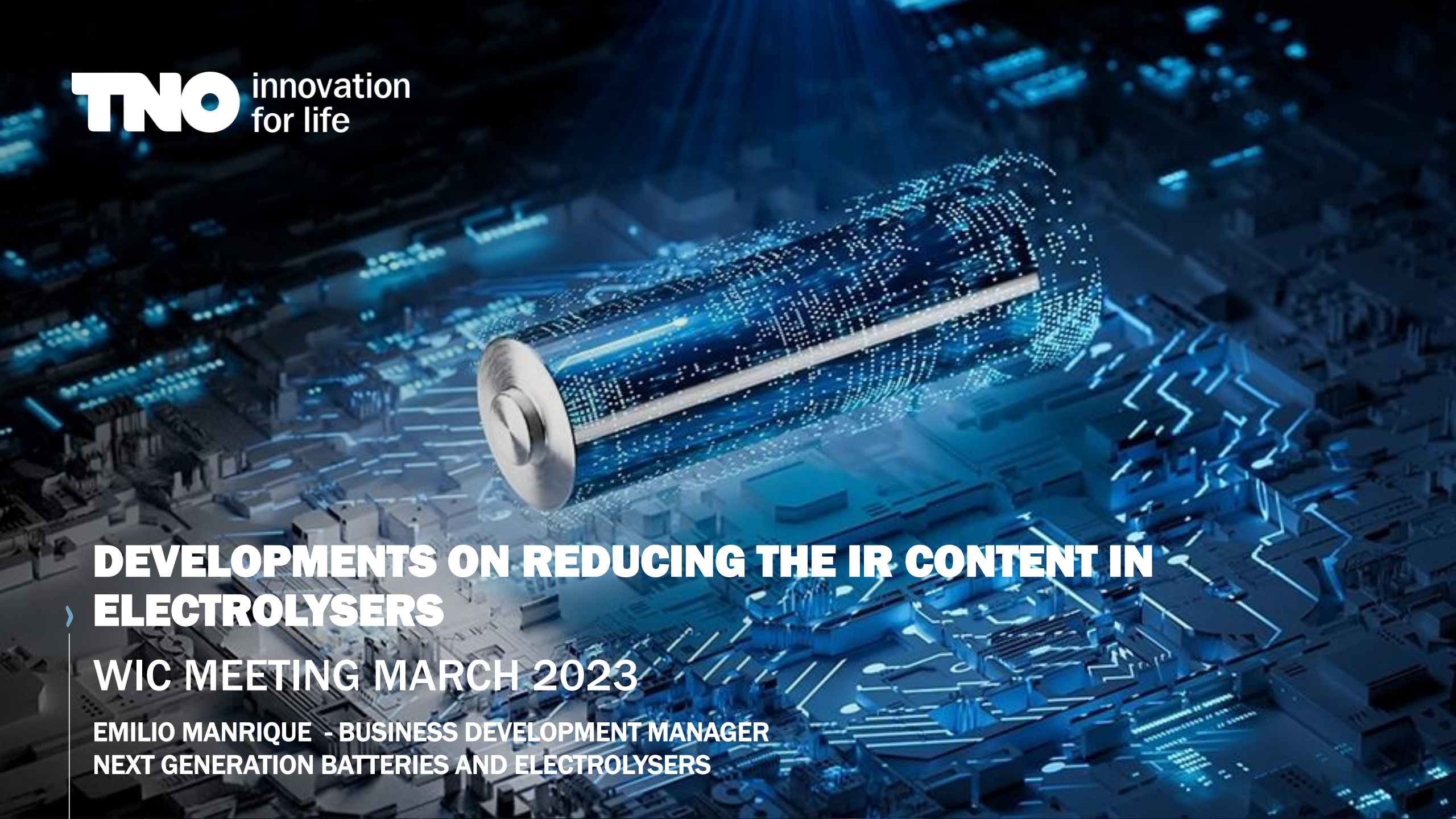


DEVELOPMENTS ON REDUCING THE IR CONTENT IN ELECTROLYSERS

WIC MEETING MARCH 2023

EMILIO MANRIQUE - BUSINESS DEVELOPMENT MANAGER
NEXT GENERATION BATTERIES AND ELECTROLYSERS

OBJECTIVES TODAY
WHAT TO EXPECT THE NEXT 20 MINUTES?

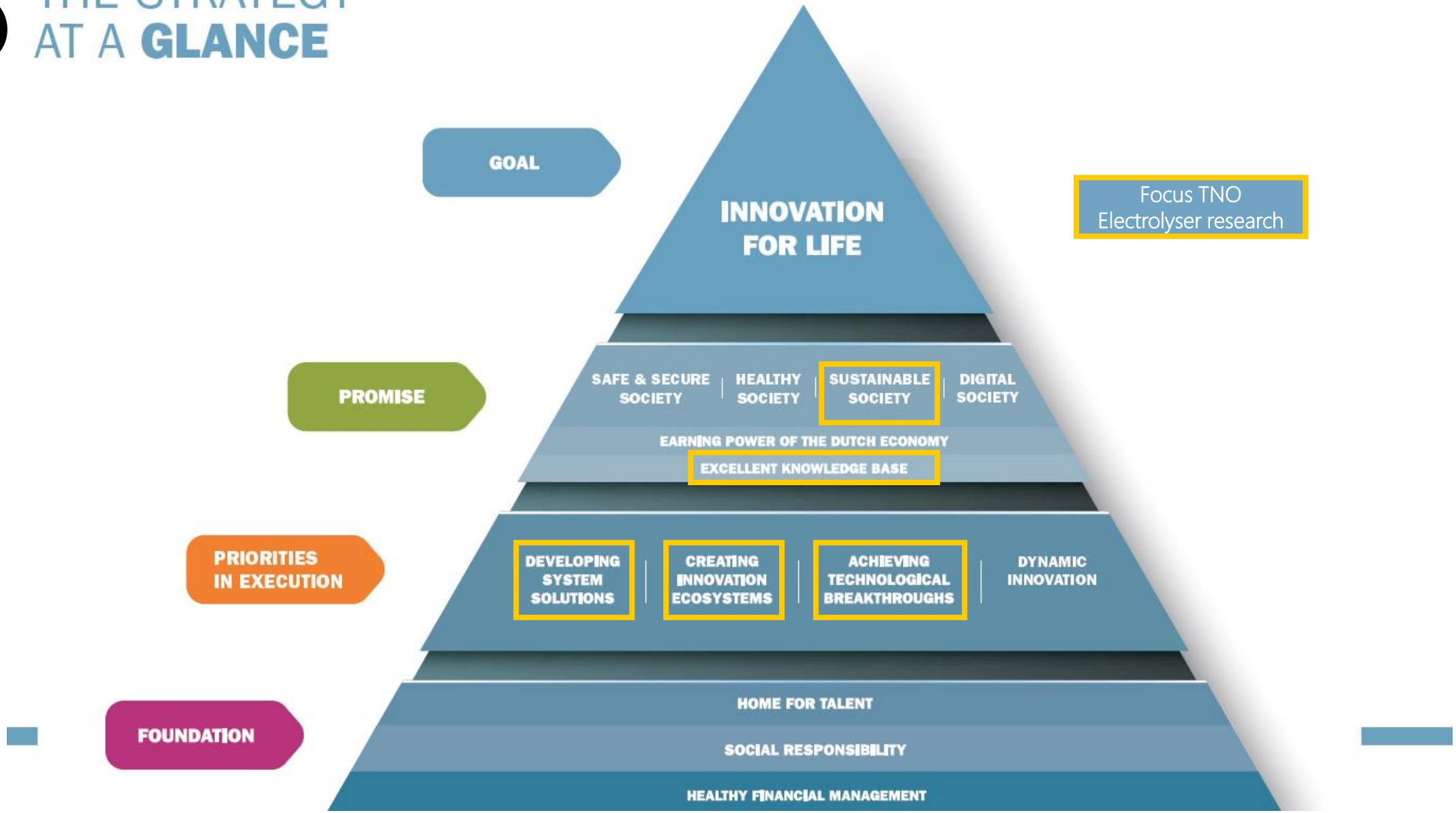
- Who is TNO?
- Roadmap Next generation PEM electrolyser technology
- Why Ir reduction is relevant?
- Ir reduction technology

‘INNOVATION FOR LIFE’

TNO CONNECTS PEOPLE AND KNOWLEDGE TO CREATE INNOVATIONS THAT BOOST THE COMPETITIVE STRENGTH OF INDUSTRY AND THE WELL-BEING OF SOCIETY IN A SUSTAINABLE WAY.
THIS IS OUR MISSION AND IT IS WHAT DRIVES US, THE OVER 3,400 PROFESSIONALS AT TNO, IN OUR WORK EVERY DAY!

TNO innovation for life

THE STRATEGY AT A GLANCE

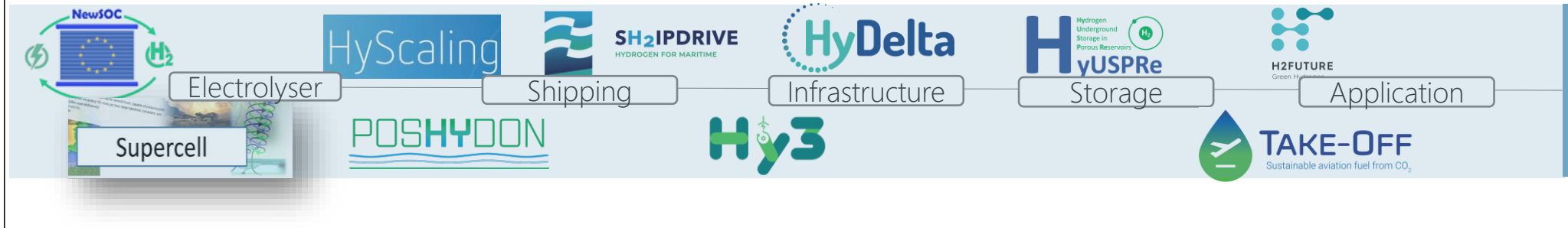


Focus TNO Electrolyser research

Source: TNO strategy 2022 - 2025: connect, change, accelerate (link)

TNO INNOVATES WITH PARTNERS IN THE H2 SUPPLY CHAIN

COLLABORATION IS ESSENTIAL TO ACCELERATE



Large R&D Projects & Programs

VOLTA CHEM

Holst Centre
Open Innovation by imec and TNO

emp NL

North Sea Energy
offshore system integration

Joint Innovation Ecosystems

NXT GEN HIGHTECH

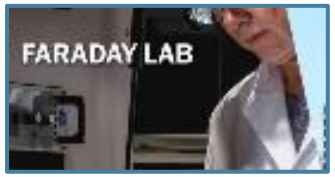
groen vermogen nl

Dutch National Growth funds

Sources: NewSOC (link), Supercell (link), HyScaling (link), PosHYdon (link), Sustainable Hydrogen Integrated Propulsion Drives (SH2IPDRIV) (link), Hy3 (link), HyDelta (link), HyUSPRe (link), Take-Off (link), H2-Future (link), Voltachem (link),Holst Centre (link) Electrolyser Makersplatform (link), North Sea Energy (link) Growthfund NextGen High-tech (link), Growthund Groenvermogen NL (link)

BASED IN
THE NETHERLANDS

INTERNATIONAL FOCUS



POSHYDON

GRONINGEN

PETTEN

AMSTERDAM

Lelystad

LEIDEN

SOESTERBERG

DEN HAAG

RIJSWIJK

UTRECHT

Rotterdam

DELFT

EINDHOVEN

BERGEN OP ZOOM

HELMOND

GELEEN

Brightsite
Transforming industry

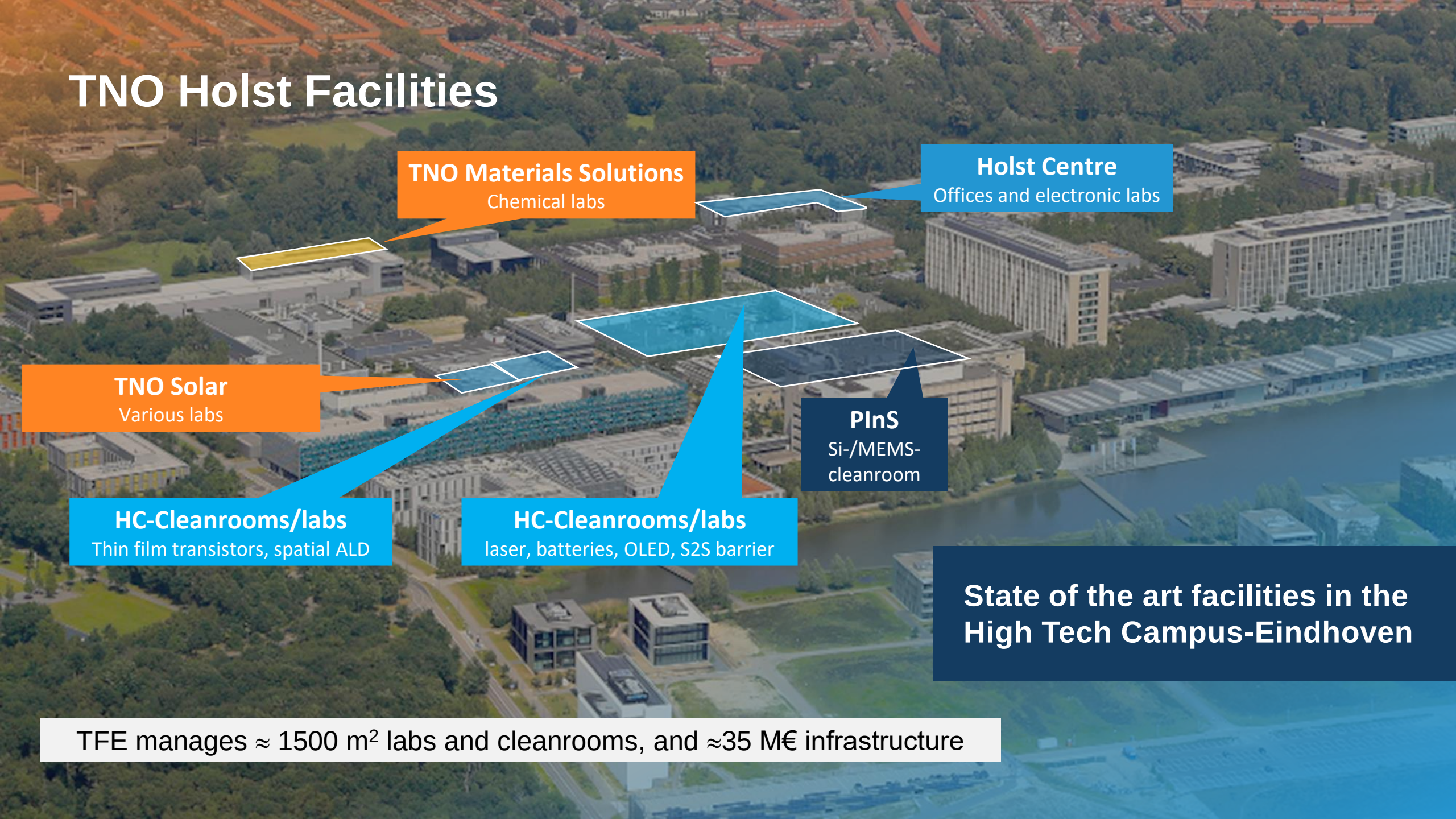
#fieldlab

TNO innovation for life

TNO Holst Centre

- ✓ Started in 2006 on initiation from Philips Research, named after Gilles Holst, first director of Philips Research
- ✓ Located at the High Tech Campus in the heart of Brainport area, home of Dutch high tech industry
- ✓ Aimed at fostering and orchestrating innovation with and between companies

TNO Holst Facilities

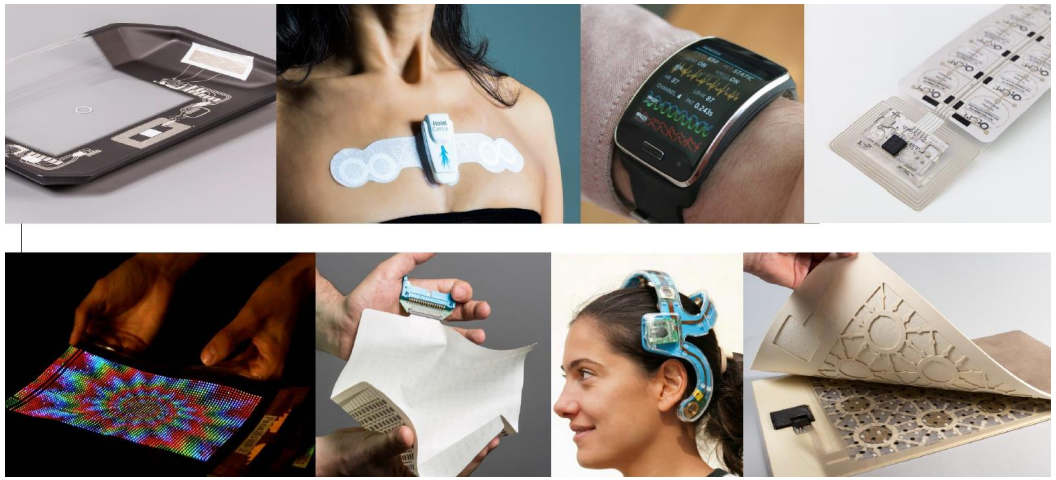


State of the art facilities in the High Tech Campus-Eindhoven

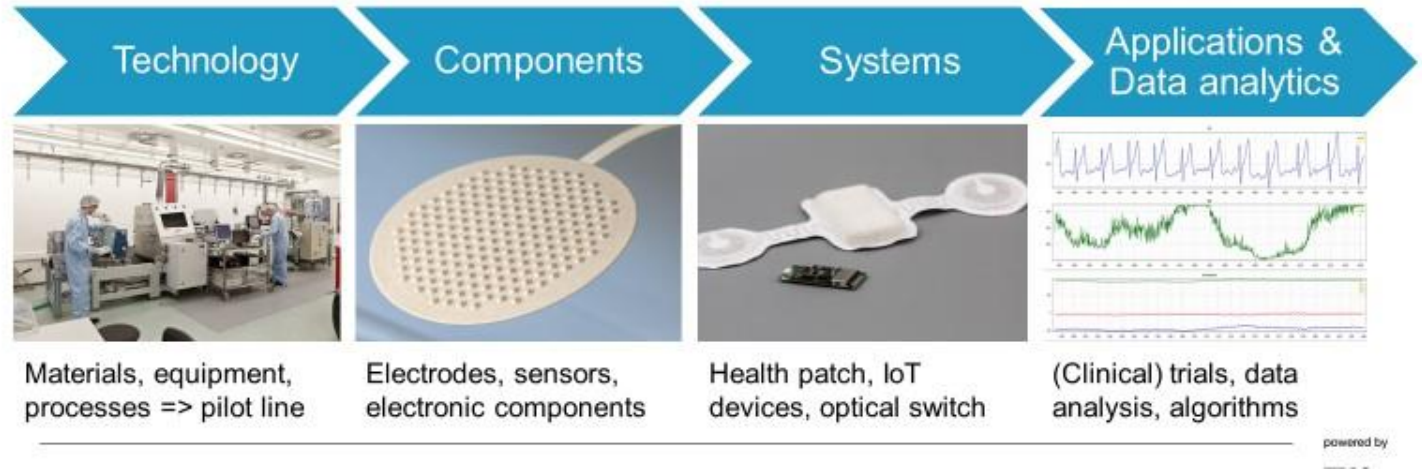
TFE manages ≈ 1500 m^2 labs and cleanrooms, and ≈35 M€ infrastructure

ACCELERATE INNOVATION IN SHARED RESEARCH PROGRAMS

BIOSTACK CENTRE



RIXTRON · Aledia · ALPINE · AMSYSTEMS · ... arranged. · AsahiKASEI
AMOREPACIFIC · BioTelemetry · EPFL · neurogyn · Johnson&Johnson · Atlas Copco · DENSO
Bambi Medical · BEYOND EYES · CEVA · covestro · CTOUCH · DUPONT · eyrise · Empo Health
faurecia · FUJIFILM Value from Innovation · Heliatek · Holland High Tech · ILLUMIX · KEIRON
LEYDENJAR TECHNOLOGIES · LionVolt · Lohmann · LIFESENSE GROUP · Mitsui Chemicals · MITSUBISHI CHEMICAL
nemho · NEOKIDNEY · nexperia · NOVACENTRIX · onera · OSRAM
PACKETCRAFT · PHILIPS · REZET · SAMSUNG · SALDtech · SEKISUI · SILICON LABS · SMART FLOOR
ShinEtsu · SPACEWELL · THUASNE · WATER FUTURE · water-link · zens



Do a virtual tour in our new lab here >> (link)

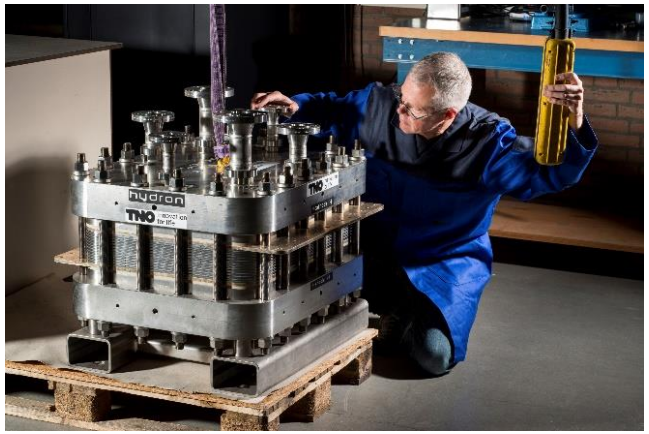
HOW CAN WE ACCELERATE INNOVATION?

FROM PEM CELL DEVELOPMENT TOWARDS INDUSTRIAL SCALE

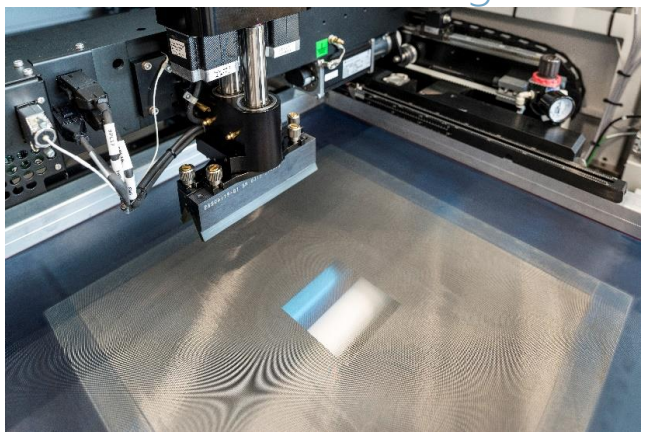
Rapid prototyping

Accelerated life time validation and benchmarking

Industrial scale R&D stack



Cell manufacturing

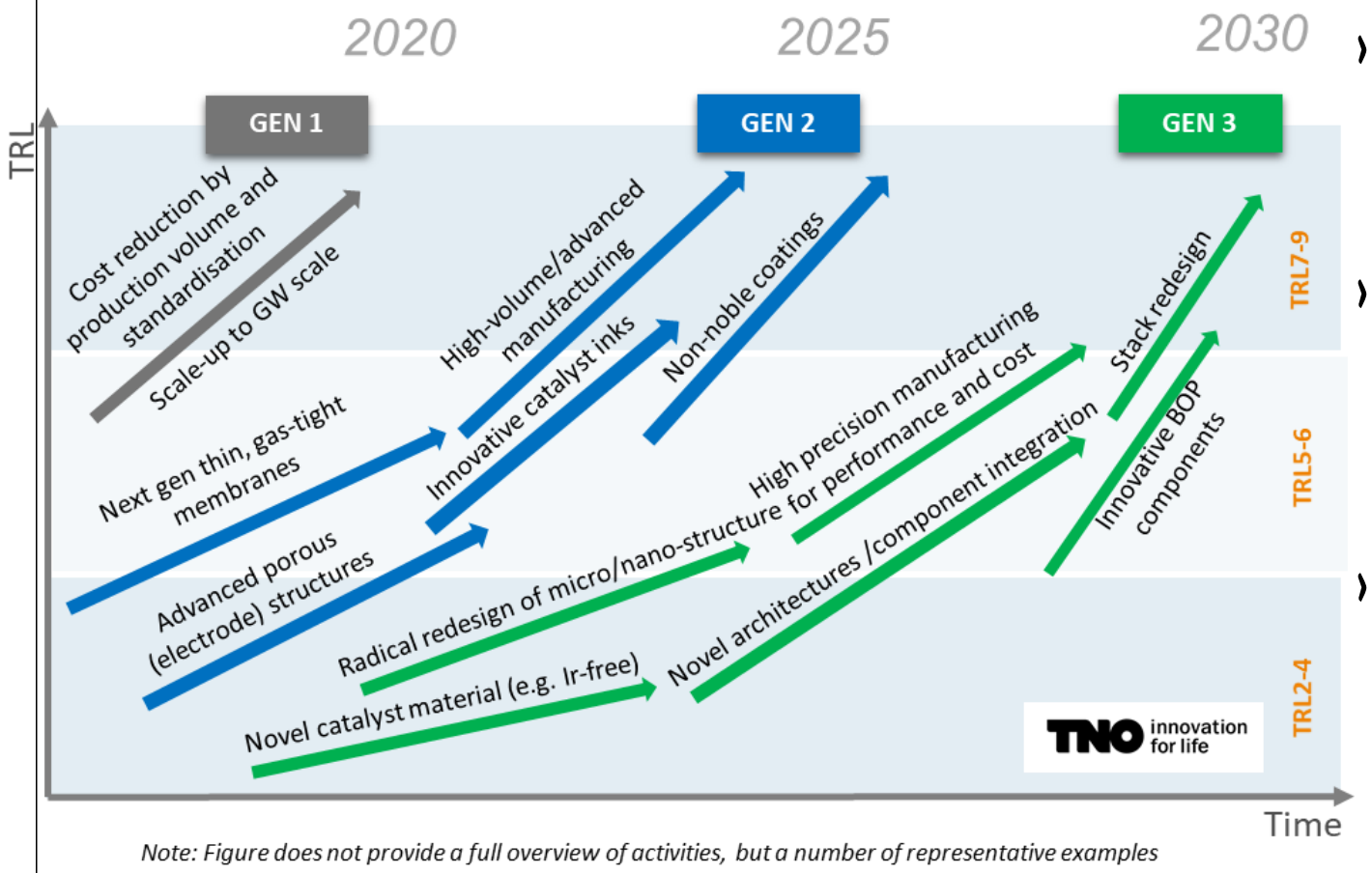


MW-size system

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

NEXT GENERATION PEM ELECTROLYSERS

PARALLEL INNOVATION PATHWAYS REQUIRED FOR ACCELERATION



Note: Figure does not provide a full overview of activities, but a number of representative examples

Market needs

- 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

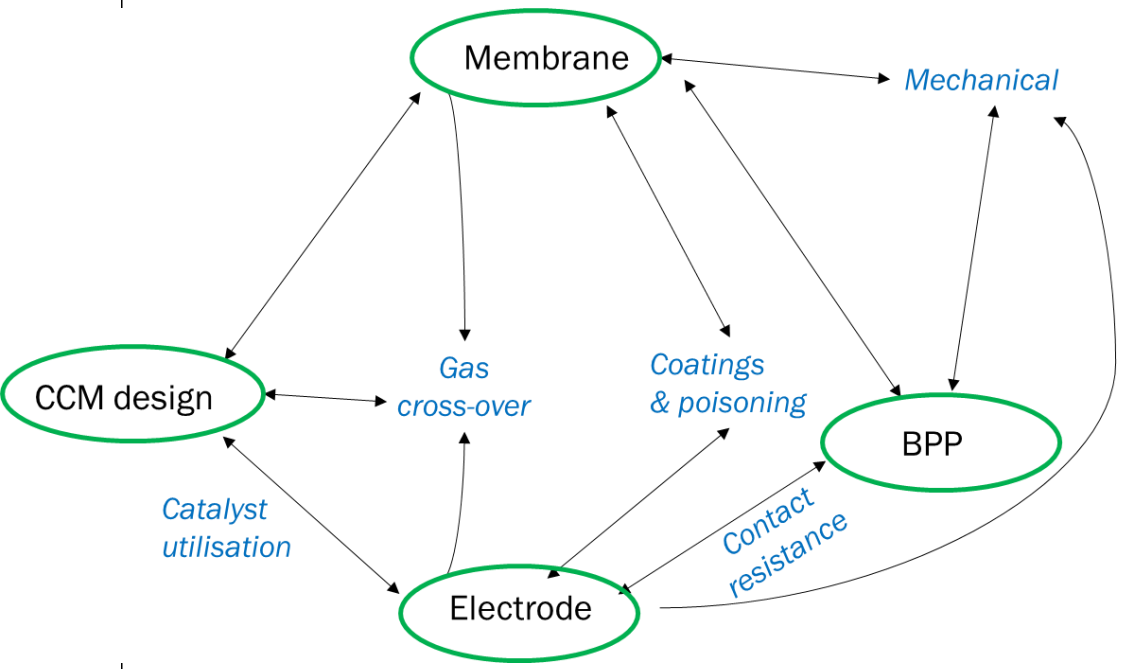
  Shared Research Programs
- 3rd generation
  - Radically new architecture of cell and stack, leading to breakthrough in performance and use of scarce materials

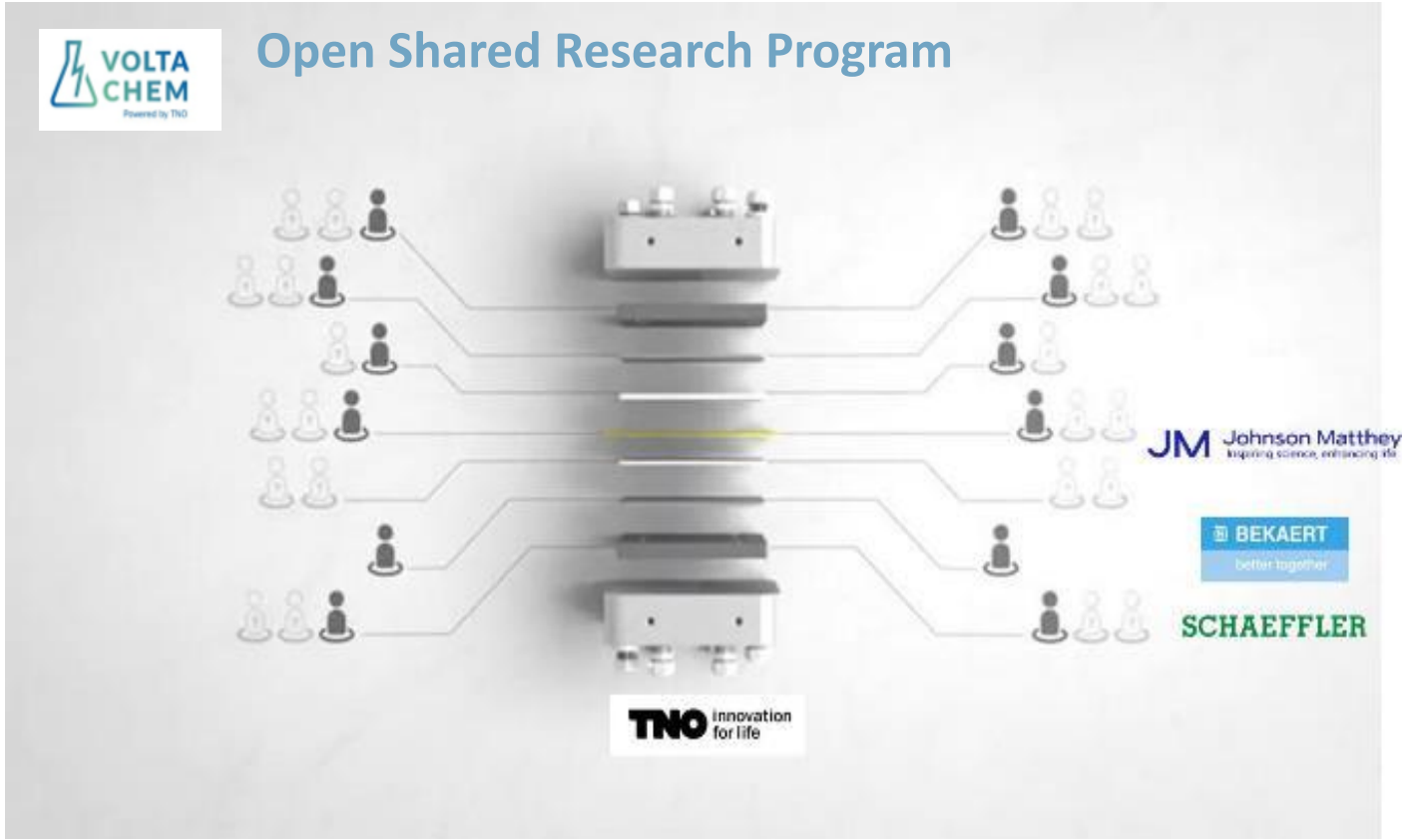
  Create new Inventions & Accelerate

Source: TNO (2022) Roadmap Next Generation PEM technology

TNO innovation for life

TOWARDS HIGH PERFORMANCE 2ND GEN PEM ELECTROLYZERS ENABLED BY NOVEL MATERIALS, READY FOR MASS PRODUCTION

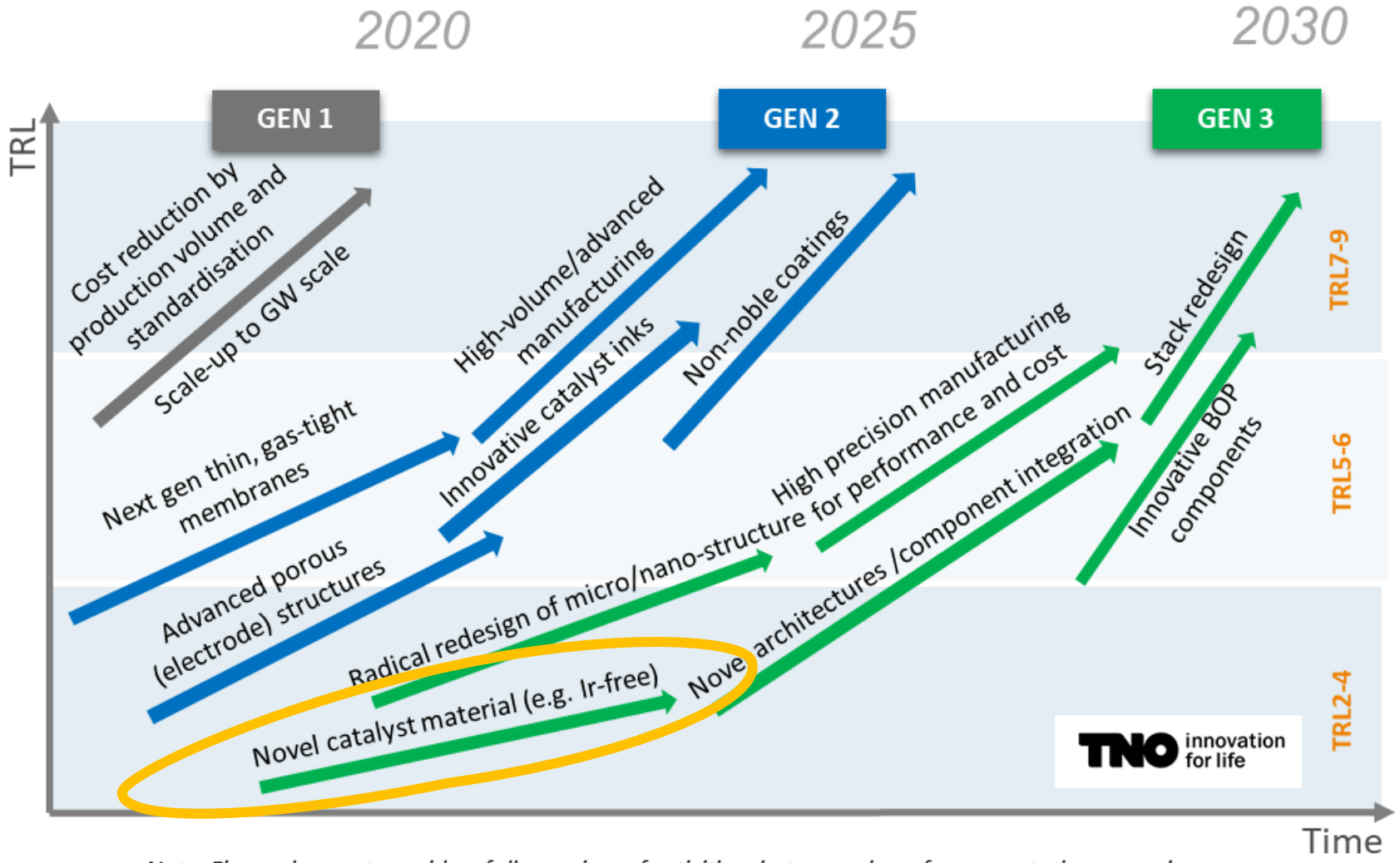




Source: TNO (2022) Shared Research Program 2nd generation PEM electrolysers (link)

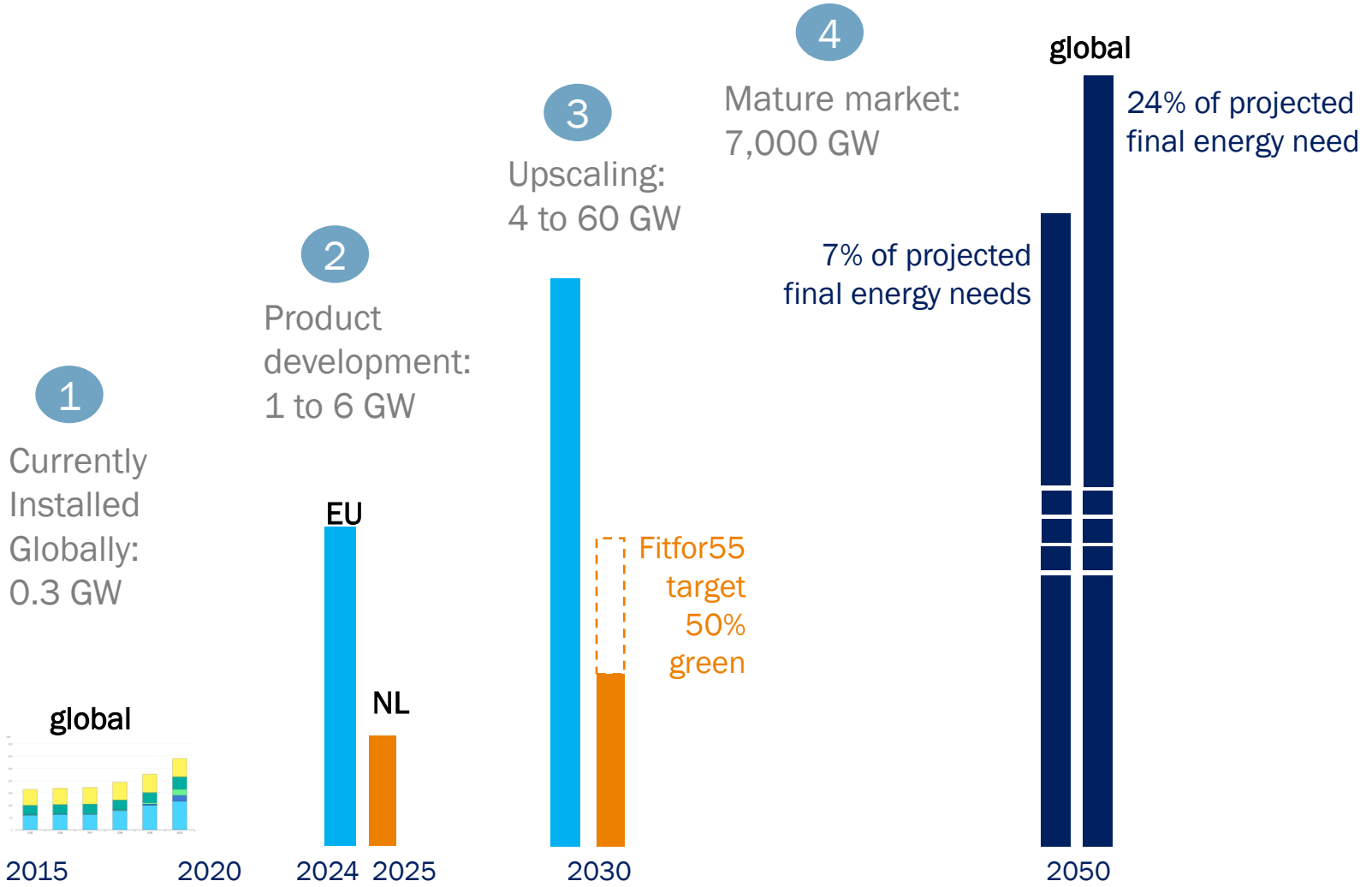
TNO innovation for life

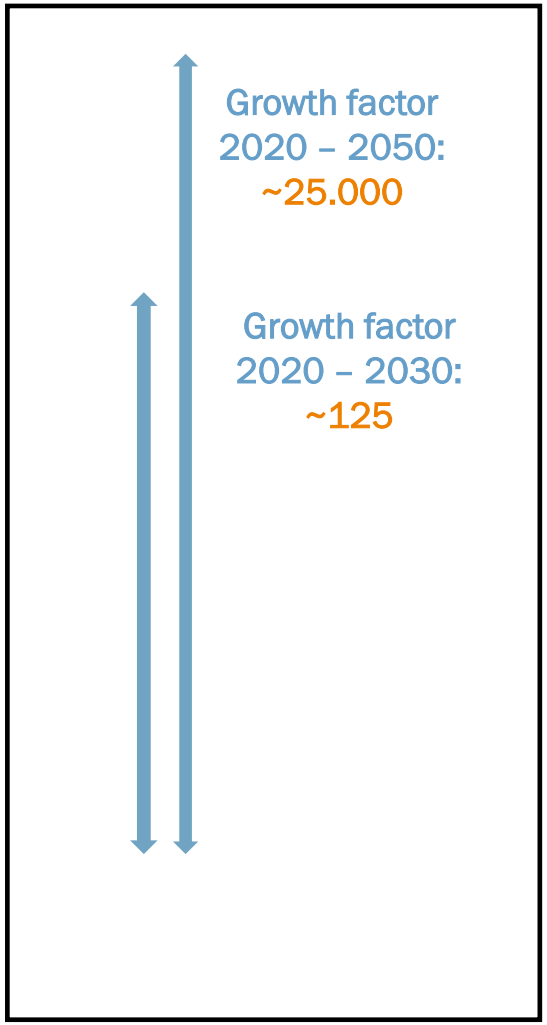
TOWARDS HIGH PERFORMANCE 2ND GEN PEM ELECTROLYZERS ENABLED BY NOVEL MATERIALS, READY FOR MASS PRODUCTION



Note: Figure does not provide a full overview of activities, but a number of representative examples

MARKET DEVELOPMENT FORECAST



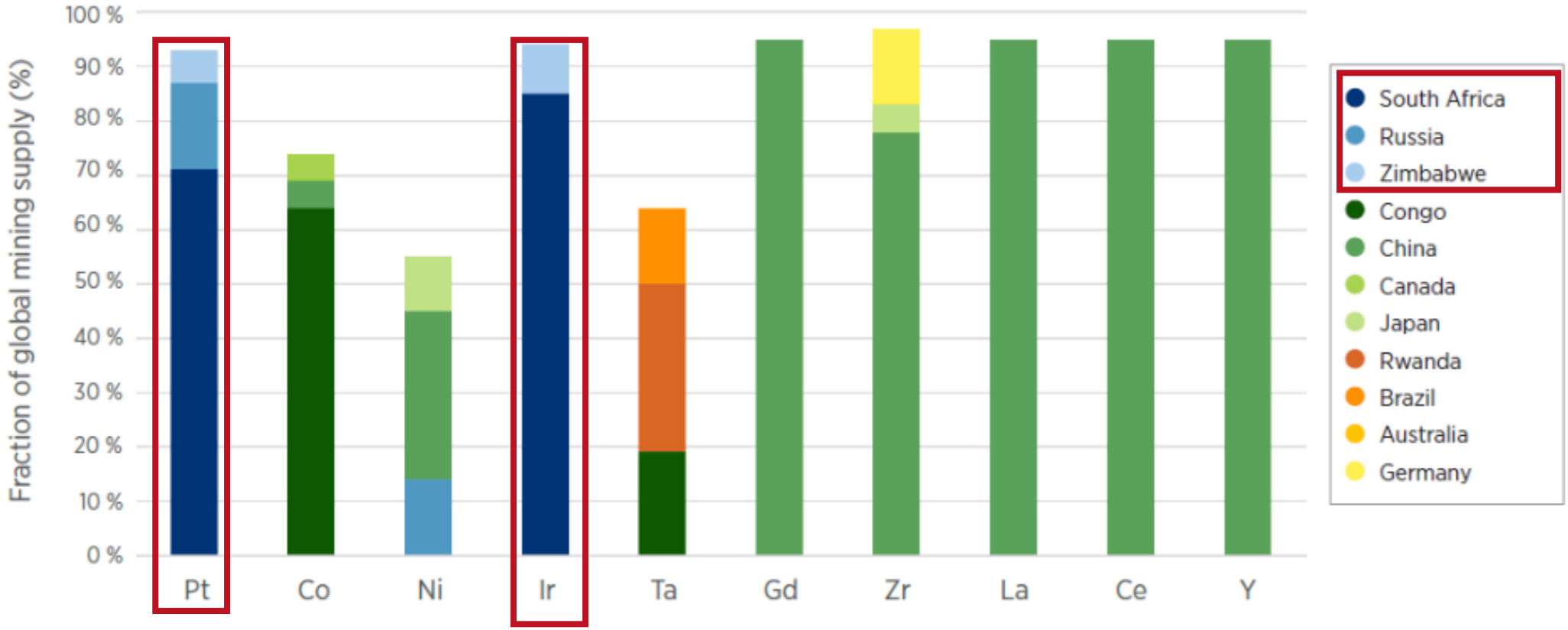


Source: IEA (2021), Global installed electrolysis capacity by region , 2015-2020 (link), Bloomberg, Hydrogen Economy Outlook – Key messages, March 2020 (link), adapted by TNO

TNO innovation for life

CRITICAL MATERIALS IN ELECTROLYSERS: A SHOW STOPPER?

Top producers of critical materials in electrolysers



Source: European Commission, 2020.

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

LOWER USE OF SCARCE MATERIALS IN ELECTROLYSERS
DIFFERENT STRATEGIES TO REDUCTION

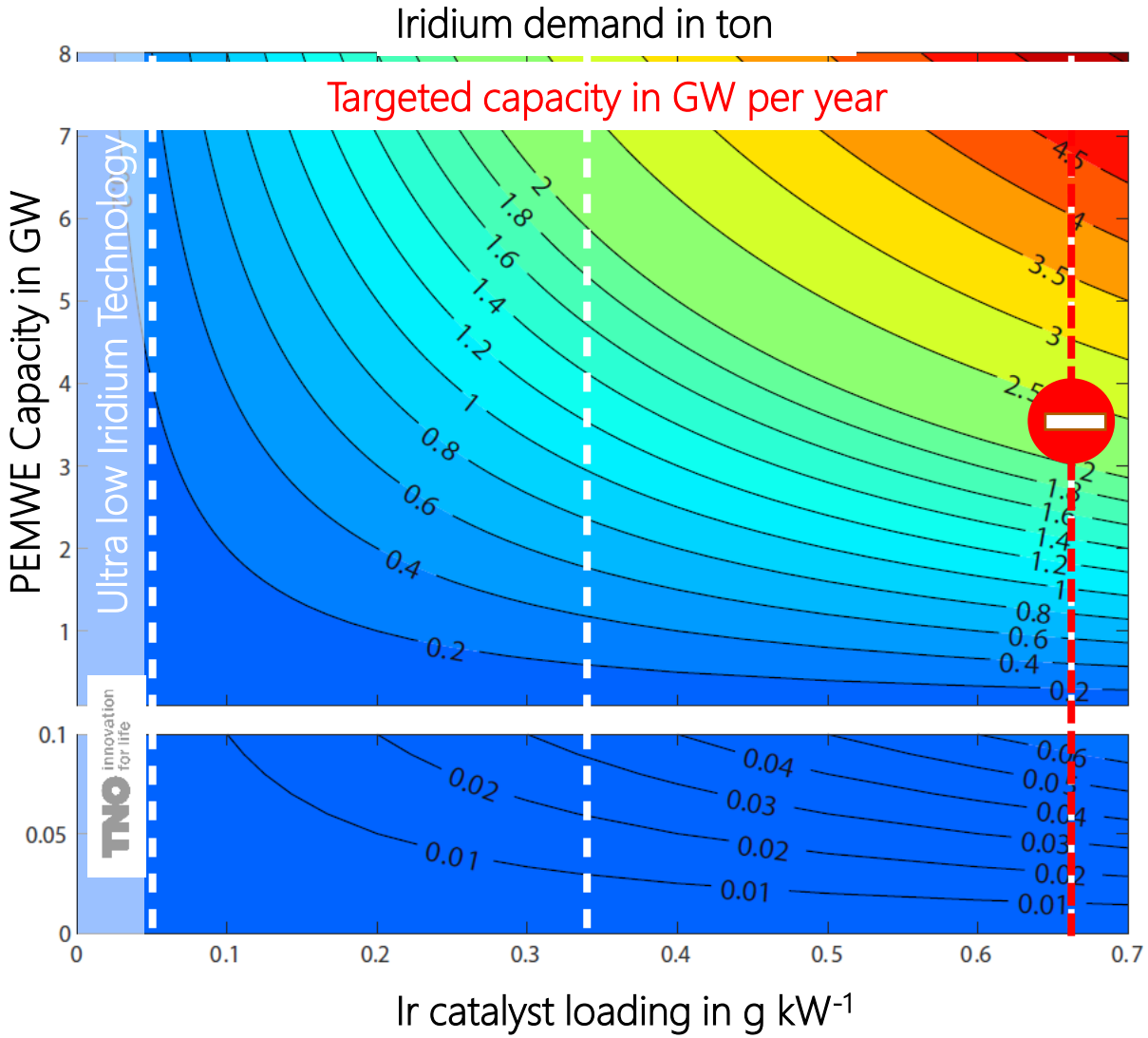
% of CRM global annual supply used as a result of each strategy (base case is EU H2 production in 2050)

	CRM	Base case	Reduction	Substitution	Higher productivity	Extended lifetime	Recycling
PEM	Iridium	122%	6%	122%	81%	91%	122%
	Platinum	25%	0.1%	0%	1%	21%	24%
AEL	Raney-Ni	0.4%	0%	0.8%	0.1%	0.3%	0.0%
	Nickel (class 1)	2%	2%	2%	0.6%	2%	2%
	Cobalt	0.1%	0.1%	0%	0%	0%	0.1%

Strategy with most potential

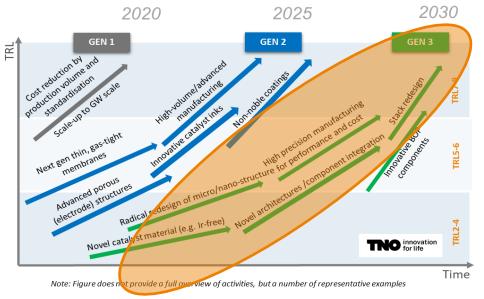
Source: TNO (2021), Part 1 - How raw materials scarcity can hinder our ambitions for green hydrogen and the energy transition as a whole (link), Part 2 - How we can prevent the scarcity of raw materials and achieve our ambitions for green hydrogen (link)

A FACTOR OF 200 REDUCTION OF IRIDIUM CATALYST FOR PEM ELECTROLYSERS IS DEMONSTRATED TO BE POSSIBLE



- The contour lines represent levels of resulting iridium demand in tonnes. White box indicates the targeted production capacity per year required to obtain 40 GW electrolyser capacity in 2030.
- Iridium demand from catalyst loading and PEM electrolyser capacity on large industrial scale with catalyst loading of 0.67 g kW^{-1} (2020 status with red dotted line) and catalyst loading below 0.01 g kW^{-1} (white left dotted line).
- TNO developed an ultra low iridium technology with an Iridium use of much lower than 0.01 g kW^{-1}. After 2,000 cycles of accelerated stress tests there was hardly no degradation in the lab. TNO have been the first to develop a method that will **require 200 times less iridium while retaining a third of the performance** with respect to state of art technology

TNO Patented PCT/NL2022/050406

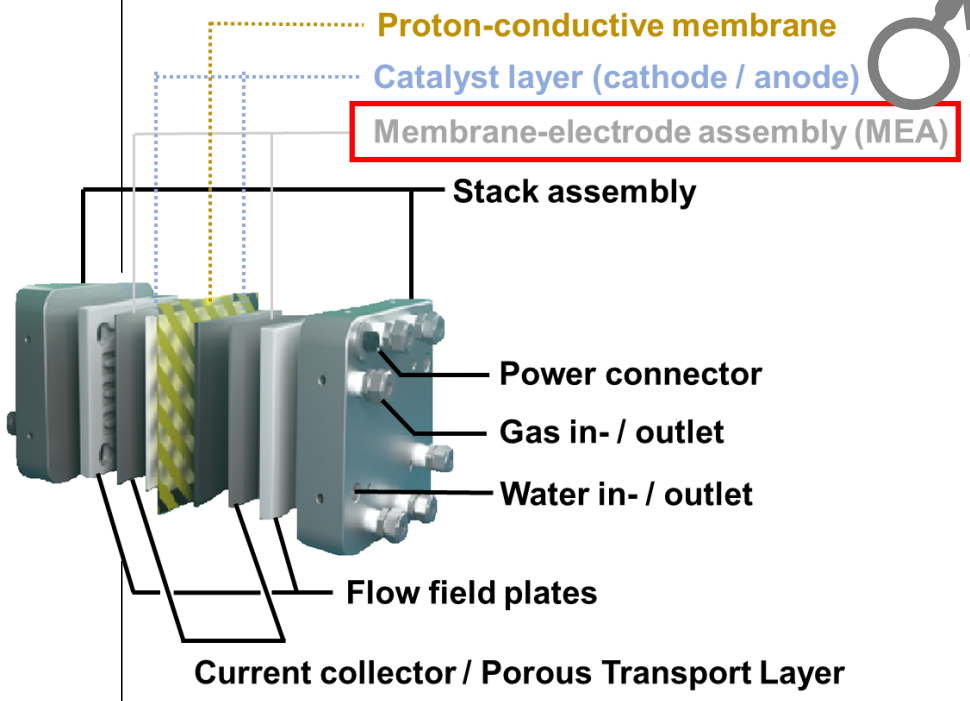


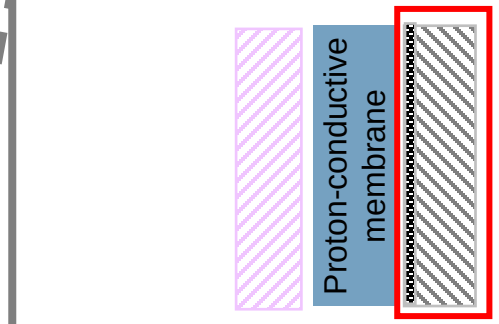
Source: "Is Iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?", C. Minke et al., Int. J. Hydrogen Energy 46 (2021) 23581-23590 (link); adapted by TNO

TNO innovation for life

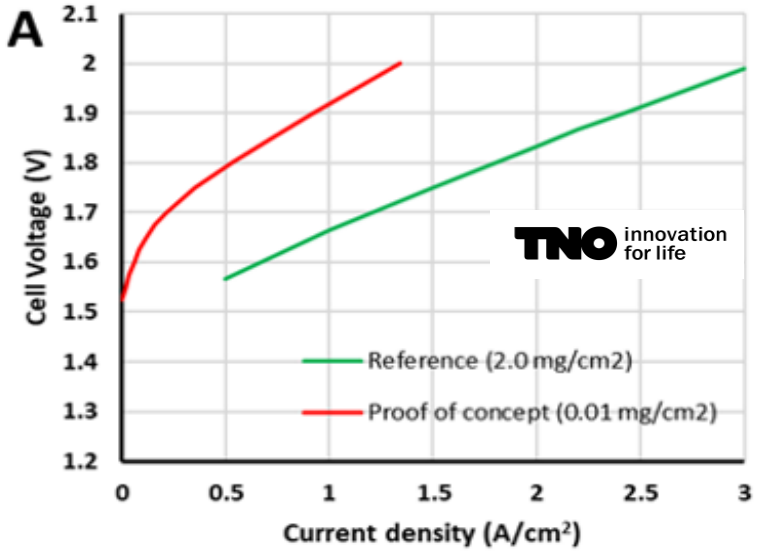
TNO Proof Points on Realizing Ultra- low Loading
WITH PARTNERSHIPS ACCELERATE DEVELOPMENT & MARKET INTRO

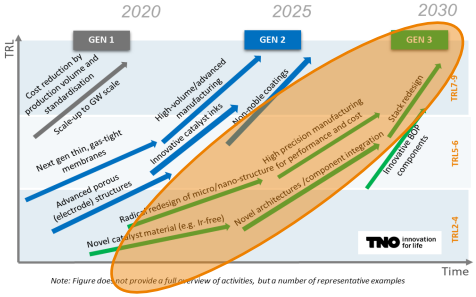
PEM shortstack





- Development of porous transport electrode (PTE)
- Catalyst coating on anode PTE (Ir = 0.01 g/cm^2)
  → No CCM
- Increased durability
- Lower capital costs
- Focus on recycling of iridium at end-of-life
- Drop-in replacement: exchange State of Art PTL and CCM with non-catalyst coated membrane and coated PTE



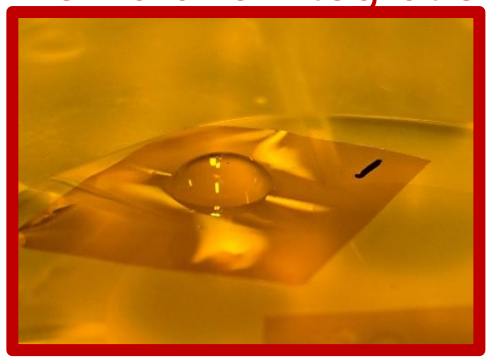


TNO Patented PCT/NL2022/050406

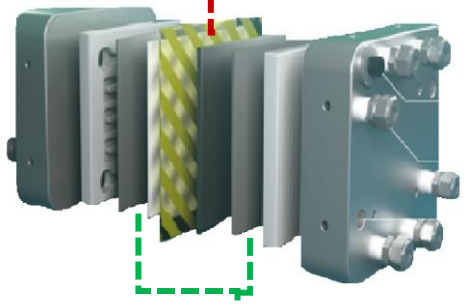

THANK YOU FOR
YOUR TIME
TNO innovation for life

OUR PROPOSITION: MONOLITHICALLY INTEGRATED HIGH-TECH ELECTROLYSIS STACKS

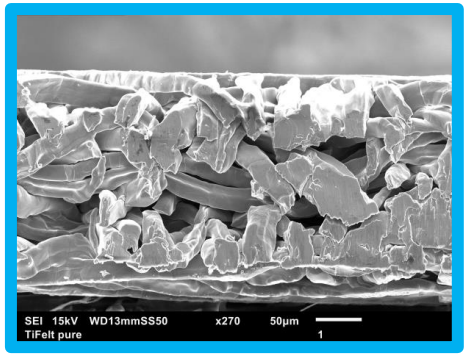
Membrane integration



Wet solution coating (e.g. Polyimide + Nafion) for membrane integration

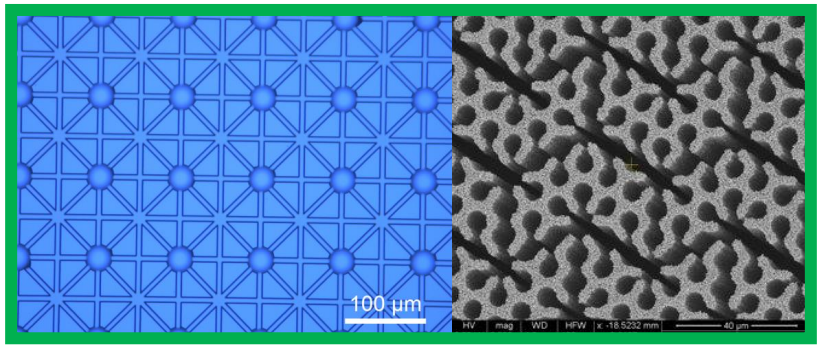


Thin films



Thin film deposition of catalysts (Ir, Pt,..) for **performance increase** and **material reduction**

Microstructures

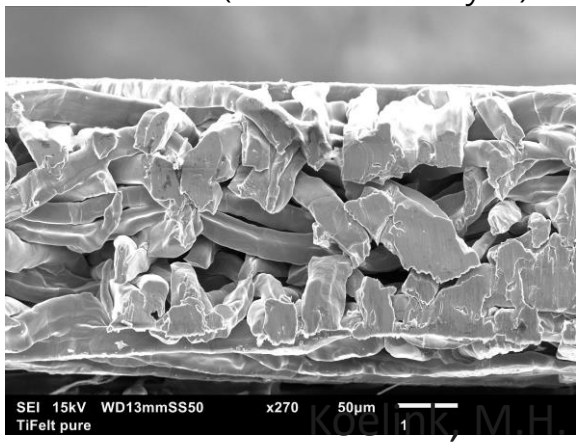


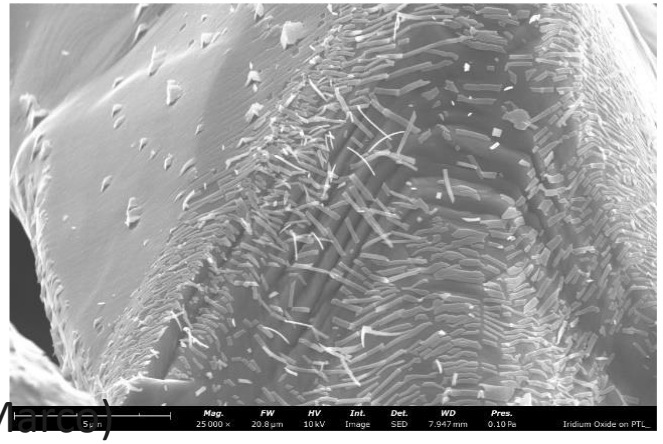
Large-area, high-aspect ratio patterned structures (lithography, CVD, …) to realize optimized microstructures for **performance increase**

Thin films

SALD FOR IR/PT REDUCTION

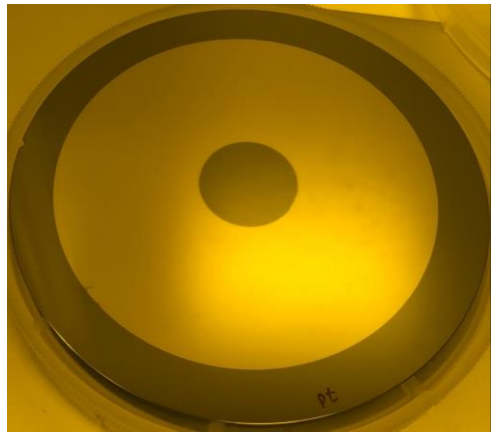
sALD IrOx (anode catalyst)

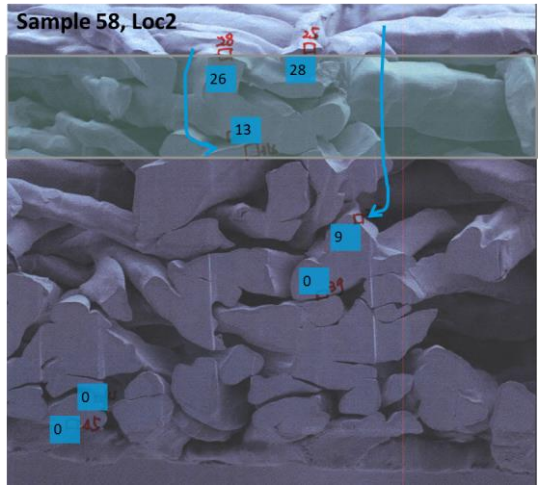


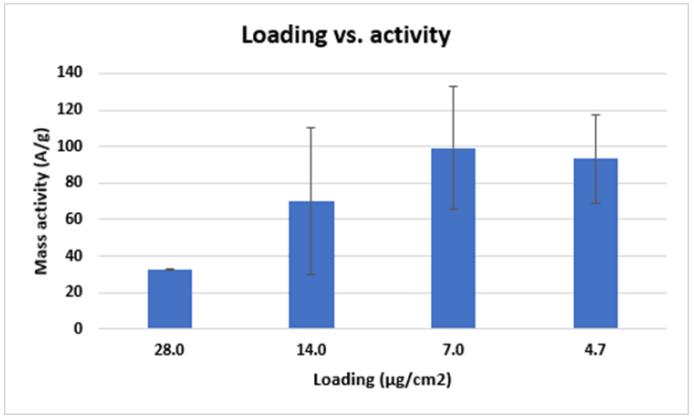


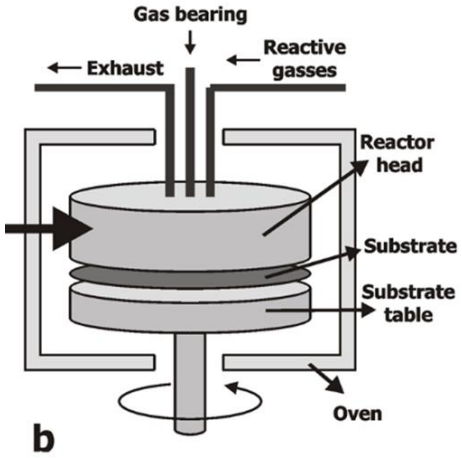
Koelink, M.H. (Marco)

sALD Pt (cathode catalyst)





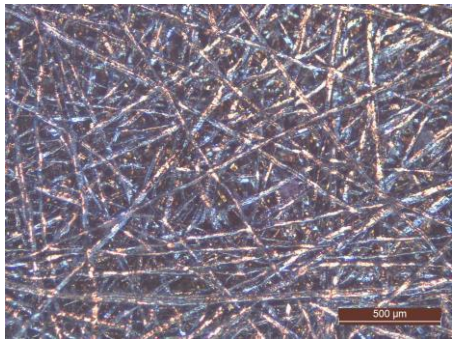




sALD Process

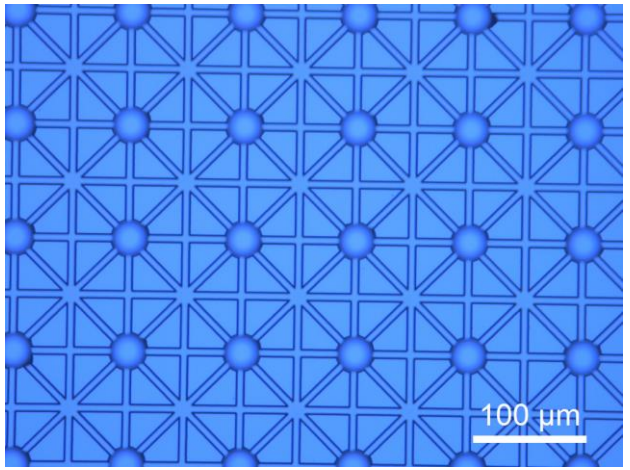
MICROSTRUCTURES FOR MASSIVE SURFACE AREA INCREASES

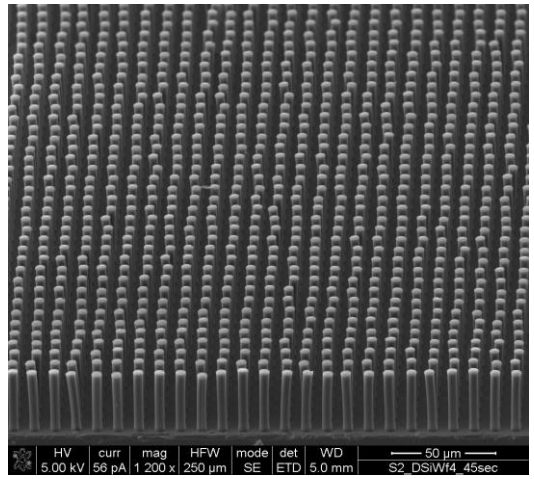
Conventional Electrolyser transport layer



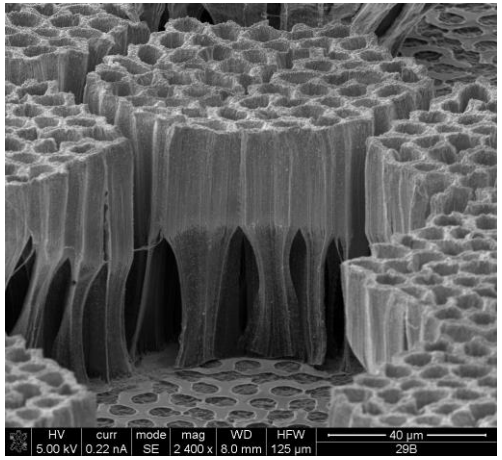
Our proposal:

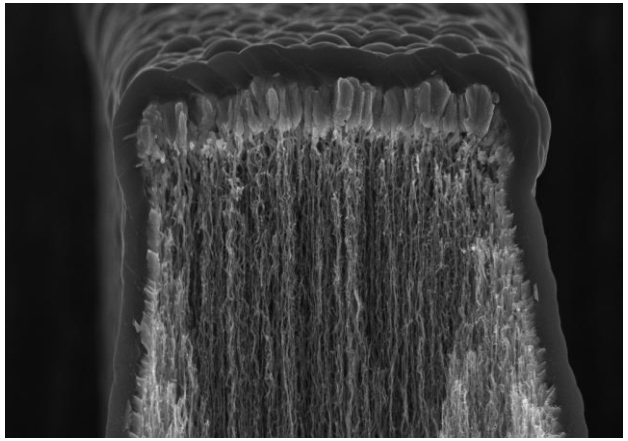
Using high-tech to create controlled microstructures which dramatically increase the surface area





And we can coat them with extreme precision and extreme conformality using thin-films





NAFION MIXED WITH POLYAMIDE MEMBRANE AND IROX

We have done research on integrating Polyamide with Nafion for need properties

We have done research on integrating Iridium Oxide with Nafion for need properties with our partners SparkNano

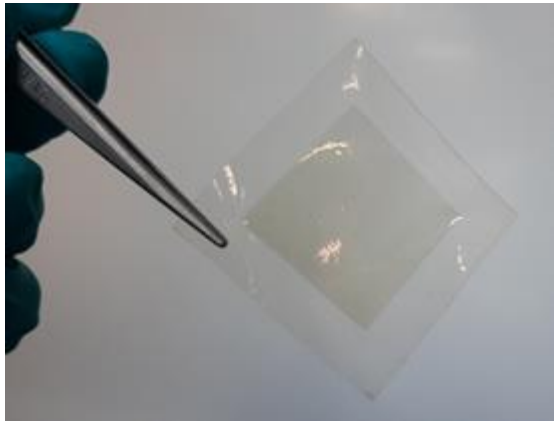


Image provided by SparkNano