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# ELEKTROLIZERY NISKOTEMPERATUROWE

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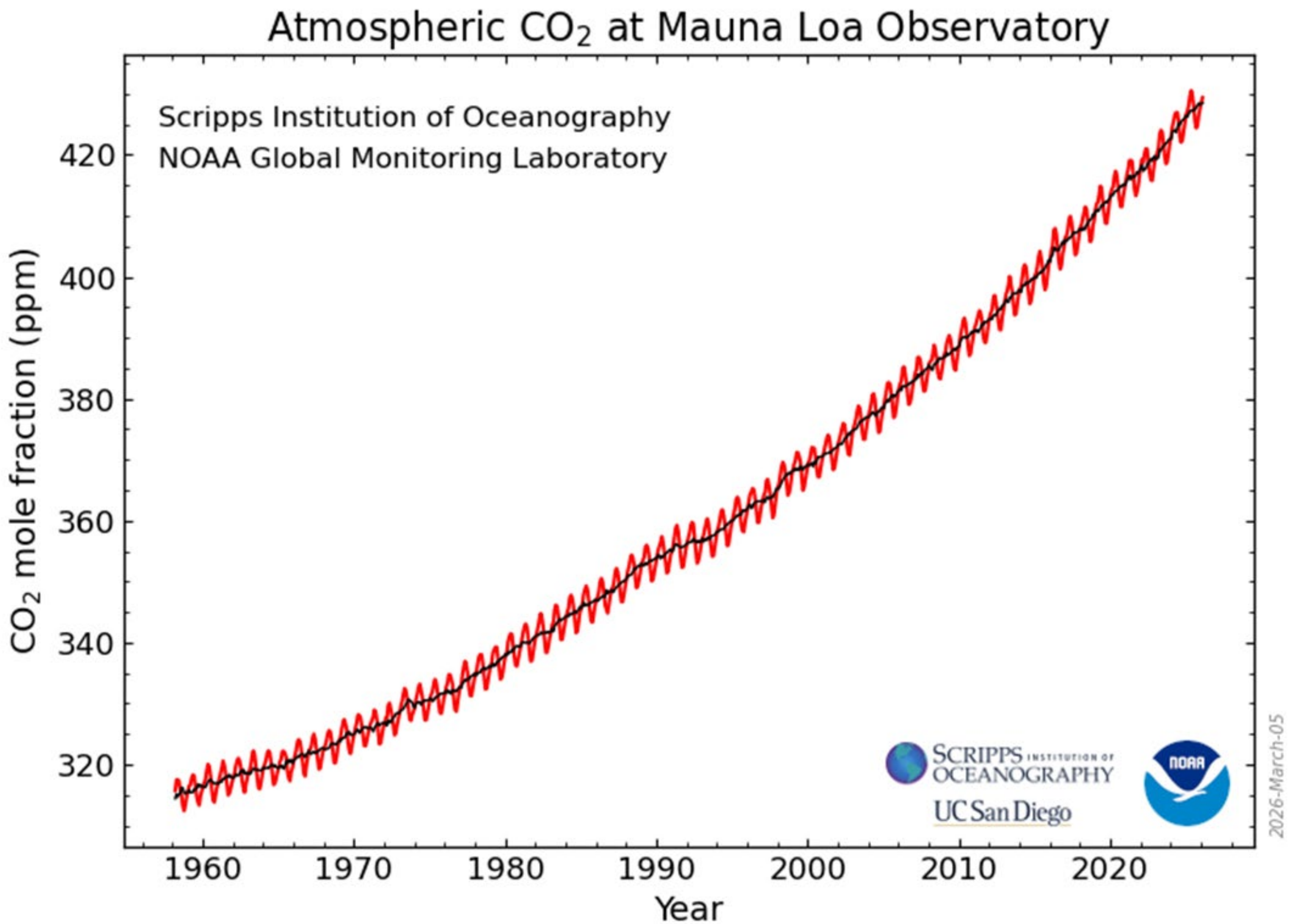
Rzeczpospolita Polska
Dofinansowane przez Unię Europejską

# Plan wykładu

1. **Dlaczego (zielony) wodór i elektroliza?** — 10 min
   Transformacja energetyczna i zielony $H_2$
2. **Podstawy elektrolizy** — 20 min
   Termodynamika, reakcje elektrodowe, straty
3. **Technologie elektrolizerów** — 20 min
   AWE, PEM, AEM — czym się różnią
4. **Od laboratorium do przemysłu** — 20 min
   Konstrukcja, stosy, systemy, skalowalność
5. **Ekonomia i przyszłość** — 20 min
   Koszty, wyzwania, Polska, perspektywy

# Motywacja...


Atmospheric $CO_2$ at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory
420
400
380
360
340
320
$CO_2$ mole fraction (ppm)
1960
1970
1980
1990
2000
2010
2020
Year
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
NOAA
2026-March-05

# Dlaczego (zielony) wodór

Większość $H_2$ pochodzi z paliw kopalnych. Elektroliza to droga do czystego wodoru.

## Szary $H_2$

Reforming parowy metanu (SMR)

**~10 kg $CO_2$/kg $H_2$**

~95% produkcji

## Niebieski $H_2$

SMR + wychwyt $CO_2$ (CCS)

**~2-5 kg $CO_2$/kg $H_2$**

CCS dodaje 50-80% kosztu

## Zielony $H_2$

Elektroliza wody + energia odnawialna

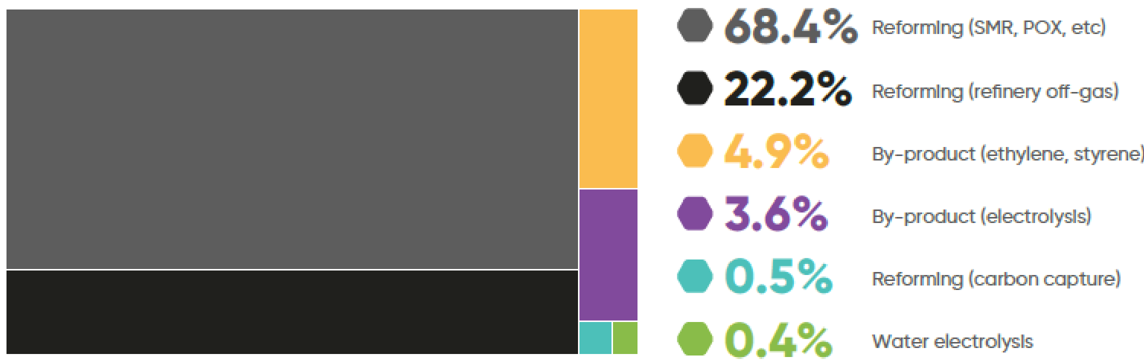
**~0 kg $CO_2$/kg $H_2$**

Technologia docelowa

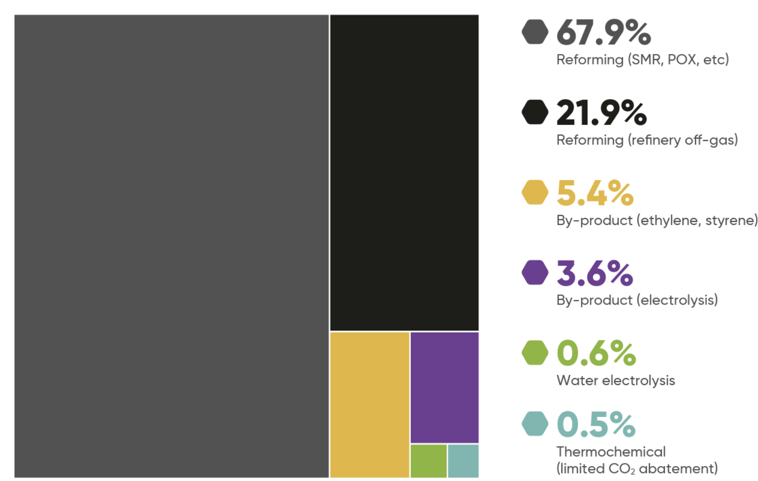
Popyt na $H_2$: ~115 Mt/rok • Tylko ~4% z elektrolizy • Cel: >100 GW mocy elektrolizerów do 2030 (IEA)

# Źródła wodoru w Europie

## Hydrogen production capacity in 2023 in Europe by production process

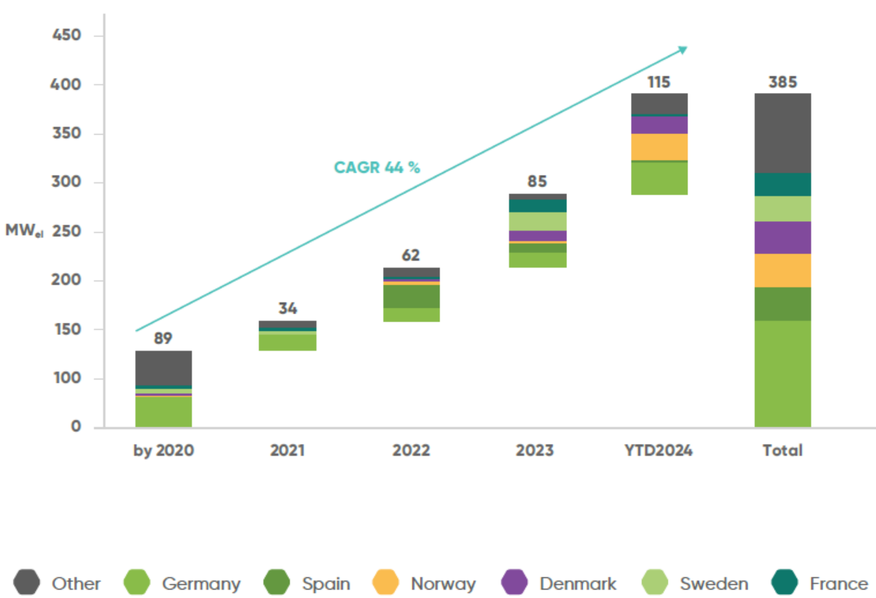



## Hydrogen production capacity in 2024 in Europe by production process (% of total)

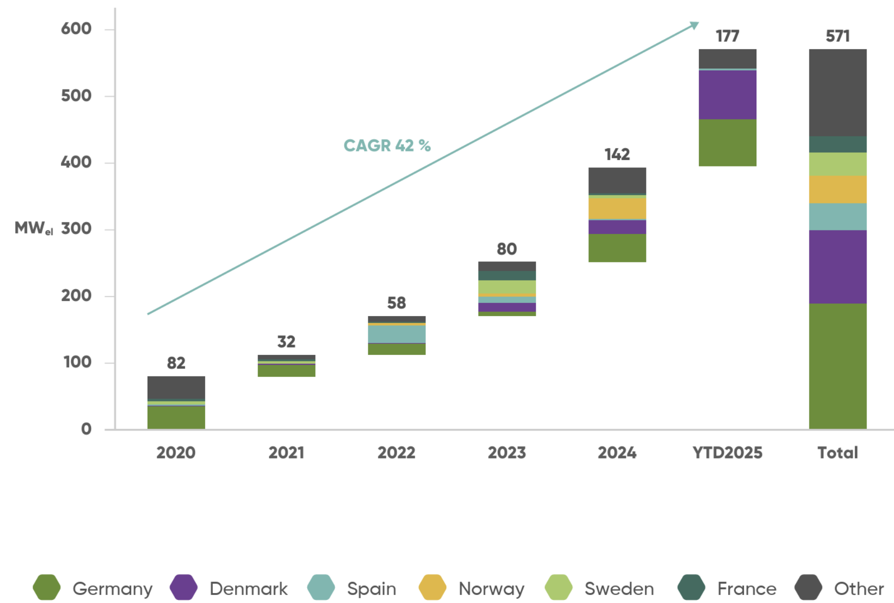


# Elektroliza wody


Installed and operational water electrolysis capacity in Europe by September 2024 and since 2020 by year




Installed and operational water electrolysis capacity installed in Europe by June 2025



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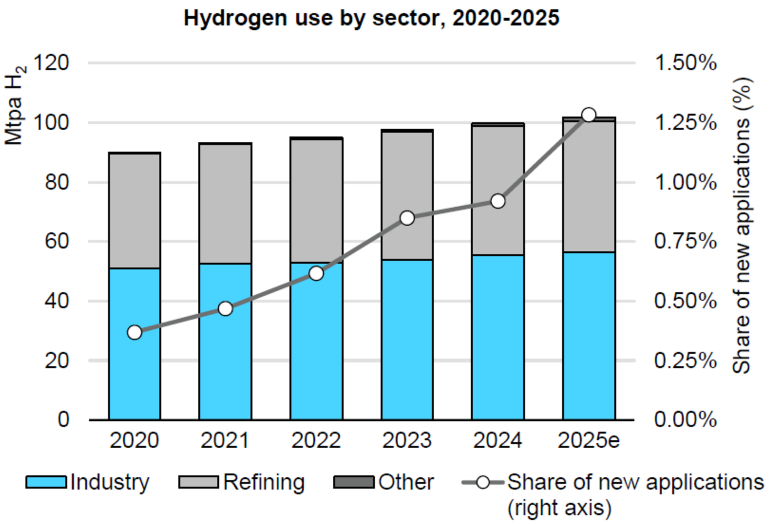
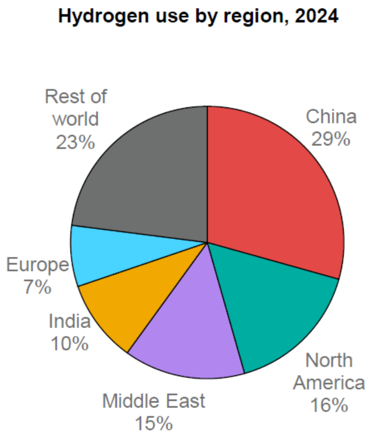
# Produkcja/zapotrzebowanie wodoru

## ~95 Mt/rok




### Rafinacja i przemysł chemiczny

Rafinacja ropy i produkcja amoniaku dominują w obecnym zapotrzebowaniu — oba to sektory trudne do dekarbonizacji

### Dekarbonizacja hutnictwa stali

Bezpośrednia redukcja żelaza (DRI) z zielonym $H_2$ staje się kluczową drogą do stali o zerowej emisji netto

### Nowe sektory zapotrzebowania

Transport dalekobieżny, żegluga, lotnictwo (przez e-paliwa), sezonowe magazynowanie energii — wszystkie rosną

*Źródło: IEA Global Hydrogen Review 2025*

# Kolorowe spektrum wodoru

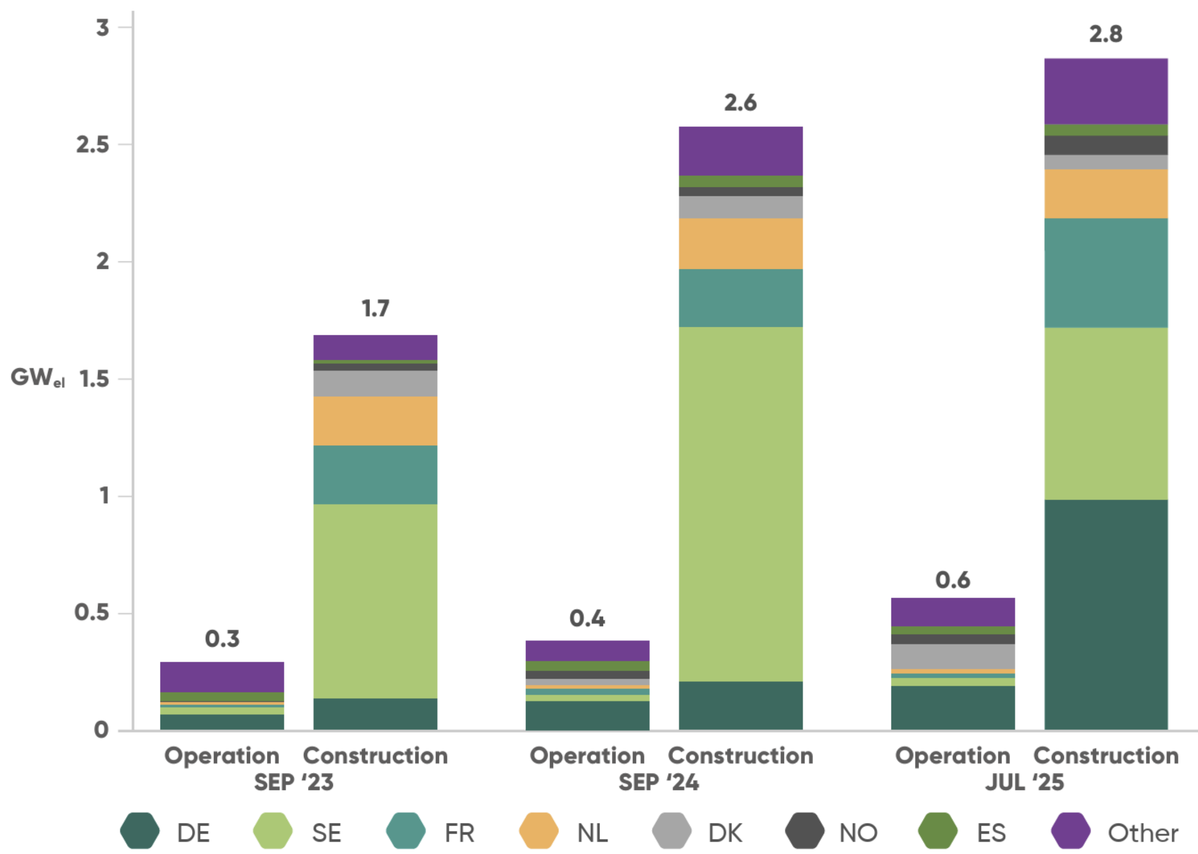
| Wodór szary | Wodór niebieski | Wodór zielony | Wodór różowy |
|---|---|---|---|
| Reforming parowy metanu (SMR) bez CCS<br>~95% obecnej produkcji | SMR z wychwytywaniem i składowaniem $CO_2$<br>Emisja $CO_2$ niższa o 60–90% | Elektroliza wody zasilana OZE<br>Zerowa emisja bezpośrednia | Elektroliza wody zasilana energią jądrową<br>Bezemisyjne źródło podstawowe |
| **~70%** | **~1%** | **<1%** | **Niszowy** |

**Cel: uczynić zielony wodór konkurencyjnym cenowo wobec wodoru szarego**

Obecny koszt zielonego $H_2$: 3,8–11,9 \$/kg | Szary $H_2$: 1,5–6,4 \$/kg | Cel DOE: 1 \$/kg do 2030 r.

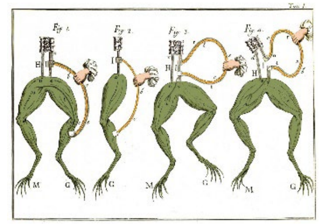
# Elektroliza wody

Operational and under construction water electrolysis capacity progression in Europe over the last three years to July 2025

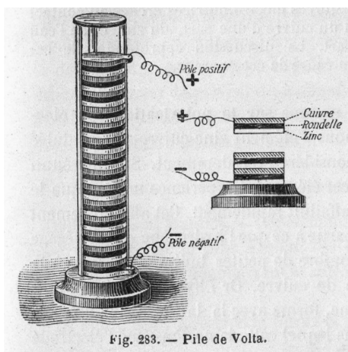


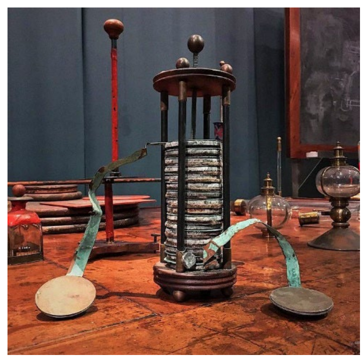
# Krótki rys historyczny

Elektryczność



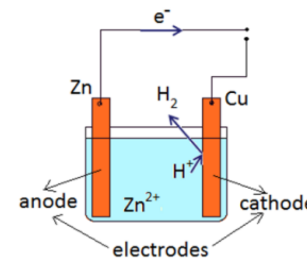
- **1791** – Luigi Galvani – bioelektryczność;
- **1800** – Allesandro Volta – stos Zn/Cu – pierwsza bateria;



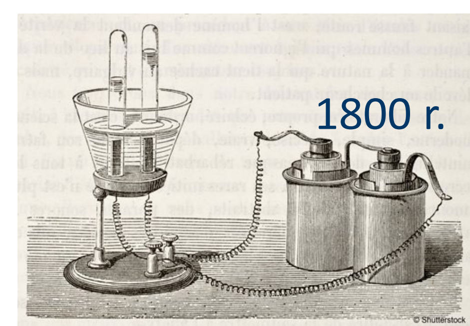



Reakcja elektrodowa:
Elektrolit $H_2SO_4$

$Zn – Zn^{2+} + 2e^-$
$2H^+ + 2e^- - H_2$




- **1800** – Nicholson i Carlisie

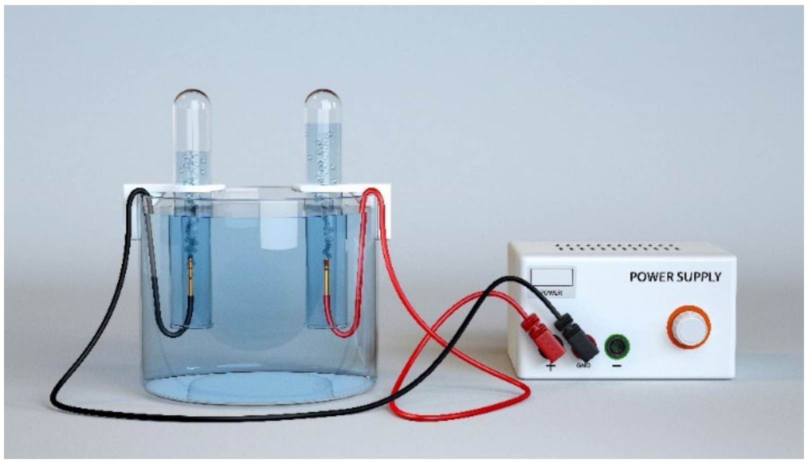


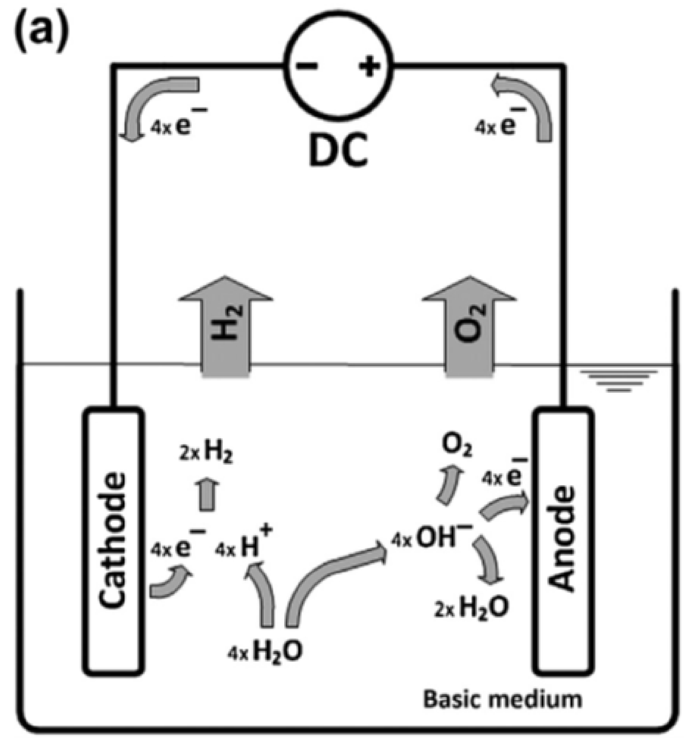
1800 r.

https://www.twelve.co/post/a-brief-history-of-electrolysis

# Elektroliza wody

"Stary" proces, ciągle z perspektywami rozwoju



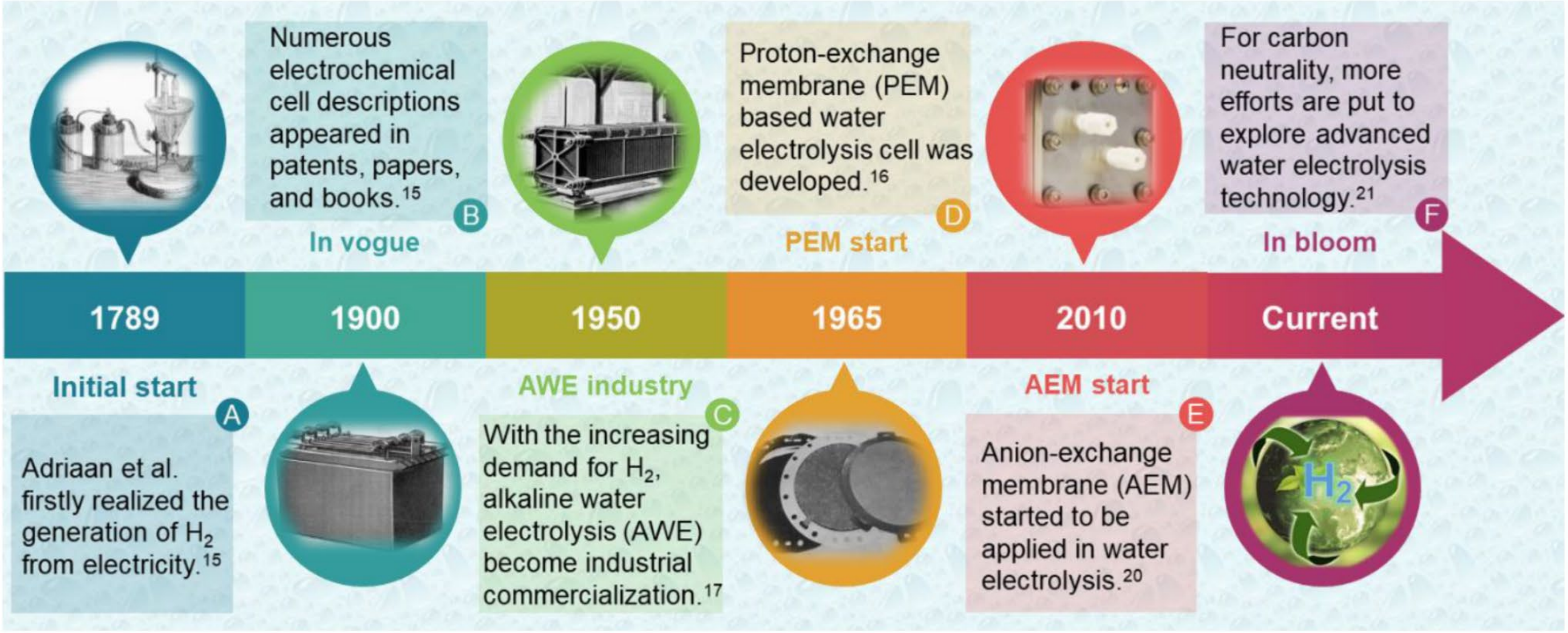

**Anoda**: $4OH^- \rightarrow 2H_2O + \mathbf{O_2} + 4e^-$

**Katoda**: $4H_2O + 4e^- \rightarrow \mathbf{2H_2} + 4OH^-$

**Warunki pracy**: temperatura 60-80 °C, elektrolit: woda + KOH (pH~14)

**Materiały**: Ni, Pt, Ir

# Elektroliza wody



# Elektroliza wody - elektrody

## Katoda — HER

**Reakcja wydzielania wodoru**

Kwaśna: $4H^+ + 4e^- \rightarrow 2H_2$

**Alkaliczna: $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$**

*Stosunkowo łatwa — niski nadpotencjał*

*Najlepsze katalizatory: Pt, stopy Ni-Mo*

## Anoda — OER

**Reakcja wydzielania tlenu**

Kwaśna: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

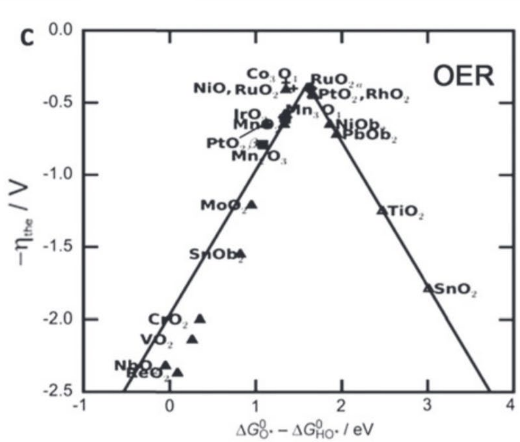
**Alkaliczna: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$**

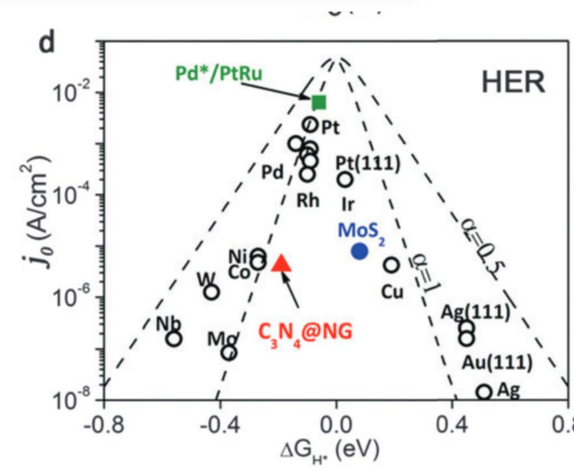
*Proces 4-elektronowy — wolna kinetyka!*

*Najlepsze: $IrO_2$, $RuO_2$, NiFe-LDH*

Table 2 Overall reaction pathway for OER in acidic and alkaline solutions

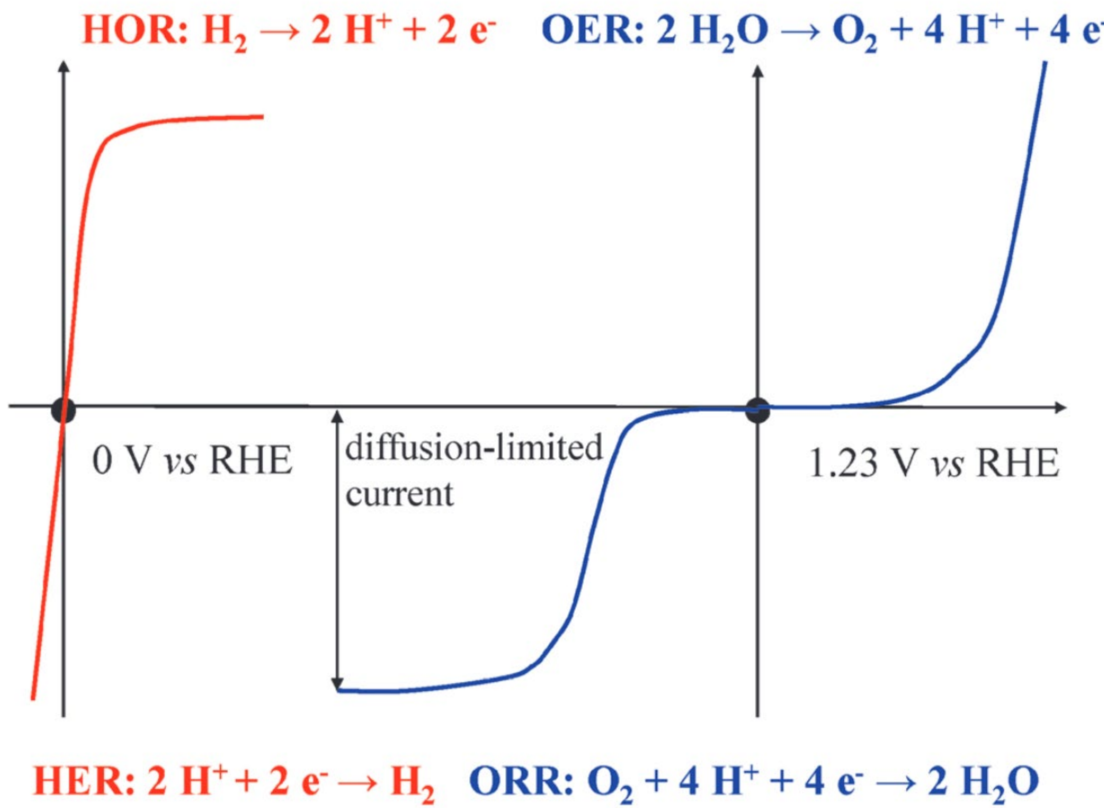
| Overall reaction (condition) | Reaction pathway |
|---|---|
| $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ (Acidic solution) | $* + H_2O \rightarrow *OH + H^+ + e^-$<br>$*OH \rightarrow *O + H^+ + e^-$<br>$*O + H_2O \rightarrow OOH* + H^+ + e^-$<br>$*OOH \rightarrow *O_2 + H^+ + e^-$<br>$*O_2 \rightarrow * + O_2$ |
| $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$ (Alkaline solution) | $* + OH^- \rightarrow *OH + e^-$<br>$*OH + OH^- \rightarrow H_2O + *O + e^-$<br>$*O + OH^- \rightarrow *OOH + e^-$<br>$*OOH + OH^- \rightarrow *O_2 + e^-$<br>$*O_2 \rightarrow * + O_2$ |



# Elektroliza wody – reakcje elektrodowe

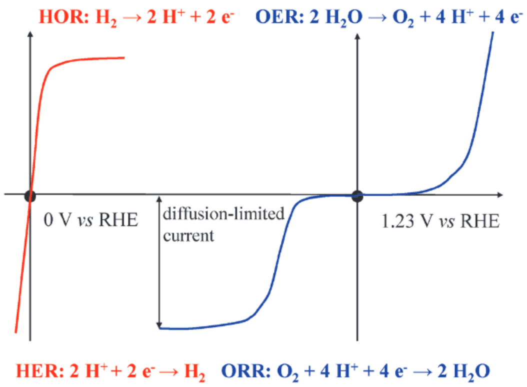
Ograniczeniem reakcji HER, jest reakcja OER...



# Wąskie gardło reakcji OER

## HER — wydzielanie wodoru

$2H^+ + 2e^- \rightarrow H_2$
Prosty transfer 2 elektronów
Dobrze poznany mechanizm
Szybka kinetyka na Pt (η ≈ 30–50 mV)
**→ Nie stanowi ograniczenia**




## OER — wydzielanie tlenu

$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
Złożony transfer 4 elektronów i 4 protonów
Wiele produktów pośrednich (M-OH, M-O, M-OOH)
Powolna kinetyka (η ≈ 200–400 mV)
**→ GŁÓWNA strata wydajności**

### Mechanizm OER w środowisku alkalicznym (klasyczna ścieżka)

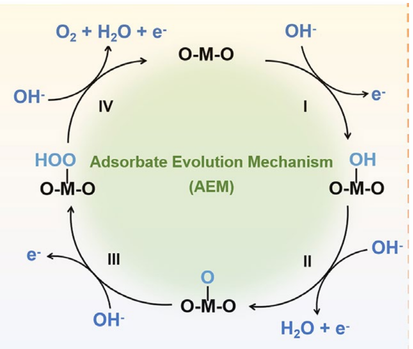
**Krok 1** $M + OH^- \rightarrow M\text{-}OH + e^-$

**Krok 2** $M\text{-}OH + OH^- \rightarrow M\text{-}O + H_2O + e^-$

**Krok 3** $M\text{-}O + OH^- \rightarrow M\text{-}OOH + e^-$

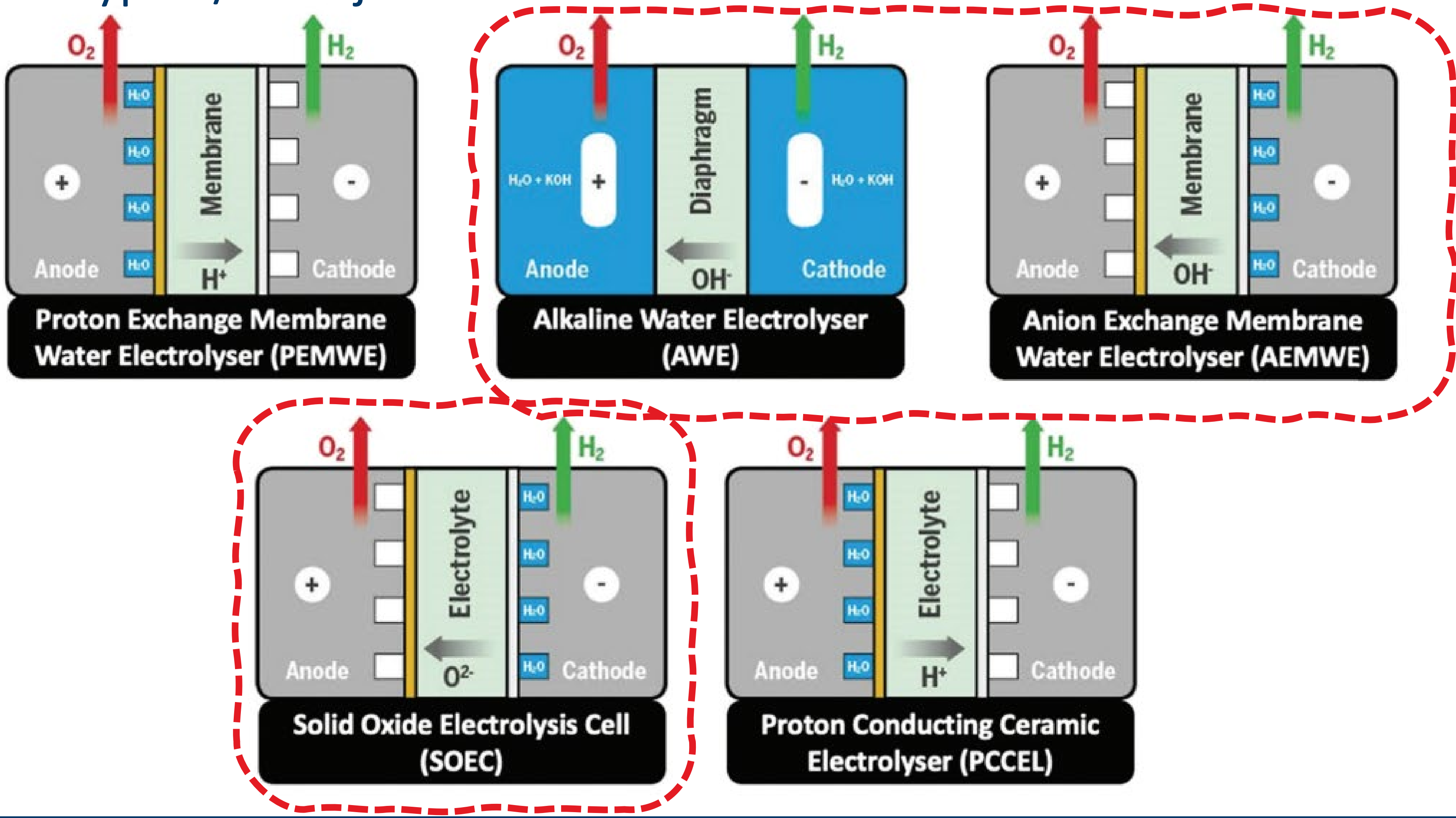
**Krok 4** $M\text{-}OOH + OH^- \rightarrow M + O_2 + H_2O + e^-$

M = miejsce aktywne na powierzchni katalizatora
Etap limitujący szybkość zależy od katalizatora — on wyznacza nachylenie Tafela



# Typy elektrolizerów

Wiele typów/rodzajów elektolizerów



# Porównanie typów elektrolizerów

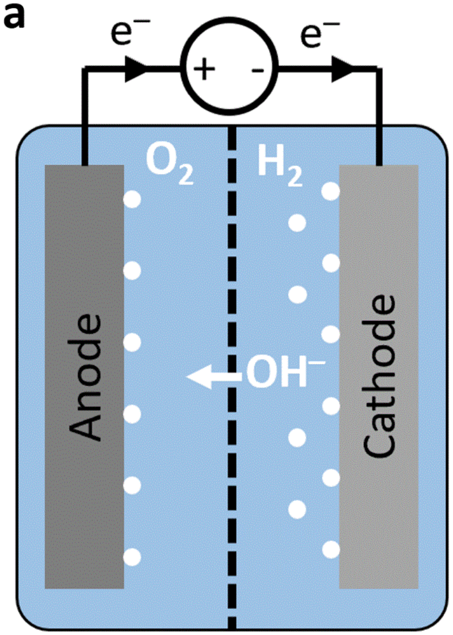
Table 1 Short description of the five types of water electrolysers. Modified from IRENA[225]

| | AWE | PEMWE | AEMWE | SOEC | PCCEL |
|---|---|---|---|---|---|
| Operating temperature | 70–90 °C | 50–80 °C | 40–60 °C | 700–850 °C | 300–600 °C |
| Operating pressure | 1–30 bar | <70 bar | <35 bar | 1 bar | 1 bar |
| Electrolyte | Potassium hydroxide (KOH) 5–7 mol $L^{-1}$ | PFSA membranes | DVB polymer support with KOH or $NaHCO_3$ 1 mol $L^{-1}$ | Yttria-stabilised zirconia (YSZ) | (Y,Yb)-Doped-Ba(Ce,Zr)$O_{3-\delta}$ |
| Separator | $ZrO_2$ stabilised with PPS mesh | Solid electrolyte (above) | Solid electrolyte (above) | Solid electrolyte (above) | Solid electrolyte (above) |
| Electrode/catalyst (oxygen side) | Nickel coated perforated stainless steel | Iridium oxide | High surface area nickel or NiFeCo alloys | Perovskite-type (*e.g.*, LSCF, LSM) | Perovskite-type (*e.g.*, LSCF, LSM |
| Electrode/catalyst (hydrogen side) | Nickel coated perforated stainless steel | Platinum nanoparticles on carbon black | High surface area nickel | Ni/YSZ | Ni/YSZ, Ni-BZY/LSC, BCFYZ |
| Porous transport layer anode | Nickel mesh (not always present) | Platinum coated sintered porous titanium | Nickel foam | Coarse nickel-mesh or foam | Coarse nickel-mesh or foam |
| Porous transport layer cathode | Nickel mesh | Sintered porous titanium or carbon cloth | Nickel foam or carbon cloth | None | None |
| Bipolar plate anode | Nickel-coated stainless steel | Platinum-coated titanium | Nickel-coated stainless steel | None | None |
| Bipolar plate cathode | Nickel-coated stainless steel | Gold-coated titanium | Nickel-coated stainless steel | Cobalt-coated stainless steel | Cobalt-coated stainless steel |
| Frames and sealing | PSU, PTFE, EPDM | PTFE, PSU, ETFE | PTFE, silicon | Ceramic glass | Ceramic glass |

# Konstrukcja elektrolizera

## Pojedyncze ogniwo – od schematu do urządzenia

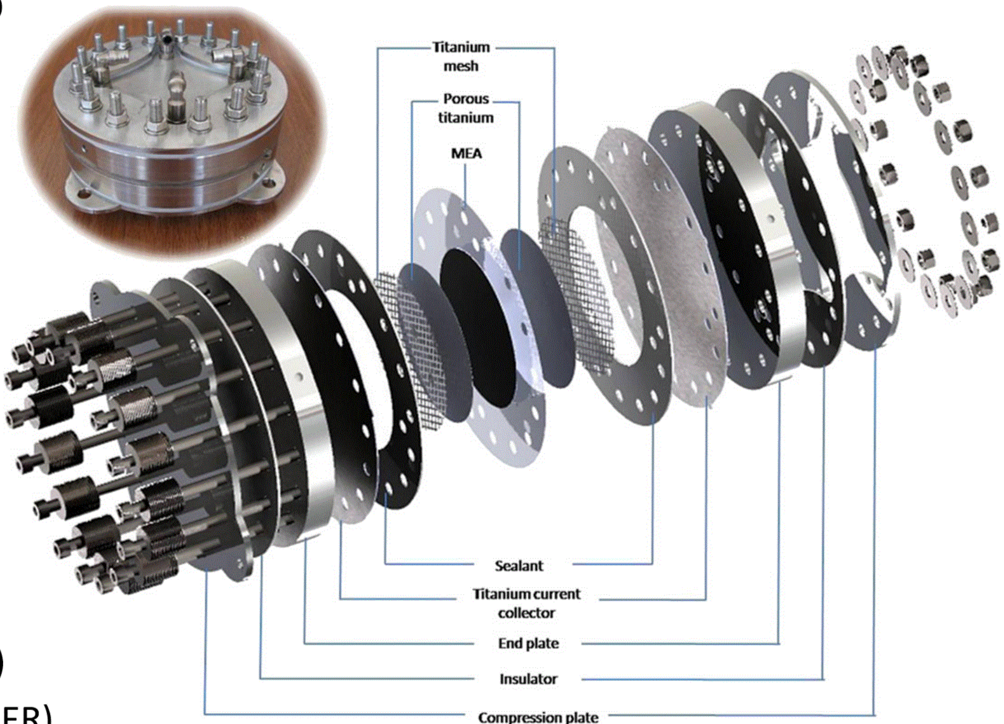
a



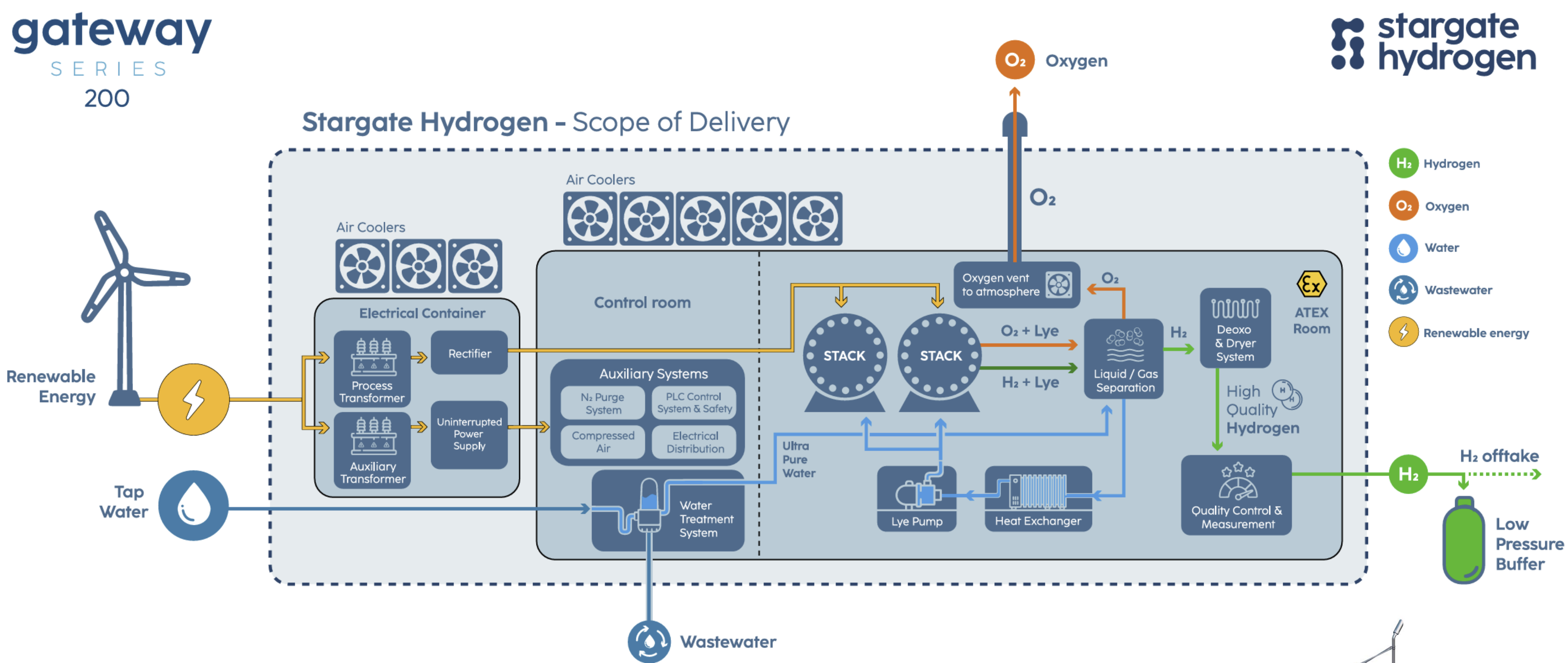

***Anode:*** $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$ (OER)

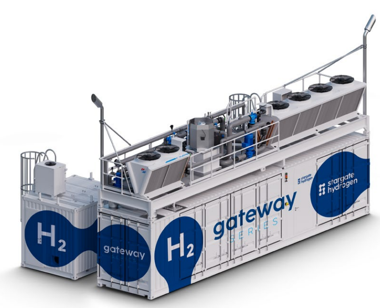
***Cathode:*** $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$ (HER)

b

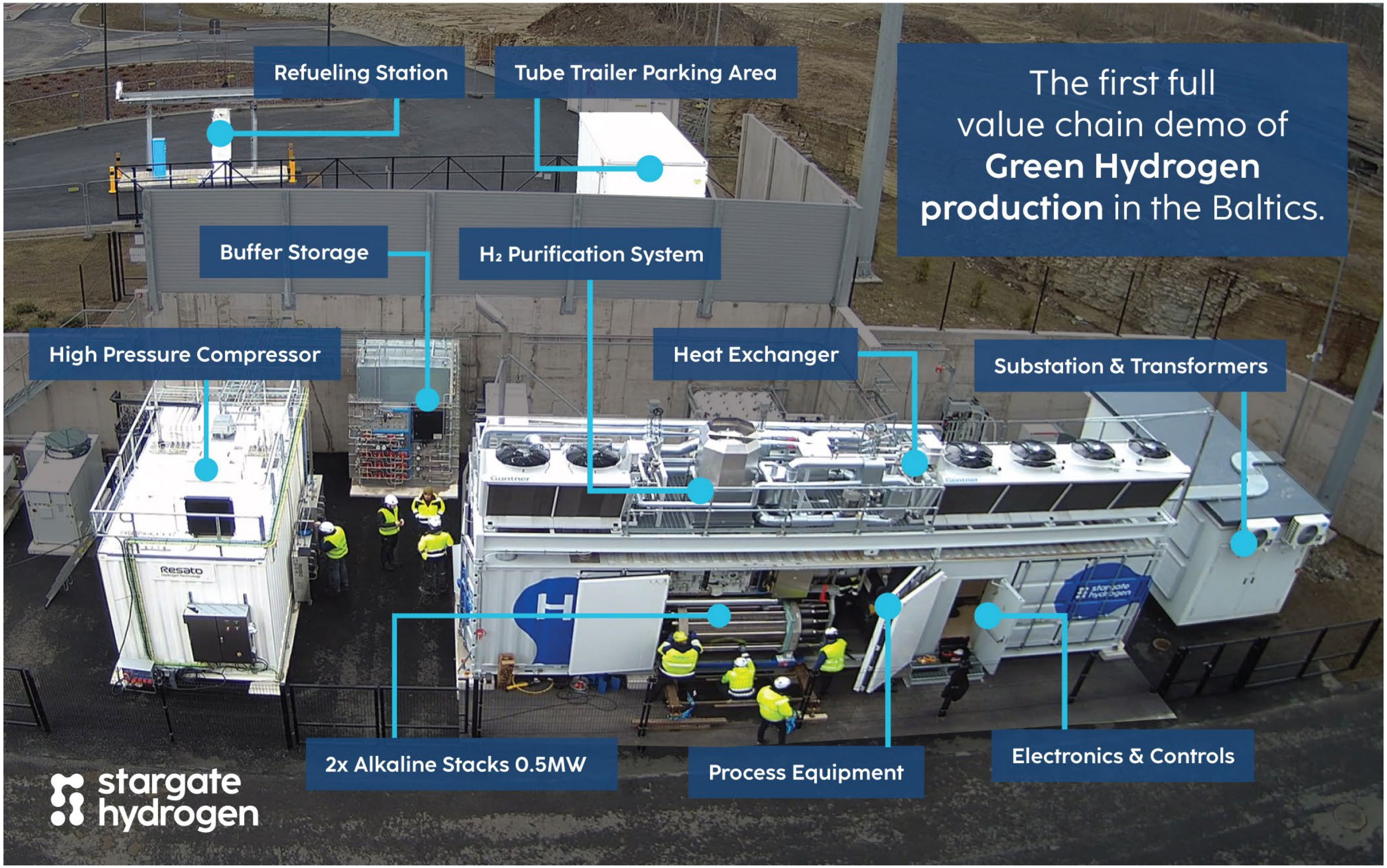


# System elektrolizera



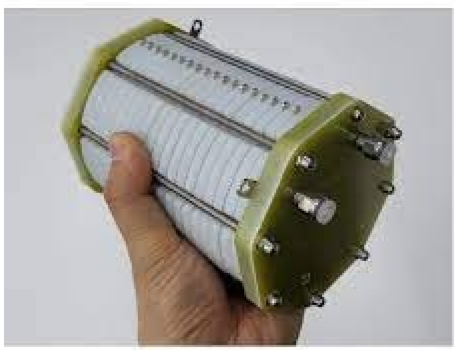



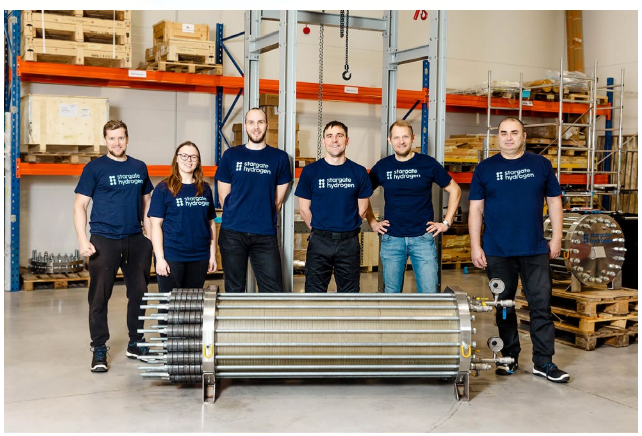
# System elektrolizera



# Skalowalność

## Prosta technologia w ogromnej skali






# Modułowość

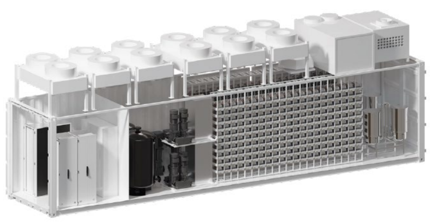
Modułowy system na bazie jednostki EL4.0

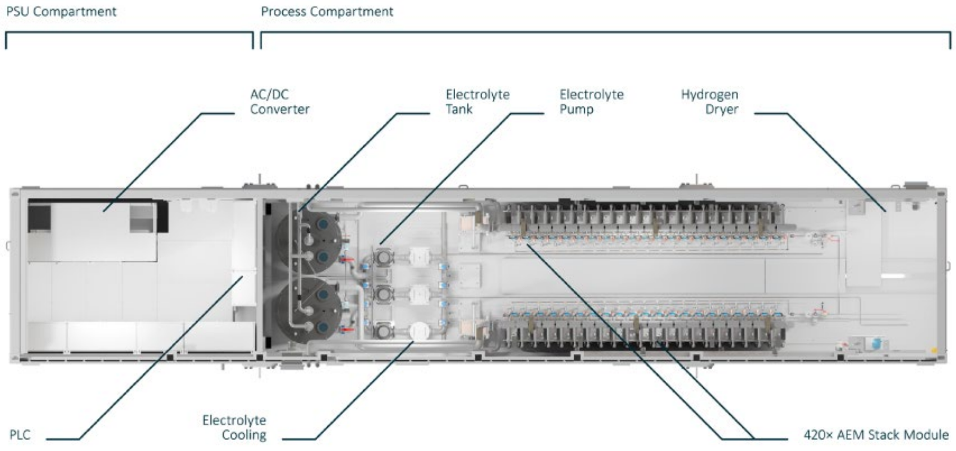
- 2.4 kW (peak 3 kW)
- Każdy ze swoim zasilaczem
- 23 ogniwa → 30-40 V


# Modułowość (Enapter)

## Nowy system Multicore

| | | |
|---|---|---|
| **Production rate** | 210 Nm³/h | Net volume flow rate |
| **Hydrogen output pressure** | Up to 35 barg | |
| **Hydrogen output purity** | 99.9% in molar fraction | |
| **Hydrogen output purity** (with optional dryer) | 99.999% in molar fraction | |
| **Flexibility** | 3% – 105% of nominal production rate | |
| **Oxygen output pressure** | Atmospheric | |
| **Nominal power consumption per Nm³ of $H_2$ produced** (beginning of life) | 4.8 kWh/Nm³ | Including all utilities inside the battery limits of module |
| **Nominal electrical power consumption** | 1,008 kW | |
| **Voltage** | 3 × 400 Vac three-phase grid | |
| **Frequency** | 50/60 Hz | |
| **Nominal water flow** | 0.19 m³/h purified water | |
| **Inlet water pressure** | 0.5 barg – 4 barg | |
| **System life** | 20 years | |
| **Hot startup time** | 0 – 100% within seconds | |
| **Cold startup time** | 0 – 100% in ca 30 minutes, depending on ambient temperature | |
| **Footprint** | L: 12.192 m × W: 2.438 m × H: 2.591 m | |
| **Weight** | Approximately 30 t | |
| **Transport dimensions** | 40 ft container | |





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# Skalowalność

nel

## Tailored Solutions

Atmospheric Alkaline Electrolysers

The A Series represents the most reliable and efficient electrolysers in the world. Our modular concept enables us to deliver customized indoor hydrogen solutions for any application, configuration and size – anywhere. Nel Hydrogen tailors each delivery to any customer requirement, from complete installation of the entire electrolyser plant, to delivery of specific modules according to customer preferences.

A150

## Turnkey Solutions

Containerized Alkaline Electrolysers

The AC150 and AC300 wrap world-class electrolyser technology in containers, for fast and robust outdoor installations. This innovative, compact design makes a superior turnkey solution, with an output pressure of 200 bar. Typical applications include on-site hydrogen gas supply for fueling stations and industrial processes.

AC150

## Large Scale $H_2$ Plants

Whether you need large quantities of hydrogen for industrial purposes, or utilization of excess renewable energy for energy storage – we have experience in both fields!

Nel Hydrogen is the acknowledged specialist in large scale electrolyser plants. The very nature of the A Series is seamless capacity upsizing from medium to large scale $H_2$ plants based on water electrolyser technology.

A3880

Our experience in large scale plants is exemplified through historical plants exceeding 30,000 Nm³/h, as well as the recent installation of new plants with an energy capacity of more than 60 MW.

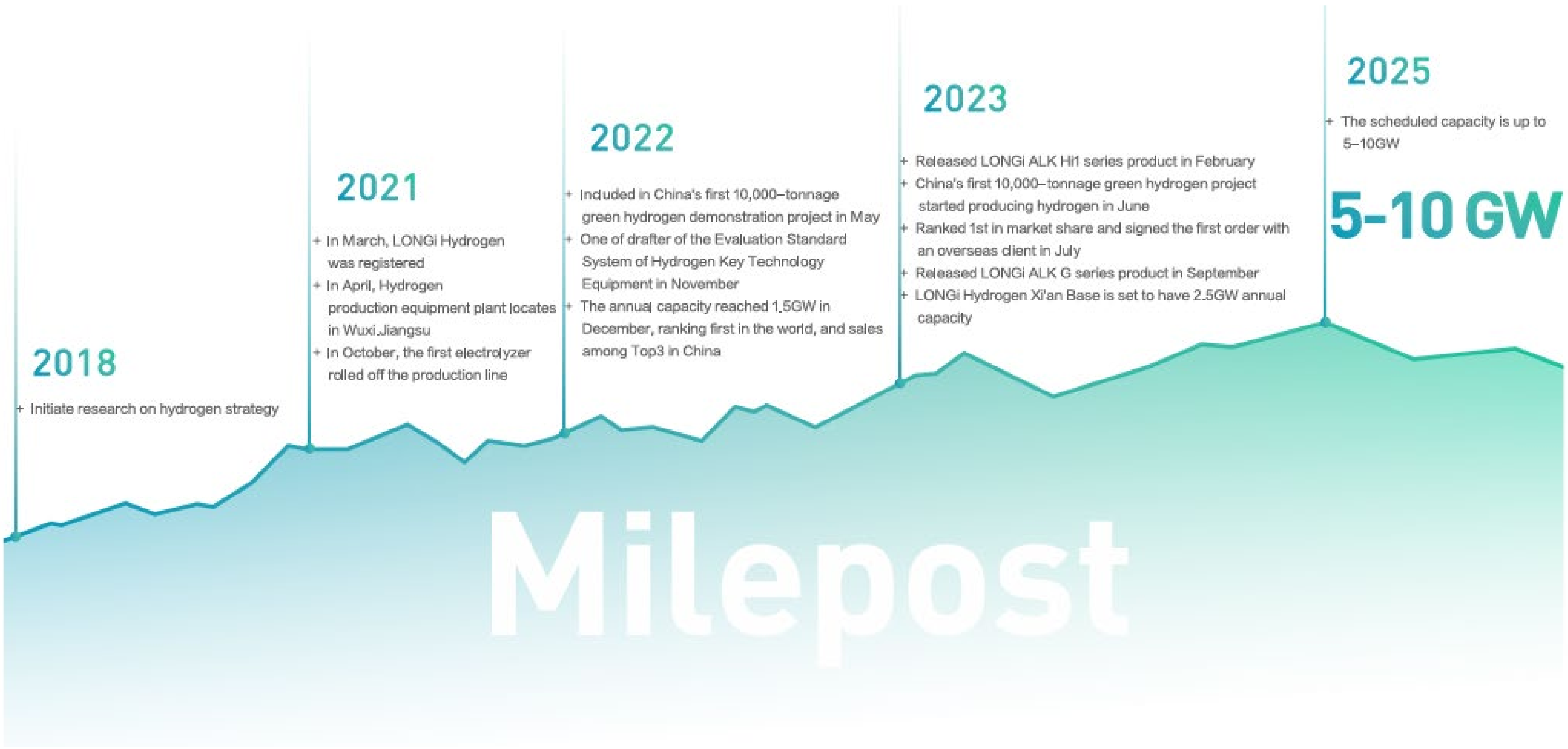
- Tailored to any demand
- Turnkey solutions
- Large capacity at minimum footprint
- High pressure for storage and distribution
- Scaled to any capacity
- More efficient than any other electrolyser

| SPECIFICATIONS | AC150 | AC300 |
|---|---|---|
| Capacity Range per Unit | 150 Nm³/h | 300 Nm³/h |
| Production Capacity Dynamic Range | 15-100% of flow range | 15-100% of flow range |
| DC Power Consumption | 3.8-4.4 kWh/Nm³ | 3.8-4.4 kWh/Nm³ |
| Purity – with optional purification | 99.99-99.999% | 99.99-99.999% |
| $O_2$-Content in $H_2$ | < 2 ppm v | < 2 ppm v |
| $H_2O$-Content in $H_2$ | < 2 ppm v | < 2 ppm v |
| Outlet Pressure | 30 barg/200 barg | 30 barg/200 barg |
| Dimensions | | |
| Footprint | NA | NA |
| Container 1 – L x W X H | 12m x 2.9m x 3.6m | 13m x 2.9m x 3.6m |
| Container 2 – L x W x H | 9m x 2.9m x 3.2m | 9m x 2.9m x 3.2m |
| Container 3 – L x W x H | NA | 9m x 2.9m x 3.2m |
| Operating Temperature | 80° C | 80° C |
| Electrolyte | 25% KOH aqueous solution | 25% KOH aqueous solution |
| Feed Water Consumption | 0.9 l/Nm³ | 0.9 l/Nm³ |

| A150 | A300 | A485 | A3880 |
|---|---|---|---|
| 50-150 Nm³/h | 150-300 Nm³/h | 300-485 Nm³/h | 2,400-3,880 Nm³/h |
| 15-100% of flow range | 15-100% of flow range | 15-100% of flow range | 15-100% of flow range |
| 3.8-4.4 kWh/Nm³ | 3.8-4.4 kWh/Nm³ | 3.8-4.4 kWh/Nm³ | 3.8 - 4.4 kWh/Nm³ |
| 99.99-99.999% | 99.99-99.999% | 99.99-99.999% | 99.99-99.999% |
| < 2 ppm v | < 2 ppm v | < 2 ppm v | < 2 ppm v |
| < 2 ppm v | < 2 ppm v | < 2 ppm v | < 2 ppm v |
| 1-200 barg | 1-200 barg | 1-200 barg | 1-200 barg |
| | | | |
| ~150m² | ~200m² | ~225m² | ~770m² |
| NA | NA | NA | NA |
| NA | NA | NA | NA |
| NA | NA | NA | NA |
| 80° C | 80° C | 80° C | 80° C |
| 25% KOH aqueous solution | 25% KOH aqueous solution | 25% KOH aqueous solution | 25% KOH aqueous solution |
| 0.9 l/Nm³ | 0.9 l/Nm³ | 0.9 l/Nm³ | 0.9 l/Nm³ |

# Rozwój technologii – przykład Chin

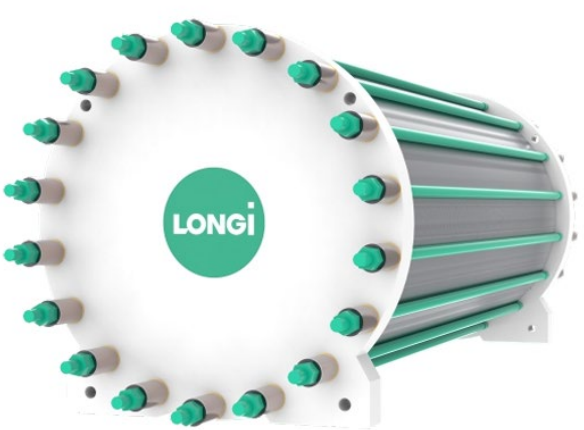
- Longi Hydrogen

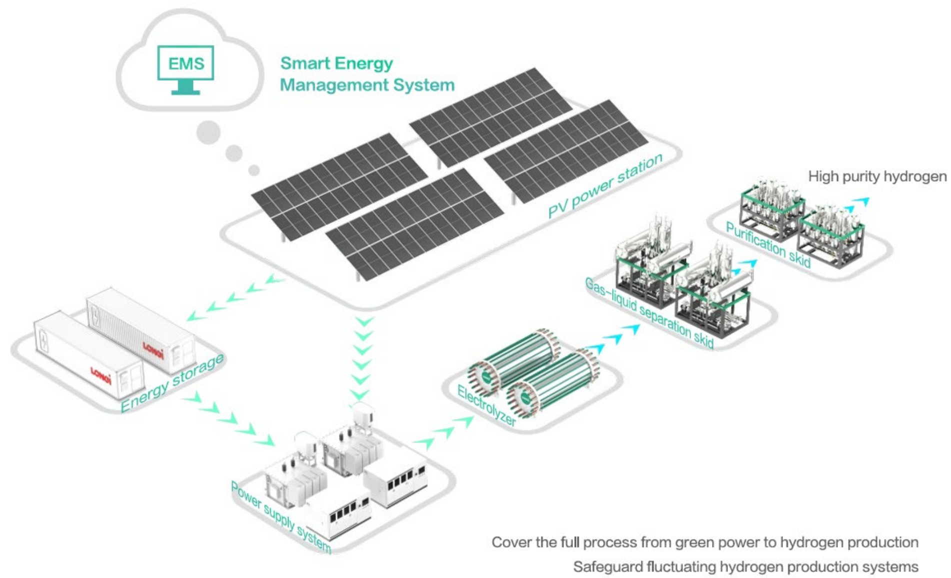


# Rozwój technologii – przykład Chin

- Longi

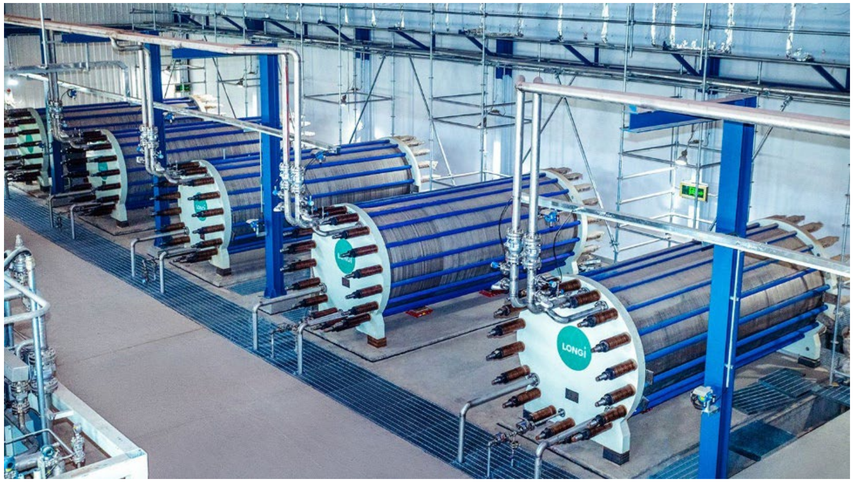
<table>
<tr><th>Parameters</th><th>Hi1 1000</th><th>Hi1 Plus 1000</th></tr>
<tr><td>Hydrogen production (Nm³/h)</td><td colspan="2">1000</td></tr>
<tr><td>Operating pressure (MPa)</td><td colspan="2">1.6</td></tr>
<tr><td>DC power consumption (kWh/Nm³)</td><td>≤4.3</td><td>≤4.1</td></tr>
<tr><td>Power fluctuation range</td><td colspan="2">30% – 110%</td></tr>
<tr><td>Hydrogen purity (purified)</td><td colspan="2">99.999%</td></tr>
<tr><td>O₂ in H₂ (ppmv)</td><td colspan="2">1</td></tr>
<tr><td>Operating temperature (℃)</td><td colspan="2">90 ± 5</td></tr>
<tr><td>Ambient temperature (℃)</td><td colspan="2">5 – 45</td></tr>
<tr><td>Electrolyte</td><td colspan="2">30% KOH</td></tr>
</table>



# Rozwój technologii – przykład Chin

- Longi

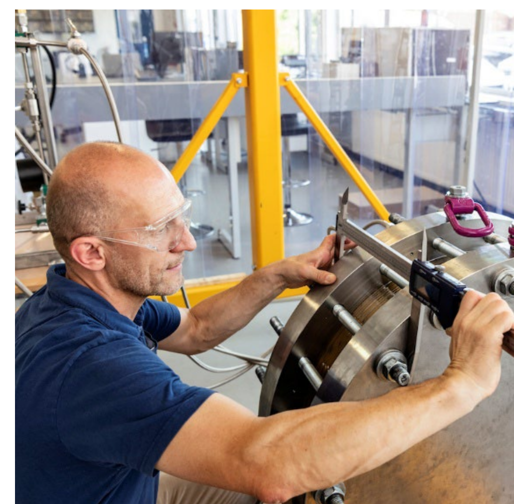

# Rozwój w Polsce

## SimpleH2 – PEM – stos 5-10 kW


## Exion Hydrogen Polskie

Elektrolizery – AWE i PEM

Stosy 500 kW...



# Rozwój w Polsce

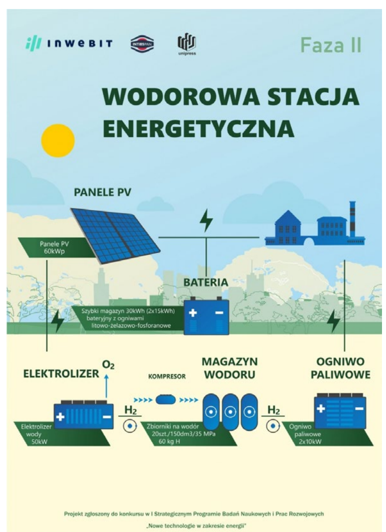
SES Hydrogen Energy

- Kocioł wodorowy 500 kW
- Stosy 500 kW

ses Hydrogen

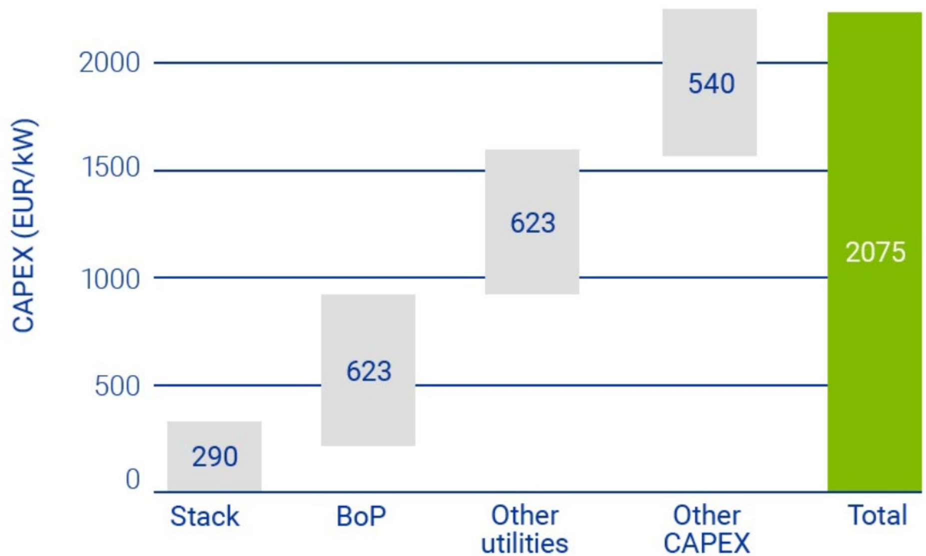
Inwebit

- Stos 5MW 2029




# Koszt elektrolizerów






In 2025, Europe's total alkaline water electrolyser CAPEX was **2,075 EUR/kW**, split between **290 EUR/kW for the stack**, **623 EUR/kW for BoP**, **623 EUR/kW for other utilities** and **540 EUR/kW for other CAPEX**.

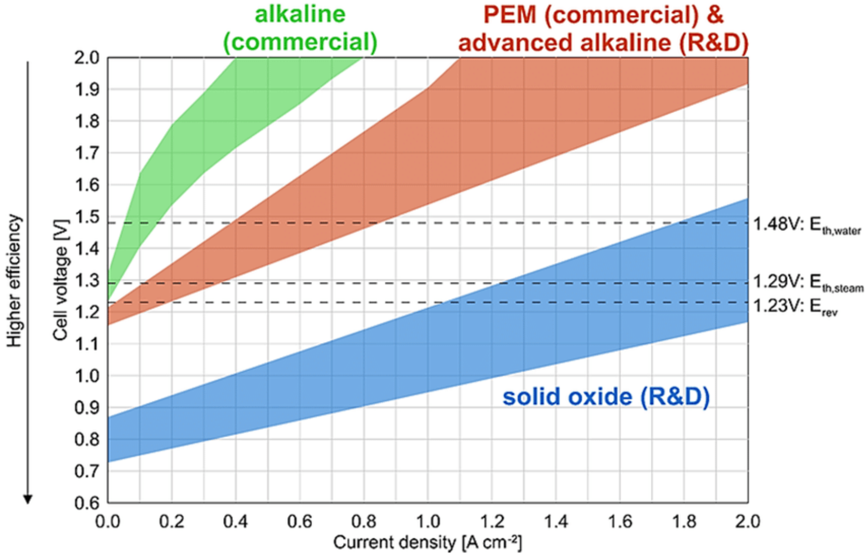
# Miejsce i rola uczelni

- Kształcenie kadr
- Badania (i rozwój) – początek zmian
  - 100 mA, 2V – 200 mW

| Lab | Pilotaż | Komercja | Przemysł | Giga-skala |
|---|---|---|---|---|
| **0.0001-0.01 kW** | **1-50 kW** | **0.1-5 MW** | **10-100+ MW** | **1+ GW** |
| 1-10 cm²<br>Pojed. ogniwo<br>Badania R&D | Krótki stos<br>10-50 ogniw<br>Enapter EL4.0 | Pełny stos<br>System zintegrowany<br>ITM, Plug Power | Wiele stosów<br>Podejście modułowe<br>LONGi, Nel | Macierz modułów<br>Projekt instalacji<br>NEOM, cele UE |

# Elektrolizery przyszłości

## Zaawansowane elektrody



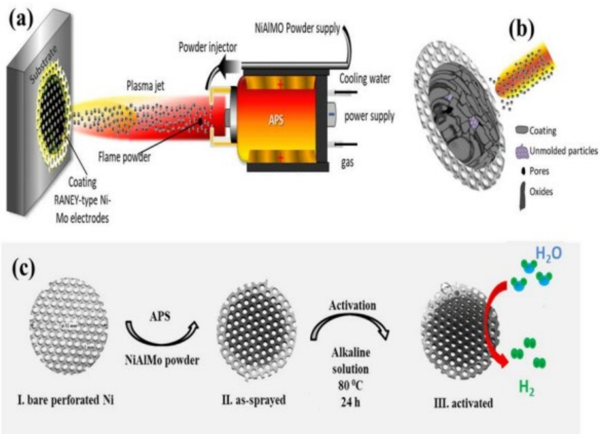




**Figure 1.** (**a**) Schematic illustration of APS coating of Raney-type Ni–Mo electrode on perforated nickel sheet. (**b**) Schematic structure of a thermal sprayed coating. (**c**) Coating process and chemical activation of Raney-type Ni–Mo electrodes.

+ możliwości membrany AEM

**Table 1.** Comparison of state of the art and future targets according to FCH JU for hydrogen production with A-WEs and PEM-WEs.[43]

| Parameter | State of the art 2012 | 2017 | FCH JU target 2020 | 2024 | 2030 |
|---|---|---|---|---|---|
| **A-WE single-cell** | | | | | |
| electricity consumption at nominal capacity [kWh $kg^{-1}$] | 57 | 51 | 50 | 49 | 48 |
| capital cost [EUR (kg $d^{-1})^{-1}$] | 8000 | 1600 | 1250 | 1000 | 800 |
| ([EUR $kW^{-1}$]) | (≈3000) | (750) | (600) | (480) | (400) |
| operation and maintenance cost [EUR (kg $d^{-1})^{-1}$ $yr^{-1}$] | 160 | 32 | 26 | 20 | 16 |
| **A-WE stack** | | | | | |
| degradation [% (1000 $h)^{-1}$] | – | 0.13 | 0.12 | 0.11 | 0.1 |
| current density [A $cm^{-2}$] | 0.3 | 0.5 | 0.7 | 0.7 | 0.8 |
| use of CRMs as catalysts [mg $W^{-1}$] | 8.9 | 7.3 | 3.4 | 2.1 | 0.7 |

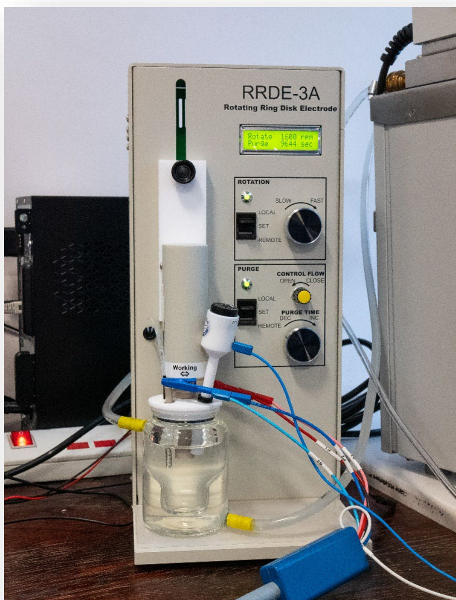
# Prace na PG: Materiały, elektrody

FNP First Team

sea4volt

Opracowanie nowych materiałów elektrodowych;

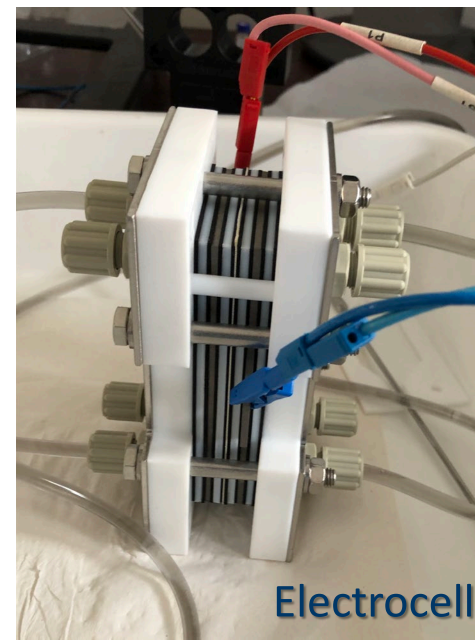
Opracowanie technologii przygotowania elektrod, metodologii pomiarowej oraz ogólnego know-how;





Elektroda rotująca

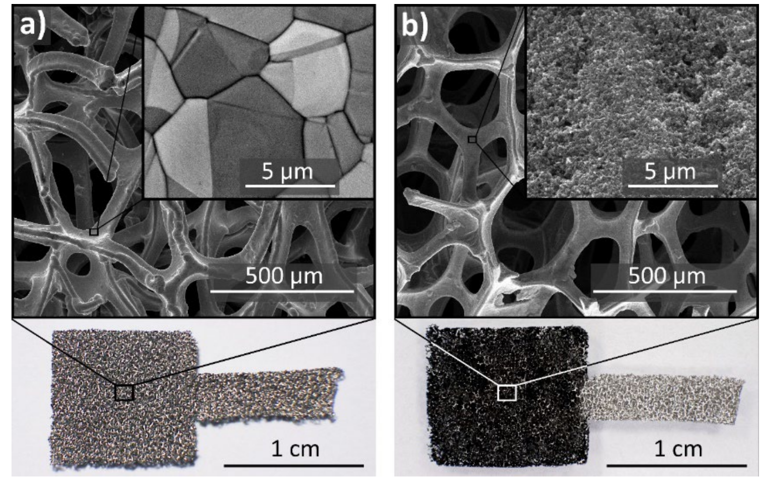

Elektroda piankowa


Electrocell

$0.196\ cm^2 < 1\ cm^2 < 10\ cm^2$

# Nasze prace: nowe materiały elektrodowe OER

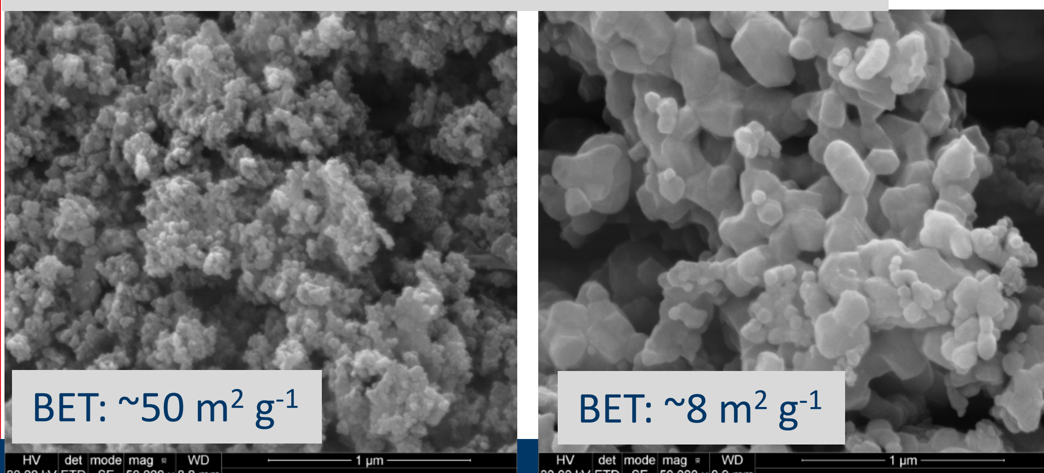
**OER** – Oxygen Evolution Reaction

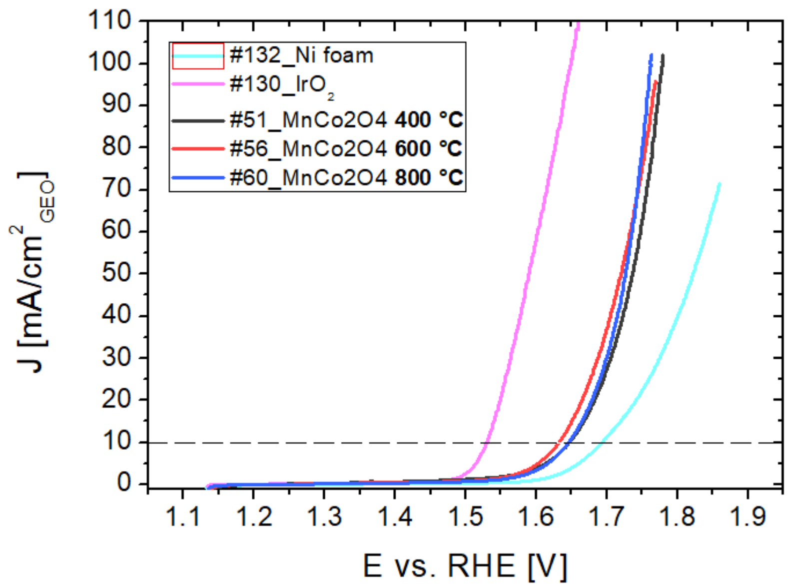



Własne materiały elektrodowe:

- $MnCo_2O_4$ oraz modyfikacje
- Synteza – otrzymywanie proszku
- Obróbka proszku – "prażenie"

Prażenie 400 °C 800 °C



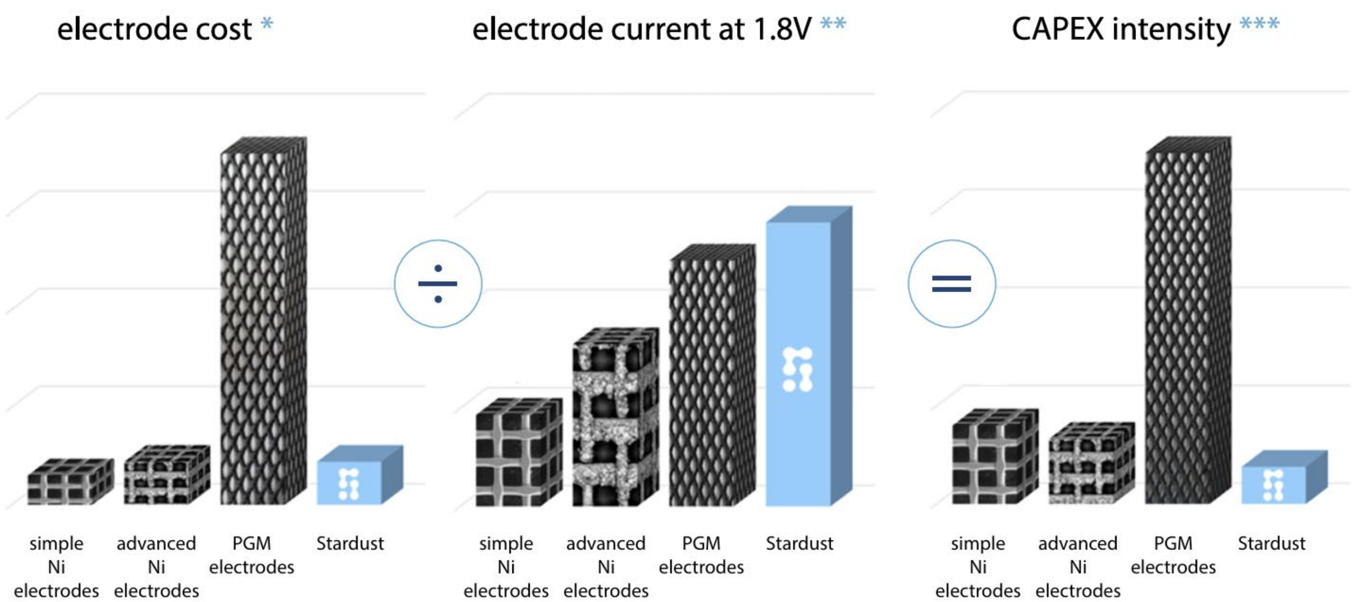
# Nowe elektrody

## Stardust electrode technology

Stargate's innovative catalyst material - Stardust - increases the current density of the electrodes used for green hydrogen production without additional investment.

**Higher current densities allow to reduce the stack size and thus CAPEX.**

stargate hydrogen



# Podsumowanie

### 01 Zielony wodór

Większość $H_2$ pochodzi z paliw kopalnych — elektroliza wody to droga do czystej produkcji wodoru

### 02 Elektroliza

Dojrzały proces (60–80 °C) oparty na reakcjach HER (katoda) i OER (anoda)

### 03 Wyzwanie OER

Wolna kinetyka $4e^-$ — katalizatory: $IrO_2$, $RuO_2$, NiFe-LDH oraz Pt, Ni-Mo (HER)

### 04 Modułowość

Od pojedynczego ogniwa do dużych systemów przemysłowych — skalowalność konstrukcji

### 05 Badania i nauka

Nowe materiały elektrodowe, membrany...