Electrochemistry for Materials Technology

ENERGY APPLICATIONS

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gem.epfl.ch

ELECTROLYSIS

H_2 from H_2O electrolysis

- H_2 does not occur naturally on Earth
- It stems mostly (95%) from fossil sources now; this relates to its main current use (which is 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 offers all energy uses (1.power, 2.heat, 3.mobility) in addition to being a chemical **feedstock** for heavy industry
- It therefore has huge decarbonisation potential, but must be made on a **massive scale (TW !!)**

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

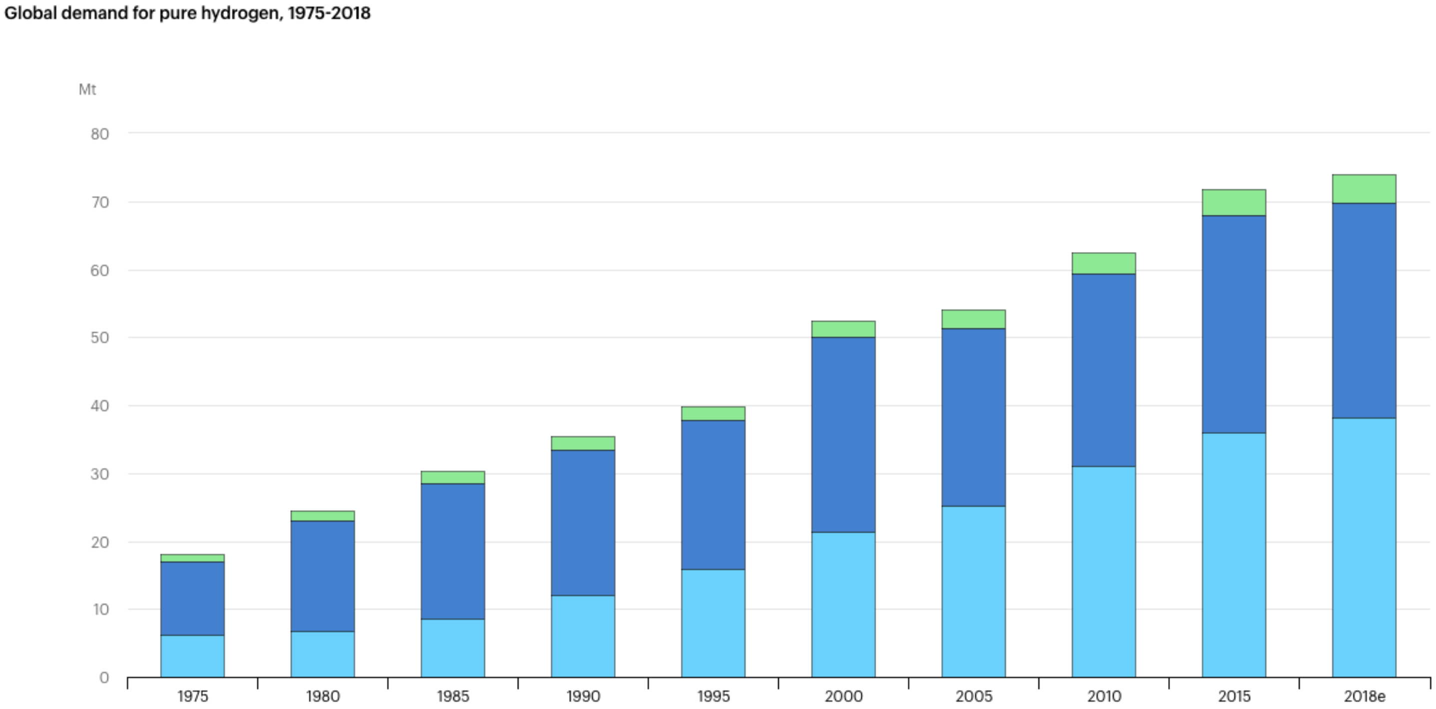
Annual H_2 production

- ~75 Mt/yr ≈ 830 10^9 m^3 /yr ≈ 9 EJ (2500 TWh) = 1.6% of world energy
  - 49% from natural gas
  - 29% from oil
  - 18% from coal
  - **4% from electrolysis**

96% from fossil sources

not green!

= 3 Mt H_2/yr
= 33 bio m^3/yr
= 100 TWh H_2 (*LHV*)
67% efficiency
150 TWhe electricity
(0.6% of world electricity)
~20 GWe


Global demand for pure hydrogen, 1975-2018

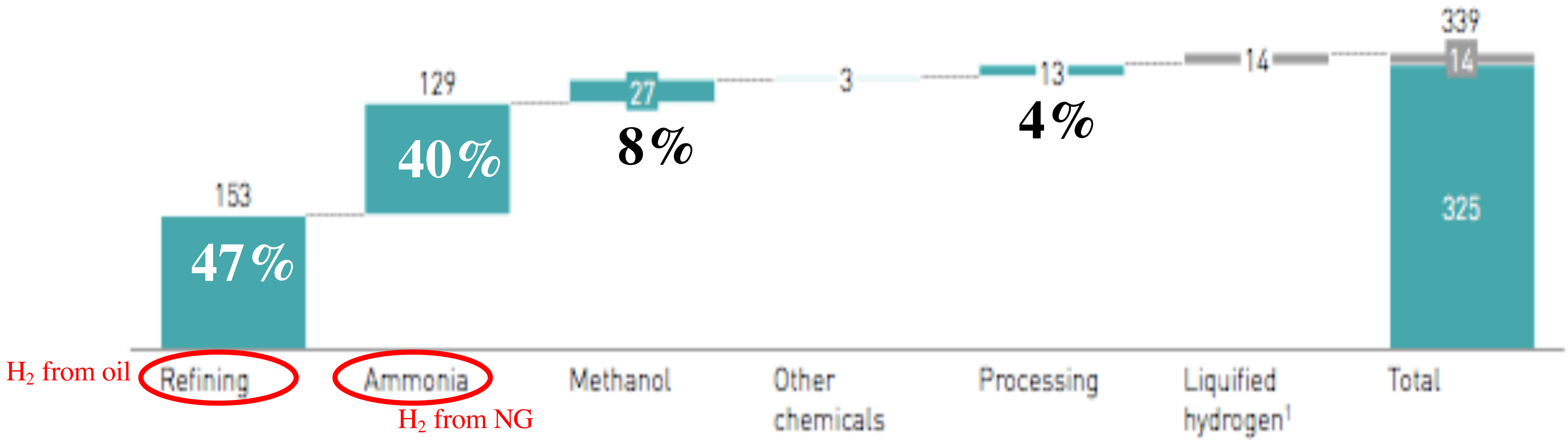
- by comparison: natural gas 4.10^{12} m^3 /yr = 140 EJ (24% of world energy – 580EJ)

H_2 current uses (EU)

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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

Total hydrogen use in the EU, in TWh



Refining
- Hydro-cracking
- Hydro-treating (e.g., fuel desulfurization)
- Biorefinery

Ammonia
- Production of ammonia (for urea and other fertilizers)

Methanol
- Production of methanol and derivatives

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

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

Liquified hydrogen
- Rocket fuel
- Automotive fuel
- Semiconductor industry

H_2 current uses (EU)

- 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 (floating on liquid tin)
  - food (fats hydrogenation)

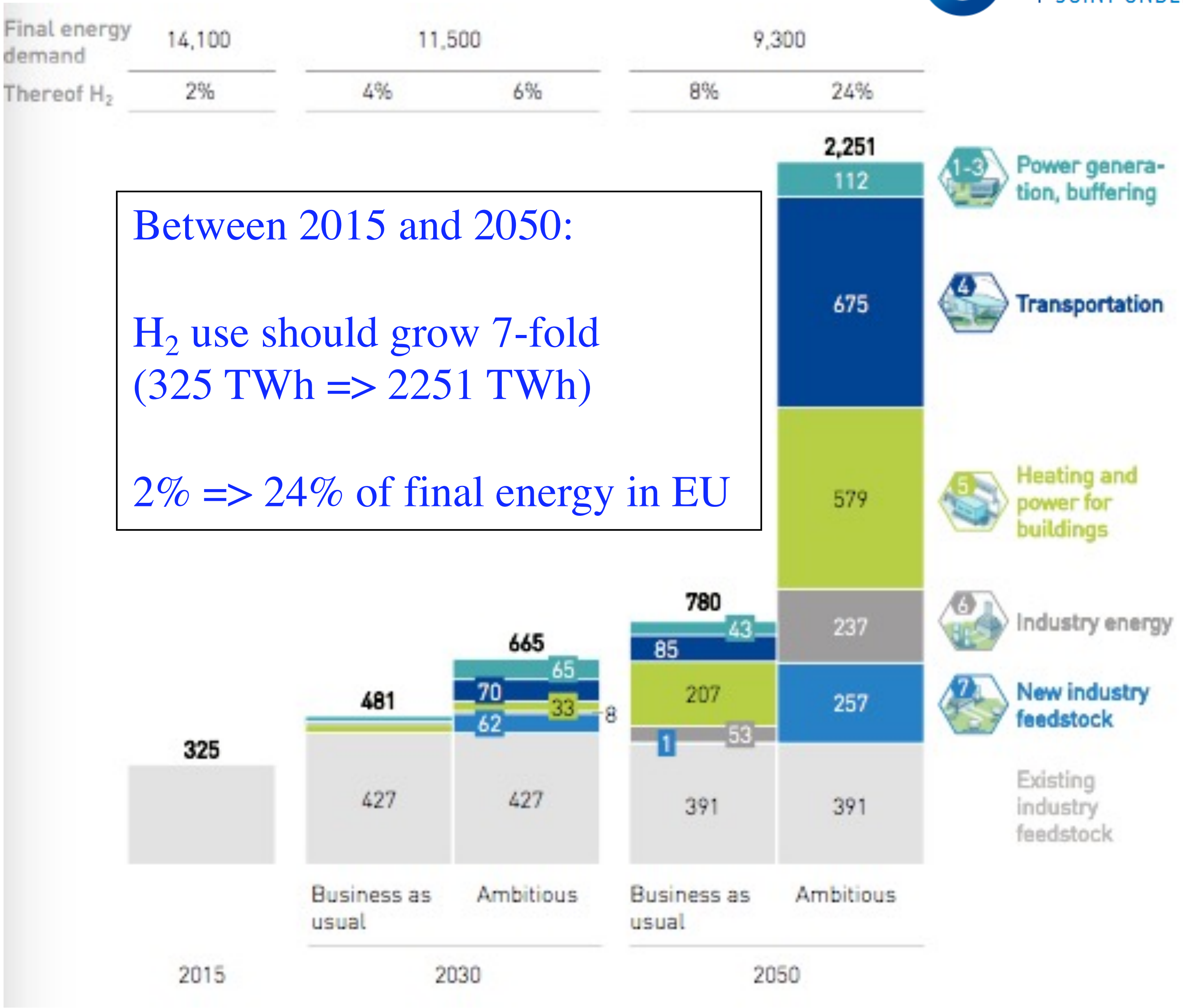
50 kWe – 2 MWe electrolysers

10 – 500 Nm^3/h H_2 flows per unit

- **325 TWh** or 1.2 EJ (2% of final EU energy)

Annual H_2 demand per segment

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING



Between 2015 and 2050:

H_2 use should grow 7-fold
(325 TWh => 2251 TWh)

2% => 24% of final energy in EU

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

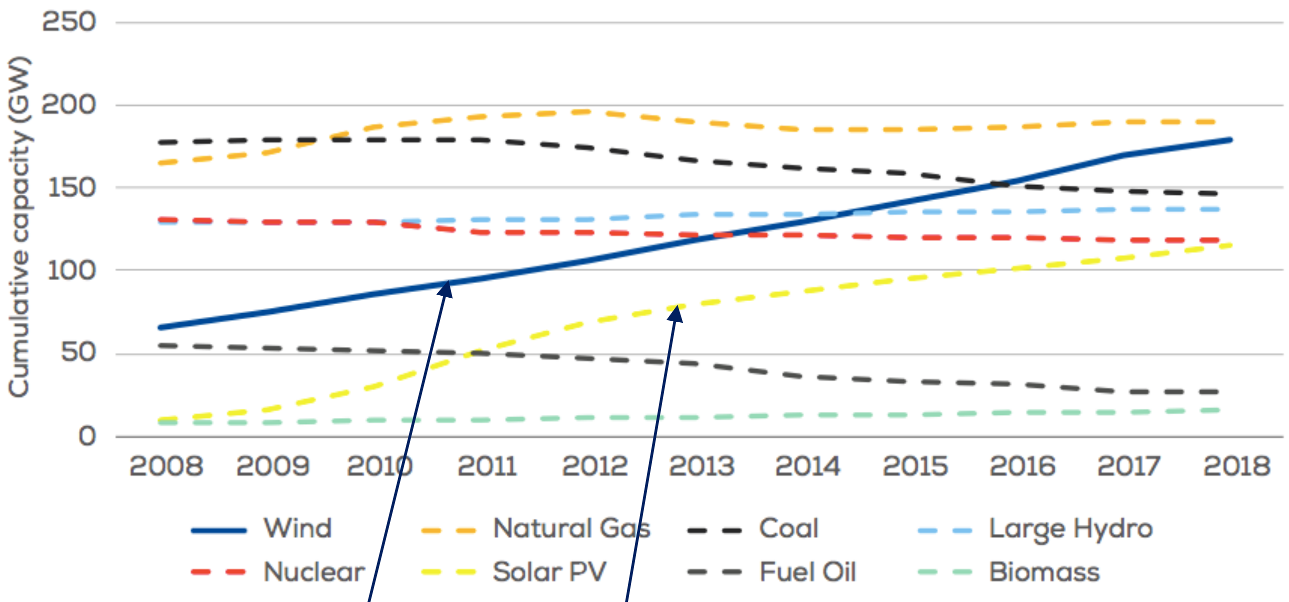
Water electrolysis

- 5 x more expensive than fossil fuel steam reforming for H_2 production (only 4% of world H_2 production is by electrolysis)
- for electricity storage (H_2 economy)
- …and mobility (FCEV: electric fuel cell cars)
- target: improve the electrolysis efficiency (V_{in})
  - power efficiency=$(P_{out}/P_{in})=(V_{out}/V_{in}).(I_{out}/I_{in})$
  - Classical alcaline (liq. OH^-) 1.8 V
  - Polymer electrolyte (80C) 1.9 V (higher current)
  - Ceramic electrolyte (800C) possible even at 1 V!

Electricity sources

FIGURE 1

Total power generation capacity in the European Union 2008-2018



Source: WindEurope

2020 :

+14.7 GW in 2020
+105 GW in 2021-2025

Wind: EU 220 GWe
458 TWhe (15% of Europe's electricity)
World : 732 GWe

Solar Europe: 137 GWe
150 TWhe (5% of Europe's electricity)

+16.5 GWe in 2020

Solar worldtotal:
710 GWe
+140 GWe in 2020

Hydro (world) : 1212 GWe

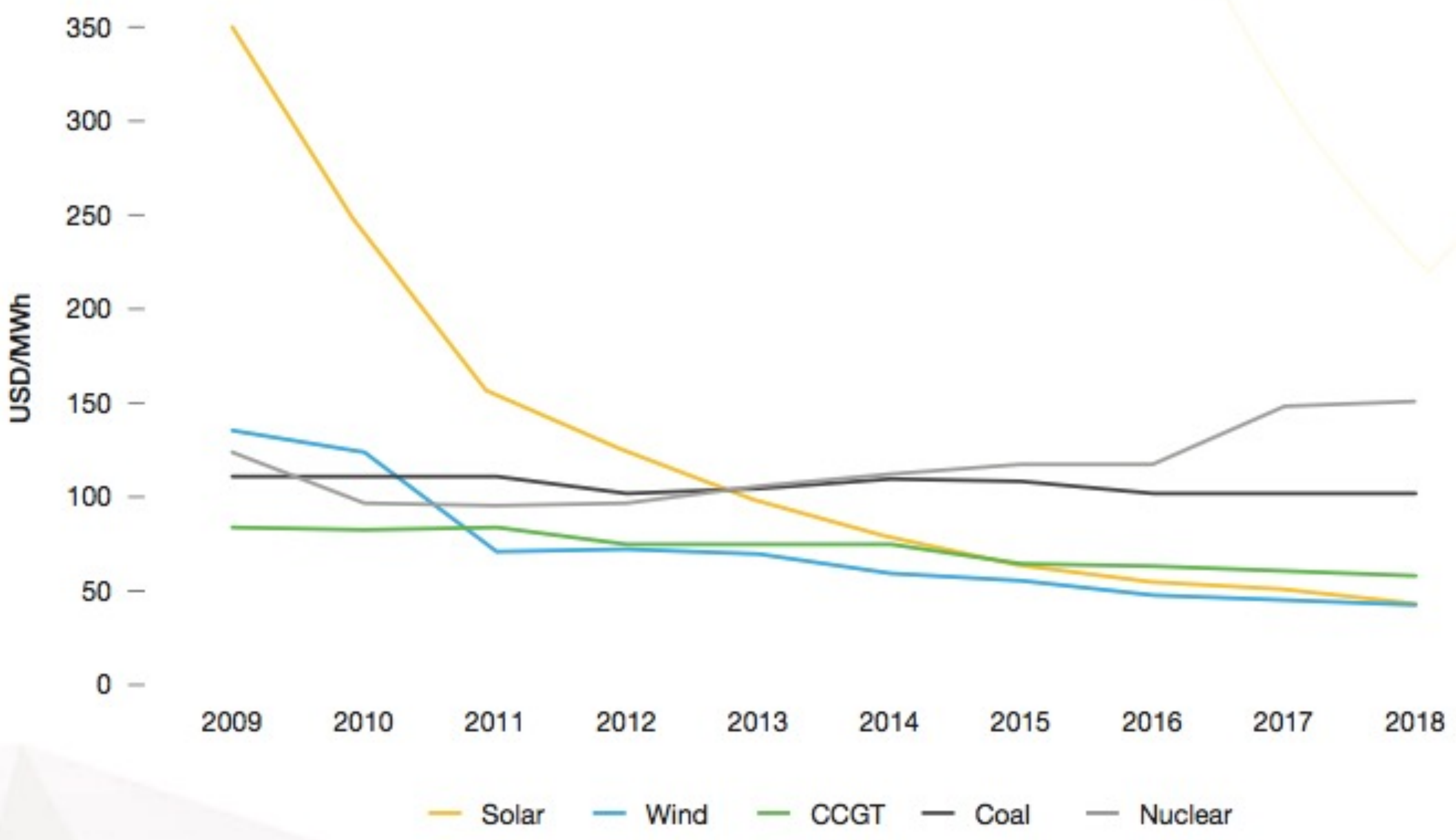
growth in Wind + Solar PV

⇨

STORAGE by ELECTROLYSIS

Solar PV and wind is the cheapest electricity

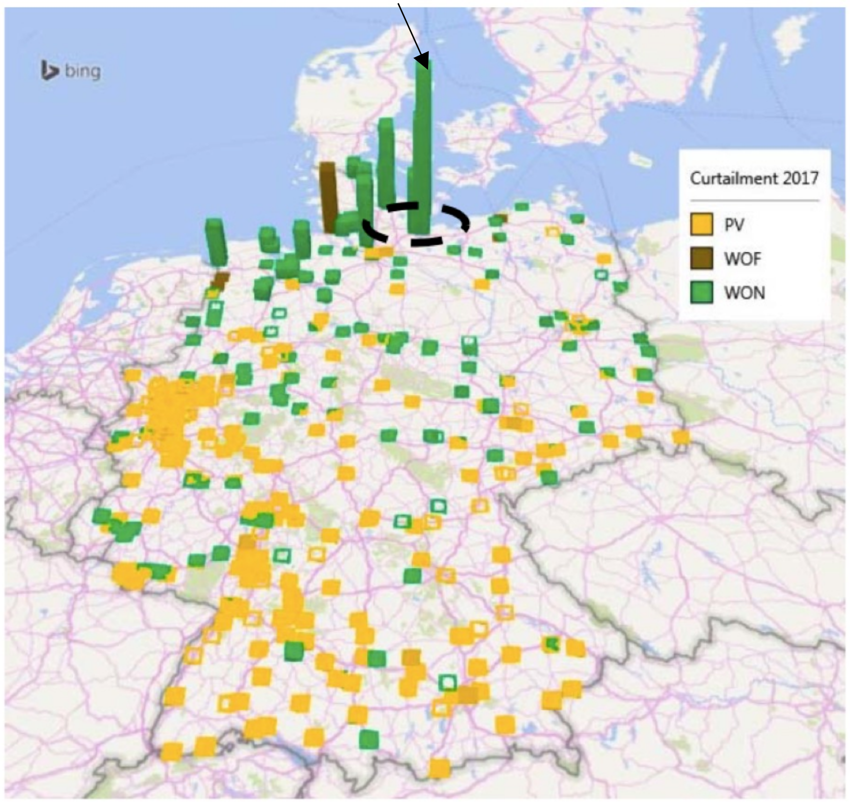
FIGURE 3 SOLAR ELECTRICITY GENERATION COST IN COMPARISON WITH OTHER POWER SOURCES 2009-2018



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

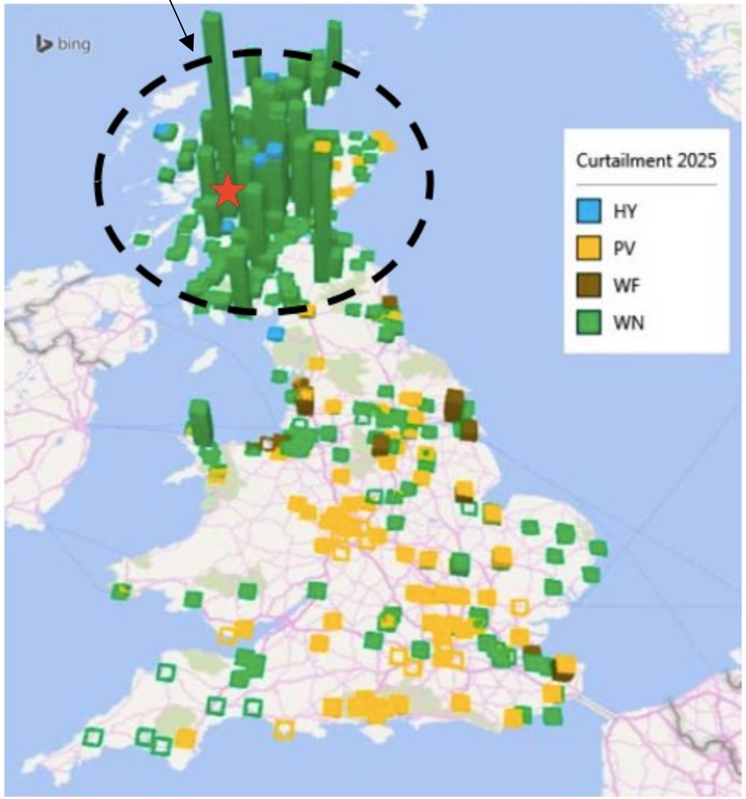
© SOLARPOWER EUROPE 2019

Excess electricity production



Max: 427 GWhe

Germany 2017

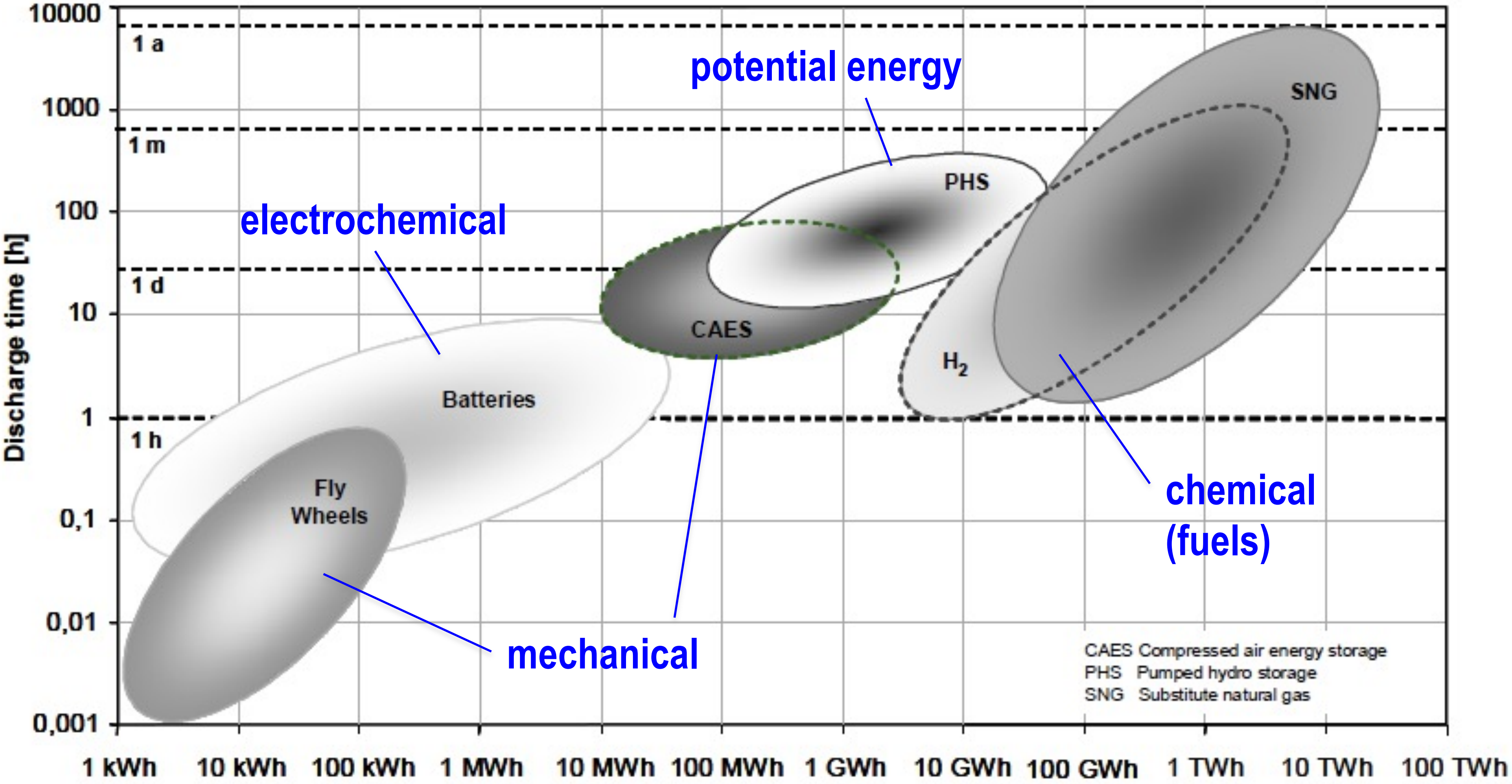


Max: 117 GWhe

UK 2025

(2017-June) STUDY ON EARLY BUSINESS CASES FOR H_2 IN ENERGY STORAGE AND MORE BROADLY POWER TO H2 APPLICATIONS
Prepared for Fuel Cells & Hydrogen Joint Undertaking by Tractebel and Hinicio

Electricity storage schemes

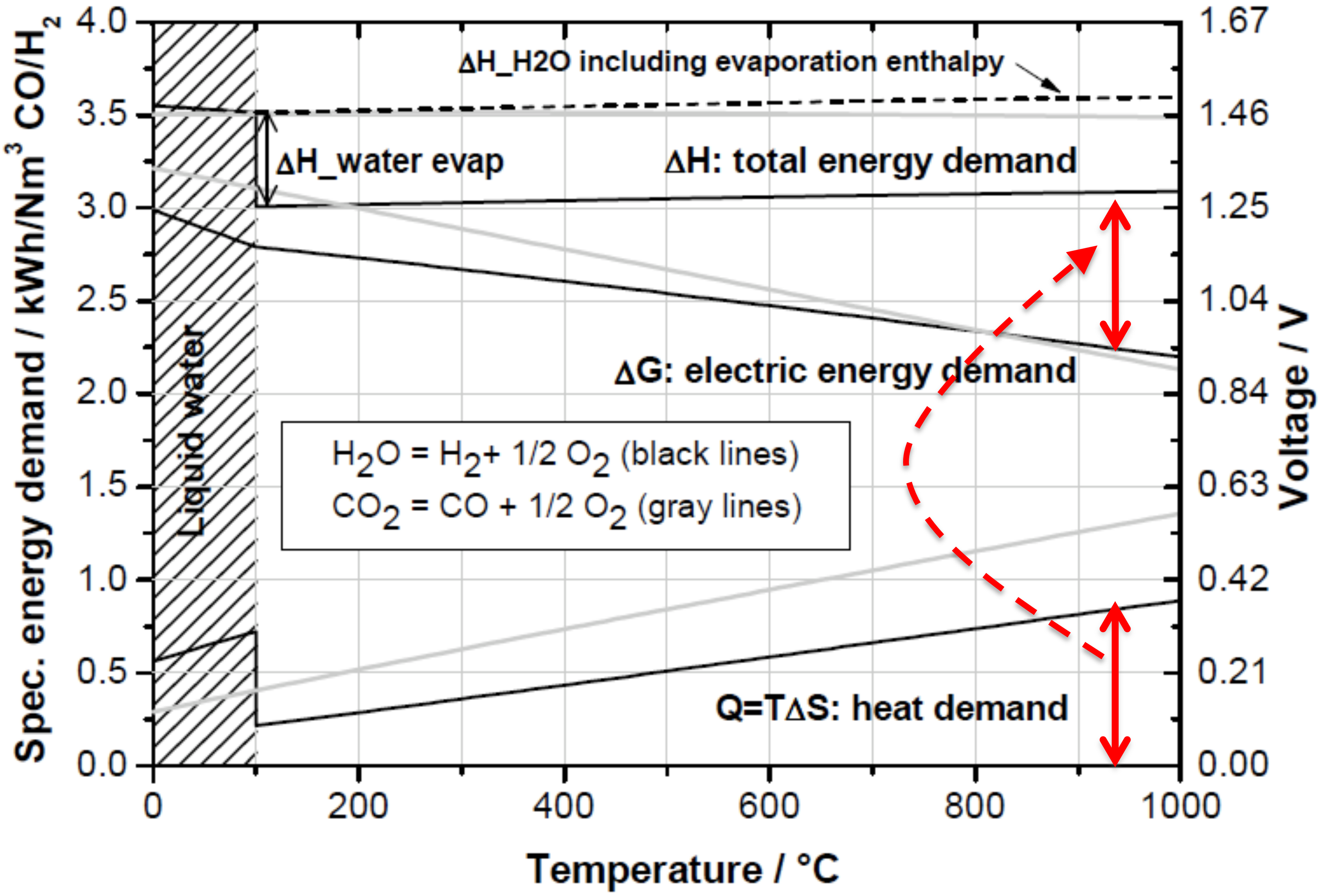


Storing Renewable Energy in the Natural Gas Grid, Methane via Power-to-Gas (P2G): A Renewable Fuel for Mobility
M. Specht, U. Zuberbühler, F. Baumgart, B. Feigl, V. Frick, B. Stürmer, M. Sterner, G. Waldstein, ZSW-Ulm

→ *converting electricity to fuel gives the largest capacities*

Thermodynamics

at 700C, 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

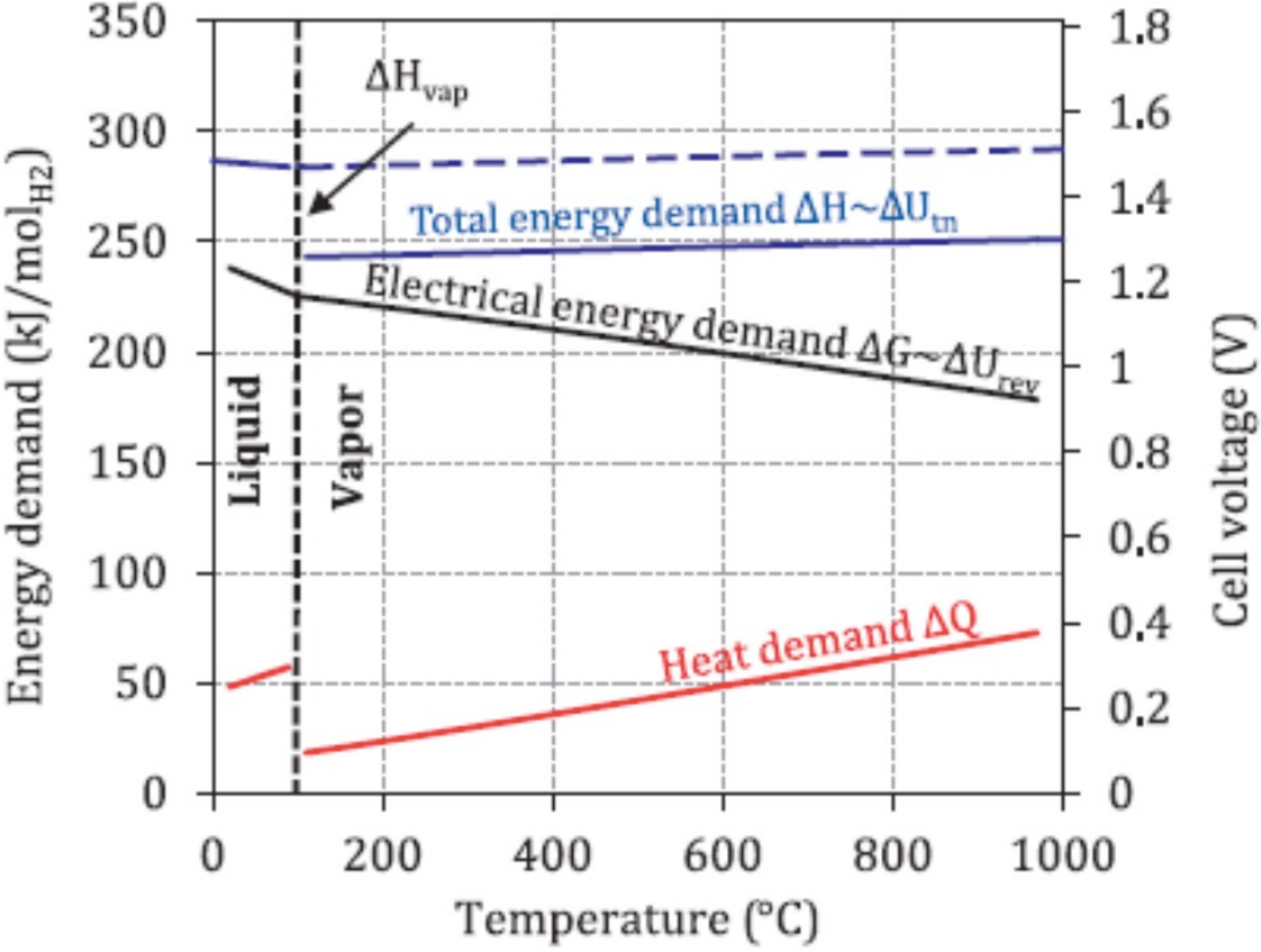
	Reaction	ΔH (kJ/mol)	MJ / Nm^3	kWh / Nm^3
Water	$H_2O(l) \Rightarrow H_2 + \frac{1}{2}O_2$	286	12.77	3.55
Steam	$H_2O(g) \Rightarrow H_2 + \frac{1}{2}O_2$	↓ $-\Delta H_{evap}$ 242	10.80	3.00
	$CO_2 \Rightarrow CO + \frac{1}{2}O_2$	283	12.63	3.51

→

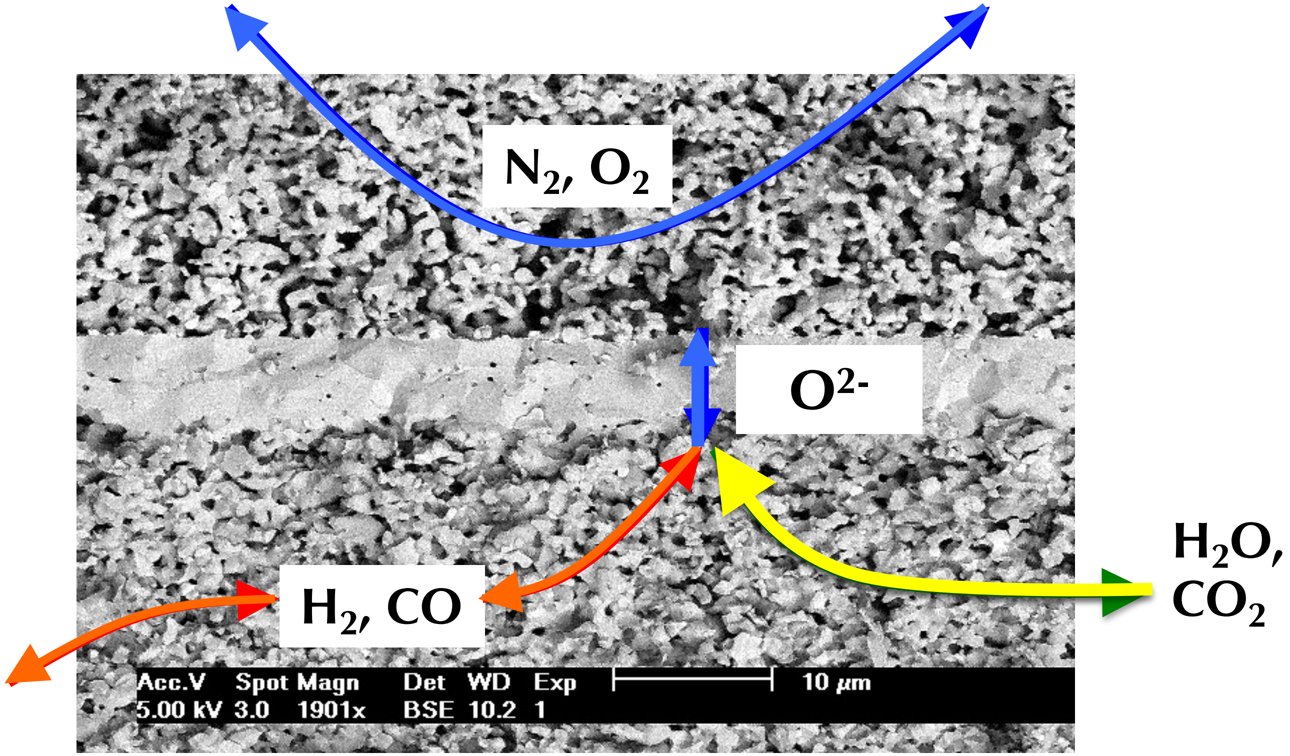
Electrolysis : energy necessary for dissociation

←

Combustion: energy liberated as heat


ΔH_vap
Total energy demand ΔH~ΔU_tn
Electrical energy demand ΔG~ΔU_rev
Heat demand ΔQ
Liquid
Vapor
Energy demand (kJ/mol_H2)
Cell voltage (V)
Temperature (°C)
0
50
100
150
200
250
300
350
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
200
400
600
800
1000

Reverse fuel cell = electrolyser



syngas-catalyst

Operating regime :

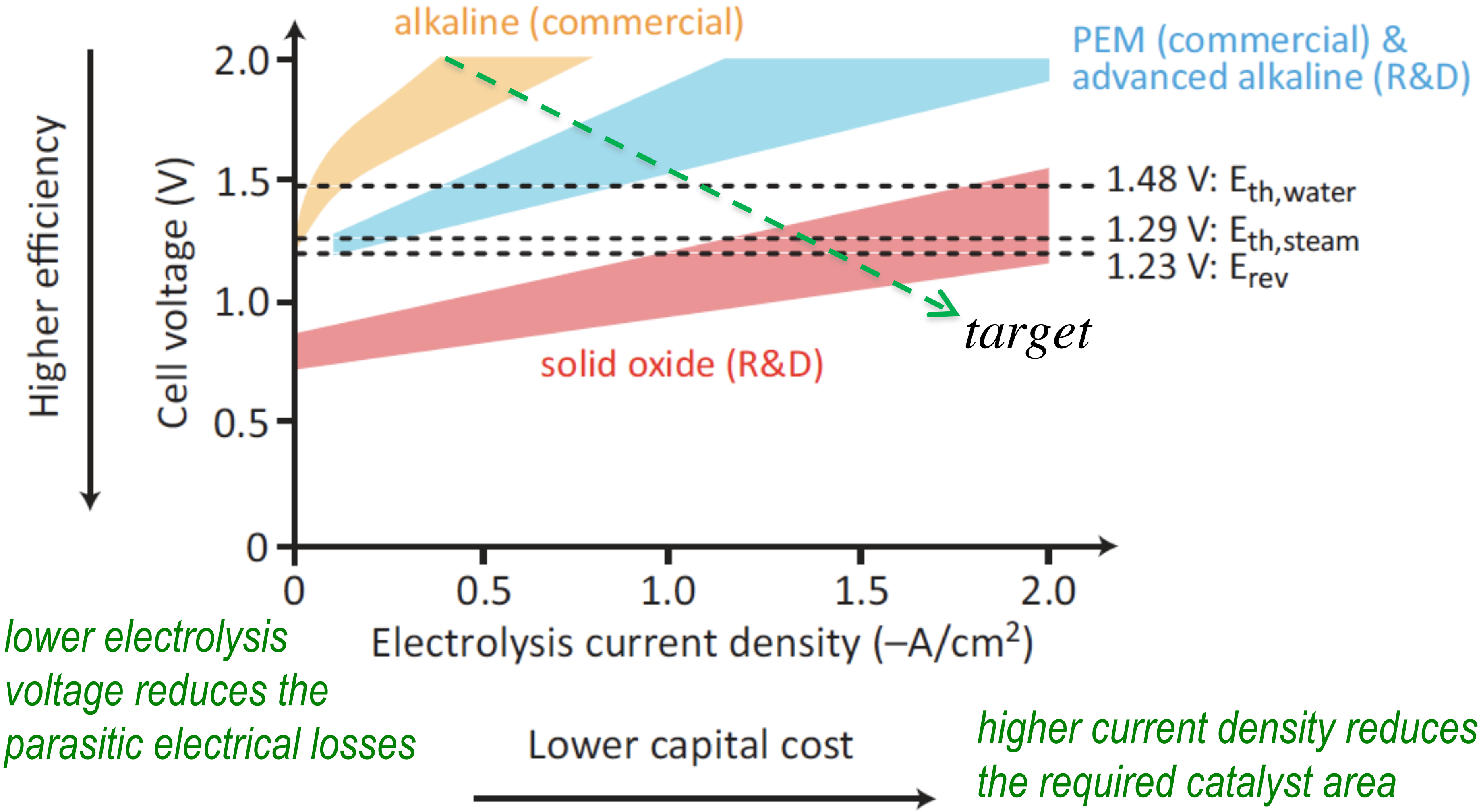
700-800° C

1 bar (to 5 bar)

FUEL CELL

ELECTROLYSER

Electrolysis technology comparison

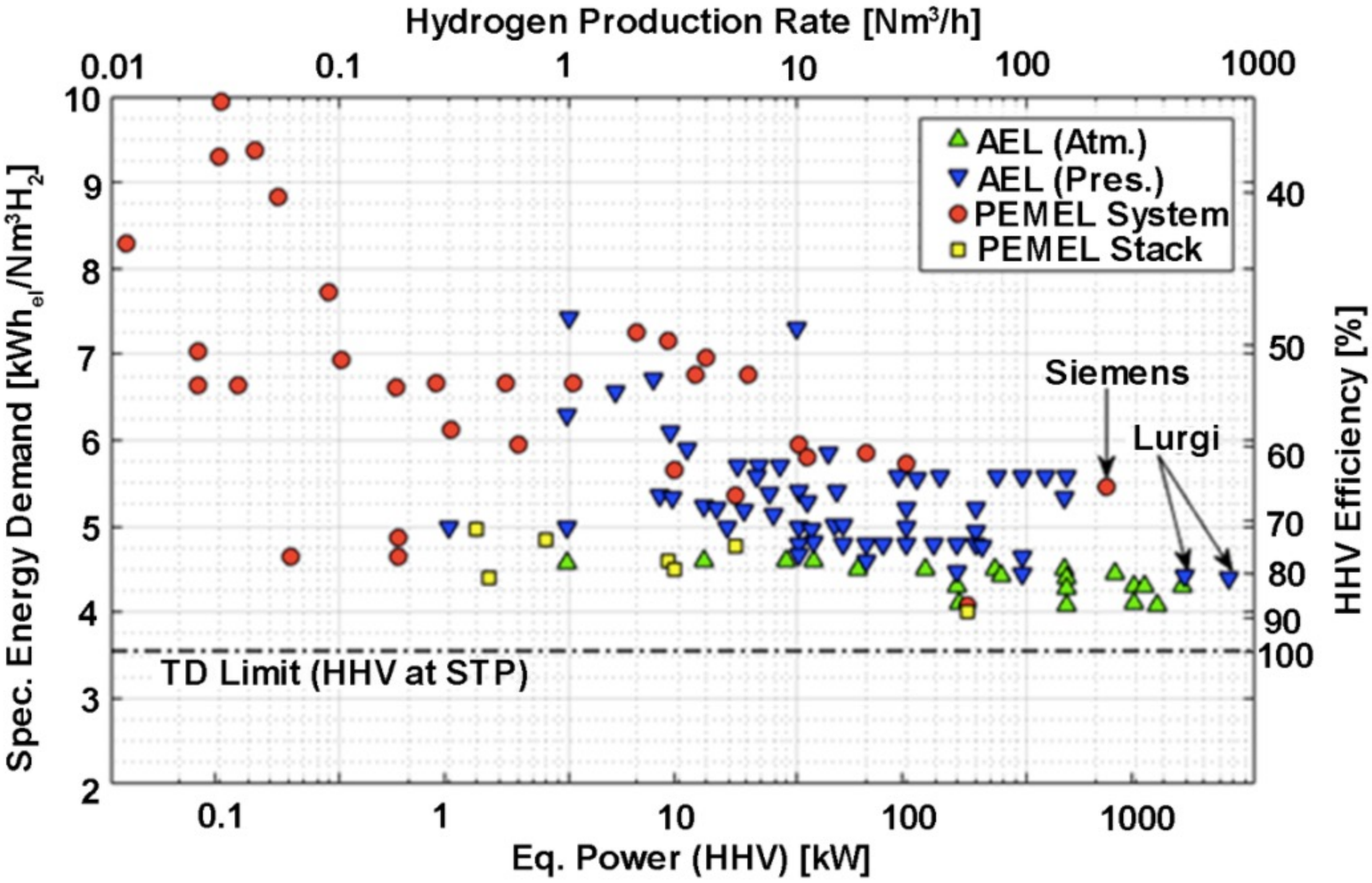


lower electrolysis voltage reduces the parasitic electrical losses

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

Electrolyser efficiencies



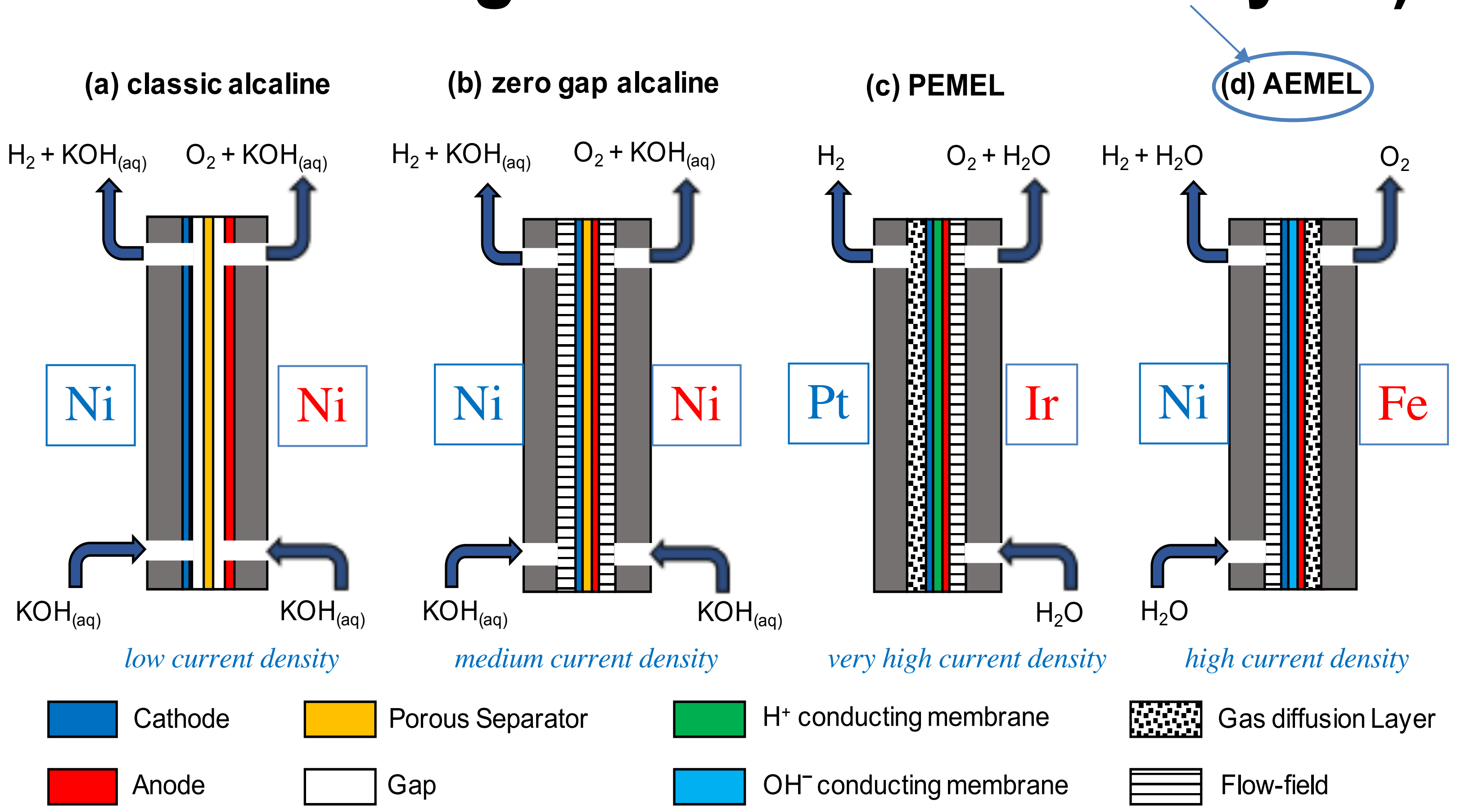
Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

slide from Prof A. Züttel, EPFL

SolydEra

Our industry partner SOLYDERA reached 98% efficiency on a 75 kWe steam electrolyzer

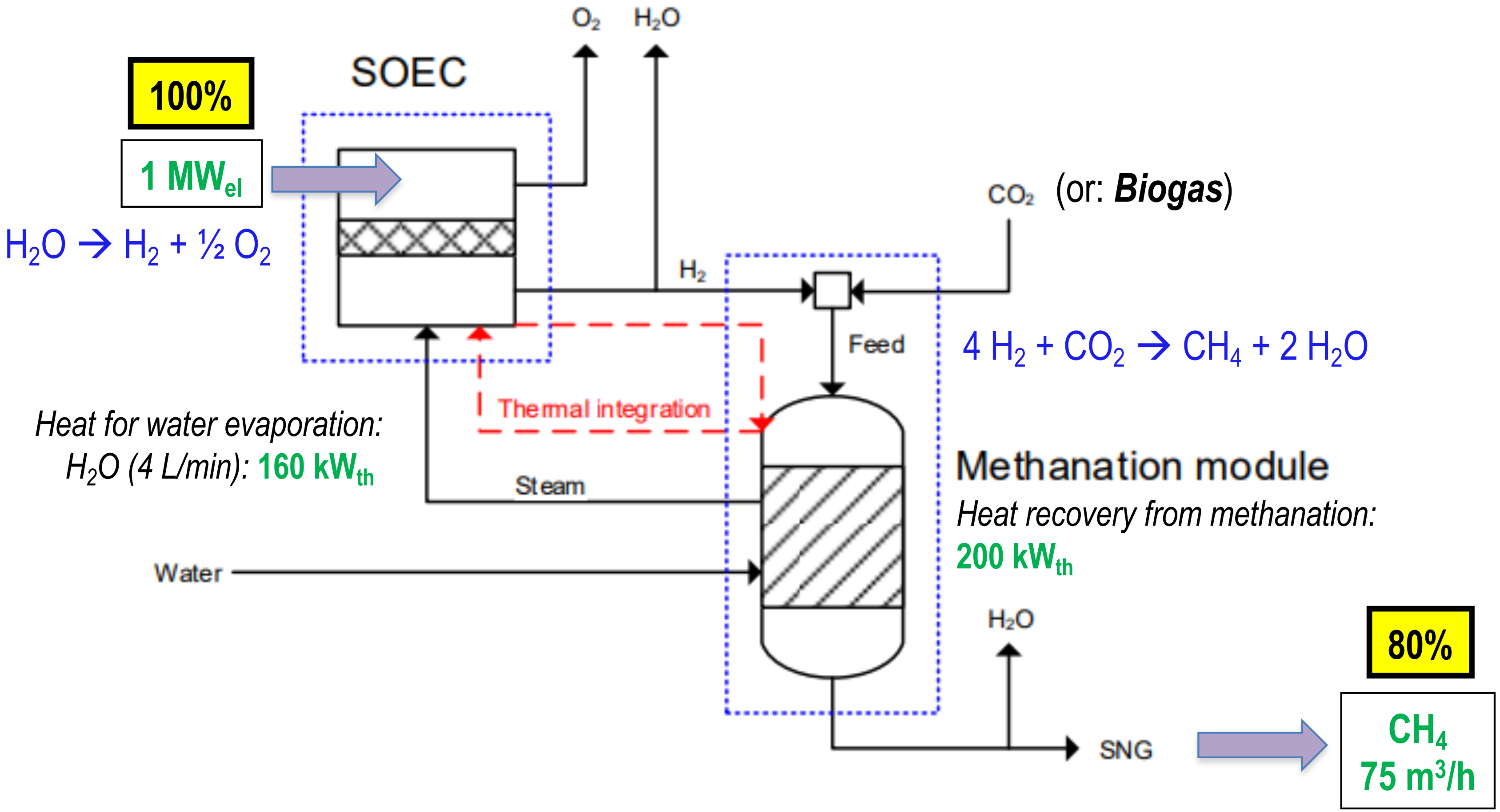
New technology : AEM
(anionic exchange membrane electrolysis)



(Figure: Dr Heron Vrubel)

- no critical materials (noble metals **Pt, Ir**) as catalysts
- alcaline medium (KOH) allows for (Ni-coated) **stainless steel** use (bipolar plates)
  (acidic medium (H^+) requires treated/coated (Au, Pt) **titanium** = more expensive)

Power-to-Gas (P2G)



100%

1 MW_{el}

$H_2O \rightarrow H_2 + ½ O_2$

(or: ***Biogas***)

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

Heat for water evaporation:
H_2O (4 L/min): 160 kW_{th}

Heat recovery from methanation:
200 kW_{th}

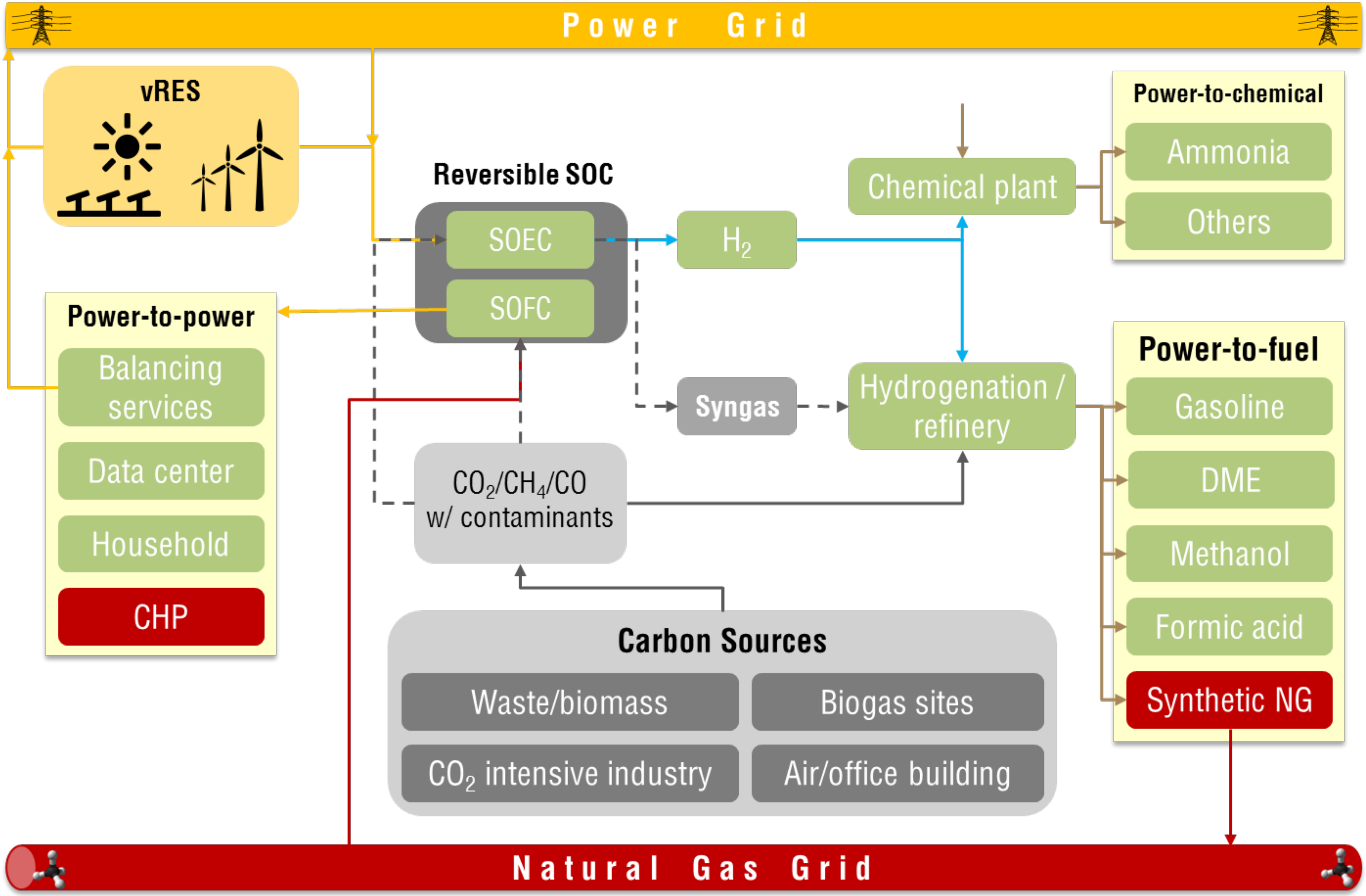
80%

CH_4
75 m^3/h

Converting H_2 to CH_4 for easy grid injection

Vision: sector coupling

(figure: Dr Ligang Wang)



European Gas network

Vested gas pipeline infrastructure.
42% of buildings are heated by NG.
112 million households

Gas consumption: 5375 TWh (19.4 EJ)
(23% of EU energy) = 512 bio m^3 NG

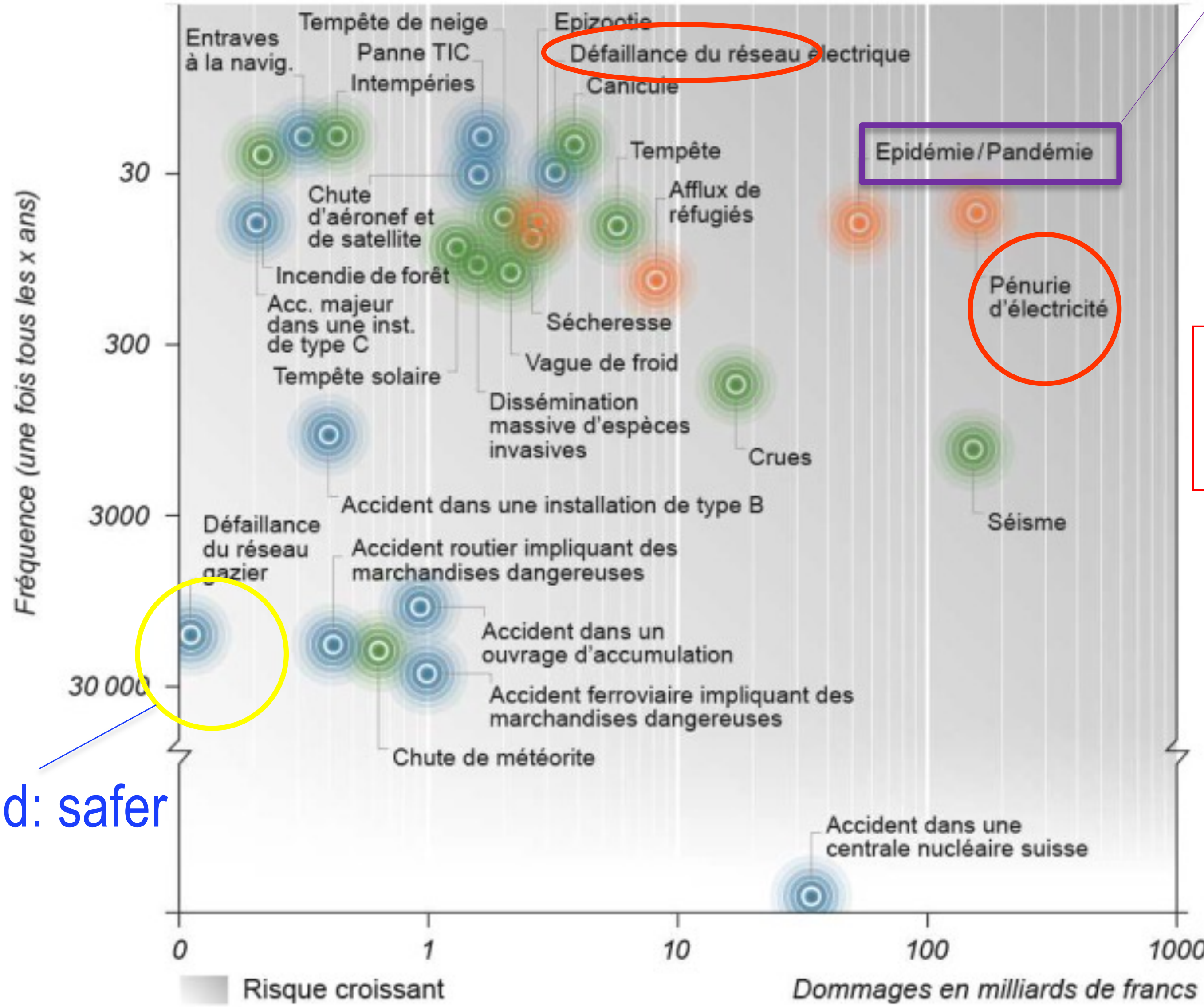
Storage capacity: 1200 TWh
= large reserve for injection of
H_2 (and green methane)

10 vol% H_2 admixing:
= 51 bio m^3 H_2 = 169 TWh (608 PJ)
>40 GWe

Eurogas Statistical Report 2018

Risks in Switzerland

Risk report (June 2015): catastrophes and situations of urgency



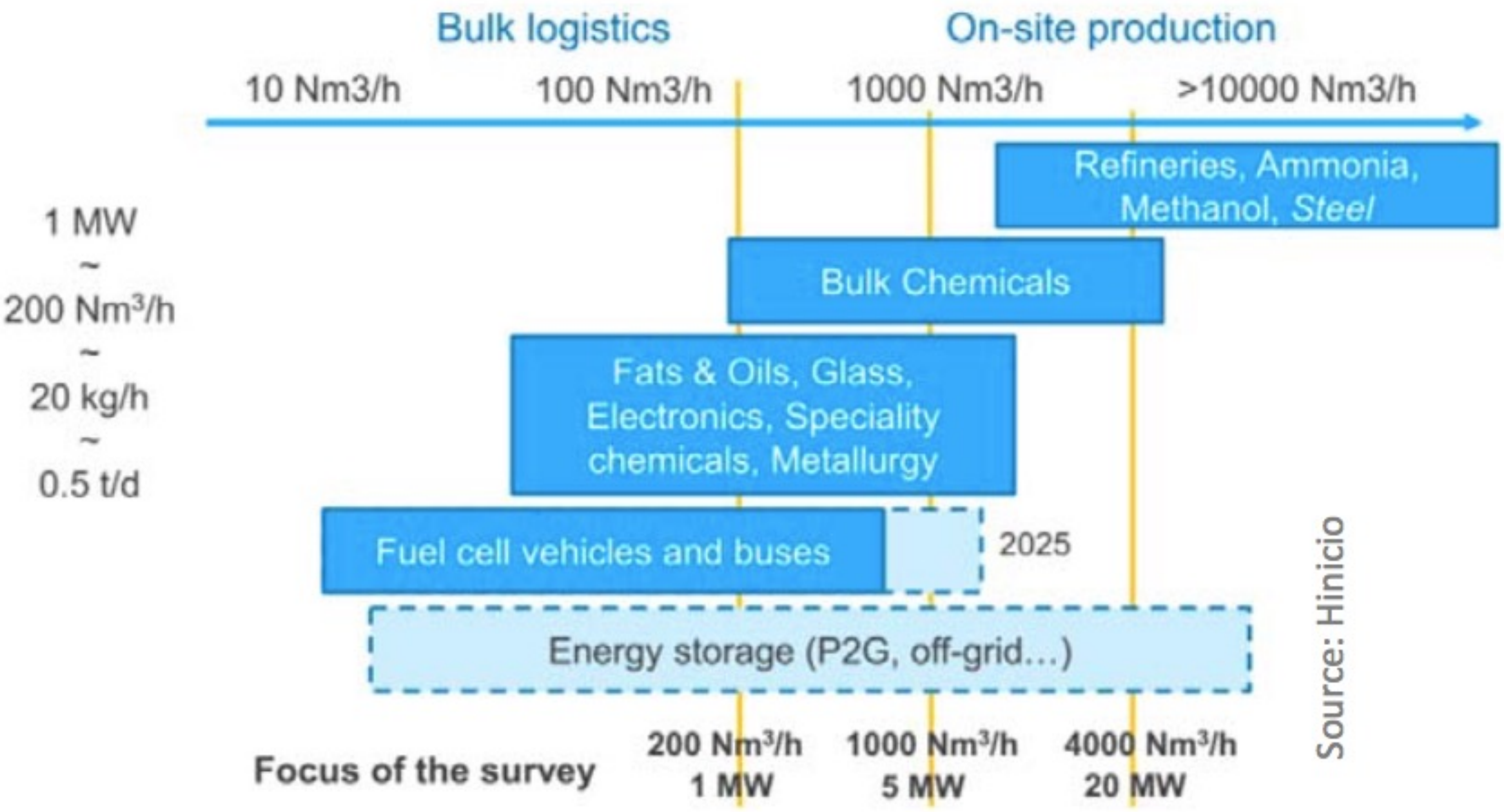
electrical grid: vulnerable

Cost of an extended black-out: 2-4 billion Fr / day

gas grid: safer

https://www.babs.admin.ch/fr/aufgabenbabs/gefaehrdrisiken/natgefaehrdanalyse.html

Electrolyser sizes (100 kWe - 10 MWe)



Source: Hinicio

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
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Largest electrolysers to date:

- 08.02.2021, 20 MWe PEMEL :

https://www.airliquide.com/fr/magazine/transition-energetique/inauguration-du-plus-grand-electrolyseur-pem-au-monde

- 18.01.2021, 88 MWe Alcaline EL :

https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/first-green-hydrogen-project-becomes-reality--thyssenkrupp-to-install-88-megawatt-water-electrolysis-plant-for-hydro-quebec-in-canada-93778

Example: oil refinery

https://refhyne.eu/

Rheinland (Shell) (D)

Consumption: **180’000 t H_2** / yr (fossil)

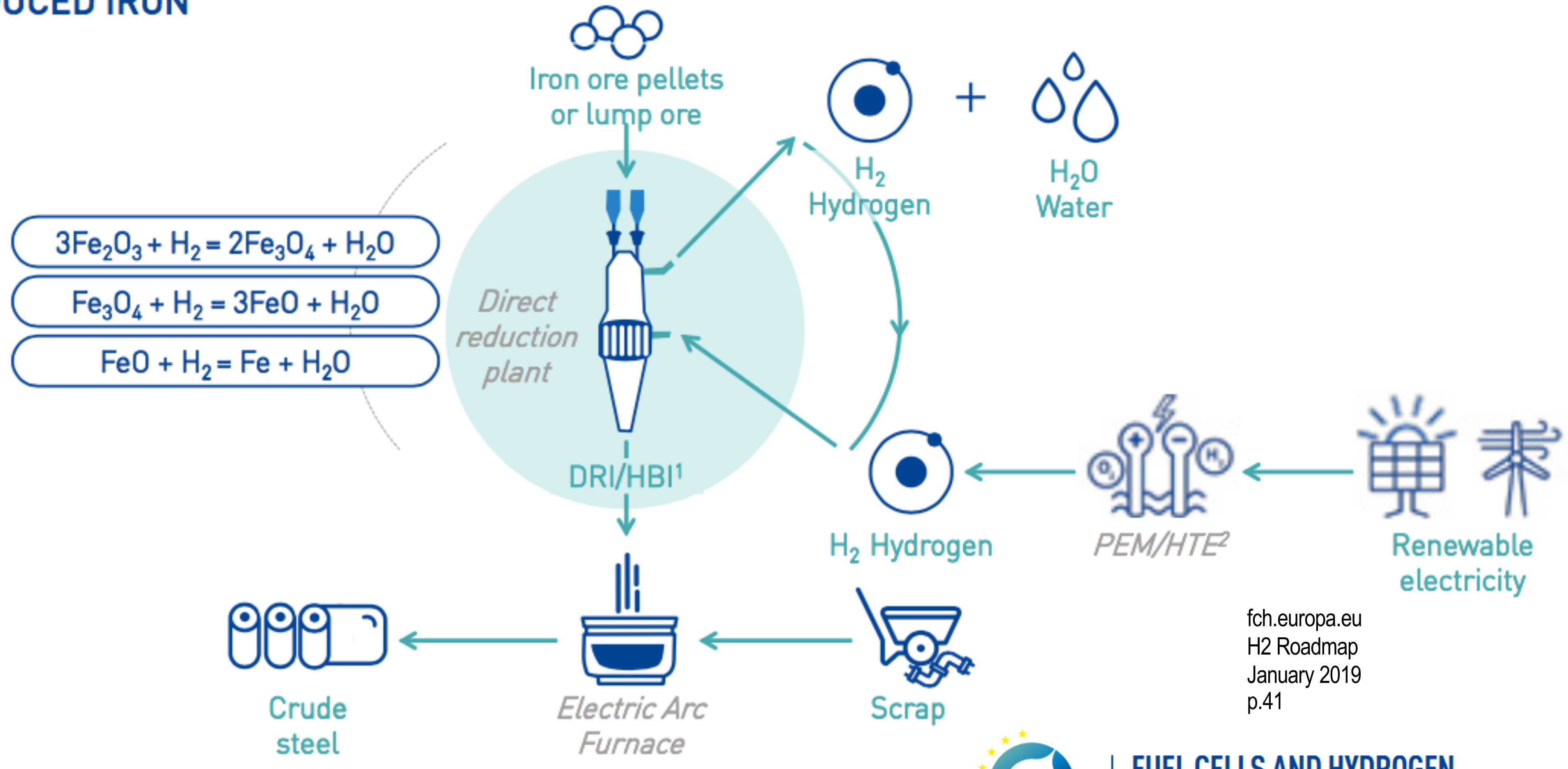
10 MWe PEM electrolyser:
=> supplies **1300 t H_2** / yr(<1% !!)

REFHYNE
CLEAN REFINERY HYDROGEN FOR EUROPE
2018-2022

FCH | FUEL CELLS AND HYDROGEN JOINT UNDERTAKING
10 M€

H_2 for steel making : DRI

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



$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$

$Fe_3O_4 + H_2 = 3FeO + H_2O$

$FeO + H_2 = Fe + H_2O$

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H2 Roadmap
January 2019
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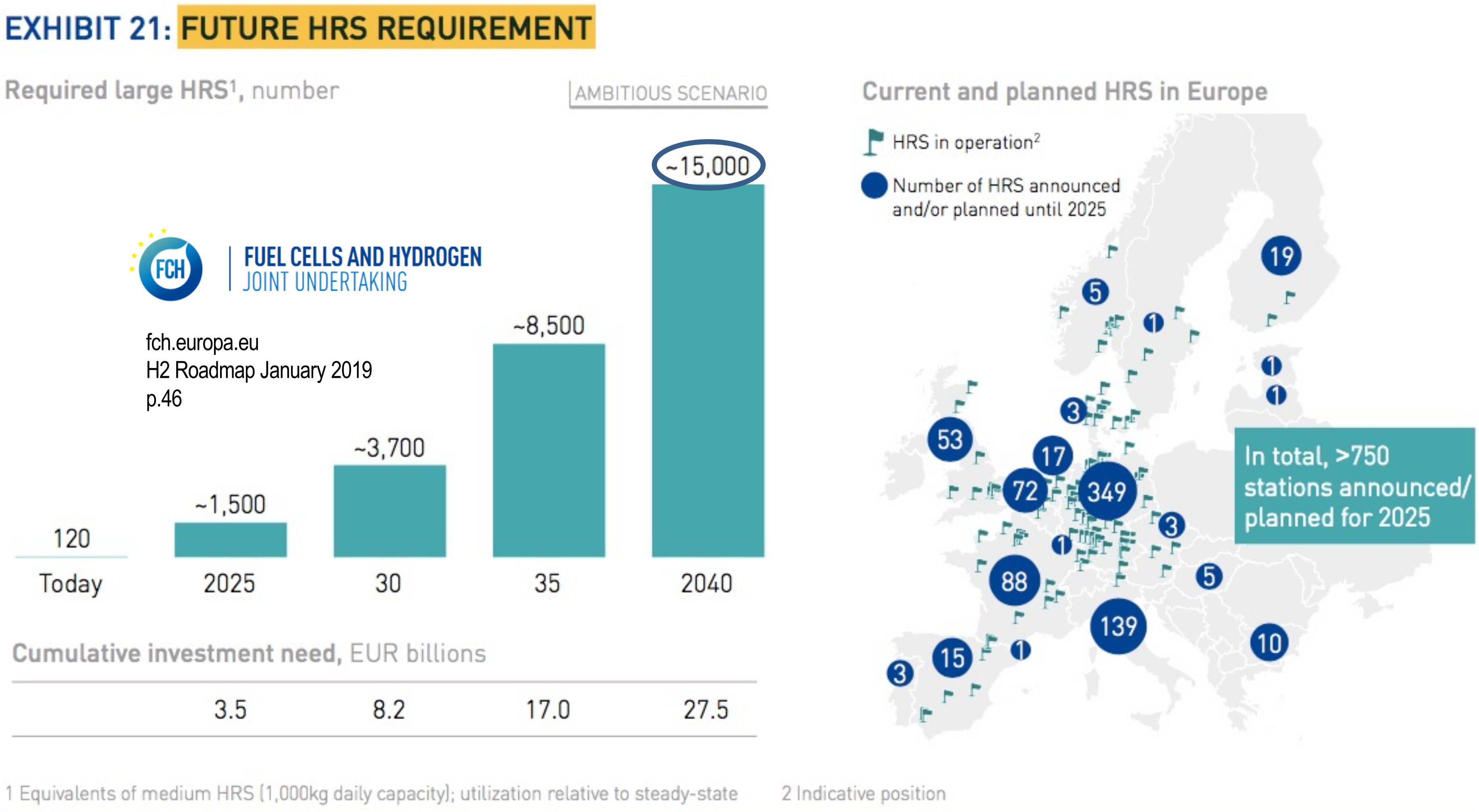
[1] Direct reduced iron/hot briquetted iron

[2] Polymer electrolyte membrane electrolysis/high temperature electrolysis

Mobility: H_2 refueling stations (HRS)

EXHIBIT 21: FUTURE HRS REQUIREMENT



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

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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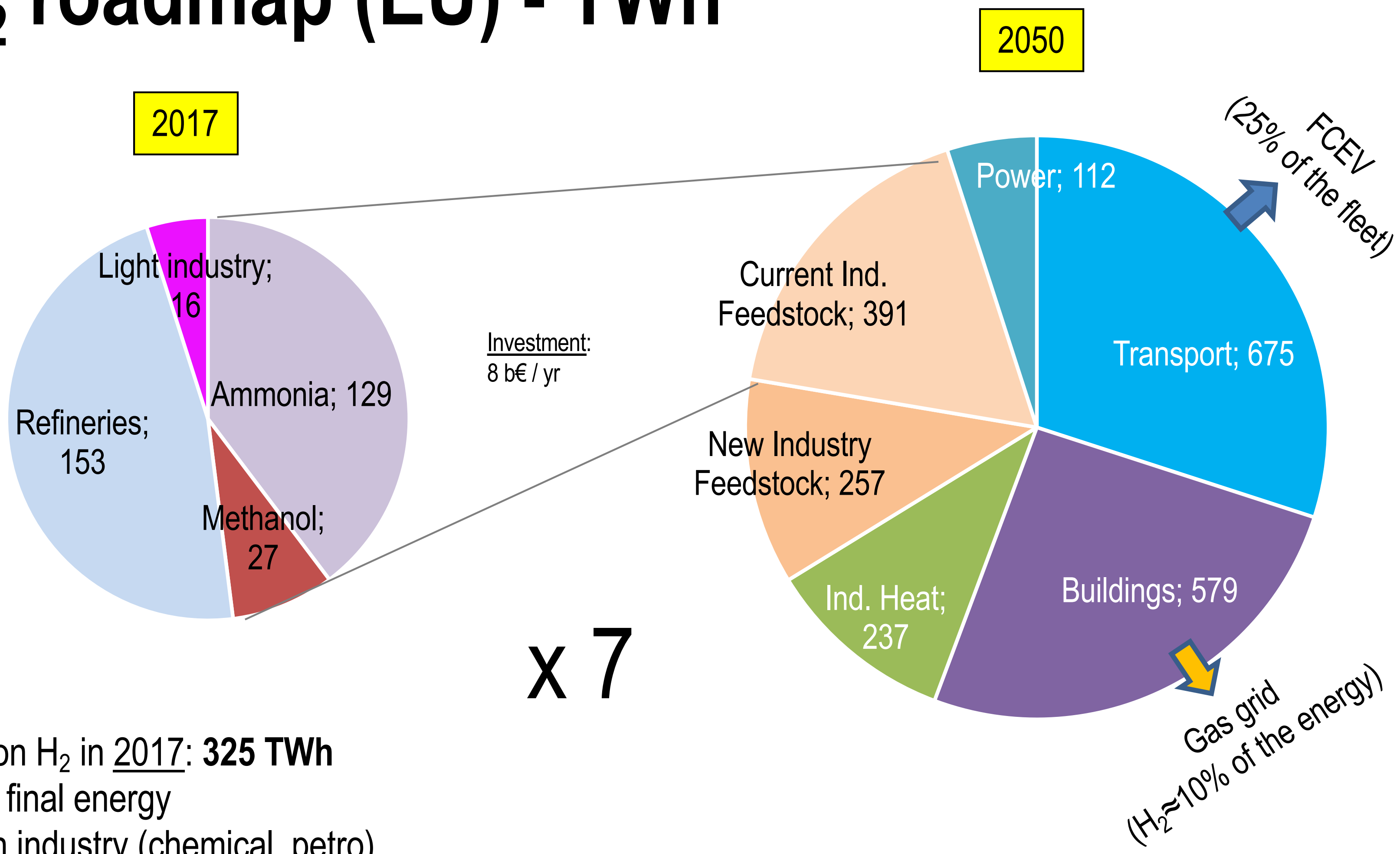
1000 kg H_2/day/HRS
=> x 15’000 HRS = 15 Mt H_2/day = 5.5 Gt H_2/yr = 198 TWh (712 PJ), >50 GWe

H_2 roadmap (EU) - TWh



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 in all sectors

(equivalent electrolysis* : **385 GWe)**

**100% load, 67% LHV efficiency electricity → H_2*

*>1100 GWe or **1.1 TWe** for electrolyser load of 3000h/yr*

Adapted from : H2 ROADMAP EUROPE:
A SUSTAINABLE PATHWAY FOR THE EUROPEAN ENERGY TRANSITION
fch.europa.eu - January 2019

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

13% of world electricity

- existing (EU): ≈2 GWe
- 66.7% LHV efficiency = **1.88V** electrolysis voltage (100% = 1.23 V)
- suppose: **1A/cm^2** current density
  => 1.88 W/cm^2 absorbed electrical 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 μm thick, polymer density ≈ 1 => 20. 10^6 m^2 x 50. 10^{-6} m = 1000 m^3 = **1000 tons** of polymer
- compare this to the annual plastics production of **330 Mtonnes** / yr
- for >1TWe installed capacity, quantities increase by factor >3
- in terms of electrolyte material, the quantity needed is thus extremely low

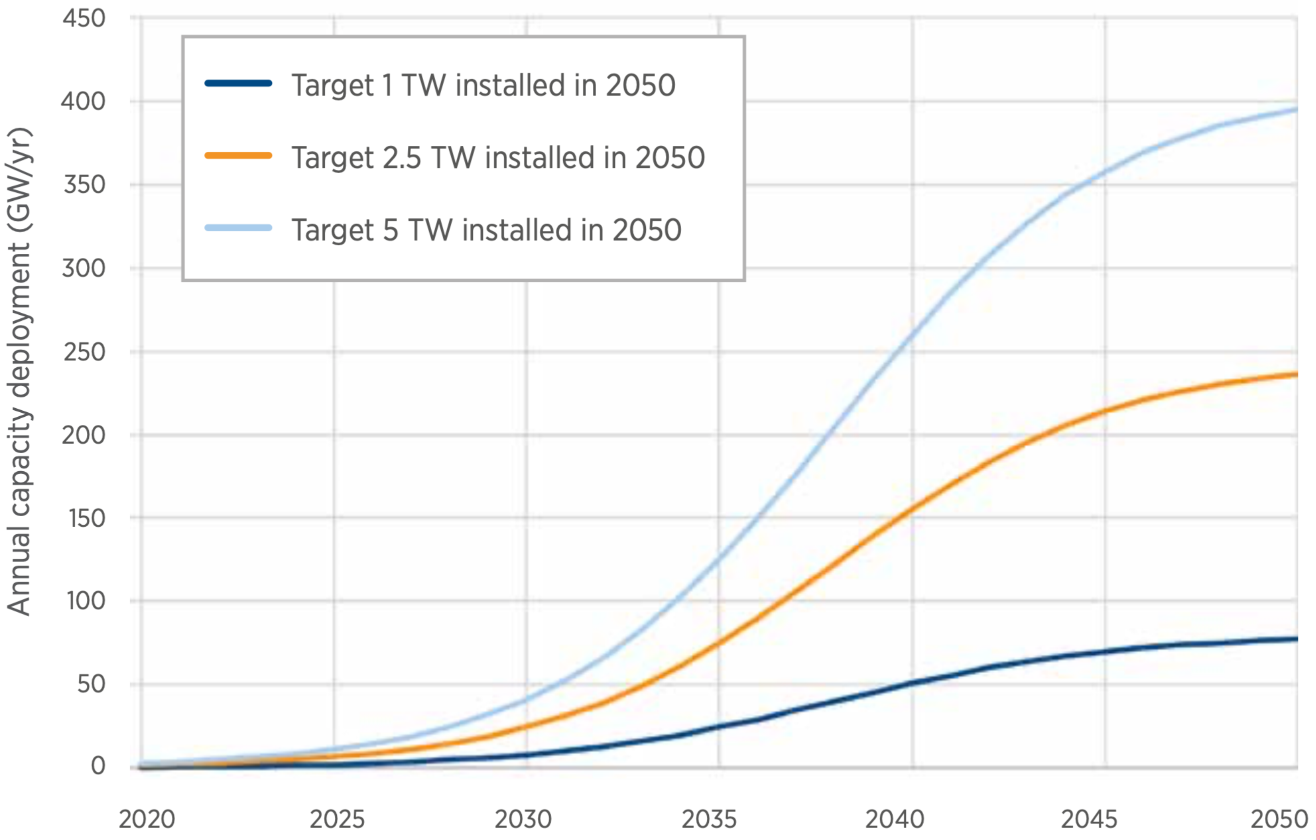
GWe/yr deployment needed

Figure 32. Estimated necessary electrolyser manufacturing capacity (GW/year) to meet different installed capacity targets by 2050.

IRENA (2020), *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.50C Climate Goal*, International Renewable Energy Agency. p.85

EU targets:
6 GWe – 2024
40 GWe – 2030

Important economies of scale above 1 GWe/yr production



Electrochemistry in industrial production

- For some important products, the only fabrication method is electrochemical (**Cl_2, NaOH**, **metal extraction,..**)
- Advantages of electrochemical methods:
  - high product selectivity (choice of catalyst and potential (V))
  - easy control of i, V; usually we use *normal* p and T (no excessive conditions)
  - high efficiency (energy cost = $\Delta G_r + \Sigma\eta =$ Gibbs free energy + the overpotentials)
- Disadvantages :
  - higher electricity cost vs. the cost of heat/fuels
  - hardware cost
- General rules :
  - choose low overpotential η for the desired reaction
  - …and high overpotential η for the secondary (side) reactions
  - use cheap catalysts (Fe, Ni, C, Pb,…)

Metal extraction

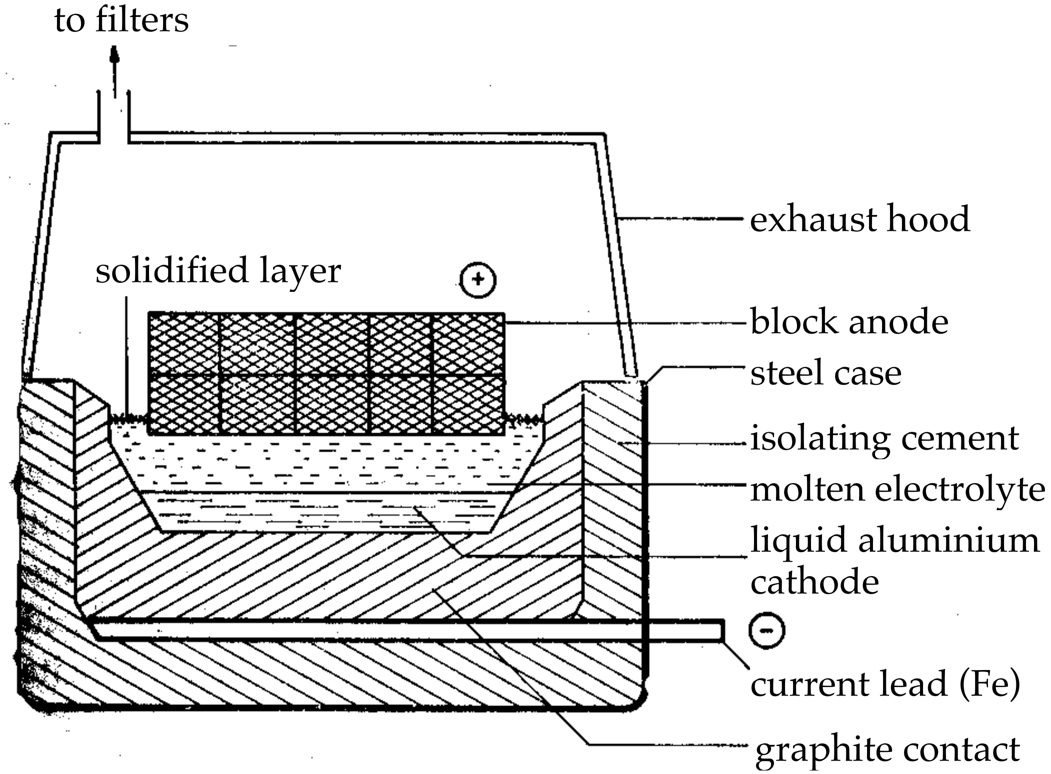
- Zn (for batteries)
- Cu, Ni, Co, … (purity)
- …

Al_2O_3 dissolves into the cryolithe molten electrolyte, to Al^{3+} and O^{2-}

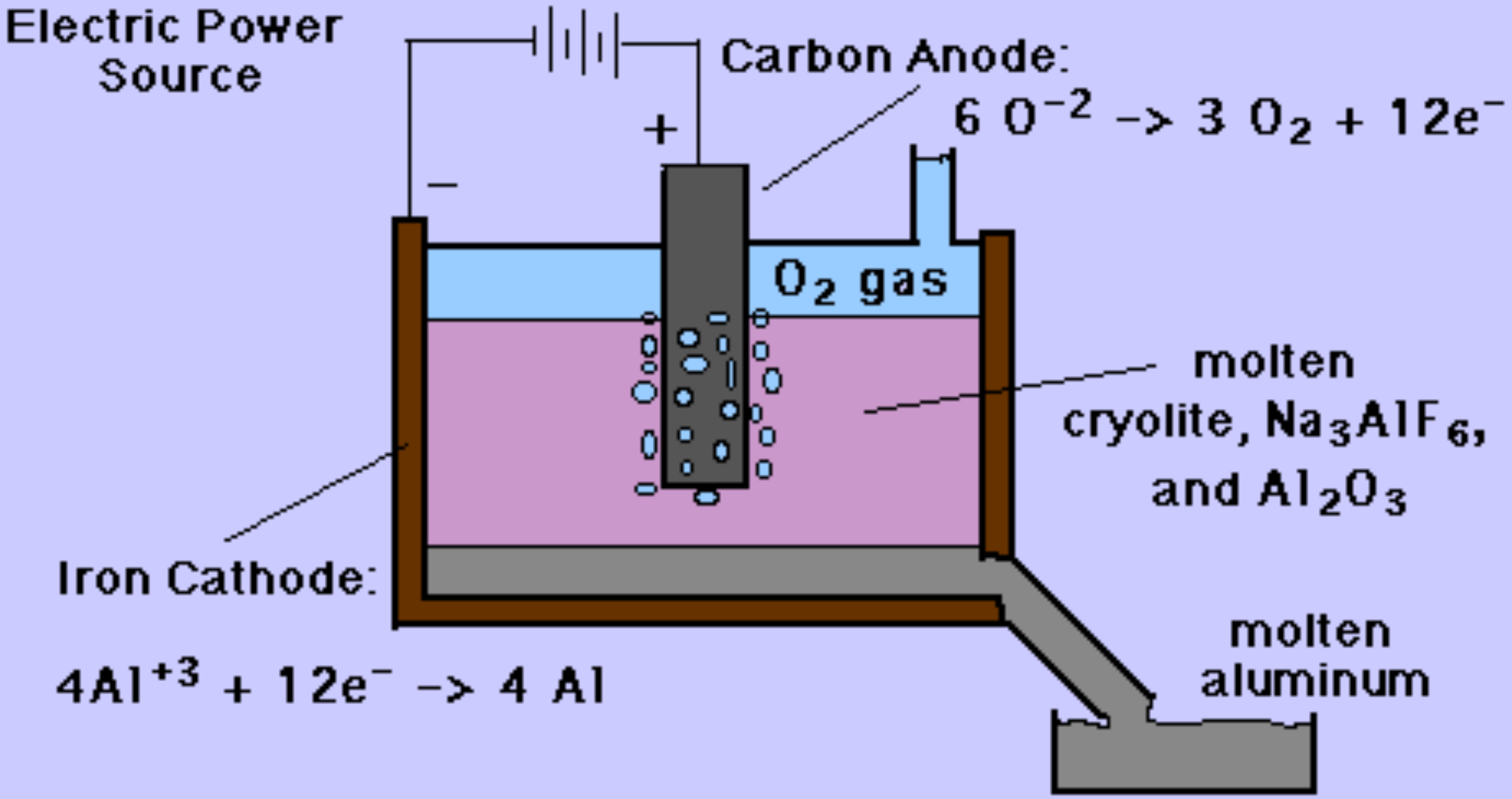
Cathode: $4Al^{3+} + 12e^- \rightarrow 4Al$

Anode: $6O^{2-} - 12e^- \rightarrow 3O_2$

Special case: Aluminium
= from a molten salt
at very high temperature



Electrolysis of Aluminum



Bauxite ore is purified to Al_2O_3, which is mixed with cryolite, a mixture of NaF and AlF_3, which melts at 1000 C.

C. Ophardt c.1997

http://www.elmhurst.edu/~chm/onlcourse/chm110/outlines/aluminum.html

Aluminium-industry

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

=> **960 TWhe**

(≈ 120 GWe)

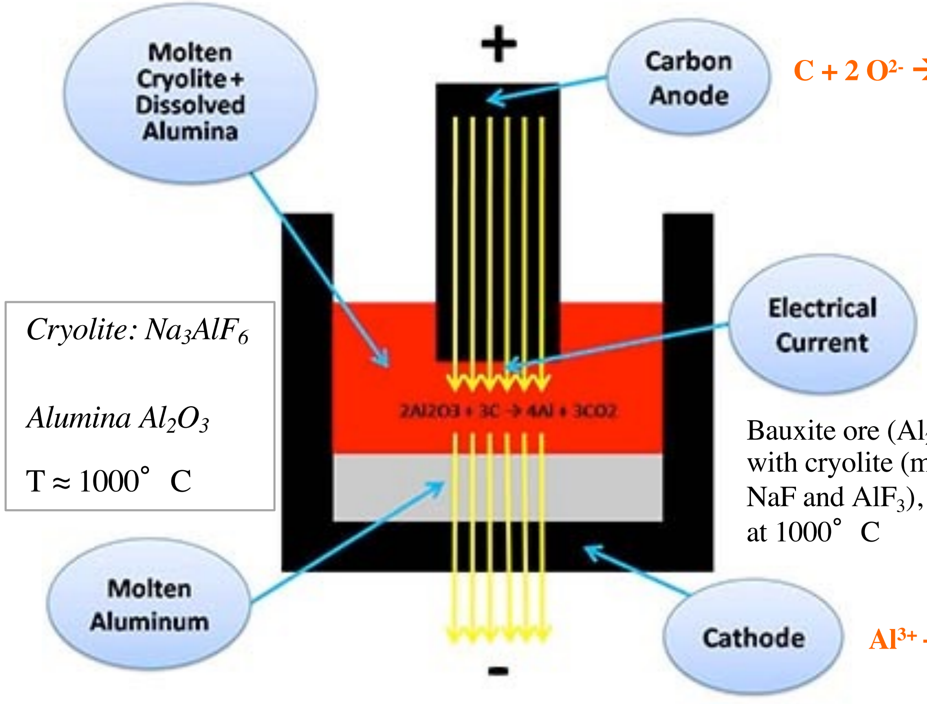
(≈ 4% of world electricity)

- 272 plants

(~0.5 GWe / plant)

Hall-Héroult Process (1886)

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



$C + 2\ O^{2-} \rightarrow CO_2 + 4e$

Cryolite: Na_3AlF_6

Alumina Al_2O_3

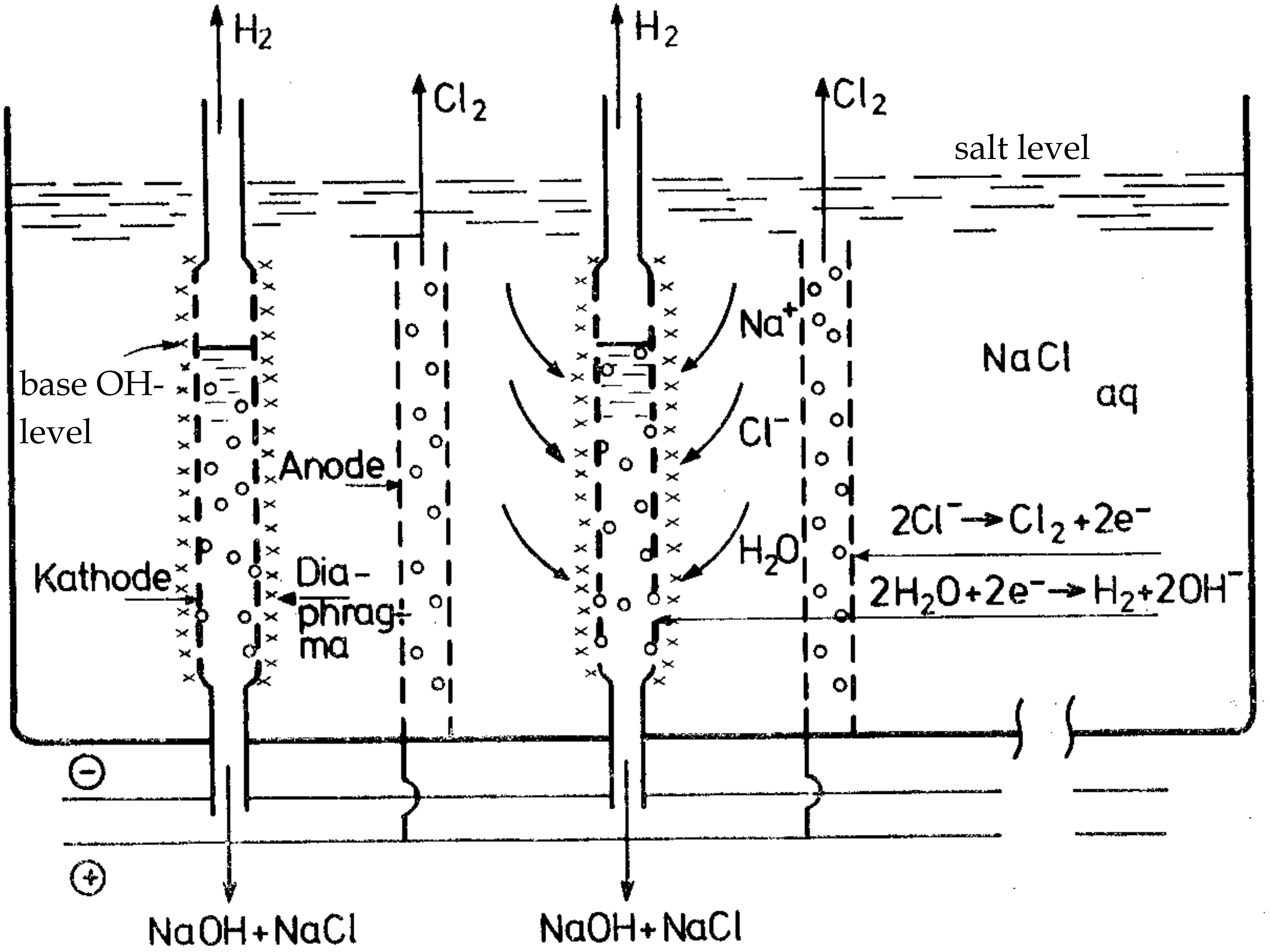
T ≈ 1000° C

Bauxite ore (Al_2O_3) is mixed with cryolite (mixture of NaF and AlF_3), which melts at 1000° C

$Al^{3+} + 3e \rightarrow Al$

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

Chlorine-alkali synthesis (Cl_2, NaOH)



Electrolytic H_2 : example of the chlor-alkali-industry

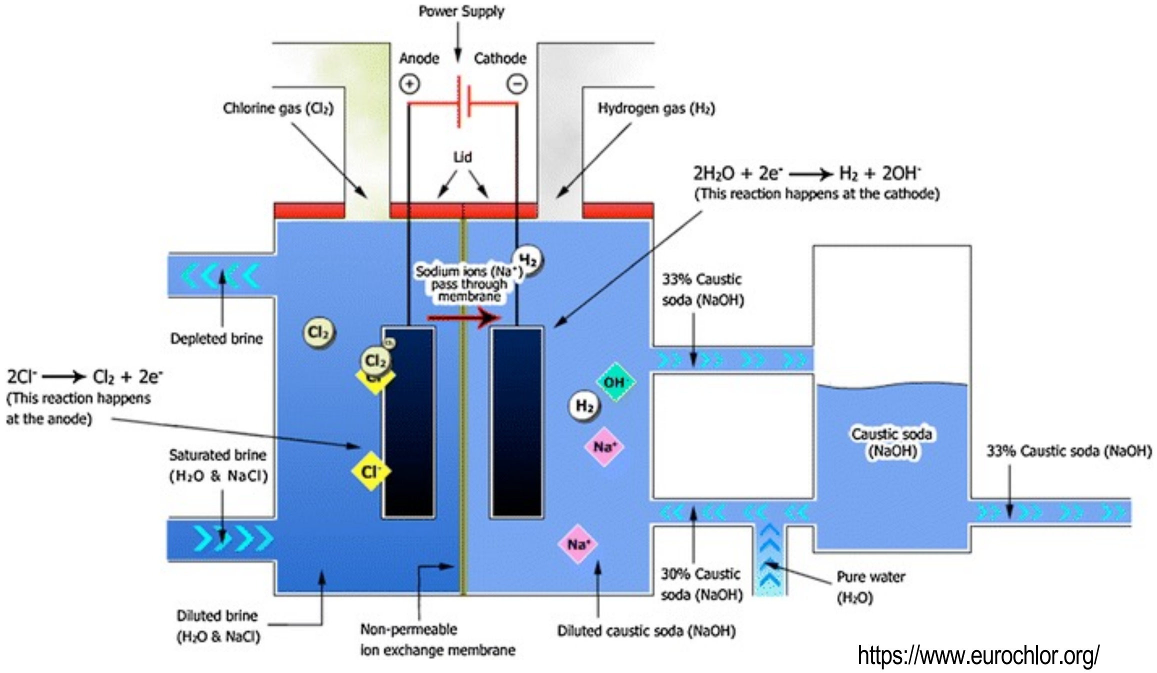
- Production 2017: 58 Mton Cl_2 (650 plants)
- Elec. consumption: 2.1 – 3.4 kWhe / kg Cl_2
- (for 2.5 kWhe / kg Cl_2) => **150 TWhe** consumed

  ≈ 20 GWe worldwide

  ≈0.6% of world electricity
- this co-produces 1.6 Mt H_2 = 54 TWh H_2, accounting for >½ of all electrolytic H_2
- ~30 MWe per plant

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

Chlorine-alkali synthesis

Cath. = Fe: $2H_2O + 2e^- \Leftrightarrow H_2 + 2OH^-$ -0.41 V

Anode= C: $2Cl^- \Leftrightarrow Cl_2 + 2e^-$ 1.37 V

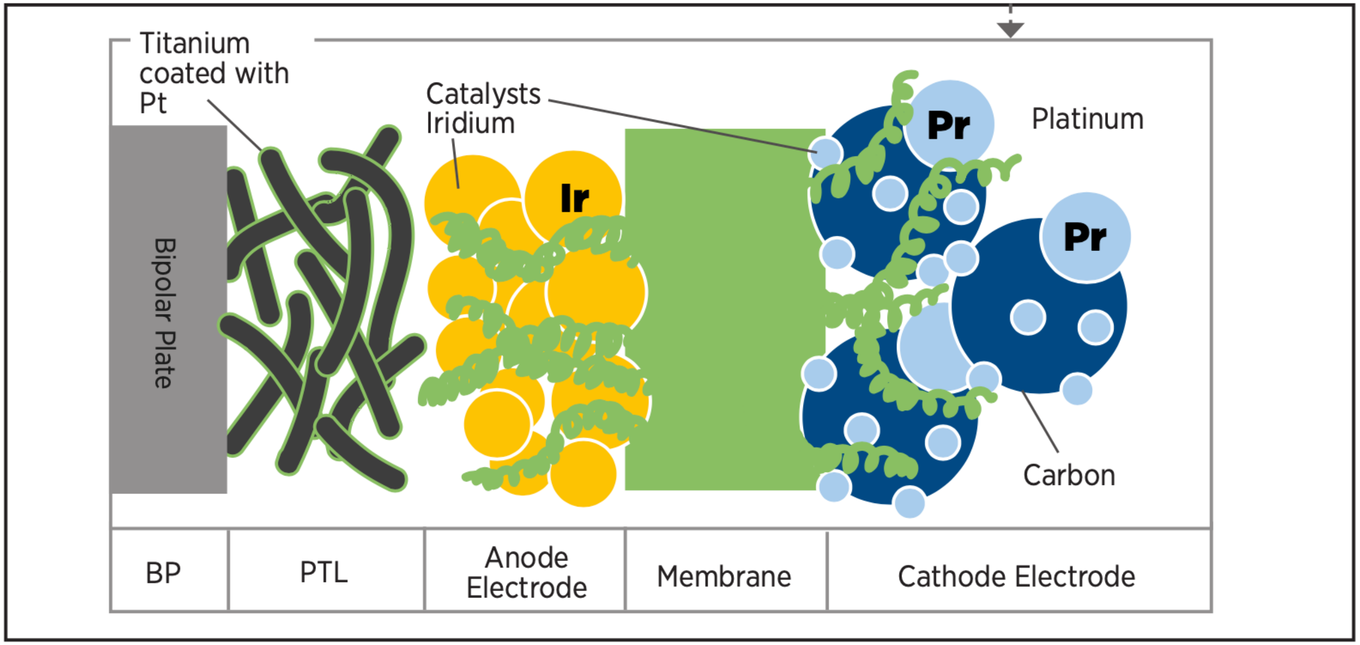
$2NaCl + 2H_2O \Rightarrow Cl_2 + H_2 + 2NaOH$ 1.8 V theor.

- Graphite : high anodic overpotential η (on purpose!) for O_2 evolution (so as to prevent water electrolysis (>1.23V) !)
- Real electrolysis voltage = 4 V (E_o = 1.8 V), 0.25A/cm^2, 40 m^2, 100’000 A (400 kW per cell)
- Losses bwt real and theoretical voltage (4 V - 1.8 V) :
  - charge transfer loss $\eta_{a,CT}$ for Fe/H_2 (0.2 V)
  - mass transfer overpotential losses $\eta_{a,conc}$, $\eta_{c,conc}$
  - ohmic drop in electrolyte (0.4 V; distance between electrodes = 1 cm)
  - Nernst potential displacement by alcaline medium (OH^-) (0.5 V)

Critical materials in PEMEL

IRENA (2020), *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.50C Climate Goal*, International Renewable Energy Agency p.28.

BiP Ti coated with
Pt on anode (O_2) and
Au on cathode (H_2)
represents 50% of stack cost;
noble metal catalysts 10%.



Porous transport layers: 1-5 mg Pt/cm^2 (2.5 g Pt/kWe)

IrO_2 tends to dissolve : high load of 2-5 mg/cm^2

Platinum Group Metals

- Pt (4 ppb), Pd (6 ppb), Rh (1 ppb), Ru (1 ppb), Ir (0.4 ppb)
- Exploitable reserves 71’000 t (proven: 100’000 t; 30’000t Pt; 1’500 t Ir)
- Production: 200 t/yr each for Pt, Pd (a cube of 2 m edge), 500 t/yr all PGM
- >150 years depletion time
- Extremely concentrated in S-Africa (90% of reserves), RUS (8%), who are the main producers. Small producers are CAN, USA, Zambia.
- >50% of use is as automotive exhaust catalysts – compulsory since 1993
  - 1000 t Pt / Pd in 1 billion cars now (1g per car)
  - 40 t / yr is recycled
- Other uses: ammonia, oil additive (for combustion), electronics (hard discs, optical fibres), glasses (liquid crystal), medicine (anti-carcinogenic)

Pt cathode / IrO_2 anode in PEMEL

- Pt example:
  - 2V, 2 A/cm^2 = 4 W/cm^2
  - 0.2 mg Pt/cm^2 cathode, 1.8 mg/cm^2 PTL, total 2 mg/cm^2
  - => 0.5 g Pt / kWe => 1 kg Pt / 2 MWe
  - suppose 20 t Pt/yr (10% of production) is dedicated to electrolysis
    => can support 40 GWe / yr
  - Remark: 1 FCEV uses 3g Pt too !
- Ir example:
  - 5 mg/cm^2 Ir
  - => 1.25 g Ir / kWe => 1 kg / 800 kWe
  - total (!) production of 8 t Ir/yr can support only 6 GWe / yr

Nickel

- Inox steel (=60% of Ni use) – austenitic
  - relatively easy to recycle
  - unreplacable as inox steel
- Special alloys (25% of use)
- Coatings (10% of use)
- **Catalysts**, electronics (5% of use)
- Example AEL (/SOE):
  - 0.5A/cm^2, 2V, 1W/cm^2, 10 mg Ni/cm^2
  - => 10 mg Ni / W => 10 kg / MWe => 10 kton / TWe
  - only 0.4% of annual Ni production of 2.7 Mt (=100 kt/yr) would support 1 TWe deployment

Metal uses today

1. **Fe** by very far the largest : 2500 Mt/yr *(= covering Malta* with 1 m of Fe)*

2. 'Larger' industrial metals >1 Mt/yr

   *Al 60 / Cr 44 / Cu 20 / Mn 20 / Zn 13.5 / **Ti 8.5** / Si 6.7 / Pb 5 / **Ni 2.7** Mt/yr*

   (=covering Malta with 1 mm of Ni)

3. 'Smaller' industrial metals < 1 Mt/yr:

   *Mg 1 / Sn 0.33 / Mo 0.25 / **Co 0.14** / V 0.11 / W 0.085 / **Li 0.082** / Cd 0.025*

   (=covering Malty with 50 μm of Co)

4. Precious metals :

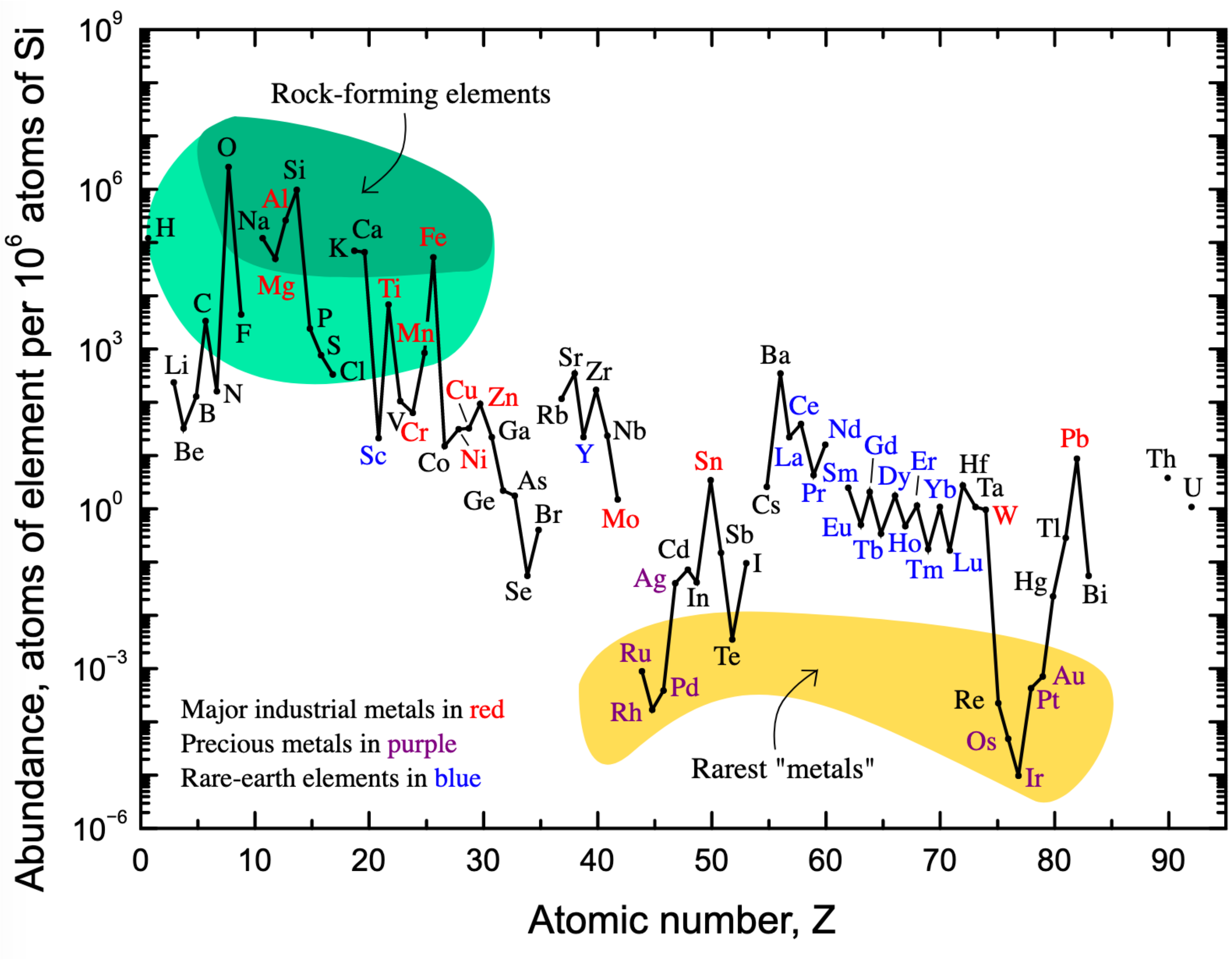
   *Ag 27'000 t, Au 3300 t, **PGM** 500 t (Pt 200 t, Pd 200 t, Rh 22 t, Ir 7 t)*

   (=covering Malta with 8.5 μm Ag, 0.56 μm Au, 31 nm Pt, 1 nm Ir)

*Malta surface: 316 km^2

Densities: Fe 7.87 Ni 8.9 Co 8.9 Ag 10.5 Au 19.3 Pt 21.5 Ir 22.5 t/m^3

Relative abundance of elements



Reserves of metals

	Metal	wt% crust	Proven reserves*	Prod. / yr	Depletion time (yrs)	Cost €/kg	Geodistribution – top 3 countries	Energy footprint
abundant	Fe	5%	200’000 Mt	2500 Mt	80 yrs	1	47% (RUS/UKR, AUS, BRA)	0.5 toe/t
	Al	8%	10’000 Mt	60 Mt	200	2	57% (AUS, BRA, CHN, Guinea)	5.6
	Ti	0.4%	1000 Mt	8.5 Mt	120	20	67% (AUS, CHN, BRA, IND)	12
rare	Ni	90 ppm	150 Mt	2.7 Mt	50	20	57% (AUS/NZ, RUS, CAN)	3.6
	Co	40 ppm	15 Mt	140 kt	100	50	58% (RDC, AUS, CAN)	
very rare	Ag	70 ppb	800 kt	27 kt	30	600	44% (Peru, Mex, CHN)	
	Pt	7 ppb	100 kt	200 t	500	24’000	92% (S-Afr, RUS, CAN)	
	Au	4 ppb	100 kt	3300 t	30	48’000	34% (S-Afr, CHN, AUS)	
	Ir	<1 ppb	1.5 kt	8 t	175	140’000	100% (S-Afr, (ZIM, RUS))	

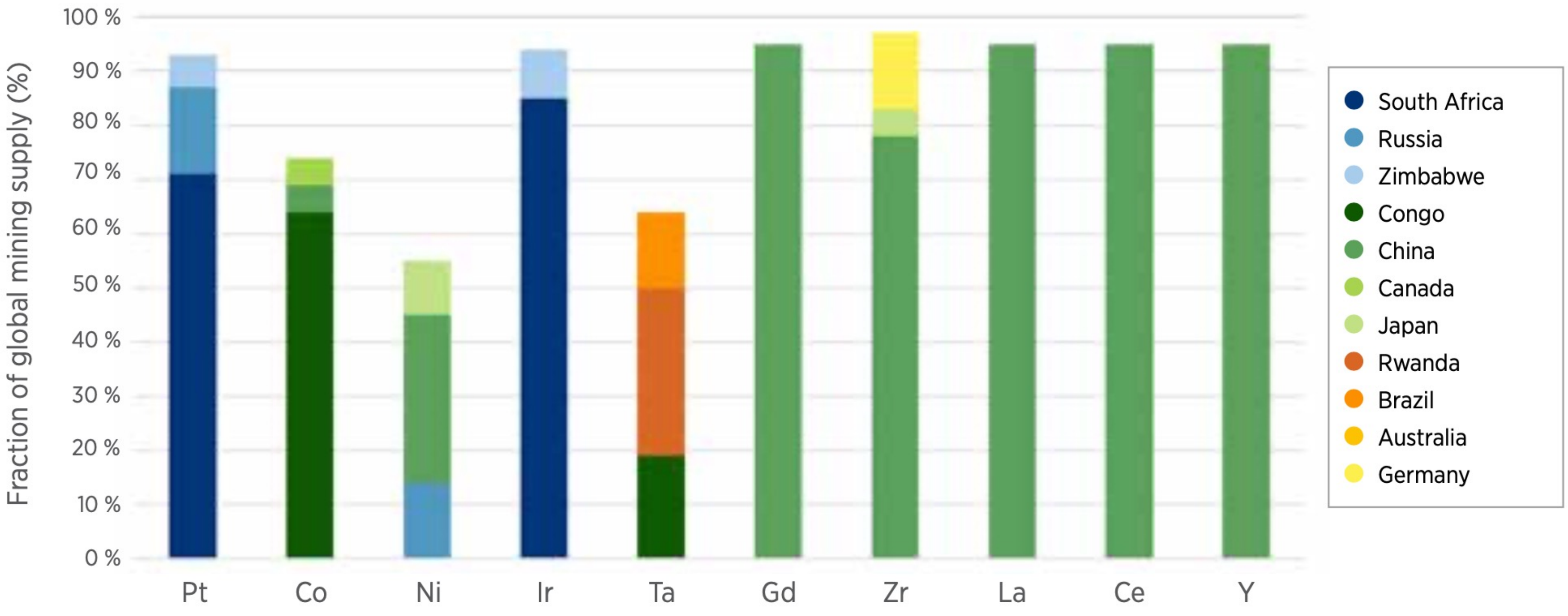
*Currently exploitable reserves ≈ ½ proven reserves ≈ only 0.01 - 0.1% of natural abundance for the rare elements

Noble metals highly concentrated in 1 country (South-Africa)

Critical materials

IRENA (2020), *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.50C Climate Goal*, International Renewable Energy Agency p.69.

Figure 24. Top producers of critical materials in electrolysers.



Source: European Commission, 2020.

General comments on metal scarcity

- Metal resources are, like fossil resources, finite. Extraction cost and energy use increase, as resources get depleted.
- Between 1995-2015, the world metal consumption has doubled.
- 100% recycling is an illusion, because of the 2nd law of thermodynamics (dispersion; quality loss upon each recycle)
  - examples of dispersive uses: dyes, pigments, catalysts, fertilisers, additives, coatings, galvanisation, solders
- Alloy fine-tuning for the pursuit of hi-tech components, or the high purity requirements of some metals, are antagonistic with recycling
  - e.g. >3000 Ni-alloys exist

Large scale green H_2 electrolysis deployment

- Several TWe cumulated installed power will be needed
- Demands massive scaling and cost reduction
- 1st cost in electrolysis = electricity consumption => high efficiency is key
- 2nd cost in electrolysis = electrolyzer => can be brought down by:

large scale production, increased lifetime,

more operating hours (3000-4000 h/yr), use of non-critical materials

- AEL: should be Pt- and Co-free; only Ni-based
- PEMEL: Pt and Ir use should drop by 10x. Alternatives to coated Ti BiP.
- AEMEL (Ni, Fe based): could be game-changing if durability and performance catch up
- Materials importance: criticality, purity, alloying and ease of recycling

Electro-organic synthesis

- for specific organic reactions: selective oxidation, hydrogenation, halogenation, dimerisation, organometal complexing,..
- catalyst adsorbates are exploited in the synthesis steps

  e.g. selective formaldehyde synthesis

$$\mathrm{Pt + H^+ + e^- \Rightarrow Pt - H \xrightarrow{R} R - H + Pt}$$

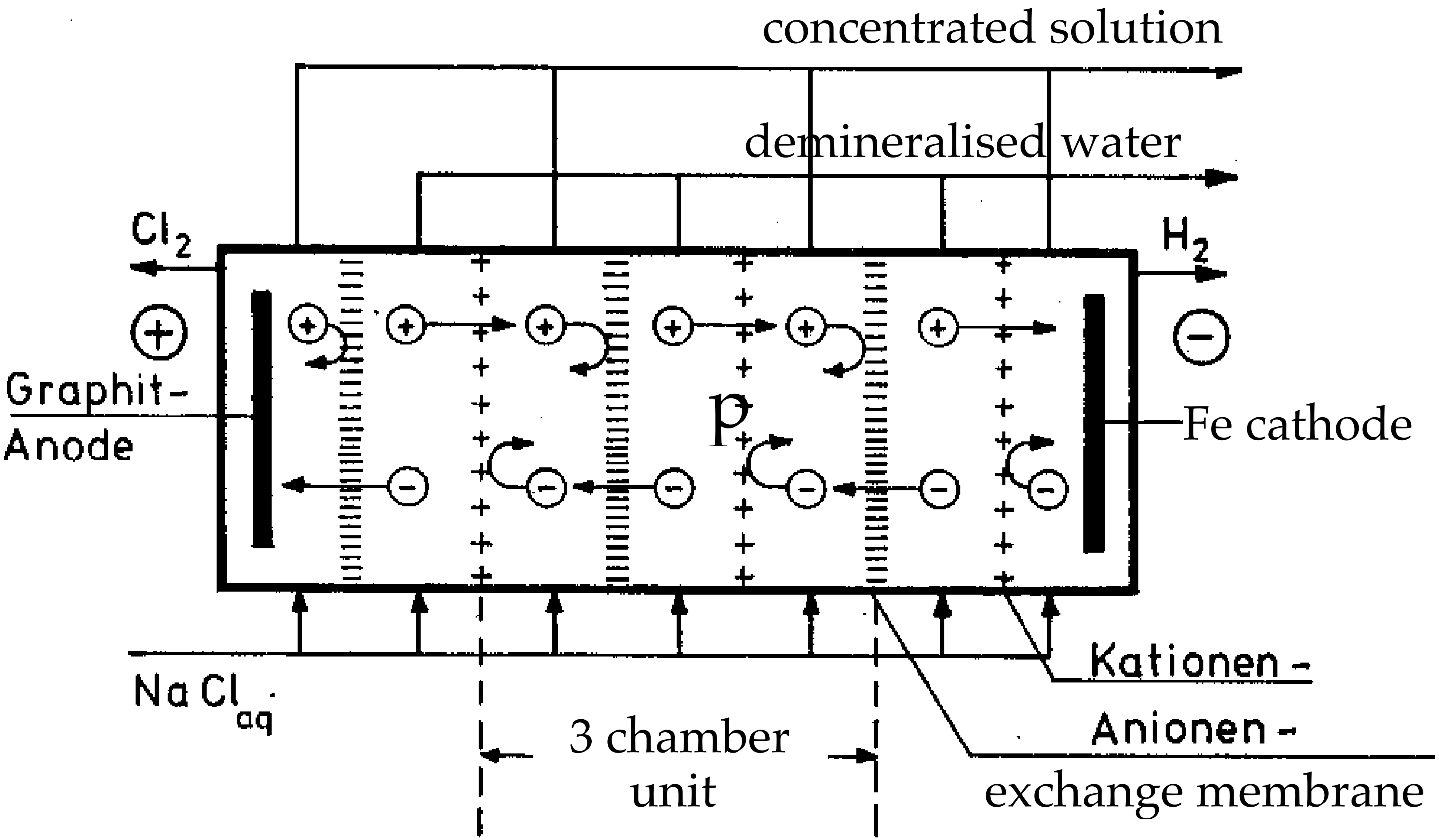
$$\mathrm{CH_3OH + Pt - O \Rightarrow CH_2O + H_2O + Pt}$$

- issue: organic salt-solvent mixtures have low conductivity (=> higher ohmic drops)
- maximisation of area/volume ratio is needed
  - ○ small electrode distances (<100 μm)
  - ○ electrodes with high inner surface (porous, rough)

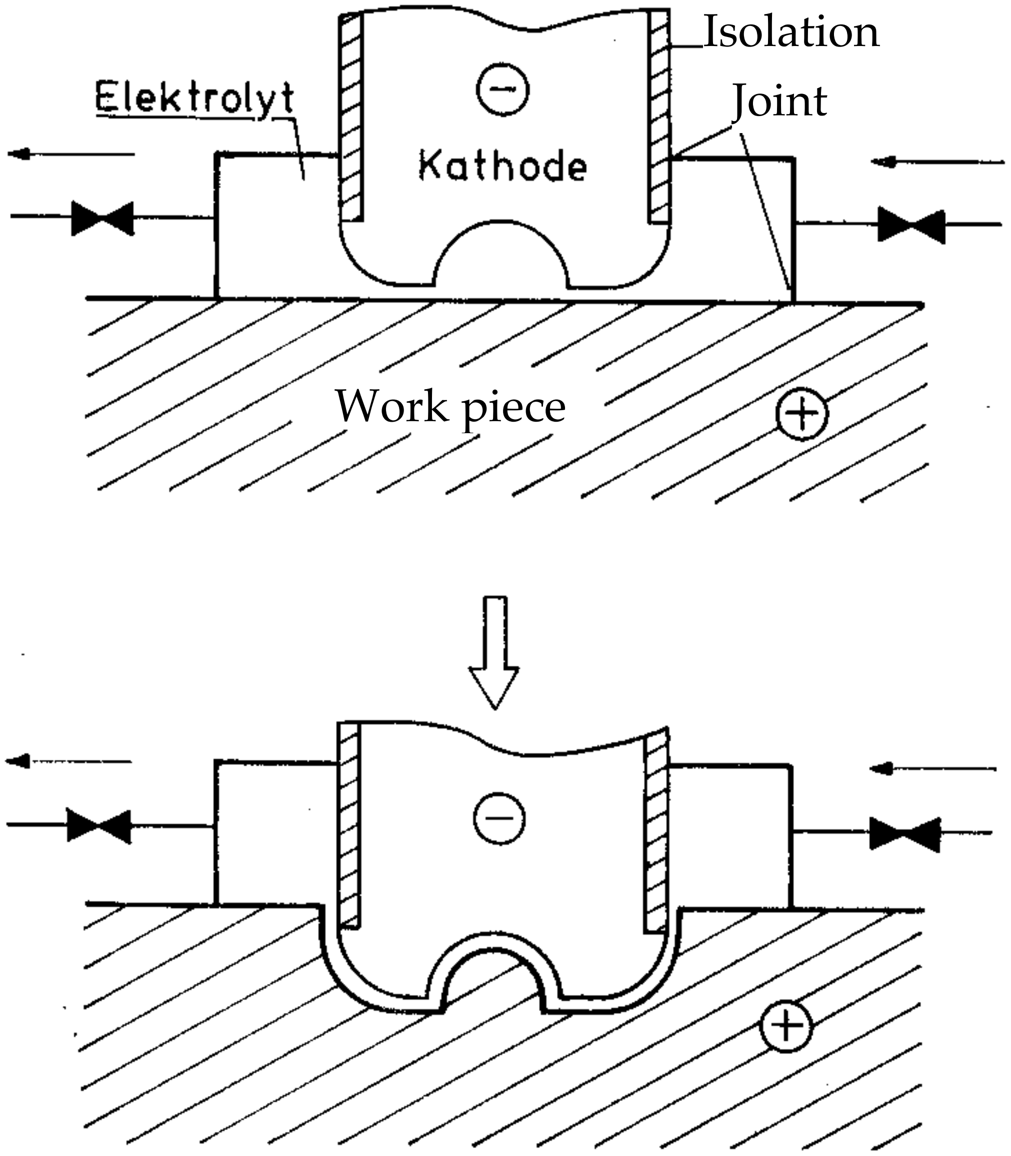
Special electrochemical applications

- Water purification (ClO^- for desinfection, trace metals)
- Electrophoresis
- Metallurgical powders (for catalyst fabrication)
- Electropolishing, electromachining
- Galvanoplastics
- Corrosion protection
- Pollution control sensors (λ-sensor)

Water desalination



Electromachining/polishing



Passivation (corrosion protection)