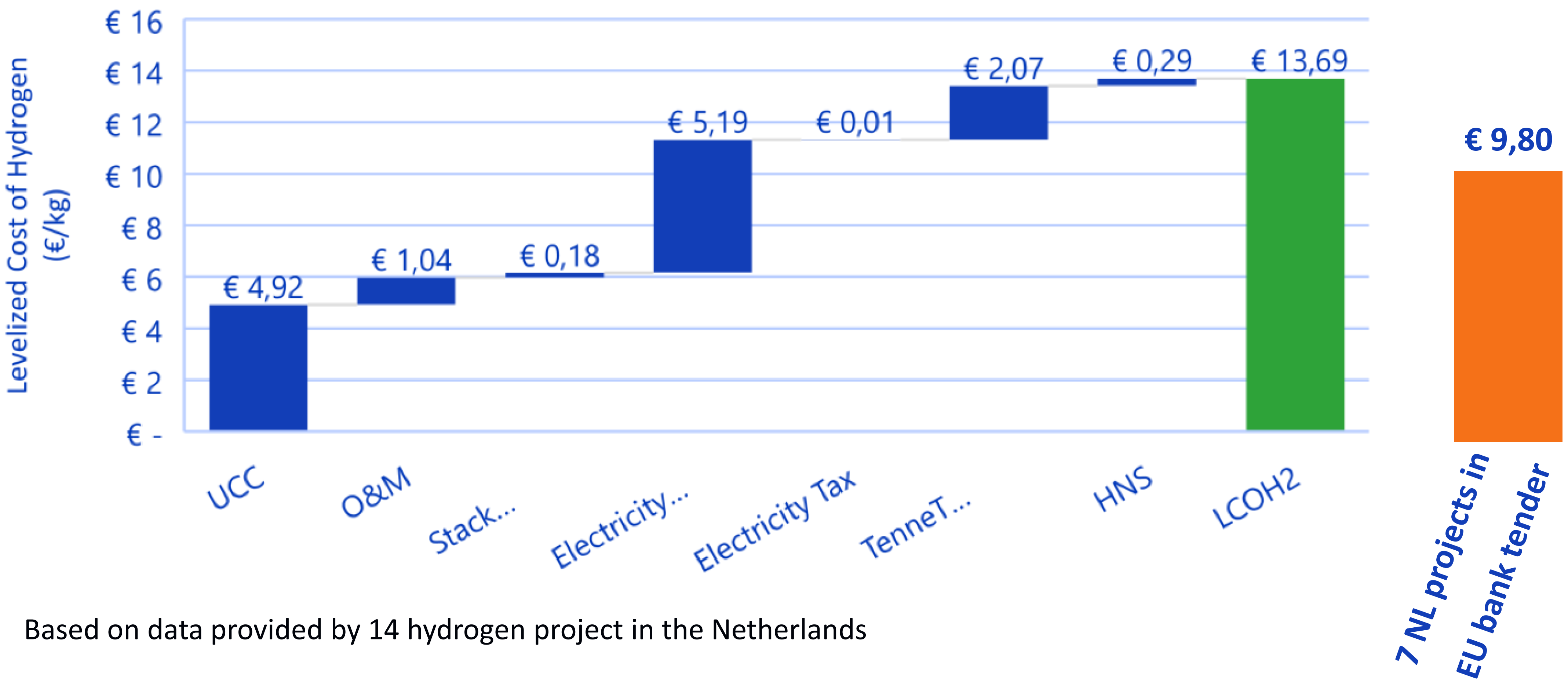
Source	Ref. year	UCC (€/kW$_e$)	E-price (€/MWh$_e$)	FLH (hrs)	$LCOH_2$ (€/kg$_{H2}$)
This Study (2024)	2023	3,050	75	4,800	13.69
EU Hydrogen Observatory (2024)	2022	1,250	86	4,120	7.87
Berenschot & TNO (2023)	2023	2,200	50	4,200	12.14
Wood Mackenzie (2023)	2023	1,820	78	4,800	6.72
Umlaut & Agora Industry (2023)	2023	1,200	70	4,000	5.98
CE Delft & TNO (2023)	2030	1,710	40	4,300	8.30

UCC differs mainly due to difference in scope

LCOH2 as well as WACC, O&M costs, project life and included network tariffs

TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link)

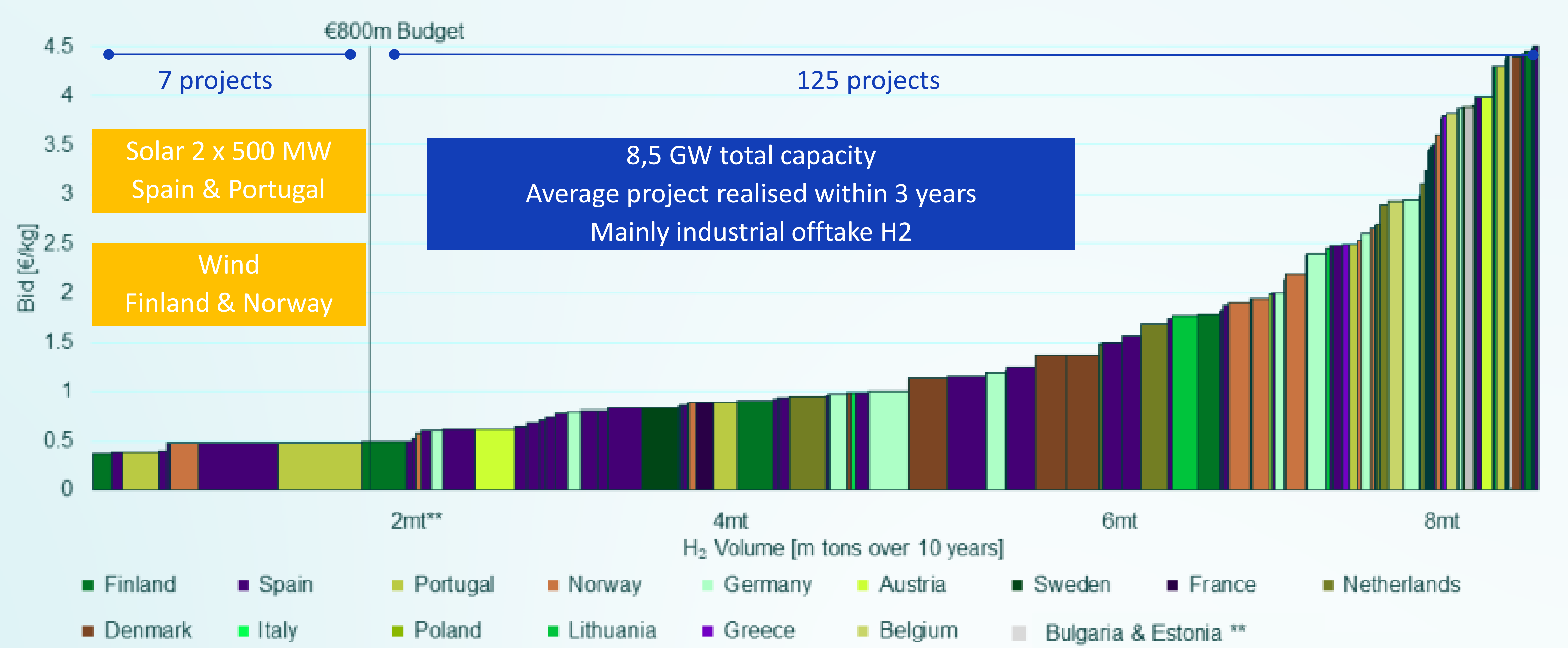
Reality Check: LCOH €10 – 14 per KG



Based on data provided by 14 hydrogen project in the Netherlands

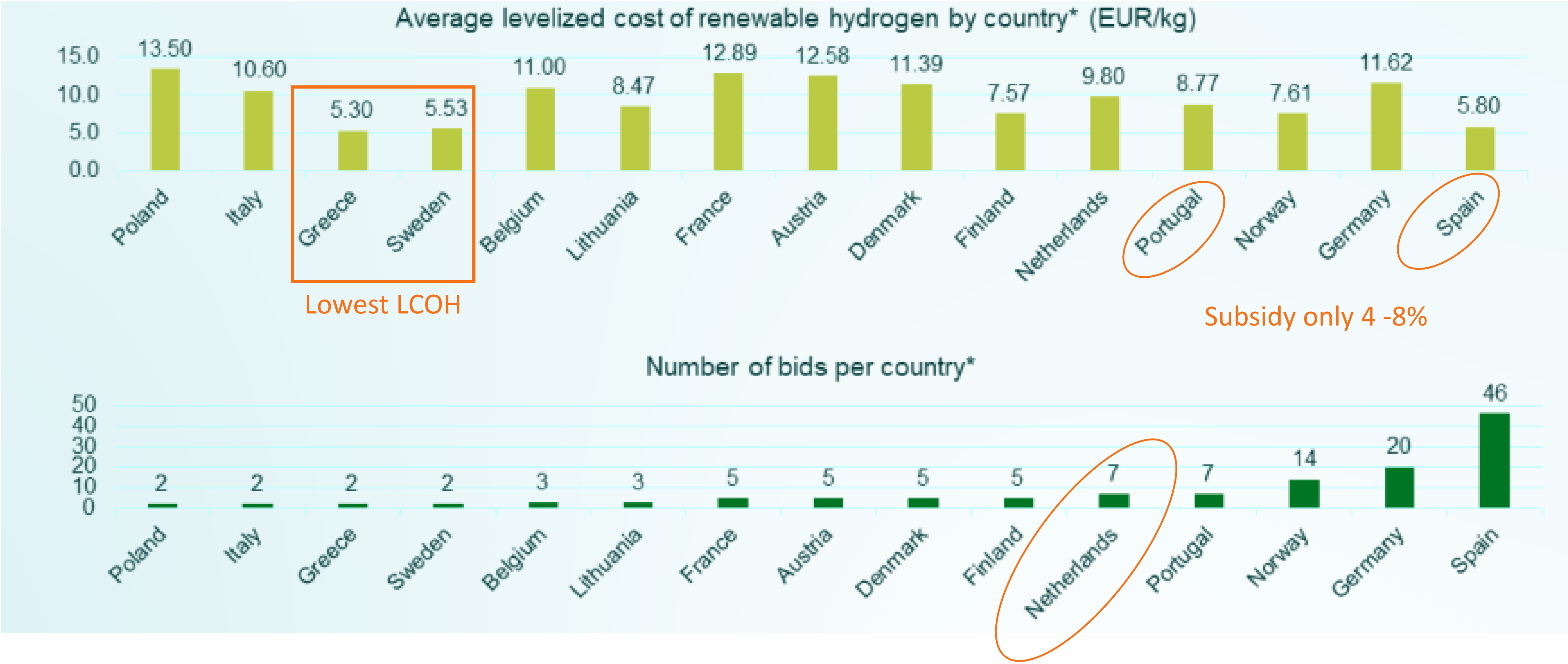
TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link) European Hydrogen Bank

European Hydrogen Bank 1st tender: 15 x oversubscribed



Source: European Hydrogen Bank (2024)

LCOH from 5,8 upto 13,5 euro Euro per KG



Source: European Hydrogen Bank (2024)

What can be the reason for these low biding prices?

- Optimistic future offtake prices? → Projects need to produce hydrogen within 5 years (end 2029)
- Strong competition → 15 times more projects than budget
- Upcoming mandate RED 3 → 42% obligation 2030
- Integrated projects with RES → Offtake for larges renewable projects

Source: European Hydrogen Bank (2024)

Some conclusions

1. Unit Capital Cost considerably higher (innovation & standardisation lead to reduction)
2. Rising electricity grid tariff impact LCOH2 (current tariff already > €2/kg)
3. Hydrogen network tariff could become an additional hurdle
4. Financing is still difficult due to uncertainties leading to high WACC
5. Still large cap to make green H2 cost competitive

→ ***Be careful comparing numbers. No absolute truth. Market still in development***

TNO (2024) Evaluation of the levelized cost of hydrogen based on proposed electrolyser projects in the Netherlands Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET) – (link)

Recommendations

1. Incorporate findings in search for a **smart mix of policy instruments** for effective support of renewable hydrogen.
2. continue close **monitoring of market developments** and to challenge cost projections
3. Lagging domestic production (and import) of renewable hydrogen could lead to a shortfall in coverage of the **cost of the hydrogen network** leading to an increase of the network tariff. → Address in a timely manner by policymakers to prevent it from causing further uncertainty for investments.
4. Put extra effort on **knowledge sharing**. Greater transparency can contribute to better policymaking, acceleration of innovation and more efficient development of the hydrogen transition.


Let’s do it together
TNO innovation for life

High-Tech applied for Next Generation Electrolysis

Emilio Manrique | Business Development Manager

WIC Meeting– 19 September 2024

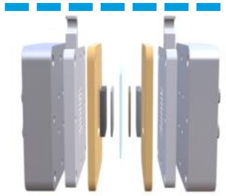
Holst Centre
powered by imec & TNO

Holst Centre:

at the High Tech Campus in the heart of Brainport area, home of Dutch high tech industry

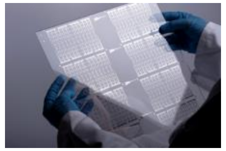
- ✓ **Started in 2006 on initiation from Philips Research, named after Gilles Holst, first director of Philips Research**
- ✓ **Part of TNO, Dutch research agency with 90 years of experience**
- ✓ **Aimed at fostering and orchestrating innovation with and between companies**

Integrated Solutions for



***HighTech* Electrolysers**

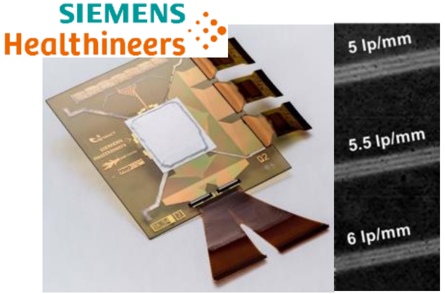
Next-Generation Batteries

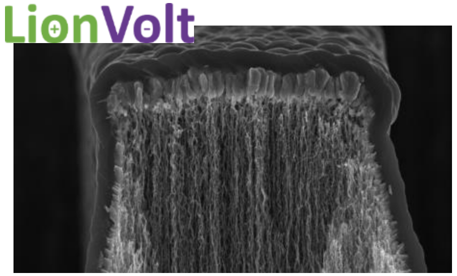


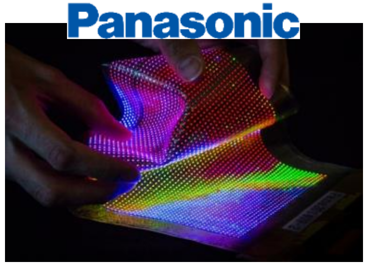
X-on-Chip

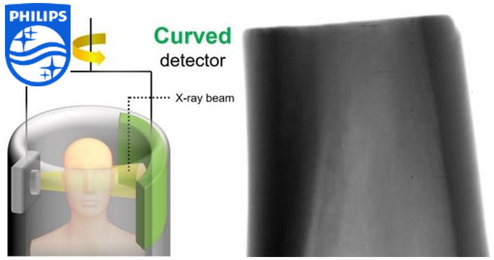
Holst History

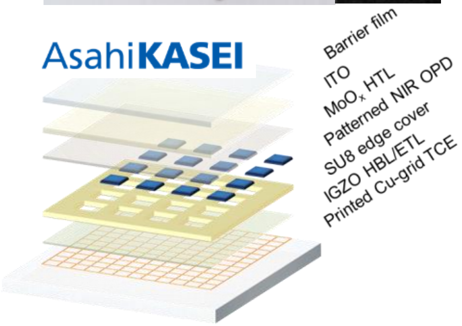
- Thin film technology for the cost-effective manufacturing of Displays, Image sensors, 3D Batteries
- Development of Spatial Atomic Layer Deposition
- Showcasing technology via state-of the-art demonstrators



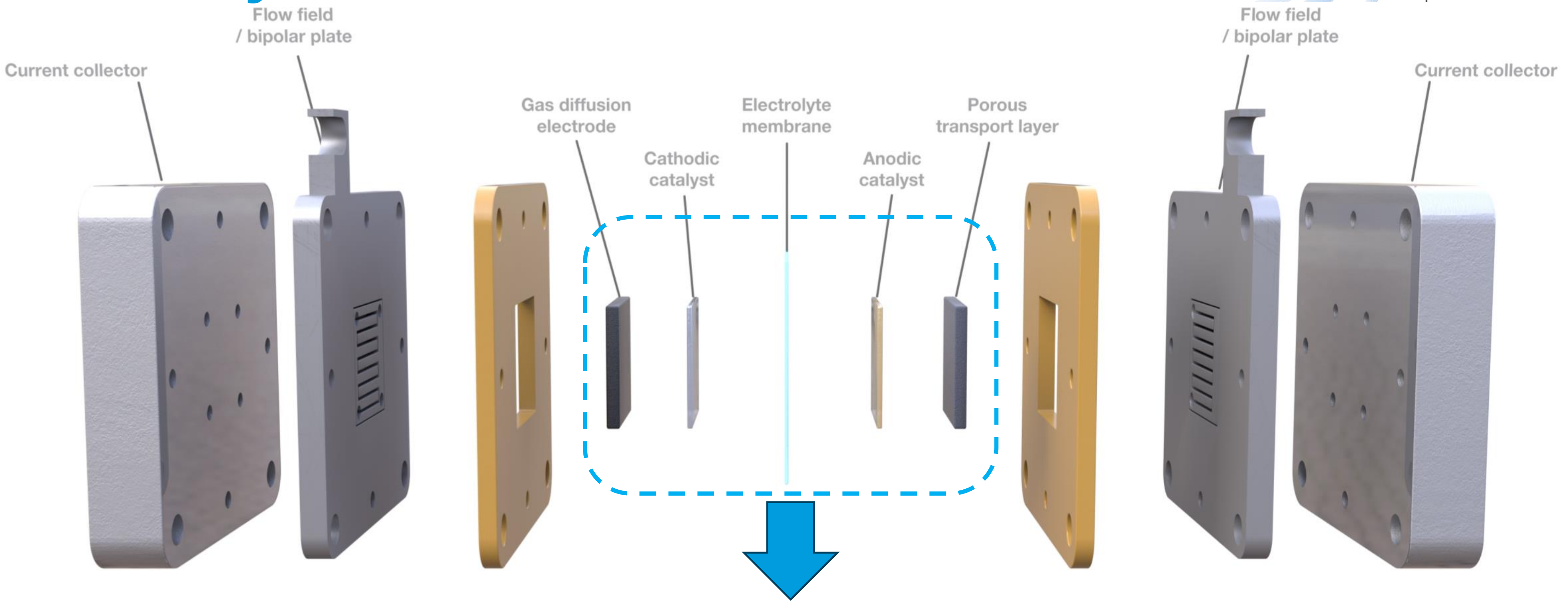








Electrolysis at Holst



1) Optimized Ultra-low **catalyst** loadings
2) PTL **enhancement**
3) Engineered **PTL** through nanostructures
4) Ultra-thin gas-crossover resistant **membranes**

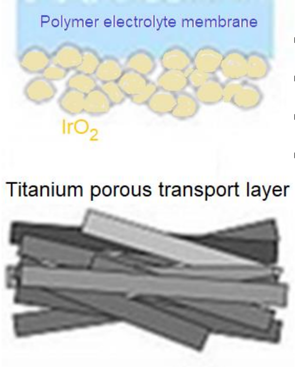
Ultra-low Catalyst Loadings

For PEM Electrolysis

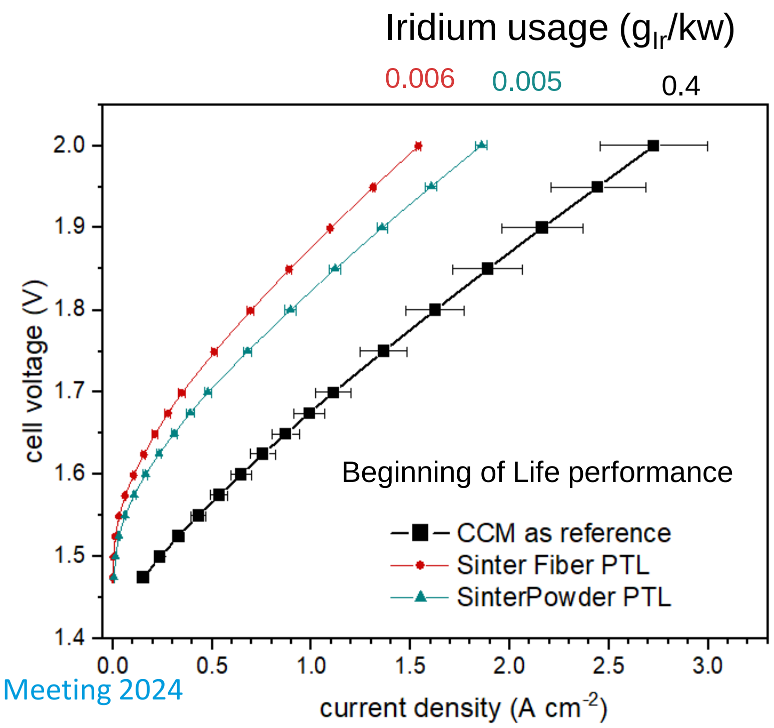
Holst Centre
powered by imec & TNO

Ultra-low Iridium in PEM electrolysis
CCE

State of the art: catalyst coated membrane (CCM)

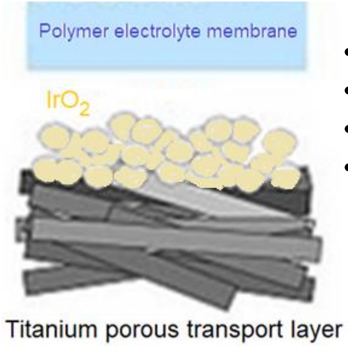


- High catalyst loadings needed
- Lateral conductivity ∝ catalyst loading
- PEM membrane can be affected during manufacturing
- Difficult to recycle when end of life reached



Our approach

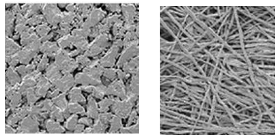
Catalyst coated electrode (CCE)



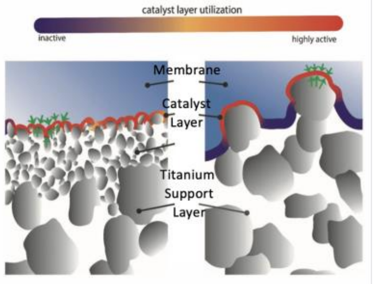
- (Ultra)low catalysts loading possible
- Lateral conductivity depends on porous transport layer (PTL)
- PEM membrane is not affected during manufacturing
- Easier to recycle when end of life reached

CCE made by Spatial Atomic Layer Deposition

(micro)structure of PTL plays a role



CCE on powder type PTLs better than fiber type PTL:
Better contact with electrolyte membrane → higher performance



EU target (2030)

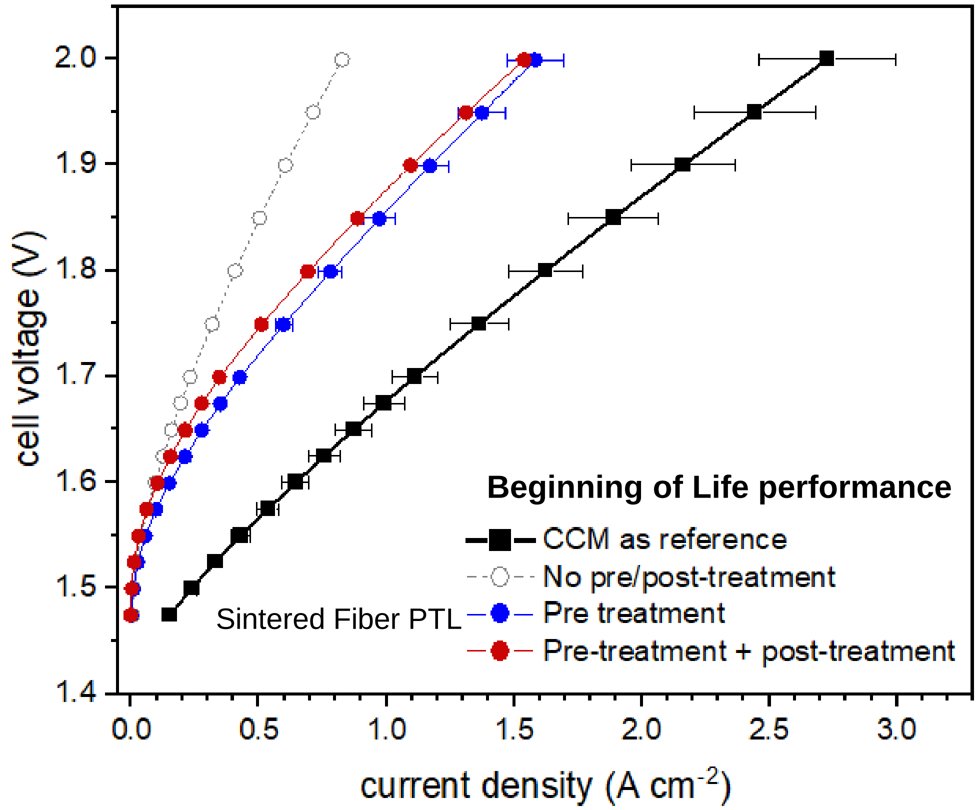
Iridium usage: 0.25 g_{Ir} / kW
Performance: 3 A/cm^2 @ 2 V

Current development: **85% Performance**

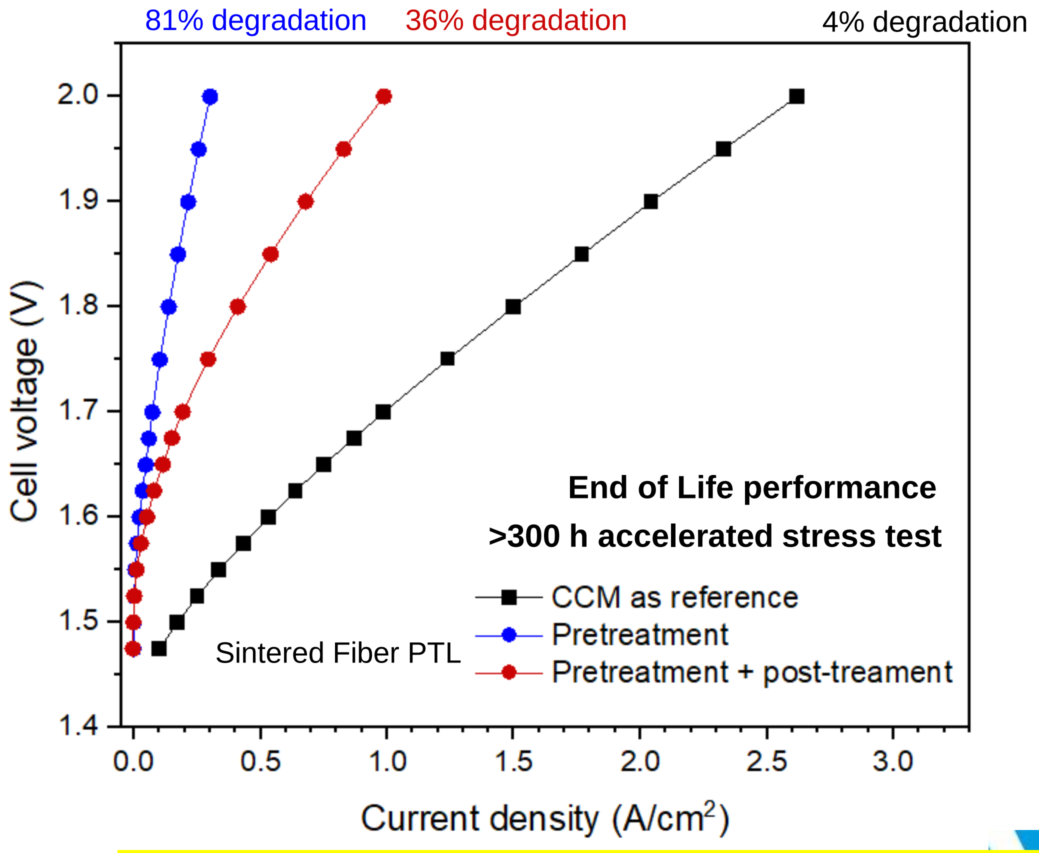
CCE in PEM electrolysis

pre and post processing treatment play key role

Pre-treatment is key for good performance



Post-treatment enhances durability of CCE



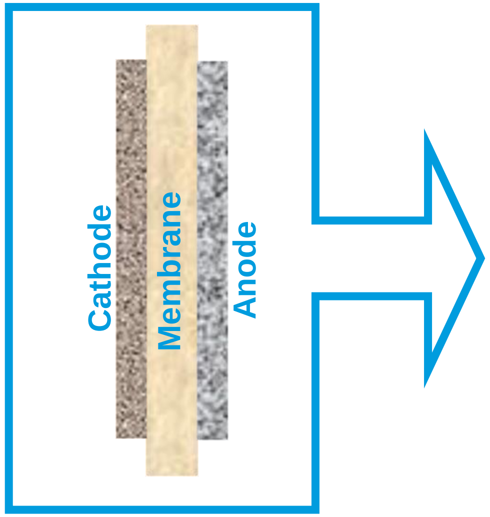
Post-mortem iridium loading ≈ loading of pristine sample!!!

Iridium catalyst is not leaching

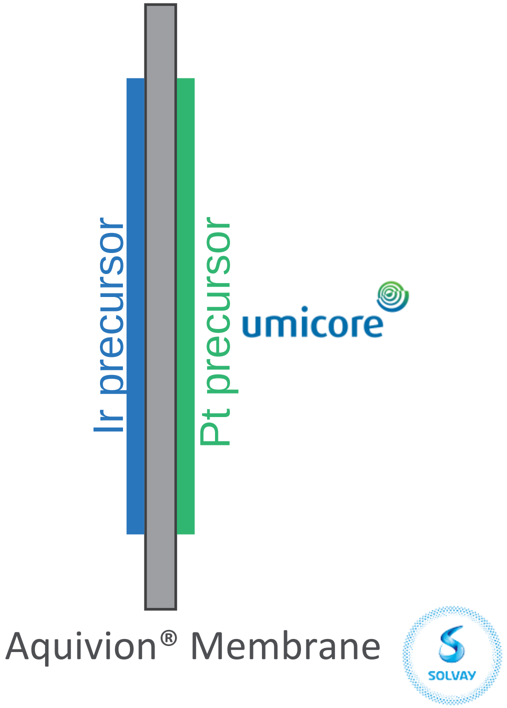
PTL oxidation affects CCE performance

Ultra-low Iridium in PEM electrolysis
CCM

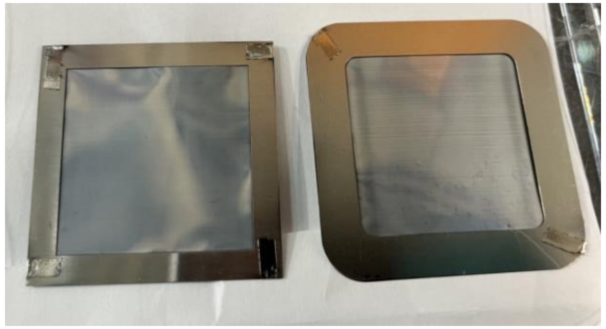
CCM (catalyst coated membrane)



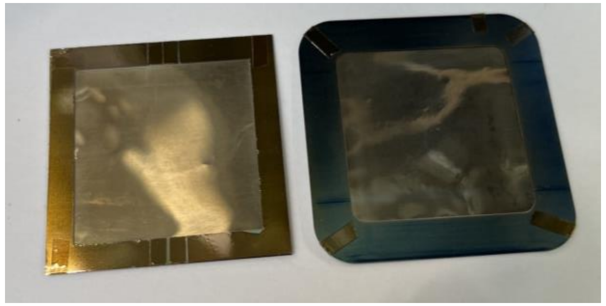
Deposition by sALD



Cathode: Pt – 0.1 mg/cm²



Anode: Ir – 0.1 mg/cm²



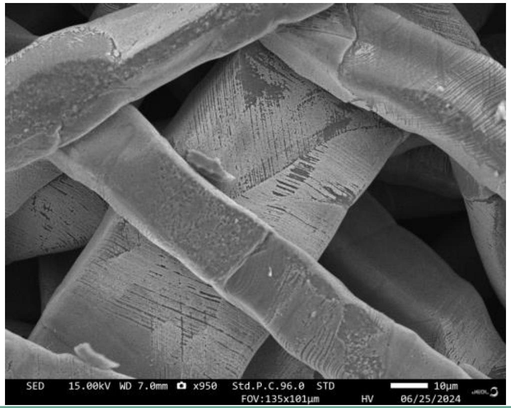
We have achieved a reduction of Ir and Pt by a factor of 15 compared to SOA!

PTL enhancing

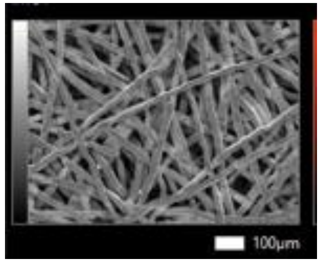
For optimized performance and high-volume non-sintered production

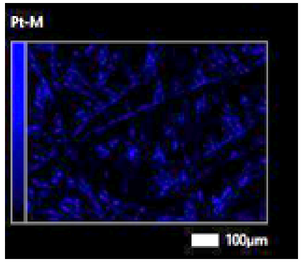
Platinization on Titanium PTL

Platinized PTL by commercial supplier



Pt distribution





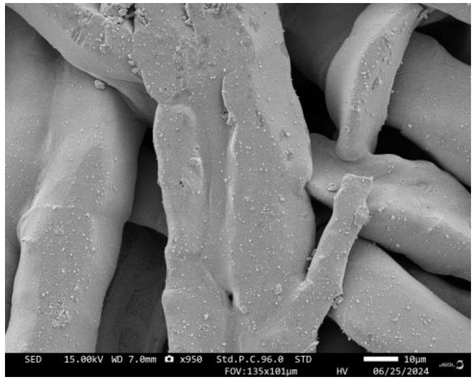
Very poor coating, Pt patches rather than a continuous film.

0.2 µm protective Pt film claimed by the supplier.

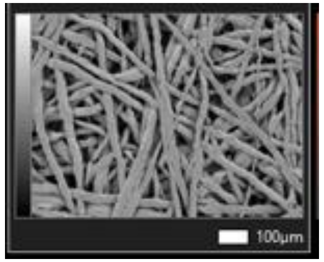
Pt loading variations along the sample: from 1.7 mg/cm^2 to 18 mg/cm^2

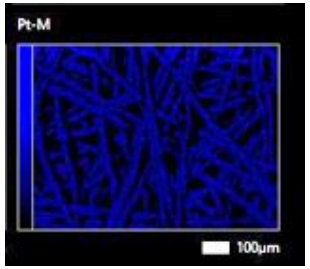
Platinized PTL by Holst developed methodology

- Etching + Pt seed layer
- Pt electroplating



Pt distribution





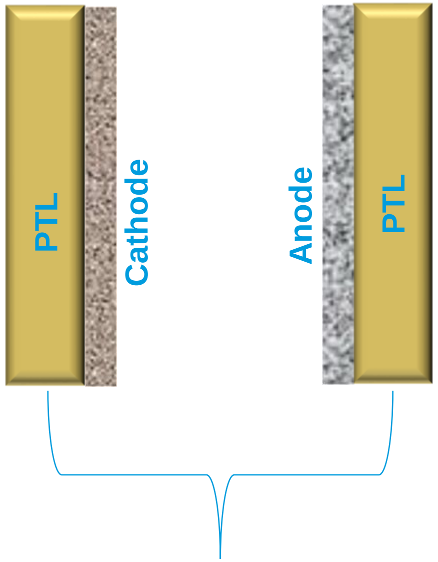
Etching – Seeding → oxide removal
Homogeneous coating

Pt loading variations along the sample: from 1.7 mg/cm^2 to 6 mg/cm^2 (electrodeposition cell still can be optimized)

A **poor Pt** coating on a Ti PTL resulted in a **30% degradation** after 400 hours of accelerated stress testing, while the **homogeneous coating** performed at Holst **reduced the degradation by a factor of 6** (to less than 5%)

CNTs on PTL – AEM

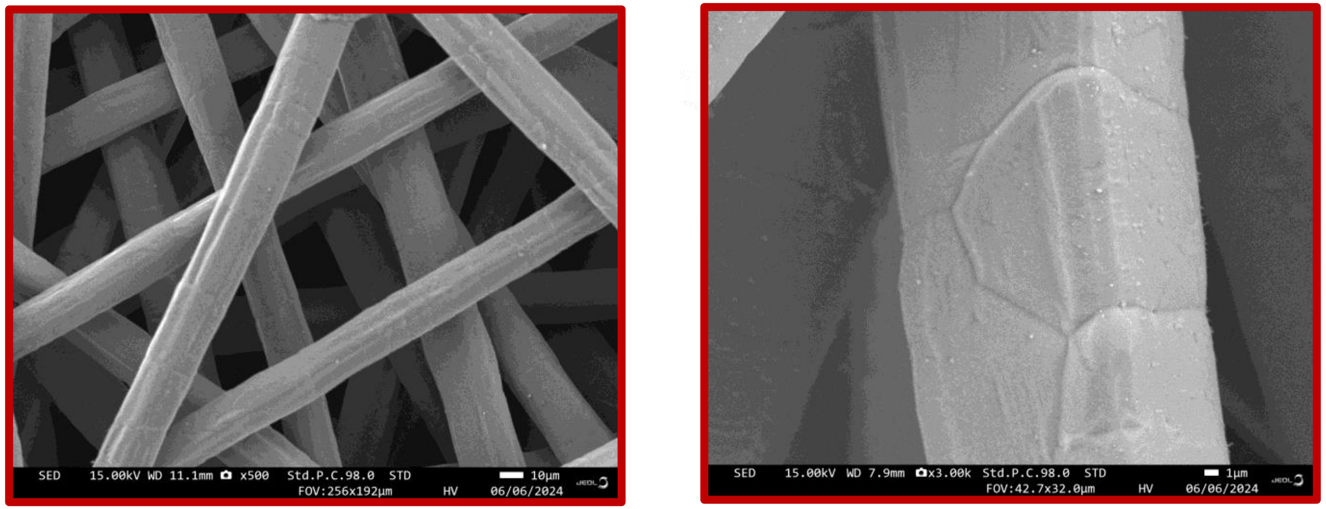
CCS (catalyst coated substrate)



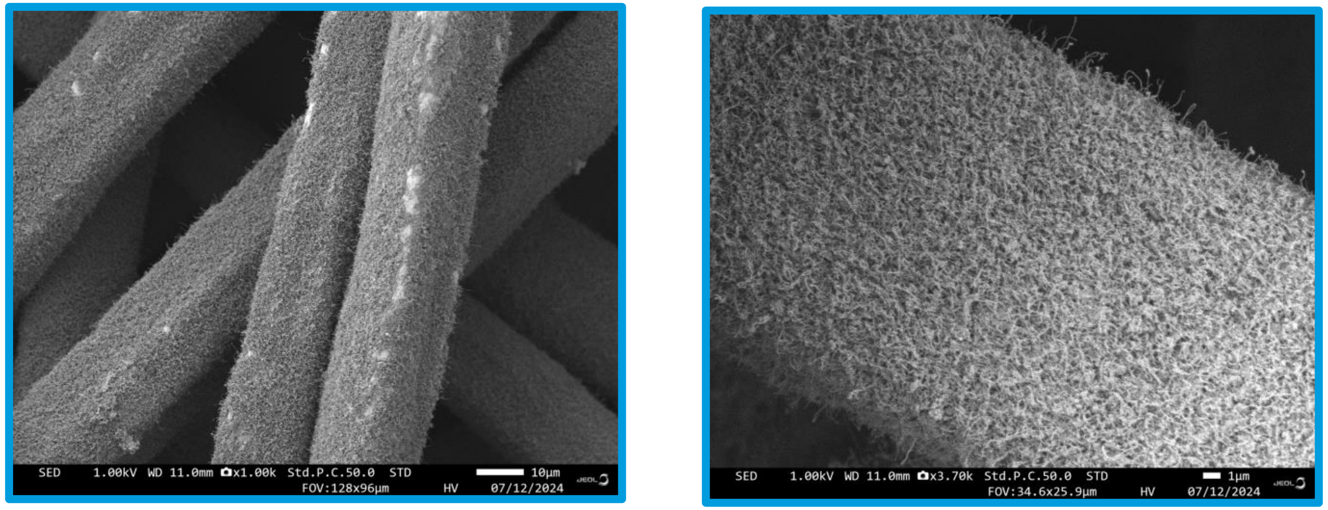
Porous transport layer (PTL): SS fiber felt

Catalyst layer → Ni
Carbon Nanotubes (CNTs)

- 3D structure → Enhance the surface area
- Improve transport of redox species on the surface
- Improve bubble transport



Pristine sample: Stainless steel porous transport layer (SS PTL)



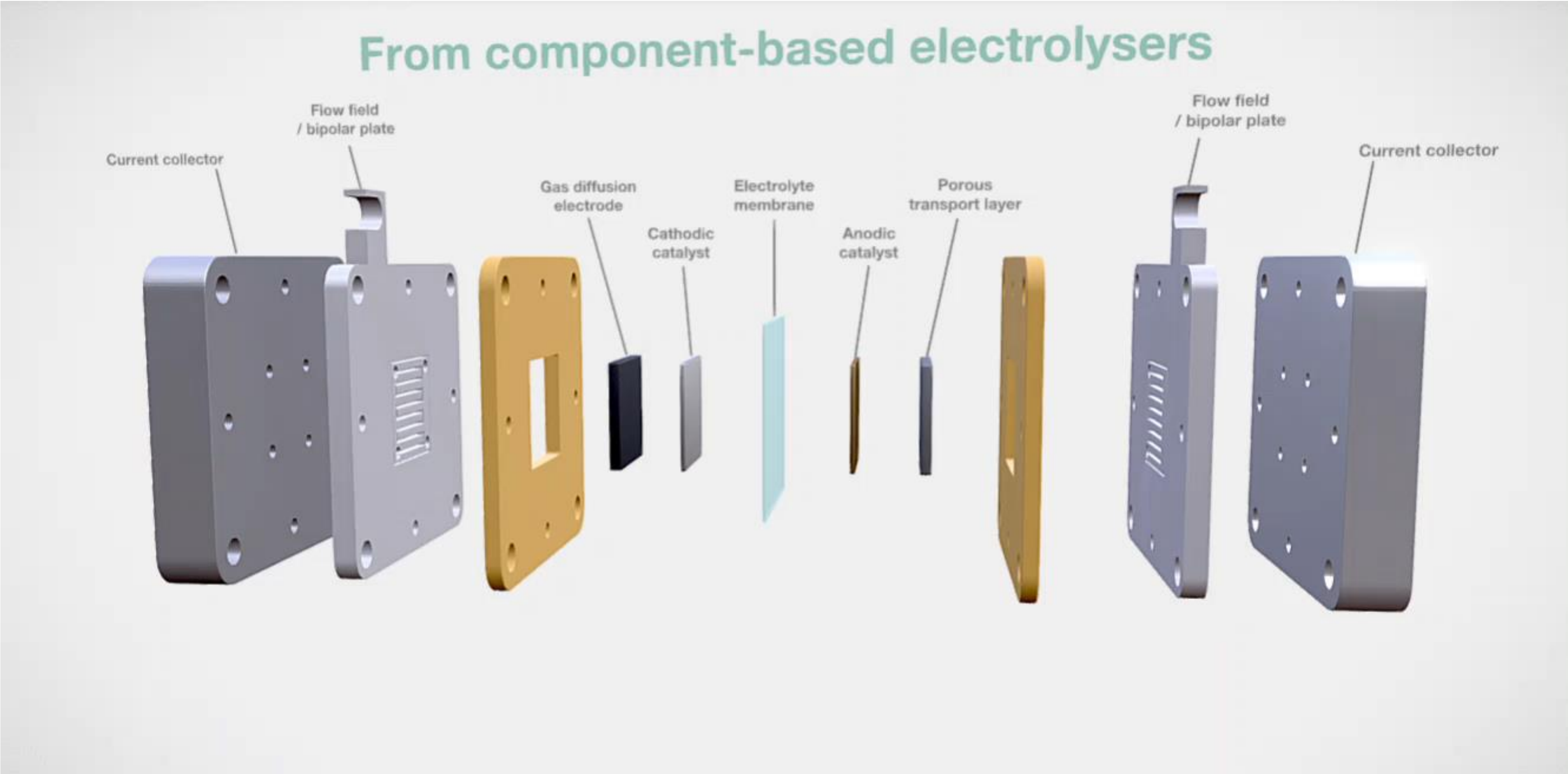
Carbon Nanotubes (CNTs) @ Stainless steel porous transport layer (SS PTL)

CNTs, manufactured at Holst by chemical vapor deposition (CVD), **enhanced the electrochemical surface area** of the stainless steel PTL by a **factor of 3!**

Holst Centre
powered by imec & TNO

Dot on the Horizon

Integrated Thin-Film Electrolyser


From component-based electrolysers
Current collector
Flow field
/ bipolar plate
Gas diffusion
electrode
Cathodic
catalyst
Electrolyte
membrane
Anodic
catalyst
Porous
transport layer
Flow field
/ bipolar plate
Current collector

Questions?

We're happy to help!

Just send me a mail or call me.

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Thank you!

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