Conversion/Storage in
Fuel Cells/Electrolysers

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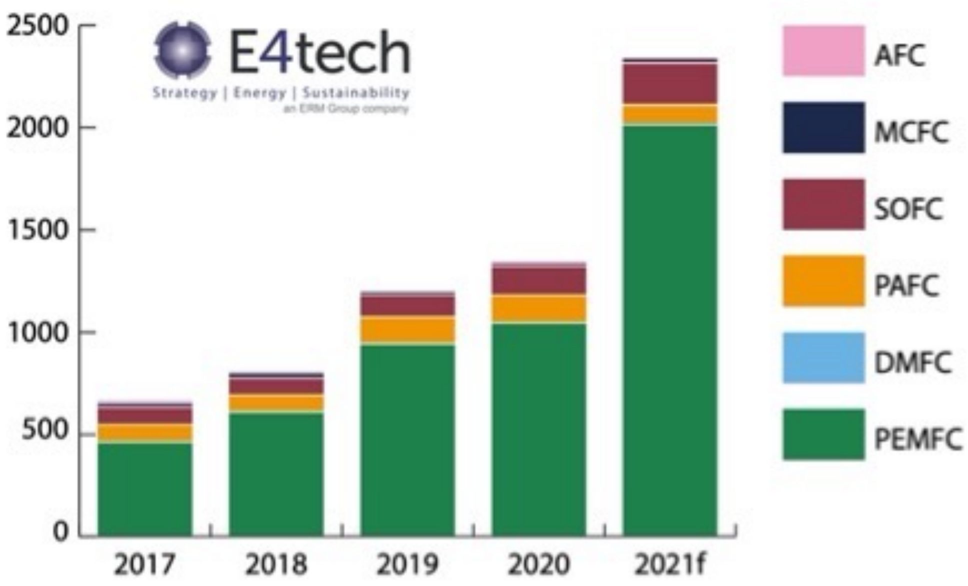
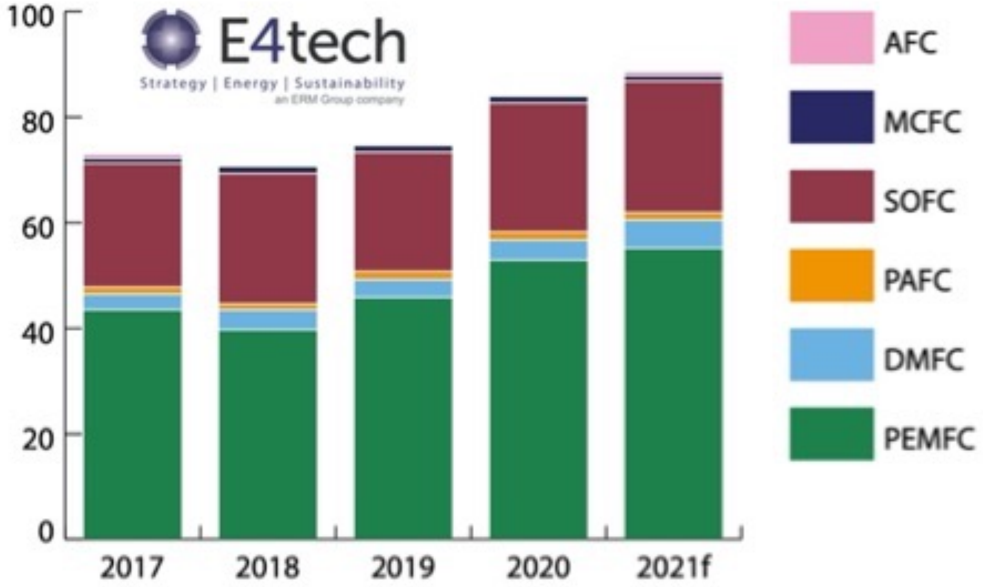
World fuel cell market growth: by type, MWe, and units





MW shipped :
2 GW **PEM**
207 MW **SOFC** (Enefarm, Bloom, prime power in USA + S-Korea).
100 MW **PAFC** (Doosan)

Units shipped :
55’000 **PEM**
25’000 **SOFC** (Enefarm programme).
200 **PAFC** Doosan units
5300 **DMFC** units (SFC Energy) for 500 kW total.
AFC very low (UK and Israel GenCell).

Facts & Figures (status 2021)

- 86'000 units shipped in 2021:
  - 40’000 Enefarm (1 kWe) units for domestic uCHP in Japan
  - 16’000 units to USA (Toyoto Mirai and forklifts)
  - 14’000 units in Europe (630 mobile units, rest uCHP and forklifts and portable).
  - 16% of all units (14’000) are forklifts (+3’500 in Europe).
- 2.3 GW shipped in 2021:
  - **Hyundai** (38% of power => Korea, 8500 Nexos)
  - **Toyota** (33% of power => Japan + California, 2500 Mirai)
  - Mirai + Nexo account for 72% of MW. With buses/trucks : 83%. With forklifts : 85% (2GW).
- Uptake of **heavy duty** (trucks, buses; 1800 in China alone). PEM supply chain is put in place.
- EU: 300 HRS by 2025, 1000 HRS by 2030
- Buses : 1100 made in 2021
- Trains: 50 now exist
- Ships : Doosan (using Ceres SOFC), Prototech/Clara (Sunfire stacks), TECO 2030 (AVL fuel cells) and Topsøe.
- 3 bio$ in shares in 2021. Large breadth of investments in 2021 (almost every type of fuel cell and every end-use market)
- The action happens in **Asia**: 1.5 GW or 65% of power. USA 0.6 GW. Europe 0.2 GW.
- **PEM mobility** accounts for 86% of power
- Other : domestic uCHP (44000 units, Japan 40000, Europe 4000); remote power ; prime power (Bloom + Doosan) in S-Korea. Portable units 6000

Green H_2 electrolysis deployment

- H_2 has uses in all sectors (industry, mobility, heating)
- **> TWe** cumulated green electrolysis power is needed
- coupled to rise in **wind** and **PV** power
- demands massive scaling and cost reduction

- Large scale electrolysis has been done before:
  - Chlor-alkali industry ~20 GWe (producing >50 TWh of H_2)
  - Aluminium industry >100 GWe (consumes 4% of the world electricity!)

- 2021 saw 2 large-size electrolyser plants deployed (in Québec) : **20 MWe** PEMEL and **88 MWe** AEL

Contents

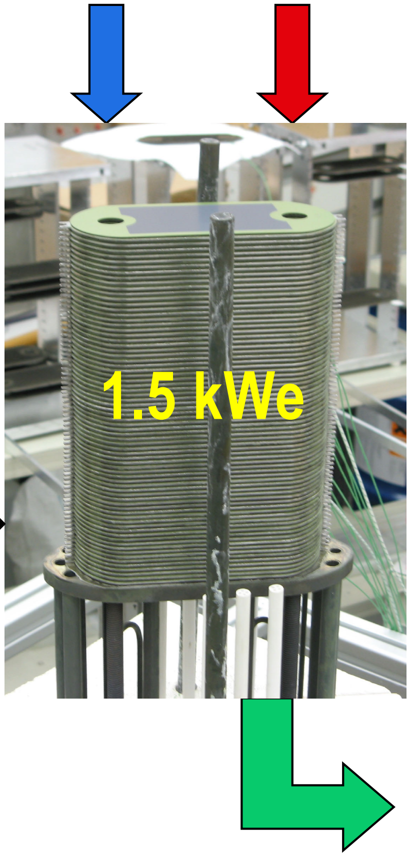
1. Fuel cell operating principle. Components of fuel cells.
2. Fuel-to-electricity **efficiency**
3. Applications, strengths & challenges
4. Fuel issue: hydrogen and hydrocarbons
5. Reverse fuel cells (=electrolysers) for (green) electricity storage: ‘Power-to-Gas’

A fuel cell at a glance

- works like a gas battery
- chemical fuel is directly converted into electricity and useful heat
- typical sizes and applications:
  - 1-20 W_e / H_2, MeOH / portable electronics
  - 1 kW_e / natural gas / a house
  - 50 kW_e / H_2 / an electric car
  - 1 MW_e / biogas / CHP
- status: R&D, P&D, pre-commercial

Air **Fuel** (natural gas, H_2, biogas,…)

100%



‘Stack’ of
66 cells
of 80 cm^2
(30A)
in series
(50 V)

Electricity 60%
Heat 30%

The key is direct conversion of fuel to electricity (=> *high efficiency*)

- **“Fuel”** = an oxidizable chemical substance
- ‘Conversion’ = here: *electrochemical* oxidation
- ‘Oxidation’ = release of electrons to an electron-accepting chemical substance (=the oxidant, usually **O_2 from the air**)
- in direct conversion, this released electron flux is exploited as **electrical current** (*dc*)

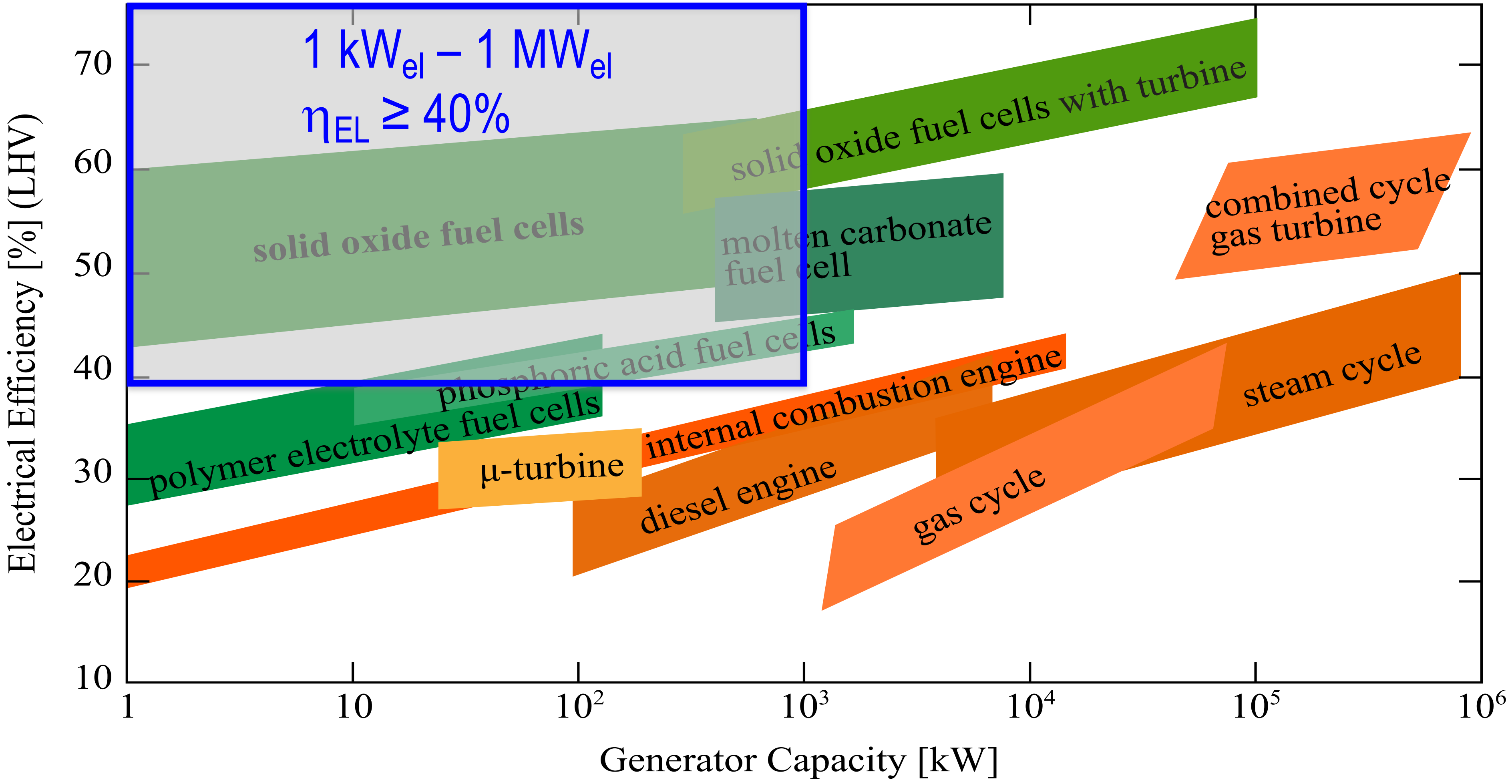
FUEL “CELL”

= battery

Electrical efficiency as fct(power size)

(based on natural gas, LHV)

(compiled by Quentin Jeangros, EPFL-CIME/Fuelmat)

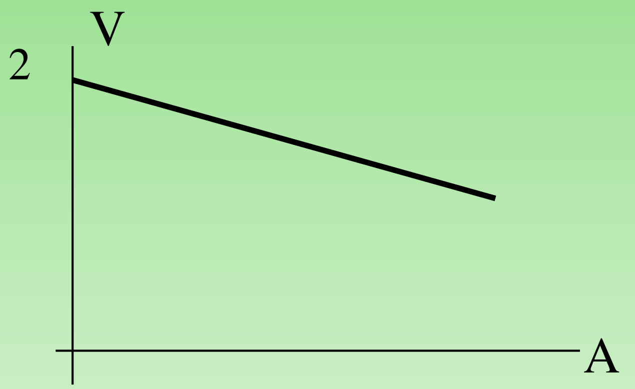


The strength of fuel cells is high electrical efficiency at 'small' power, virtually without pollution

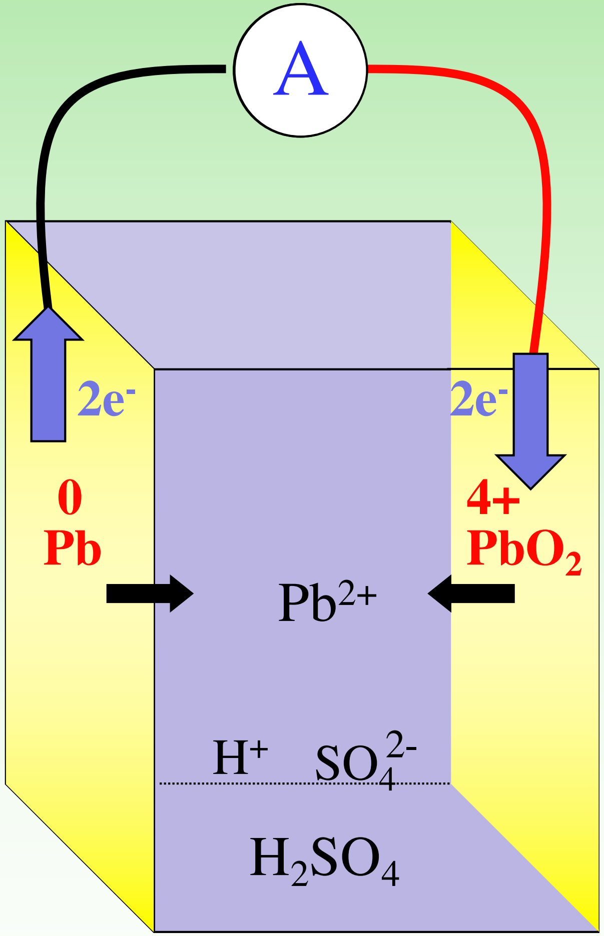
Part 1: operating principle; components

- Electrochemistry of a *battery*
- Electrochemistry of a *fuel cell*
- Components of fuel cells
- **Types (5)** of fuel cells

Classical car battery : ‘lead (Pb) -acid’



< 2 V



$$Pb \Leftrightarrow Pb^{2+} + 2e^-$$

$$PbO_2 + 2e^- + 4H^+ \Leftrightarrow Pb^{2+} + 2H_2O$$

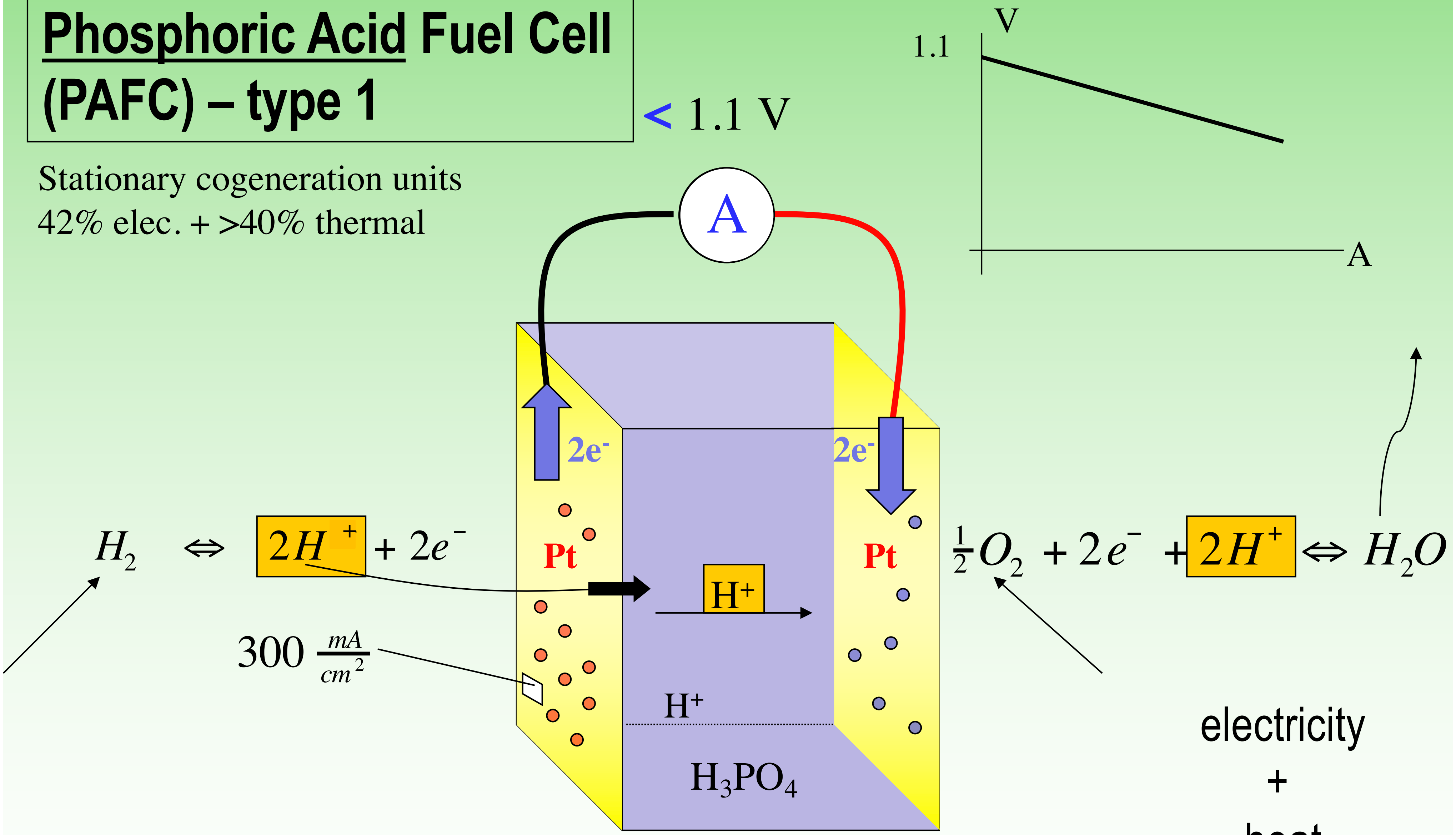
$$Pb + PbO_2 + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$$

electrodes are consumed (« active mass »)

Phosphoric Acid Fuel Cell (PAFC) – type 1

< 1.1 V

Stationary cogeneration units
42% elec. + >40% thermal



$H_2 \Leftrightarrow \boxed{2H^+} + 2e^-$

$300\ \frac{mA}{cm^2}$

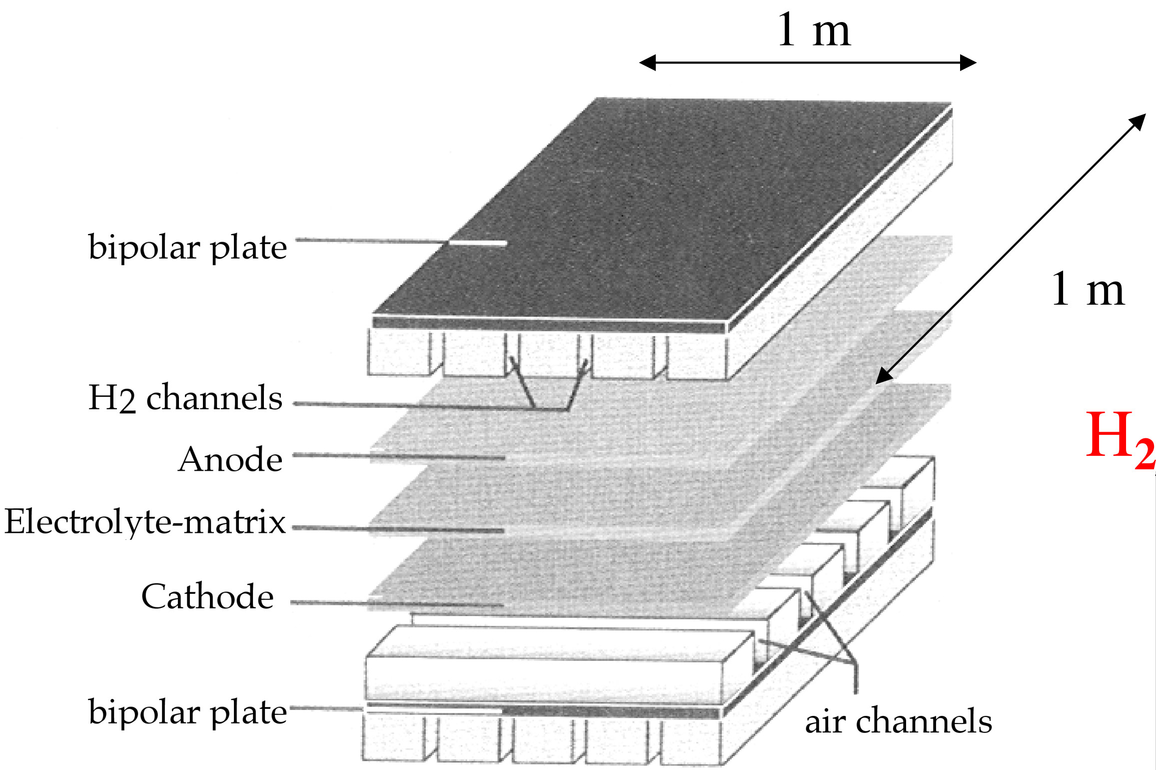
$\frac{1}{2}O_2 + 2e^- + \boxed{2H^+} \Leftrightarrow H_2O$

$$H_2 + \tfrac{1}{2}O_2 \Leftrightarrow H_2O$$

- gases are consumed
- electrodes are invariable (=catalysts)

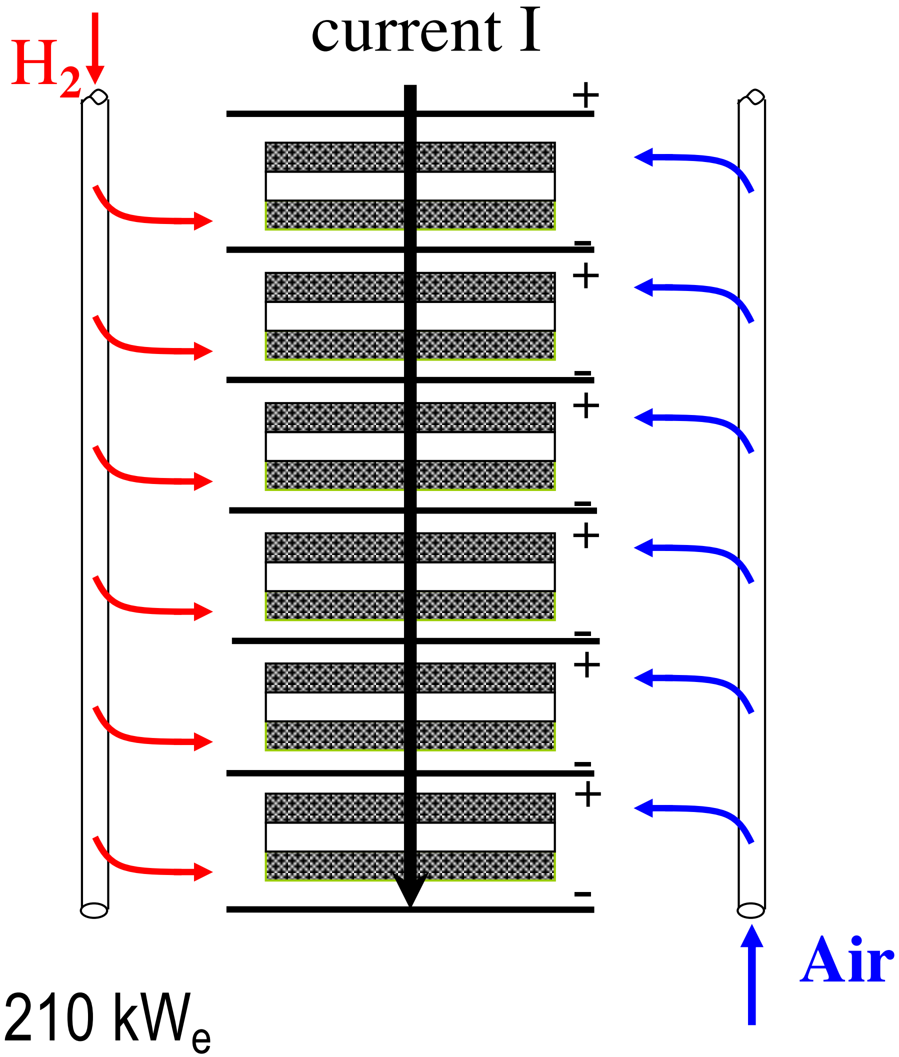
electricity
+
heat

200C



(Source: Ledjeff, 'Brennstoffzellen')

Increase electrode surface :
→ high **current** I (A)



Series connection :
add up the **voltages** (V)

Electric **power** P = **V** * **I**
f.ex. 100 cells of 1 m^2 surface

70 V * **3000 A** = 210 kW_e

Units exist from 50 kW_e to several MW_e

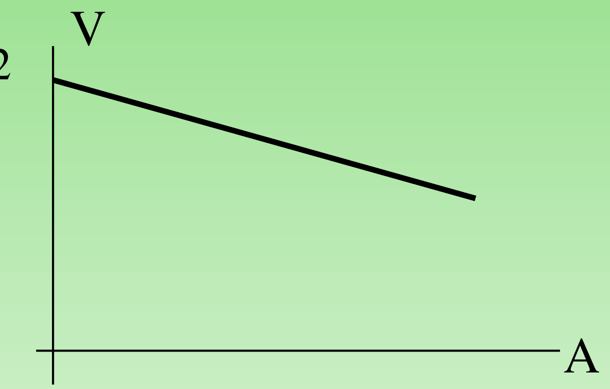
Typical PAFC size is 200 kW_e or 400 kW_e, operated on natural gas (NG)

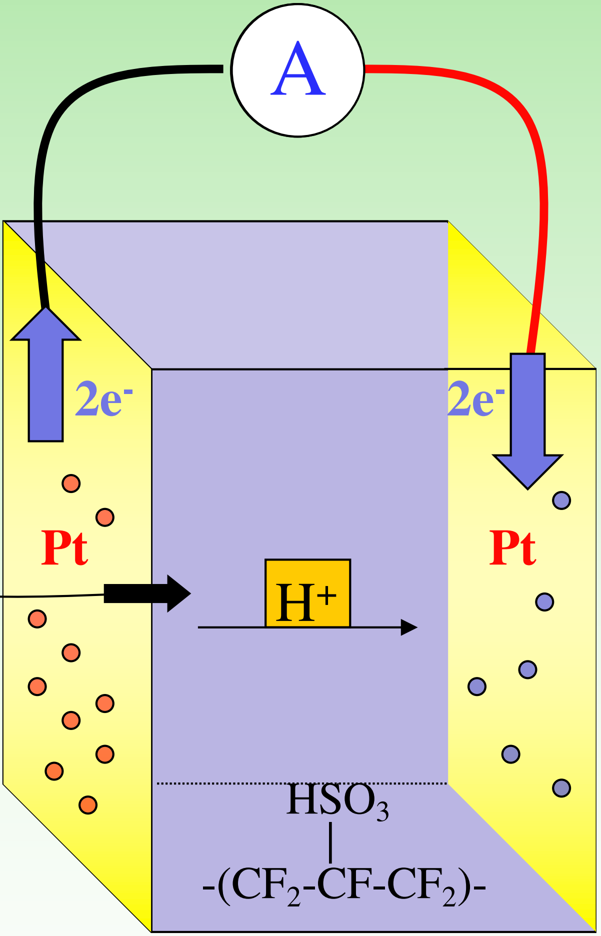
(source : Thoma & Renz AG, Basel, CH)

Polymer Membrane FC
Polymer Electrolyte FC
(PEM or PEFC) – type 2

For mobility mainly (vehicles)
>50% H_2-to-elec. efficiency

< 1.2 V





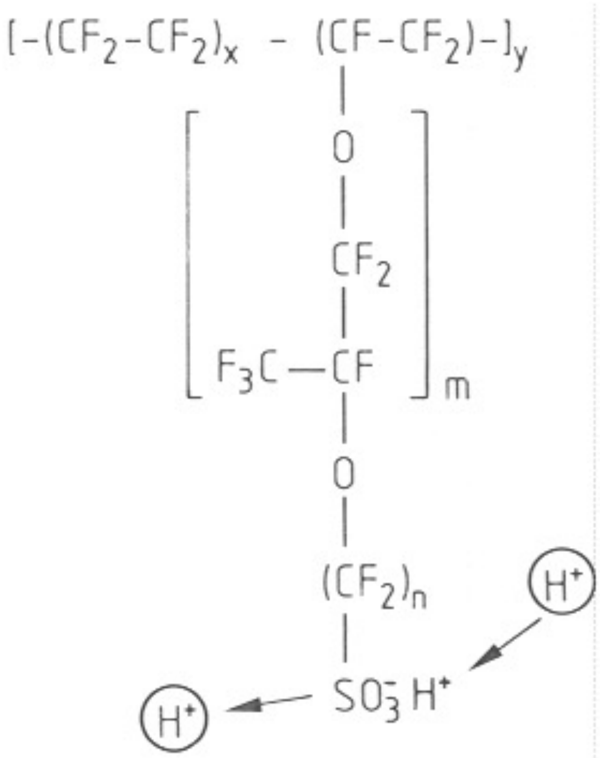
$H_2 \Leftrightarrow \boxed{2H^+} + 2e^-$

$\frac{1}{2}O_2 + 2e^- + \boxed{2H^+} \Leftrightarrow H_2O$

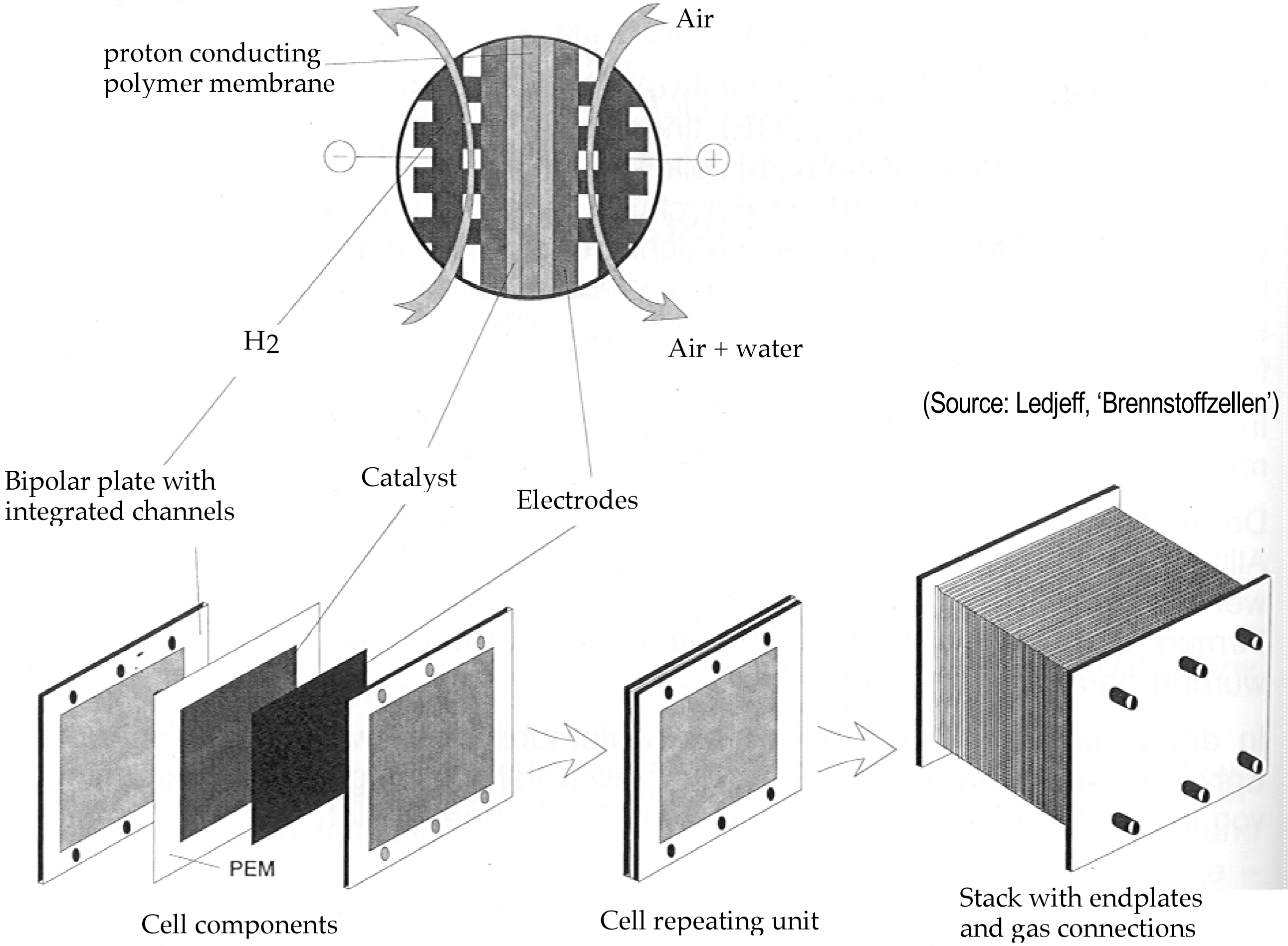
$$H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O$$

mobile
↑
cold start
↑
0-80C

polymer membrane (50 µm thin)



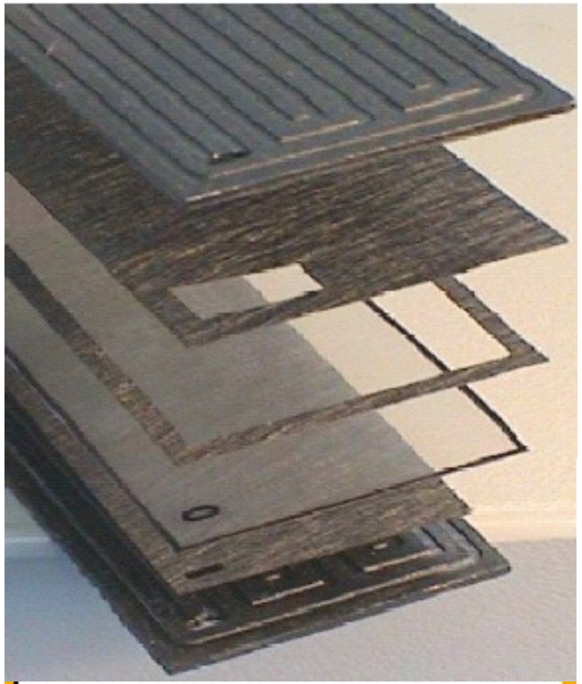
series connection (« stack »)



(Source: Ledjeff, 'Brennstoffzellen')

http://www.youtube.com/watch?v=yowRvfFtMgQ

PEFC applications




70 kW$_e$

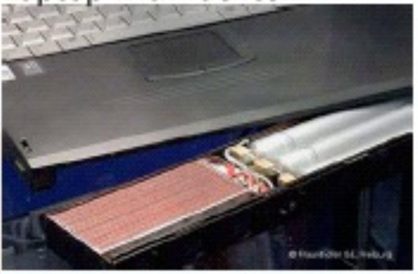

2 kW$_e$


5 kW$_e$

5 - 50 W$_e$

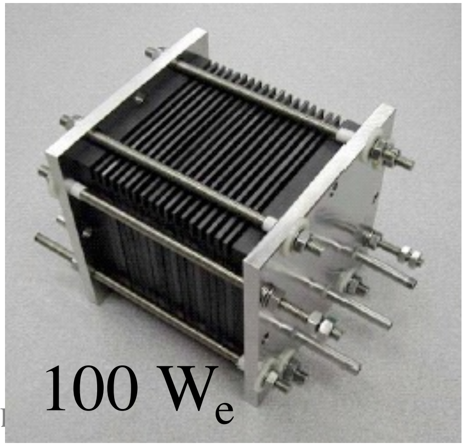
Fuel cell camcorder

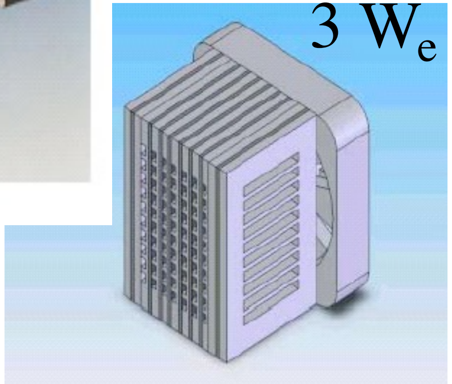
Laptop with fuel cell



Fuel cell power box

Professional camera with fuel cell


100 W$_e$


3 W$_e$

Comment (1)

- The 2 fuel cell types seen so far use **proton** (H^+) **conduction**, in a liquid (acid) or a wet membrane (polymer)
- They operate at 200C (acid) or below 100C (polymer)
- At such **low temperature**, the **only fuel** reactive enough to be (electrochemically) oxidized is **hydrogen** (H_2)
  - …and methanol (MeOH), but with much reduced power output
- Moreover, the **only electrodes** capable to catalyze this reaction ($H_2 + ½O_2 \rightarrow H_2O$) at such low temperature are the **noble metals** (Pt-group)

=> limited to H_2 and Pt

Comment (2)

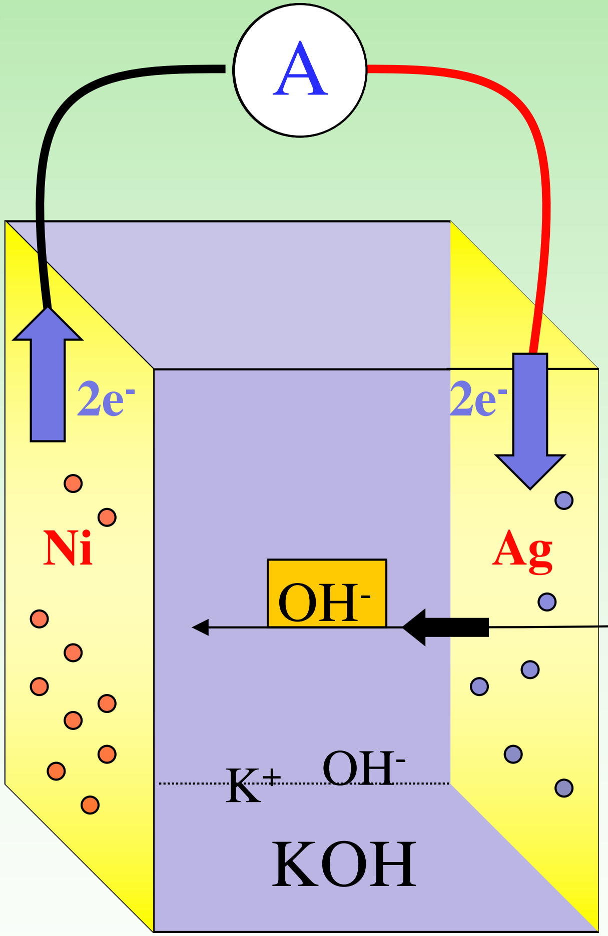
- The following 3 fuel cell types use a form of **oxygen ion conduction**
- Two of them use a ceramic resp. molten salt conductor, which operate at high temperature (>600C)
- At such **high temperature, other fuels than H_2** become reactive enough for (electrochemical oxidation) (CO, **CH_4**,..)
- Moreover, high temperature is favorable for fast electrode kinetics, making **cheaper catalysts** than noble metals possible (Ni, oxides,..)

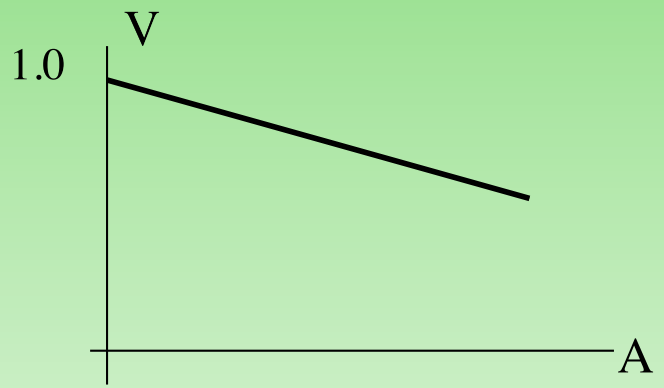
=> possible with hydrocarbons, on Ni catalyst

Alcaline Fuel Cell (AFC) – type 3

For mobility or stationary applic.

< 1 V





$$H_2 + \boxed{2OH^-} \Leftrightarrow 2H_2O + 2e^-$$

$$\tfrac{1}{2}O_2 + 2e^- + H_2O \Leftrightarrow \boxed{2OH^-}$$

$$H_2 + \tfrac{1}{2}O_2 \Leftrightarrow H_2O$$

12 kW_e

application: transport

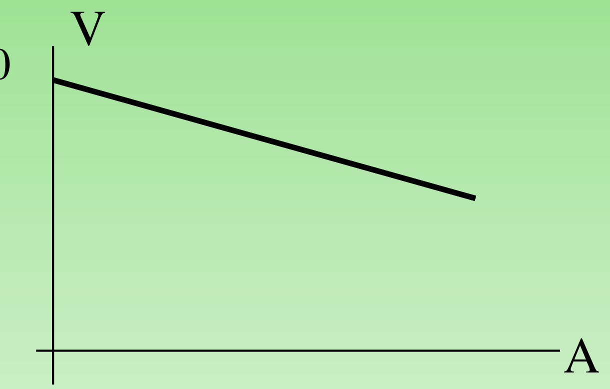
↑

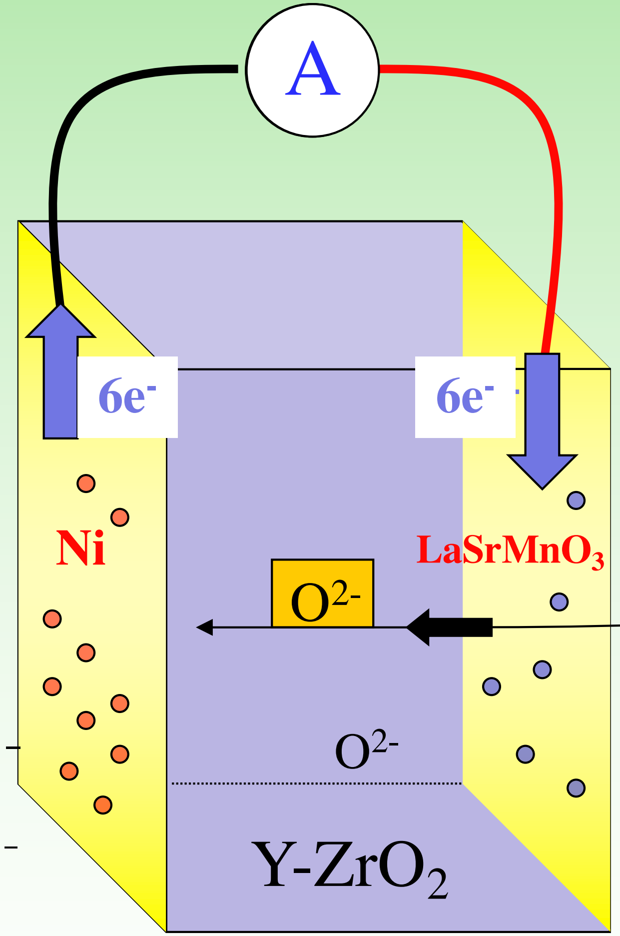
80C

Solid Oxide Fuel Cell (SOFC) – type 4

For stationary cogeneration
>60% elec.eff + 30% thermal

< 1 V





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

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

$CH_4 + 4O^{2-} \Leftrightarrow 2H_2O + CO_2 + 8e^-$

$CH_3OH + 3O^{2-} \Leftrightarrow 2H_2O + CO_2 + 6e^-$

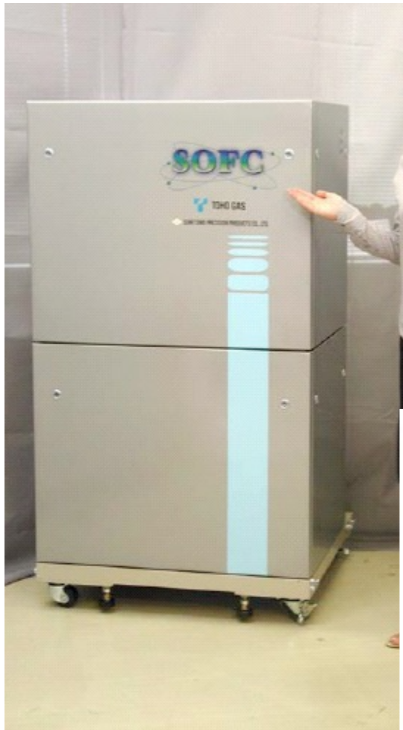
$\frac{1}{2}O_2 + 2e^- \Leftrightarrow \boxed{O^{2-}}$

$$H_2 + \tfrac{1}{2}O_2 \Leftrightarrow H_2O$$

cogeneration

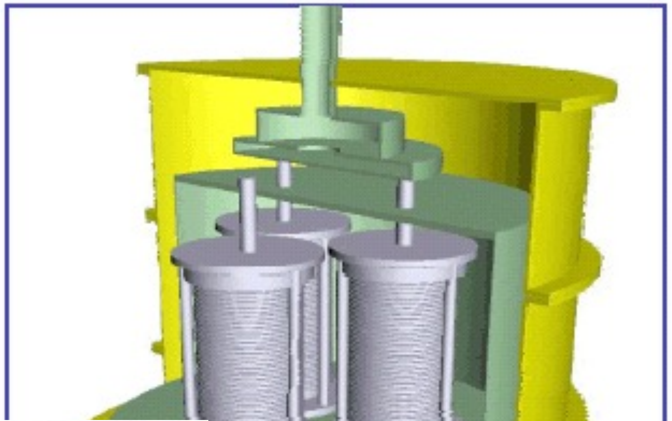
↑

600-1000C

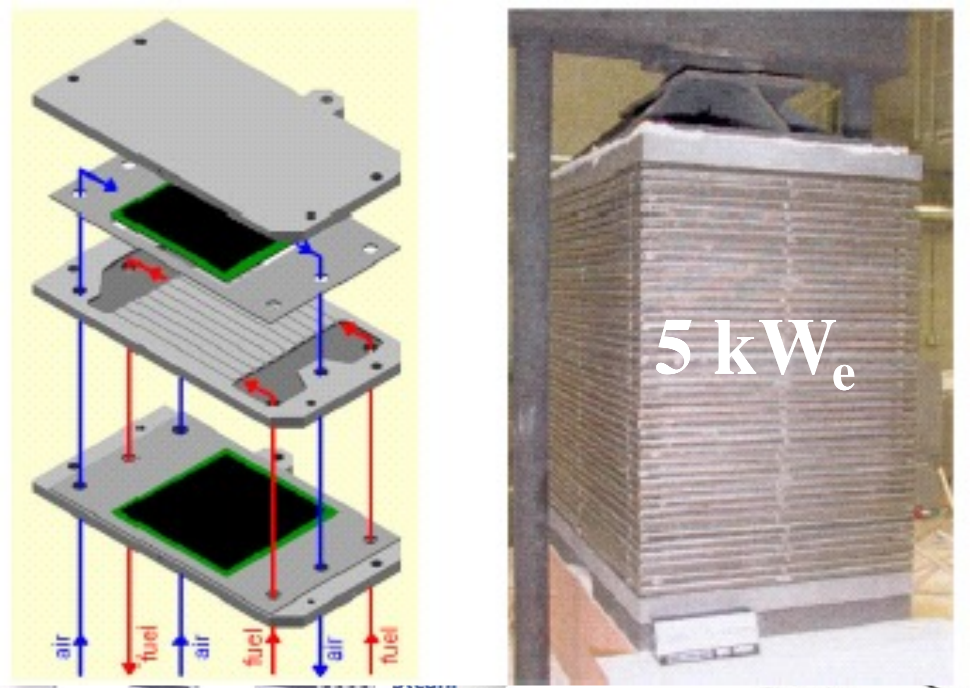


TOHO
GAS
1 kW_e

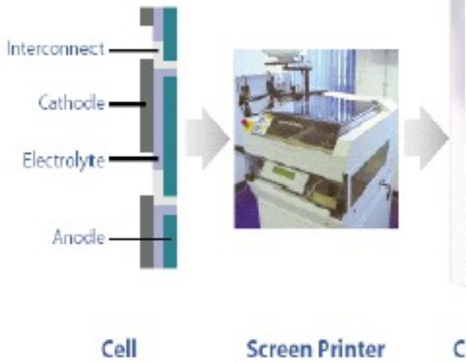
Kansai
Electric
3 kW_e



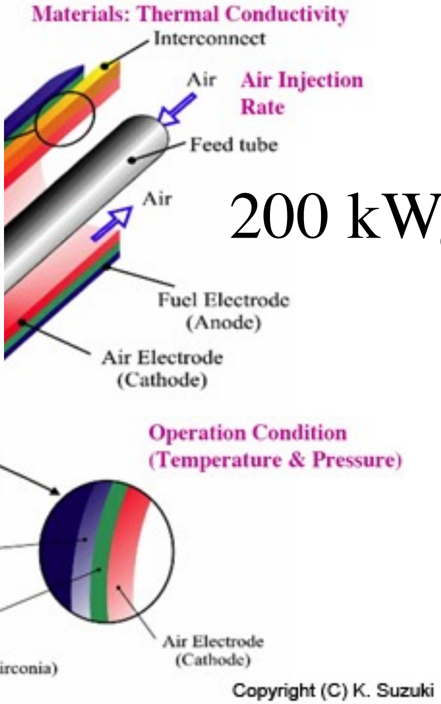
FZJülich (D)



200 kW_e



RollsRoyce Power (UK)

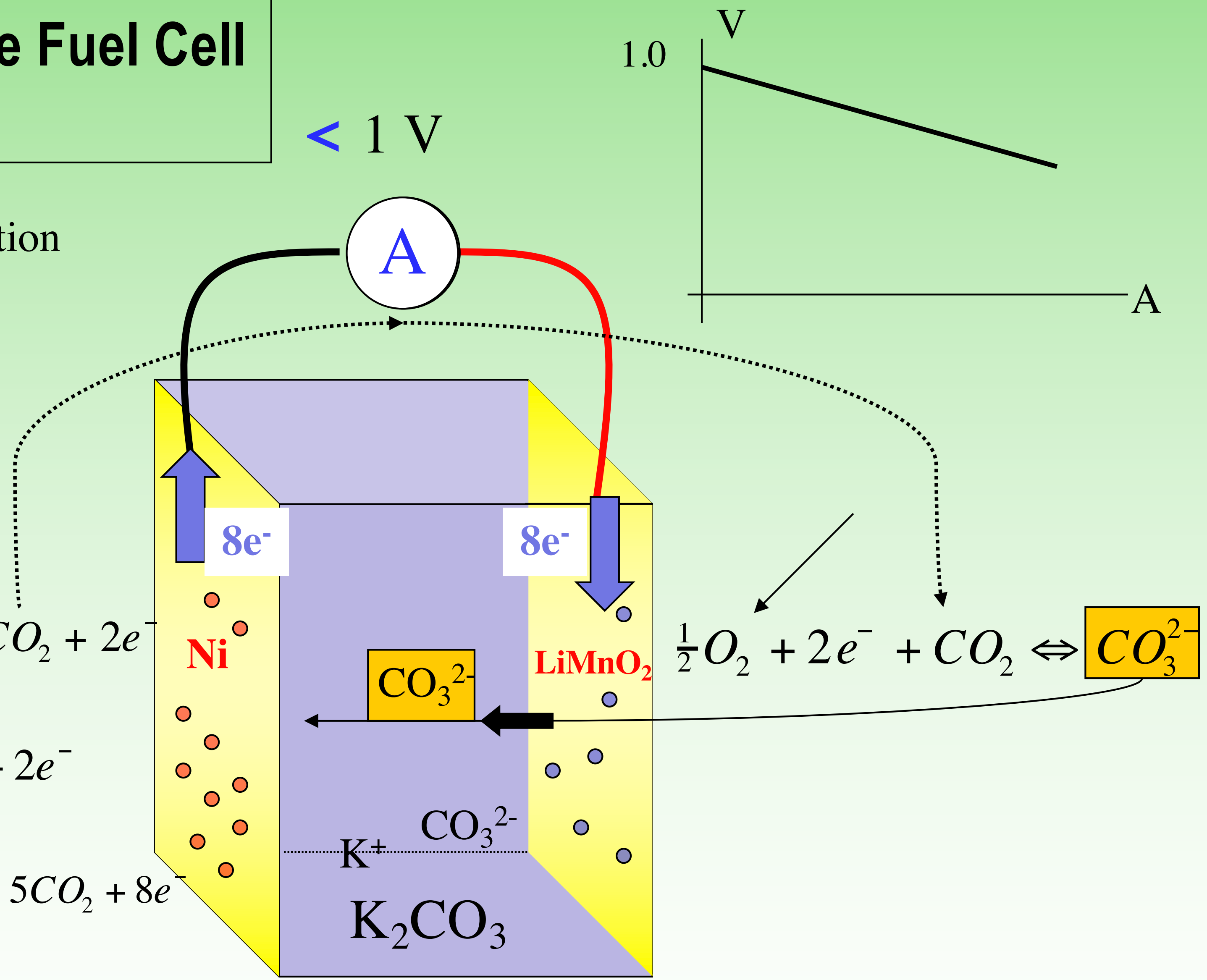


200 kW_e

Siemens-Westinghouse

Molten Carbonate Fuel Cell (MCFC) – type 5

For stationary cogeneration
~50% elec. eff.



$H_2 + \boxed{CO_3^{2-}} \Leftrightarrow H_2O + CO_2 + 2e^-$

$CO + CO_3^{2-} \Leftrightarrow 2CO_2 + 2e^-$

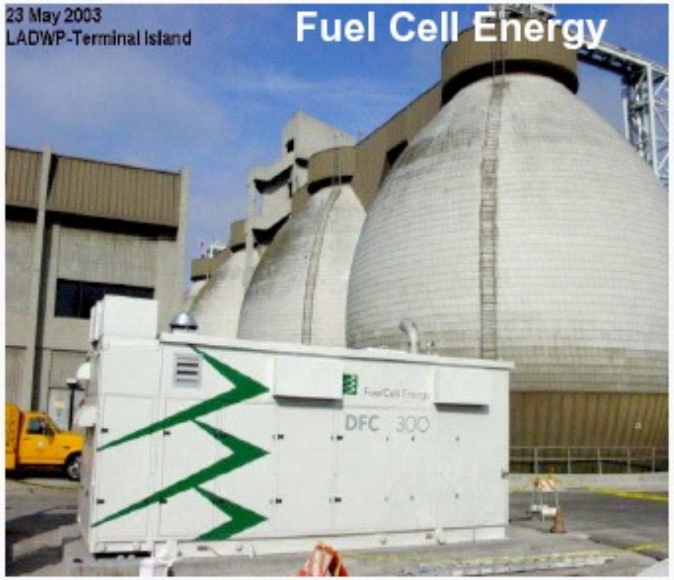
$CH_4 + 4CO_3^{2-} \Leftrightarrow 2H_2O + 5CO_2 + 8e^-$

$\tfrac{1}{2}O_2 + 2e^- + CO_2 \Leftrightarrow \boxed{CO_3^{2-}}$

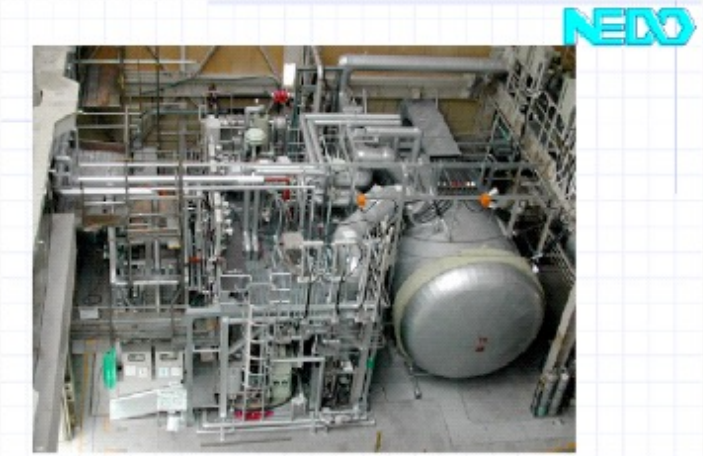
$$H_2 + \tfrac{1}{2}O_2 \Leftrightarrow H_2O$$

650C

Photos courtesy of: FCE, AFC, MTU,NEDO, KEPRI



Germany



Full View of 300kW-class Compact System
in KAWAGOE Test Station

MCFC cogeneration units of 300 kW_e - 3 MW_e

Overview of the 5 fuel cell types

"direct" methanol ←

Type	Electrolyte	Temperature	Fuel
AFC	liquid alcaline	20-100° C	H_2
PEFC DMFC	membrane polymer	20-100° C	H_2 (or methanol)
PAFC	liquid acid	200° C	H_2 (from nat. gas)
MCFC	molten salt	650° C	**hydrocarbons**
SOFC	ceramic	600-1000° C	**hydrocarbons**

Materials in fuel cells: low *vs* high T

Type	**Electrolyte**	**Cathode**	**Anode**	**Interconnect**	**Dimensions**
AFC	KOH	Ag	Ni	steel	flat,50-400cm^2
PEFC	« Nafion » (=« sulfonate de teflon »)	**Pt** on C	**Pt**(-Ru)	graphite	flat, 5-400 cm^2
PAFC	H_3PO_4	**Pt** on C	**Pt** on C	graphite	flat, 1 m^2
MCFC	$(Na,K,Li)_2$-CO_3	NiO or $LiCoO_2$	**Ni**	inox	flat, 1 m^2
SOFC	90% ZrO_2 + 10% Y_2O_3	$LaSrMnO_3$	**Ni**	Steel Cr or ferritic	flat / 100 cm^2 tubes / (2 m long * 2 cm diam.)

Part 2: Fuel-to-electricity efficiency

- **Thermodynamics** (equilibrium or Nernst voltage), $i = 0$
  - Nernst equation

- **Losses** (real operating voltage), $i \neq 0$
  - ionic conduction loss (ohmic)
  - electrodes kinetics loss (non-ohmic: 'polarisation')
    - charge transfer (Butler-Volmer equation)
    - mass transfer (diffusion, adsorption,...)

- Fuel '**utilisation**' (u_F) or fuel conversion loss

From chemical energy (total enthalpy ΔH) to electrical power (P = V*I)

$\Delta H_{reaction}$ *total* enthalpy = total chemical (**heat**) energy at inlet
= heating value of the used fuel (kJ/mol, kJ/kg)

↓

$\Delta G_{reaction}$ *free* enthalpy = theoretical useful **work** (kJ/mol, kJ/kg)

↓ *in a fuel cell: electrical work*

↓ $\Delta G = -nFE_{Nernst}$

F: Faraday constant 96500 C/mol
n: number of electrons released per fuel molecule

E_{Nernst} *equilibrium* voltage (V) $i = 0$

↓

V_{cell} *operating* voltage (V) $i \neq 0$
- includes all **losses** in the internal circuit

From Gibbs enthalpy to Nernst voltage

- a H_2/O_2 fuel cell at i = 0 creates an **equilibrium voltage of 1.23 V** (at 25C, 1 bar)
- the Gibbs enthalpy of reaction ΔG_r (=theoretical maximal work) for

  $H_2 + 0.5\ O_2 \rightarrow H_2O$ is given by

  $\Delta G^0_r (25°\ C, 1\ atm) = -237'150$ J/mole
- The link between thermodynamics and voltage is given by

  $\mathbf{\Delta G^0_r = - nF.E^0}$ (with n = exchanged electrons; n = 2 for H_2/O_2)

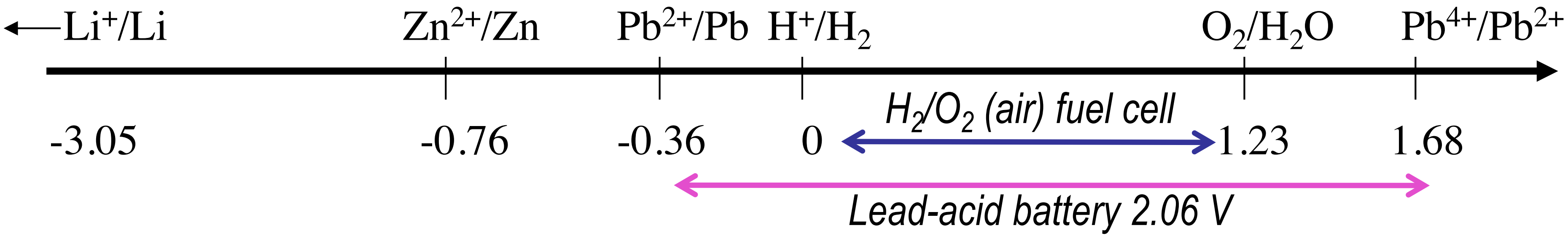
  energy (J/mol) = charge (C/mol) * voltage (V)

  with F = Faraday constant = the charge of 1 mol electrons (96484 C/mol)

  → therefore $E^0 = (\Delta G^0_r/2F) = 237150 / (2*96484) = 1.23$ V at 298 K, 1bar

  (^{0} : standard concentration conditions: 1 atm, 1 mole/L,…)

Electrochemical series of elements



Electrical conduction losses

- Across any layer of thickness *d* in the fuel cell where current passes through a section *S*, a voltage drop ΔV occurs, according to Ohm's Law :

$$\Delta V = R.I$$

with $R = \rho . d/S$ (ρ = resistivity, Ωcm)

or $\sigma = 1/\rho$ (σ = conductivity, $\Omega^{-1}cm^{-1}$, S/cm)

- σ = concentration of charge carriers (c) * their mobility (u)

  = fct(c, n, ion size, temperature) (cf. viscosity of the medium)

$$u = \frac{\vec{v}}{\vec{E}} = \frac{ne_0}{6\pi r\eta}$$

v: speed of charge carrier (m/s)
E: electrical field (V/m)
n: ion charge (1 for H^+; 2 for O^{2-}, ..)
e_0 : elemental charge 1.6 E-19 C
r : radius of ionic charge carrier (m)
η : viscosity of conductor (Pa.s)

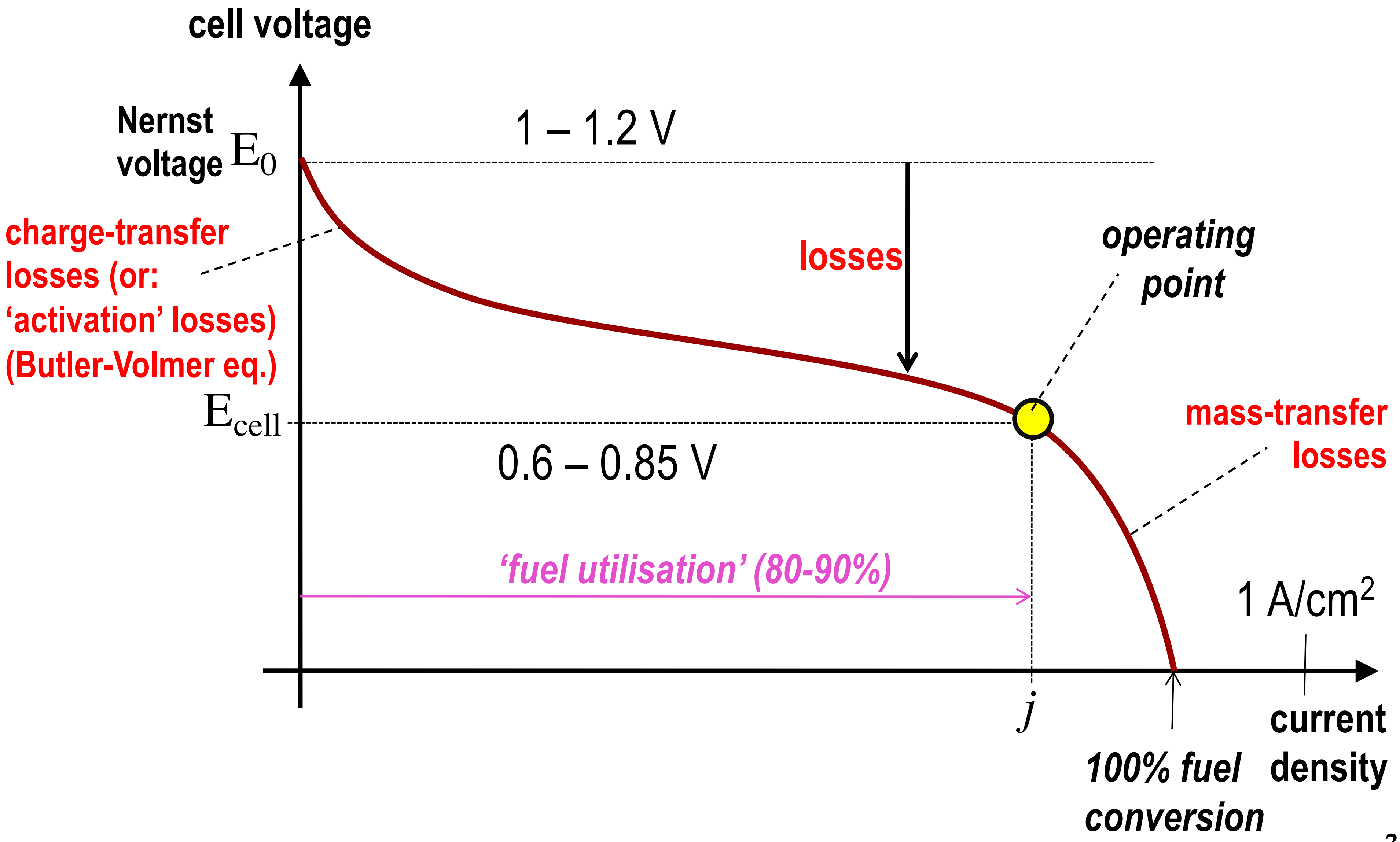
- The **main ohmic loss** occurs in the **electrolyte** membrane (ionic conductor)

Electrode kinetics losses

- Physico-chemical processes occur in/on the electrodes and at the electrode/electrolyte interfaces :
  - **charge transfer** : η_{CT}
  - **mass transfer** : η_{diff} (diffusion), η_{ads} (adsorption), …
- These cause voltage losses which are *non-linear* with current, hence non-ohmic (IMPEDANCE); we speak about "**OVERPOTENTIAL**" η or "**POLARISATION**" loss (in V)

Example:	H_2	$\rightarrow$	$2\ H^+ + 2\ e^-$	overall reaction
=> in detail:	$H_{2,g}$	$\rightarrow$	$H_{2,ad}$	adsorption
	$H_{2,ad}$	$\rightarrow$	$H_{ad}+H_{ad}$	chemical reaction (dissociation)
	H_{ad}	$\rightarrow$	$H^+ + e^-$	charge transfer (* 2)

Characteristic i-V (current-voltage) curve



Useful electrical power from the fuel cell

$$P = \Sigma E_{cell} \bullet I$$

$$E_{cell} = E_{Nernst}(p,T) - I.\Sigma R_{ohmic} - \left|\Sigma\eta_{cathode}\right| - \Sigma\eta_{anode}$$

E_{Nernst} (1 atm, 200° C, I = 0 A) = 1.1 V	R_{ohmic} = 0.25 Ωcm^2
@ typical current density = 0.4 A/cm^2 :	$\eta_{cathode}$ = 0.2 V, η_{anode} = 0.1 V
=> typical operating voltage E_{cell} = 0.7 V	power density = 0.28 W/cm^2

Example of phosphoric acid fuel cell (PAFC) :
160 cells in series → 160 * 0.7 V = 112 V
electrodes 0.7 m * 0.7 m = 0.49 m^2 → 4900 cm^2 * 0.4 A/cm^2 = 1960 A
⇒ Power = 112 V * 1960 A = 220 kW$_e$ *dc* gross

The module (0.5 m^3) delivers 200 kW$_{el}$ *ac* net (+ 200 kW$_{thermal}$) with an electrical efficiency of 40% and a total cogeneration efficiency of >80%.
(natural gas input: 500 kW)

Fuel cell electrical efficiency

$$\eta_{cell} = \frac{P[W]}{\dot{f}[mol/s]\bullet\Delta H_{293K}[J/mol]}$$

$$\eta_{cell} = \frac{I\bullet E_{cell}}{\dot{f}[mol/s]\bullet\Delta H_{293K}[J/mol]}\,\frac{\Delta G(p,T)}{\Delta G(p,T)}$$

$$\eta_{cell} = \frac{I[A]}{\dot{f}[mol/s]\bullet nF[C/mol]}\,\frac{E_{cell}\;[V]}{E_{Nernst}[V]}\,\frac{\Delta G(p,T)[J/mol]}{\Delta H_{293K}[J/mol]}$$

$$\boxed{\eta_{cell} = \eta_I \bullet \eta_V \bullet \eta_{THDYN}}$$

current efficiency, “fuel utilisation”

voltage efficiency

thermodynamic efficiency

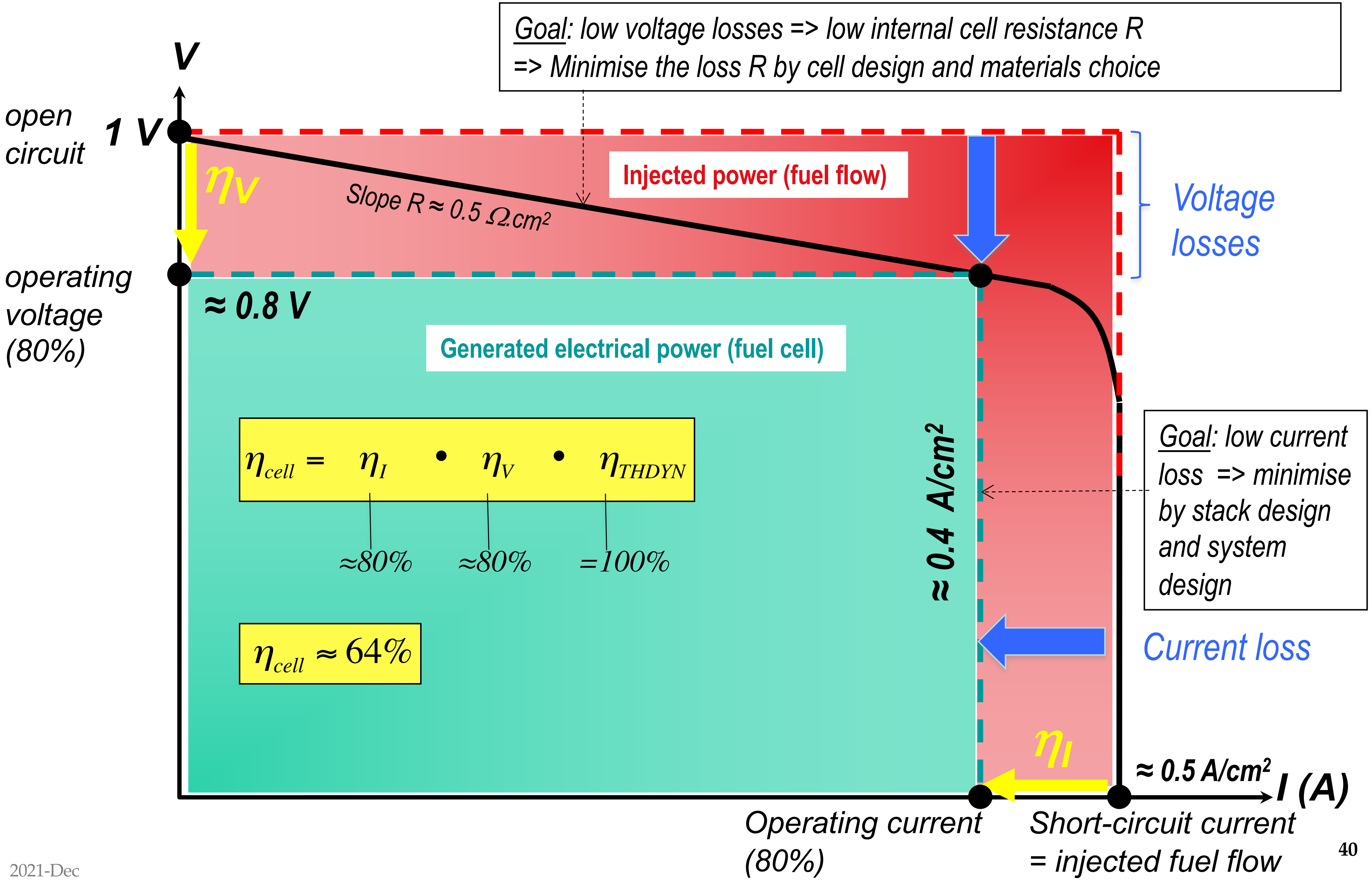
Example: H_2 *vs* CH_4, with air

	H_2, 80° C (PEFC)	H_2, 800° C (SOFC)	CH_4, 800° C (SOFC)
Fuel utilisation	1	0.85	0.8
* Voltage efficiency	0.65	0.8	0.8
* Thermodynamic efficiency (LHV)	0.93	0.78	**1**
= Electrical efficiency (LHV)	0.6	0.53	0.64

- Such values have been achieved in real systems.
- There will usually be co-generation of useful heat, for total efficiencies of ≈ 90%.
- CH_4 has the intrinsic benefit of presenting **no entropy loss**.
- H_2 carries an additional intrinsic loss as it has to be synthesized first.

➔ **Methane-FC (natural gas, biogas) are (in principle) more efficient than H_2-FC**

Current-voltage characteristic, <u>full</u> load



<u>Goal</u>: low voltage losses => low internal cell resistance R
=> Minimise the loss R by cell design and materials choice

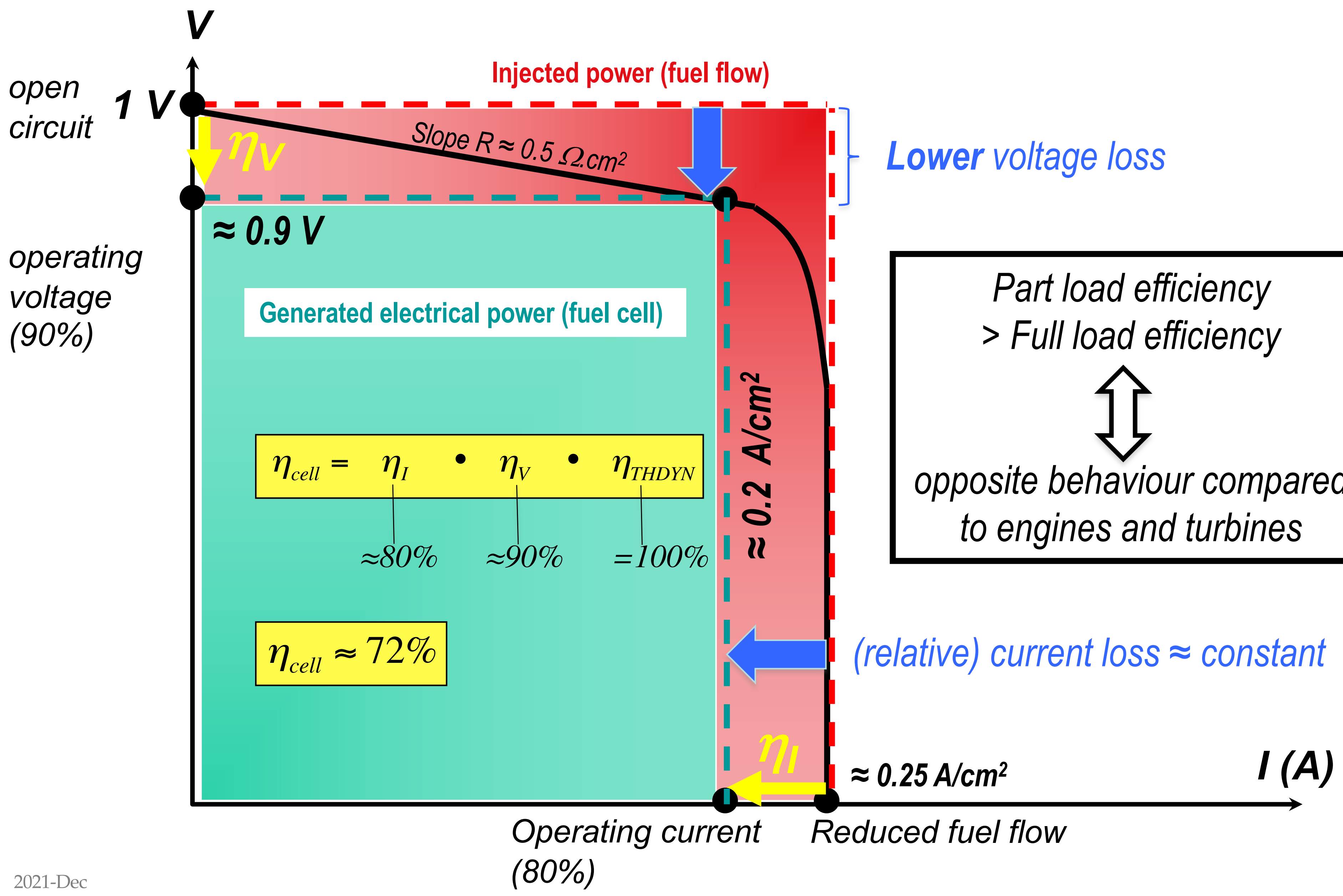
<u>Goal</u>: low current loss => minimise by stack design and system design

$$\eta_{cell} = \eta_I \bullet \eta_V \bullet \eta_{THDYN}$$

$\eta_I \approx 80\%$, $\eta_V \approx 80\%$, $\eta_{THDYN} = 100\%$

$$\eta_{cell} \approx 64\%$$

Current-voltage characteristic, part load



$$\eta_{cell} = \eta_I \bullet \eta_V \bullet \eta_{THDYN}$$

$\eta_I \approx 80\%$, $\eta_V \approx 90\%$, $\eta_{THDYN} = 100\%$

$$\eta_{cell} \approx 72\%$$

Part load efficiency
> Full load efficiency
⇕
opposite behaviour compared to engines and turbines

Comparison with direct combustion

CH_4 + air => $H_2O + CO_2$ + heat

combustion

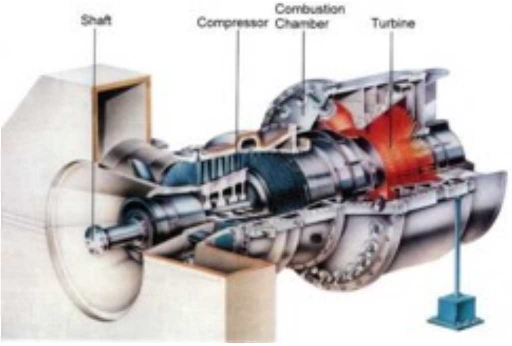
emissions

ENGINES

http://www.sdeciepower.com/8.3L_Natural_Gas_Engine.htm

0.1 – 5 MW_{el}
η_{EL} 33-45%

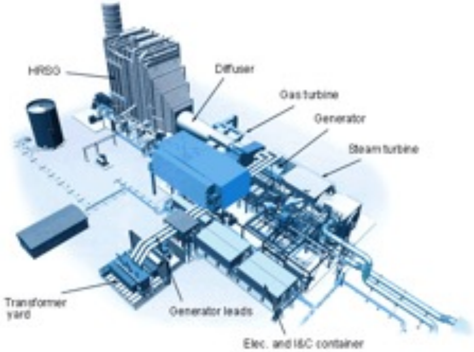
TURBINES



http://www.wartsila.com/sv/kraftverk/learning-center/gas-turbine-for-power-generation

5-100 MW_{el}
η_{EL} 27-40%

COMBINED CYCLES



http://www.zeroco2.no/capture/sources-of-co2/combined-cycle-power-plant

50-500 MW_{el}
η_{EL} 50-60%

---

no polluting emissions

$CH_4 + 4\ O^{2-}$ ← $4\ O^{2-}$

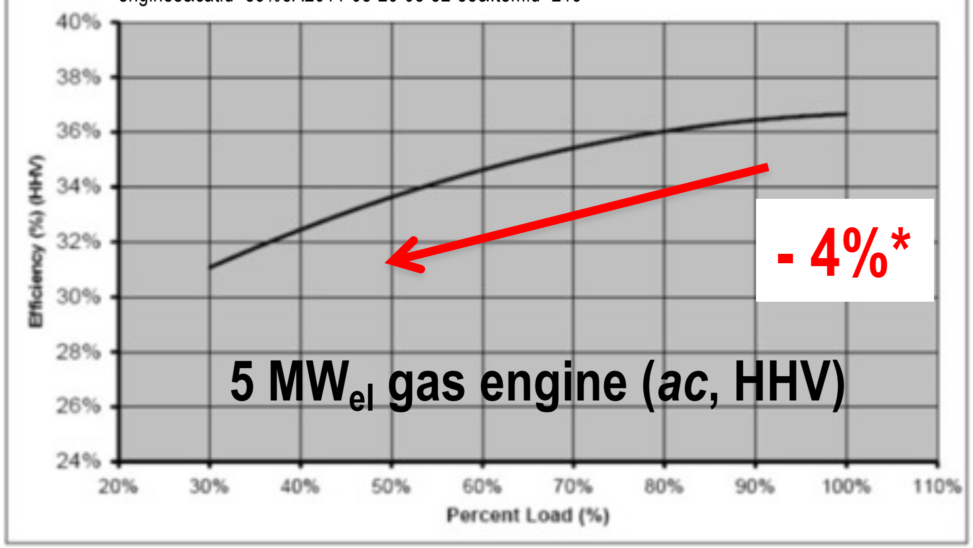
$H_2O + CO_2 + 8e^-$ → $8e^-$ + air (O_2, N_2)

electrochemical conversion

1 – 100 kW_{el}
η_{EL} 50-60%

CH_4 + air => $H_2O + CO_2$ + ***dc current*** + cogenerated useful heat

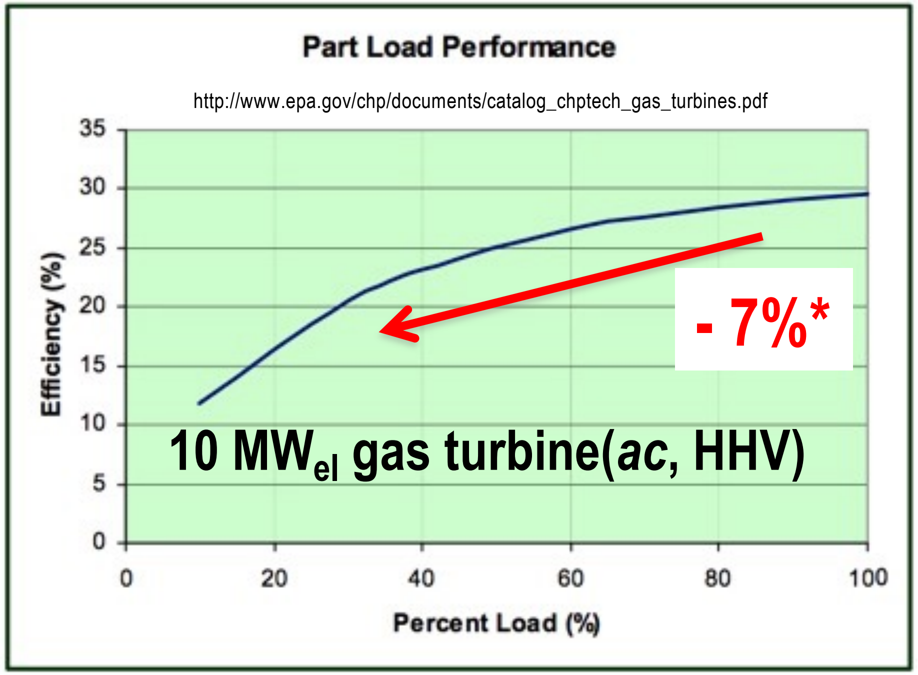
Part load performance: comparison



http://www.tabanenergy.com/en/index.php?option=com_content&view=article&id=82%3Areciprocating-engines&catid=39%3A2011-05-20-08-52-58&Itemid=219

- 4%*

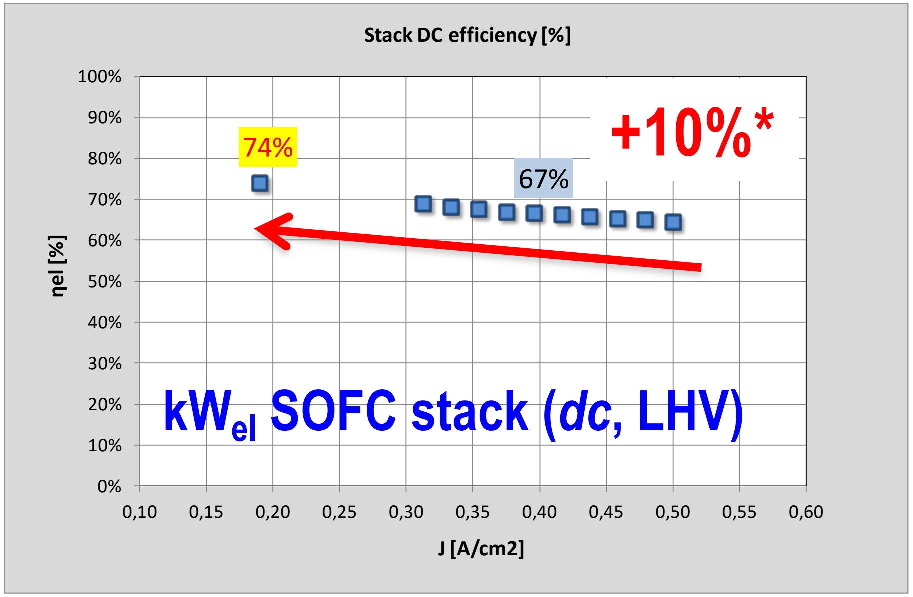
5 MW_{el} gas engine (*ac*, HHV)



http://www.epa.gov/chp/documents/catalog_chptech_gas_turbines.pdf

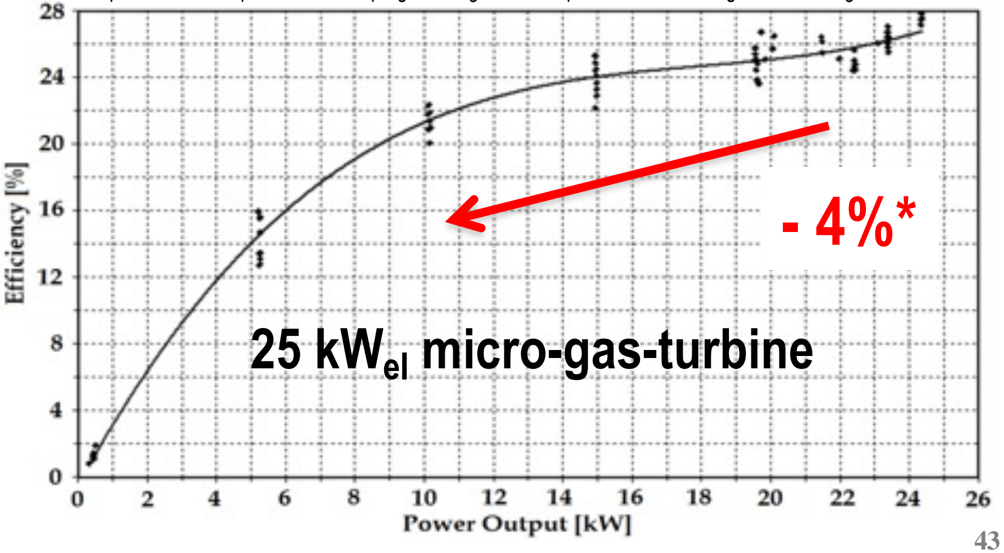
- 7%*

10 MW_{el} gas turbine(*ac*, HHV)



+10%*

kW_{el} SOFC stack (*dc*, LHV)



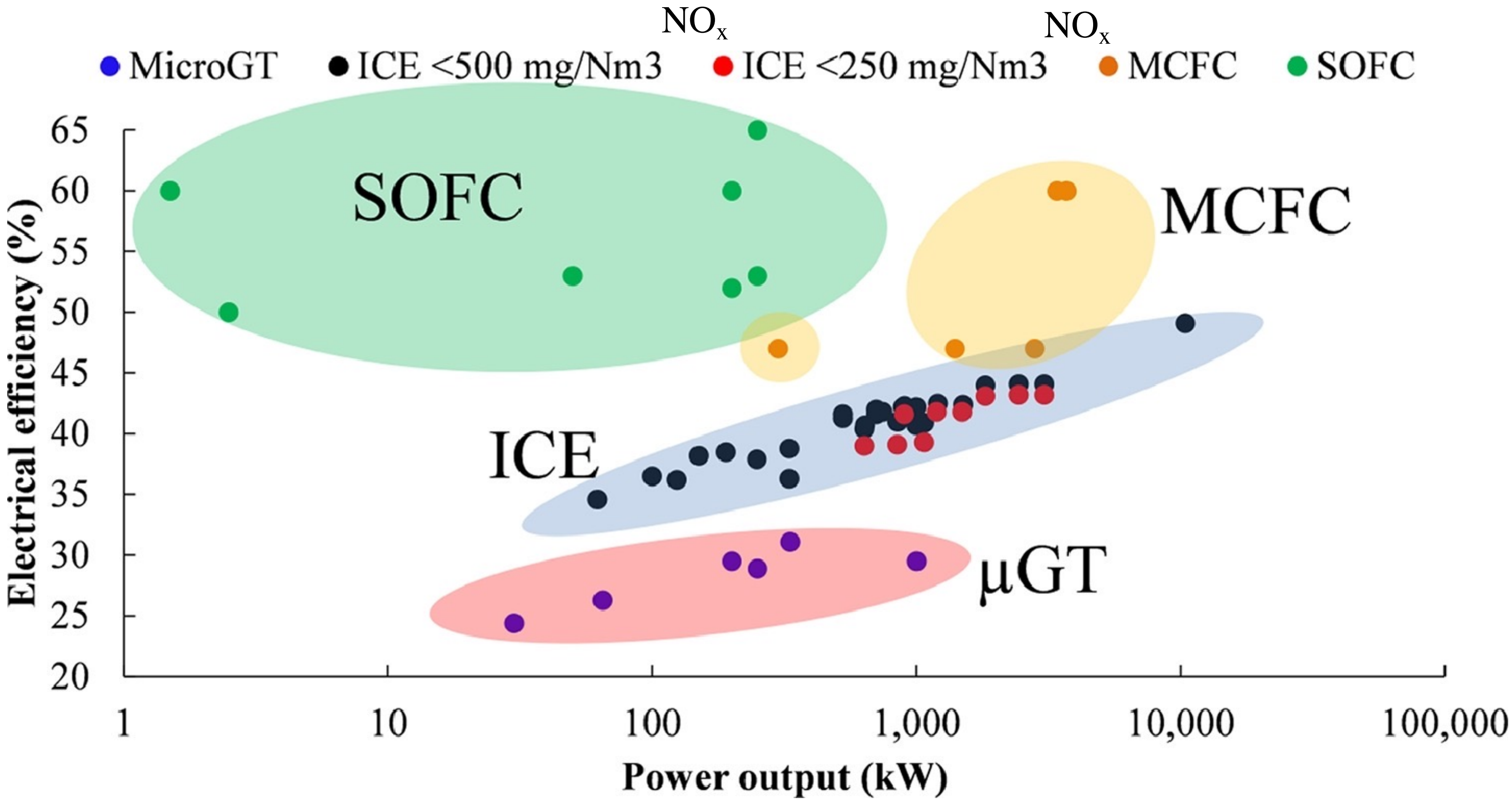
http://www.intechopen.com/books/progress-in-gas-turbine-performance/micro-gas-turbine-engine-a-review

- 4%*

25 kW_{el} micro-gas-turbine

*from 100% to 40% power modulation

Best efficiency and lowest emissions



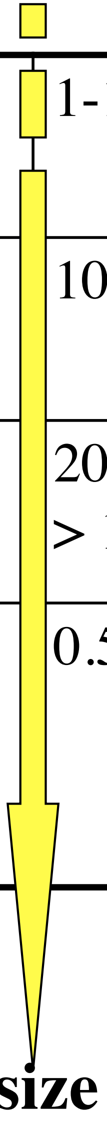
SOFC : < 2 ppm NOx (≈mg/Nm^3), >>100x less than combustion

Part 3 :

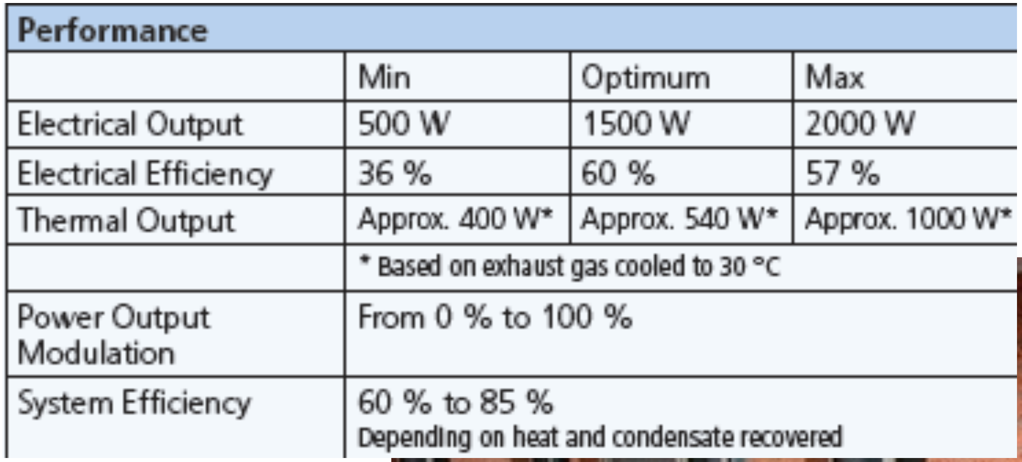
- Applications, examples
- Strengths, advantages
- Challenges, problems to solve

Which fuel cell for which application ?

Portable	1-100 W	electronics (3C market)	DMFC, PEFC
Small cogen.	10 kW - 100 kW	“UPS” (reduced competition from µT or diesel engine)	PEFC, SOFC
Transport	20 kW - 200 kW > 1 MW	vehicles, buses ships	PEFC, DMFC, AFC MCFC, SOFC
Medium cogen.	0.5 MW - 10 MW	offices, schools, universities, supermarkets, hotels, data centers, hospitals, industry (chem/steel/ food/WW/telecom)	PAFC MCFC SOFC



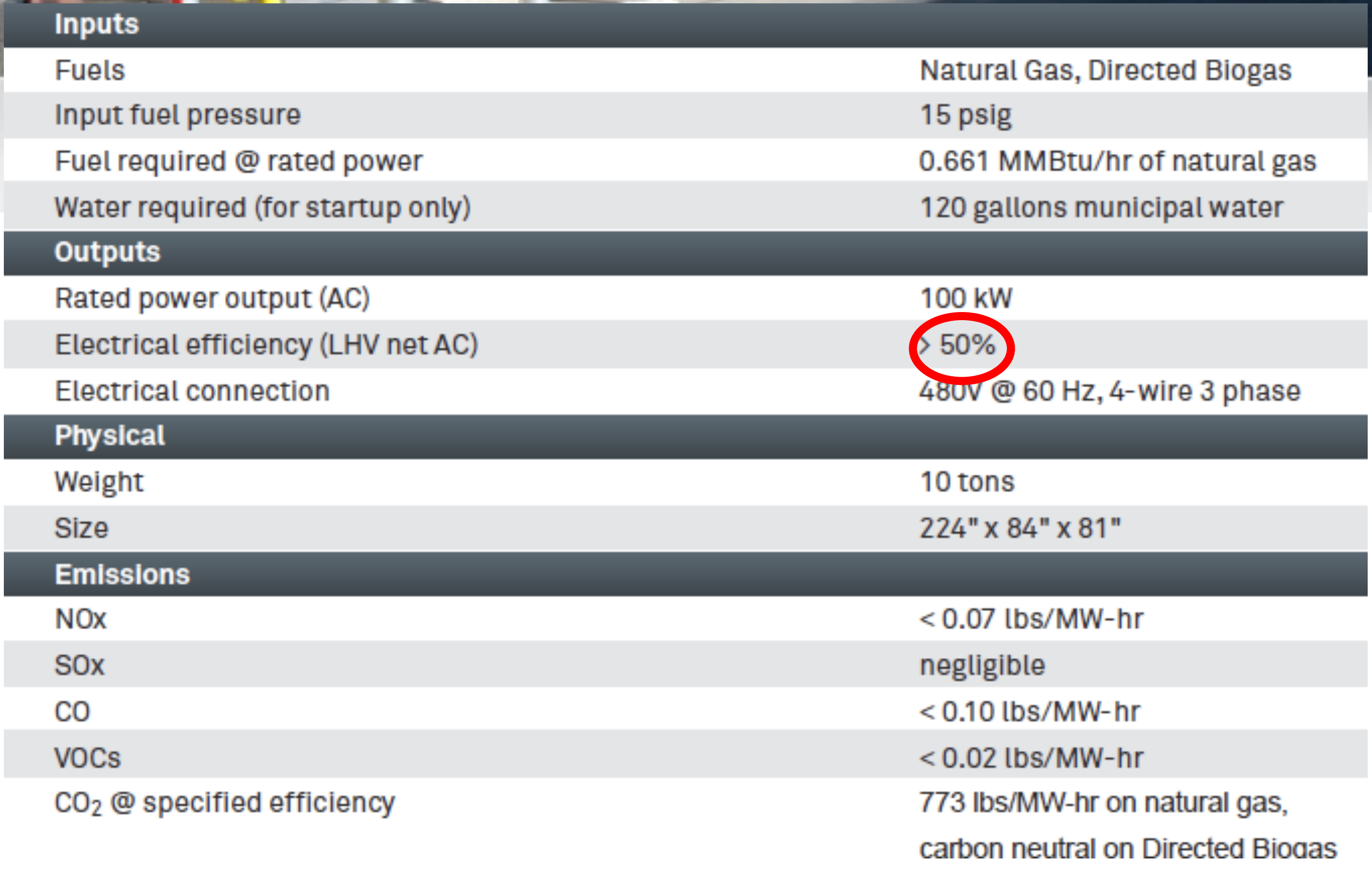
2 kW$_e$ net 63% *ac* efficiency (SOFC)



Performance			
	Min	Optimum	Max
Electrical Output	500 W	1500 W	2000 W
Electrical Efficiency	36 %	60 %	57 %
Thermal Output	Approx. 400 W*	Approx. 540 W*	Approx. 1000 W*
	* Based on exhaust gas cooled to 30 °C		
Power Output Modulation	From 0 % to 100 %		
System Efficiency	60 % to 85 % Depending on heat and condensate recovered		

= world record,
at this small power scale

Multi-100 kWe Bloom Energy Box (SOFC)

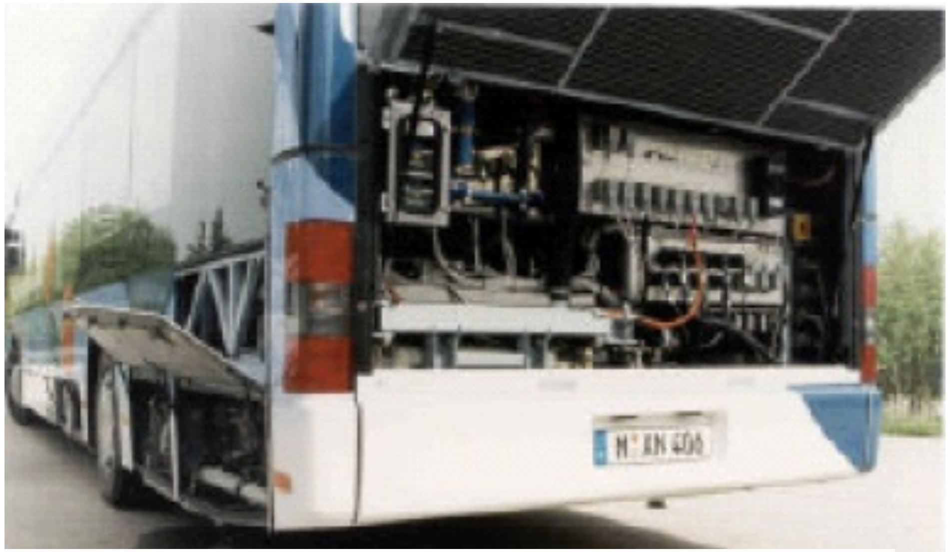


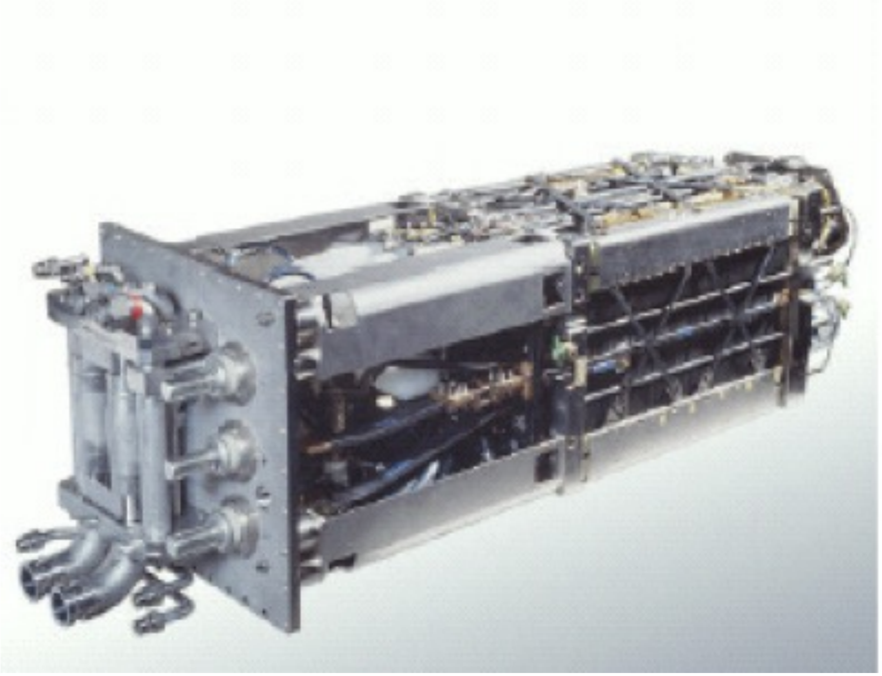
Inputs	
Fuels	Natural Gas, Directed Biogas
Input fuel pressure	15 psig
Fuel required @ rated power	0.661 MMBtu/hr of natural gas
Water required (for startup only)	120 gallons municipal water
Outputs	
Rated power output (AC)	100 kW
Electrical efficiency (LHV net AC)	> 50%
Electrical connection	480V @ 60 Hz, 4-wire 3 phase
Physical	
Weight	10 tons
Size	224" x 84" x 81"
Emissions	
NOx	< 0.07 lbs/MW-hr
SOx	negligible
CO	< 0.10 lbs/MW-hr
VOCs	< 0.02 lbs/MW-hr
CO_2 @ specified efficiency	773 lbs/MW-hr on natural gas, carbon neutral on Directed Biogas

60-65%

www.bloomenergy.com/products

Siemens: MAN City Bus (PEFC)

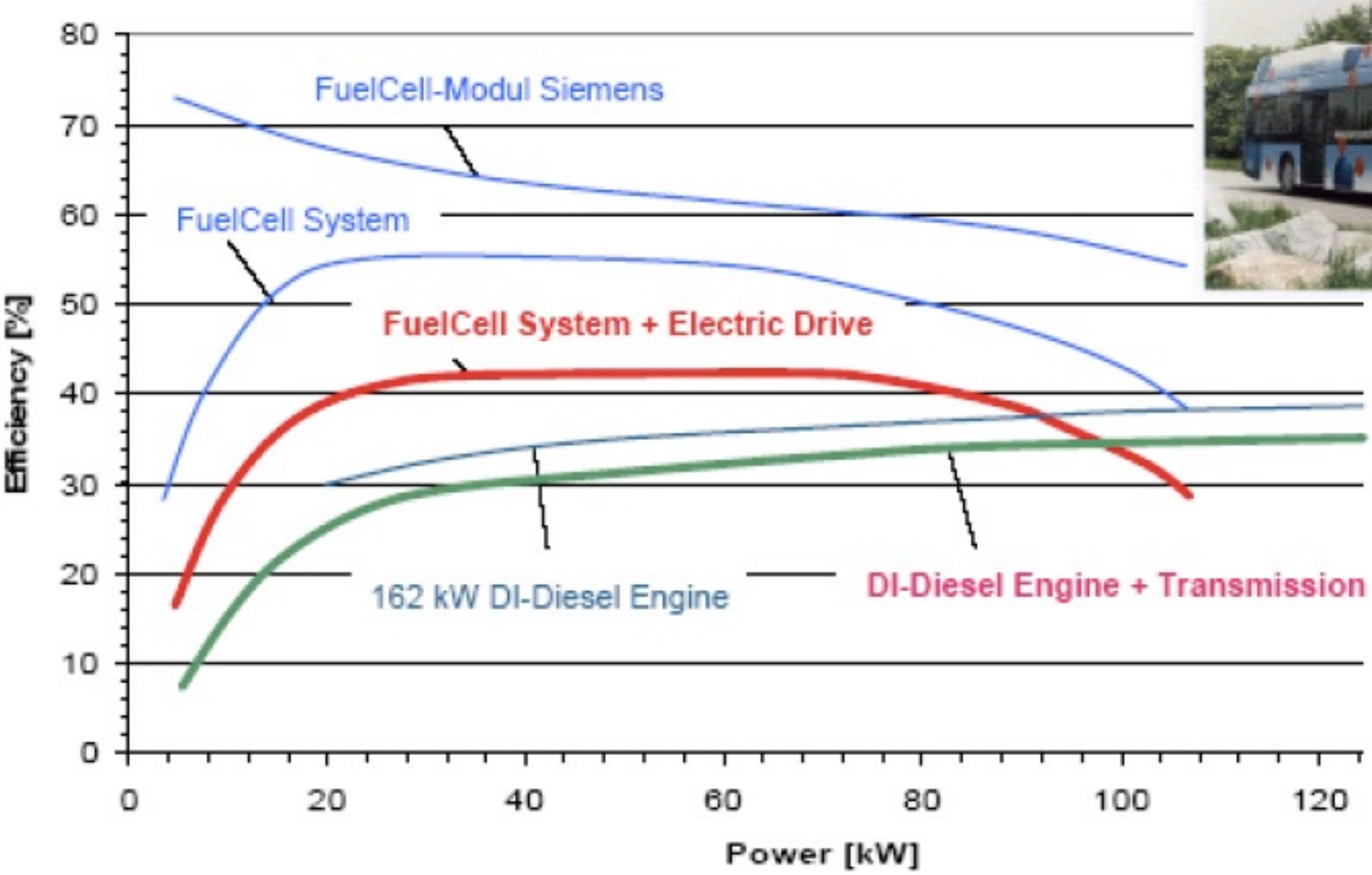




number of cells		320
rated power	≈	120 kW
rated current		560 A
rated voltage	≈	215 V
operating temperature		80° C
dimension	≈	$176x53x50\ cm^3$
weight	≈	900 kg
Rated efficiency (at 20% load)	≈	68 %
(at rated load)	≈	56 %

(Copied from G.G. Scherer, Tutorial, European Fuel Cell Forum, Lucerne)

Measured efficiency (MA City Bus)



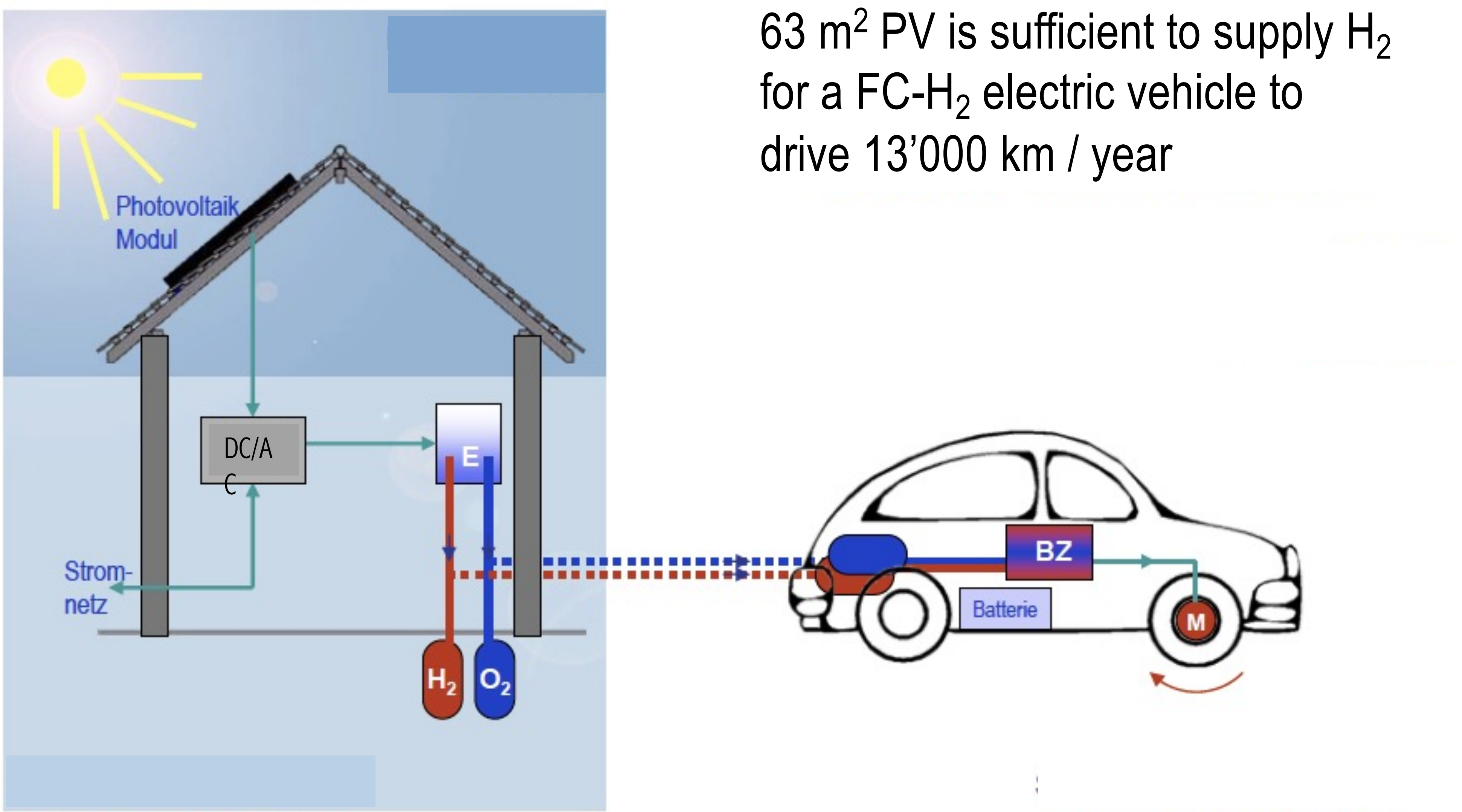
(Copied from G.G. Scherer, Tutorial, European Fuel Cell Forium, Lucerne)

Toshiba Announces World's Smallest Direct Methanol Fuel Cell With Energy Output of 100 Milliwatts

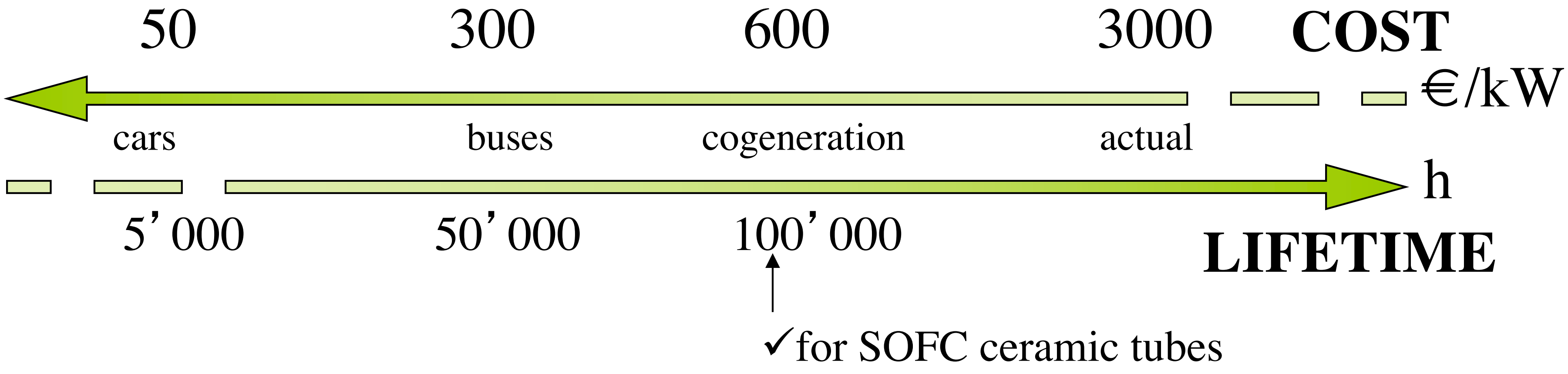
(Copied from G.G. Scherer, Tutorial, European Fuel Cell Forium, Lucerne)

H_2-Mobility: Swisshydrogen concept

63 m^2 PV is sufficient to supply H_2 for a FC-H_2 electric vehicle to drive 13’000 km / year



Challenges



50	300	600	3000	**COST** €/kW
cars	buses	cogeneration	actual	
5’000	50’000	100’000		h **LIFETIME**

✓for SOFC ceramic tubes

Cost target and **lifetime** requirements
depend on the **application** and the market competition.

As a whole, the **reliability** of FC systems requires further R&D advances

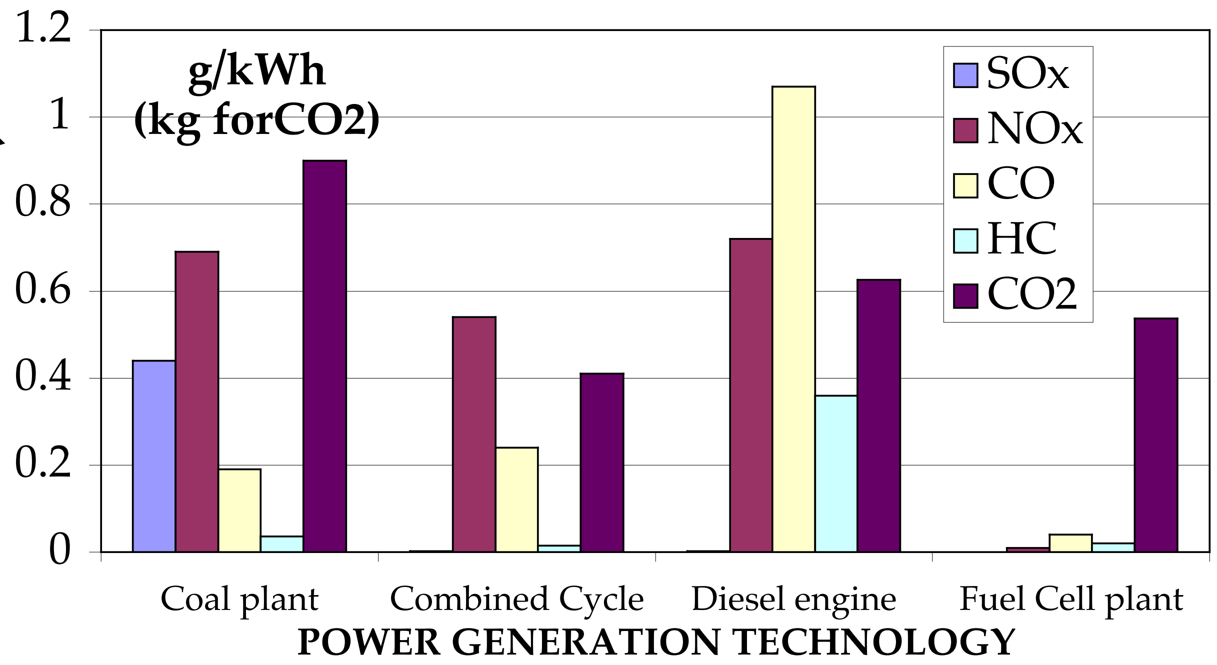
Strengths

- **High electrical efficiency at small power size, and in partial load**

  >50% **< 1 MW_e** **30…100%**

- **<u>cogeneration</u>** (ELECTRICITY + HEAT/COLD)

- low emissions



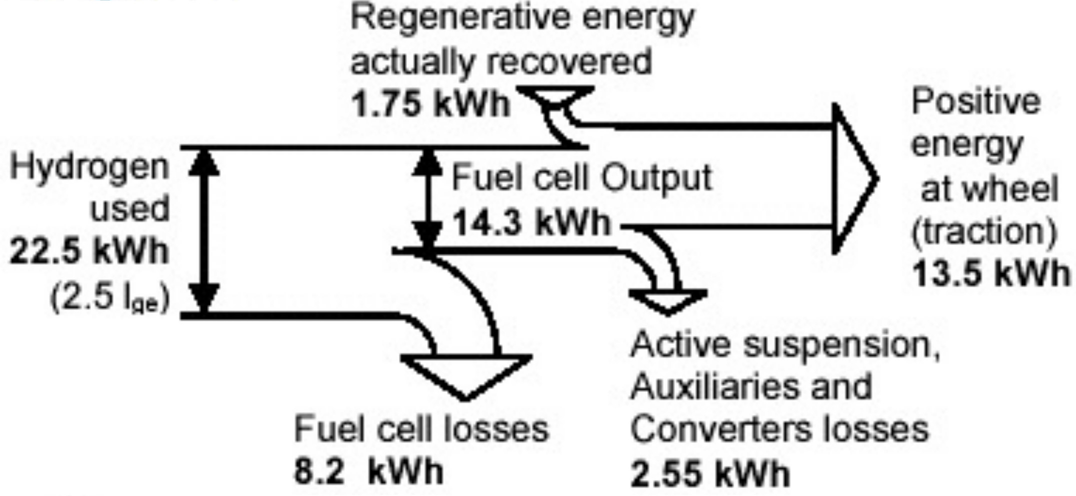
- silent
- modular
- multi-fuel

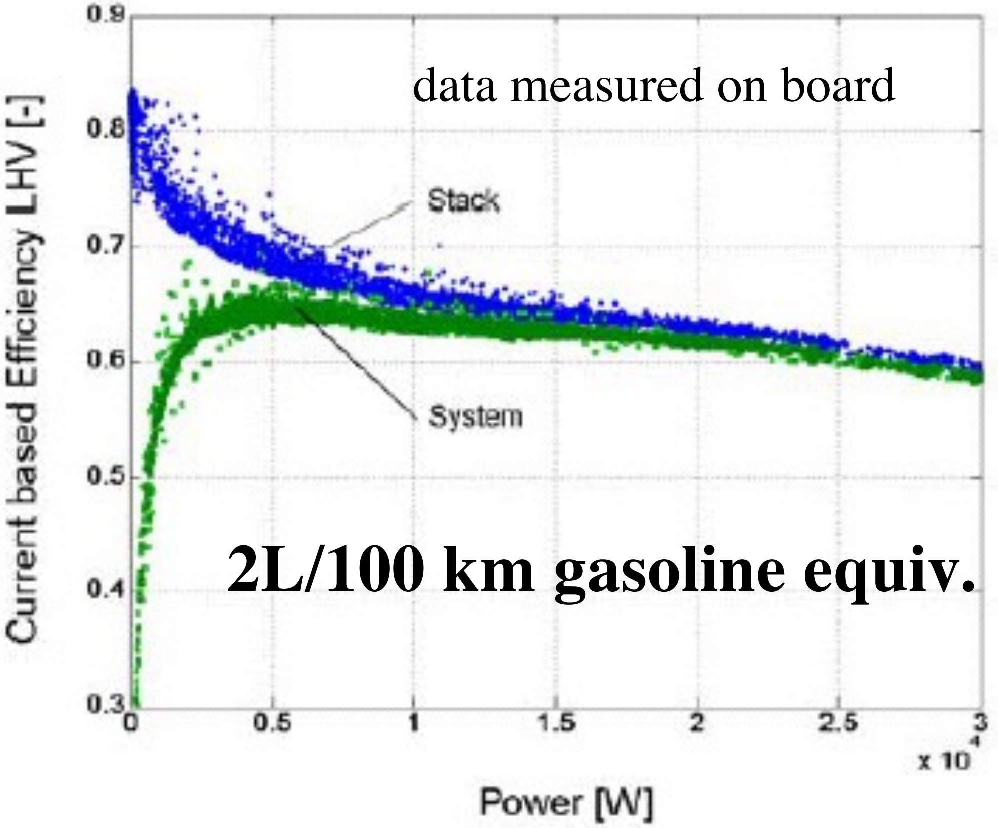
implantation in urban areas

PAUL SCHERRER INSTITUT PSI

MICHELIN A better way forward

HY-LIGHT



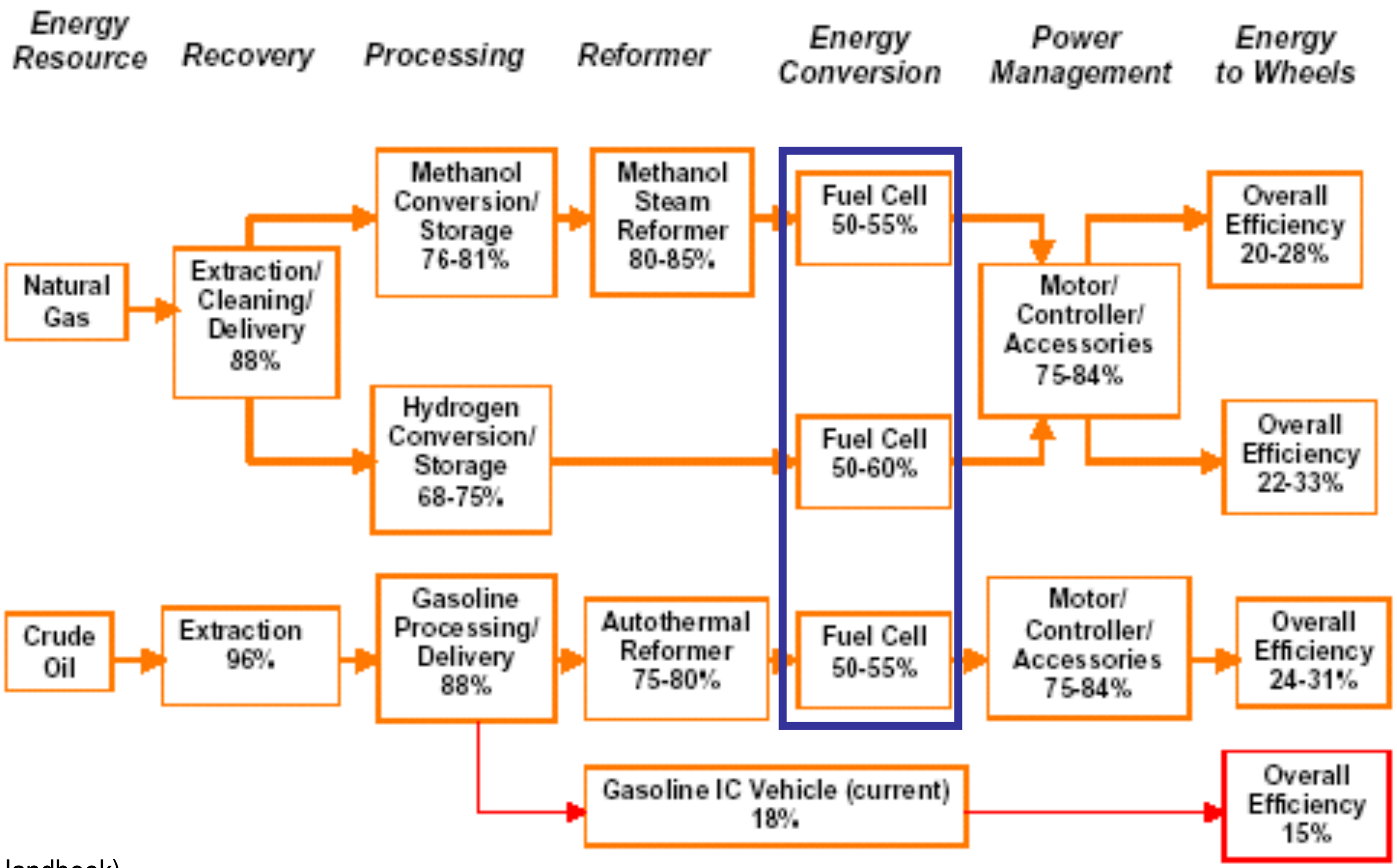


data measured on board

2L/100 km gasoline equiv.

(source : F. Büchi, PSI)

Full cycle energy efficiency



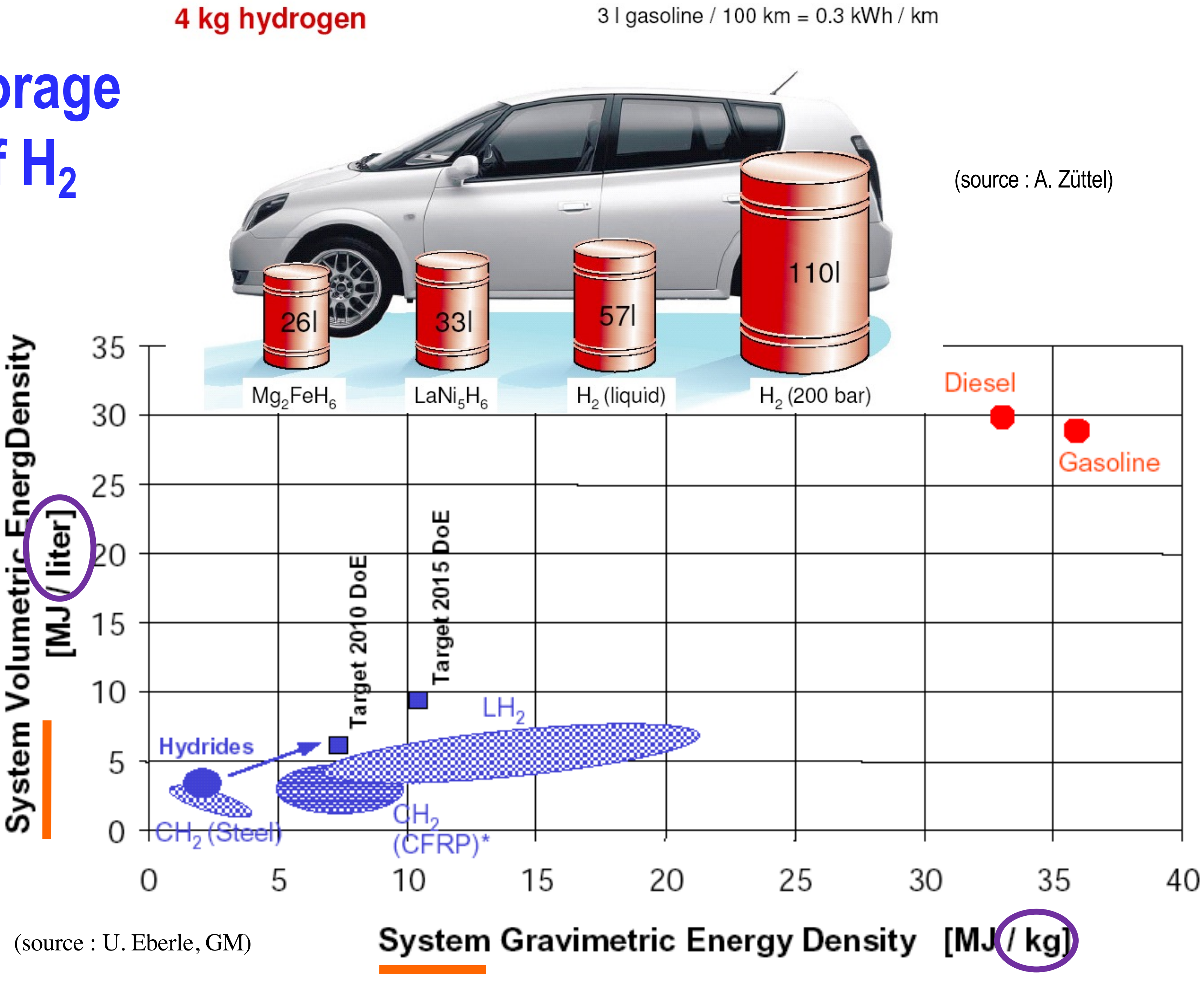
(source : FC Handbook)

→ **“well-to-wheel” efficiency must be considered**

Part 4 : The fuel issue

- Operating **temperature** as decisive parameter
- Fuel ‘processing’ (= fuel preparation)
- H_2 as **mobility** fuel
- Hydrocarbons for **stationary** application
- Importance of <u>integrated</u> fuel cell <u>systems</u>

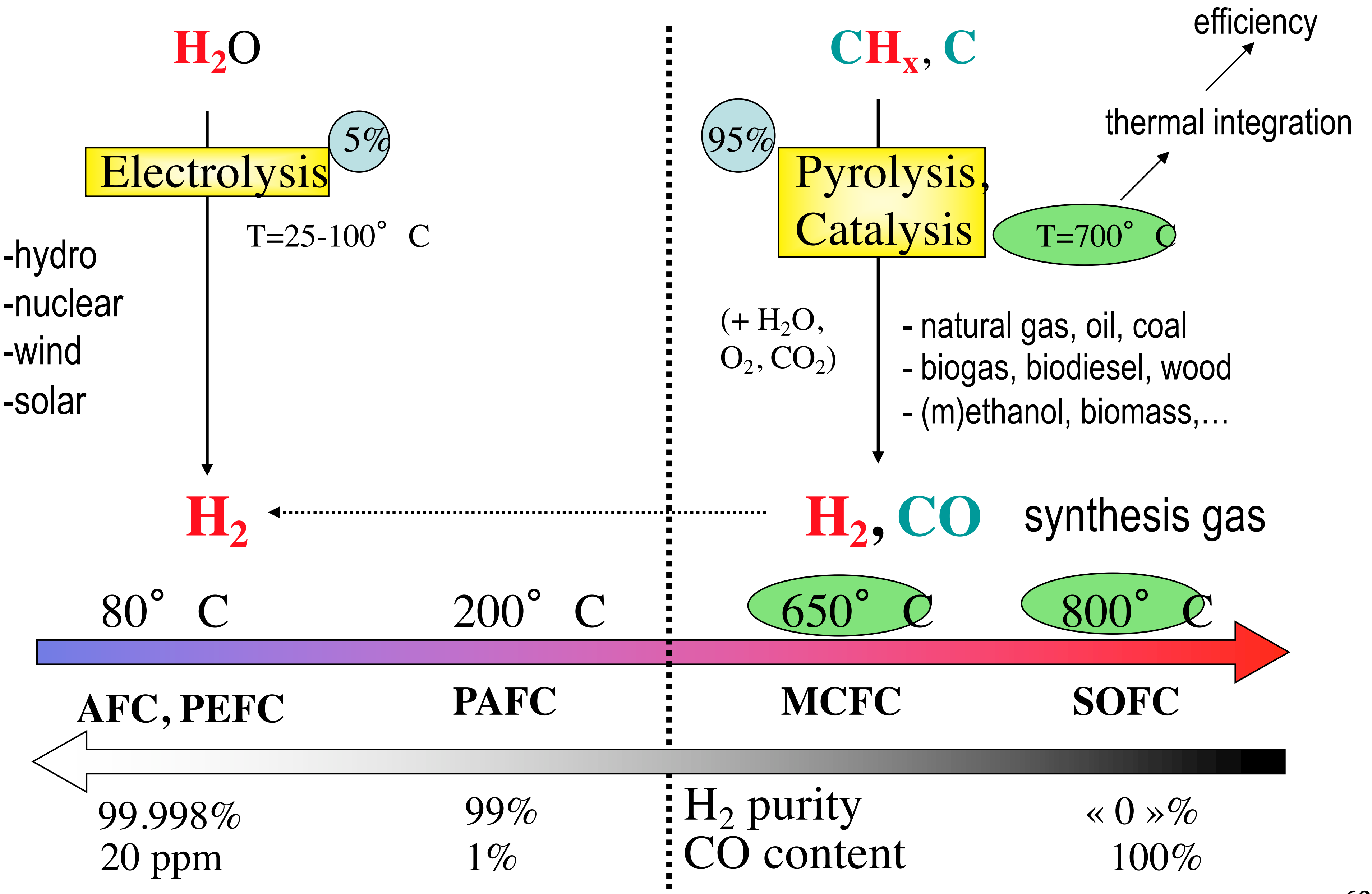
Storage of H_2



(source : A. Züttel)

(source : U. Eberle, GM)

Temperature and fuel



H_2O

5%

Electrolysis

T=25-100° C

-hydro
-nuclear
-wind
-solar

H_2

CH_x, C

95%

Pyrolysis, Catalysis

T=700° C

thermal integration → efficiency

(+ H_2O, O_2, CO_2)

- natural gas, oil, coal
- biogas, biodiesel, wood
- (m)ethanol, biomass,…

H_2, CO synthesis gas

80° C	200° C	650° C	800° C
AFC, PEFC	PAFC	MCFC	SOFC
99.998%	99%		« 0 »%
20 ppm	1%		100%

H_2 purity
CO content

Fuel cell processing basics

- any hydrocarbon fuel (CH_x) is converted to syngas (H_2, CO)
- **syngas** can directly feed high temperature FC
- to feed low temperature FC, chemical steps are necessary to reduce CO content to only traces, as CO blocks the Pt-catalyst

=> *fundamental difference between low and high T - fuel cells :*

	Low T	**High T**
Fuel	**H_2**	**CH_x**
Catalyst	**Pt**	**Ni**
CO	= poison	= fuel

Main fuel chemical reactions

✔ *methods to transform a primary hydrocarbon (e.g. natural gas, biogas,..) into syngas (the mixture of H_2, CO)*

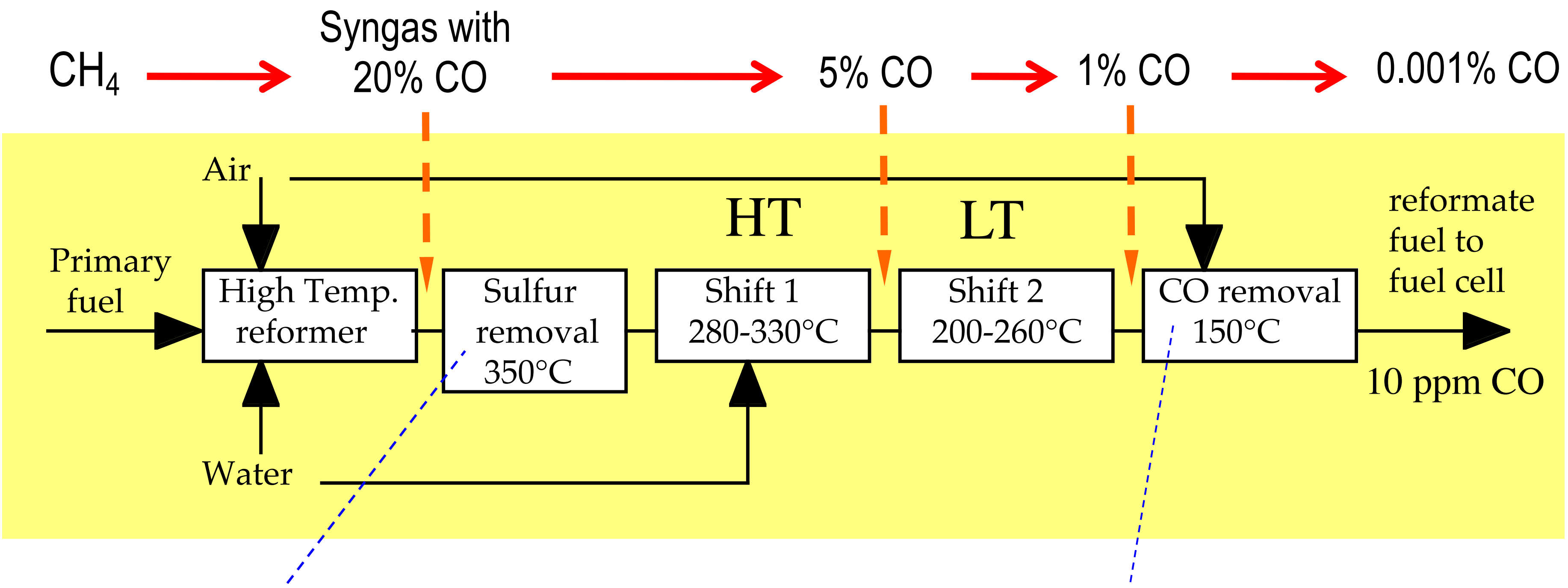
Steam reforming SR	$CH_4 + H_2O \leftrightarrow 3H_2 + CO$
Dry reforming	$CH_4 + CO_2 \leftrightarrow 2H_2 + 2CO$
Partial Oxidation POX	$CH_4 + \frac{1}{2}O_2 \Rightarrow 2H_2 + CO$
(Water gas) shift	$CO + H_2O \leftrightarrow H_2 + CO_2$
Pyrolysis (“cracking”)	$CH_4 \Rightarrow 2H_2 + C$
Boudouard	$2CO \Leftrightarrow CO_2 + C$
Reverse gasification	$CO + H_2O \leftrightarrow H_2O + C$

☒ *reactions that deposit solid carbon (to be avoided!)*

✔ *method to ‘shift’ fuel from CO into H_2*

From primary fuel to pure H_2 (for PEFC)

See f. ex. http://hygear.nl/products-services/hydrogen-generation-systems/



CH_4 → Syngas with 20% CO → 5% CO → 1% CO → 0.001% CO

Air

Primary fuel

High Temp. reformer

Water

Sulfur removal 350°C

HT

Shift 1 280-330°C

LT

Shift 2 200-260°C

CO removal 150°C

reformate fuel to fuel cell

10 ppm CO

by ZnO adsorber (→ ZnS) at 300-400° C,
or active carbon filters at ambient T

PROX : **<u>pr</u>**eferential **<u>ox</u>**idation of CO in a H_2-rich flow, to reduce CO content from 1% to 10 ppm

→ pure H_2 fuel preparation can be costly and bulky, and penalizes overall efficiency

→ for this reason, transport applications **MUST tank H_2 from new H_2-distribution infrastructure** and cannot generate H_2 on-board from tanked liquid hydrocarbons

Electric mobility

- **mobility** demand consumes ⅓ of final energy and is a bigger bottleneck (**fossil** resource: gasoline, diesel, kerosene) than **electricity** demand (⅙ of final energy), for which many alternatives sources exist, and than **heating** demand (rest, ca. ½), which has enormous saving potential (insulation, heat pumps)
- biofuels cannot cover, by far, the current mobility fuel demand

→ a substantial shift to transport electrification seems likely (FC vehicles, batteries, train, e-buses)

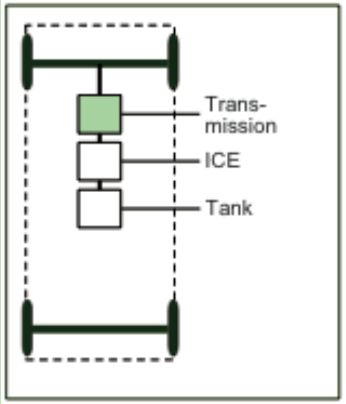
A portfolio of power-trains for Europe:
a fact-based analysis

Possible drive trains: ICE, electric, FC and hybrids

☐ ICE power-train 🟩 Transmission 🟩 Electric power-train 🟩 Battery ■ FC power-train

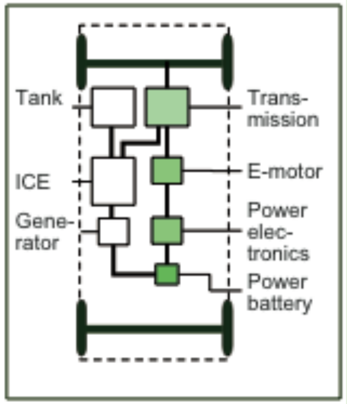
Internal combustion engine (ICE) vehicle

Current technology (2010)



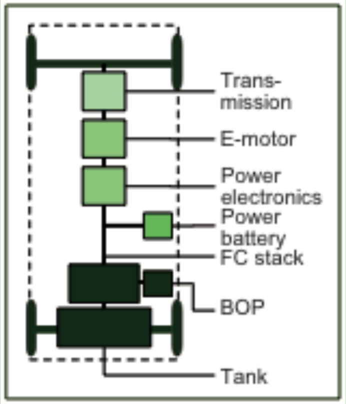
- **Conventional** internal combustion engine
- **No dependency** on electric infrastructure
- **High fuel consumption** and exhaust emissions
- **High range**: typically 800-1200 km

Advanced (2015/20)



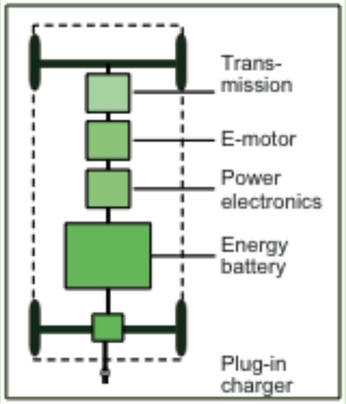
- **Parallel** hybrid configuration of electric and ICE drive; also known as hybrid electric vehicle (HEV)
- **ICE is primary mover** of the vehicle with support from small electric motor
- **Small battery** charged by the ICE
- Fully electric driving only at **low speed for smaller distances** (<5 km)
- **Better fuel economy** than conventional ICE

Fuel cell electric vehicle (FCEV)



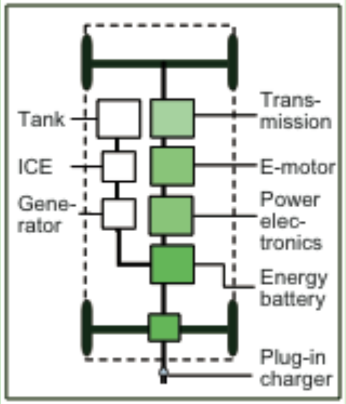
- **Series** configuration of fuel cell system and electric drive
- **Fuel cell stack** based on PEM technology
- Hydrogen tank pressure typically 350 or 700 bar
- **Medium range**: typically 400-600 km

Battery electric vehicle (BEV)



- **Purely electric** drive
- Large battery capacity, Li-ion technology
- Only charging of battery **from the grid** while stationary[1]
- **Short range**: typically 150-250 km (based on battery weight of 70-180 kg[2])

Plug-in hybrid electric vehicle (PHEV)

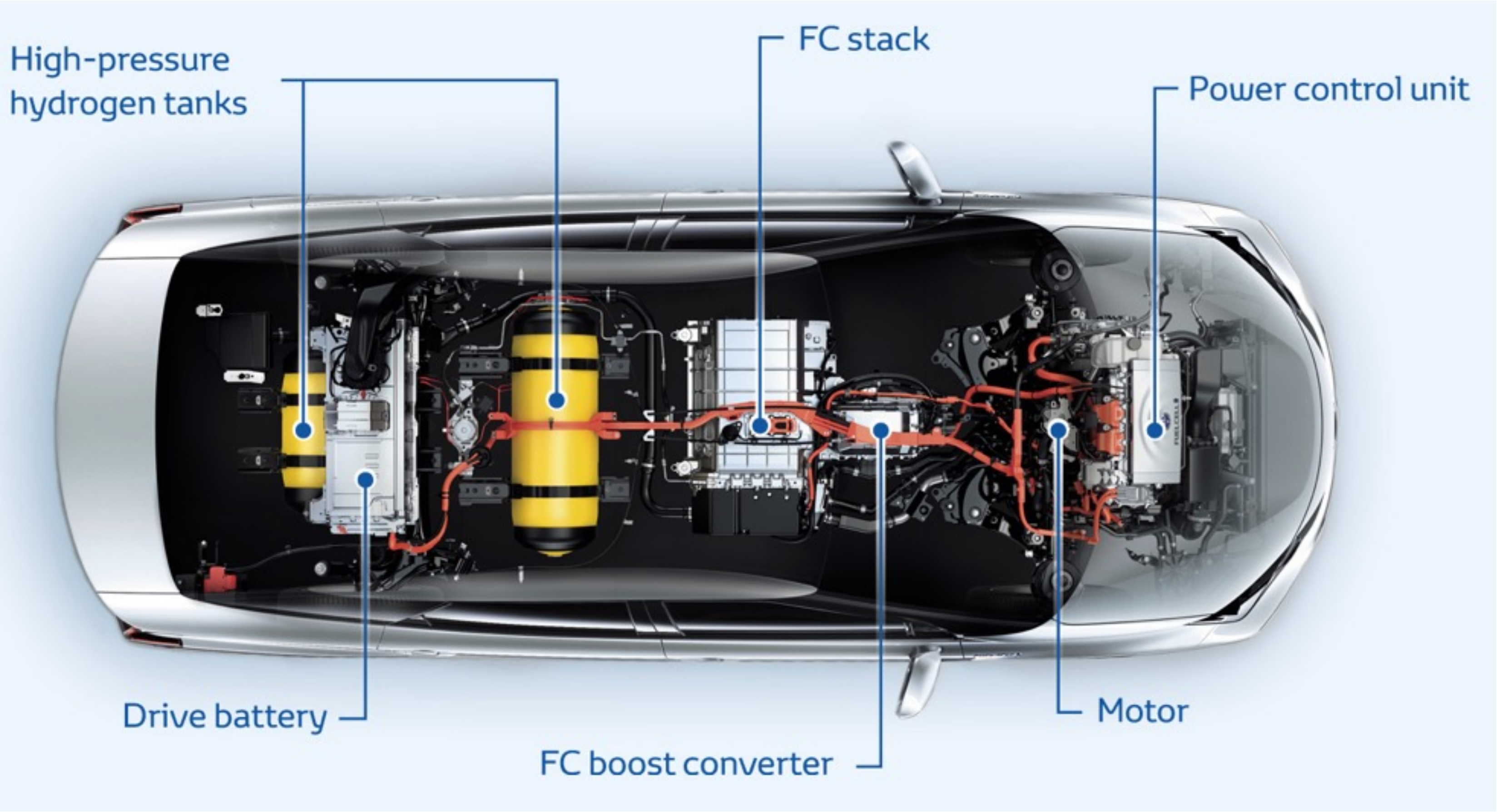


- **Series hybrid** configuration of electric and ICE drive[3]
- **Smaller battery capacity** than BEV, (Li-ion)
- Vehicle can be **plugged-in** to charge from the grid
- **Small ICE**-based generator for larger range ('range extender')
- **Short range**: typically 40-60 km) electric driving. (based on battery weight of 20-80 kg[2])

Source : EU Report 2012

Toyota Mirai

650 km range - H_2 700 bar - 3 min refill - 114 kW max



http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/

http://www.theverge.com/2014/11/18/7242785/toyotas-new-hydrogen-powered-mirai-sedan-will-be-on-sale-next-year

Electricity Storage

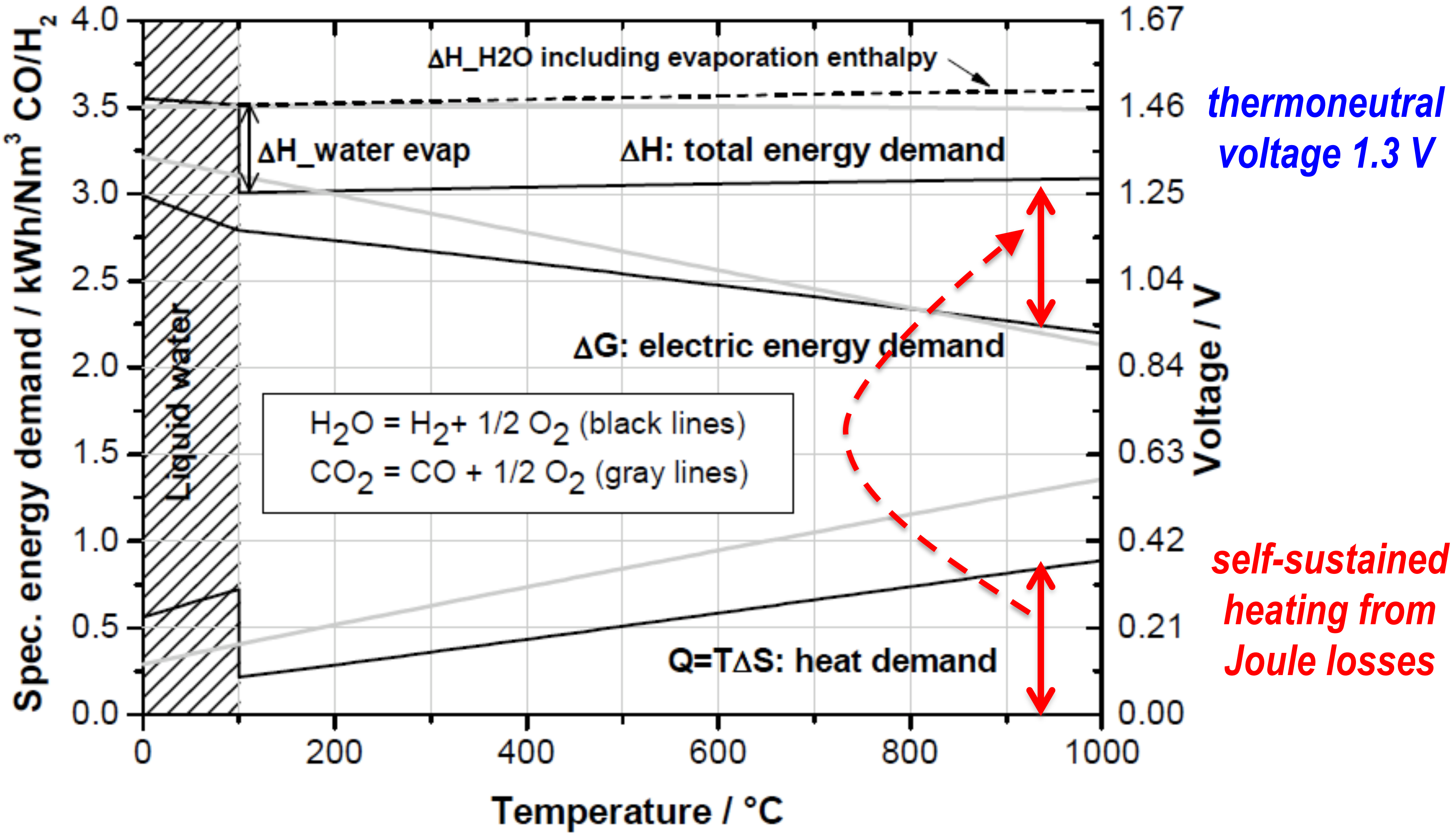
- the electrical grid has virtually no storage capacity
- **seasonal** electricity demand varies
- the difference (summer-winter) is exacerbated when replacing base-load power (nuclear, coal, run-off river hydro) with renewables like PV, wind and hydrodams (summer-excess, winter-deficit)

→ long term storage is required

- as **fuel** by electrolysis (H_2, CH_4, …) => **“Power-to-Gas”**
- in batteries

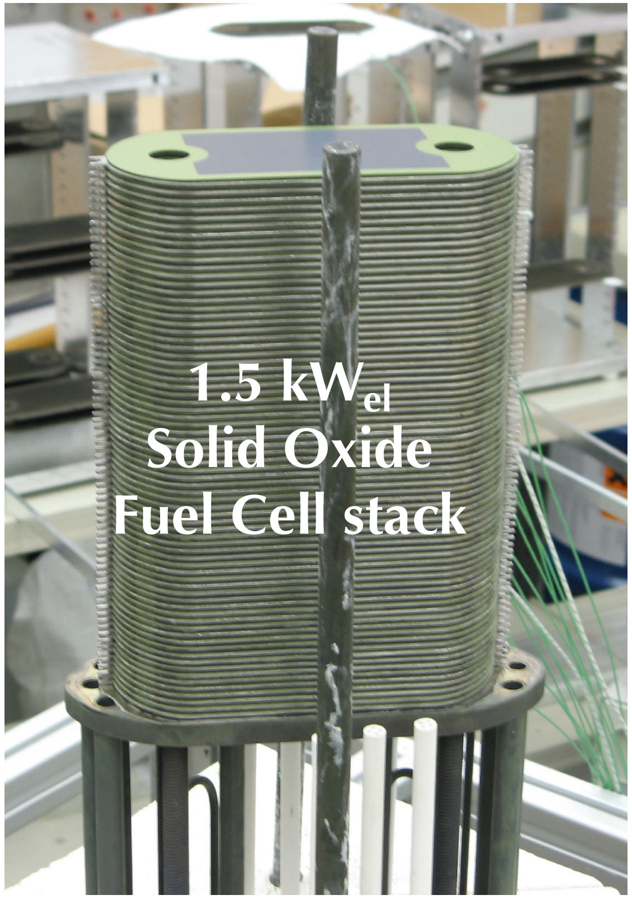
Thermodynamics of electrolysis

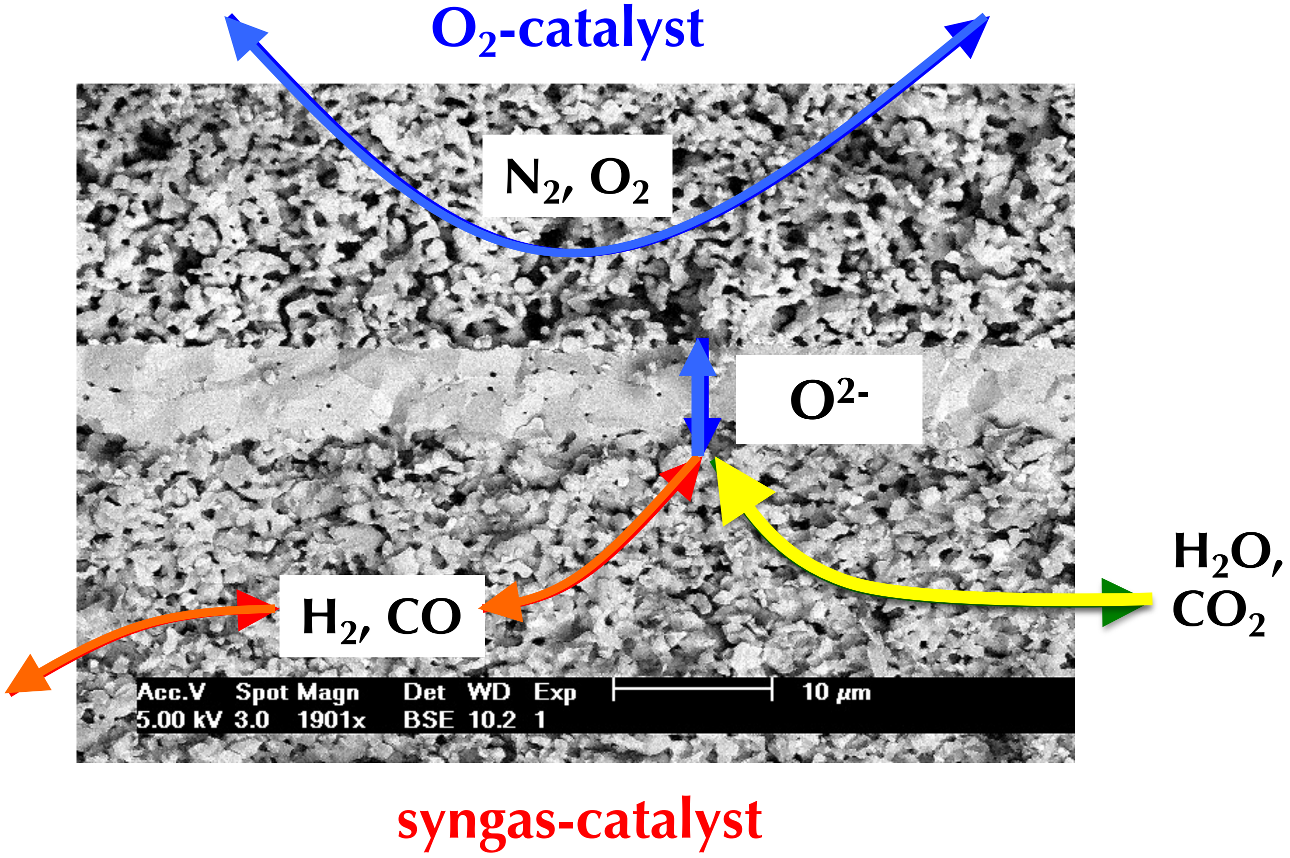
at 700° C, electrical input is reduced by 1/3 compared to liquid water electrolysis



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 = electrolyzer

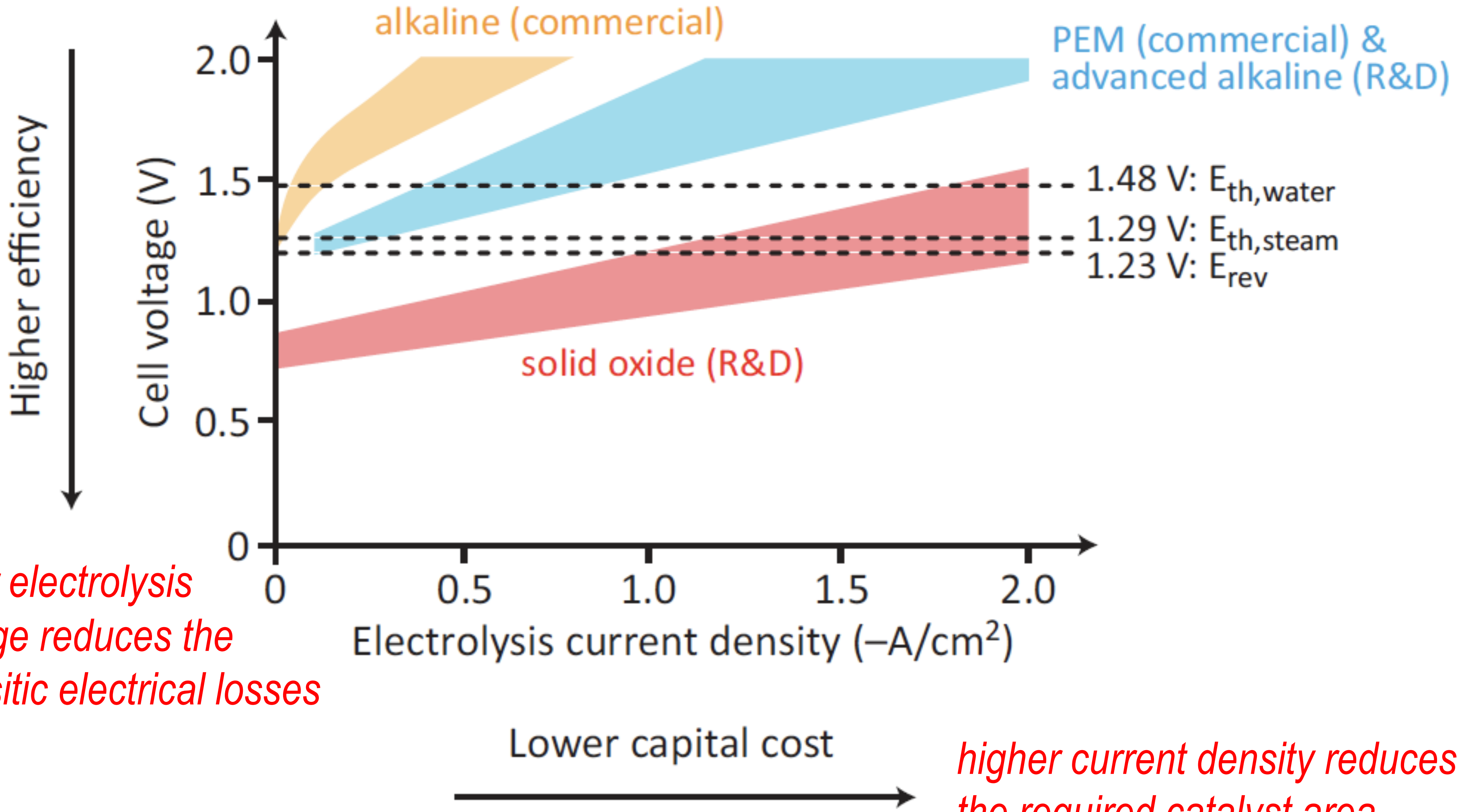




<u>Operating regime</u> :
700-800C
1 bar (to 5 bar)

FUEL CELL
ELECTROLYSER

Electrolysis technologies (3)



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 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

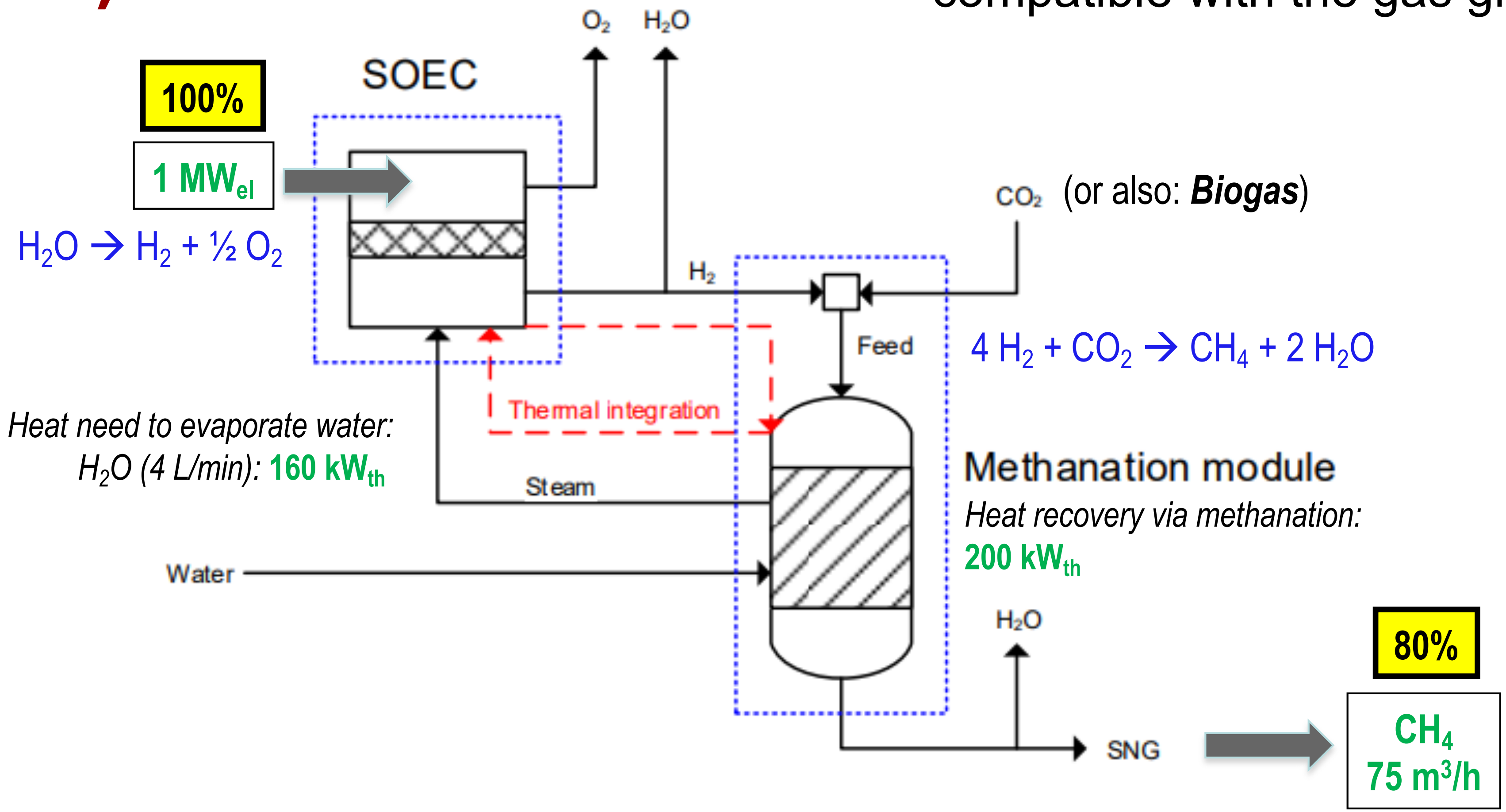
CRITICAL MATERIALS

COSTLY

EFFICIENCY

Power-to-Gas : $H_2 \rightarrow CH_4$ (P2G)

compatible with the gas grid



100%

1 MW_{el}

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

Heat need to evaporate water:
H_2O (4 L/min): **160 kW_{th}**

(or also: ***Biogas***)

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

Methanation module

Heat recovery via methanation:
200 kW_{th}

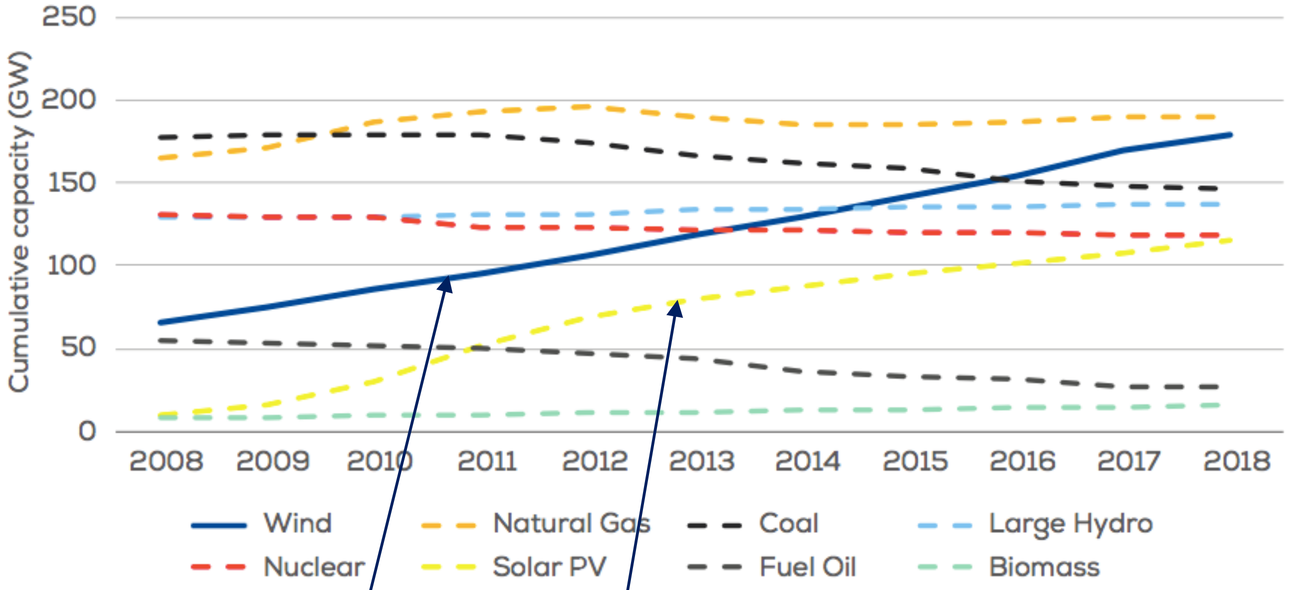
80%

CH_4
75 m^3/h

Electricity generation sources (EU)

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

Summary

- great progress in Fuel Cells since 2 decades
  - H_2-cars and buses (50 – 200 kW_e PEFC, H_2)
  - residential micro-CHP (1-2 kW_e SOFC, natural gas)
  - efficient clean cogeneration plants (MW_e-sized PAFC, SOFC, MCFC, incl. biogas plants)
- big effort in R & D continues
- competition (engines, batteries,…) progresses a lot too
- H_2-storage & distribution remains an issue
- electrolysers (reverse fuel cells) are coming up strongly (combined with renewable electricity increase (PV, wind); there is demand for giga-factories to produce **green H_2** at large scale