Electrochemistry for Materials Technology

ENERGY APPLICATIONS

MER Dr Jan Van herle
EPFL-Valais GEM (Group of Energy Materials)
gem.epfl.ch

ELECTROLYSIS

H_2 from H_2O electrolysis

- H_2 hardly occurs naturally on Earth (‘white’ H_2)
- It stems mainly from fossil sources; this relates to H_2’s current uses (which is chemical, not energetical)
- Green H_2 can be made – via electrolysis - from variable renewable electricity (PV, wind, hydro) which is part of 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 high alternative potential, but must be made on a **massive scale (TW)**

H_2 rainbow

- **Grey H_2** : made from fossil sources
- **Blue H_2** : made from fossil sources but with carbon capture
- **Green H_2** : made from renewable sources
- **Yellow**/**pink** H_2 : from nuclear electricity

White H_2 : natural H_2 sites

Annual H_2 production

- ~100 Mt/yr ≈ 1.1 10^{12} m^3 /yr ≈ 12 EJ (3330 TWh) = 2% of world energy
  - 49% from natural gas
  - 29% from oil
  - 18% from coal
  - **4% from electrolysis** → mostly fossil

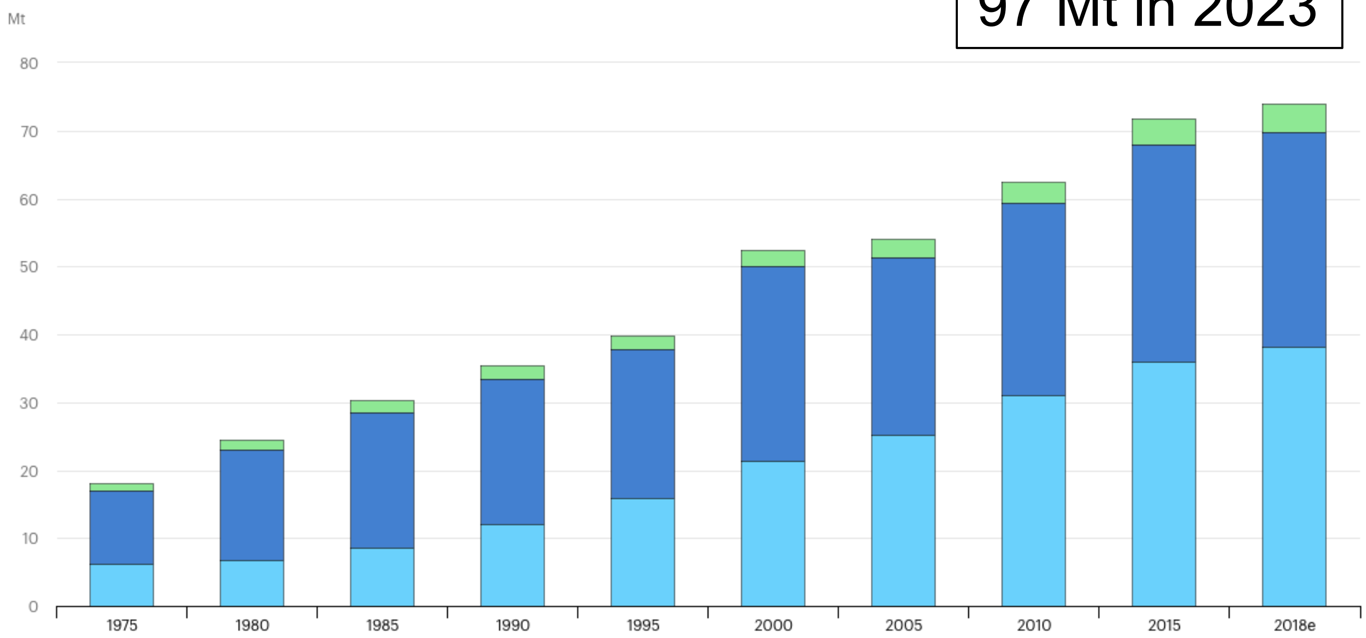
96% from fossil sources

= 4 Mt H_2/yr
= 44 bio m^3/yr
= 130 TWh H_2 (*LHV*)

↑ *67% efficiency*

200 TWhe electricity
(0.8% of world electricity)
~30 GWe

Global demand for pure hydrogen, 1975-2018



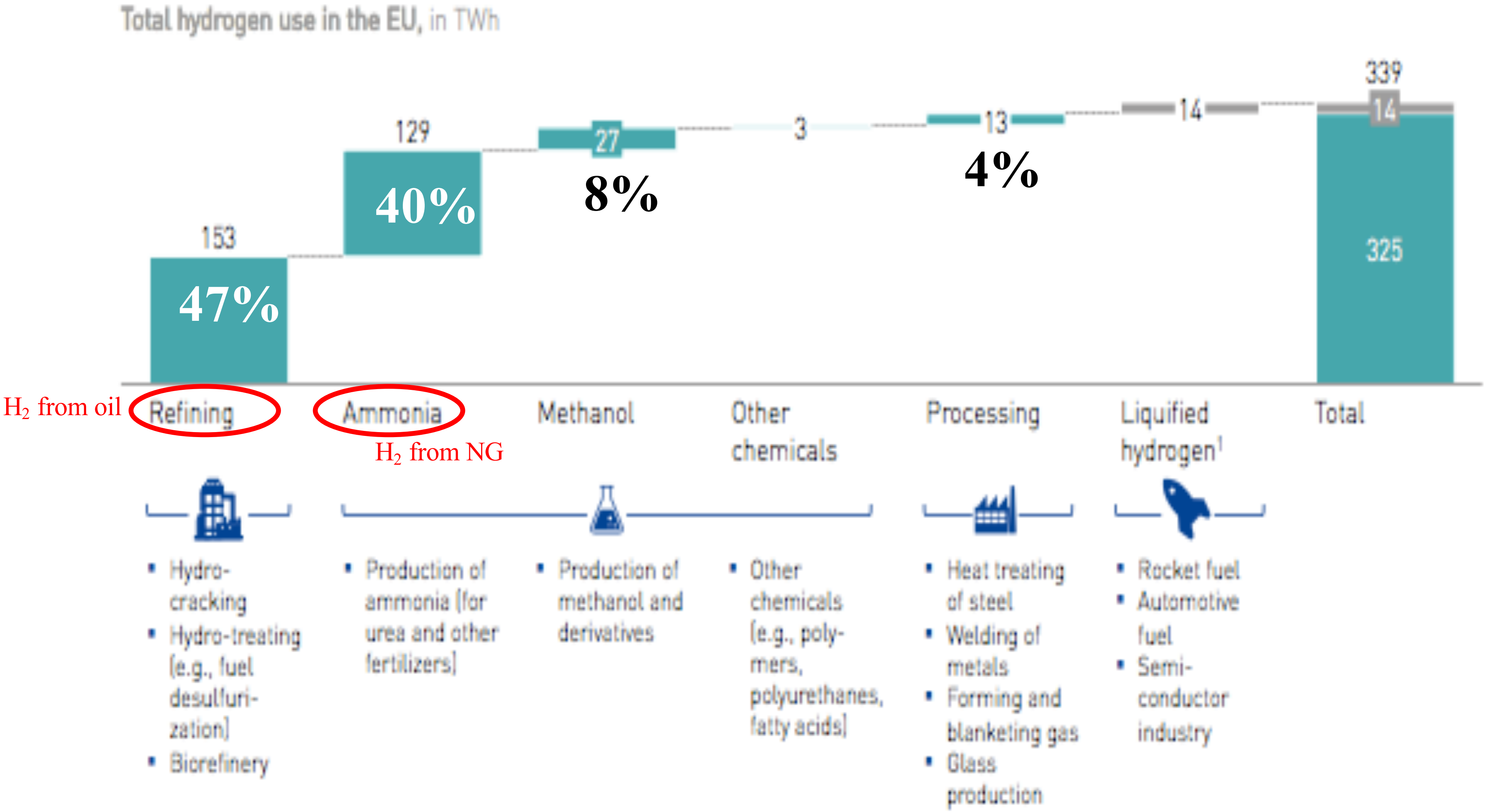
97 Mt in 2023

- 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



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

- Production of ammonia (for urea and other fertilizers)

- Production of methanol and derivatives

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

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

- Rocket fuel
- Automotive fuel
- Semi-conductor industry

H_2 current uses (EU)

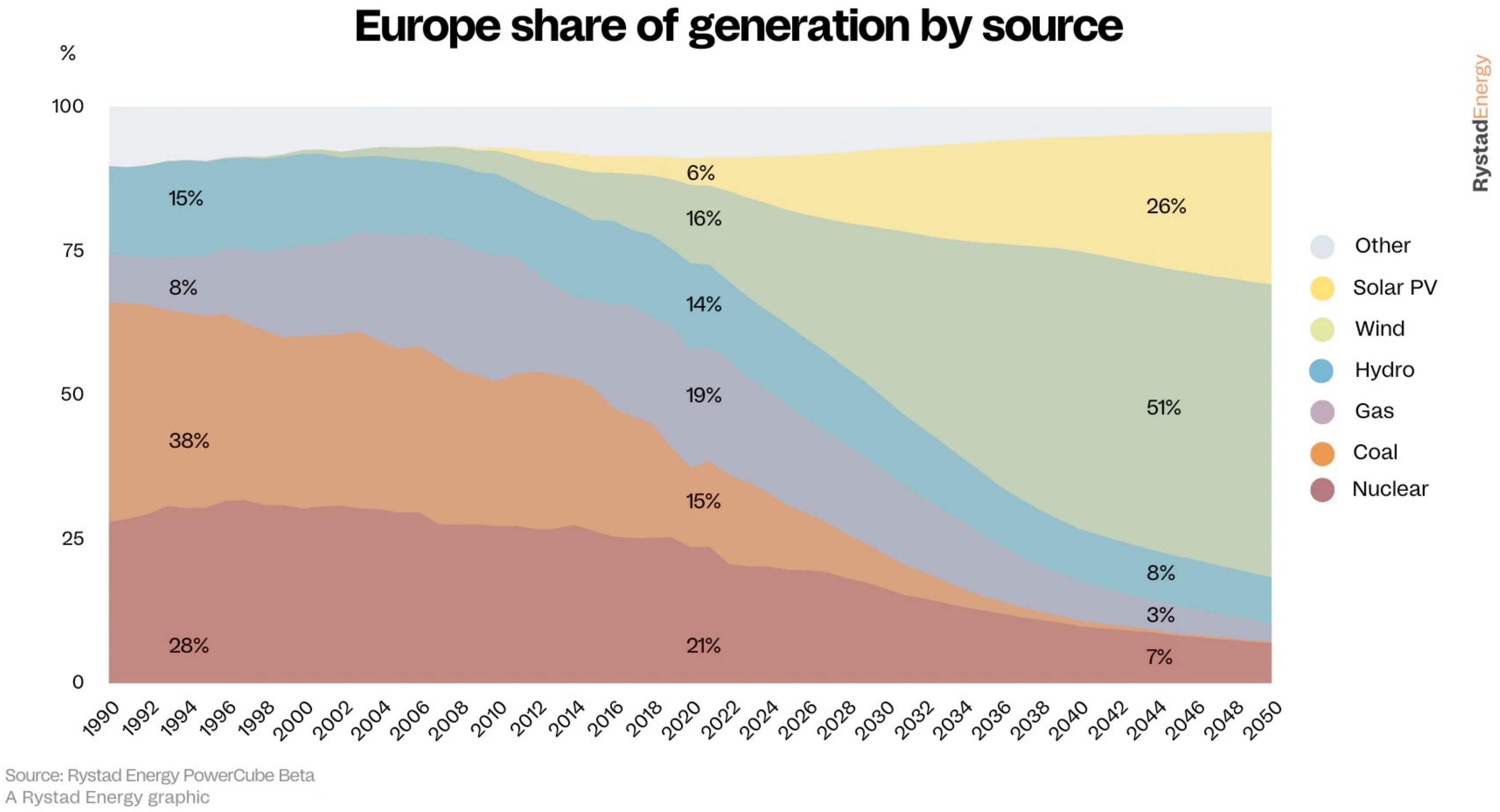
- **Refineries** (47%): hydrodesulphurisation (HDS), hydro-cracking
- **Ammonia** (NH_3) production (fertiliser) (40%)
- Methanol (8%) and other chemicals (1%)
- 'Light' industries (4%): where *reducing* atmosphere is needed
  - metal treatment
  - semiconductor industry
  - glass making (floating on 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)

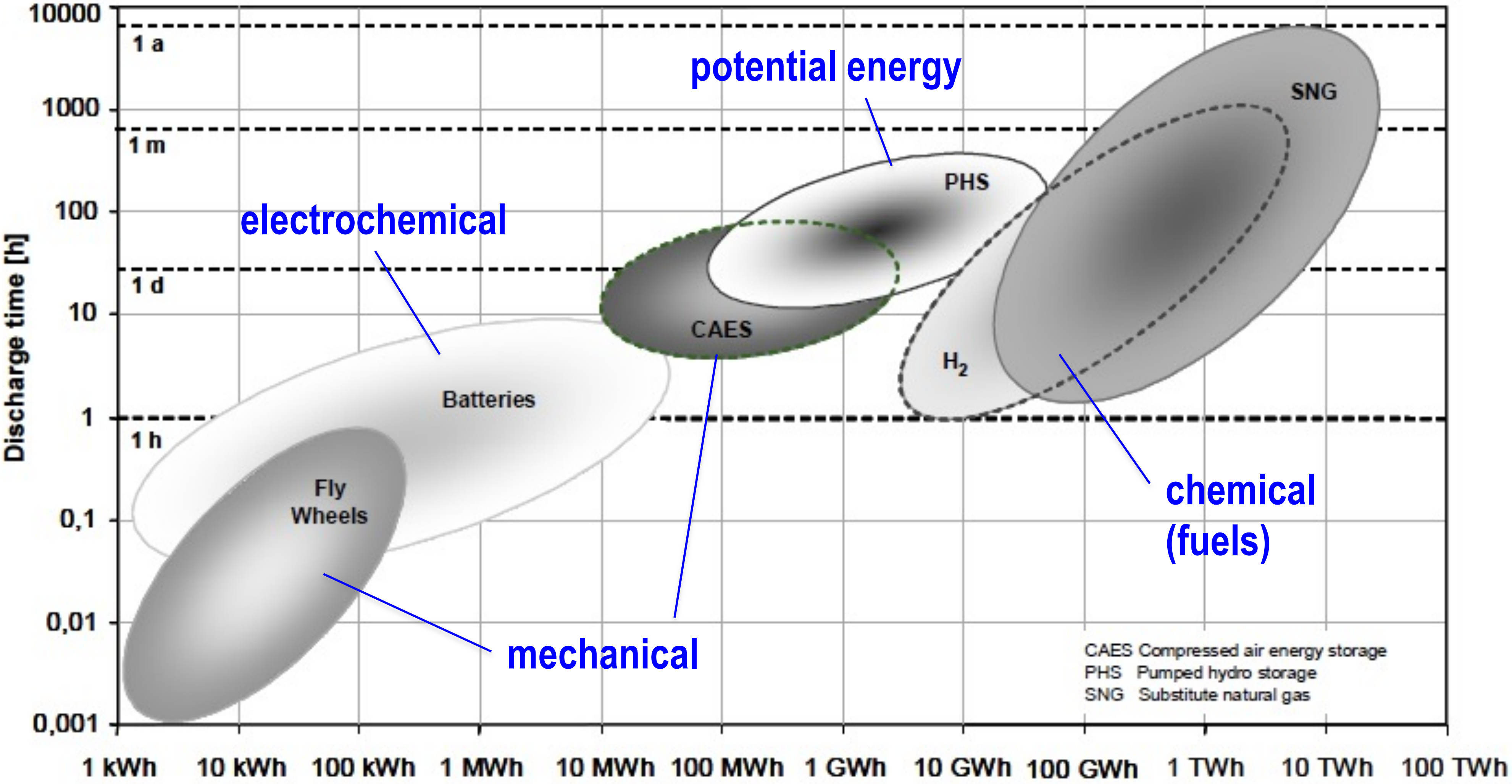
Power generation transition



Source: Rystad Energy PowerCube Beta
A Rystad Energy graphic

https://www.rystadenergy.com/news/energy-crisis-the-beginning-of-the-end-for-gas-fired-power-in-europe

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 of H_2O splitting

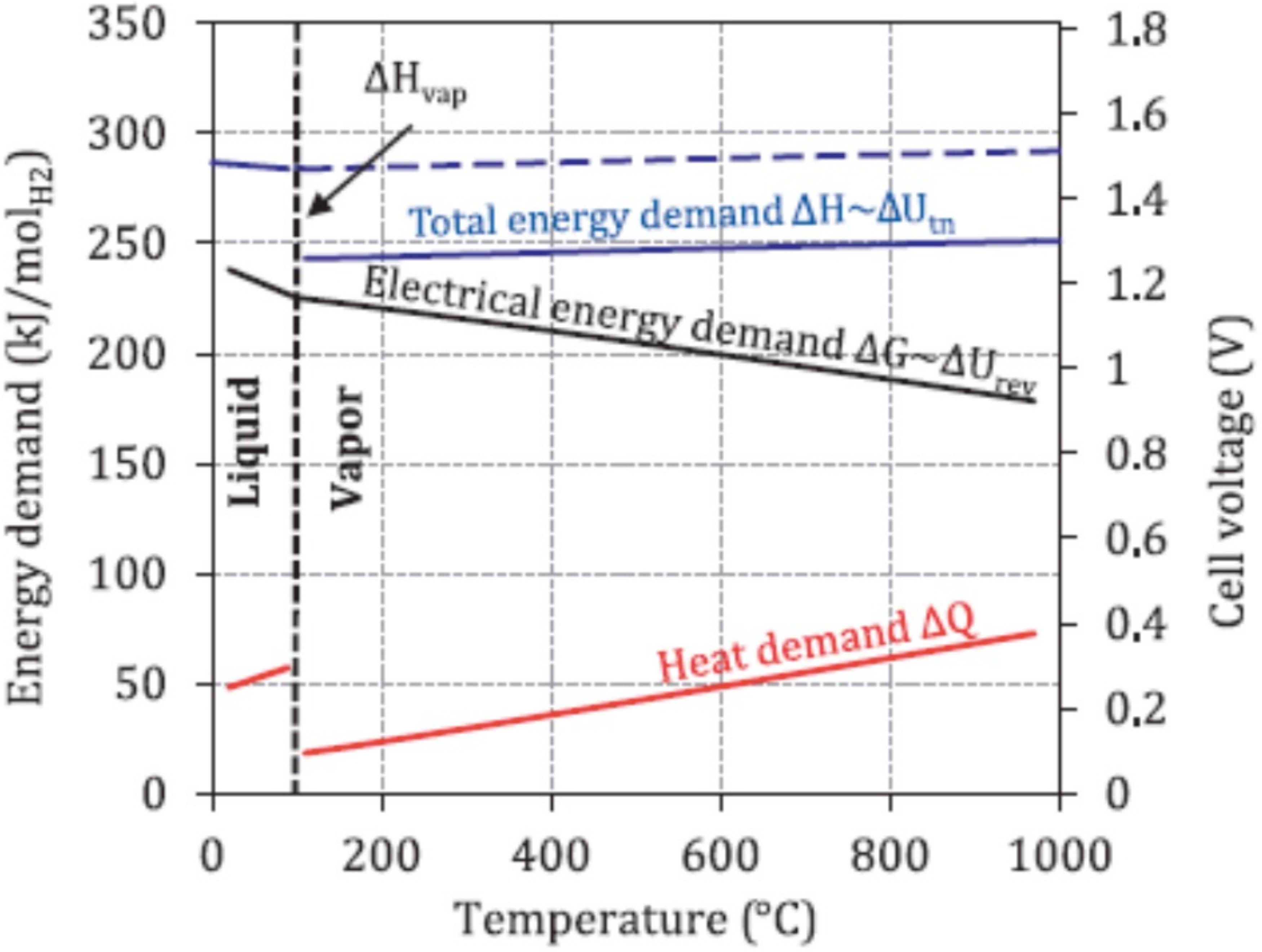
	Reaction	ΔH (kJ/mol)	MJ / Nm³	kWh / Nm³
Water	$H_2O(l) \Rightarrow H_2 + \frac{1}{2}O_2$	286	12.77	3.55
Steam	$H_2O(g) \Rightarrow H_2 + \frac{1}{2}O_2$	↓ $-\Delta H_{evap}$ 242	10.80	3.00
	$CO_2 \Rightarrow CO + \frac{1}{2}O_2$	283	12.63	3.51

→

Electrolysis : energy necessary for dissociation

←

Combustion: energy liberated as heat

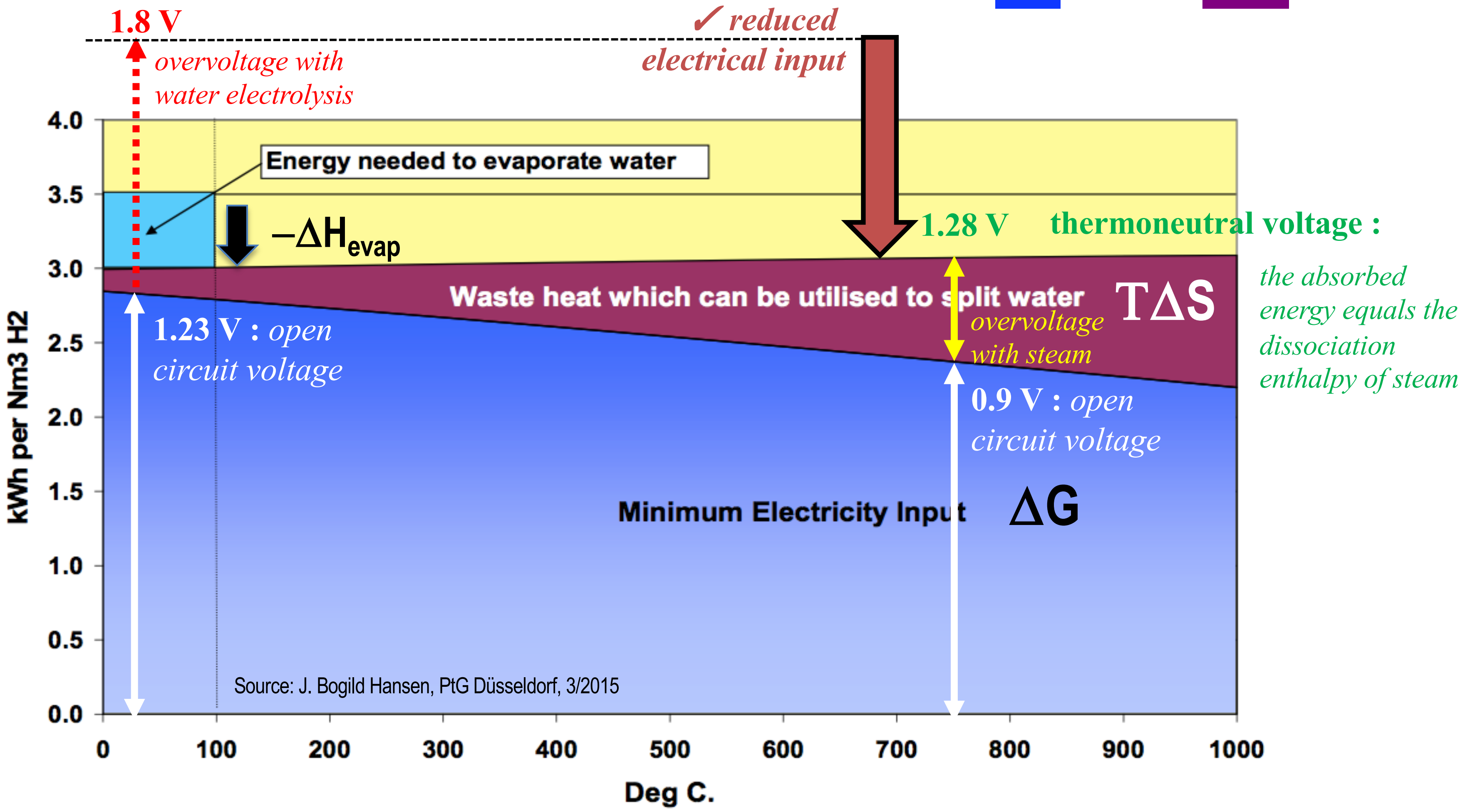

350
300
250
200
150
100
50
0
Energy demand (kJ/mol$_{H2}$)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Cell voltage (V)
0
200
400
600
800
1000
Temperature (°C)
ΔH_{vap}
Total energy demand $\Delta H \sim \Delta U_{tn}$
Electrical energy demand $\Delta G \sim \Delta U_{rev}$
Heat demand ΔQ
Liquid
Vapor

Electrolysis thermodynamics

ΔH = total energy

= electricity + heat

= ΔG + $T\Delta S$



1.8 V *overvoltage with water electrolysis*

✓ *reduced electrical input*

1.28 V **thermoneutral voltage :** *the absorbed energy equals the dissociation enthalpy of steam*

overvoltage with steam

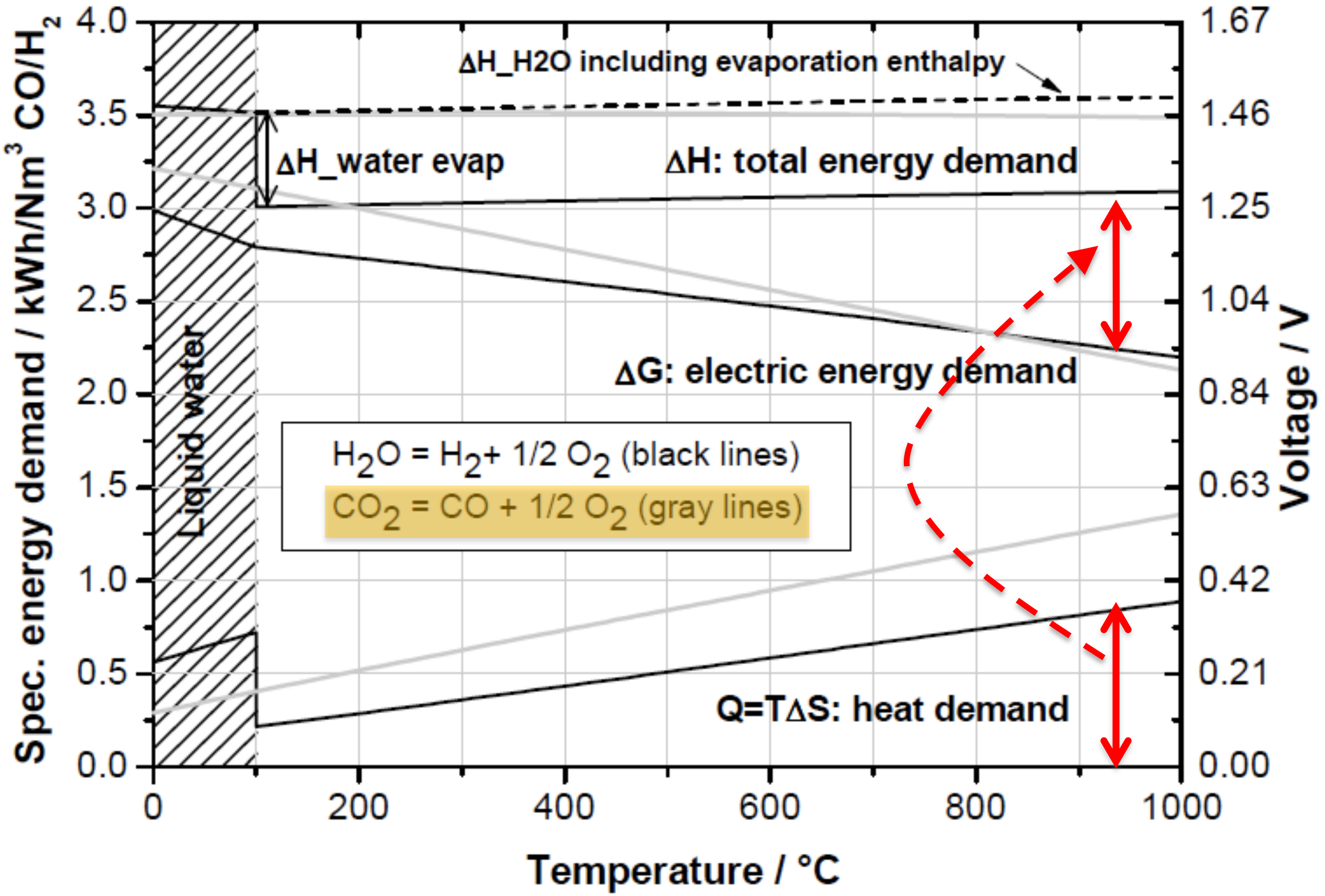
1.23 V : *open circuit voltage*

0.9 V : *open circuit voltage*

Source: J. Bogild Hansen, PtG Düsseldorf, 3/2015

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

CO_2 electrolysis is efficient at high T too

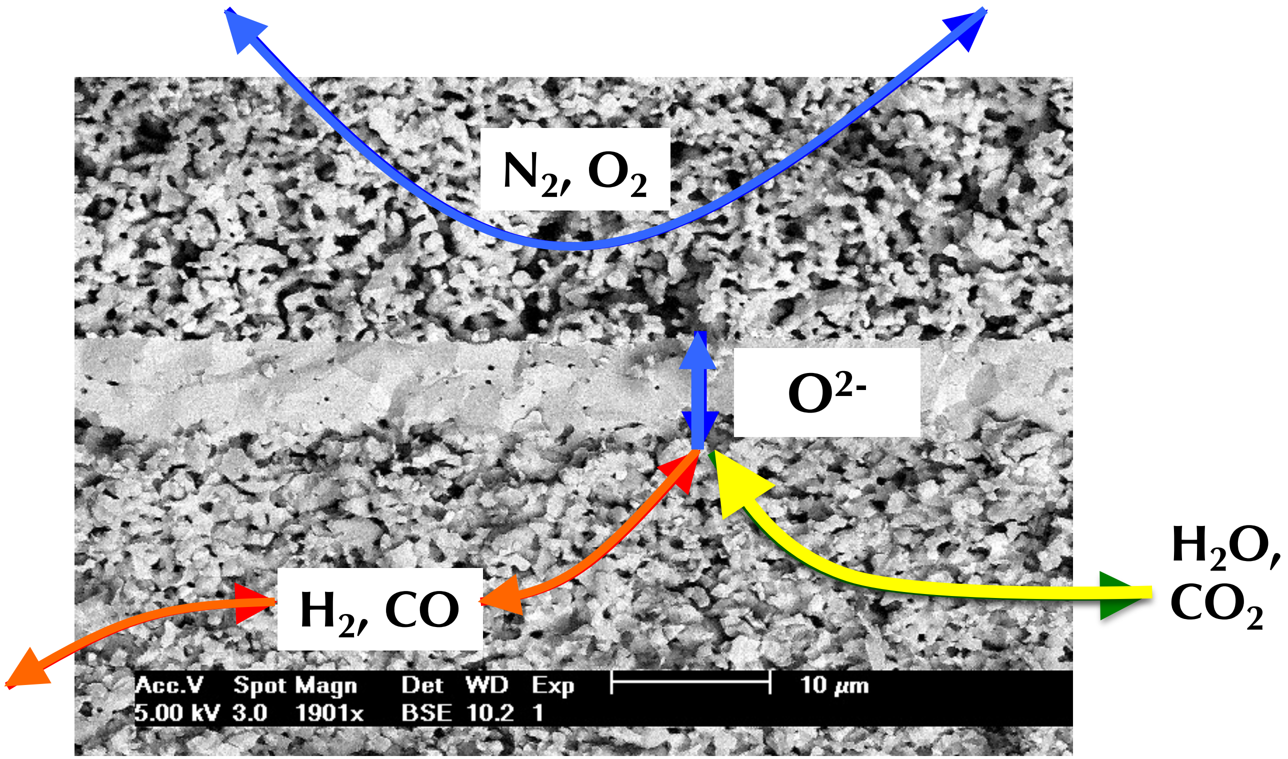


thermoneutral voltage 1.3 V

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.

Reverse fuel cell = electrolyser

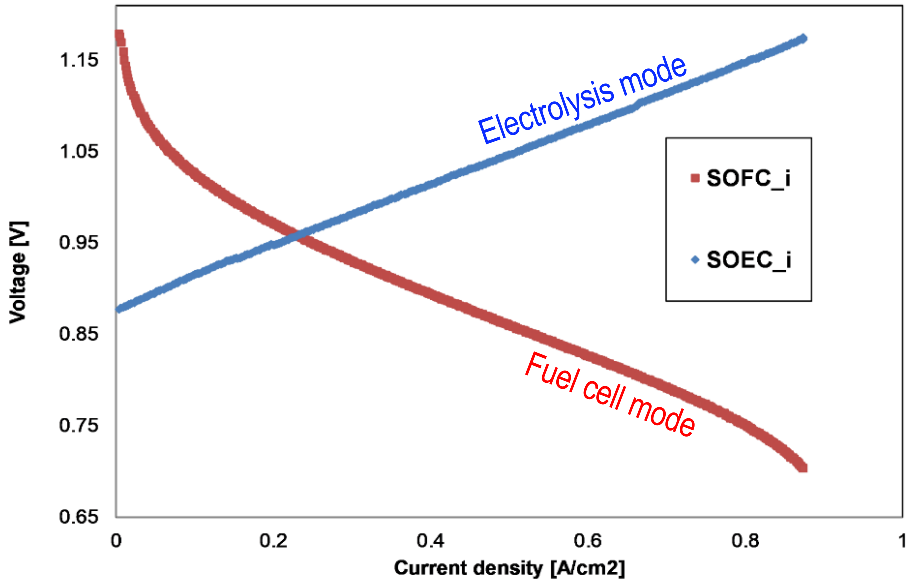


syngas-catalyst

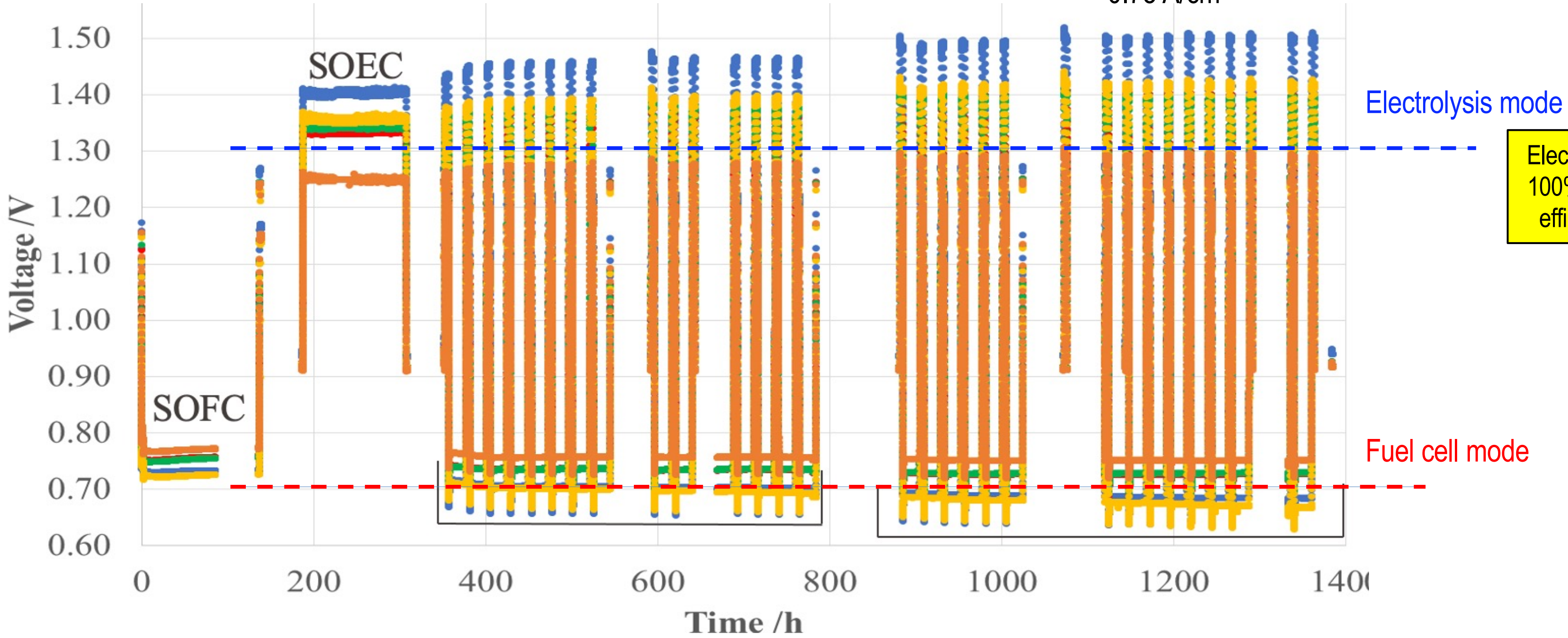
Operating regime :
700-800° C
1 bar (to 5 bar)

FUEL CELL
ELECTROLYSER

SOLID OXIDE CELL
= fully **reversible**

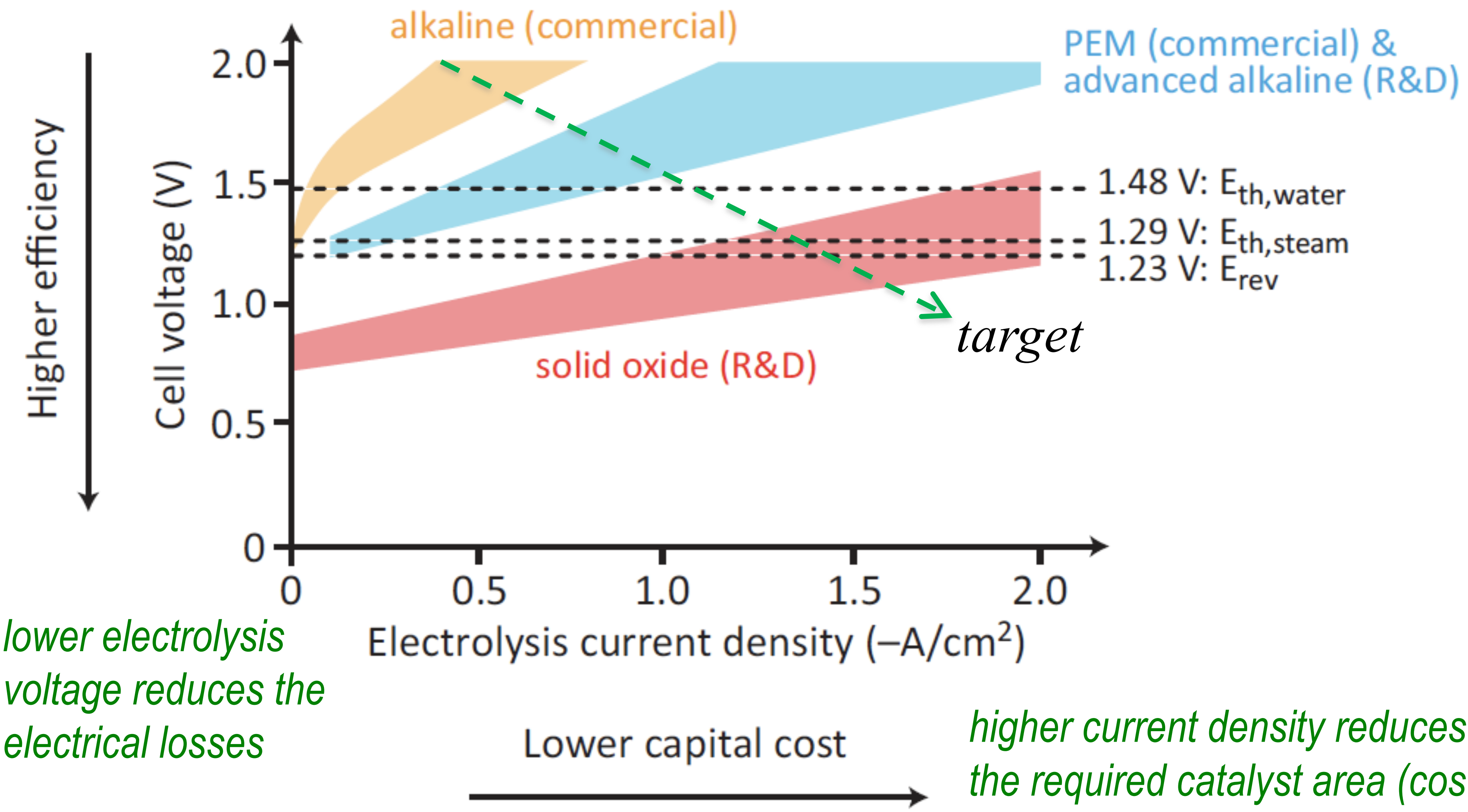


$0.75\ A/cm^2$



Electrolysis:
100% gross
efficiency

Electrolysis technology comparison



lower electrolysis voltage reduces the electrical losses

higher current density reduces the required catalyst area (cost)

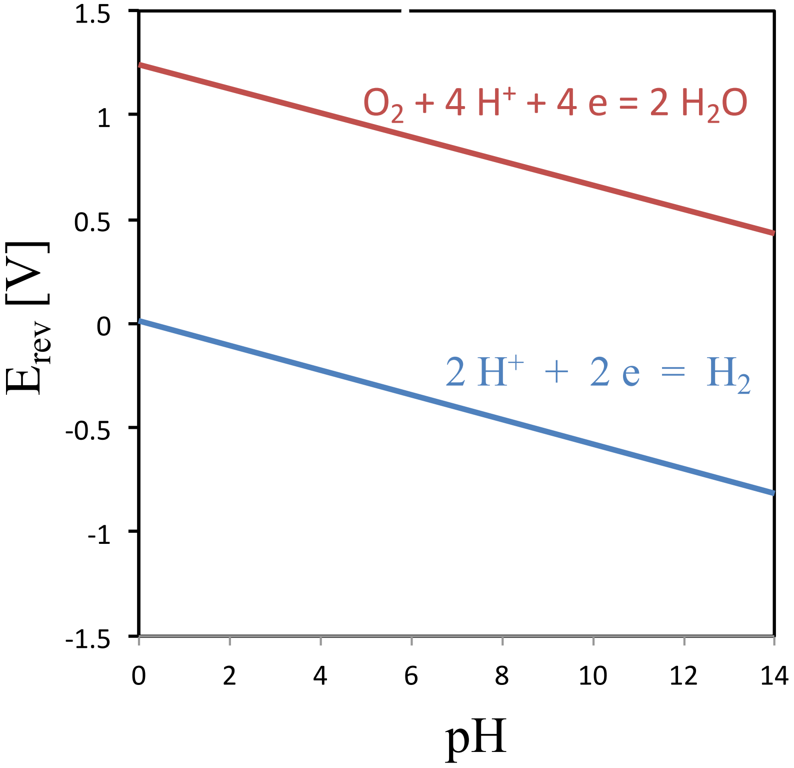
Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy
Christopher Graves, Sune D. Ebbesen, Mogens Mogensen, Klaus S. Lackner
Renewable and Sustainable Energy Reviews 15 (2011) 1–23

Pourbaix diagram (E_{rev} vs pH plot) for hydrogen and oxygen reactions

T = 25° C

$a_{O2} = 1$

$a_{H2} = 1$



$E_{rev,O2} = 1.23\text{ V} - 0.059\text{ pH}$

$E_{rev,H2} = -\,0.059\text{ pH}$

E depends on the pH

Water electrolysis in acid / alcaline solution

- in **acid** solution (PEMEL):
  - only noble metals are stable and the most efficient catalysts (**Pt** for H_2-evolution, **IrO_2** for O_2-evolution)
  - interconnects are easily corroded; **Ti-**sheets are used, that are plated with gold/platinum
  - the Nafion membranes (proton-conducting) are expensive

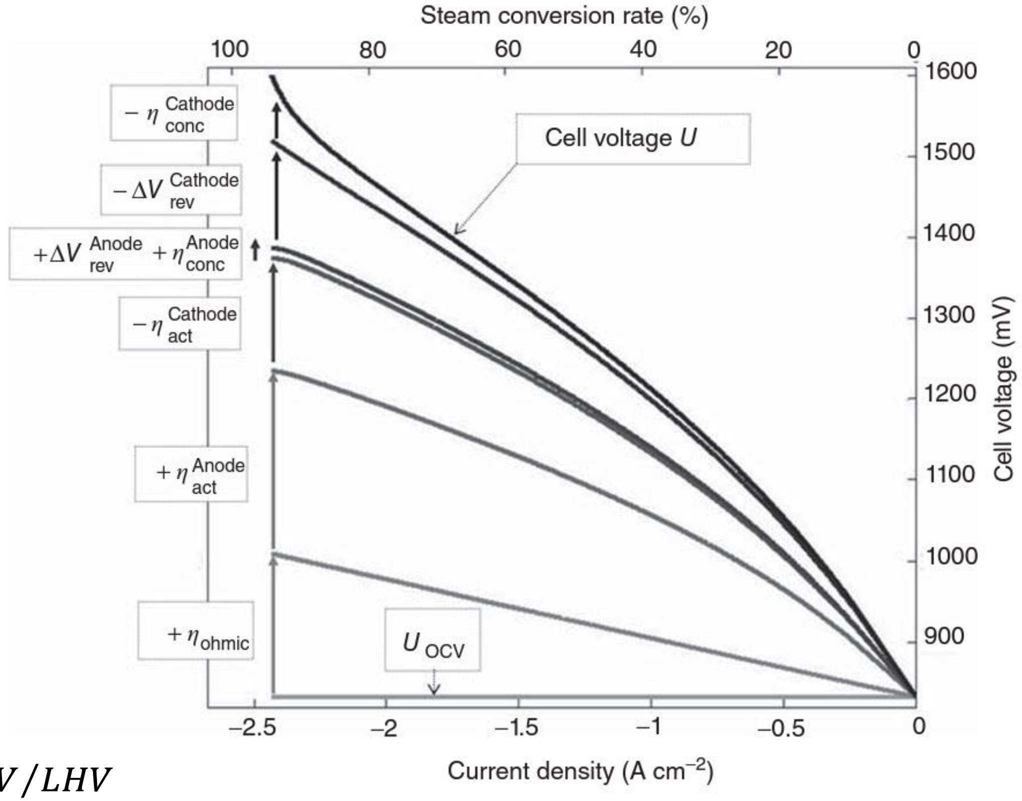
- in **alcaline** solution (AEL, AEMEL):
  - catalysts such as Ni and Fe are stable and sufficiently effective
  - stainless steel interconnects can be used
  - separators are non-conducting Zirfon diaphragms (‘zero-gap’), or anionic conducting thin gas-tight polymer films

Efficiency

Hydrogen production :

flowrate $\dot{n}_{H_2} = \eta_F \frac{nI}{zF}$ (stack current I, n number of cells)

Faradaic efficiency

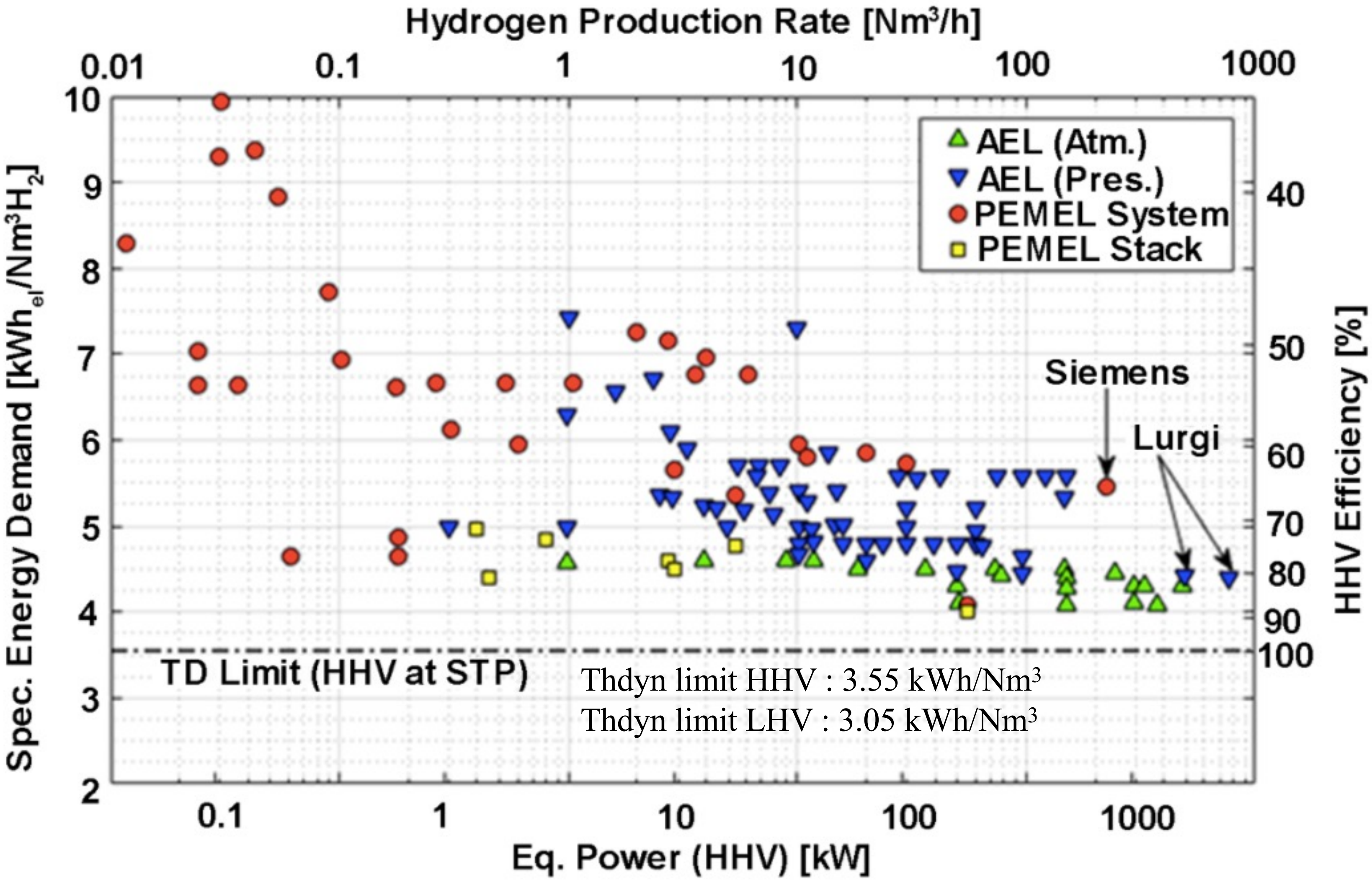


Electrical efficiency:

$$\eta_{HHV/LHV} = \frac{\dot{V}_{H_2}\Delta H_{HHV/LHV}}{P_{el}} = \frac{\dot{V}_{H_2}\Delta H_{HHV/LHV}}{I.V_{appl}}$$

With H_2 flowrate production and current I always being proportional to eachother, electrical **efficiency** is essentially determined by the applied **voltage**, and 100% at the thermo-neutral voltage.

Electrolyser efficiencies



Thdyn limit HHV : 3.55 kWh/Nm^3

Thdyn limit LHV : 3.05 kWh/Nm^3

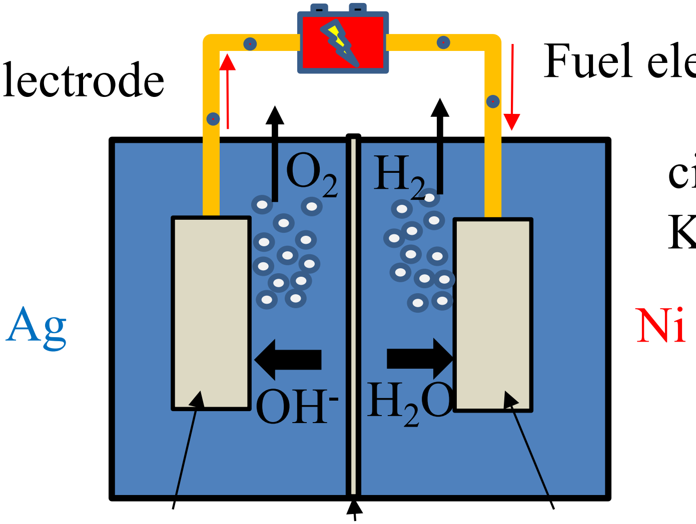
Ref.: Noris Gallandat, Krzysztof Romanowicz, Andreas Züttel, "An Analytical Model for the Electrolyser Performance Derived from Materials Parameters", Journal of Power and Energy Engineering 5 (2017), pp. 34 - 49, http://www.scirp.org/journal/jpee, ISSN Online: 2327-5901 ISSN Print: 2327-588X

slide from Prof A. Züttel, EPFL

Alkaline electrolysis (AEL)

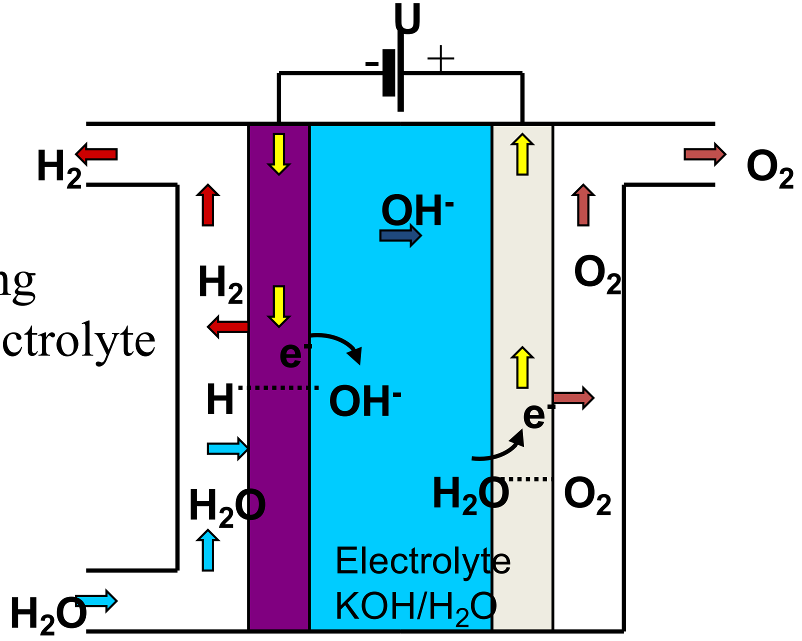
Air electrode

Fuel electrode



circulating KOH electrolyte

Diaphragm

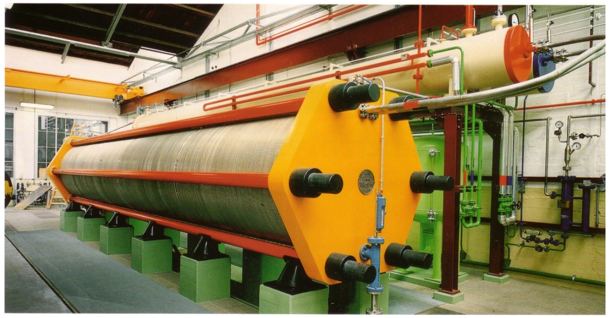


Cathode

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

Anode

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



4 MWe
68% LHV eff.

Advantages :

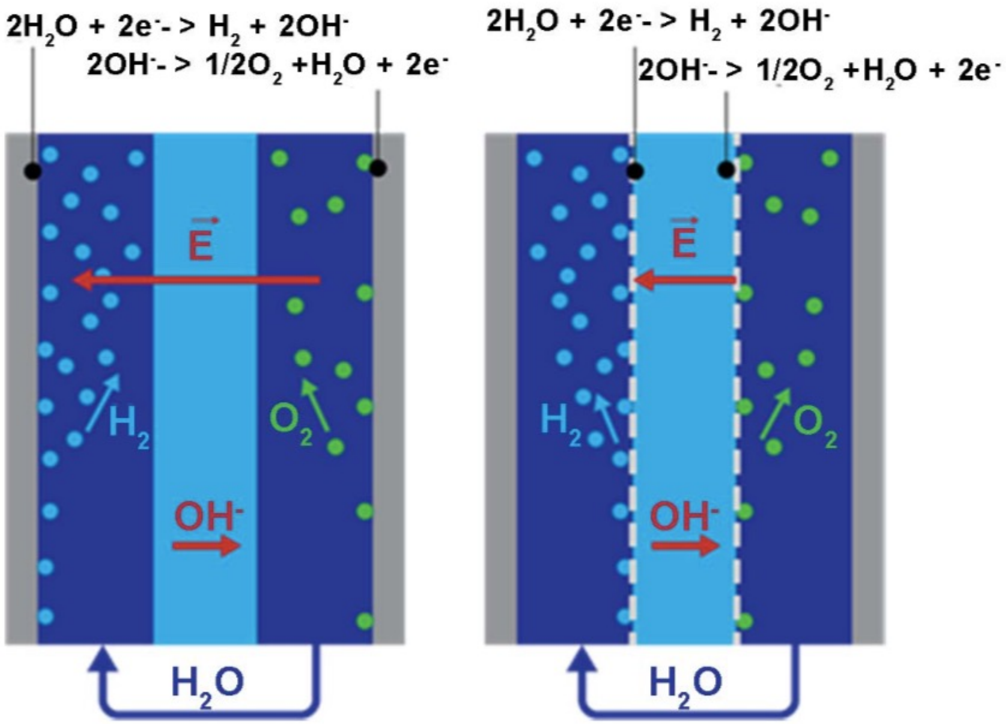
- Mature technology
- Large capacity (1400 Nm^3/h)
- Low cost
- Long life

Limitations:

- Low current density
- Limited load range
- Gas crossover at part-load

Electrolyte resistance and gas bubbles

The generated gas bubbles (H_2, O_2) in the electrodes create a void where a liquid water film should be. This corresponds to an effective resistance.

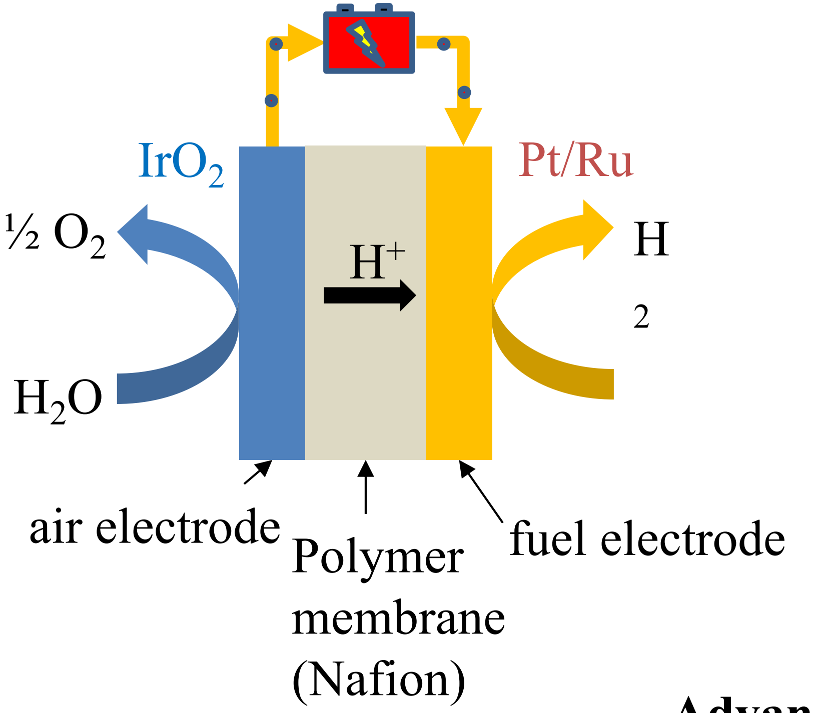


alkaline electrolyzer zero-gap alkaline electrolyzer

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

Polymer electrolyte membrane electrolysis (PEMEL)



IrO_2

Pt/Ru

½ O_2

H^+

H_2

H_2O

air electrode

Polymer membrane (Nafion)

fuel electrode

At air electrode :

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

At fuel electrode :

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

Advantages :

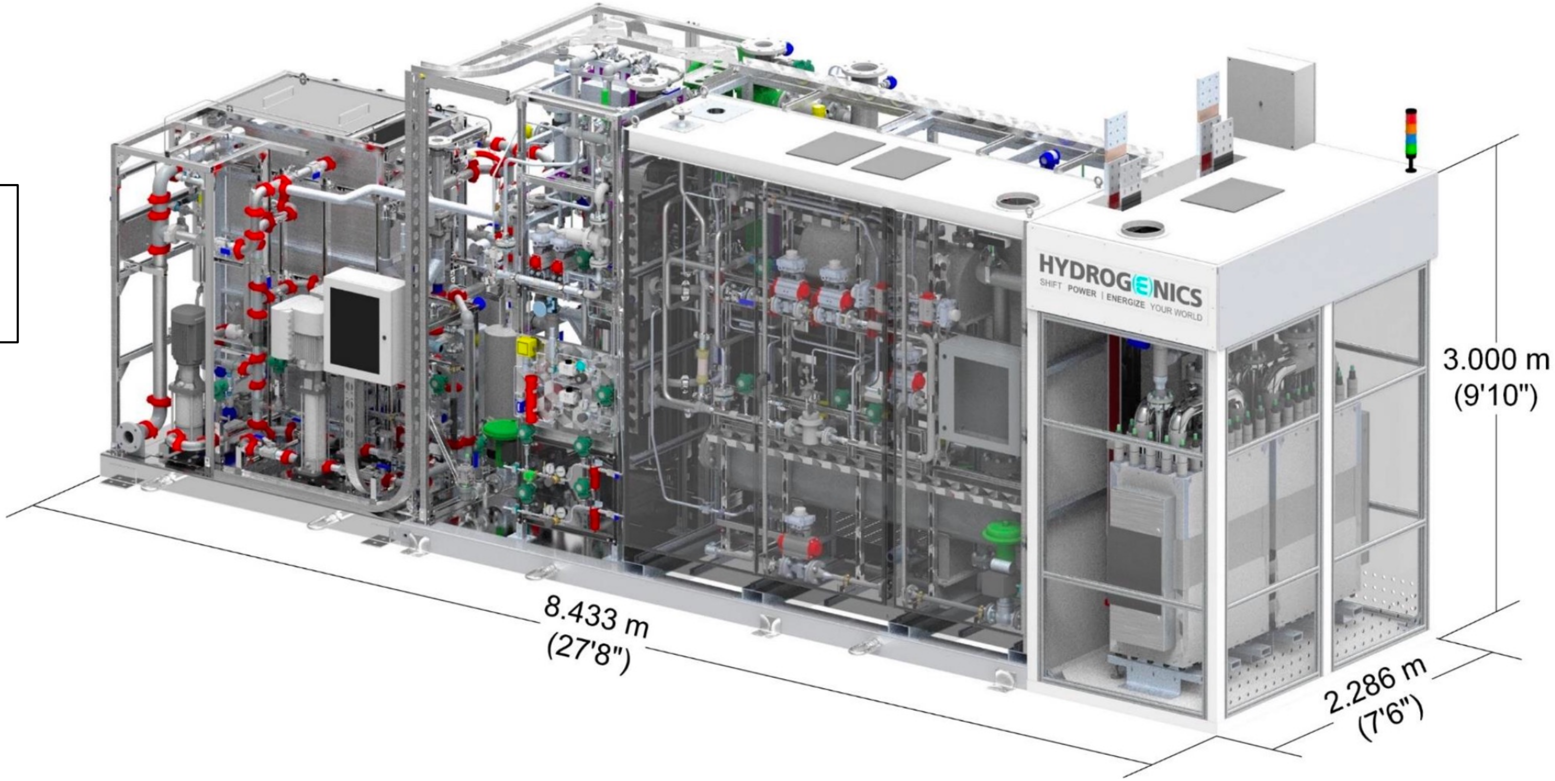
- High current density
- Wide load range
- Dynamic

Limitations:

scarce and expensive materials
(noble metal catalysts;
treated Ti interconnect)
Gas crossover

HYLYZER®-1000 ELECTROLYZER

5 MWe
1000 Nm^3/h

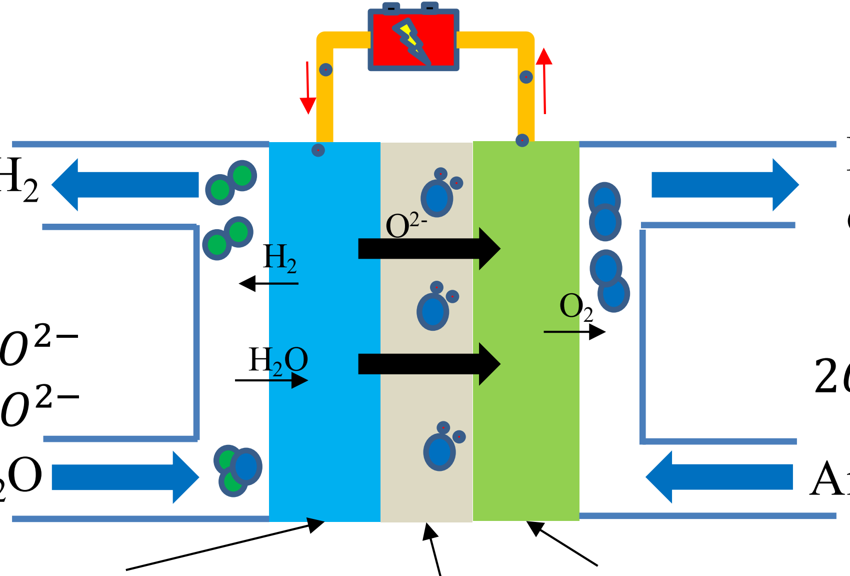


Ref.: Denis THOMAS, Cummins – Hydrogenics, “POWER TO HYDROGEN TO POWER SOLUTION PEM Water electrolysis”, e: denis.thomas@cummins.com, FLEXnCONFU Webinar, 3 November 2020

slide from Prof A. Züttel, EPFL

Solid oxide electrolysis (steam, CO_2) - SOE

Temperature: 650 -900 C



H_2

Pure Oxygen
or Air

Fuel electrode:

$$CO_2 + 2e^- \rightarrow CO + O^{2-}$$
$$H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

Air electrode:

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

H_2O

Air (or nothing)

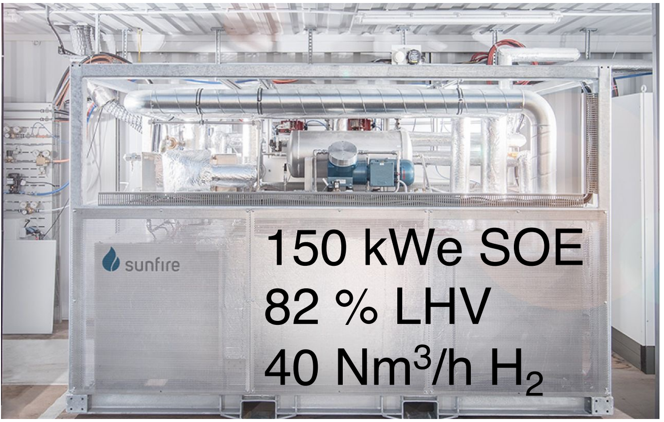
Fuel electrode
Ni

Electrolyte
(Y-ZrO_2)

Air electrode
oxide, e.g. $LaSrCoFeO_3$

SOE systems

SUNFIRE
POWERCORE



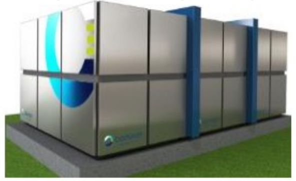
150 kWe SOE
82 % LHV
40 Nm³/h H_2

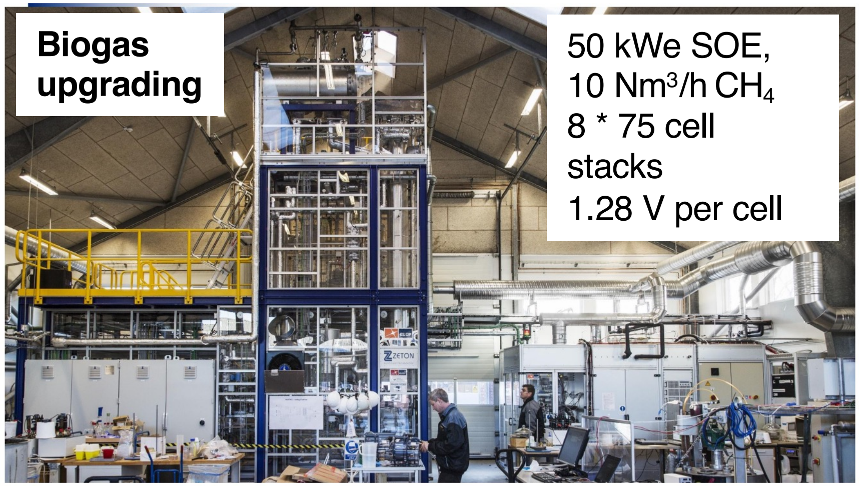
Convion C50
50kW, NG, Biogas

Validation 2015

CONVION SOFC

X00 concept
175 kWe, Biogas
ηe > 53 %
2016



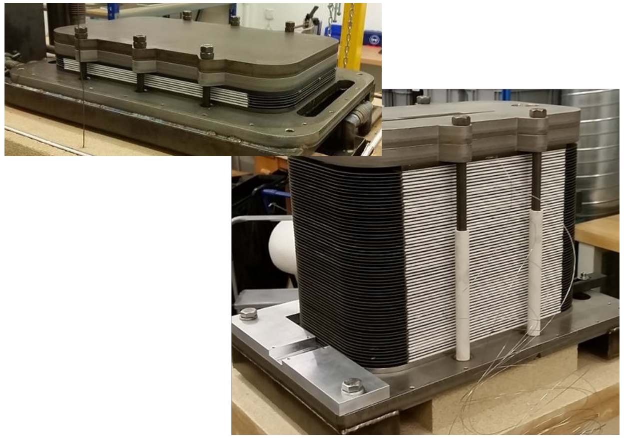


Biogas upgrading

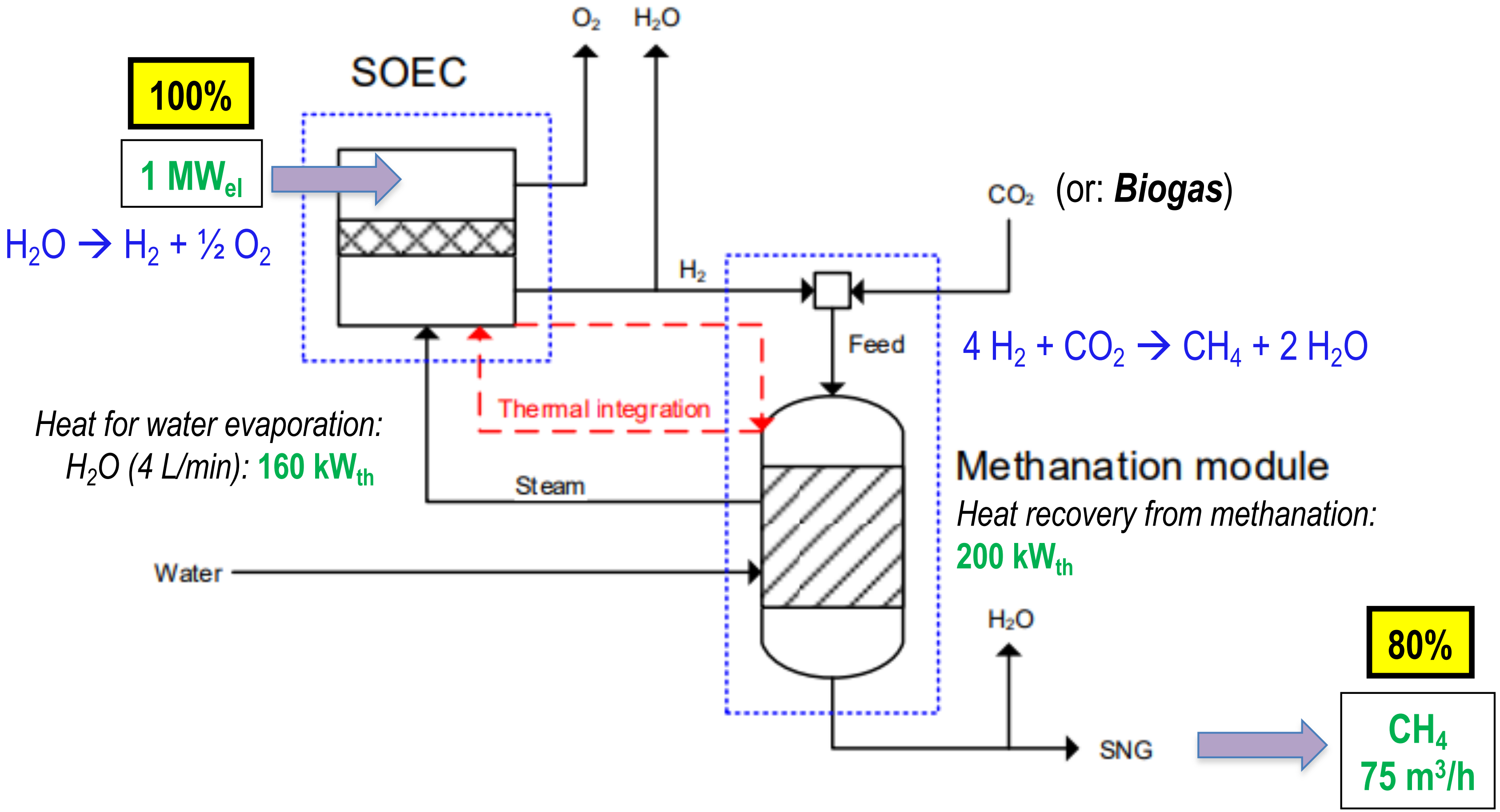
50 kWe SOE,
10 Nm³/h CH_4
8 * 75 cell stacks
1.28 V per cell

HALDOR TOPSØE

SolydEra 30-kWe SOE



Beyond SOE: Power-to-Gas (P2G)



Thermal coupling of steam electrolysis with CH_4 synthesis
Converting H_2 to CH_4 for gas grid injection

European Gas network

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

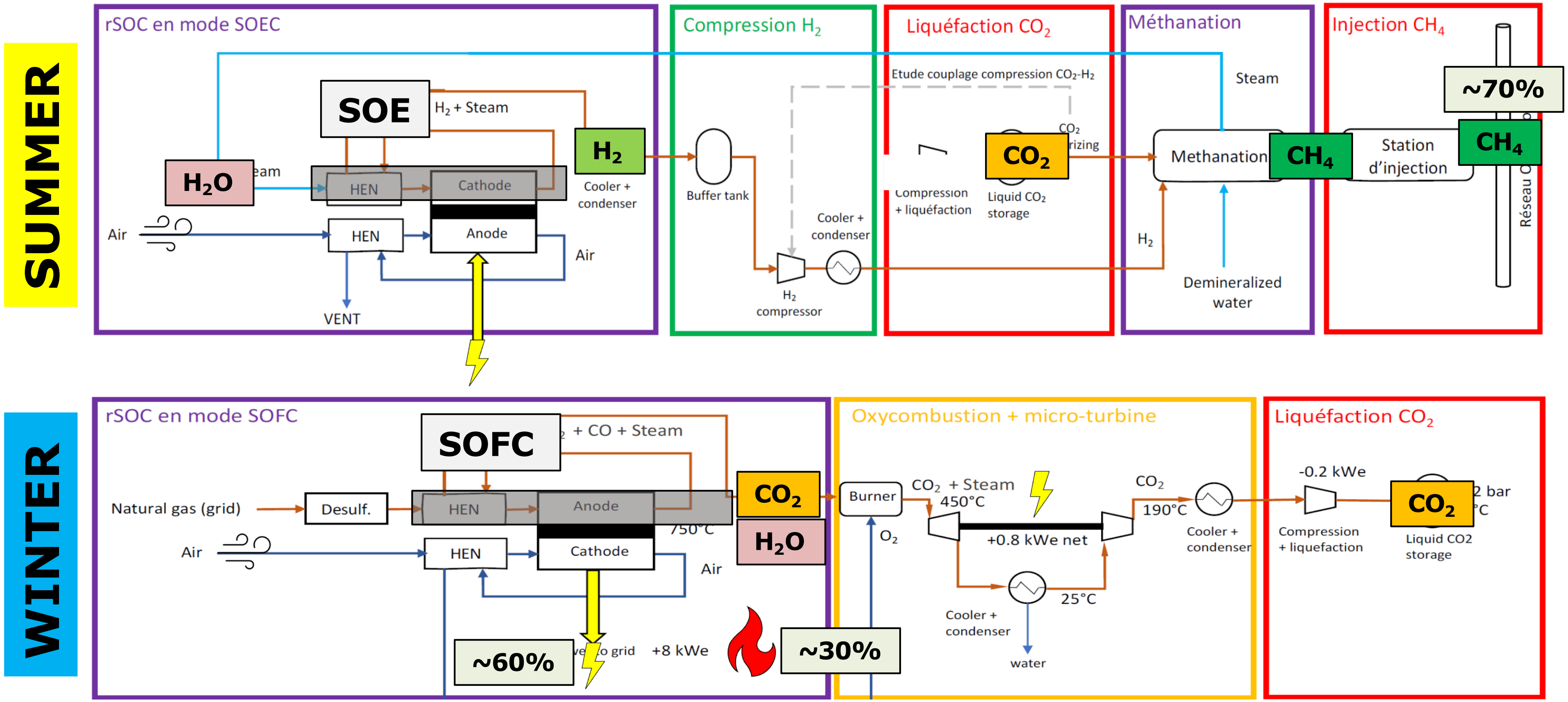
Gas consumption: 5375 TWh (19.4 EJ)
(23% of EU energy) = 512 bio m^3 NG

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

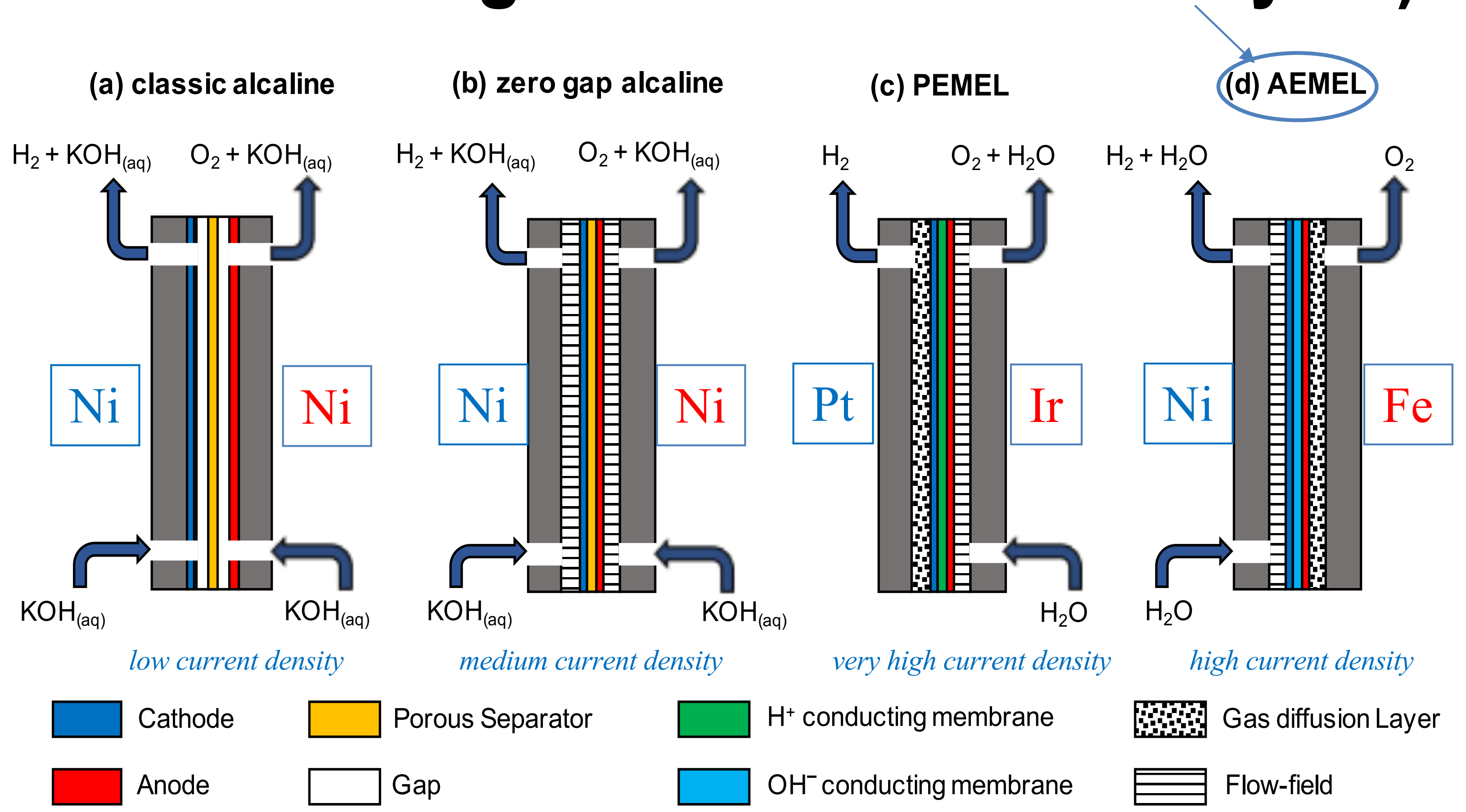
10 vol% H_2 admixing:
= 51 bio m^3 H_2 = 169 TWh (608 PJ)
>40 GWe

Eurogas Statistical Report 2018

Real seasonal storage, via the gas grid, and reversible Solid Oxide Cells



Recent 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)

Electrolysis comparison

Technology	AEL	PEMEL	AEMEL	SOE
Electrolyte	Alcaline water	Protonic polymer membrane	Alcaline polymer membrane	Oxide ceramic
Transfered species	OH^-	H^+	OH^-	O^{2-}
Temperature	80°C	80°C	50°C	800°C
Cathode (H_2)	Ni	Pt / Ru	Ni	Ni
Anode (O_2)	Ni	IrO_2	FeOOH, MnO_2	$LaSrCoFeO_3$
Interconnect	stainless steel	Titanium	stainless steel	FeCr steel
Current density	low	v. high	medium	medium
Voltage	1.8 V	1.95 V	1.8 V	1.3 V
Maturity	commercial	v. high	low	low
Reversible	no	no	~no	yes

CRITICAL MATERIALS

COSTLY

EFFICIENCY

Example: oil refinery

https://refhyne.eu/

Rheinland (Shell) (D)

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

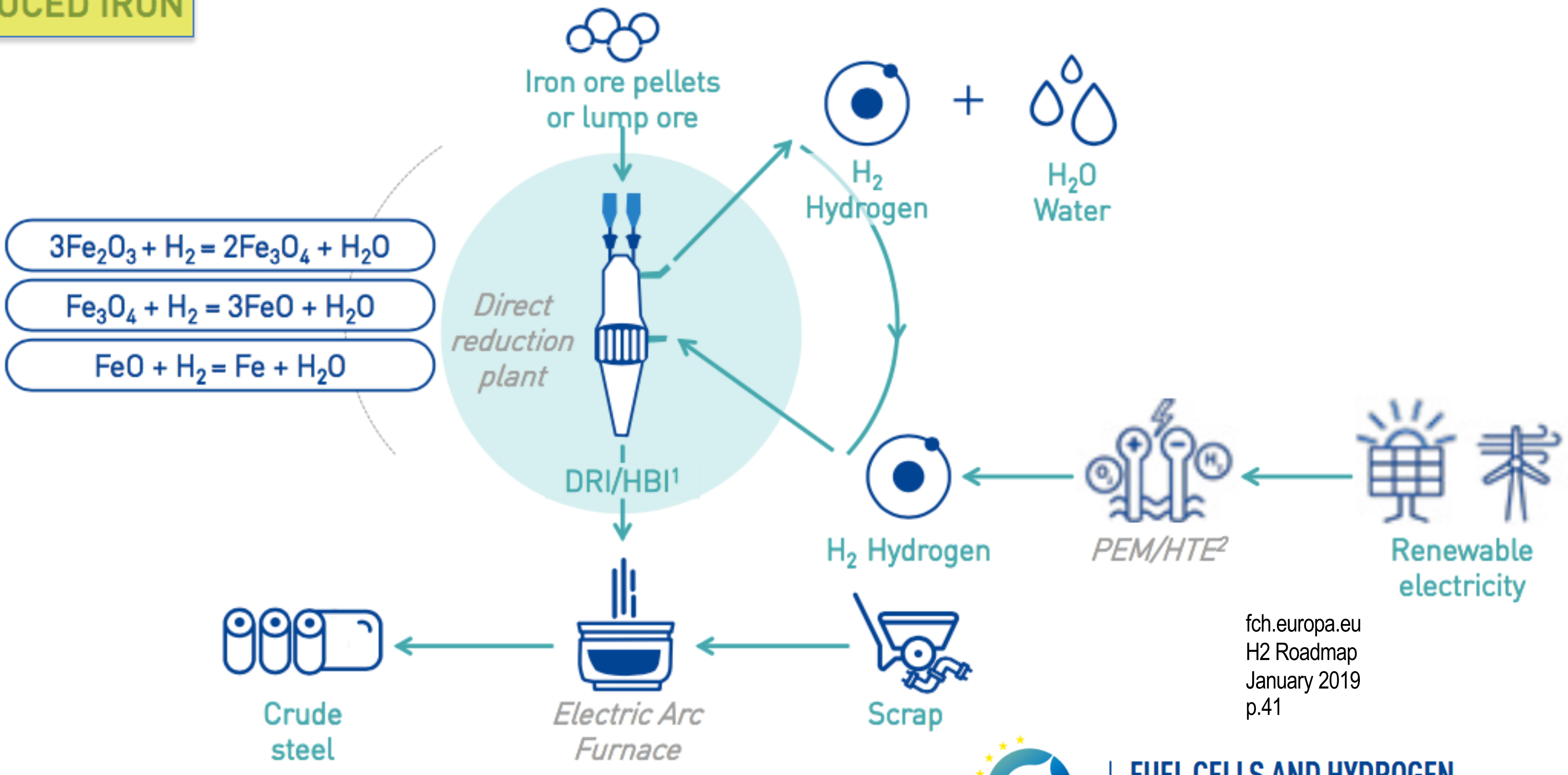
10 MWe PEM electrolyser:
=> supplies **1300 t H_2** / yr(<1% !!)

REFHYNE CLEAN REFINERY HYDROGEN FOR EUROPE 2018-2022

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



$$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$$

$$Fe_3O_4 + H_2 = 3FeO + H_2O$$

$$FeO + H_2 = Fe + H_2O$$

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

Other electrolysis processes

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,…)

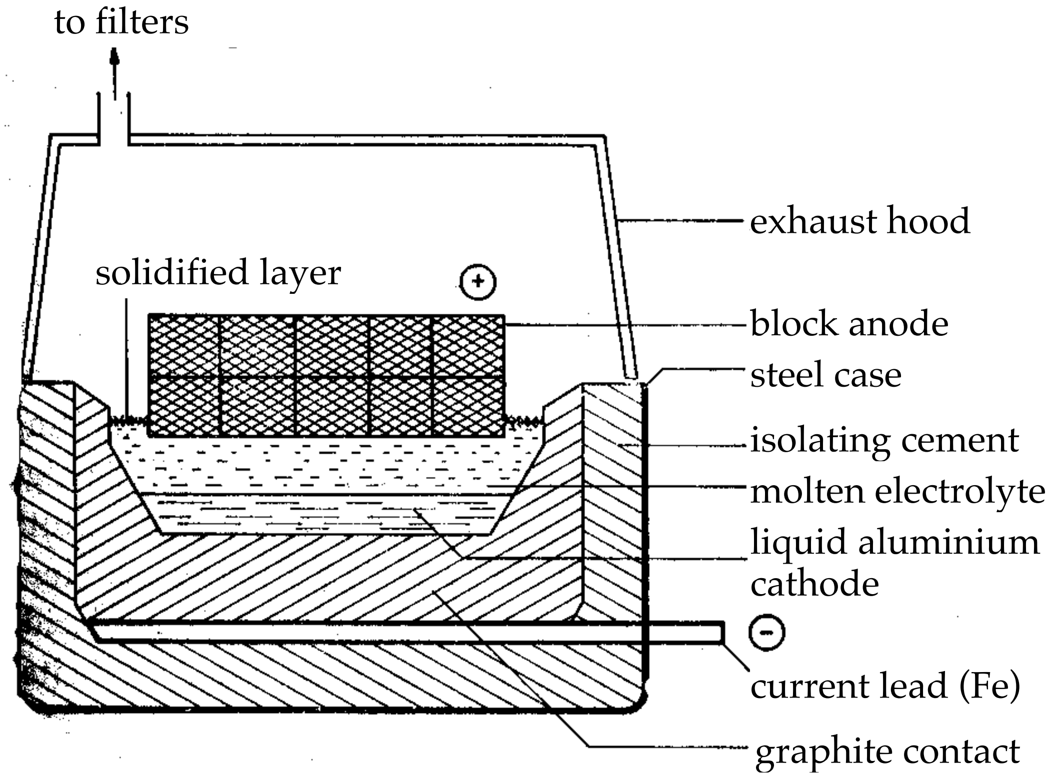
Metal extraction

- 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



Aluminium-industry

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

=> **960 TWhe**

(≈ 120 GWe)

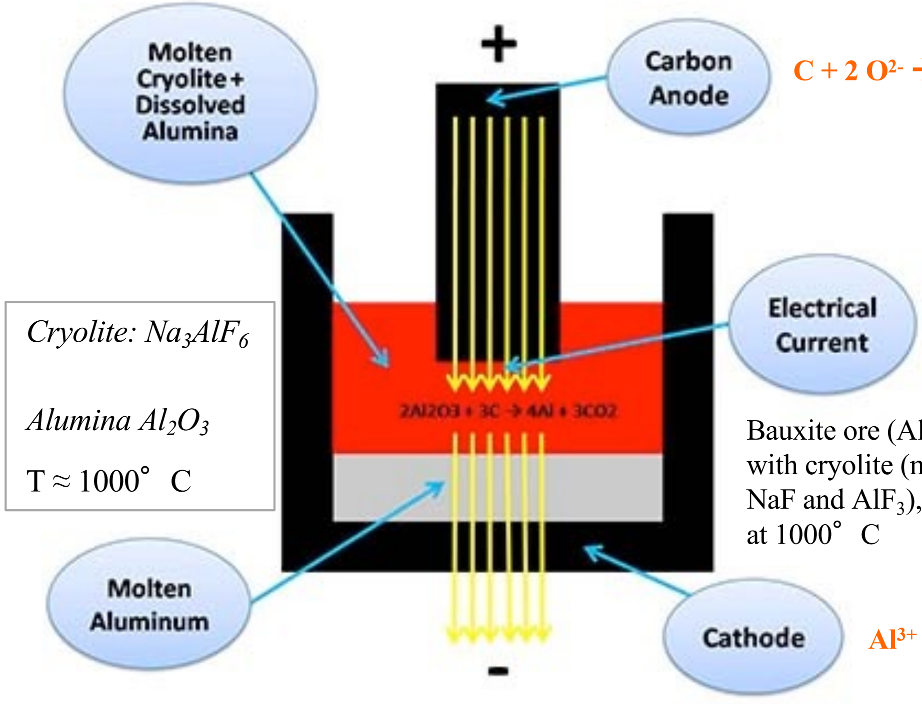
(≈ 4% of world electricity)

- 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

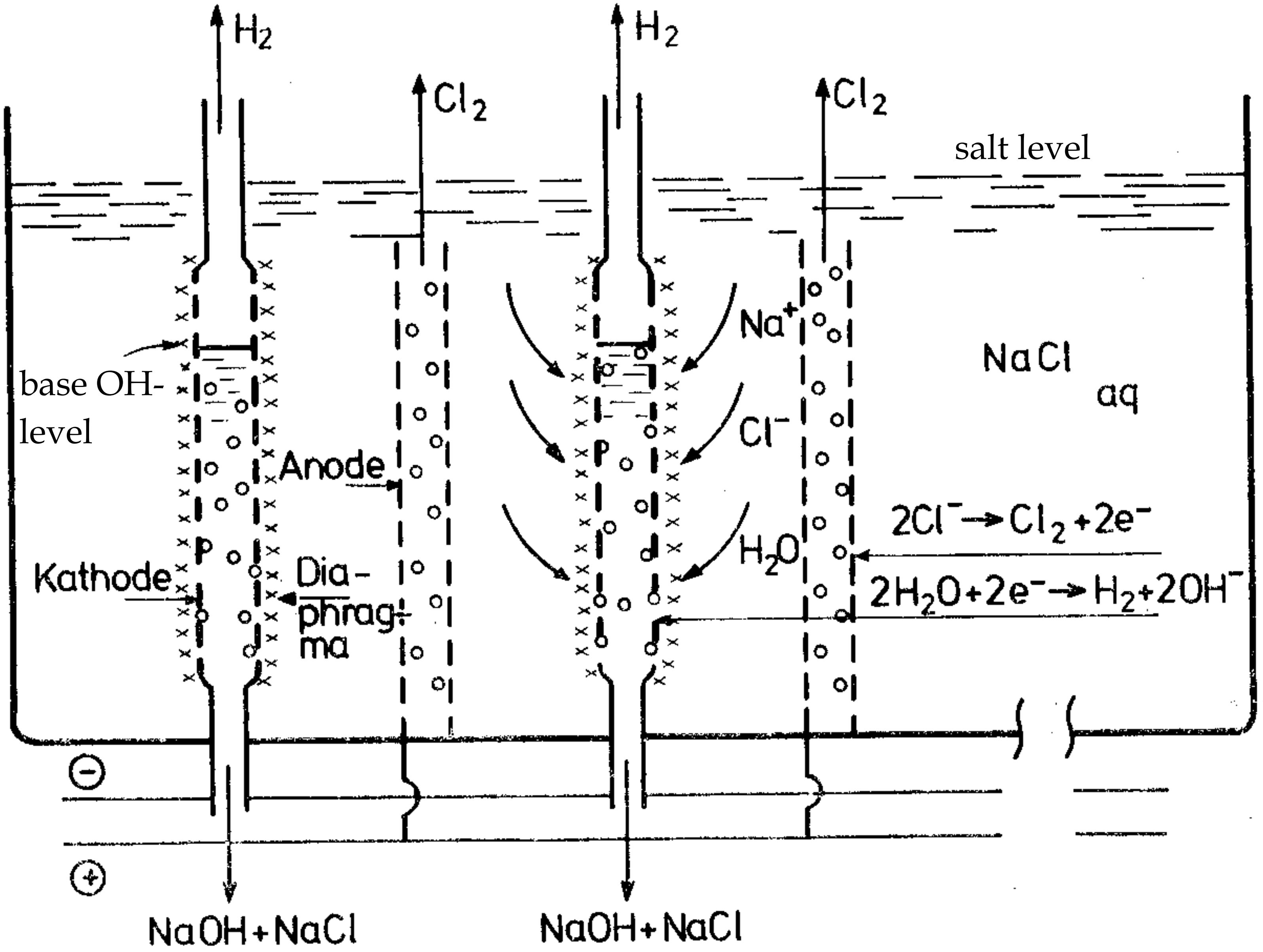
$T \approx 1000°\ C$

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

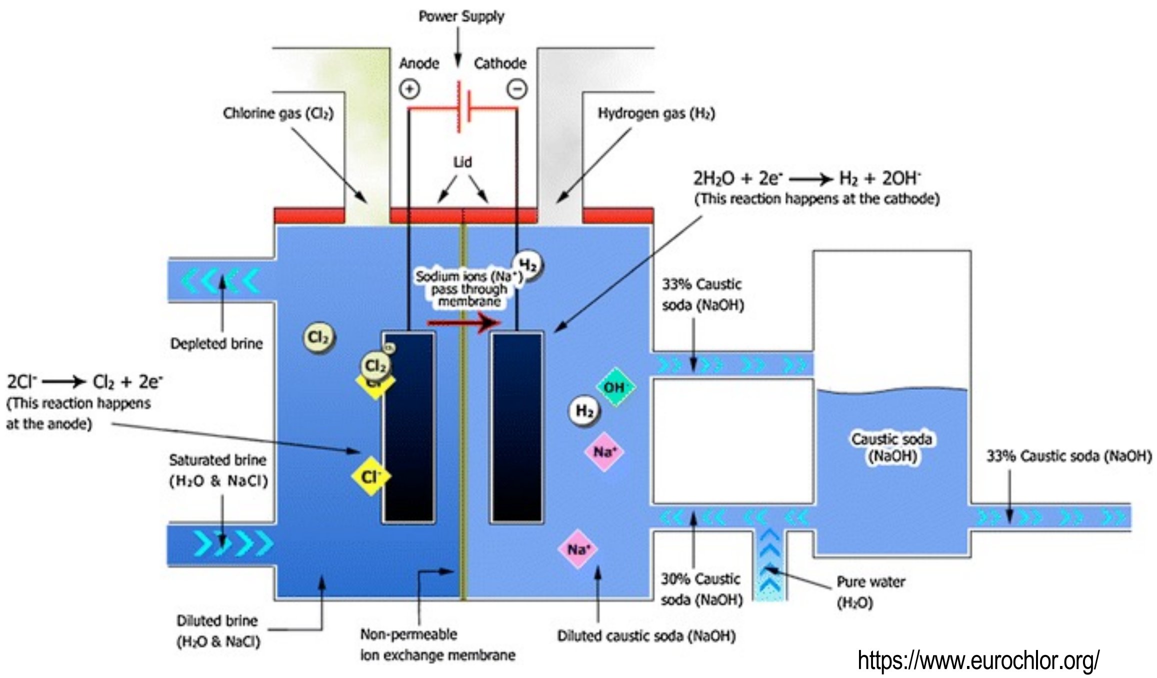
- Production 2017: 58 Mton Cl_2 (650 plants)
- Elec. consumption: 2.1 – 3.4 kWhe / kg Cl_2
- (for 2.5 kWhe / kg Cl_2) => **150 TWhe** consumed

  ≈ 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: $2H_2O + 2e^- \Leftrightarrow H_2 + 2OH^-$ -0.82 V

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

$2NaCl + 2H_2O \Rightarrow Cl_2 + H_2 + 2NaOH$ **2.19 V** theor.

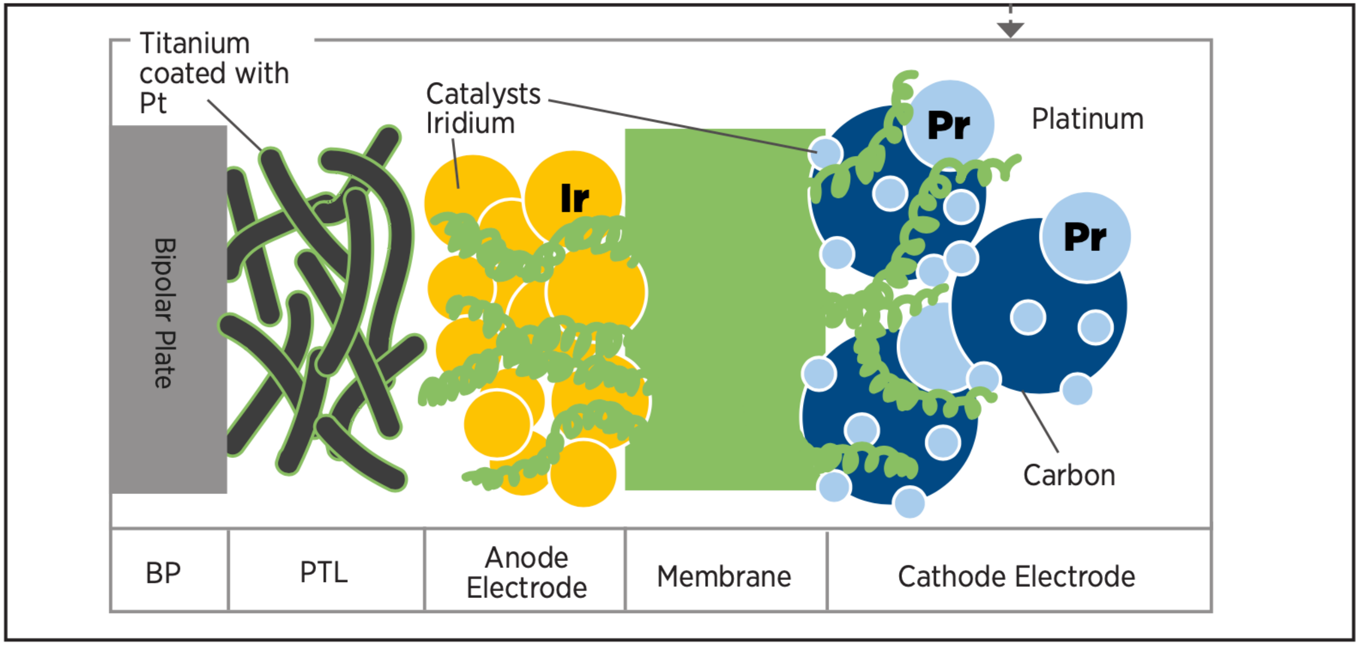
- Graphite : high anodic overpotential η (on purpose!) for O_2 evolution (so as to prevent water electrolysis (>**1.23 V**) !)
- Real electrolysis voltage > 3 V (E_o = 2.19 V), 0.25 A/cm^2, 40 m^2, 100’000 A (400 kW per cell)
- Losses between real and theoretical voltage (3 V – 2.19 V) :
  - charge transfer 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^-) (0.4 V)

Comments on Materials availability

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 abundance), Pd (6 ppb), Rh (1 ppb), Ru (1 ppb), Ir (0.4 ppb)
- Exploitable reserves 71’000 t (proven: 100’000 t; 30’000 t 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 (1 g per car)
  - 40 t / yr is recycled
- Other uses for PGM: 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:
  - 2 V, 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 FC-EV uses 3 g Pt
- **Ir** example:
  - 5 mg/cm^2 Ir
  - => 1.25 g Ir / kWe => 1 kg / 800 kWe
  - total (!) production of 8 ton 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 Ni-use)
- Coatings (10% of Ni-use)
- **Catalysts**, electronics (5% of Ni-use)
- Example AEL (/SOE):
  - 0.5 A/cm^2, 2 V, 1 W/cm^2, 50 mg Ni/cm^2
  - → 50 mg Ni / W => 50 kg / MWe => 50 kton / TWe
  - only **0.2%** of 1 year global Ni production of 2.7 Mt would support 1 TWe deployment

World metal production

Jacques Leclerc 2007

1. **Fe** by <u>very far</u> the largest : 2500 Mt/yr *(= covers Geneva canton * under 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*
   (=covers Geneva with 1 mm of Ni)

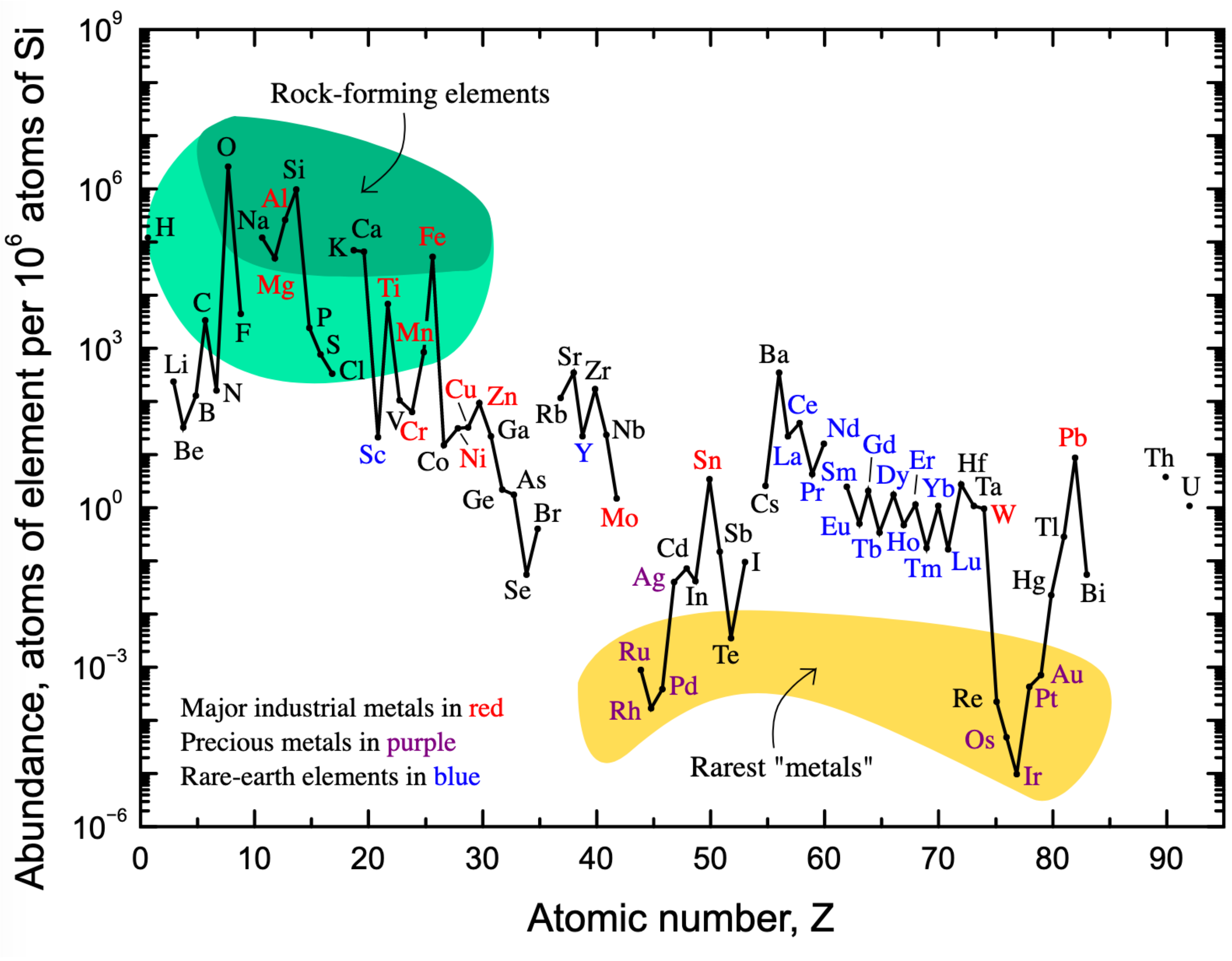
3. 'Smaller' industrial metals < 1 Mt/yr:
   Mg 1 / Sn 0.33 / Mo 0.25 / ***Co 0.14*** */ V 0.11 / W 0.085 /* ***Li 0.082*** */ Cd 0.025*
   (=covers Geneva with 50 μm of Co)

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)*

   (=covers Geneva with 30 nm Pt, 1 nm Ir)

*Geneva canton surface: 282 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

toe = ton oil equivalent

	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))	

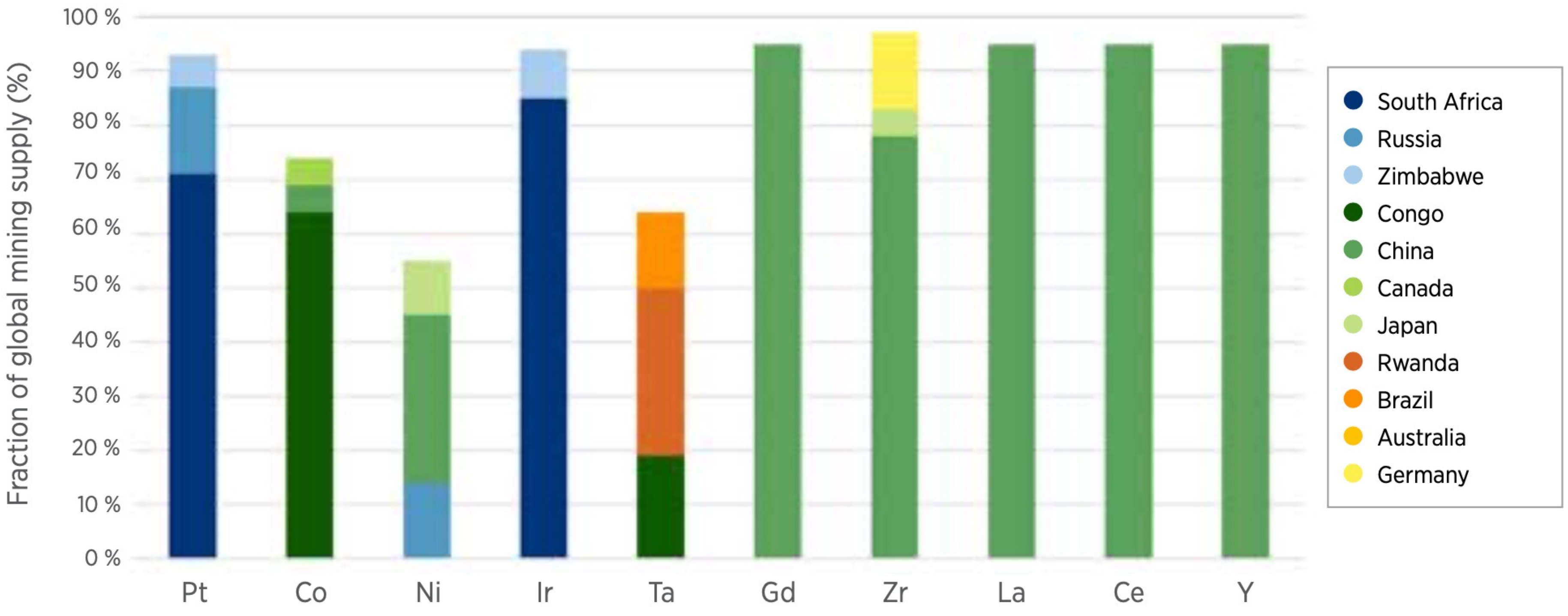
*Currently exploitable reserves ≈ ½ proven reserves ≈ only 0.01 - 0.1% of natural abundance for the rare elements

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.

Comments on metal scarcity

- Metal resources are, like fossil resources, finite. Extraction cost and energy use increase as the resources get more 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 in the pursuit of hi-tech components, or the high purity requirements of some metals, are antagonistic with recycling
  - e.g. >3000 Ni-alloys exist
  - e.g. PV panels with multiple doped semiconductors

Large scale H_2 electrolysis deployment

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

large scale production, increased lifetime,

long 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
- **SOE** (Ni, some rare earths Ce, Y) : highest efficiency; integrate with heat sources
- Materials importance: criticality, purity, alloying and ease of recycling