# Hydrogen $H_2$ for decarbonation in energy and industry uses: present and future

# Learning objectives

- Overview of $H_2$ uses, now and in future
  - possible for all energy sectors, and heavy industry
- Key is
  - renewable electricity => electrolysis (‘Power-to-Gas’)
  - massive scaling & deployment is needed
- Thermodynamics and efficiency of electrolysis
  - various technologies (water ($H^+$ / $OH^-$), steam)
  - heat integration
- Storage technologies and distribution paths of $H_2$

# $H_2$ and renewable energy

- $H_2$ does not occur naturally on Earth
- It stems mostly from fossil sources; this relates to its main current use (=chemical, not energetical)
- Green $H_2$ can be made – via electrolysis - mainly from variable renewable electricity (PV, wind), which is driving the energy transition and must be stored
- $H_2$ presents all energy uses (power, heat, mobility) in addition to being a heavy industry feedstock
- It therefore has huge decarbonation potential, but must be made on massive scale (100s of GW)

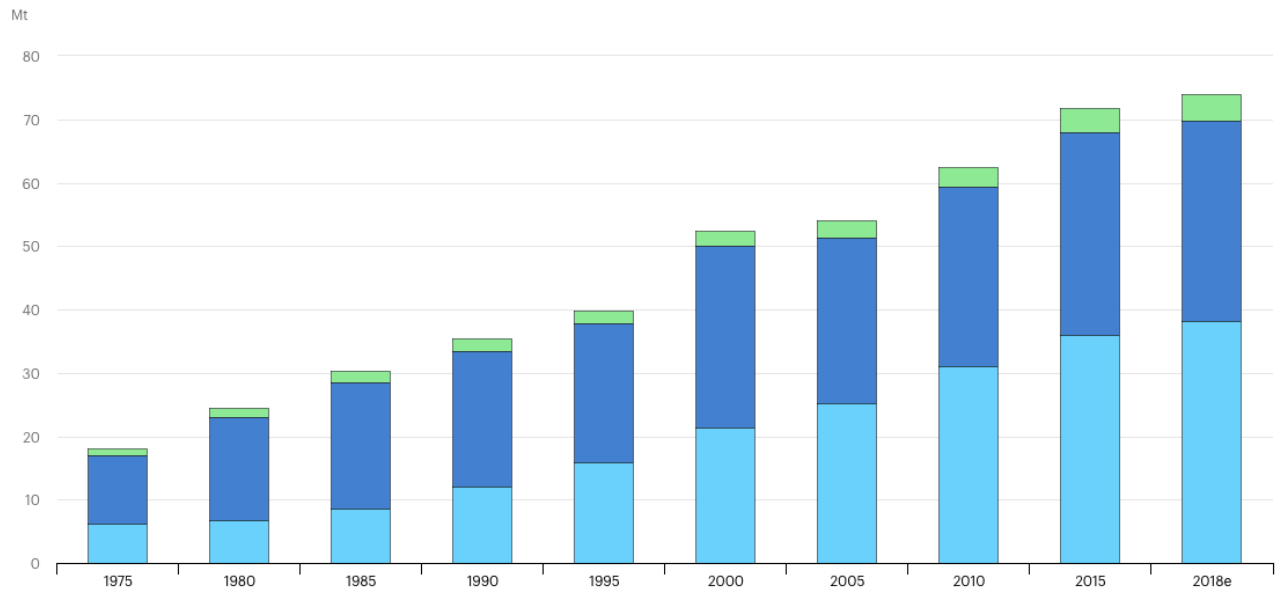
# Grey, blue, green $H_2$

- **Grey $H_2$** : made from fossil sources
- **Blue $H_2$** : made from fossil sources but including carbon capture
- **Green $H_2$** : made from renewable sources

# Annual $H_2$ production

- ≈75 Mt/yr ≈ 830 $10^9$ $m^3$ /yr ≈ 10 EJ (2800 TWh) = 2% of world energy
  - 49% from natural gas
  - 29% from oil
  - 18% from coal
  - 4% from electrolysis

} 96% from fossil sources



Global demand for pure hydrogen, 1975-2018

- By comparison: natural gas 4000 $10^9$ $m^3$ /yr = 140 EJ (24% of world energy – 580EJ)

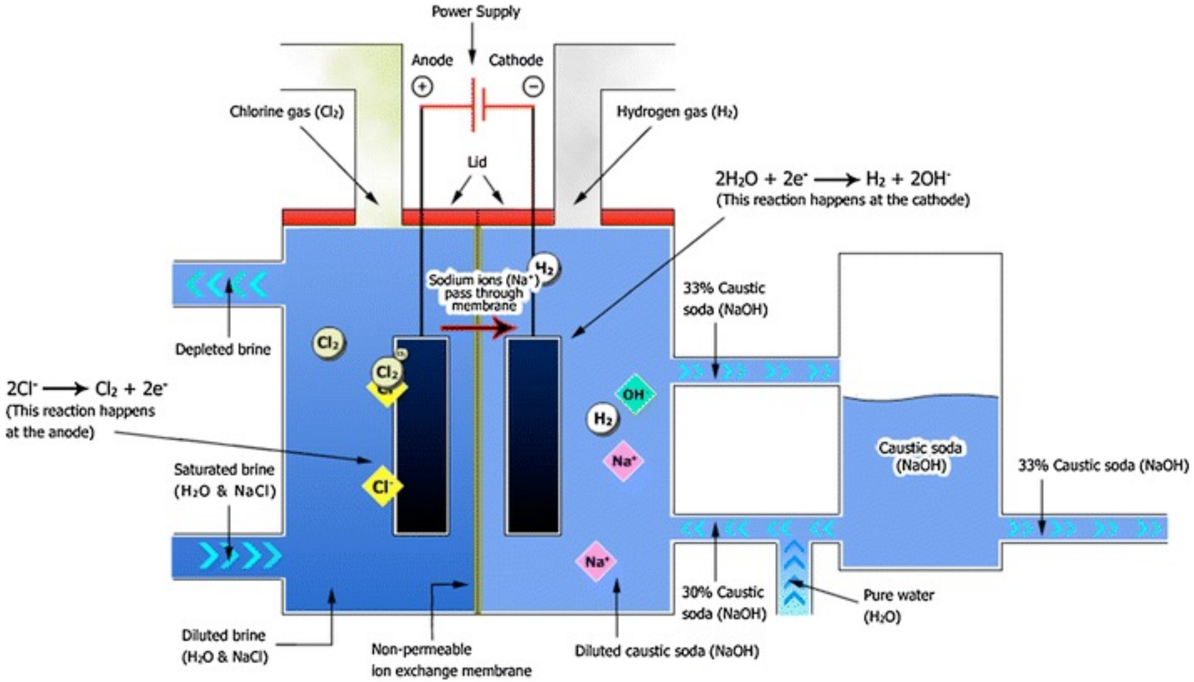
# Electrolytic $H_2$ : e.g. chlor-alcaline-industry

- Production 2017: 58 Mton $Cl_2$ (650 plants)
- Elec. consumption: 2.1 – 3.4 kWhe / kg $Cl_2$
- (take average of 2.5 kWhe / kg $Cl_2$ ) => 150 TWhe

  ≈ 25-30 GWe worldwide
- ≈0.6% of world electricity (25 PWh)
- this co-produces 1.6 Mt $H_2$ = 54 TWh $H_2$, accounting for >½ of all electrolytic $H_2$

Chlor-alkali process (1888)

$$2NaCl + 2H_2O \Rightarrow 2NaOH + Cl_2 + H_2$$



https://www.eurochlor.org/

*Lakshmanan, S. & Murugesan, T. Clean Techn Environ Policy (2014) 16: 225. https://doi.org/10.1007/s10098-013-0630-6*

# $H_2$ production from fossil fuels

| Process | Reaction | ΔH (kJ/mol) | T (°C) | P (bar) | Efficiency (% HHV) |
|---|---|---|---|---|---|
| Steam reforming | $CH_4 + H_2O \rightarrow 3\ H_2 + CO$ | +206 | 500-700 | 1-30 | 85 |
| Partial oxidation | $CH_4 + 1/2O_2 \rightarrow 2\ H_2 + CO$ | -36 | 700 (**C**POX)<br>>1000 (POX) | 1-150 | 60-75 |
| Autothermal reforming | $CH_4 + xH_2O + yO_2 \rightarrow H_2, CO$ | 0 | 700-900 | 1-50 | 70-80 |
| Pyrolysis | $CH_4 \rightarrow 2\ H_2 + C$ | +75 | 600-900 | 1-10 | 50 |
| Gasification | $C(H_xO_y) + H_2O \rightarrow H_2 + CO$ | +132 | 1100 | 50-70 | 60 |
| Shift reaction | $CO + H_2O \rightarrow H_2 + CO_2$ | -41 | HTS 350<br>LTS 200 | 1-30 | - |

linde-le.de

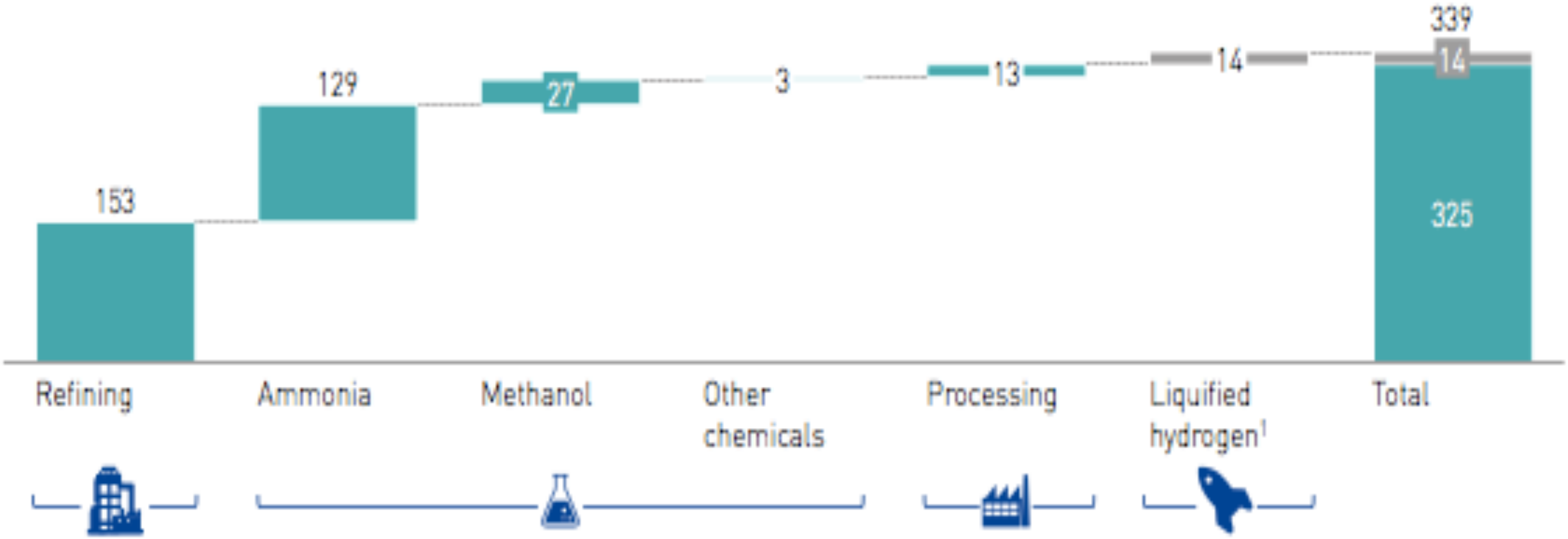
Linde, Texas, STR, HT-shift, PSA
NG, 110000 $m^3/h$, 99.99% pure $H_2$

# Thermal reforming

- Steam reforming (STR):
  - 🙂 100 $m^3/h$ to 140’000 $m^3/h$ plants
  - 🙂 catalyst lifetime (Ni) > 10 yrs
  - 🙂 very well known and established
  - 🙂 highest $H_2$ yield, lowest operation temperature
  - ☹ endothermal, sluggish, large scale
  - 🙂 80-90% efficiency, 10’000 $h^{-1}$ GHSV (ratio gas flow : reactor volume)
- Partial oxidation (POX):
  - 😐 in reality a substoichiometric combustion reaction followed by STR
  - 🙂 simple, fast, compact
  - ☹ low $H_2$ yield, high T, difficult T-control, risk of carbon deposits
  - ☹ 70-75% efficiency, 80’000 $h^{-1}$ GHSV
- Autothermal reforming (ATR):
  - 🙂 intermediate behaviour between STR and POX
  - 😐 75-85% efficiency, 25’000 $h^{-1}$ GHSV

# Current uses of $H_2$ (EU)

**Total hydrogen use in the EU,** in TWh



- Hydro-cracking
- Hydro-treating (e.g., fuel desulfuri-zation)
- Biorefinery

- Production of ammonia (for urea and other fertilizers)

- Production of methanol and derivatives

- Other chemicals (e.g., poly-mers, polyurethanes, fatty acids)

- Heat treating of steel
- Welding of metals
- Forming and blanketing gas
- Glass production

- Rocket fuel
- Automotive fuel
- Semi-conductor industry

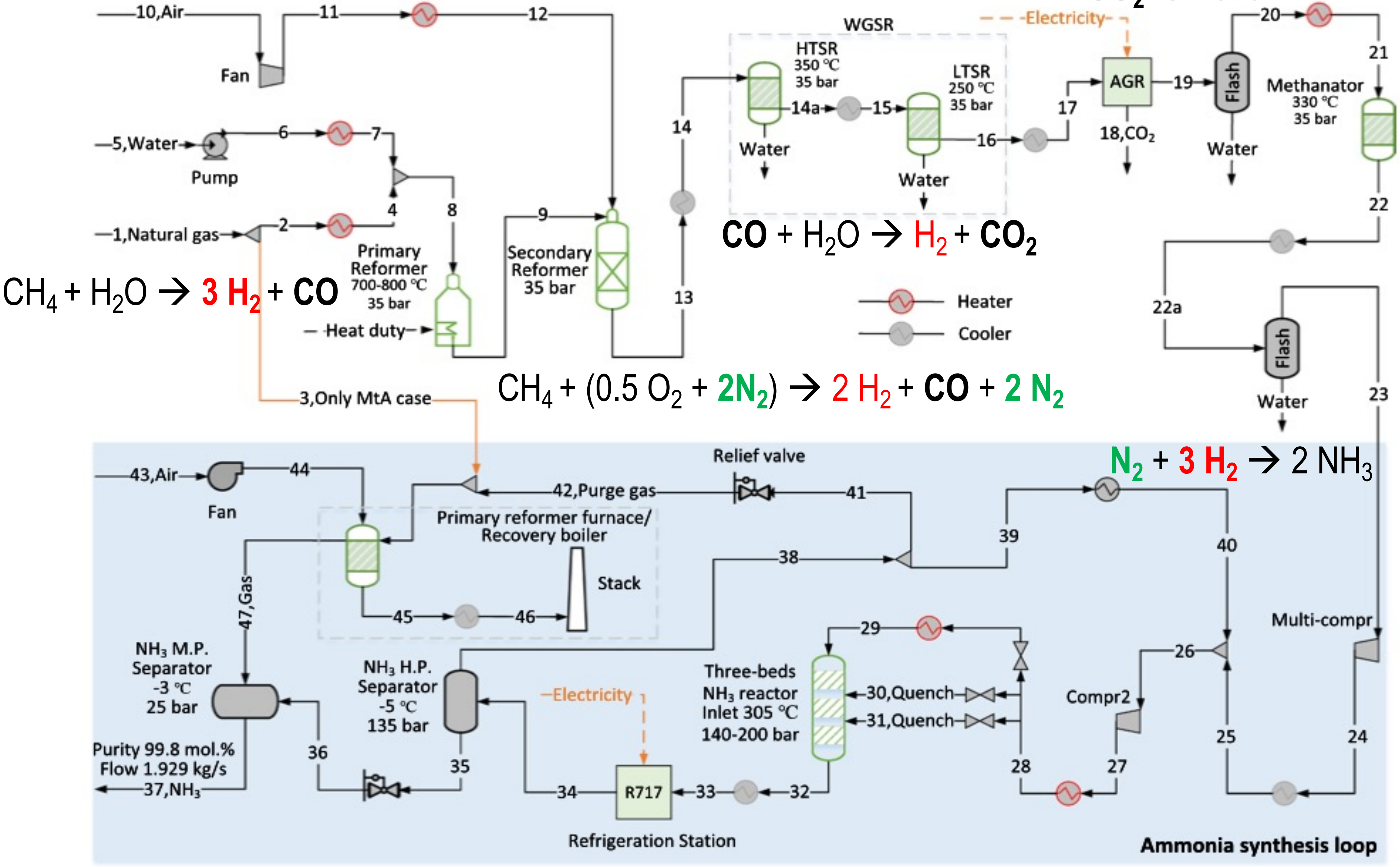
FCH | FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

fch.europa.eu
H2 Raodmap for Europe, January 2019
Exhibit 17 p.40

# $H_2$ current uses

- Refineries (47%): hydrodesulphurisation (HDS), hydro-cracking
- Ammonia ($NH_3$) production (fertiliser) (40%)
- Methanol (8%) and other chemicals (1%)
- 'Light' industries (4%): where reducing atmosphere is needed
  - metal treatment
  - semiconductor industry
  - glass making (glass floating on liquid tin baths)
  - food (fats hydrogenation)
- 325 TWh or 1.2 EJ (2% of final EU energy)

# Example: ammonia synthesis plant



$CO_2$ removal

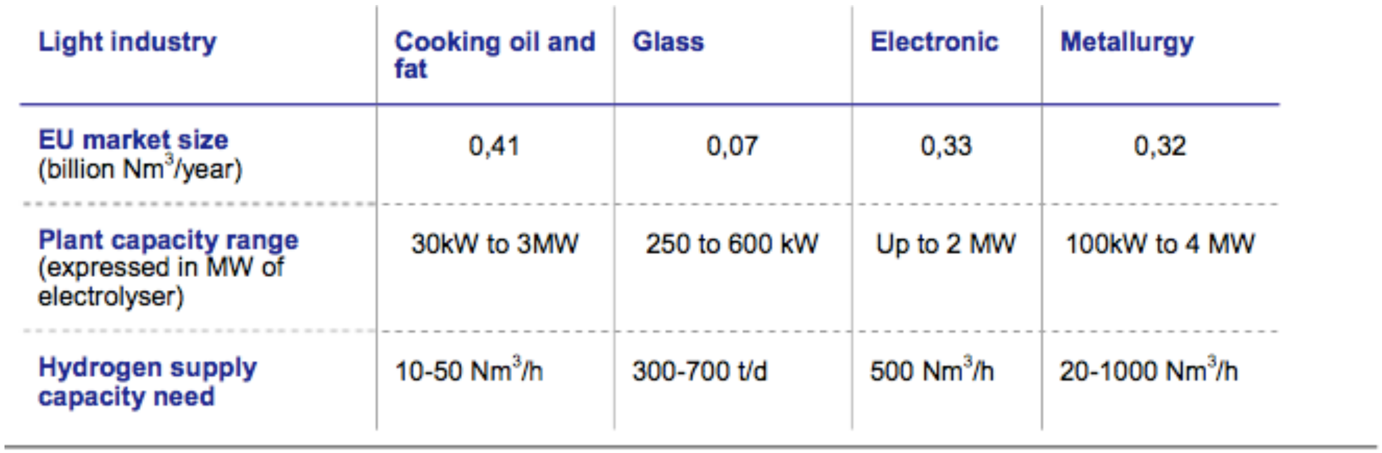
$CO + H_2O \rightarrow H_2 + CO_2$

$CH_4 + H_2O \rightarrow 3\ H_2 + CO$

$CH_4 + (0.5\ O_2 + 2N_2) \rightarrow 2\ H_2 + CO + 2\ N_2$

$N_2 + 3\ H_2 \rightarrow 2\ NH_3$

Techno-economic comparison of green ammonia production processes, Fig. 1
H Zhang, L Wang, J Van herle, F Maréchal, U Desideri, *Applied Energy* **259, 114135 (2020)**



| **Light industry** | **Cooking oil and fat** | **Glass** | **Electronic** | **Metallurgy** |
|---|---|---|---|---|
| **EU market size** (billion $Nm^3$/year) | 0,41 | 0,07 | 0,33 | 0,32 |
| **Plant capacity range** (expressed in MW of electrolyser) | 30kW to 3MW | 250 to 600 kW | Up to 2 MW | 100kW to 4 MW |
| **Hydrogen supply capacity need** | 10-50 $Nm^3$/h | 300-700 t/d | 500 $Nm^3$/h | 20-1000 $Nm^3$/h |

Table 38: Overview of the light industry hydrogen market

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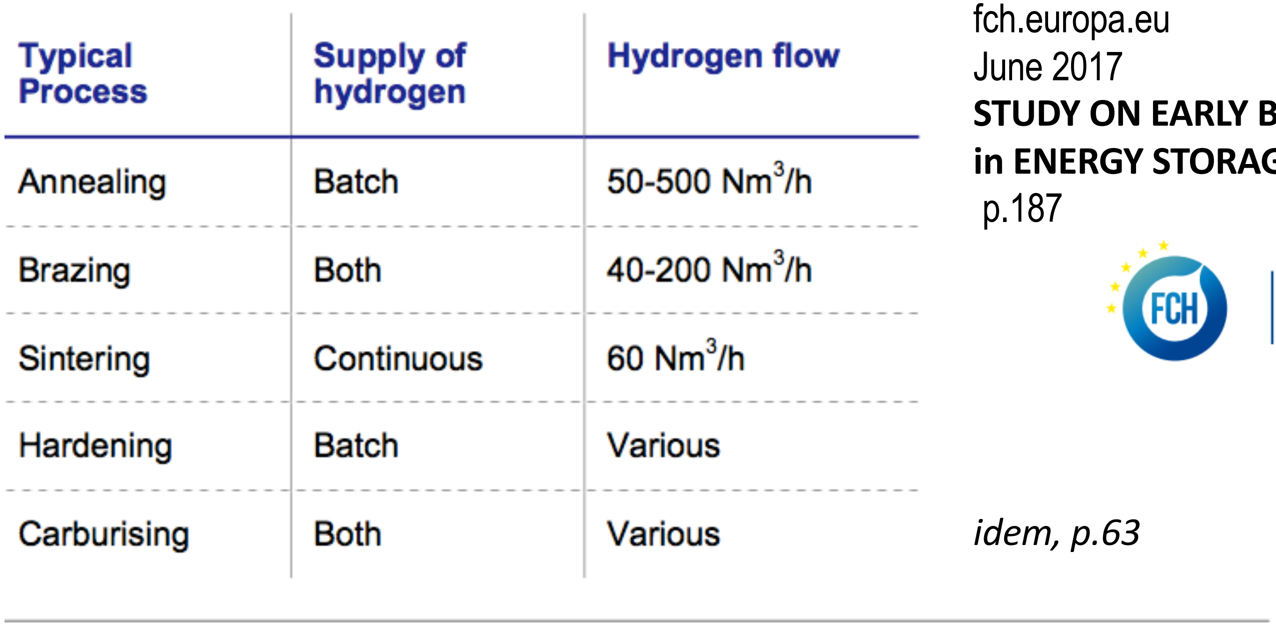
June 2017
**STUDY ON EARLY BUSINESS CASES FOR $H_2$**
**in ENERGY STORAGE AND POWER-TO-$H_2$ APPLICATIONS**
p.187

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING



| **Typical Process** | **Supply of hydrogen** | **Hydrogen flow** |
|---|---|---|
| Annealing | Batch | 50-500 $Nm^3$/h |
| Brazing | Both | 40-200 $Nm^3$/h |
| Sintering | Continuous | 60 $Nm^3$/h |
| Hardening | Batch | Various |
| Carburising | Both | Various |

*idem, p.63*

Table 99: Typical metal heat-treatment processes [43]

# Future uses and impact of $H_2$

# Annual $H_2$ demand per segment

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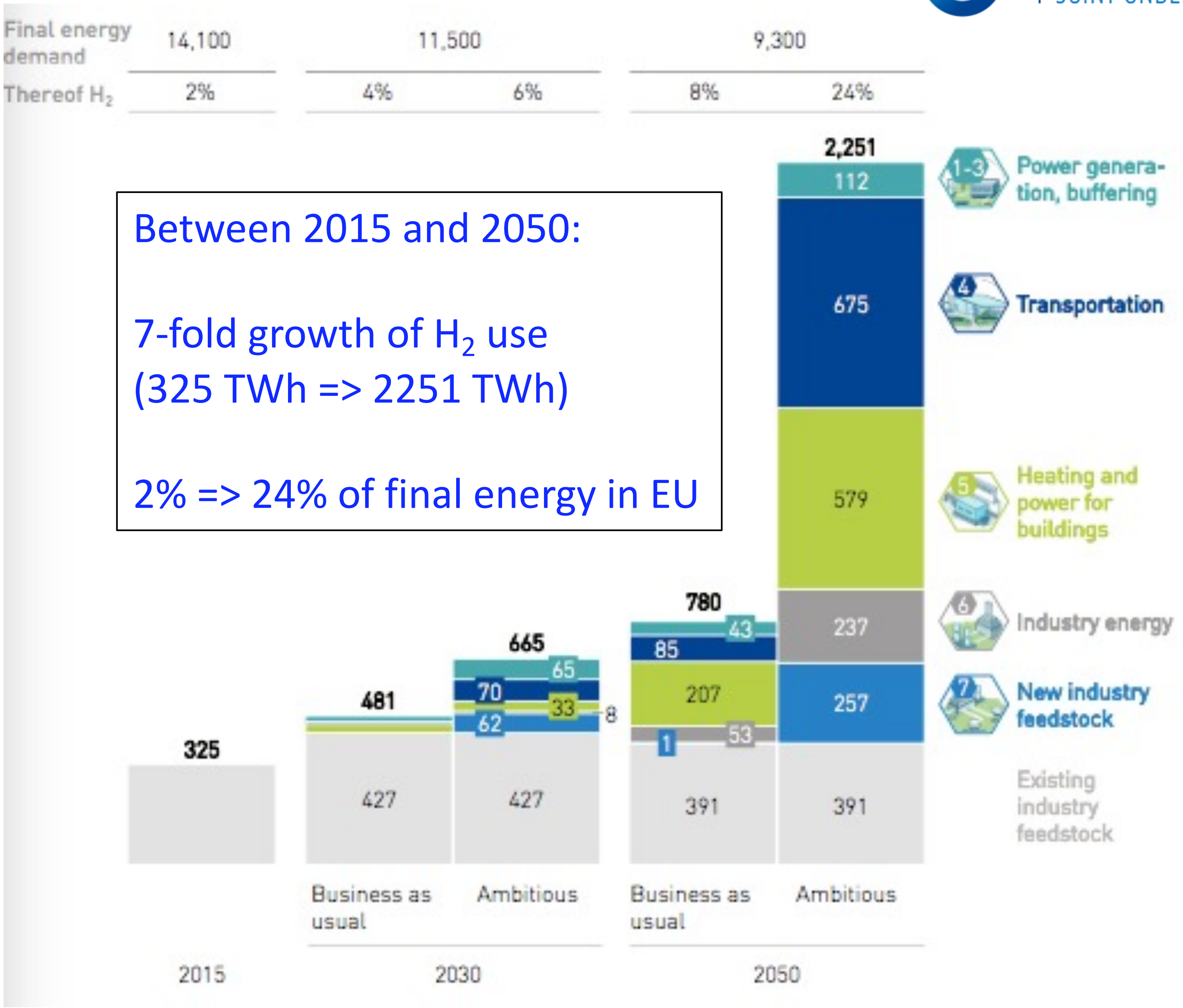
H2 Raodmap for Europe
January 2019
Exhibit 2 p.8
Exhibit 22 p 49



Between 2015 and 2050:

7-fold growth of $H_2$ use
(325 TWh => 2251 TWh)

2% => 24% of final energy in EU

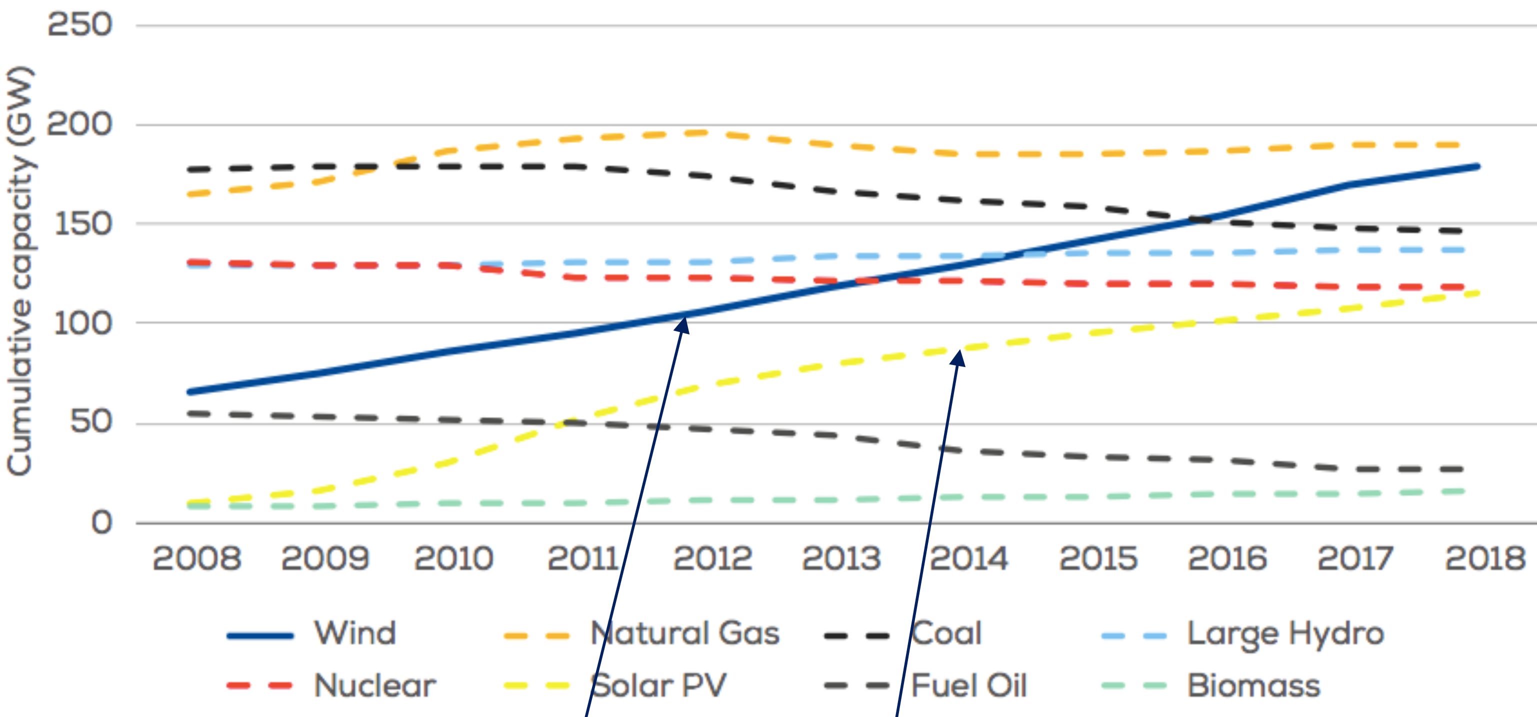
# Future $H_2$ uses

- Mobility : fuel cell vehicles
- Residential heating : natural gas network admixing, and/or $H_2$ pipelines
- Industry:
  - – industry heating: replacing coal, natural gas
  - – industry feedstock:
    - refineries
    - ammonia, methanol, other industries
    - steel making
  - – light industries

# Where will this $H_2$ come from?

**FIGURE 1**

Total power generation capacity in the European Union 2008-2018



Source: WindEurope

2018 (EU) :

Wind: 179 GWe
362 TWhe (14%)
26.7 b€ inv. (2018)

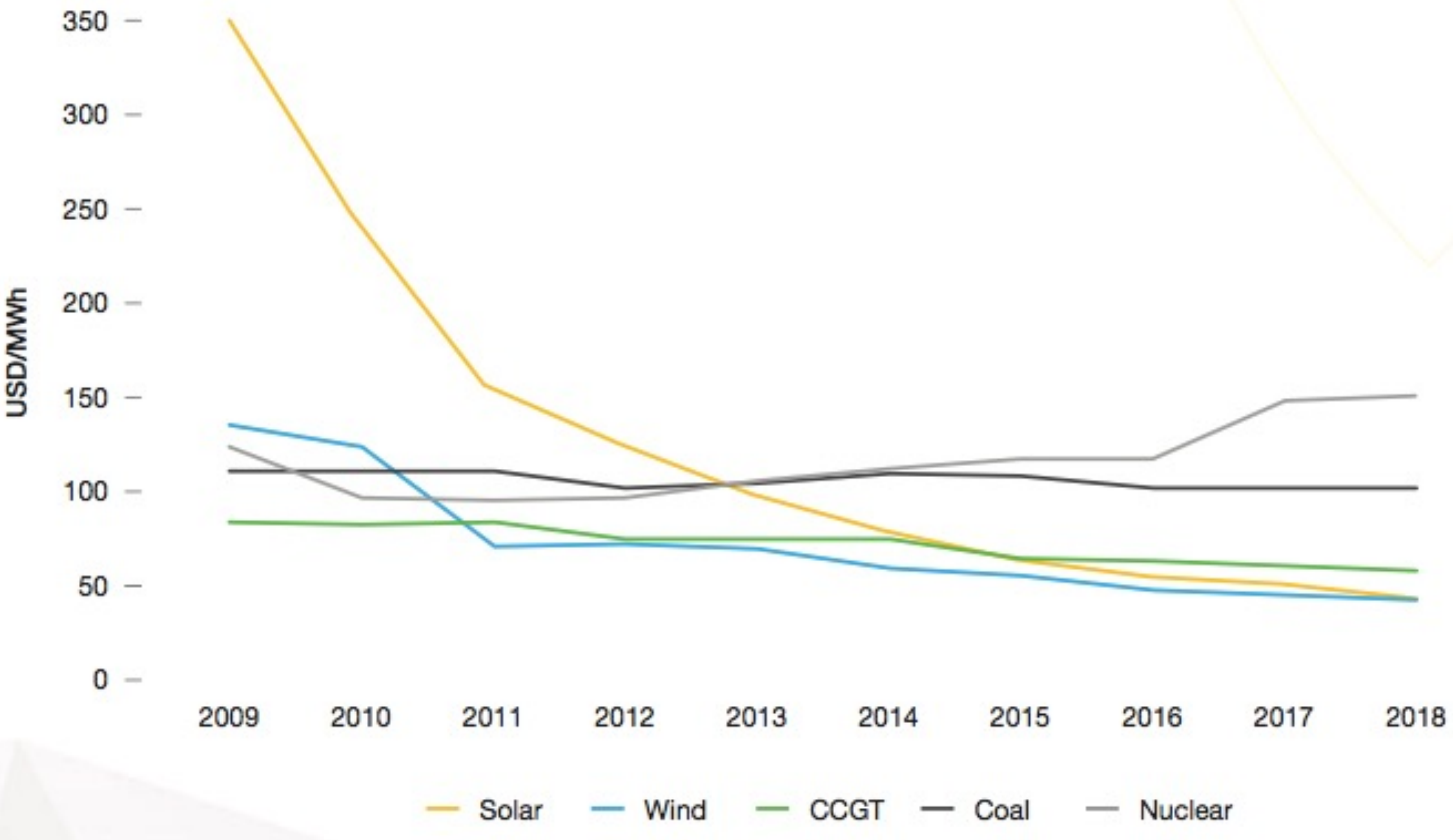
Solar: 126 GWe
120 TWhe (4.6%)

Solar worldwide:
+102 GWe in 2018
Total 509 GWe
(2.2% of electricity)

**From growth in Wind + Solar PV** ⇨ **STORAGE by ELECTROLYSIS**

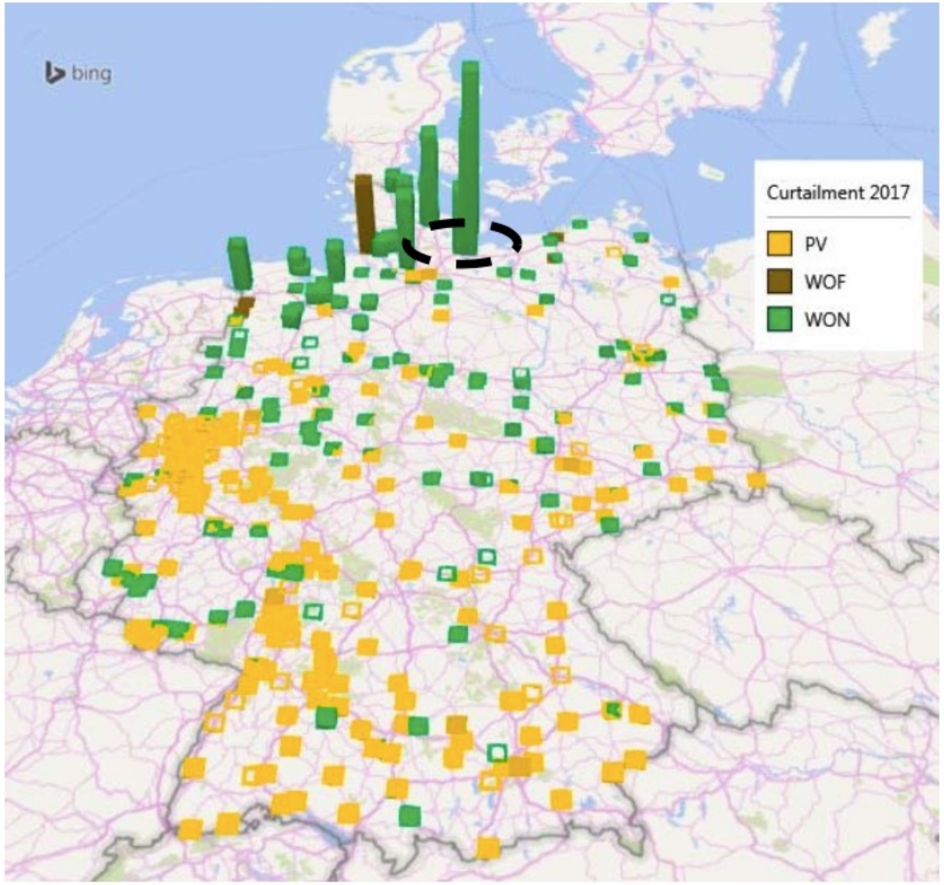
# Solar PV and wind is the cheapest electricity!

FIGURE 3 SOLAR ELECTRICITY GENERATION COST IN COMPARISON WITH OTHER POWER SOURCES 2009-2018

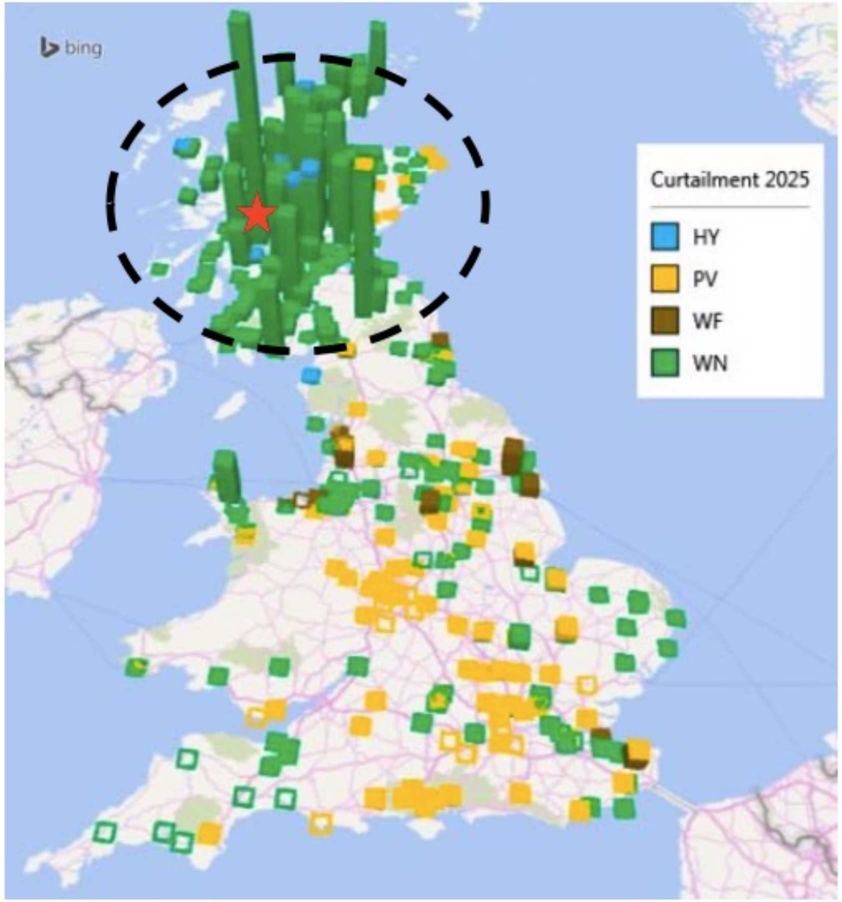


**Source:** Lazard (2018). All prices in 2019 USD.

# 'Curtailment' (excess electricity production)



Germany, 2017, max bar height = 428 GWh.



UK, 2025, max bar height = 117 GWh.

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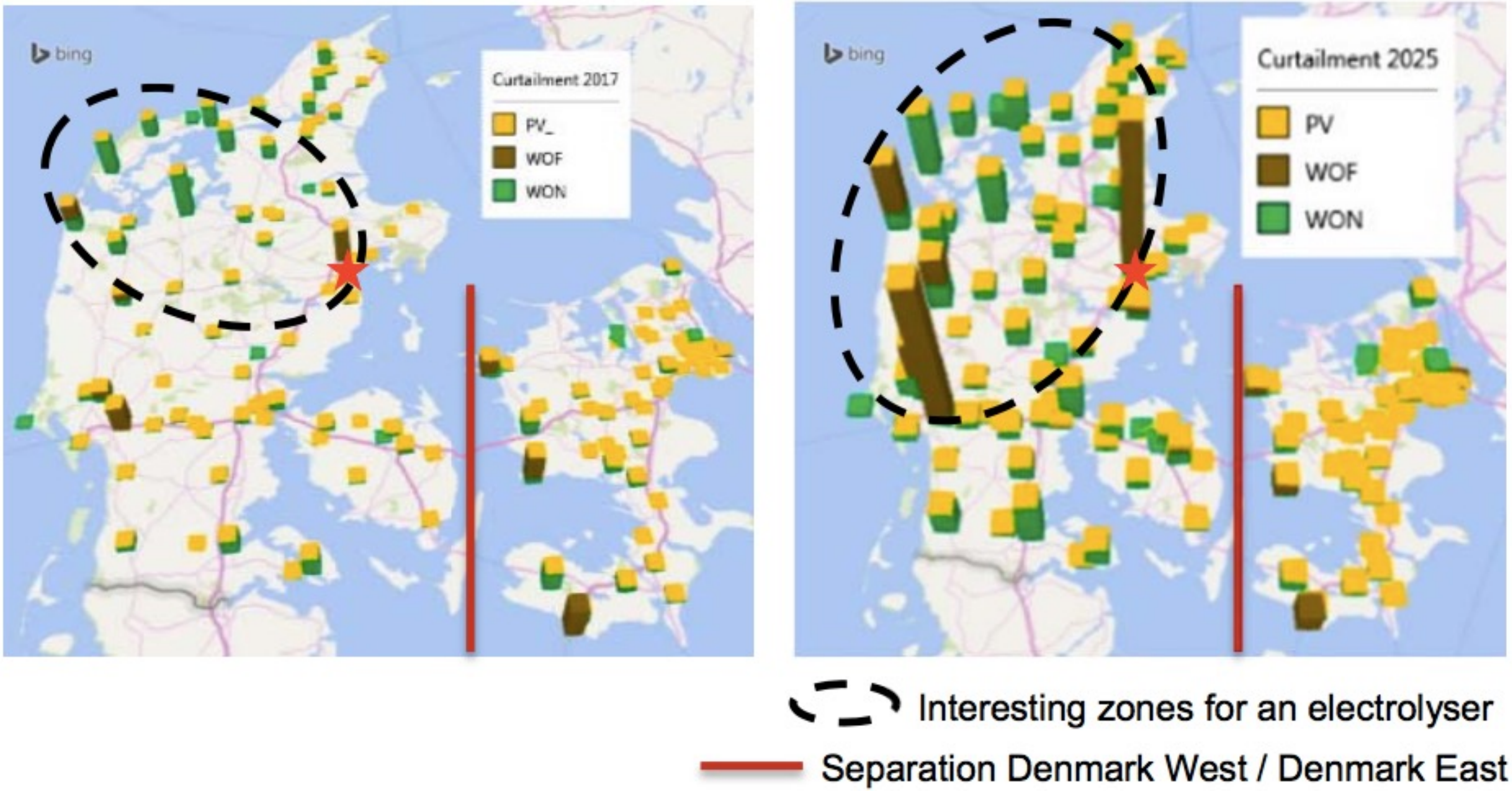
**STUDY ON EARLY BUSINESS CASES FOR H2**
**IN ENERGY STORAGE AND POWER TO H2 APPLICATIONS**
p. 33 fig. 10



DK: 2017 (left) and 2025 (right). Max bar height 2025 = 442 GWh

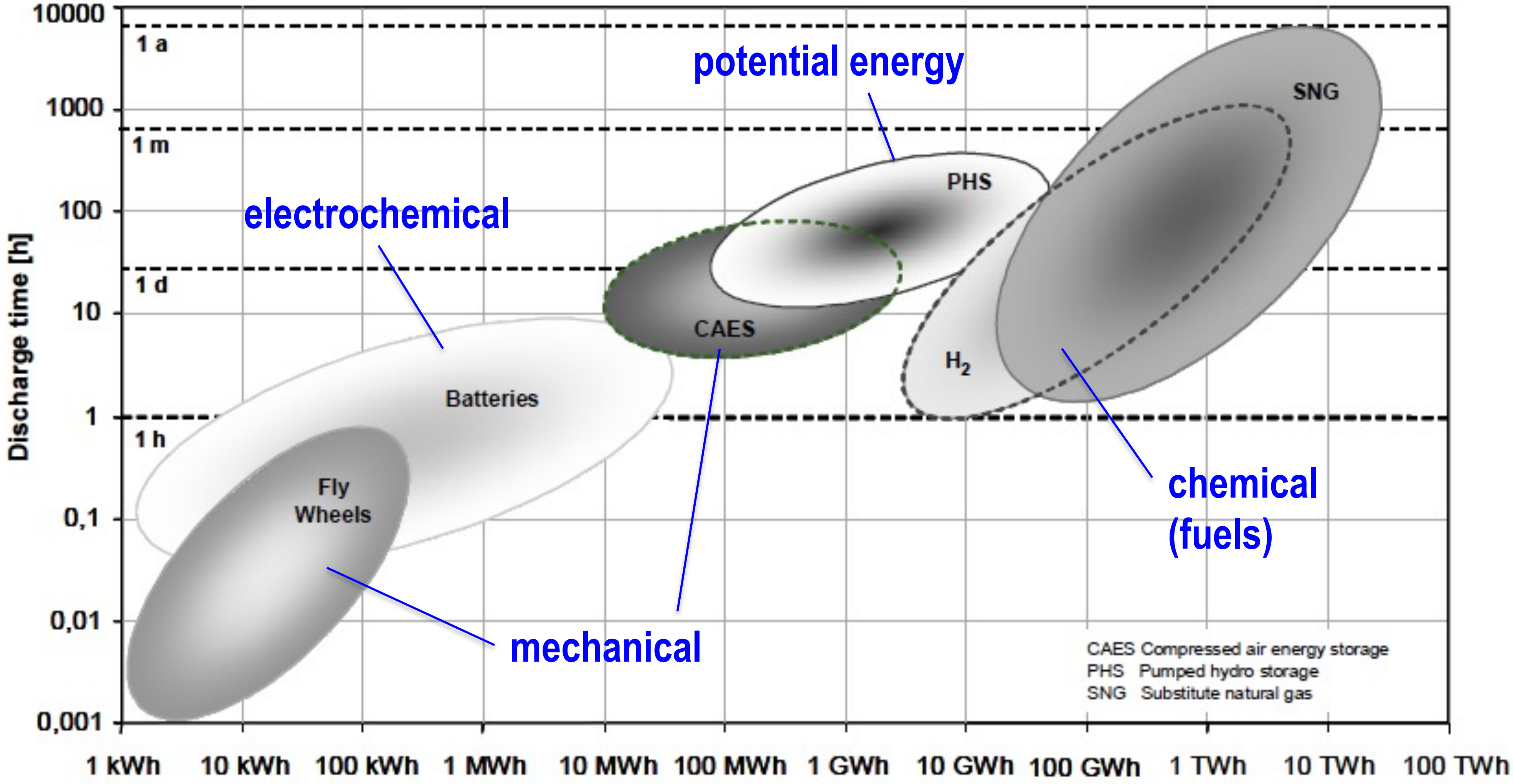
# Electricity Storage as Power-to-Gas

- the electrical grid has little storage capacity
- seasonal electricity demand varies significantly
- the difference (summer-winter) is exacerbated when replacing base-load (nuclear) with renewables like PV and hydro (summer-excess, winter-deficit)

→long term storage is required

- as fuel by electrolysis ($H_2$, $CH_4$, …)

# Storage schemes overview

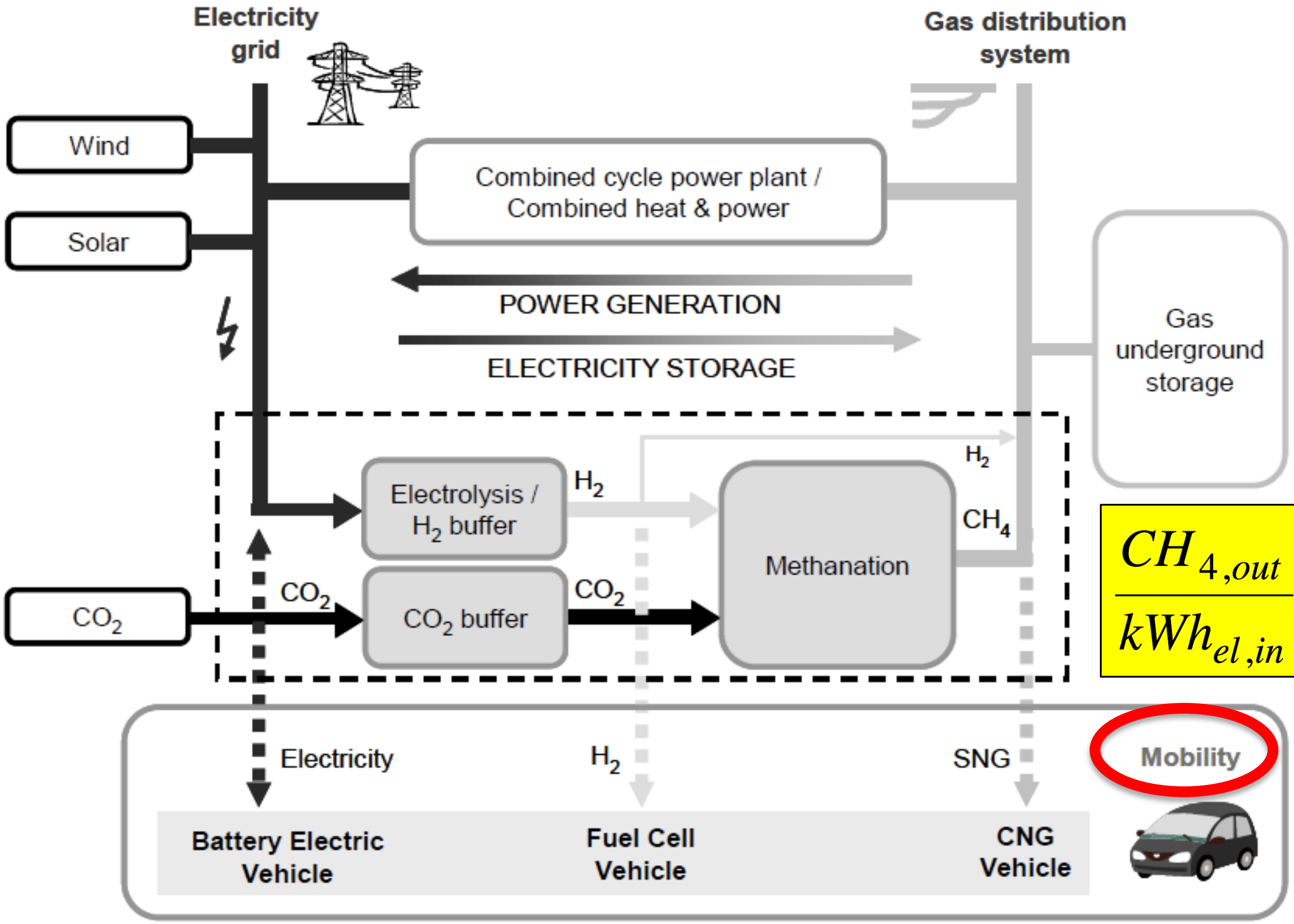


CAES Compressed air energy storage
PHS Pumped hydro storage
SNG Substitute natural gas

**Storing Renewable Energy in the Natural Gas Grid, Methane via Power-to-Gas (P2G): A Renewable Fuel for Mobility**
M. Specht, U. Zuberbühler, F. Baumgart, B. Feigl, V. Frick, B. Stürmer, M. Sterner, G. Waldstein, ZSW-Ulm

*→ converting electricity to fuel gives the largest capacities*

# ‘Power-to-Gas’ concept



$$\frac{CH_{4,out}}{kWh_{el,in}} \geq 60\%$$

**Storing Renewable Energy in the Natural Gas Grid, Methane via Power-to-Gas (P2G): A Renewable Fuel for Mobility**
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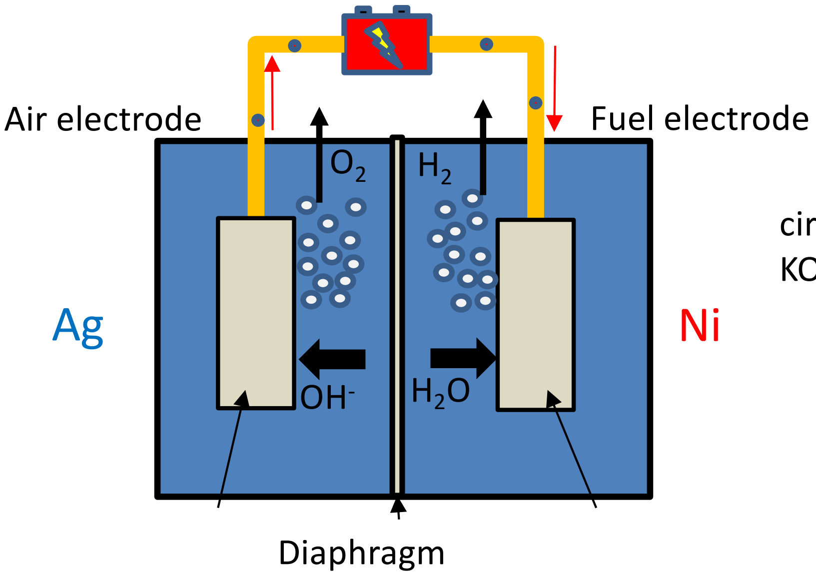
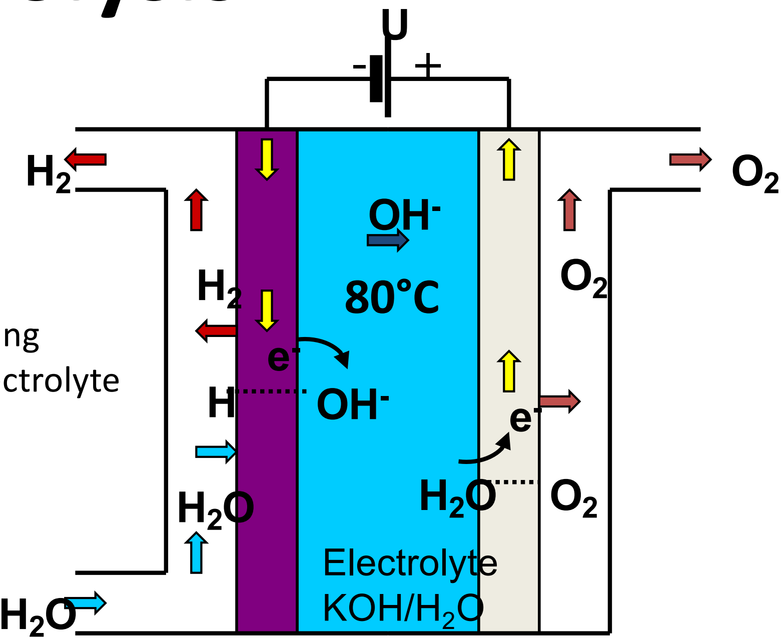
# Electrolyser Technologies

- AEL : alkaline water
- PEMEL : polymer electrolyte membrane (water)
- (AEMEL : anionin electrolyte membrane )
- SOEL : solid oxide ceramic (steam)
- (PCCEL : proton conducting ceramic (steam) )

# 1. Alkaline electrolysis



circulating
KOH electrolyte



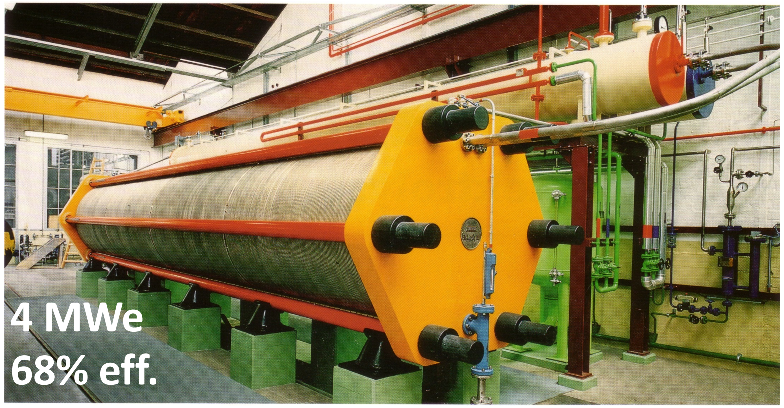
Ni Cathode

$2H_2O + 2e^- \rightarrow 2OH^- + H_2$

Anode Ag

$2OH^- \rightarrow ½O_2 + 2e^- + H_2O$

1– 30 bar



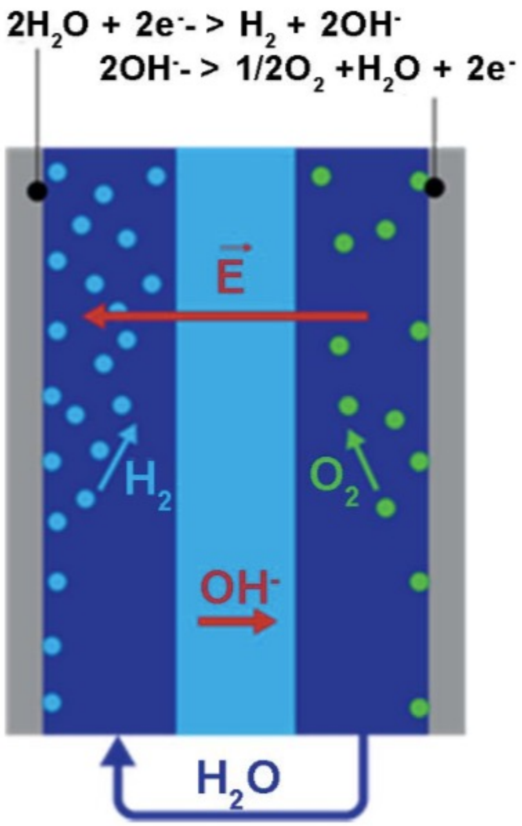
Djeva, Monthey (VS)

**Advantages** :
- Mature technology
- Large capacity (1400 $Nm^3/h$)
- Low cost
- Long life

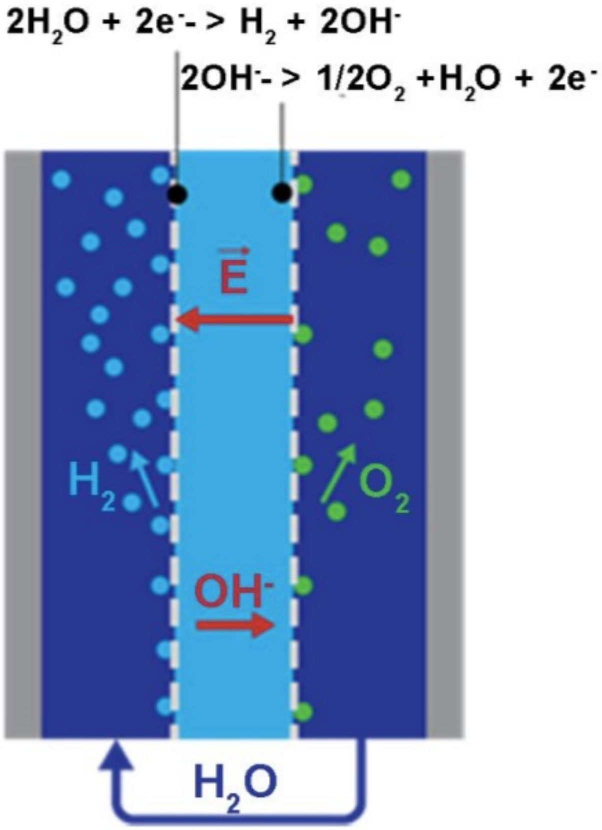
**Limitations**:
- Low current density
- Limited load range
- Limited dynamics
- Gas crossover at higher p

*slide adapted from T.Macherel, Prof A. Züttel, EPFL*

# Electrolyte Resistance and Gas Bubbles



alkaline electrolyzer

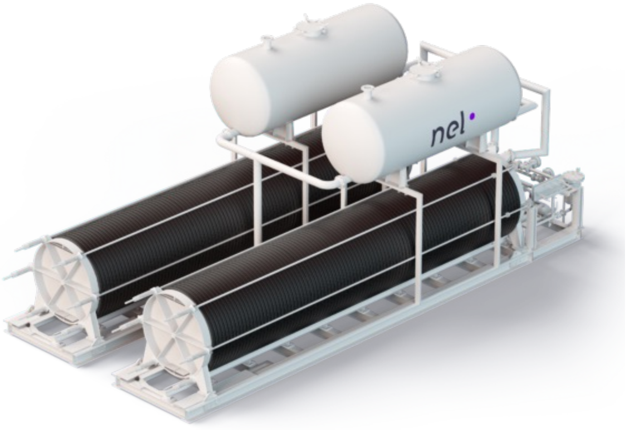


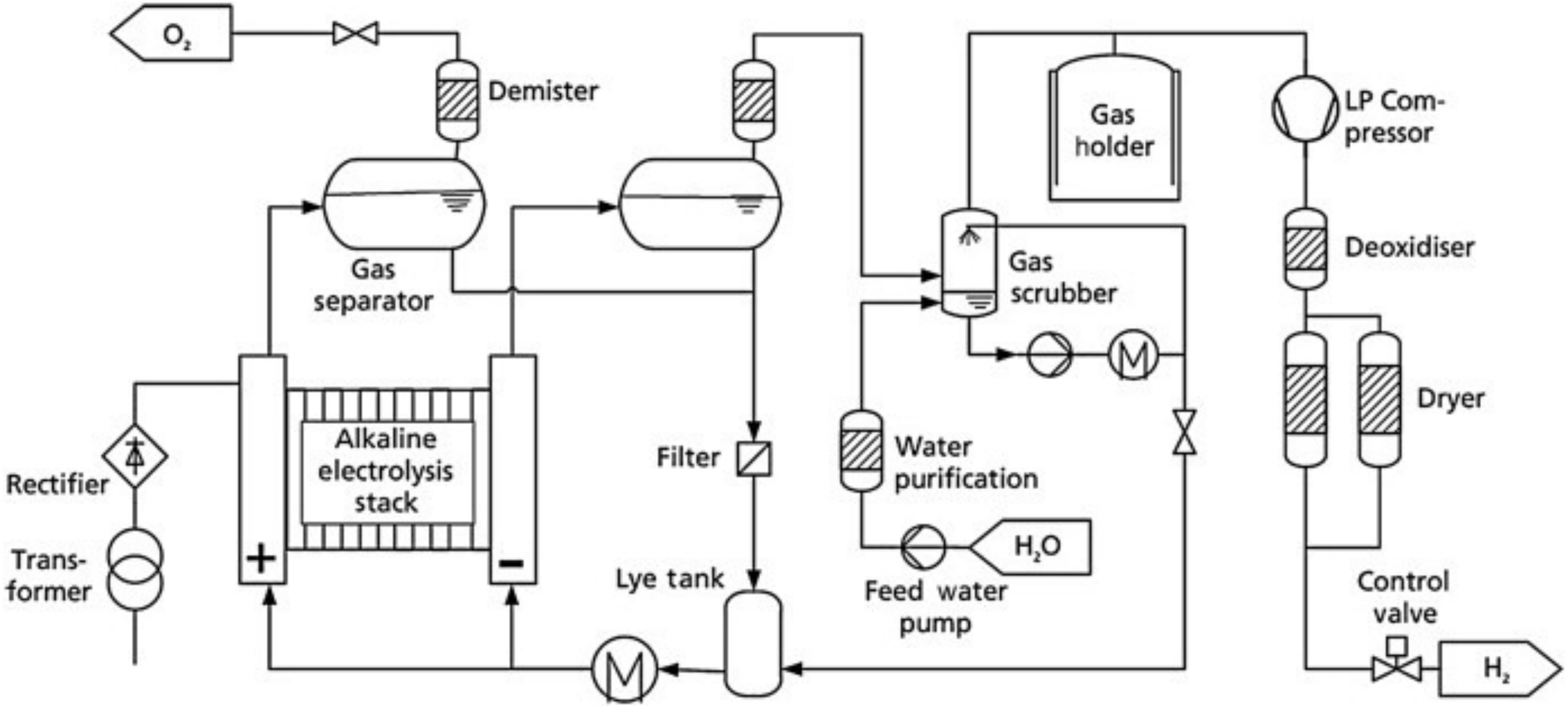
**zero-gap** alkaline electrolyzer

Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

*slide from Prof A. Züttel, EPFL*

# Alkaline Electrolyzer System

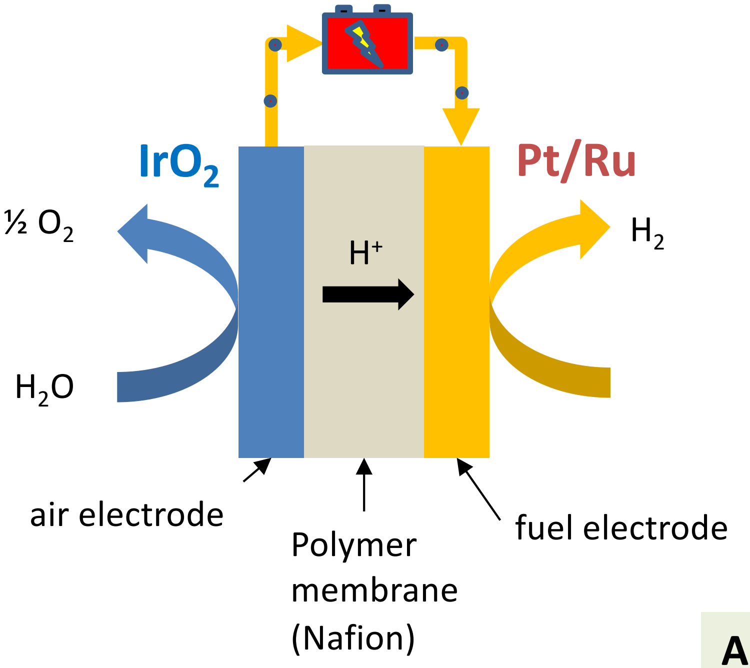




Ref.: Tom Smolinka,Emile Tabu Ojong, Jürgen Garche, "Electrochemical Energy Storage for Renewable Sources and Grid Balancing, Chapter 8 - Hydrogen Production from Renewable Energies—Electrolyzer Technologies, Electrochemical Energy Storage for Renewable Sources and Grid Balancing 2015, Pages 103-128

*slide from Prof A. Züttel, EPFL*

# 2. Polymer electrolyte membrane electrolysis



At air electrode (anode) :

$$H_2O_{(l)} \rightarrow \frac{1}{2}O_{2(g)} + 2H^+ + 2e^-$$

At fuel electrode (cathode) :

$$2H^+ + 2e^- \rightarrow H_{2(g)}$$

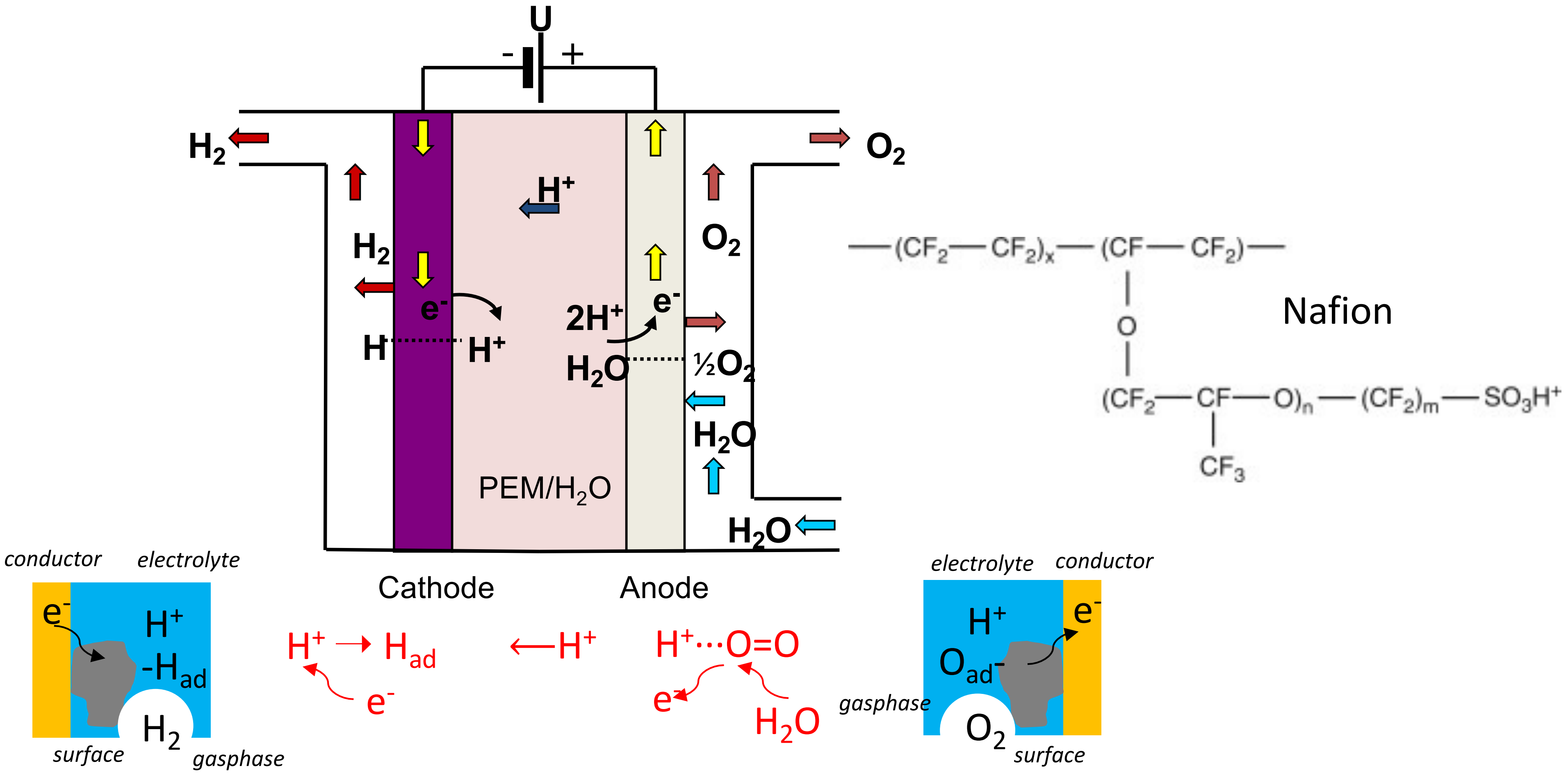
**Advantages** :
- High current density
- Wide load range
- Fast dynamics

**Limitations**:
- scarce and expensive **materials**
(noble metal catalysts; treated Ti interconnect)
- gas crossover

*slide from T.Macherel, EPFL*

# PEM electrolyser

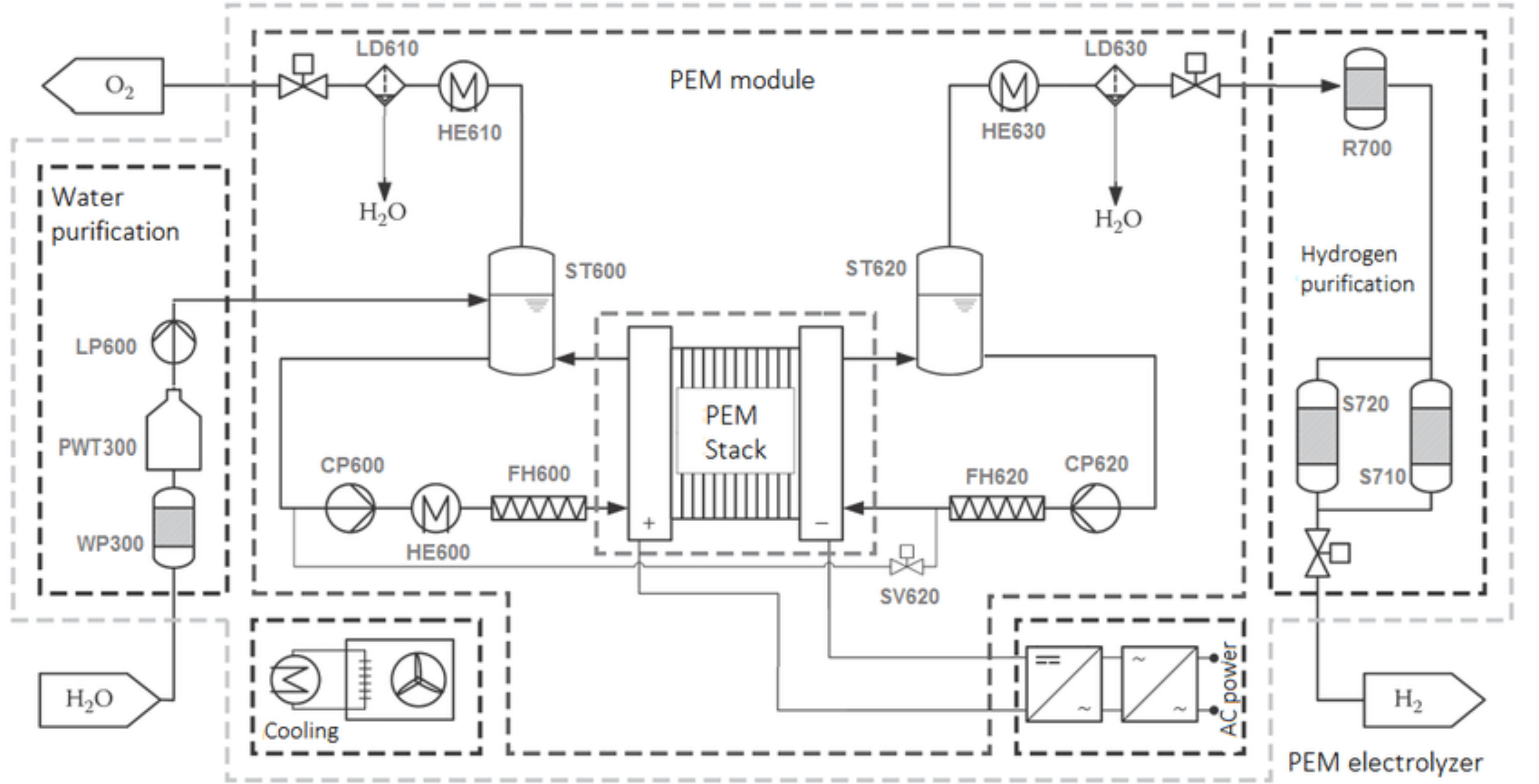
*slide from Prof A. Züttel, EPFL*



PEMEL started in the 1960s with the development of proton-conducting **acid** polymers, mainly perfluoro sulfonic acid (PFSA) polymer, among which the commercially established **NAFION**.

The sulfonic acid groups in the polymeric structure make the electrolyte **acidity very high** such that **only noble metal catalysts** (Pt, Ru, Ir), are able to sustain this environment. This increases PEMEL cost. For the membrane to be ionically conductive, it must be wet; furthermore, backward penetration of oxygen molecules may occur, which accounts for about 5% electric current consumption.

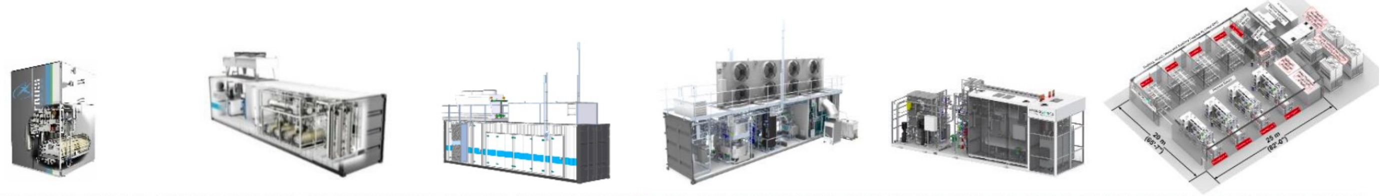
# PEMEL System



Ref.: Tom Smolinka,Emile Tabu Ojong, Jürgen Garche, "Electrochemical Energy Storage for Renewable Sources and Grid Balancing, Chapter 8 - Hydrogen Production from Renewable Energies—Electrolyzer Technologies, Electrochemical Energy Storage for Renewable Sources and Grid Balancing 2015, 103-128

*slide from Prof A. Züttel, EPFL*

# WATER ELECTROLYZERS : PRODUCT LINE

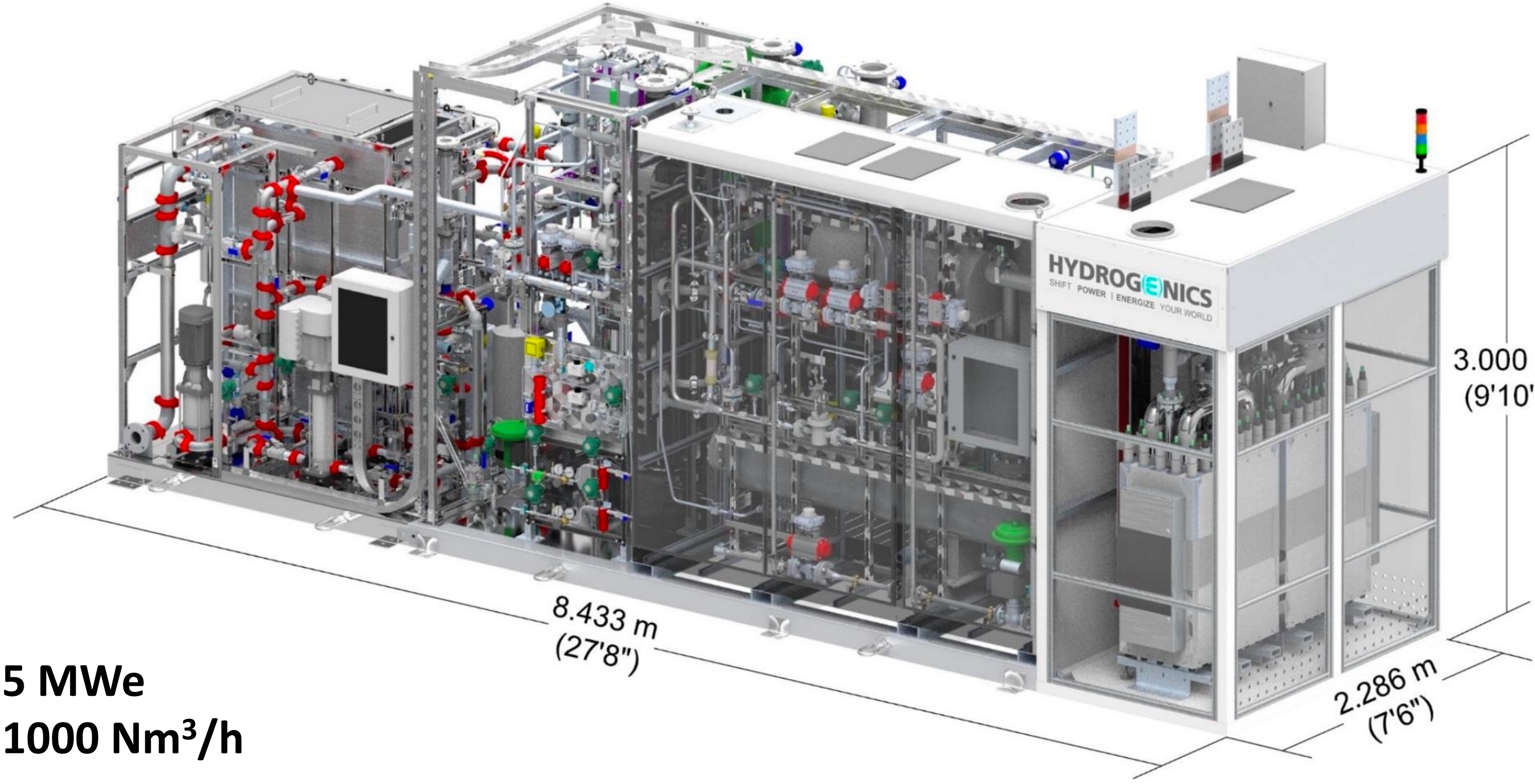


| | Alkaline | | | PEM (Proton Exchange Membrane) | | |
|---|---|---|---|---|---|---|
| | **HySTAT®-15-10** | **HySTAT®-60-10** | **HySTAT®-100-10** | **HyLYZER® -500-30** | **HyLYZER® -1.000-30** | **HyLYZER® -4.000-30** |
| **Output pressure** | 10 barg (27 barg optional) | | | 30 barg | | |
| **Design** | Indoor/outdoor | Indoor/outdoor | Indoor/outdoor | Indoor/outdoor | Indoor | Indoor |
| **Number of cell stacks** | 1 | 4 | 6 | 2 | 2 | 8 |
| **Nominal hydrogen flow** | 15 Nm$^3$/h | 60 Nm$^3$/h | 100 Nm$^3$/h | 500 Nm$^3$/h | 1.000 Nm$^3$/h | 4.000 Nm$^3$/h |
| **Nominal input power** | 80 kW | 300 kW | 500 kW | 2.5 MW | 5 MW | 20 MW |
| **AC power consumption (utilities included, at nominal capacity)** | 5.0 to 5.4 kWh/Nm$^3$ | | | ≤ 5.1 kWh/Nm$^3$ | DC power consumption:<br>4.3 kWh/Nm$^3$ ± 0.1 (at nameplate hydrogen flow) | |
| **Turndown ratio** | 40-100% | 10-100% | 5-100% | 5-100% | 5-125% | |
| **Hydrogen purity** | 99.998%<br>O2 < 2 ppm, N2 < 12 ppm (higher purities optional) | | | 99.998%<br>O2 < 2 ppm, N2 < 12 ppm (higher purities optional) | | |
| **Tap water consumption** | <1.4 liters / Nm$^3$ H2 | | | <1.4 liters / Nm$^3$ H2 | | |
| **Footprint (in containers)** | 1 x 20 ft | 1 x 40 ft | 1 x 40 ft | 2 x 40 ft | (LxWxH)<br>8.4 x 2.3 x 3.0 m | 20 x 25 m<br>(500 m$^2$) |
| **Utilities (AC-DC rectifiers, reverse osmosis, cooling, instrument air, H2 dryer)** | Incl. | Incl. | Incl. | Incl. | Optional | Optional |

Ref.: Denis THOMAS, Cummins – Hydrogenics, “POWER TO HYDROGEN TO POWER SOLUTION PEM Water electrolysis”,
e:denis.thomas@cummins.com, FLEXnCONFU Webinar, 3 November 2020

*slide from Prof A. Züttel, EPFL*

# HYLYZER®-1000 ELECTROLYZER

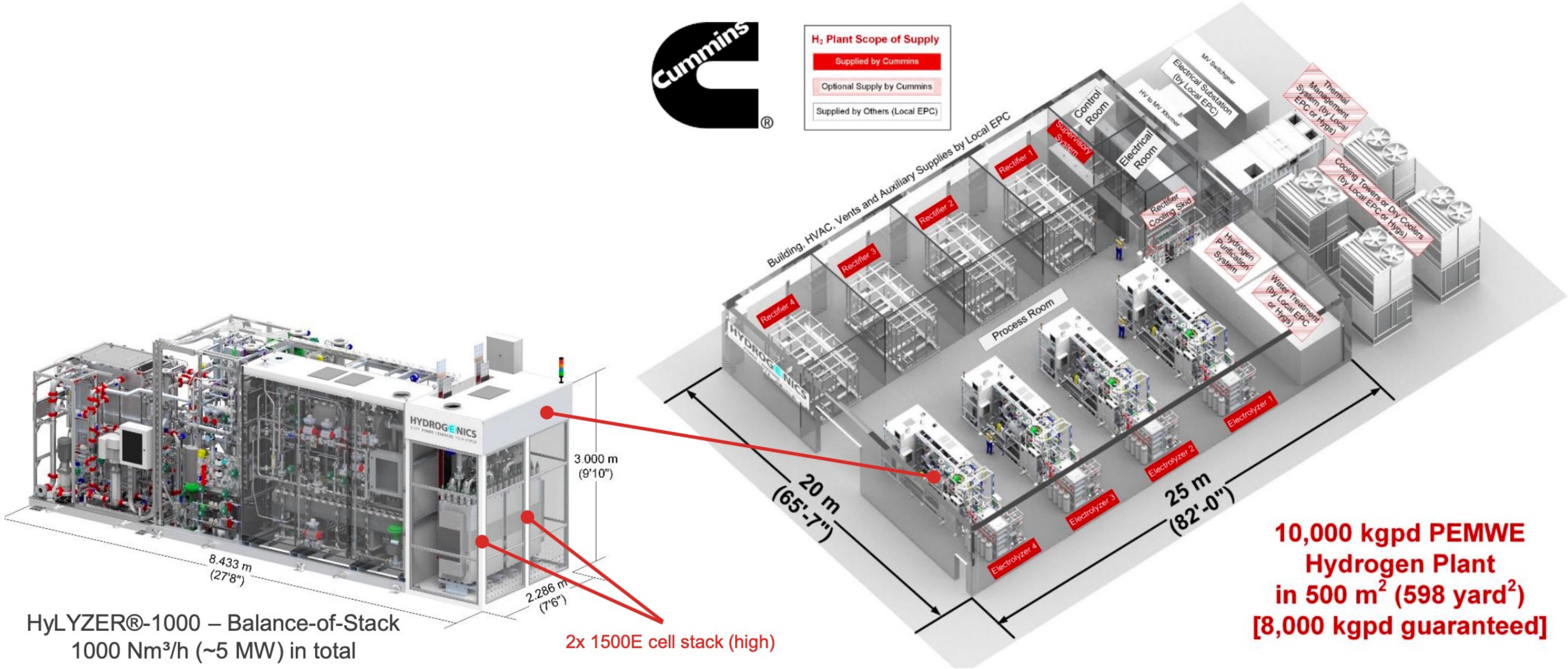


**5 MWe**
**1000 Nm$^3$/h**

Ref.: Denis THOMAS, Cummins – Hydrogenics, “POWER TO HYDROGEN TO POWER SOLUTION PEM Water electrolysis”, e: denis.thomas@cummins.com, FLEXnCONFU Webinar, 3 November 2020

*slide from Prof A. Züttel, EPFL*

# SCALABLE PRODUCT PLATFORM
# 8,000 KG/DAY / 20MW / 4X HYLYZER®–1000



HyLYZER®-1000 – Balance-of-Stack
1000 Nm³/h (~5 MW) in total

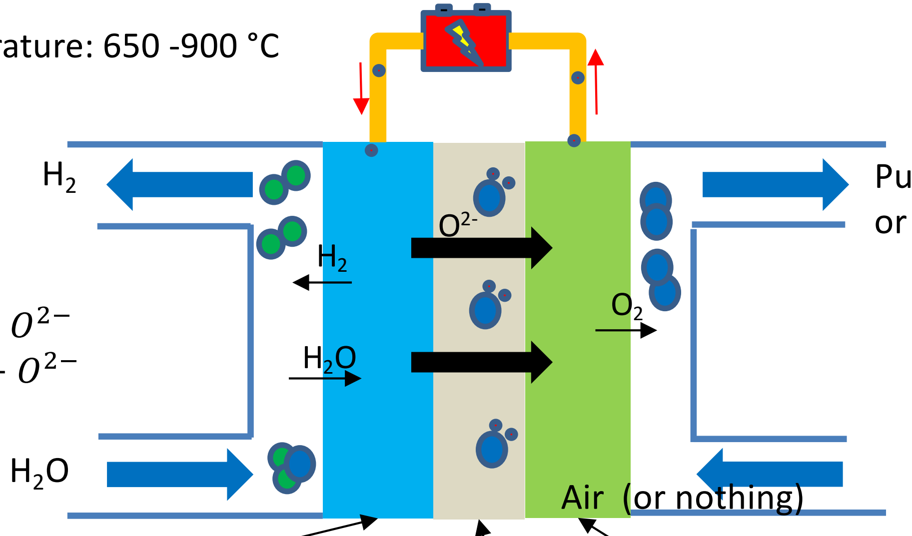
2x 1500E cell stack (high)

**10,000 kgpd PEMWE
Hydrogen Plant
in 500 m$^2$ (598 yard$^2$)
[8,000 kgpd guaranteed]**

Ref.: Denis THOMAS, Cummins – Hydrogenics, “POWER TO HYDROGEN TO POWER SOLUTION PEM Water electrolysis”, e: denis.thomas@cummins.com, FLEXnCONFU Webinar, 3 November 2020

*slide from Prof A. Züttel, EPFL*

# 3. Solid oxide electrolysis (steam, $CO_2$)



Temperature: 650 -900 °C

Fuel electrode:

$$CO_2 + 2e^- \rightarrow CO + O^{2-}$$

$$H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

Air electrode:

$$2O^{2-} \rightarrow O_2 + 4e^-$$

Fuel electrode

Ni

Electrolyte

(Y-$ZrO_2$)

Air electrode

oxide, e.g. $LaSrCoFeO_3$

*slide from T.Macherel, EPFL*

# Fuel cell: fuel → electricity

**Stationary**

>600°C

*ceramic* membrane (SOFC)

fuel
catalyst: **Ni**

oxygen
catalyst: **oxide**

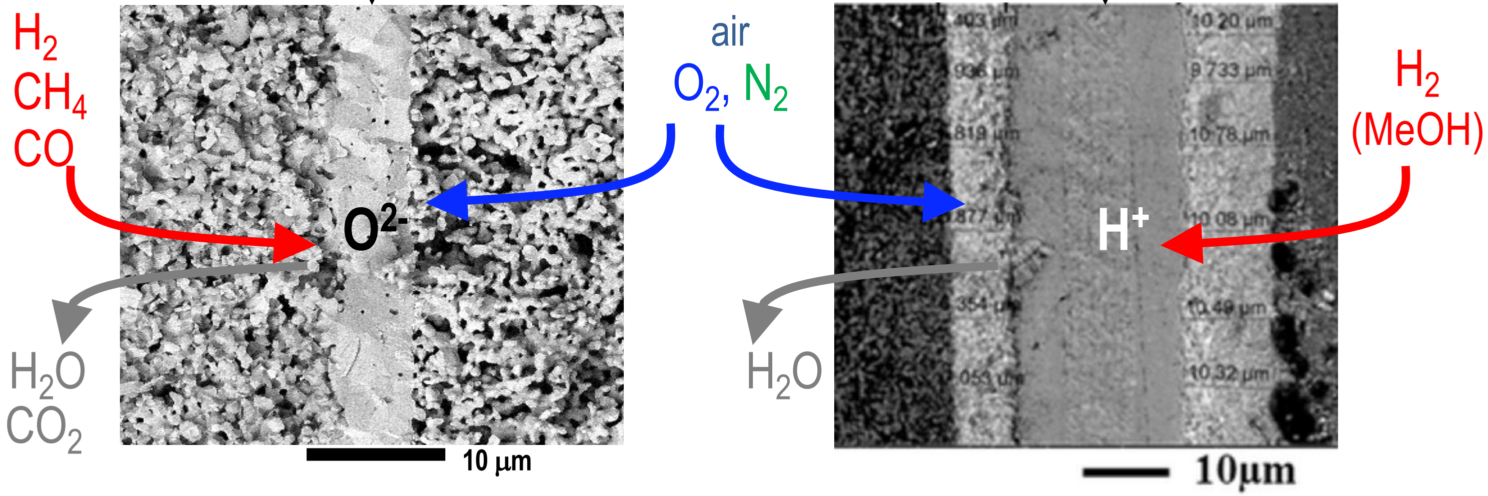
**Mobility / Portable**

(PEFC) *polymer* membrane

<100°C

oxygen
catalyst: **Pt**

fuel
catalyst: **Pt**



Charles J. Banas et al. J. Electrochem. Soc. 2018; 165: F3015-F3023

From natural gas, biogas, syngas, ethanol,…

From hydrogen only

# Electrolyser: electricity → fuel

**Stationary (Electrolysis)**

>600°C | *ceramic* membrane (SOFC)

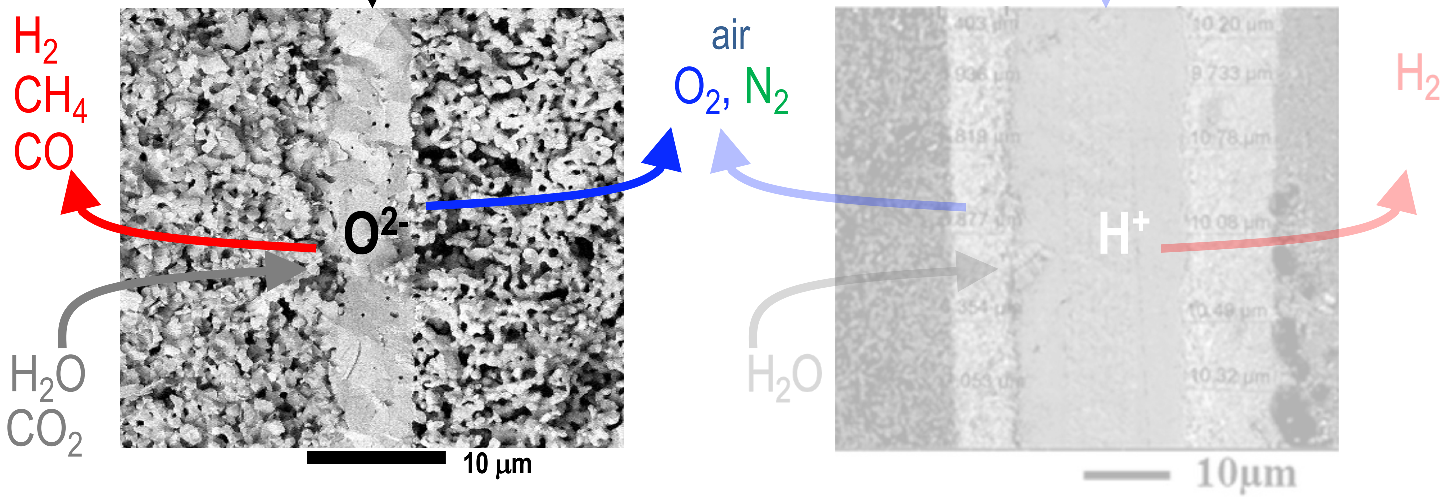
(PEFC) *polymer* membrane | <100°C

fuel
catalyst: **Ni**

oxygen
catalyst: **oxide**

oxygen
catalyst: **Pt**

fuel
catalyst: **Pt**



Charles J. Banas et al. J. Electrochem. Soc. 2018; 165: F3015-F3023

To hydrogen, syngas, methane

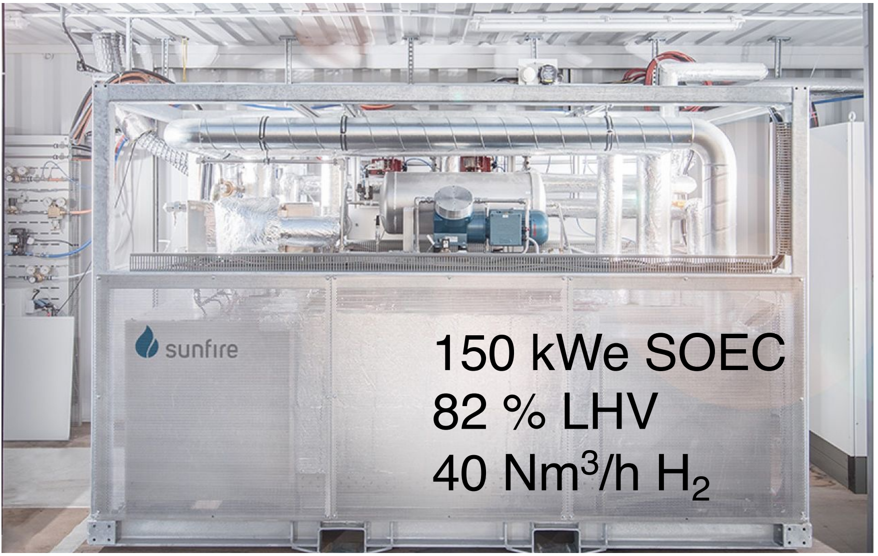
*With the same device* → ***reversible***

To hydrogen only

*Needs a different device* → ***not reversible***

# Solid-oxide system development & manufacturers

SUNFIRE
POWERCORE



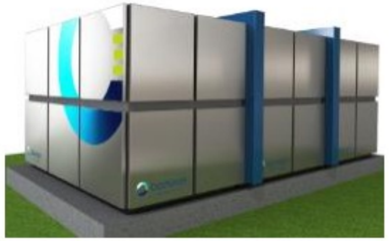
150 kWe SOEC
82 % LHV
40 $Nm^3/h$ $H_2$

**Convion C50**
**50kW, NG, Biogas**

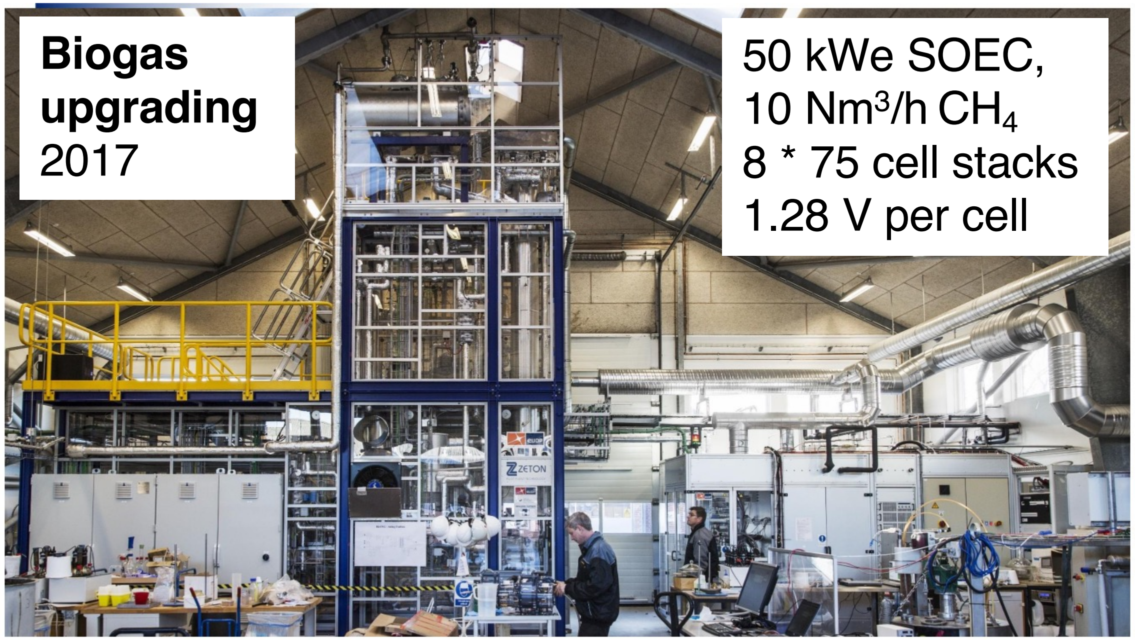
**Validation 2015**

**CONVION SOFC**

**X00 concept**
175 kWe, Biogas
ηe > 53 %
2016

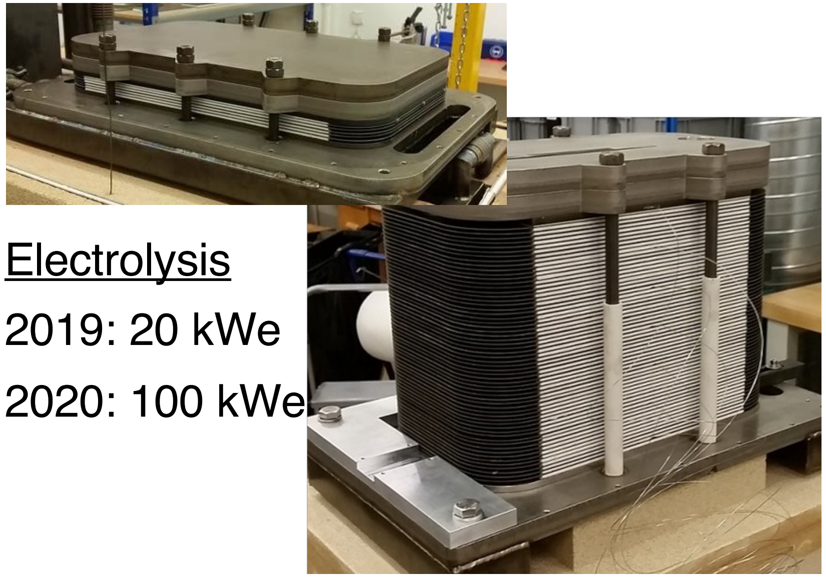


**Biogas upgrading**
2017



50 kWe SOEC,
10 $Nm^3/h$ $CH_4$
8 * 75 cell stacks
1.28 V per cell

## SOLIDPower 5-kW SOFC stack



Electrolysis

2019: 20 kWe

2020: 100 kWe

# Summary of electrolyser types

PEM | Alkaline | Solid oxide

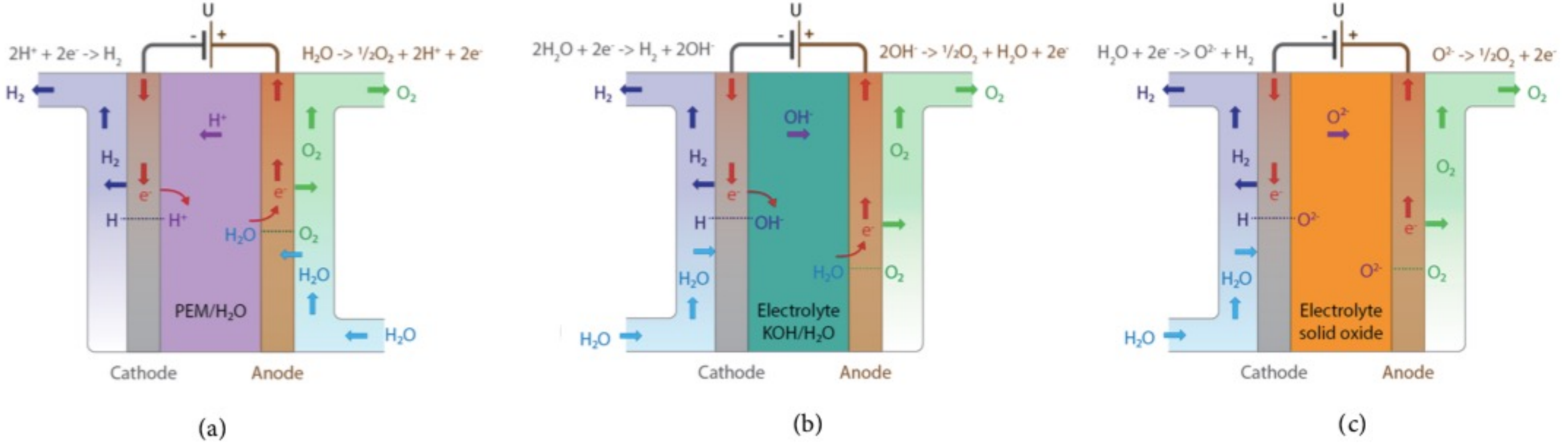


**Figure 2.** The three types of electrolysers: (a) Acidic (PEM: Polymer Electrolyte Membrane); (b) Alkaline (AEL); and (c) Solid oxide (SOEC) electrolyser cells.

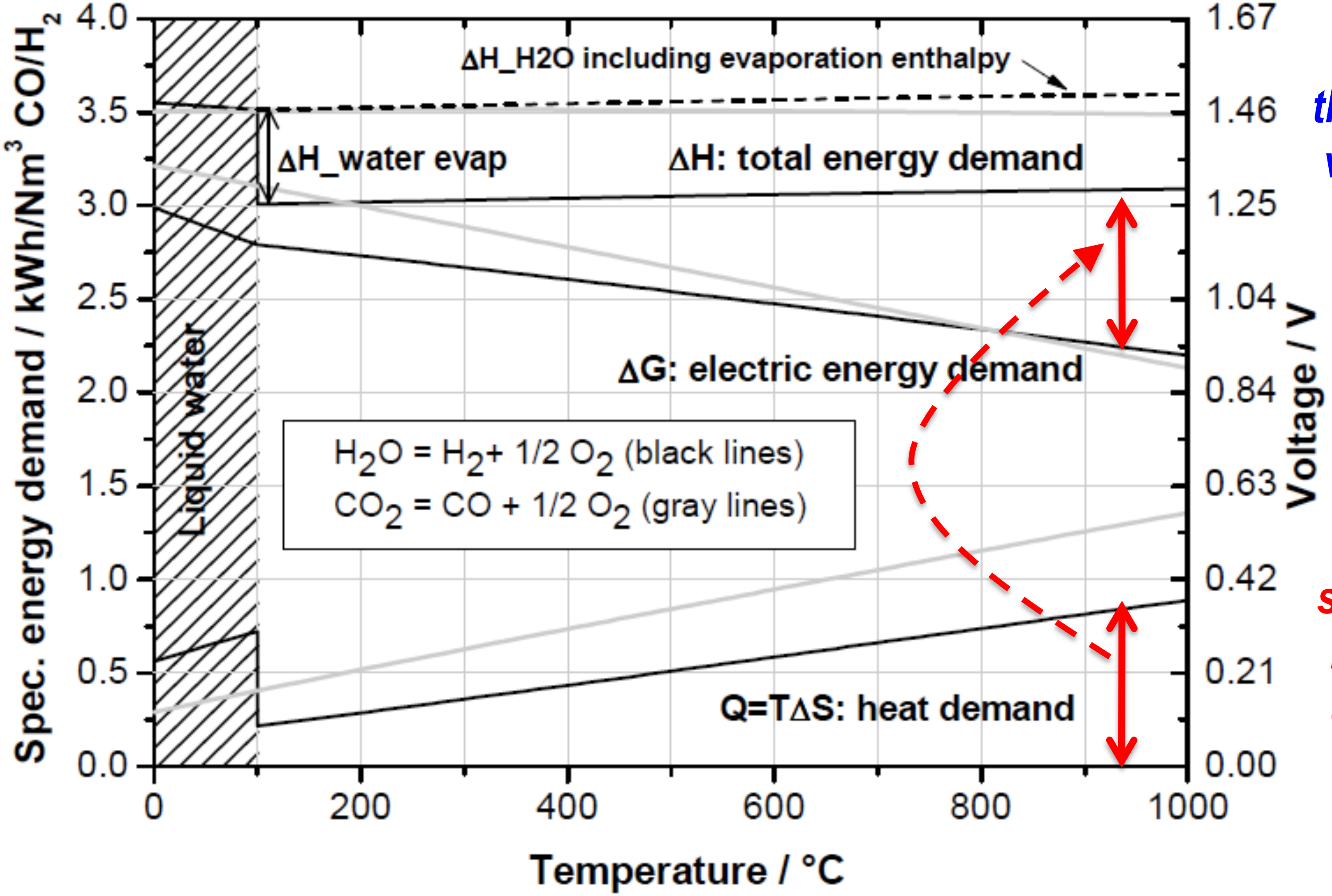
| | | | |
|---|---|---|---|
| **C** | $2H^+ + 2e^- \rightarrow H_2$ | $2H_2O + 2e^- \rightarrow 2OH^- + H_2$ | $H_2O + 2e^- \rightarrow O^{2-} + H_2$ |
| **A** | $2H_2O \rightarrow ½O_2 + 2e^- + 2H^+$ | $2OH^- \rightarrow ½O_2 + 2e^- + H_2O$ | $O^{2-} \rightarrow ½O_2 + 2e^-$ |

Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

*slide from Prof A. Züttel, EPFL*

# Thermodynamics of electrolysis

*at 700° C, electrical input is reduced by 1/3 compared to liquid water electrolysis*



*thermoneutral voltage 1.3 V*

*self-sustained heating from Joule losses*

Q. Fu, ROLE OF ELECTROLYSIS IN REGENERATIVE SYNGAS AND SYNFUEL PRODUCTION,in Syngas: Production, Applications and Environmental Impact, Editor: A. Indarto and J. Palgunadi , 2011 Nova Science Publishers, Inc.

# Thermodynamics of splitting steam vs water

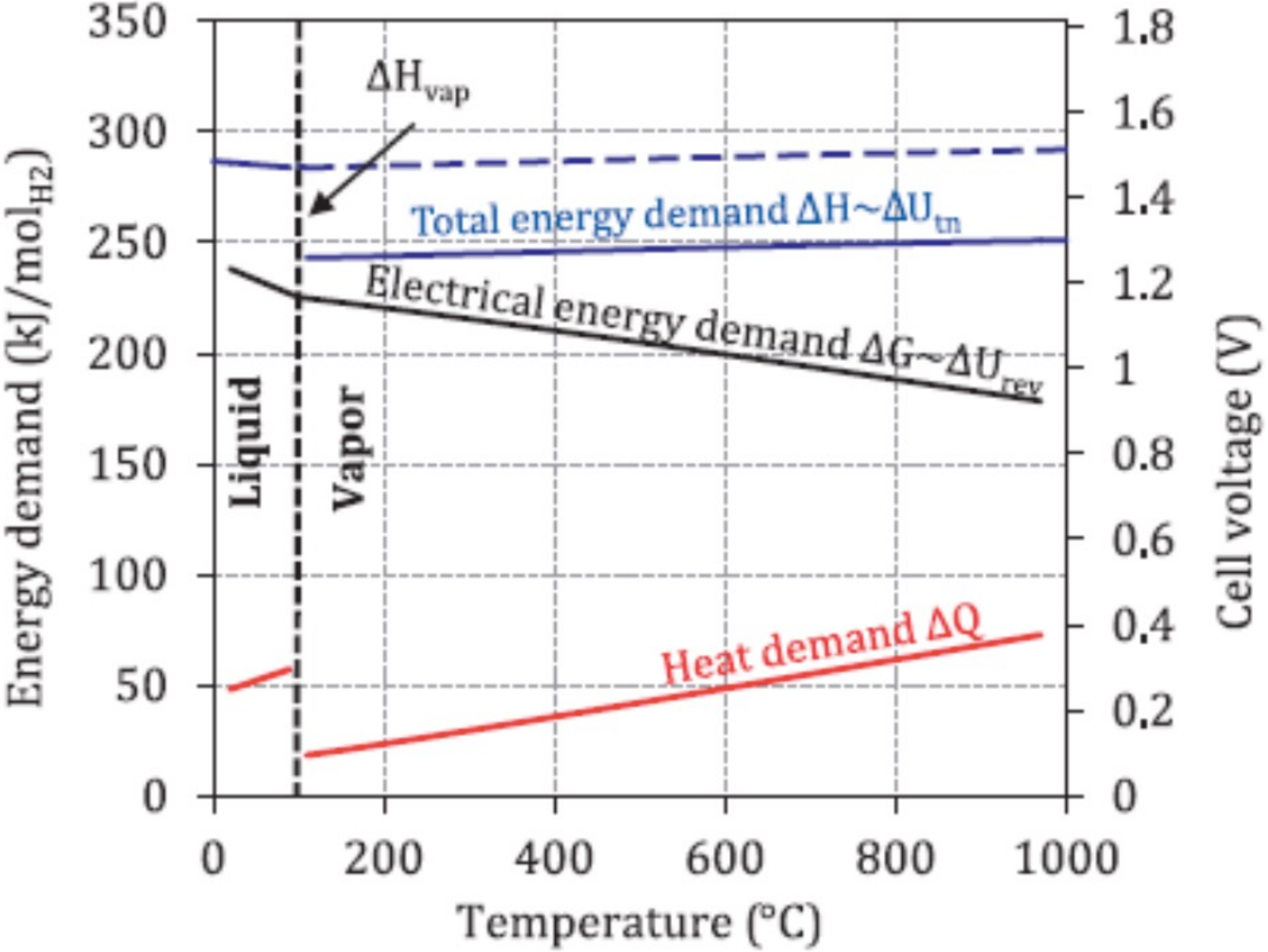
| | Reaction | ΔH (kJ/mol) | MJ / $Nm^3$ | kWh / $Nm^3$ |
|---|---|---|---|---|
| **Water** | $H_2O(l) \Rightarrow H_2 + \frac{1}{2}O_2$ | 286<br>$\downarrow -\Delta H_{evap}$ | 12.77 | 3.55 |
| **Steam** | $H_2O(g) \Rightarrow H_2 + \frac{1}{2}O_2$ | 242 | 10.80 | 3.00 |
| | $CO_2 \Rightarrow CO + \frac{1}{2}O_2$ | 283 | 12.63 | 3.51 |

→

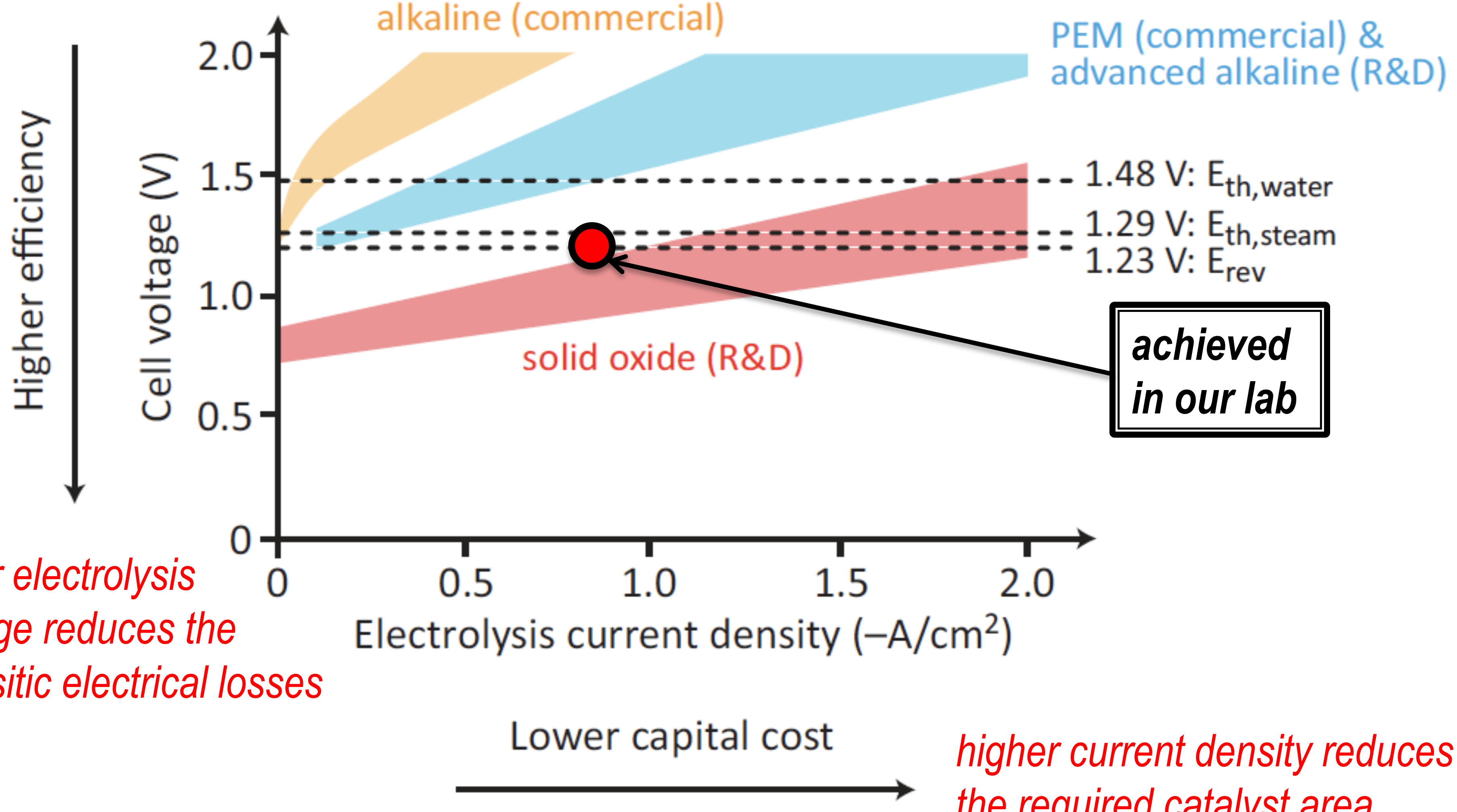
*Electrolysis : energy necessary for dissociation*

←

*Combustion: energy liberated as heat*


Energy demand (kJ/mol$_{H2}$)
350
300
250
200
150
100
50
0
Cell voltage (V)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Temperature (°C)
0
200
400
600
800
1000
$\Delta H_{vap}$
Total energy demand $\Delta H \sim \Delta U_{tn}$
Electrical energy demand $\Delta G \sim \Delta U_{rev}$
Heat demand $\Delta Q$
Liquid
Vapor

# Electrolysis technology comparison



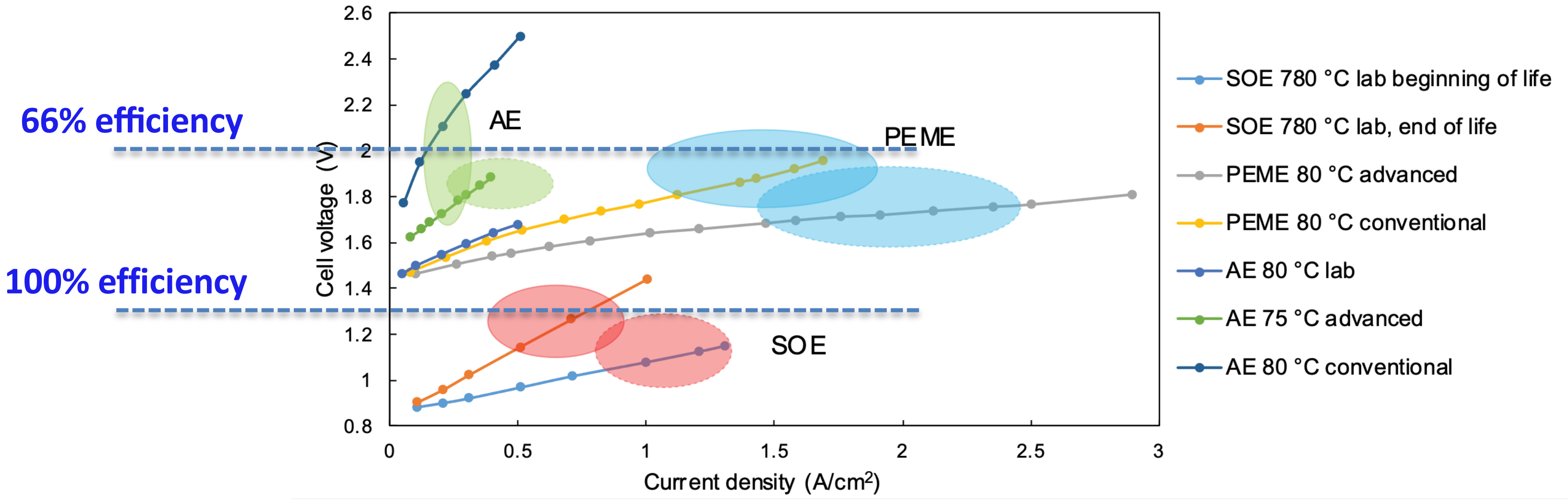
***achieved in our lab***

*lower electrolysis voltage reduces the parasitic electrical losses*

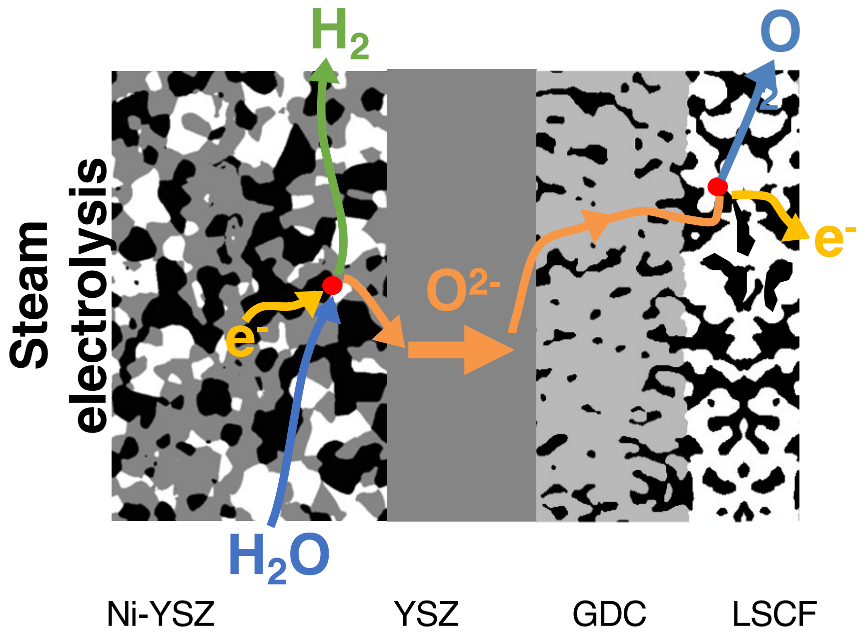
*higher current density reduces the required catalyst area*

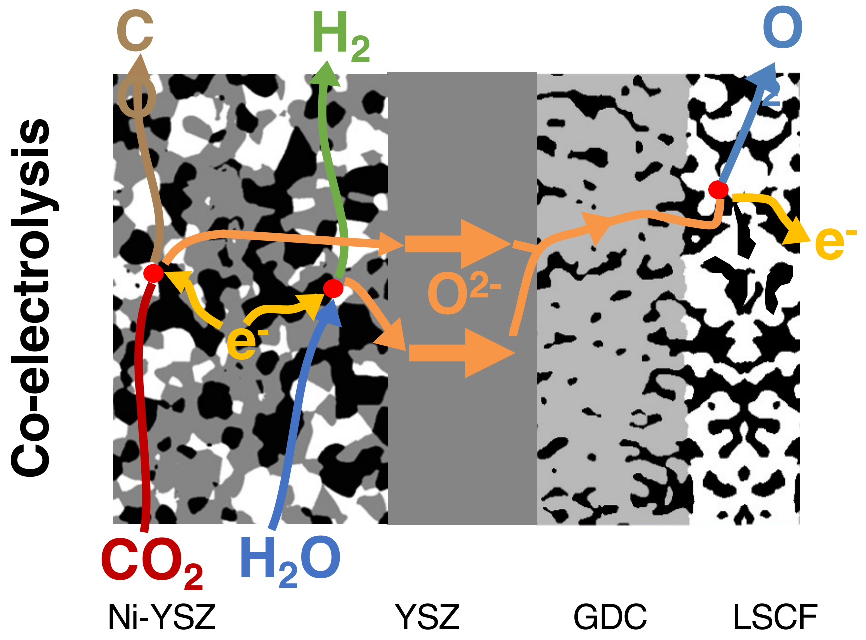
Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy
Christopher Graves, Sune D. Ebbesen, Mogens Mogensen, Klaus S. Lackner
Renewable and Sustainable Energy Reviews 15 (2011) 1–23

# Electrolysis of water (alcaline AE, PEME) and steam (solid oxide - SOE)



- ☐ Solid-oxide electrolysis (650 – 900 °C)





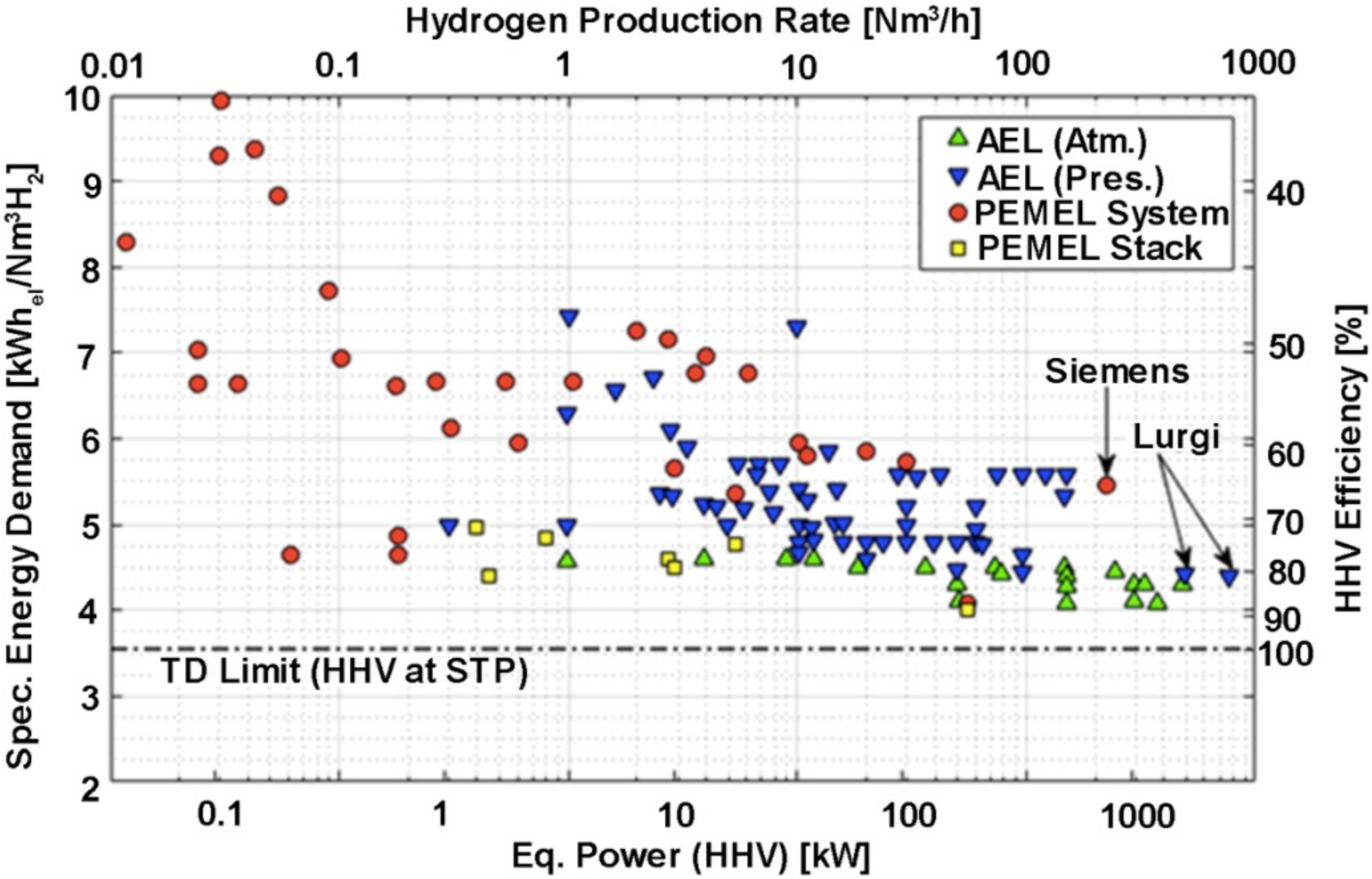
# Electrolysis key figures

| | Alcaline | PEM | Solid oxide |
|---|---|---|---|
| medium | liq. $H_2O$ | liq. $H_2O$ | steam (+ $CO_2$) |
| temperature | 80°C | 80°C | 800°C |
| current, $A/cm^2$ | 0.25 – 0.5 | 0.5 – 1.5 | 0.8* |
| voltage, V | 1.7 - 2.0 | 1.5 – 2.0 | 1.25* |
| stack efficiency | ≤ 85% | ≤ 85% | ≈ 100% |
| system efficiency * | ≤ 75% | ≤ 75% | ≤ 90% |
| $kWh_{el}$ / $m^3$ $H_2$ | ≈ 5 | ≈ 5 | ≈ 3.5 |
| lifetime | 10-20 yrs | 1-2 yr | 1 yr |

** losses: insulation, compression, inverter*

***figures achieved in our lab***

# Efficiencies (AEL, PEMEL)



Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

*slide from Prof A. Züttel, EPFL*

# Electrolyzer Companies

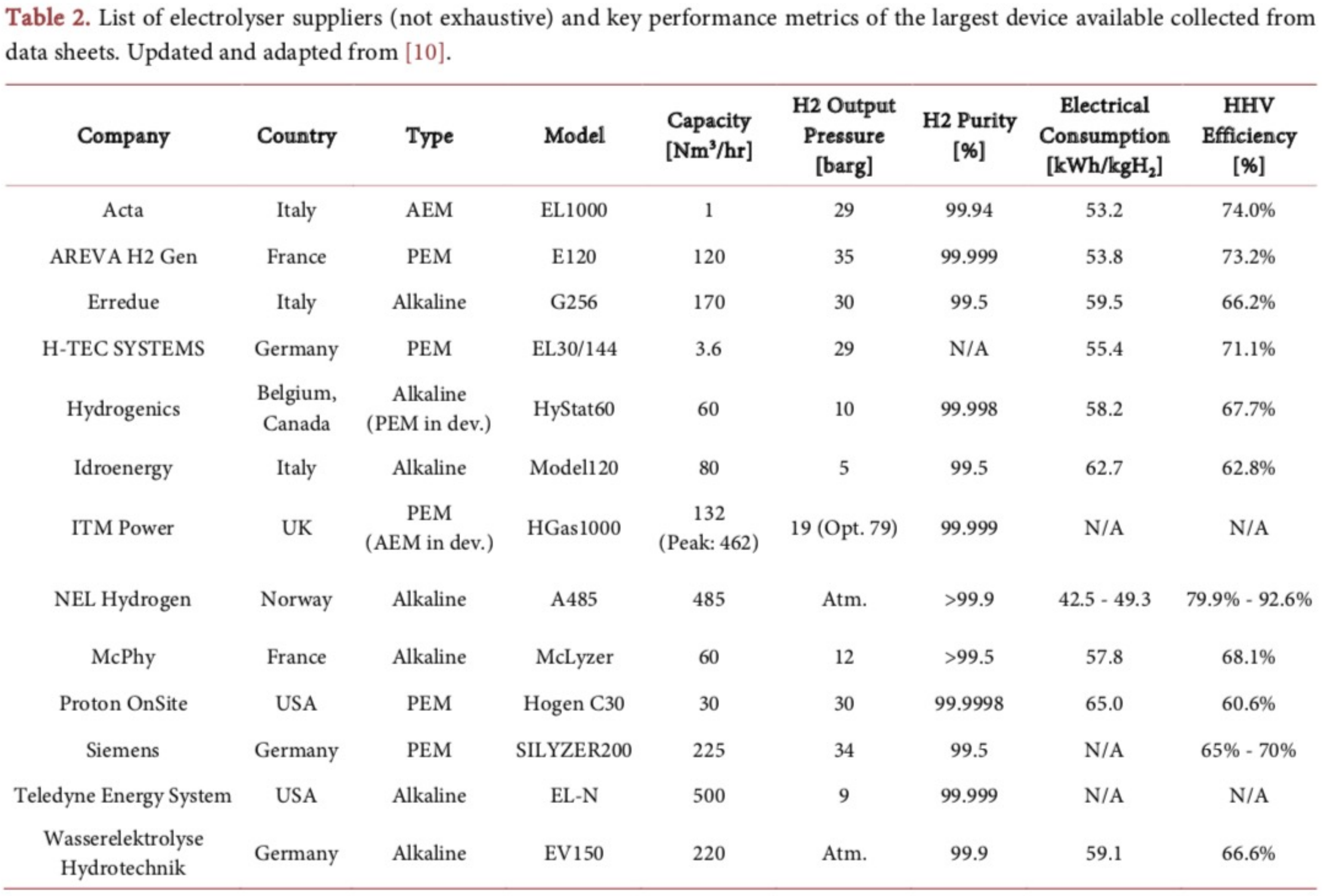


**Table 2.** List of electrolyser suppliers (not exhaustive) and key performance metrics of the largest device available collected from data sheets. Updated and adapted from [10].

| Company | Country | Type | Model | Capacity [Nm³/hr] | H2 Output Pressure [barg] | H2 Purity [%] | Electrical Consumption [kWh/kgH$_2$] | HHV Efficiency [%] |
|---|---|---|---|---|---|---|---|---|
| Acta | Italy | AEM | EL1000 | 1 | 29 | 99.94 | 53.2 | 74.0% |
| AREVA H2 Gen | France | PEM | E120 | 120 | 35 | 99.999 | 53.8 | 73.2% |
| Erredue | Italy | Alkaline | G256 | 170 | 30 | 99.5 | 59.5 | 66.2% |
| H-TEC SYSTEMS | Germany | PEM | EL30/144 | 3.6 | 29 | N/A | 55.4 | 71.1% |
| Hydrogenics | Belgium, Canada | Alkaline (PEM in dev.) | HyStat60 | 60 | 10 | 99.998 | 58.2 | 67.7% |
| Idroenergy | Italy | Alkaline | Model120 | 80 | 5 | 99.5 | 62.7 | 62.8% |
| ITM Power | UK | PEM (AEM in dev.) | HGas1000 | 132 (Peak: 462) | 19 (Opt. 79) | 99.999 | N/A | N/A |
| NEL Hydrogen | Norway | Alkaline | A485 | 485 | Atm. | >99.9 | 42.5 - 49.3 | 79.9% - 92.6% |
| McPhy | France | Alkaline | McLyzer | 60 | 12 | >99.5 | 57.8 | 68.1% |
| Proton OnSite | USA | PEM | Hogen C30 | 30 | 30 | 99.9998 | 65.0 | 60.6% |
| Siemens | Germany | PEM | SILYZER200 | 225 | 34 | 99.5 | N/A | 65% - 70% |
| Teledyne Energy System | USA | Alkaline | EL-N | 500 | 9 | 99.999 | N/A | N/A |
| Wasserelektrolyse Hydrotechnik | Germany | Alkaline | EV150 | 220 | Atm. | 99.9 | 59.1 | 66.6% |

Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

*slide from Prof A. Züttel, EPFL*

# Electrolyser Cost

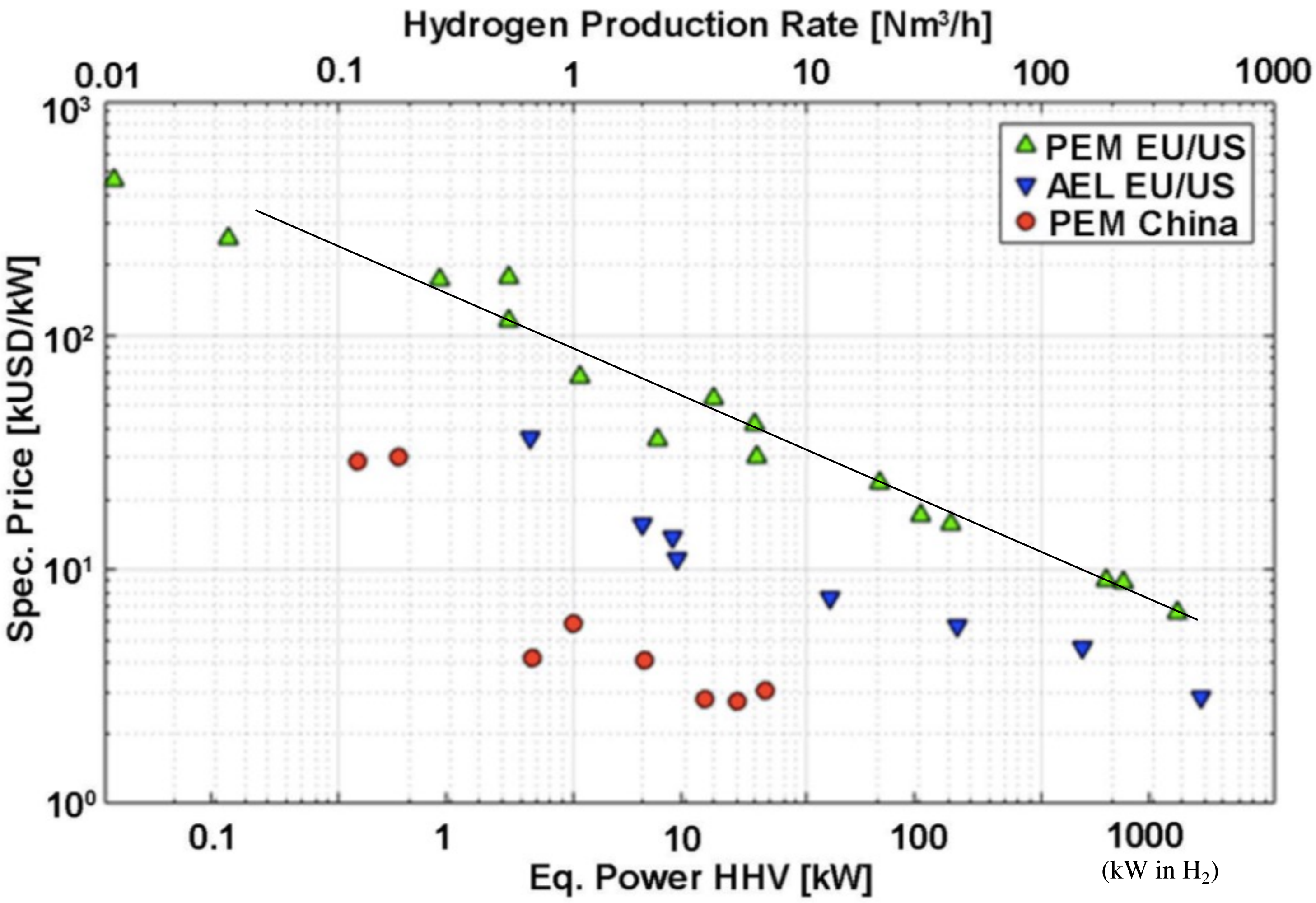
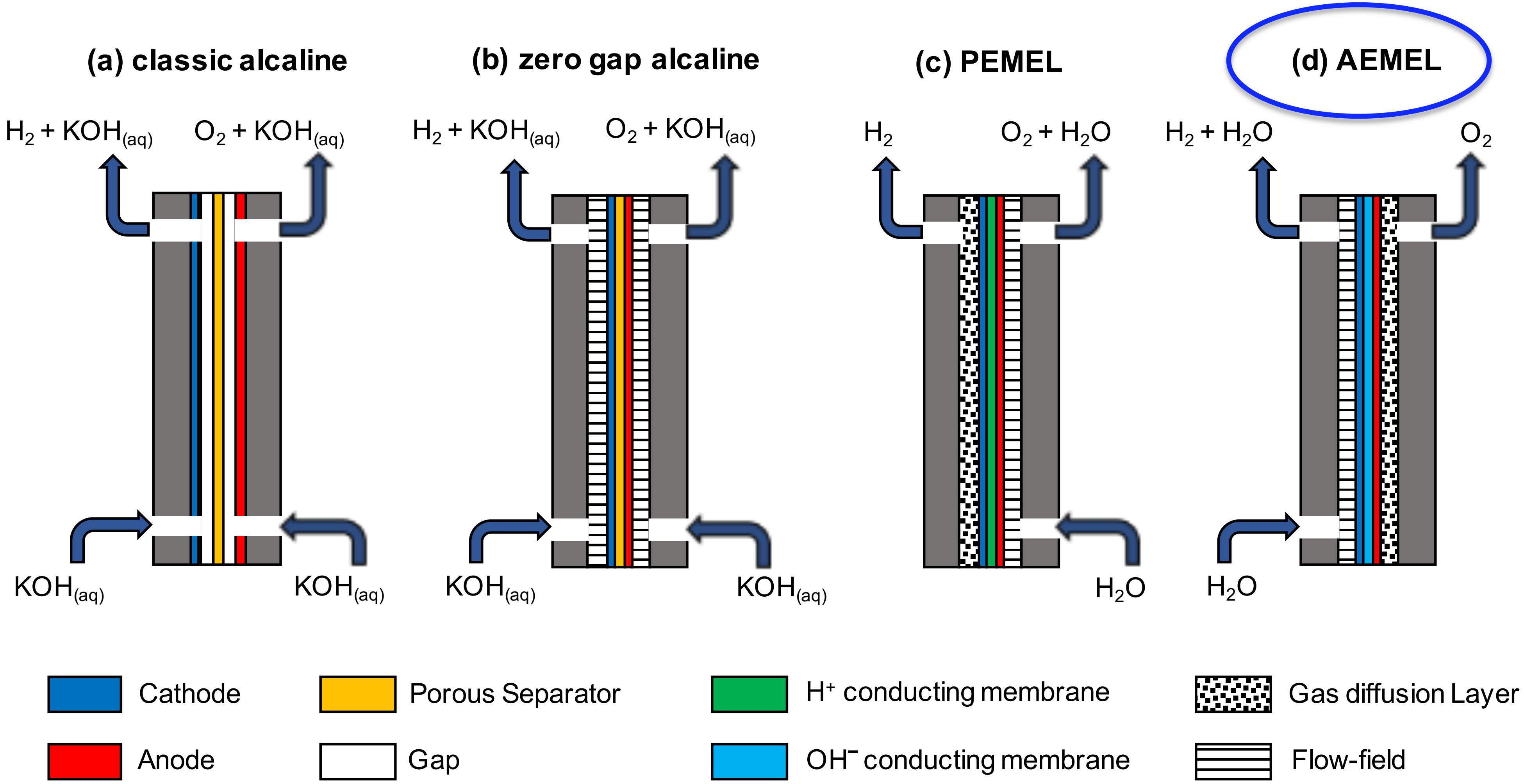


**Figure 4.** Specific price of electrolysers per production capacity.

Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

*slide from Prof A. Züttel, EPFL*

# 4. Recent : AEM
# (anionic exchange membrane electrolysis)



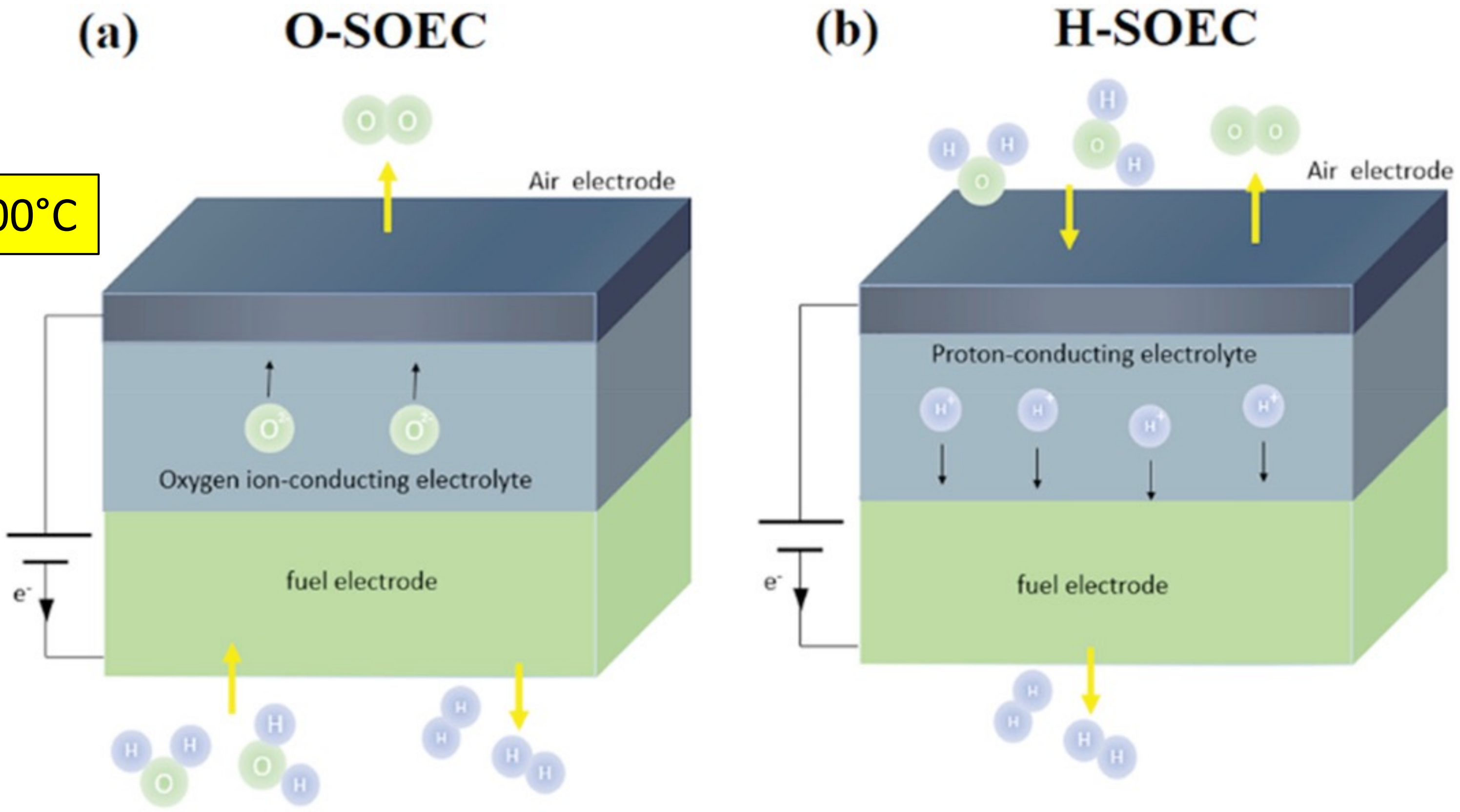
*(graph : Dr Heron Vrubel)*

AEMEL : combination of PEMEL and classical alcaline

Advantages: no noble metal catalyst, no expensive Ti bipolar plates

# 5. Recent: proton conducting ceramic electrolyser (PCCEL)

700°C

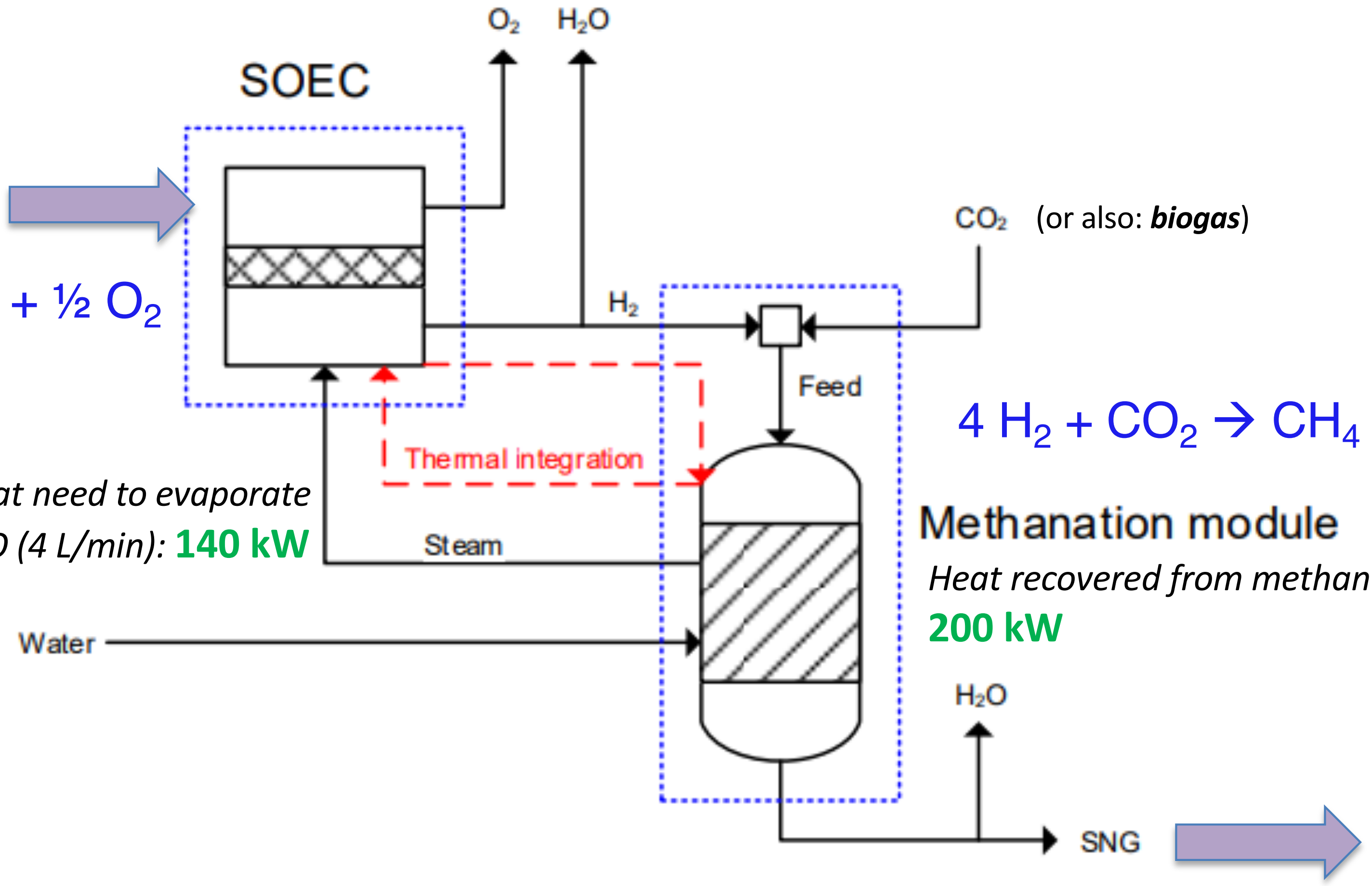


500°C

**Progress Report on Proton Conducting Solid Oxide Electrolysis Cells**
Libin Lei, Jihao Zhang, Zhihao Yuan, Jianping Liu, Meng Ni, Fanglin Chen
Advanced Functional Materials Vol 29 Iss 37, 18 July 2019
https://doi.org/10.1002/adfm.201903805

Direct formation of dry $H_2$ product

# SOE (Solid Oxide Electrolysis) based Power-to-$CH_4$



**100%**

**1 $MW_{el}$**

$H_2O \rightarrow H_2 + \frac{1}{2} O_2$

(or also: ***biogas***)

$4 H_2 + CO_2 \rightarrow CH_4 + 2 H_2O$

*Heat need to evaporate $H_2O$ (4 L/min):* **140 kW**

Methanation module

*Heat recovered from methanation:* **200 kW**

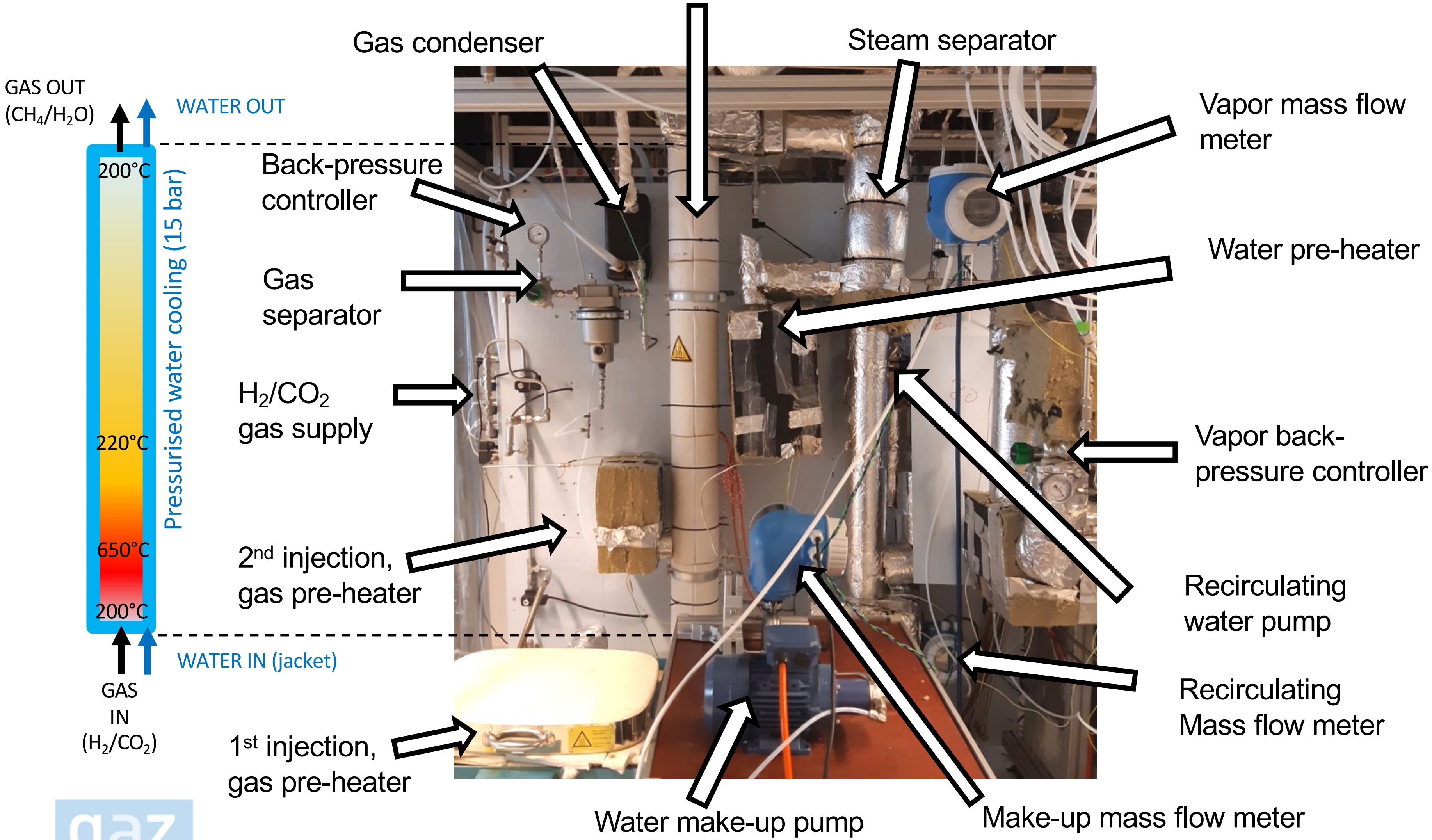
**$CH_4$ 80 $m^3$/h**

**80%**

❑ Direct steam generation with the exothermal methanator

# Methanation

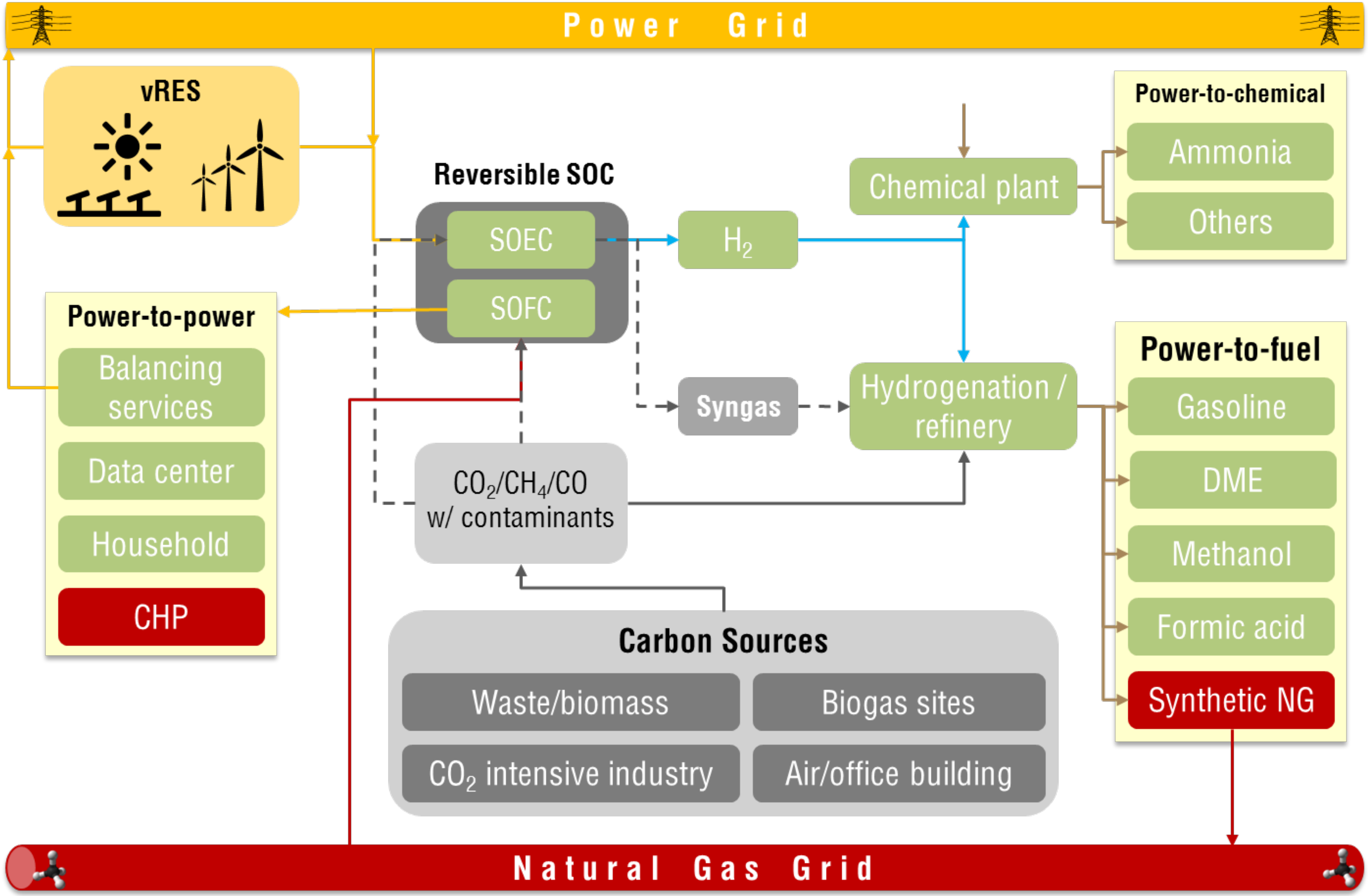
$H_2+CO_2 \Rightarrow CH_4$



- ☐ Direct steam generation with the exothermal methanator

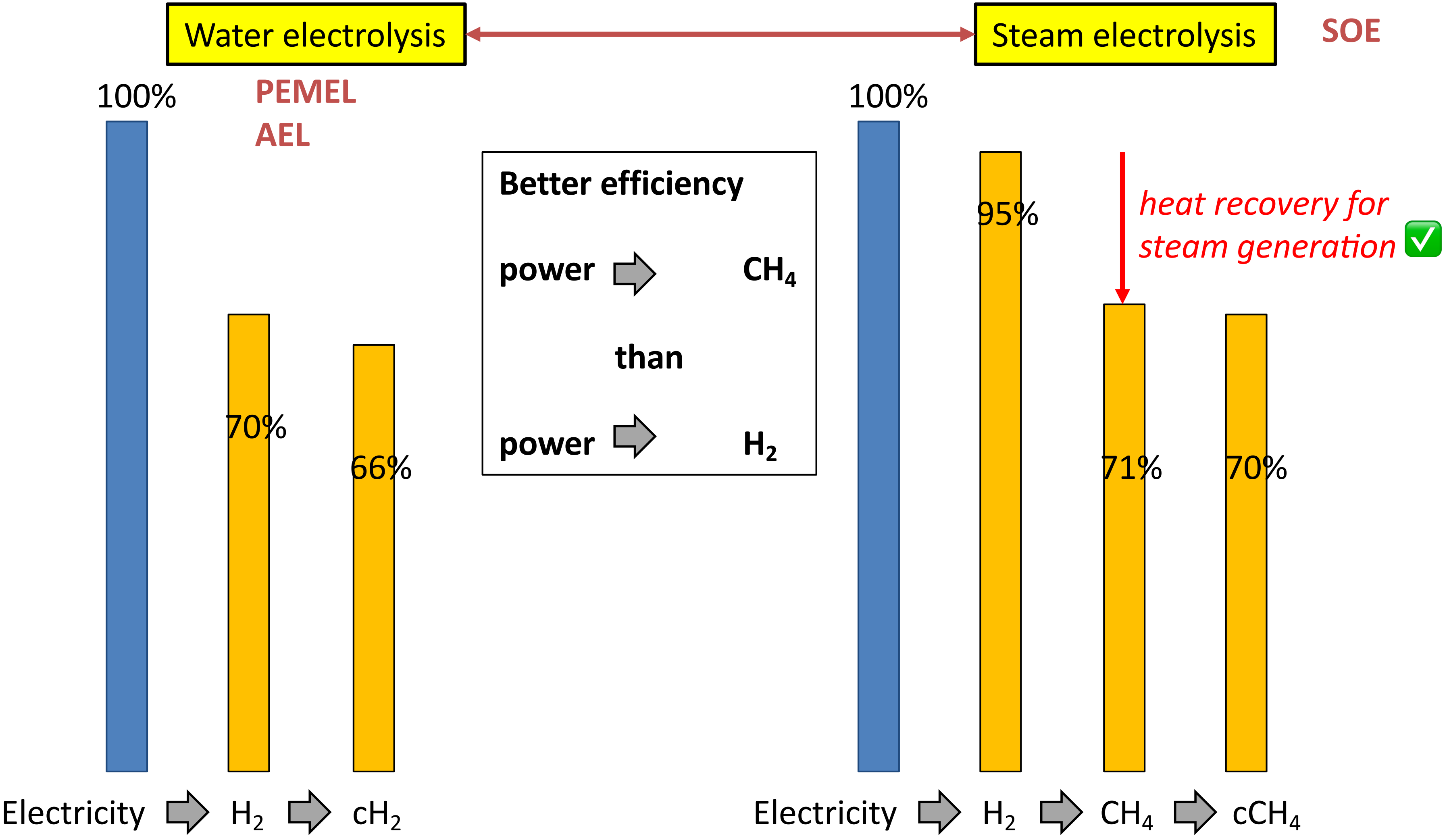
# Vision

*(figure: Dr Ligang Wang)*



# P2G : $H_2$ or $CH_4$ or ..?

| $H_2$ | $CH_4$ |
|---|---|
| • 1-step synthesis<br>• mobility without $CO_2$ | • 2-step synthesis<br>• Need $CO_2$ source<br>• Heat management |
| • Limited injection in gas grid<br>• Compression & transport loss<br>• Difficult to store | • No limit for gas grid injection<br>• Low compression/transport loss |



**Better efficiency**

**power** ➡ **$CH_4$**

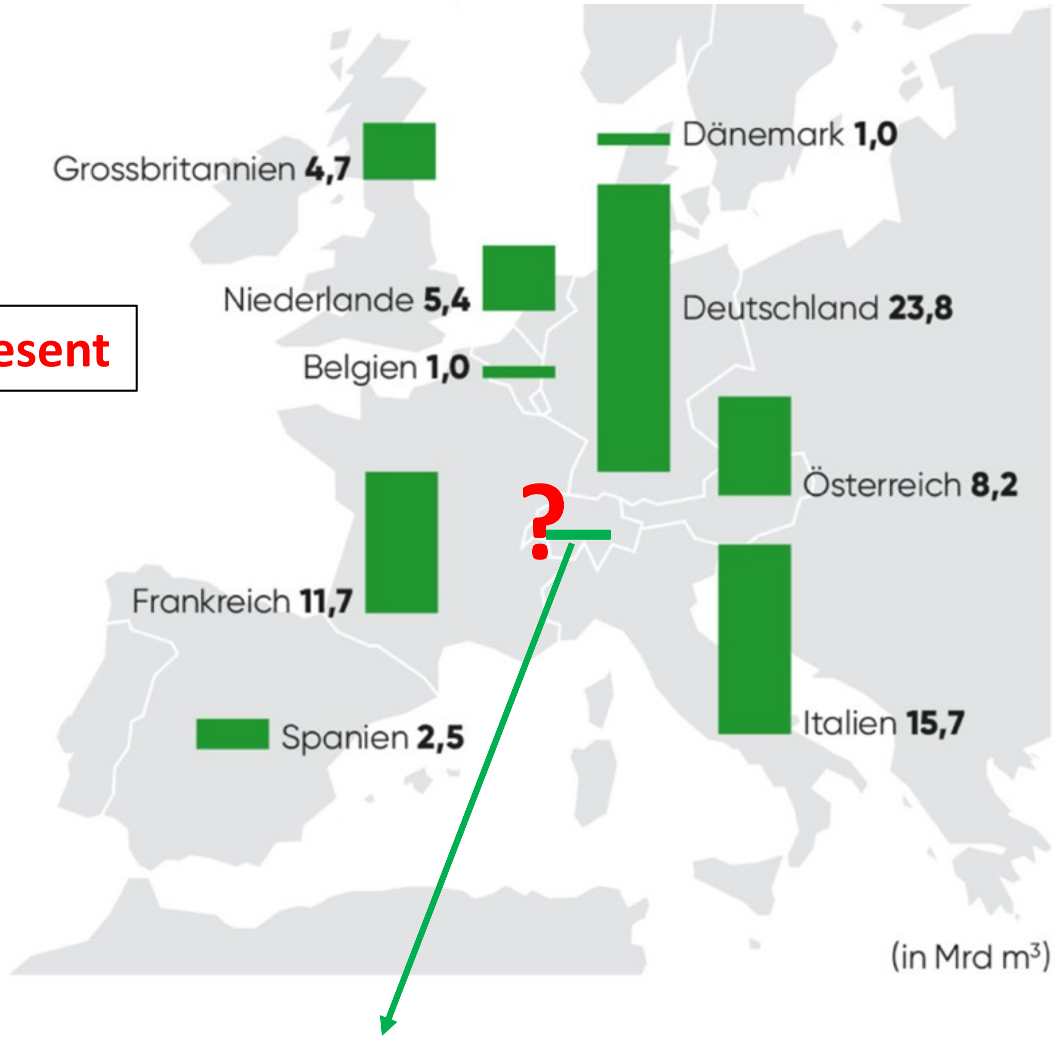
**than**

**power** ➡ **$H_2$**

# Seasonal gas storage in Switzerland?

*https://gazenergie.ch/de/wissen/detail/knowledge-topic/7-erdgas-speicher/*

no NG storage at present



10 TWh of NG require 14 TWhe of electricity, expected to be coverable from future 30-60 TWhe of PV and 40 TWhe of hydro

with 1 bio $m^3$ gas (10 TWh), the Swiss winter electricity gap would be covered (i.e. a deficit of ~1 TWhe / month).

# Electrolyser sizes (1-100 MW)

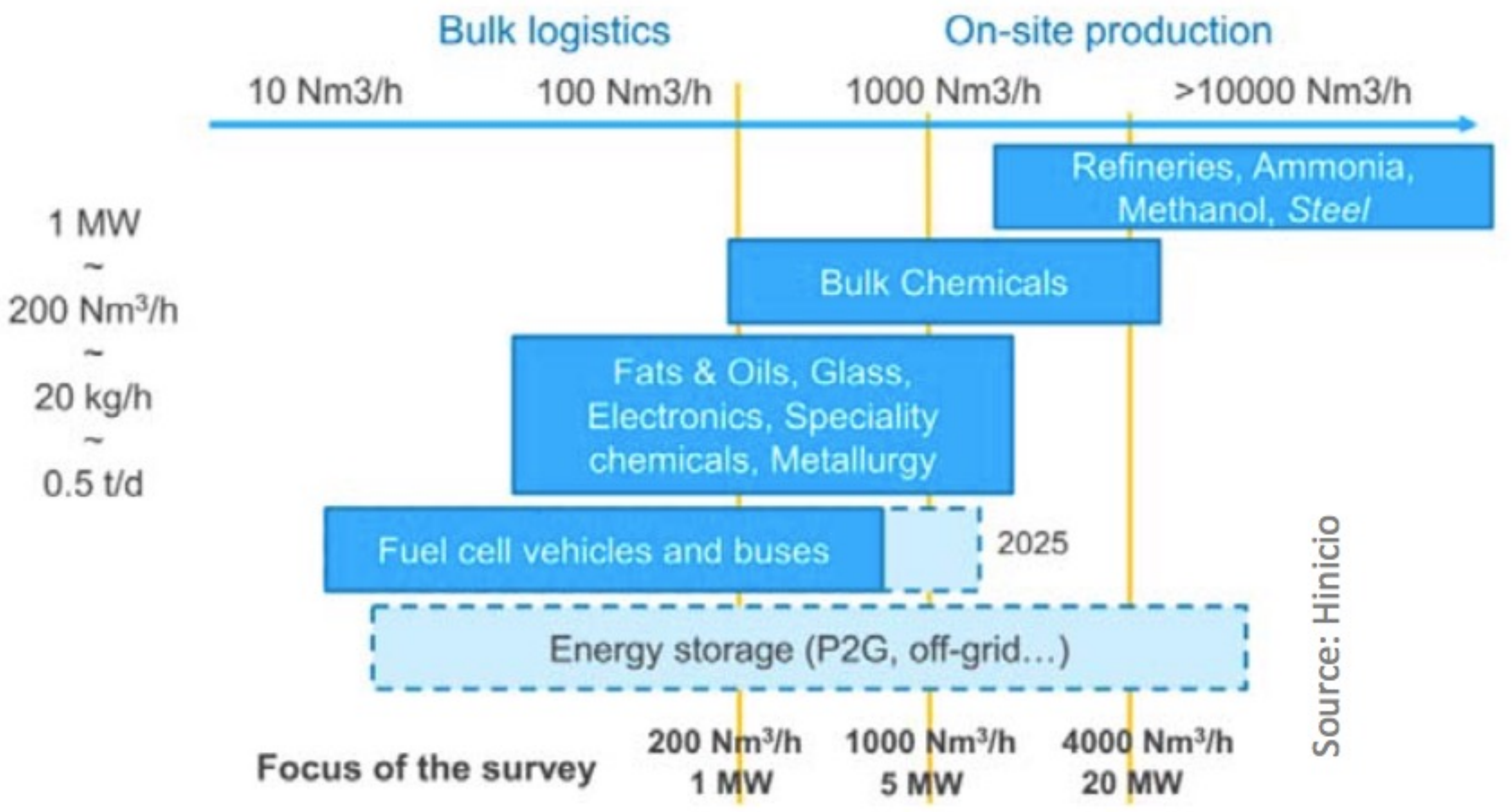


Figure 108: Selection of electrolyser size

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

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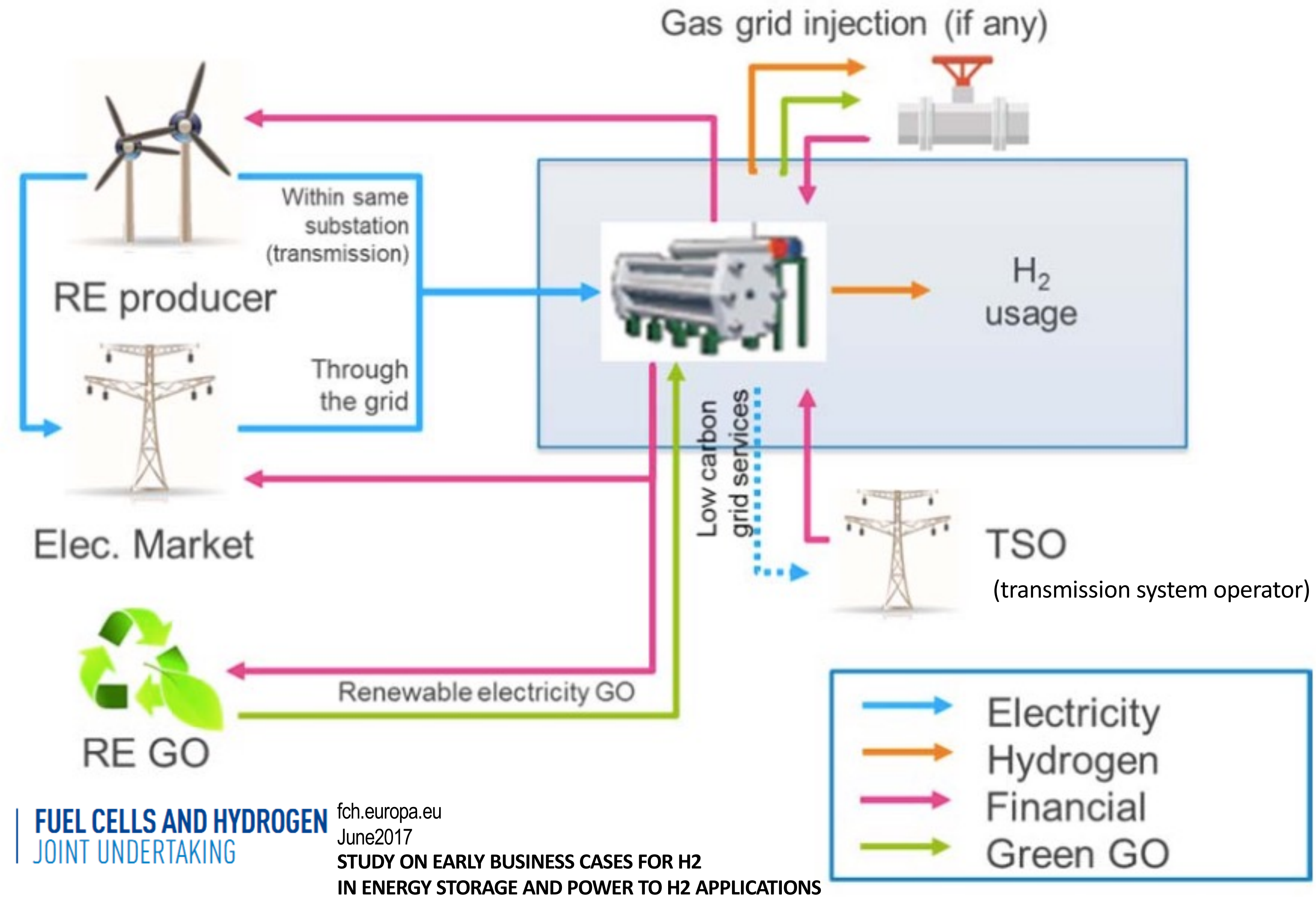
June2017
**STUDY ON EARLY BUSINESS CASES FOR H2**
**IN ENERGY STORAGE AND POWER TO H2 APPLICATIONS**
p. 163

# Electrolyser business models



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p.120 Fig. 78

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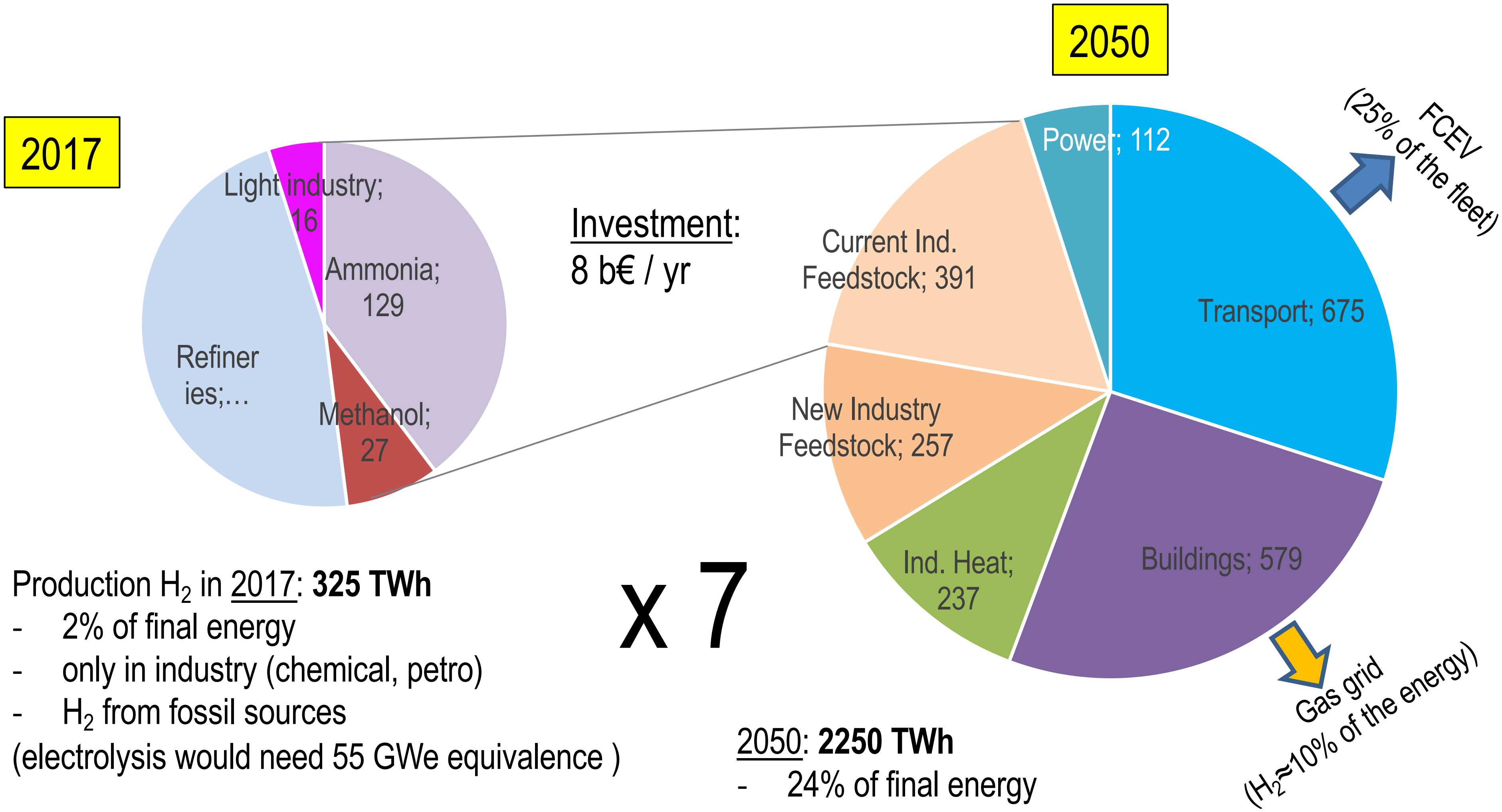
**STUDY ON EARLY BUSINESS CASES FOR H2**
**IN ENERGY STORAGE AND POWER TO H2 APPLICATIONS**
p.120 Fig. 78

# Explanations:

- Electricity is purchased from the electricity market at the **wholesale** electricity price. In case of instantaneous local **curtailment**, electricity is directly purchased from the curtailed renewable power plant, leading to a **lower price** than the wholesale electricity price.
- **Grid fees** are charged by the electricity grid operator for connection to the network at a defined price.
- **Taxes and levies** on the use of electricity are set. The situation greatly differs from one country to another.
- **Grid services (participation to frequency reserve)** are provided to the TSO and lead to remuneration.
- In the case of **gas grid injection**, $H_2$ is sold to the gas grid operator as green gas through a **feed-in tariff**.
- Hydrogen is certified as green by purchasing guarantees of **green origin** for the electricity that is purchased from the electricity grid (“grey mix”), via the European GO market.

# Future of $H_2$ in Europe

# $H_2$ roadmap (EU) - TWh



Investment:
8 b€ / yr

x 7

Production $H_2$ in 2017: **325 TWh**
- 2% of final energy
- only in industry (chemical, petro)
- $H_2$ from fossil sources

(electrolysis would need 55 GWe equivalence )

2050: **2250 TWh**
- 24% of final energy
- multiple uses

(equivalent electrolysis : **385 GWe)**

*Adapted from : H2 ROADMAP EUROPE:*
*A SUSTAINABLE PATHWAY FOR THE EUROPEAN ENERGY TRANSITION*

*fch.europa.eu - January 2019*

# Example: oil refinery

Rheinland refinery (Shell) (D)

Consumption: **180’000 t $H_2$** / yr (from fossils)

10 MWe PEM-electrolyser:
=> supplies **1300 t $H_2$** / yr (<1% !!)

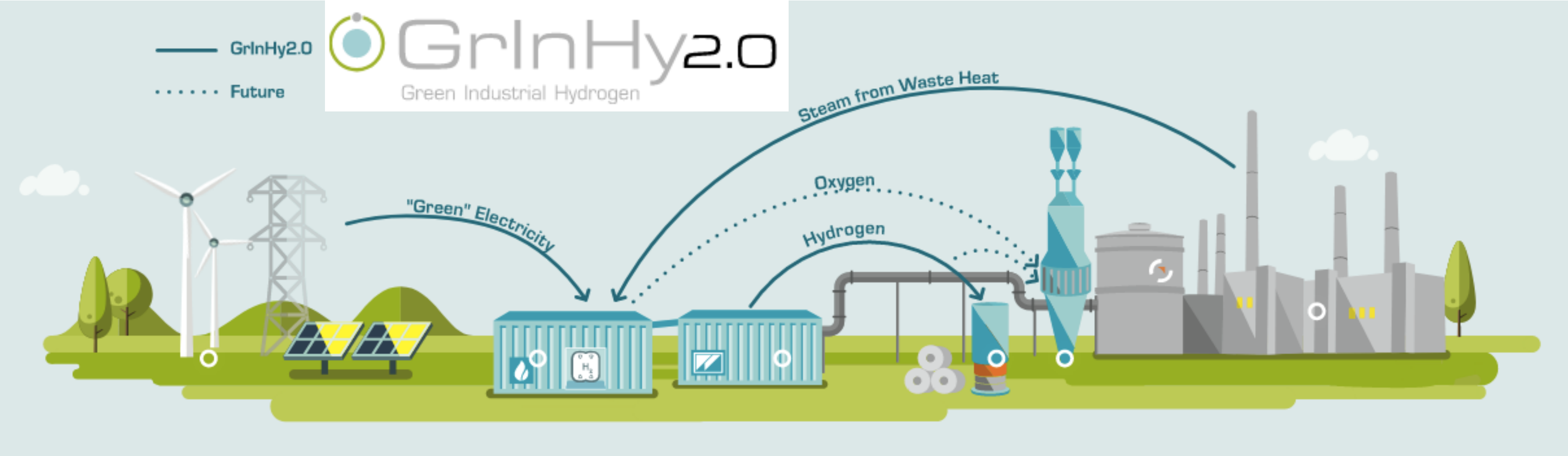
REFHYNE
CLEAN REFINERY HYDROGEN FOR EUROPE
2018-2022

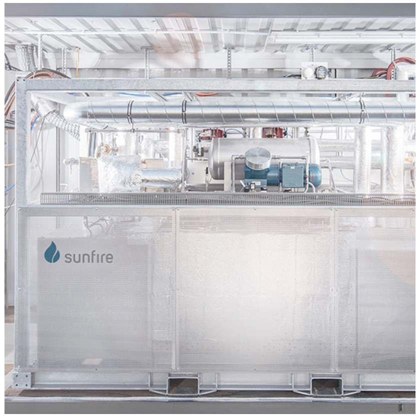
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING 10 M€

https://refhyne.eu/

# Example: steel industry

https://www.green-industrial-hydrogen.com/





2016 - 2022

FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

4.5 M€

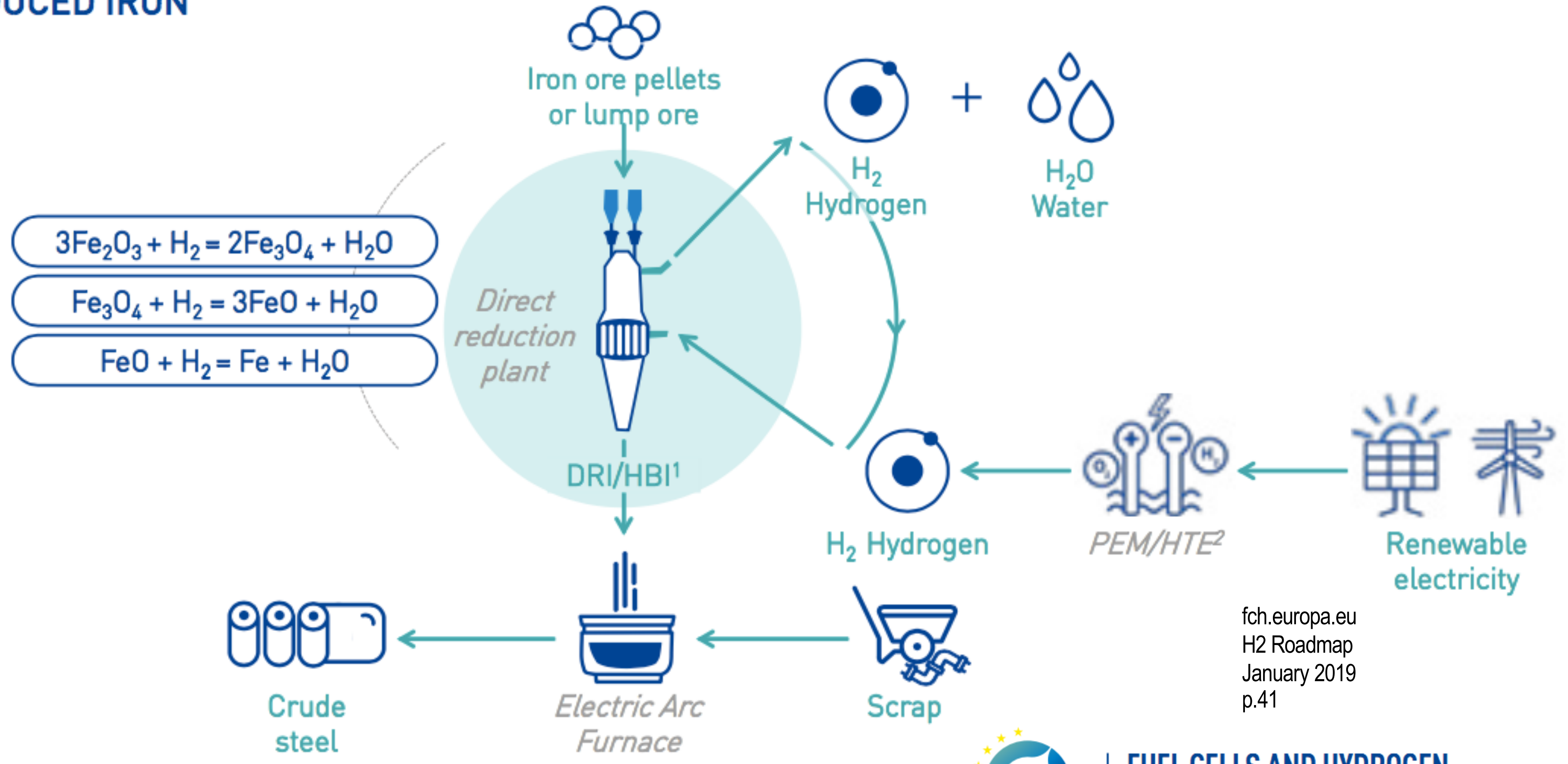
720 kWe solid oxide steam electrolyser

200 Nm$^3$/h $H_2$ (84% efficiency LHV)

100 t $H_2$ @ < 7€/kg

# $H_2$ for steel making : DRI

## EXHIBIT 18: DEEPLY DECARBONIZED STEELMAKING THROUGH HYDROGEN-BASED DIRECT REDUCED IRON



fch.europa.eu
H2 Roadmap
January 2019
p.41

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

[1] Direct reduced iron/hot briquetted iron

[2] Polymer electrolyte membrane electrolysis/high temperature electrolysis

# Fuel Cell Electric Vehicle: battery car with $H_2$ range extension

- Purely electric vehicles are limited in range (km), recharge time (h) and (battery) materials (Li)
- Adding a $H_2$ tank and PEFC to an electric car with a smaller battery extends the driving range (x 2 or x 3)
- a $H_2$-refill takes 2 minutes
- $H_2$ filling stations can be coupled to PV plants and windmills, or (small) hydro-plants, via electrolysers
- The hybrid operation keeps the battery in a high charging state, extending its lifetime

# More remarks on E-mobility

$H_2$ is specially suited for larger vehicles (utility, truck, bus,…). Batteries don't reach the range.

FCEV = same autonomy as an ICE and same refill speed (15x faster than 'fast battery charge' stations).

Infrastructure in HRS occupies 1/10th of the space of fast battery charge stations, at ½ of CAPEX. Costs of ≈2 M€ per HRS can be financed with a fossil fuel tax of 0.01€/L.

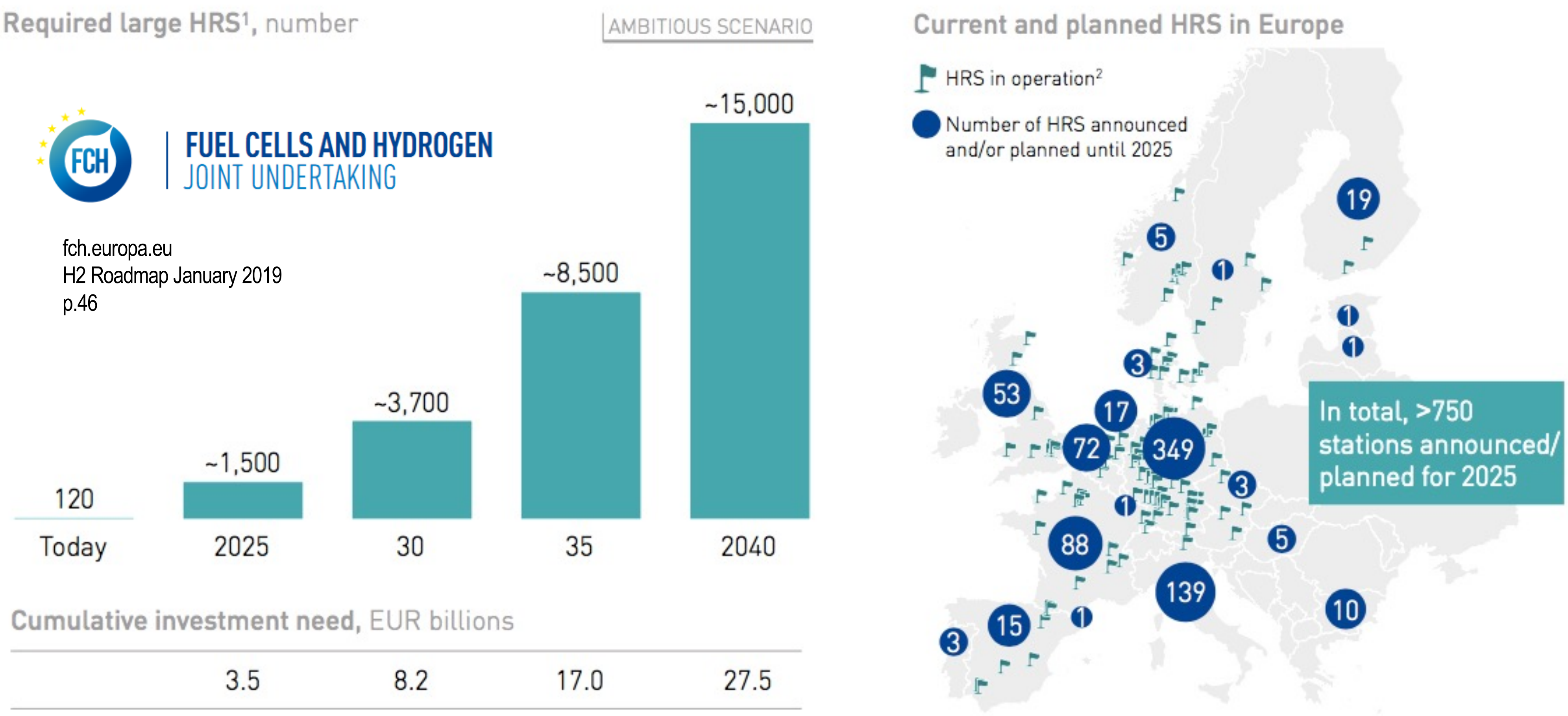
HRS discharge the electrical grid when needed (electrolysis with excess renewables); fast battery charge stations always increase the demand on the grid.

fabrication of FC requires less energy and materials than batteries and engines.

Europe is behind in batteries. When only going for BEV, the value chain creation will risk to take place outside Europe.

# Future $H_2$ refueling stations (HRS)

## EXHIBIT 21: FUTURE HRS REQUIREMENT



In total, >750 stations announced/ planned for 2025

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

fch.europa.eu
H2 Roadmap January 2019
p.46

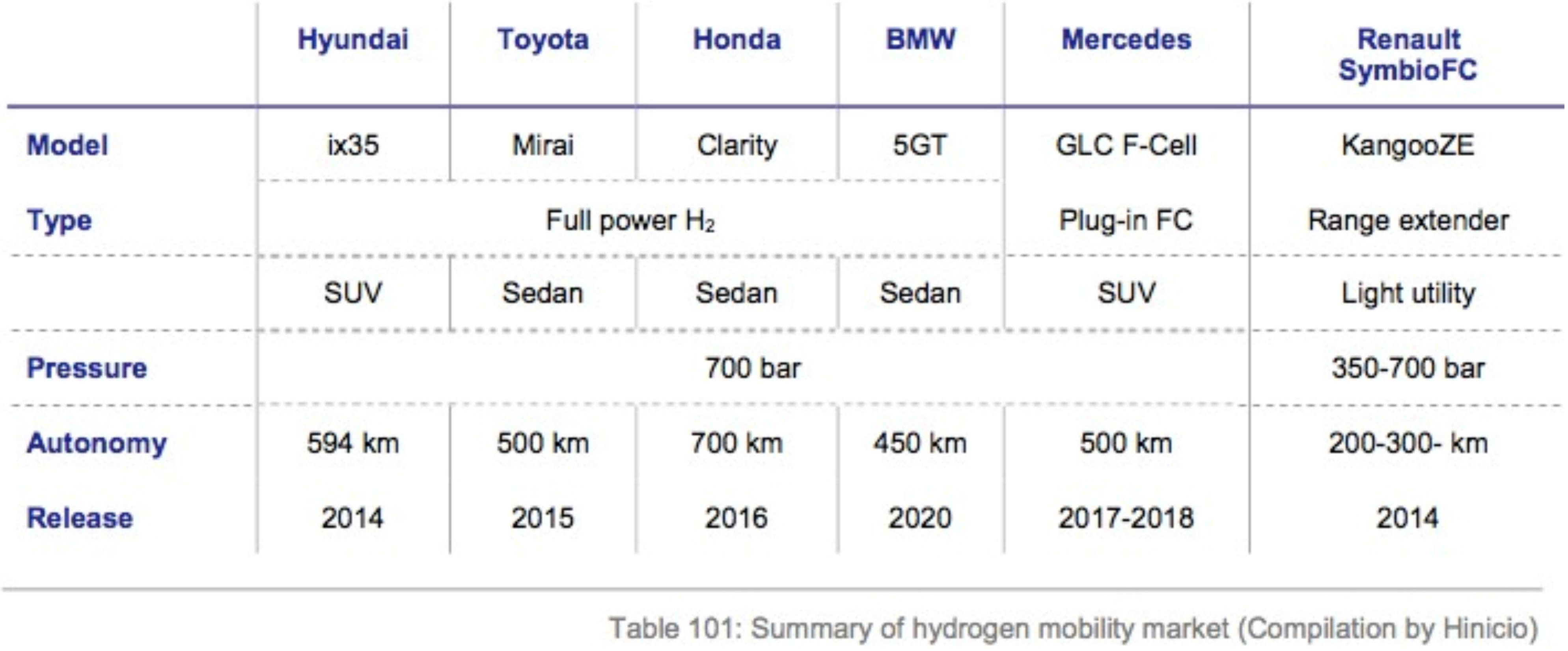
**Cumulative investment need,** EUR billions

| 2025 | 30 | 35 | 2040 |
|---|---|---|---|
| 3.5 | 8.2 | 17.0 | 27.5 |

[1] Equivalents of medium HRS (1,000kg daily capacity); utilization relative to steady-state

[2] Indicative position

# Status of $H_2$ fuel cell vehicles



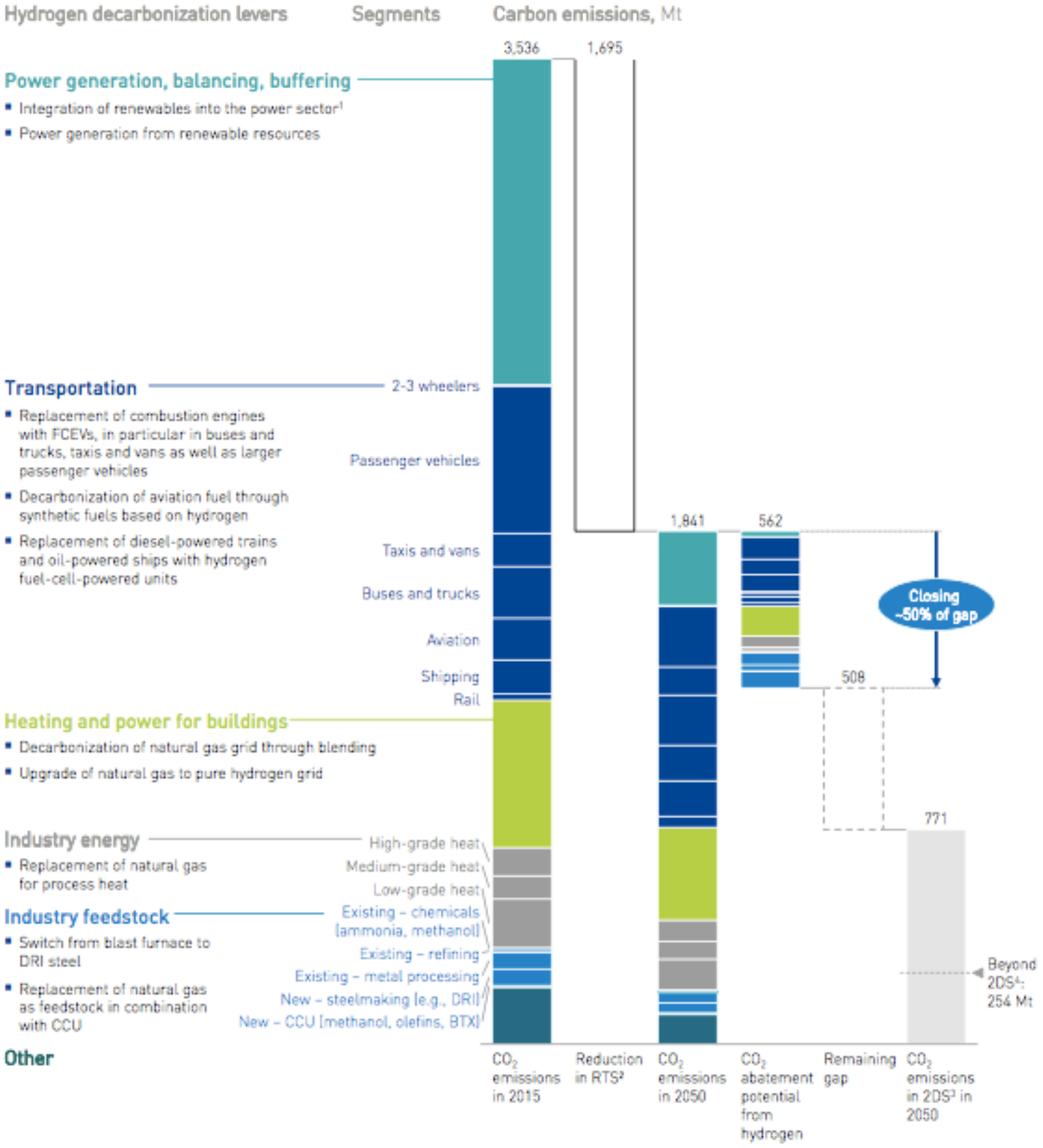
| | Hyundai | Toyota | Honda | BMW | Mercedes | Renault SymbioFC |
|---|---|---|---|---|---|---|
| **Model** | ix35 | Mirai | Clarity | 5GT | GLC F-Cell | KangooZE |
| **Type** | Full power $H_2$ | | | | Plug-in FC | Range extender |
| | SUV | Sedan | Sedan | Sedan | SUV | Light utility |
| **Pressure** | 700 bar | | | | | 350-700 bar |
| **Autonomy** | 594 km | 500 km | 700 km | 450 km | 500 km | 200-300- km |
| **Release** | 2014 | 2015 | 2016 | 2020 | 2017-2018 | 2014 |

Table 101: Summary of hydrogen mobility market (Compilation by Hinicio)

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

fch.europa.eu
**STUDY ON EARLY BUSINESS CASES FOR H2**
**IN ENERGY STORAGE AND POWER TO H2 APPLICATIONS**
June2017
p.190

# $H_2$ ROADMAP EUROPE:
# A SUSTAINABLE PATHWAY FOR THE EUROPEAN ENERGY TRANSITION

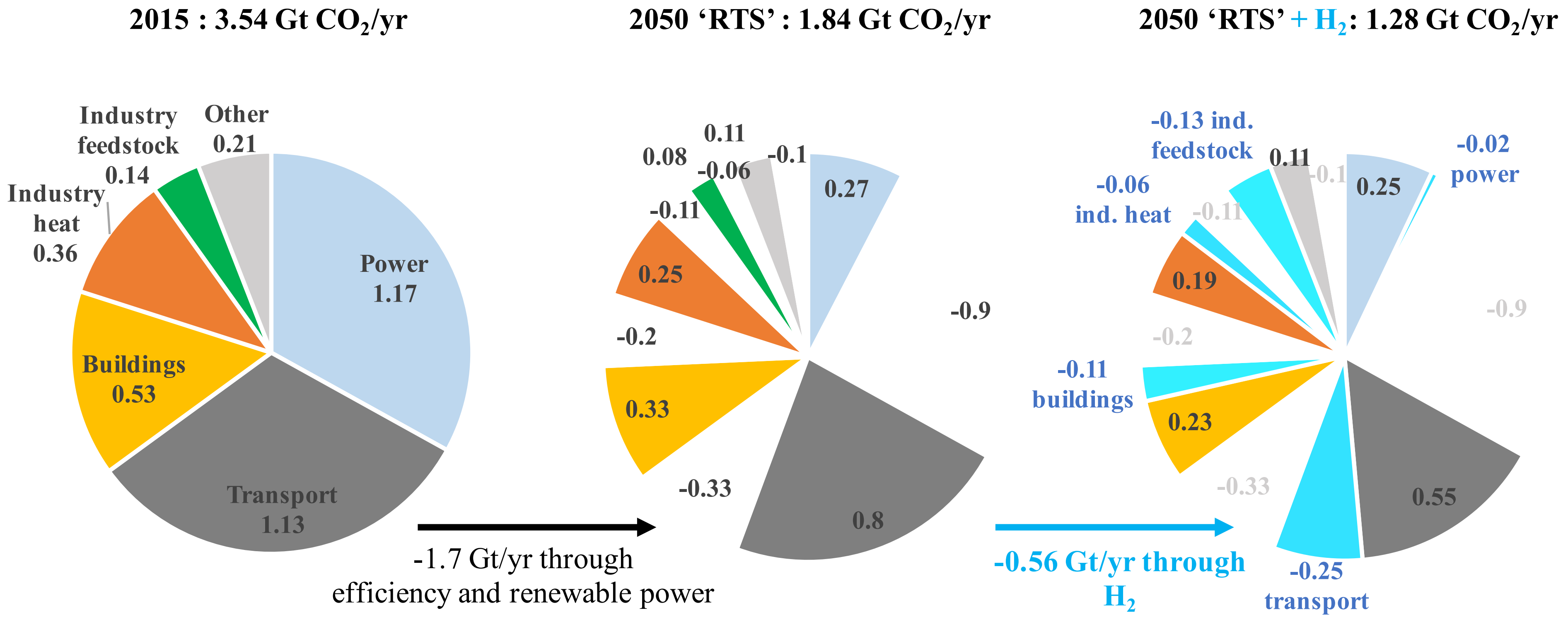


# Associated $CO_2$ emissions reduction

fch.europa.eu
January 2019

**FUEL CELLS AND HYDROGEN**
JOINT UNDERTAKING

# $H_2$ will decarbonize energy supply and heavy industry



$H_2$ = up to 24% of energy in 2050 in Europe.
7-fold increase from now.
This demands huge electrolysis capacities (100s of GWe), mainly from wind and PV.

# 385 GWe in electrolysis: is this feasible? (3400 TWhe)

https://schweiz.fandom.com/wiki/Liste_der_gr%C3%B6ssten_Seen_in_der_Schweiz

- existing (EU): ≈2 GWe
- 66.7% efficiency = **1.88V** electrolysis voltage
  (100% = 1.25 V)
- suppose: **1A/cm$^2$** current density
  => 1.88 W/cm$^2$ absorbed electroc power density
- for 385 GWe we then need $385.10^9$ W / 1.88 Wcm$^{-2}$ = $205.10^9$ cm$^2$ = 20.5 km$^2$ membrane surface ; 0.6 km$^3$ water consumption
- *Swiss Lake of Murten : 22.8 km$^2$; 0.6 km$^3$ volume*
- membrane of 50 $\mu$m thick, density ≈ 1 => $20.\ 10^6$ m$^2$ x $50.\ 10^{-6}$ m = 1000 m$^3$ = 1000 tons
- compare this to the annual plastics production (polymers) = 330 Mtonnes / yr

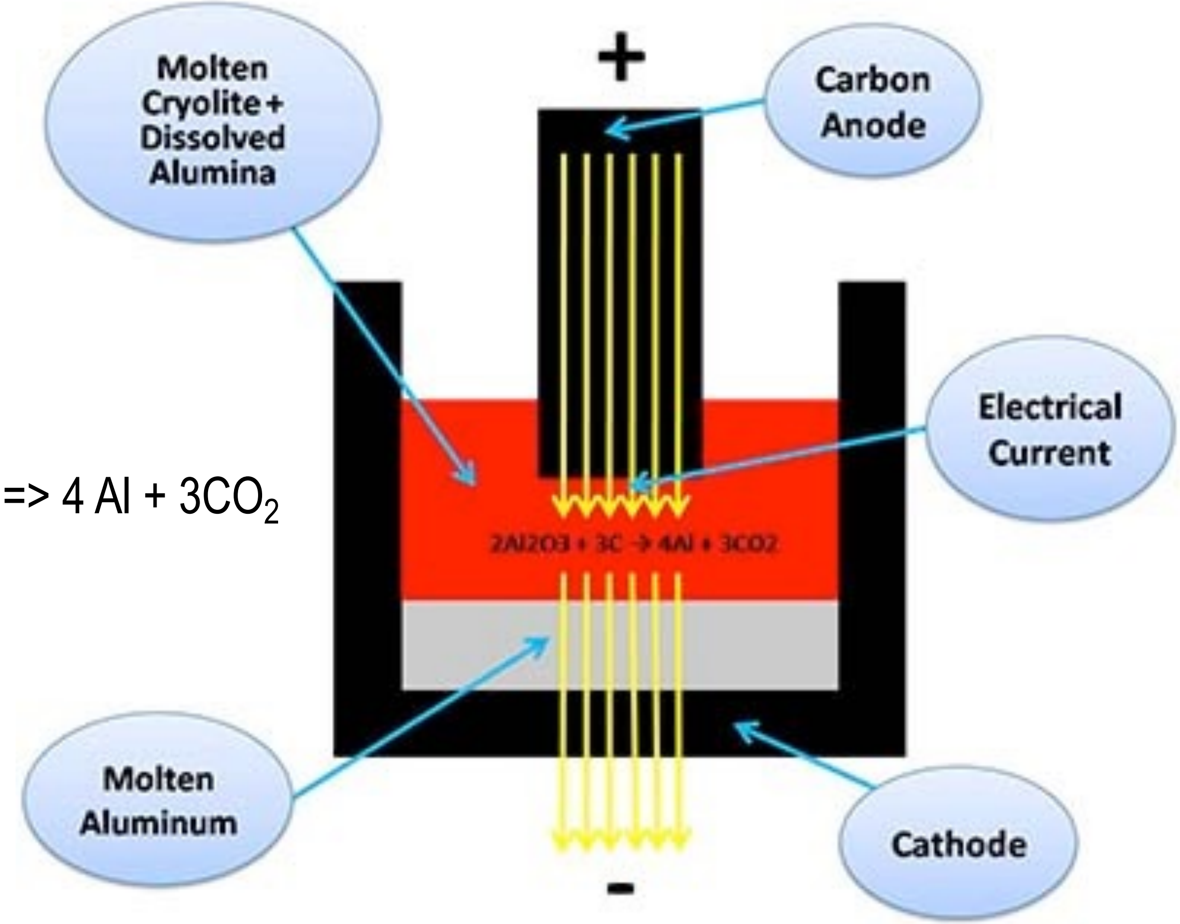
# Example from the aluminium-industry

- Production 2018: 64 Mton
- Cons.: 15 kWhe / kg Al

=> 960 TWhe (≈ **110 GWe**)

(≈4% of world electricity)

Hall-Héroult Process (1886)



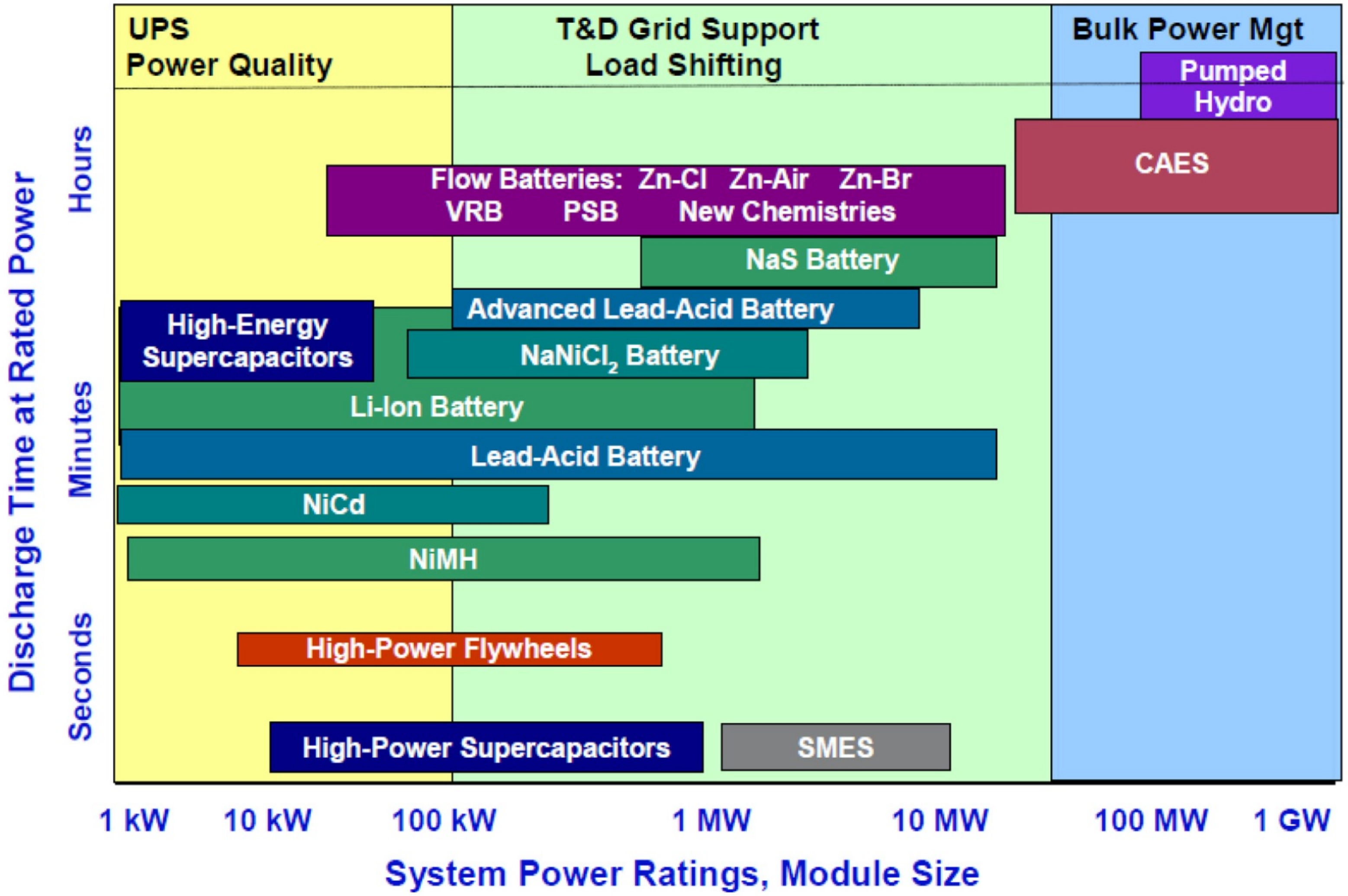
$2\,Al_2O_3 + 3C \Rightarrow 4\,Al + 3CO_2$

*http://www.aluminum-production.com/process_basics.html*

# Current situation in <u>electricity</u> storage

# Possible technologies for electricity storage

*A.Z. AL Shaqsi, K. Sopian and A. Al-Hinai / Energy Reports 6 (2020) 288–306* 293



# Existing storage capacity

**Energy Storage Technology and Cost Characterization Report, July 2019**
K Mongird, V Viswanathan, P Balducci, J Alam, PNNL-28866
https://www.energy.gov/eere/water/hydrowires-initiative

**2018: 173 GWe, of which**
**98% pumped hydro schemes**

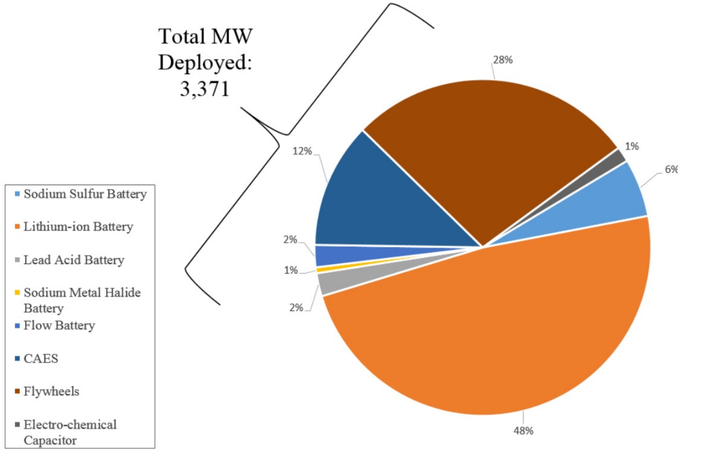
## 2.0 Worldwide Energy Storage Deployments by Technology

As of 2018, nearly 173 GW of energy storage had been deployed across the world. Table 2.1 outlines the current total installed capacity in megawatts by technology type worldwide up to 2018. Information was gathered from the DOE Storage Database (DOE 2018a) and compiled by technology type. Note that some of the records from the database are unverified and therefore the numbers below should be considered approximate.

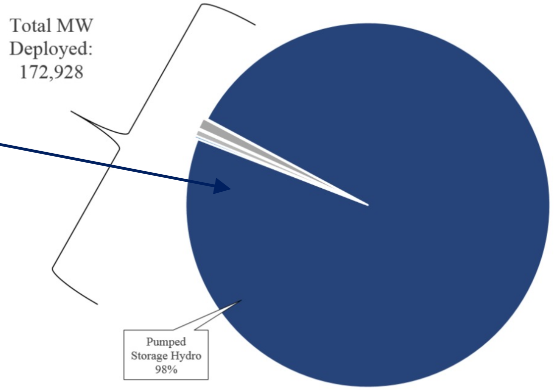
**Table 2.1.** Worldwide deployment by technology type, 2018.

| Technology | MW Deployed |
|---|---|
| Sodium sulfur | 189 |
| Lithium-ion | 1,629 |
| Lead acid | 75 |
| Sodium metal halide | 19 |
| Flow battery | 72 |
| PSH | 169,557 |
| CAES | 407 |
| Flywheels | 931 |
| Electrochemical capacitor | 49 |
| Total | 172,928 |

Li-ion dominate batteries schemes



Breakdown of energy storage deployed internationally by technology type and excluding pumped storage hydro.

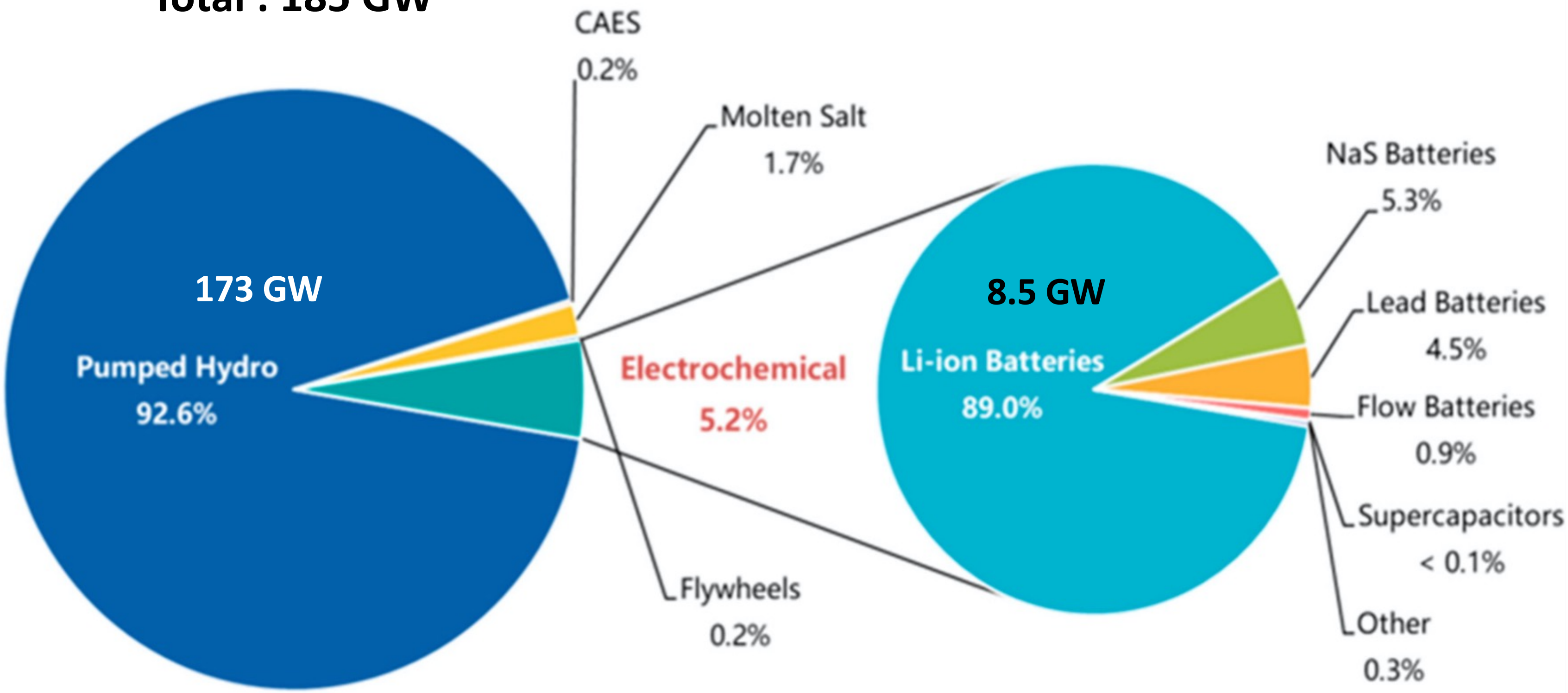


Proportion of megawatts of internationally deployed pumped storage hydro in comparison to other technologies.

# Rapid growth in storage capacity (esp. Li-ion)

*March 2020*

**Total : 185 GW**

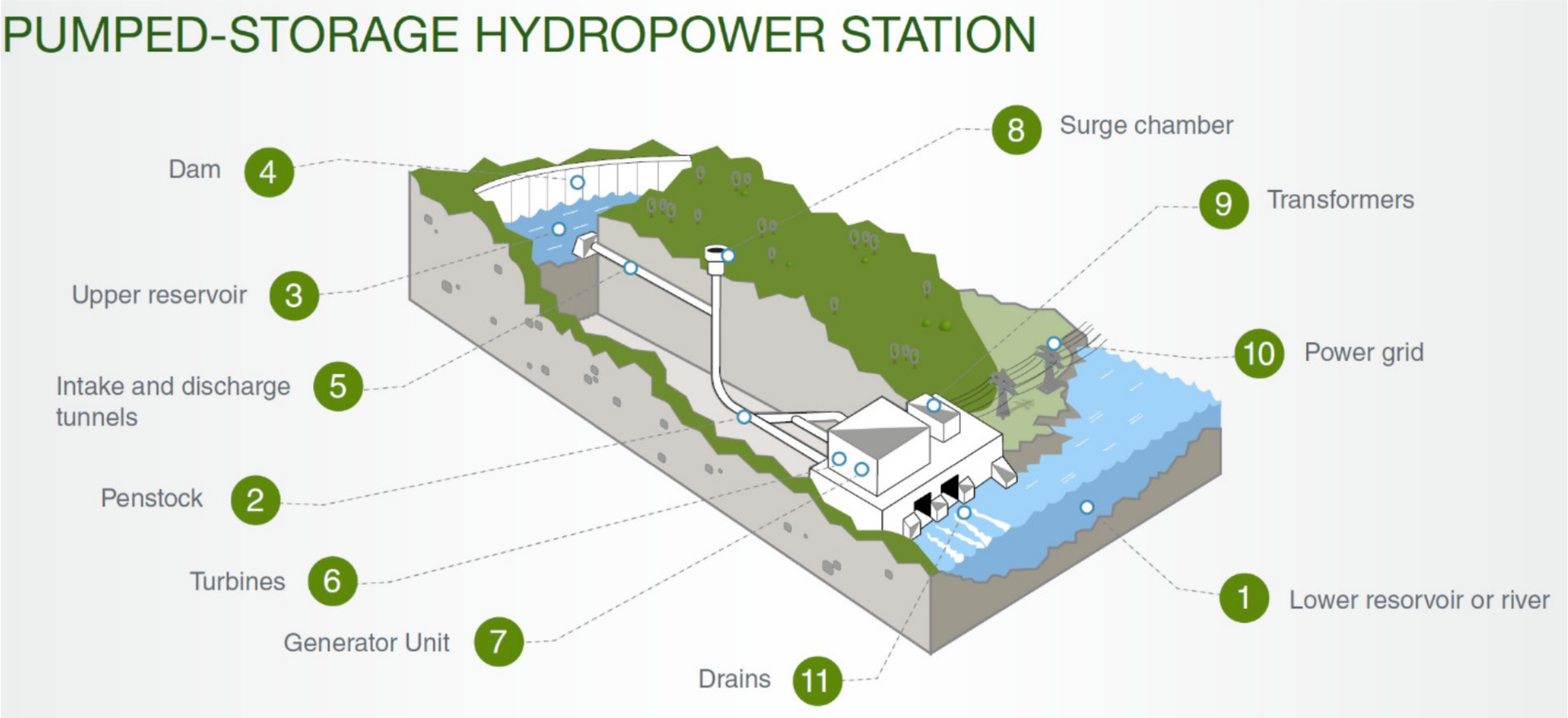


*Sustainability* 2020, *12*, 10511; doi:10.3390/su122410511
A Review of Energy Storage Technologies Application Potentials in Renewable Energy Sources Grid Integration
Henok Ayele Behabtu, Maarten Messagie, Thierry Coosemans, Maitane Berecibar, Kinde Anlay Fante, Abraham Alem Kebede, Joeri Van Mierlo

# Pumped HydroStorage (PHS)

**Source: Electricity Storage Technology Review, June 2020, for US-DOE**

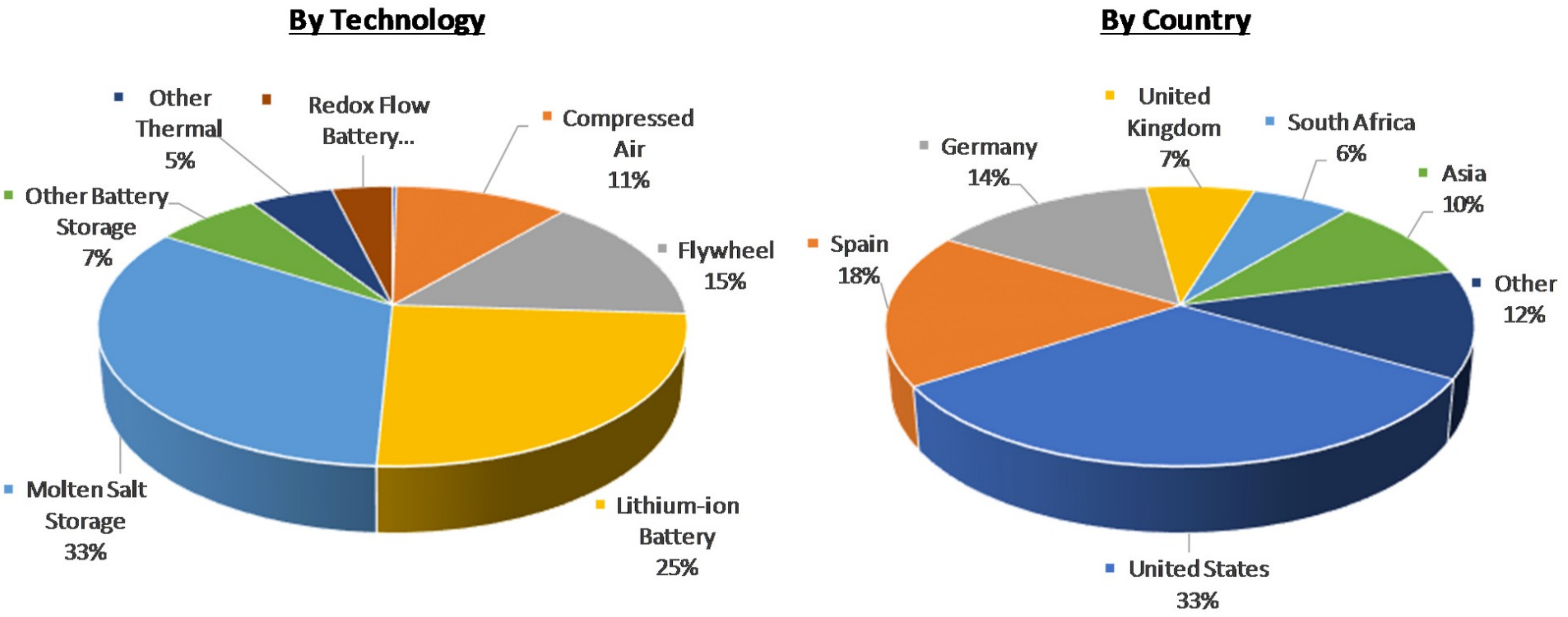
*Figure 18. Diagram of A Pumped Storage Hydropower Station*



*Source:* (Iberdrola n.d.)

**Source: Electricity Storage Technology Review, June 2020, for US-DOE**

# *Figure 2. Worldwide Electricity Storage Operating Capacity by Technology and by Country, 2020* *(excluding pumped hydro)*


**By Technology**

**By Country**

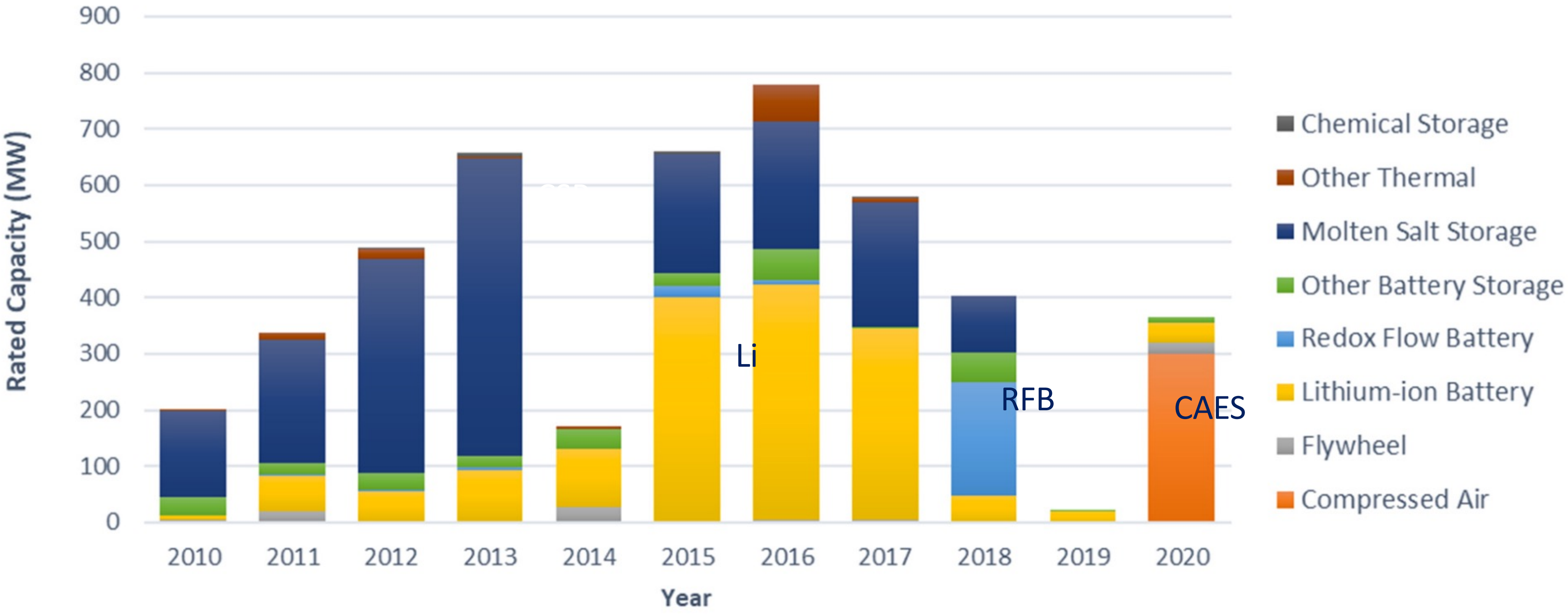
*Note: Capacity excludes Pumped Hydro Storage*

*Source: DOE Global Energy Storage Database (Sandia 2020), as of February 2020.*

**Source: Electricity Storage Technology Review, June 2020, for US-DOE**

*Figure 3. Worldwide Storage Capacity Additions, 2010 to 2020*

*(excluding pumped hydro)*

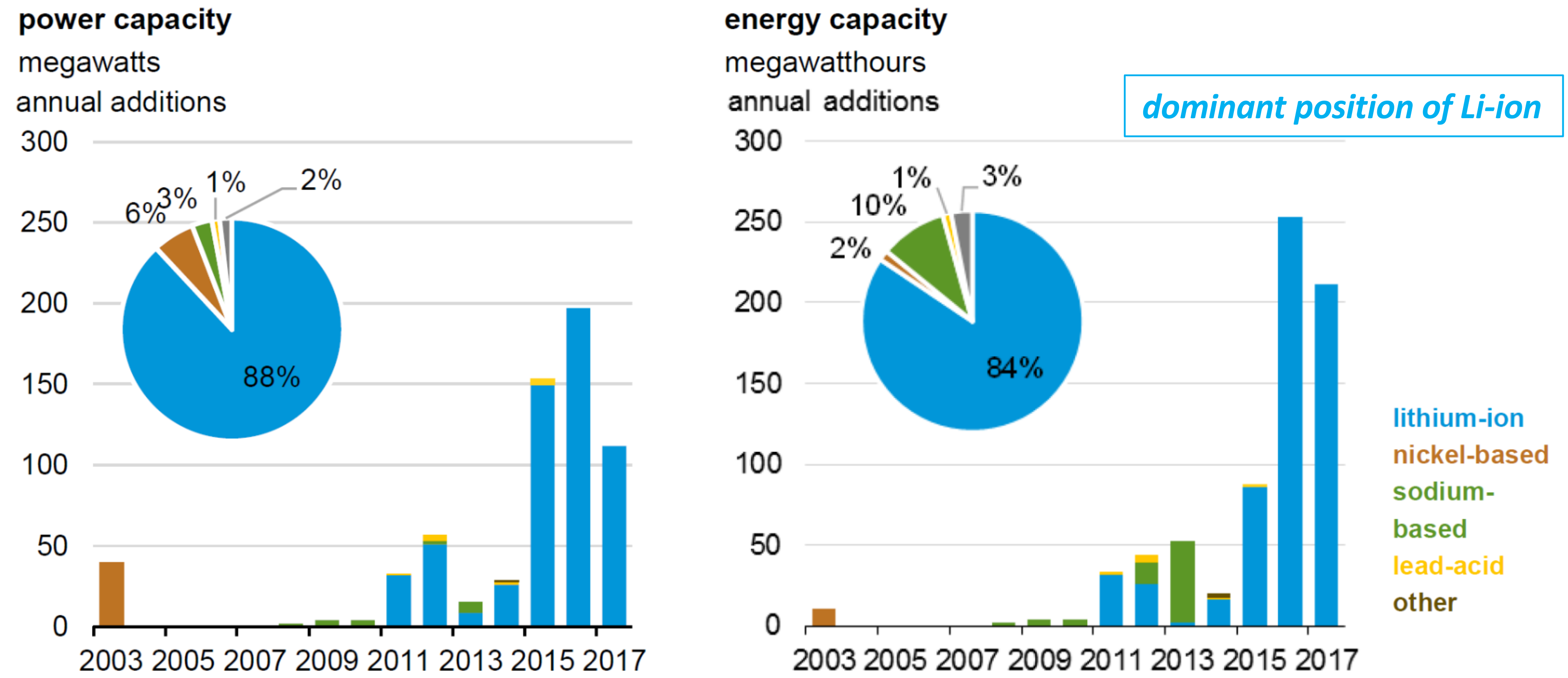


*Note: Capacity excludes Pumped Hydro Storage*

*Source: DOE Global Energy Storage Database (Sandia 2020), as of February 2020.*

Source: Electricity Storage Technology Review, June 2020, for US-DOE

*Figure 15. U.S. Large-Scale BES Power Capacity and Energy Capacity by Chemistry, 2003-2017*



*dominant position of Li-ion*

*Source: U.S. Energy Information Administration, Form EIA-861, Annual Electric Power Industry Report*

*Source:* (Cabral 2018)

# Proper cost metric: LCOS (levelized cost of storage)

$$LCOS\left[\frac{\$}{MWh}\right]=\frac{\overset{\text{dominant cost}}{\boxed{\text{Investment cost}}}+\sum_{n}^{N}\frac{\text{O\&M cost}}{(1+r)^{n}}+\sum_{n}^{N}\frac{\overset{2^{nd}\text{ largest}}{\boxed{\text{Charging cost}}}}{(1+r)^{n}}+\frac{\text{End-of-life cost}}{(1+r)^{N+1}}}{\sum_{n}^{N}\frac{Elec_{Discharged}}{(1+r)^{n}}}.$$

- = total lifetime cost of the investment in an electricity storage technology, divided by its cumulative delivered electricity (‘discounted cost per unit of discharged electrical energy’)
- this metric accounts for all technical and economic parameters affecting the **lifetime cost of discharging stored electricity**.
- directly comparable to the levelized cost of electricity (LCOE) for electricity generation technologies.
- key parameters that affect the LCOS of each technology, set by the respective applications, are: nominal power capacity (kW), discharge duration (h), annual cycles (number), and electricity price (€/kWhe)

*Schmidt et al., Joule 3, 81–100*
*January 16, 2019 a 2018 Elsevier Inc.*
*https://doi.org/10.1016/j.joule.2018.12.008*

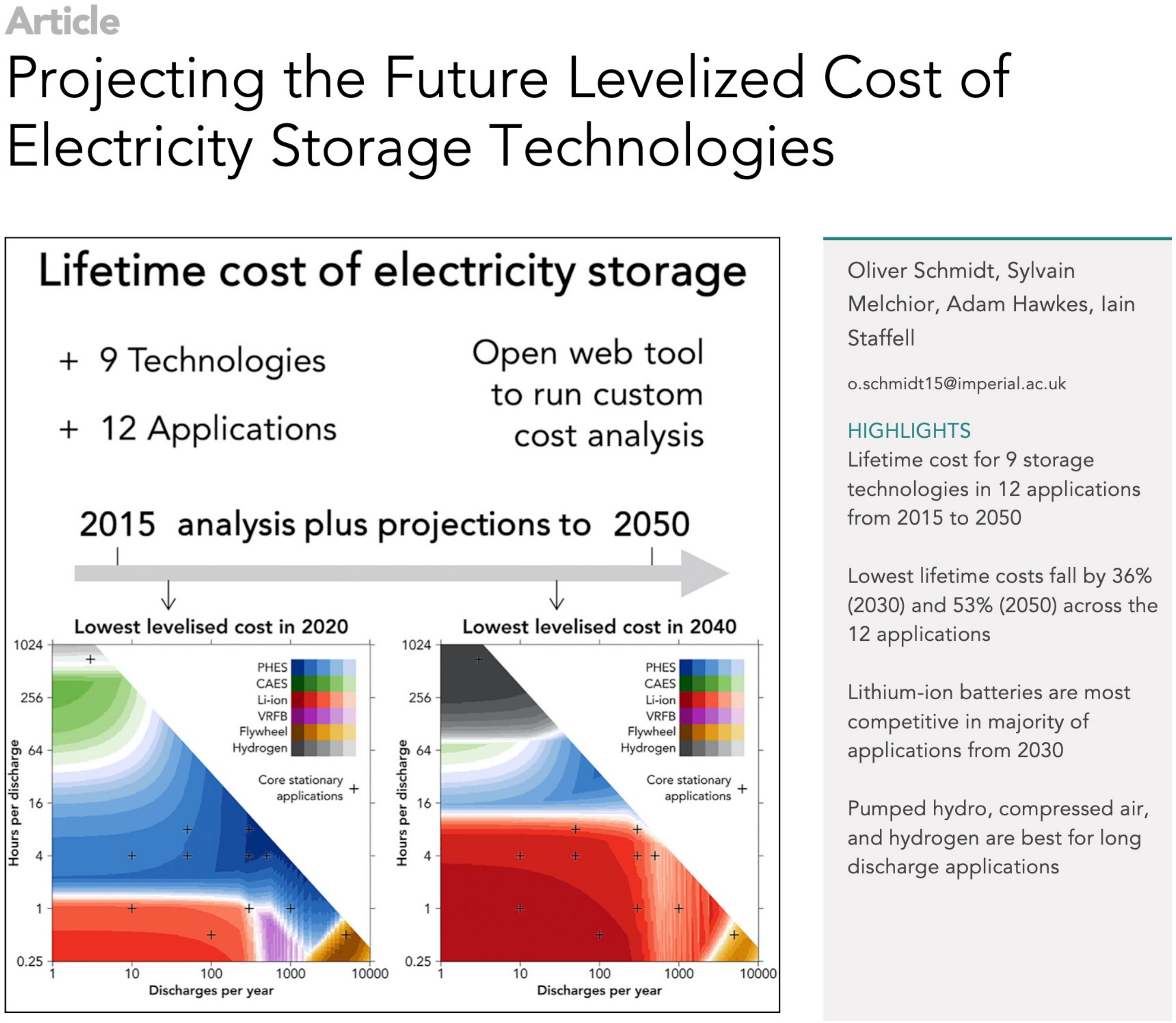
# Study outcome

*Schmidt et al., Joule 3, 81–100*
*January 16, 2019 a 2018 Elsevier Inc.*
*https://doi.org/10.1016/j.joule.2018.12.008*

**PHS / CAES**: ‘slow’ response time (>10 s) and large minimum sizes (>5 MWe) => not suited for primary elec.grid response and power quality and small-scale consumption.

**Flywheels and supercapacitors** : short discharge (<1 h) => not suited for longer-term power.

**Seasonal storage** (months, >700h): only met by technologies where energy storage capacity is fully independent of power capacity. **(PtG, $H_2$)**



Article

Projecting the Future Levelized Cost of Electricity Storage Technologies

Lifetime cost of electricity storage

+ 9 Technologies
+ 12 Applications

Open web tool to run custom cost analysis

2015 analysis plus projections to 2050

Oliver Schmidt, Sylvain Melchior, Adam Hawkes, Iain Staffell

o.schmidt15@imperial.ac.uk

HIGHLIGHTS

Lifetime cost for 9 storage technologies in 12 applications from 2015 to 2050

Lowest lifetime costs fall by 36% (2030) and 53% (2050) across the 12 applications

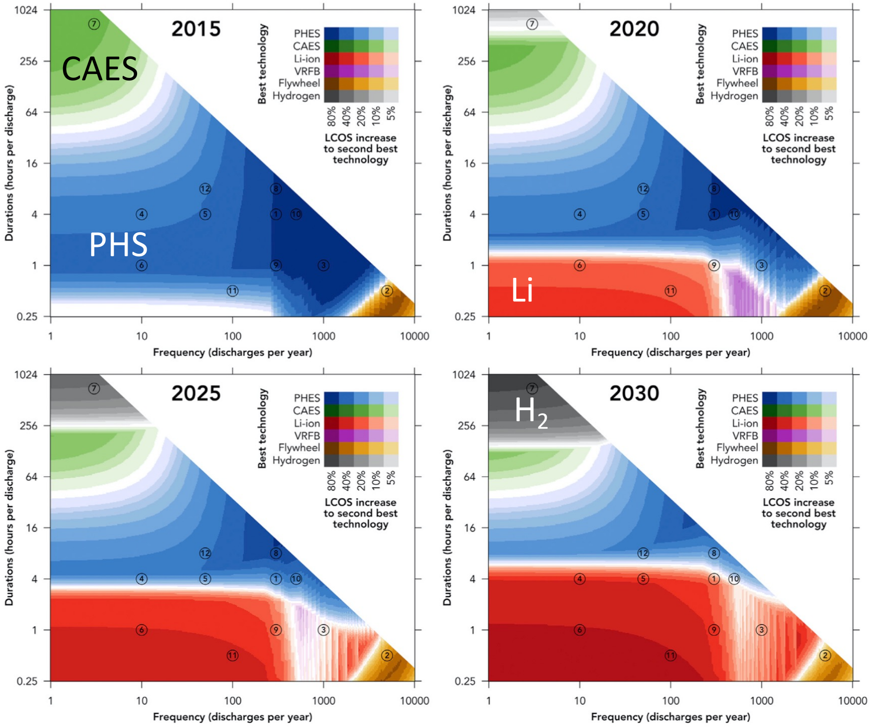
Lithium-ion batteries are most competitive in majority of applications from 2030

Pumped hydro, compressed air, and hydrogen are best for long discharge applications

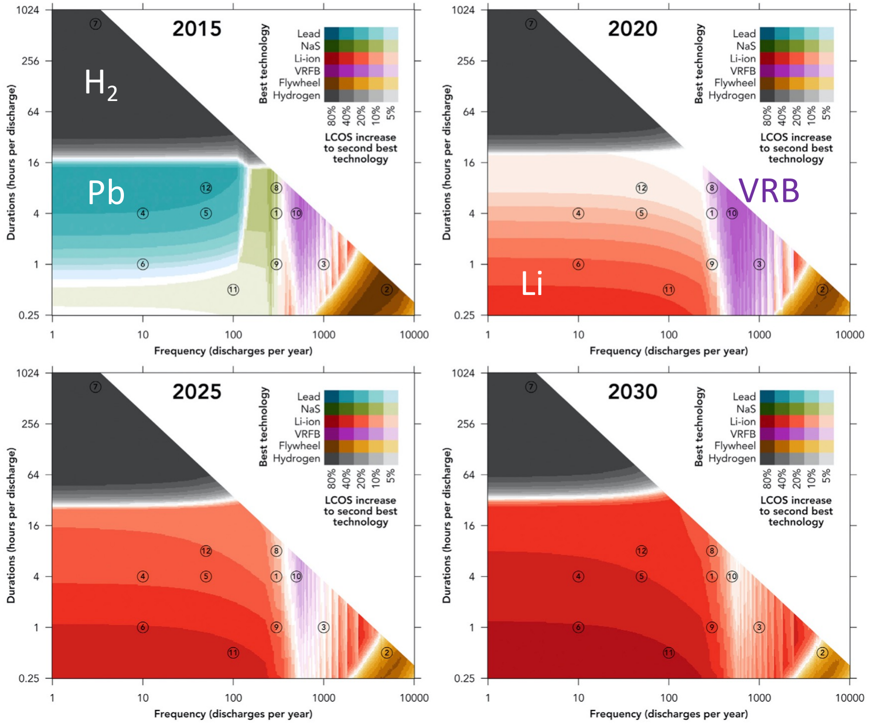
*Schmidt et al., Joule 3, 81–100*
*January 16, 2019 a 2018 Elsevier Inc.*
*https://doi.org/10.1016/j.joule.2018.12.008*

# Excluding PHS & CAES, $H_2$ is already more cost-effective than batteries for discharges > 1day !

All technologies



Technologies excluding PHS / CAES



# Summary on electricity storage

- By far the most used today : pumped hydro storage (**PHS**)
  - 93% of world total (173 GWe)
  - minimal size of **5 Mwe**

- Smaller scale and short term : **batteries**
  - 5% of world total (9 GWe), dominated by Li-ion (90%)
  - maximal discharge time = **1 day**
  - adapted for residential PV (**1-20 kWe**)

- Middle segment between PHS and batteries is ideally captured by **P2G**
  - from few **10 kWe to few MWe**
  - energy size and power size are uncoupled => long term storage
  - for storage > 1 day, P2G is economical today already