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

Learning objectives

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

H_2 and renewable energy

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

Grey, blue, green H_2

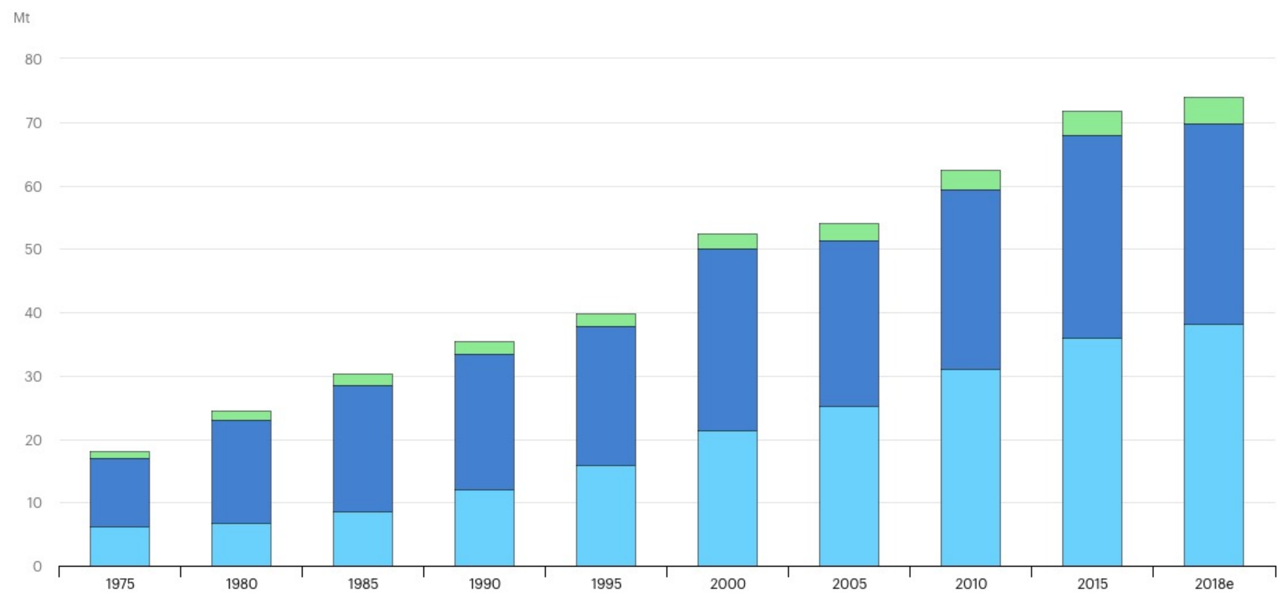
- **Grey H_2** : made from fossil sources
- **Blue H_2** : made from fossil sources but including carbon capture
- **Green H_2** : made from renewable sources

Annual H_2 production

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

96% from fossil sources

Global demand for pure hydrogen, 1975-2018



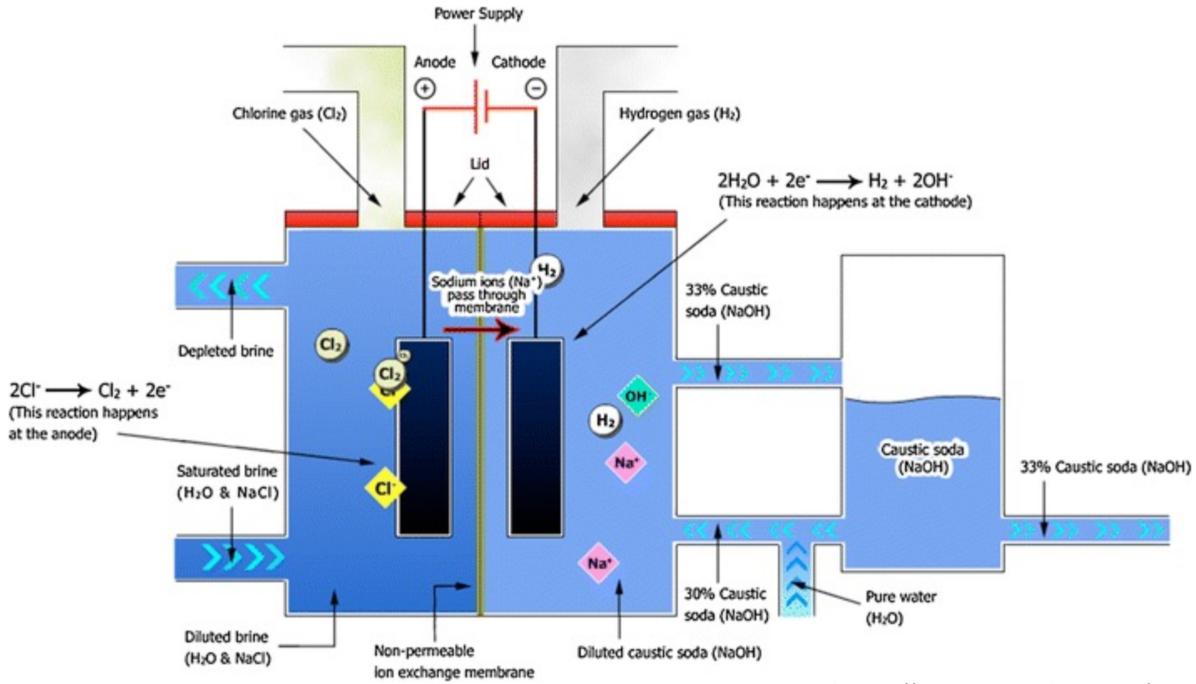
- By comparison: natural gas 4000 10^9 m^3 /yr = 140 EJ (24% of world energy – 580EJ)

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

- Production 2017: 58 Mton Cl_2 (650 plants)
- Elec. consumption: 2.1 – 3.4 kWhe / kg Cl_2
- (take average of 2.5 kWhe / kg Cl_2) => 150 TWhe
  ≈ 25-30 GWe worldwide
- ≈0.6% of world electricity (25 PWh)
- this co-produces 1.6 Mt H_2 = 54 TWh H_2, accounting for >½ of all electrolytic H_2

Chlor-alkali process (1888)

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



https://www.eurochlor.org/

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

H_2 production from fossil fuels

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

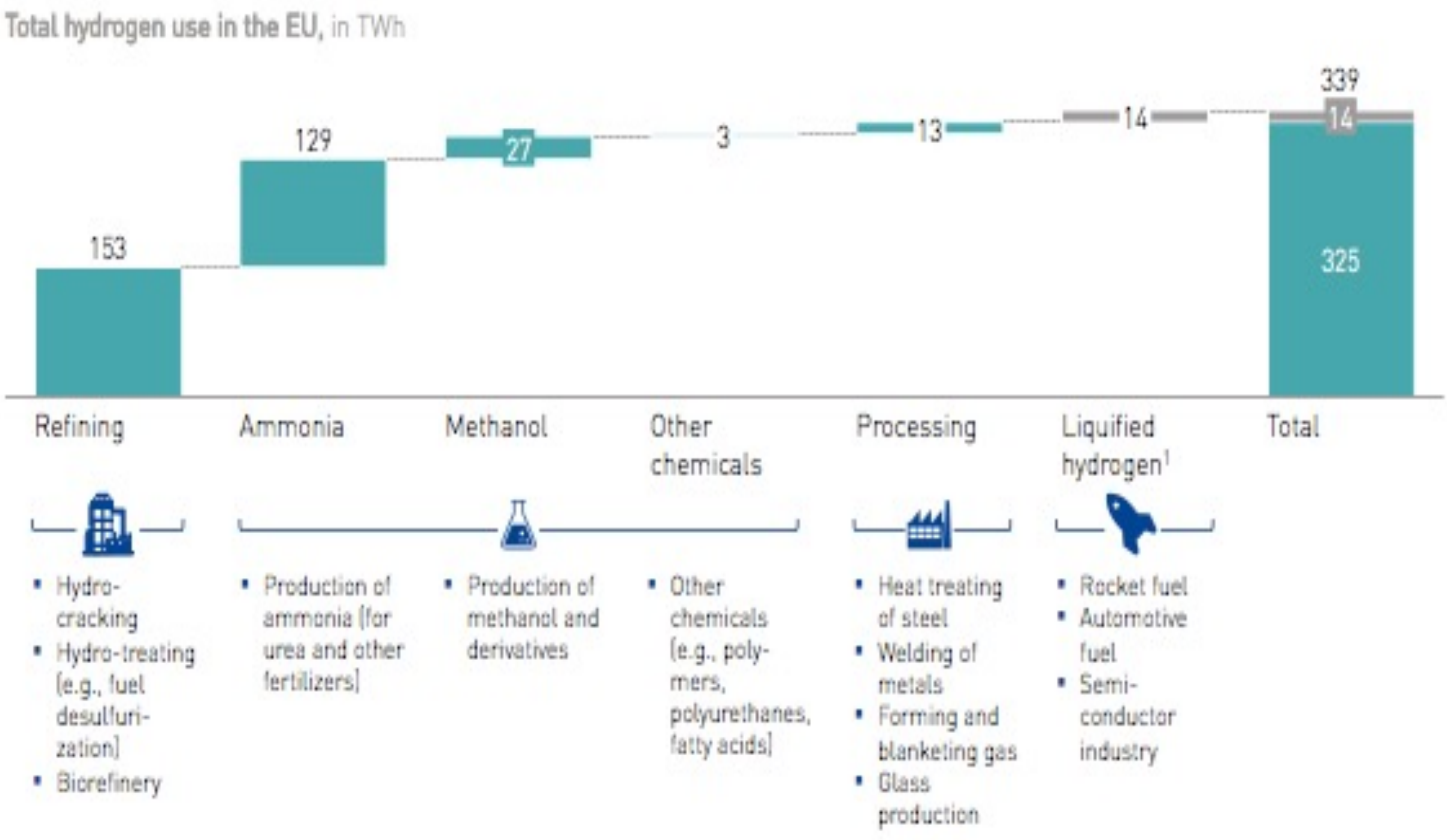
linde-le.de

Thermal reforming

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

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

Current uses of H_2 (EU)



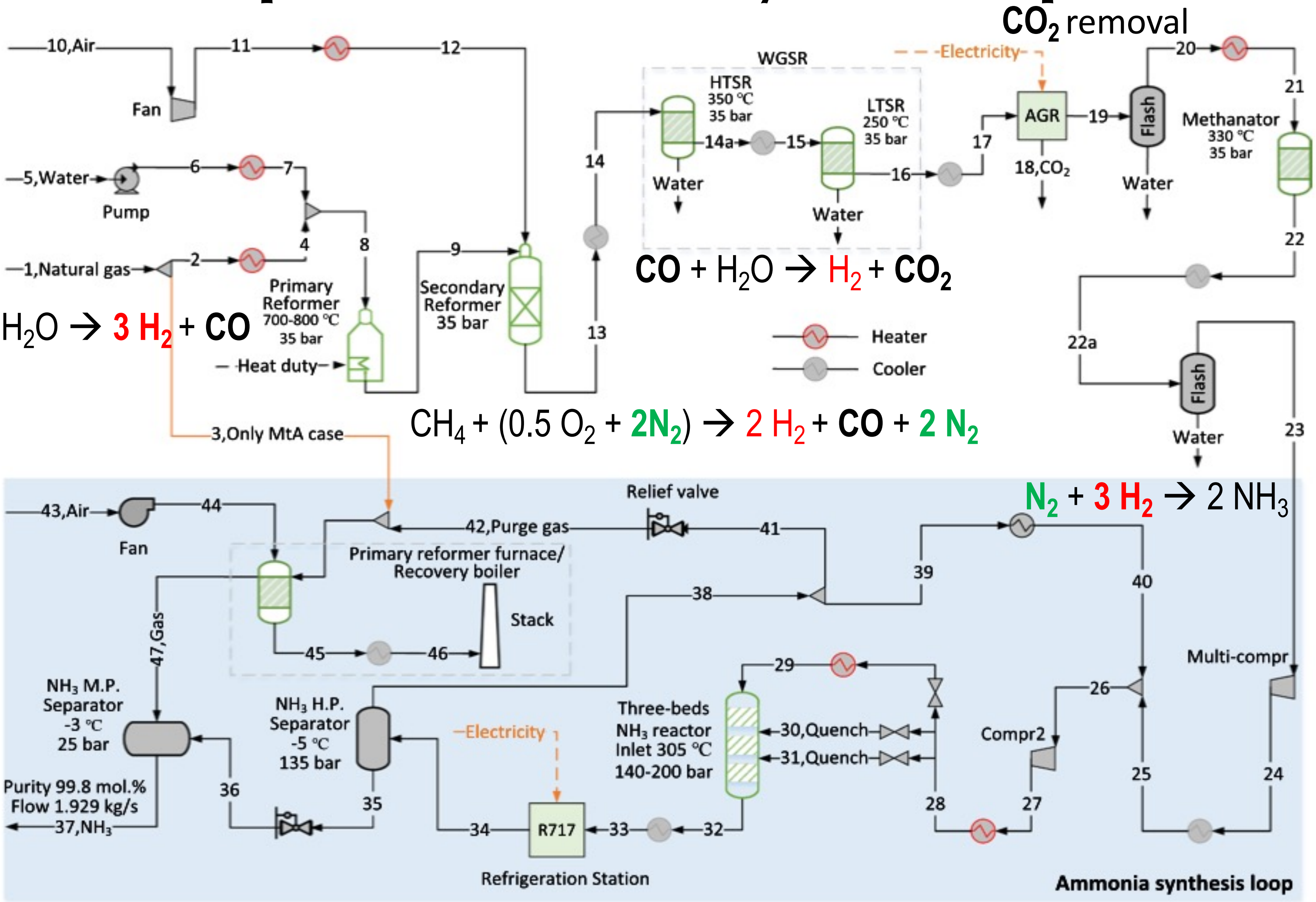
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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

H_2 current uses

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

Example: ammonia synthesis plant



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

$$CO + H_2O \rightarrow H_2 + CO_2$$

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

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

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

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

Table 38: Overview of the light industry hydrogen market

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

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

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

idem, p.63

Future uses and impact of H_2

Annual H_2 demand per segment

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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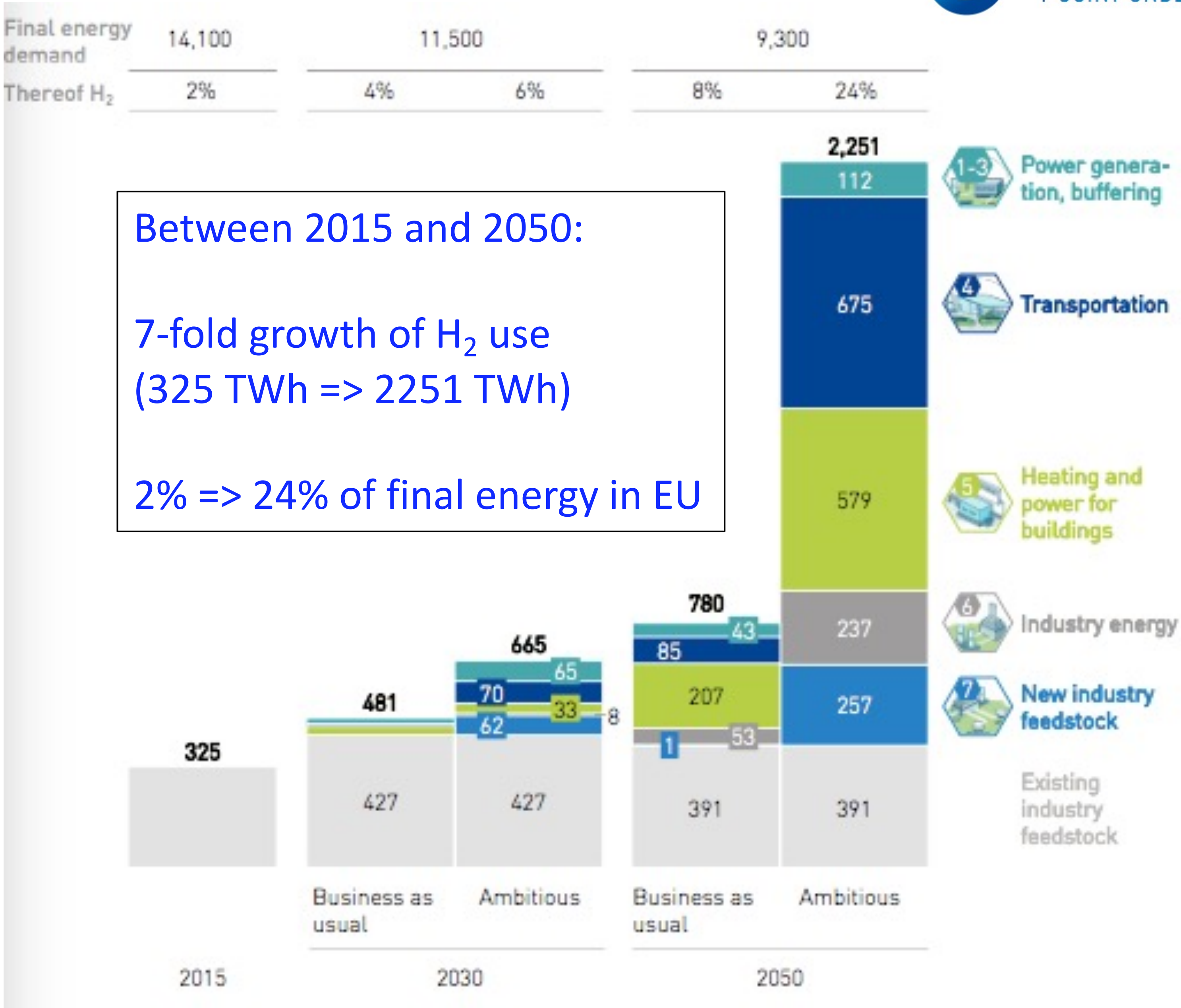
H2 Raodmap for Europe
January 2019
Exhibit 2 p.8
Exhibit 22 p 49



Between 2015 and 2050:

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

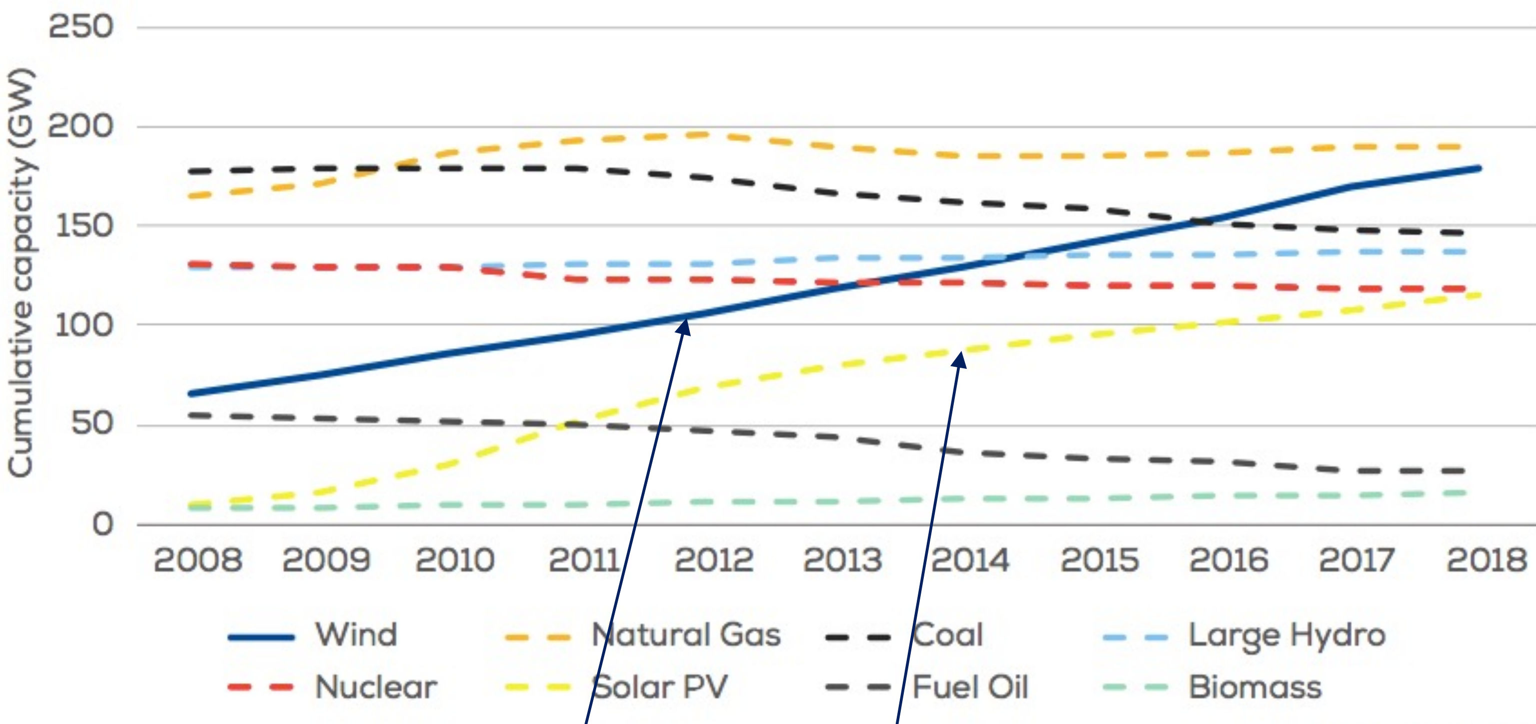
2% => 24% of final energy in EU

Future H_2 uses

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

Where will this H_2 come from?

FIGURE 1
Total power generation capacity in the European Union 2008-2018



Source: WindEurope

2018 (EU) :

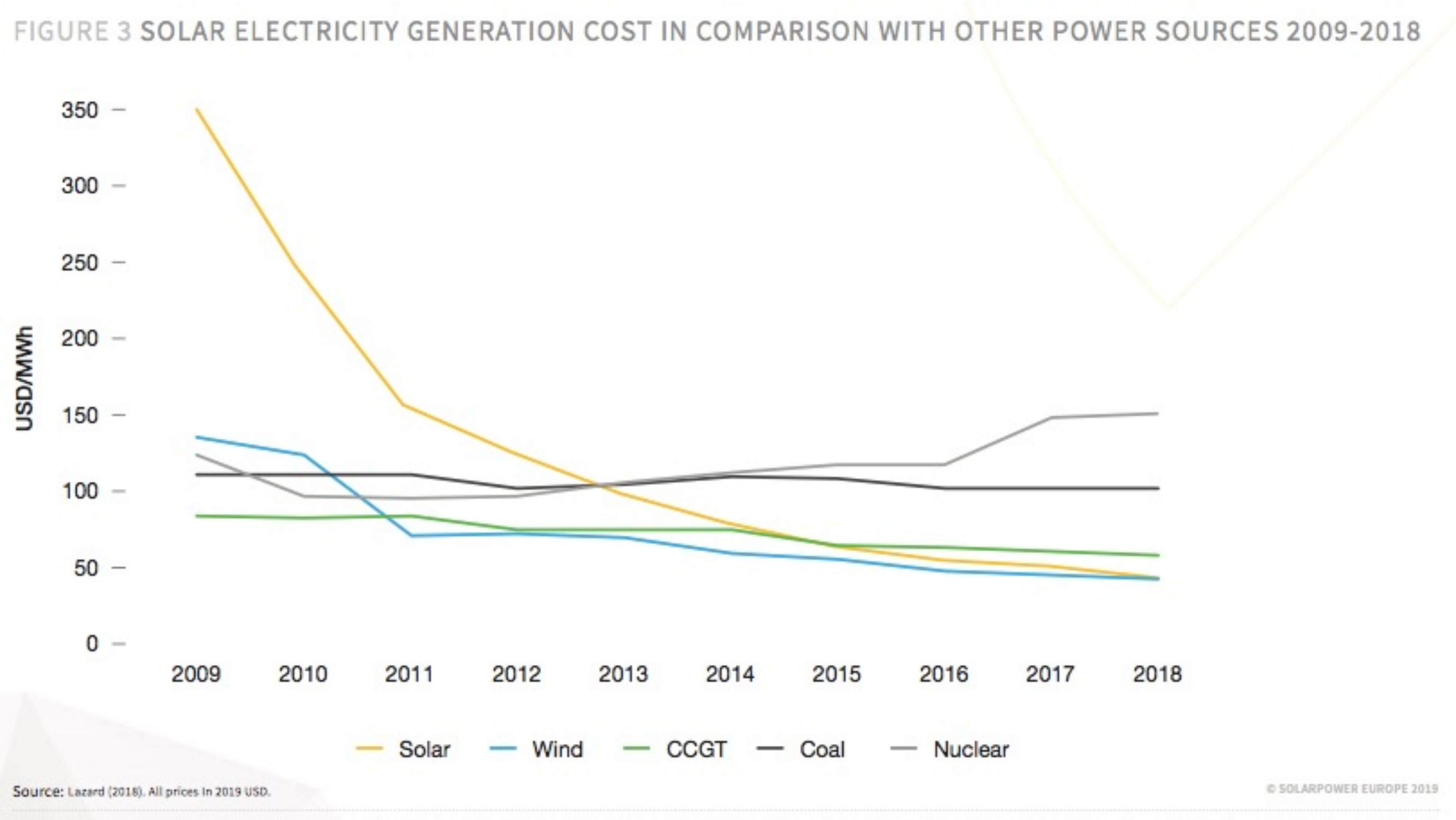
Wind: 179 GWe
362 TWhe (14%)
26.7 b€ inv. (2018)

Solar: 126 GWe
120 TWhe (4.6%)

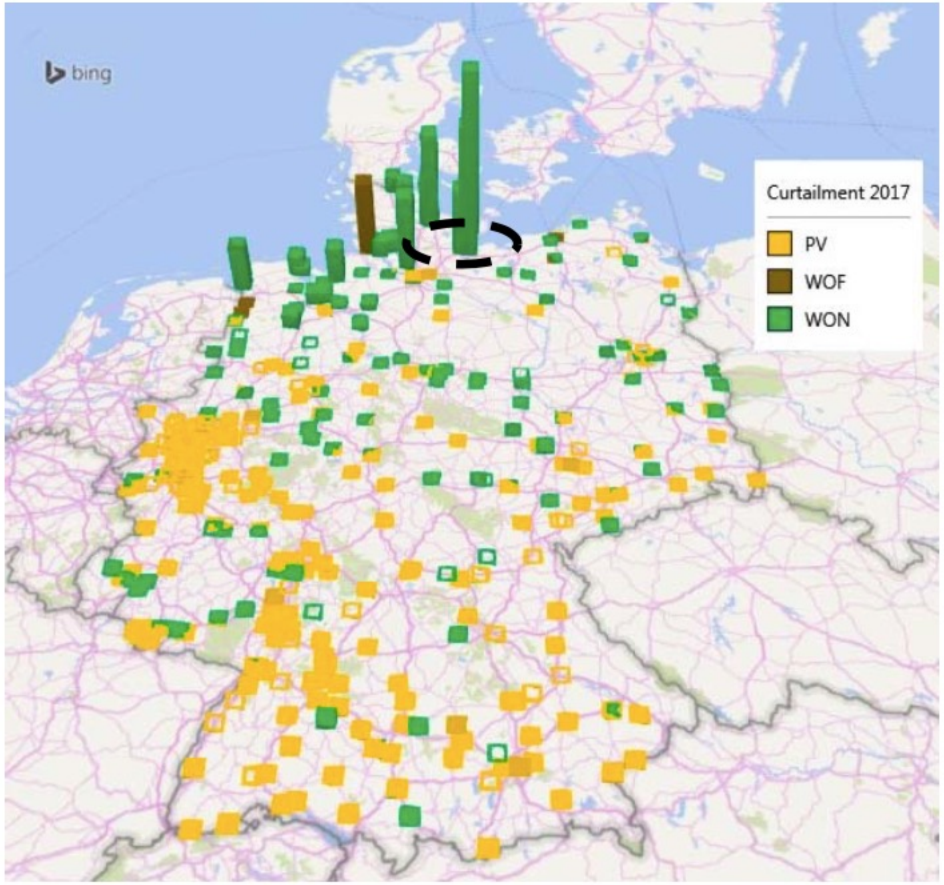
Solar worldwide:
+102 GWe in 2018
Total 509 GWe
(2.2% of electricity)

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

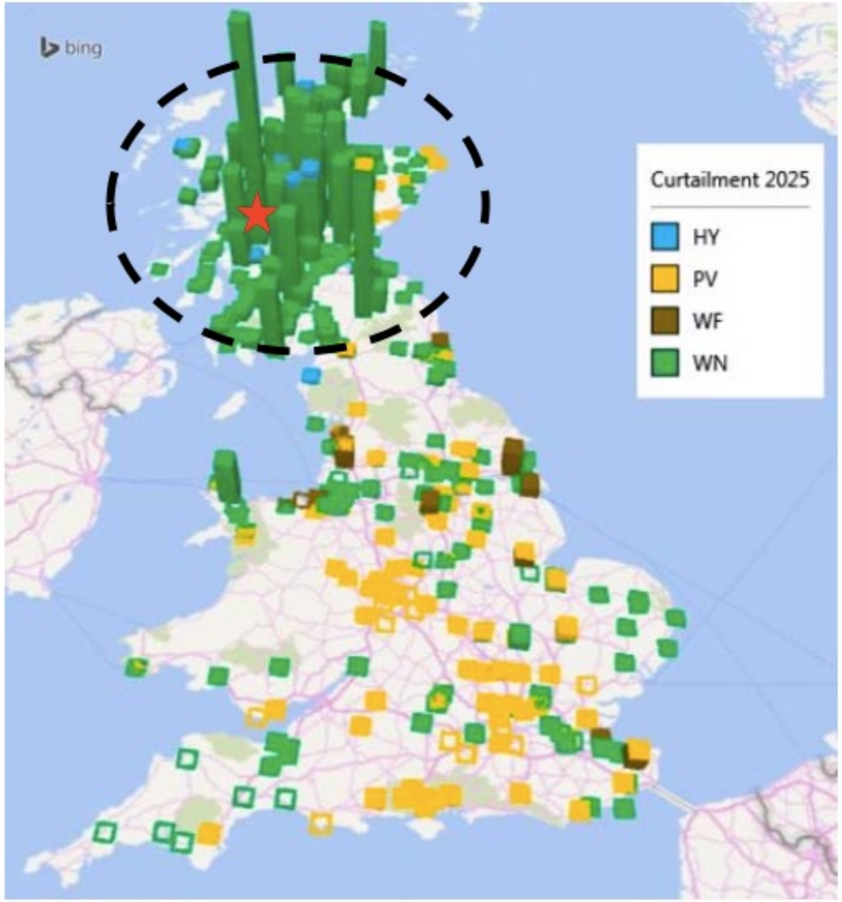
Solar PV and wind is the cheapest electricity!



‘Curtailment’ (excess electricity production)



Germany, 2017, max bar height = 428 GWh.



UK, 2025, max bar height = 117 GWh.

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

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STUDY ON EARLY BUSINESS CASES FOR H2
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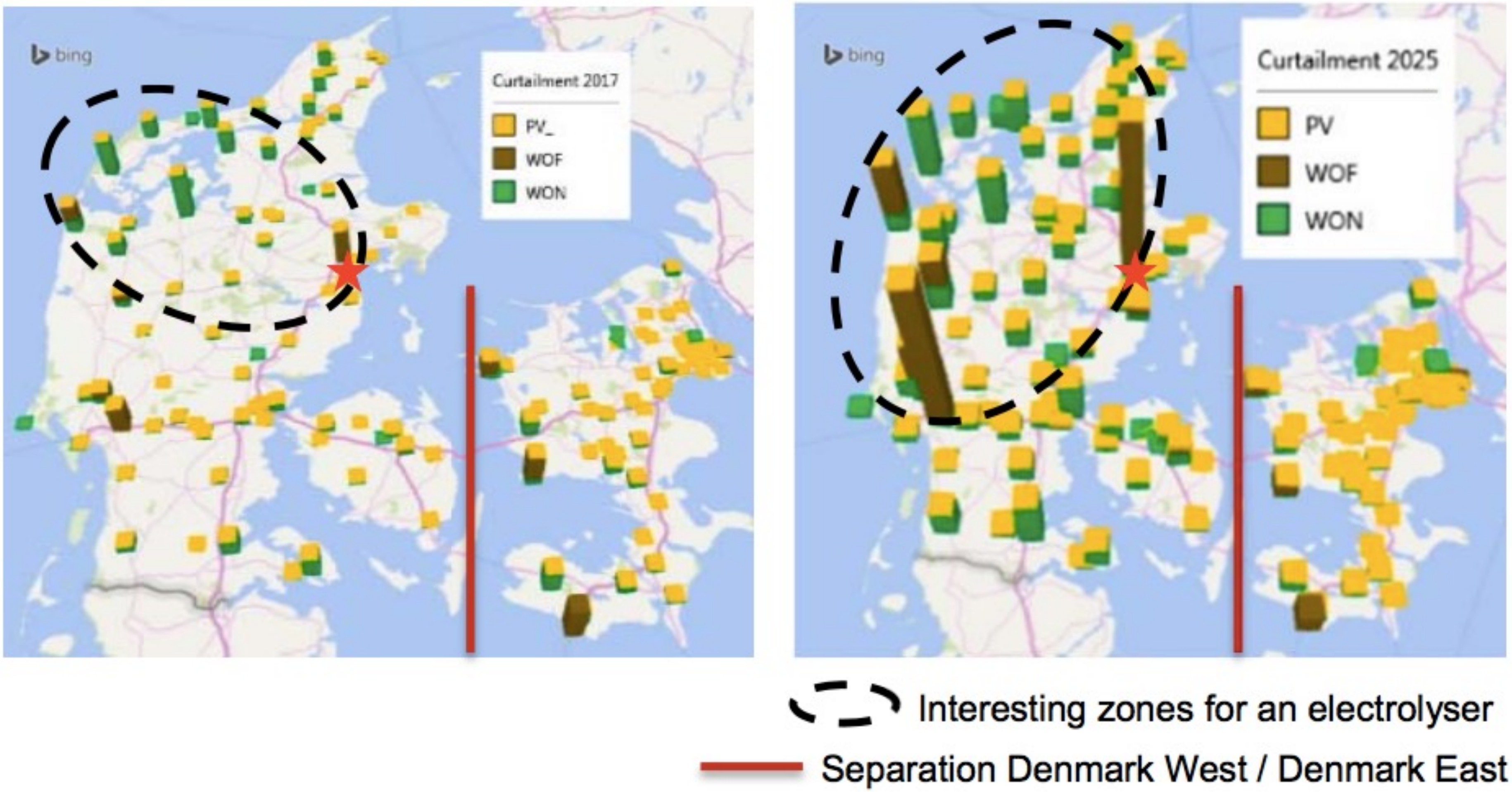
p. 33 fig. 10



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

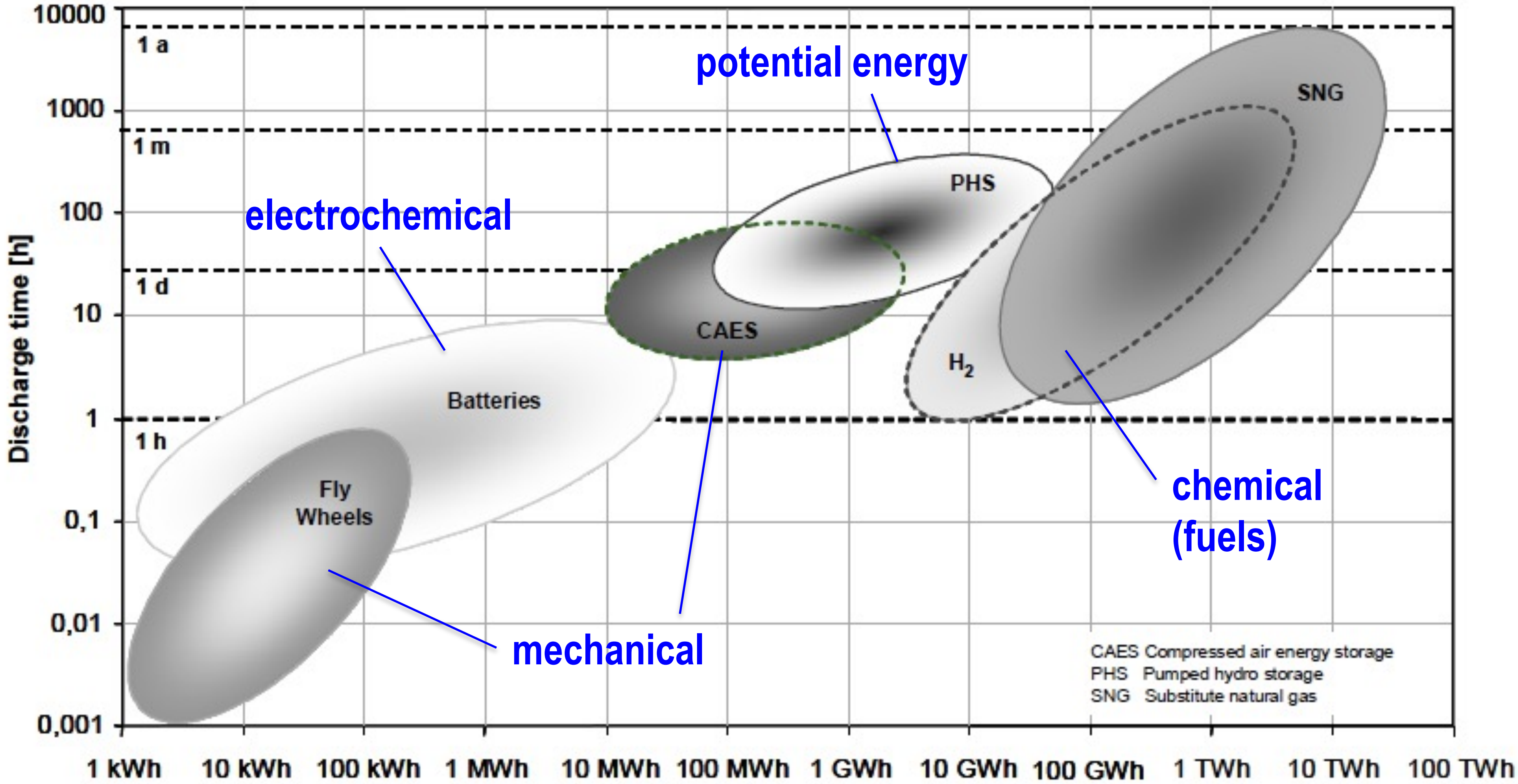
Electricity Storage as Power-to-Gas

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

→long term storage is required

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

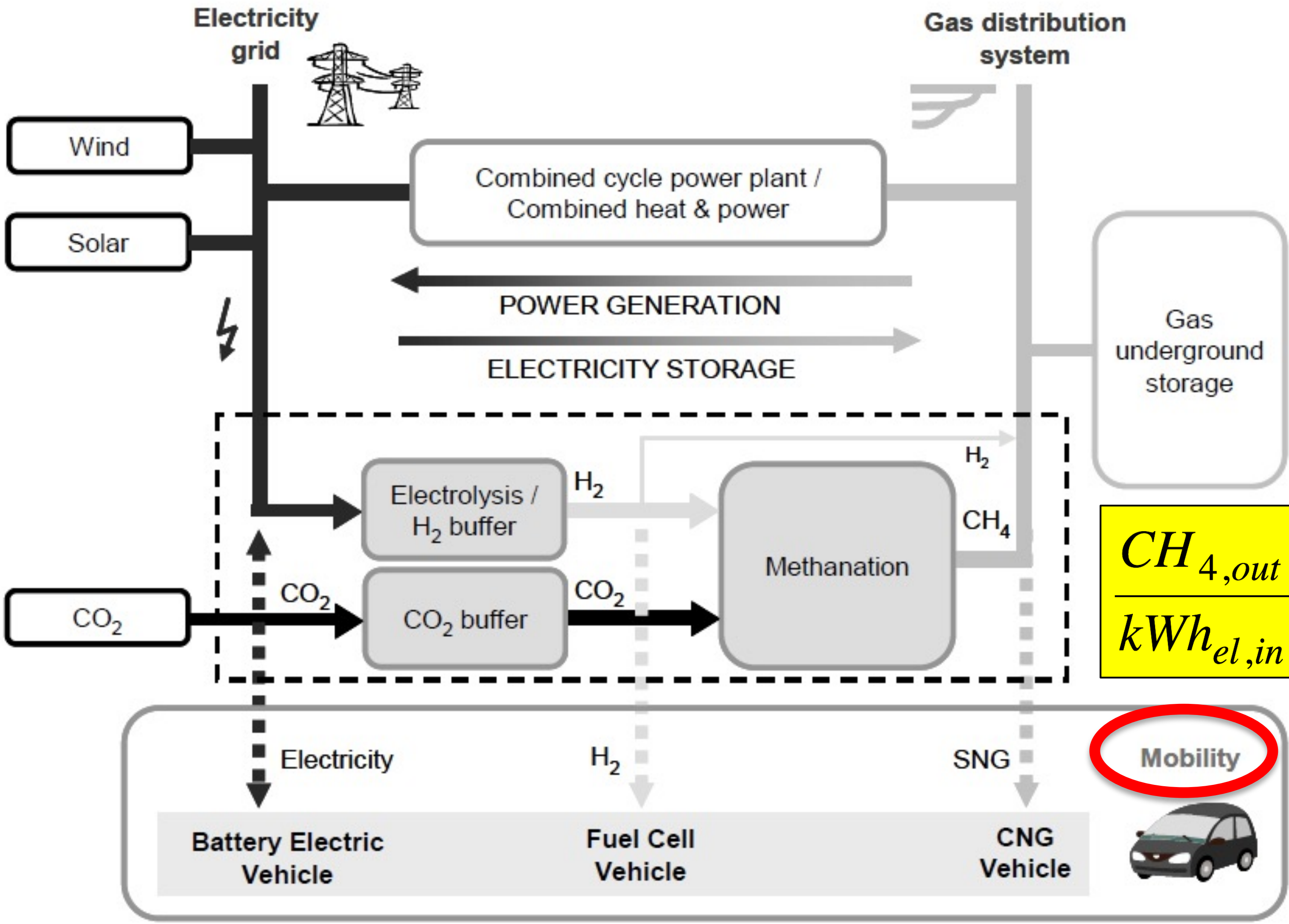
Storage schemes overview



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

→ converting electricity to fuel gives the largest capacities

'Power-to-Gas' concept



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

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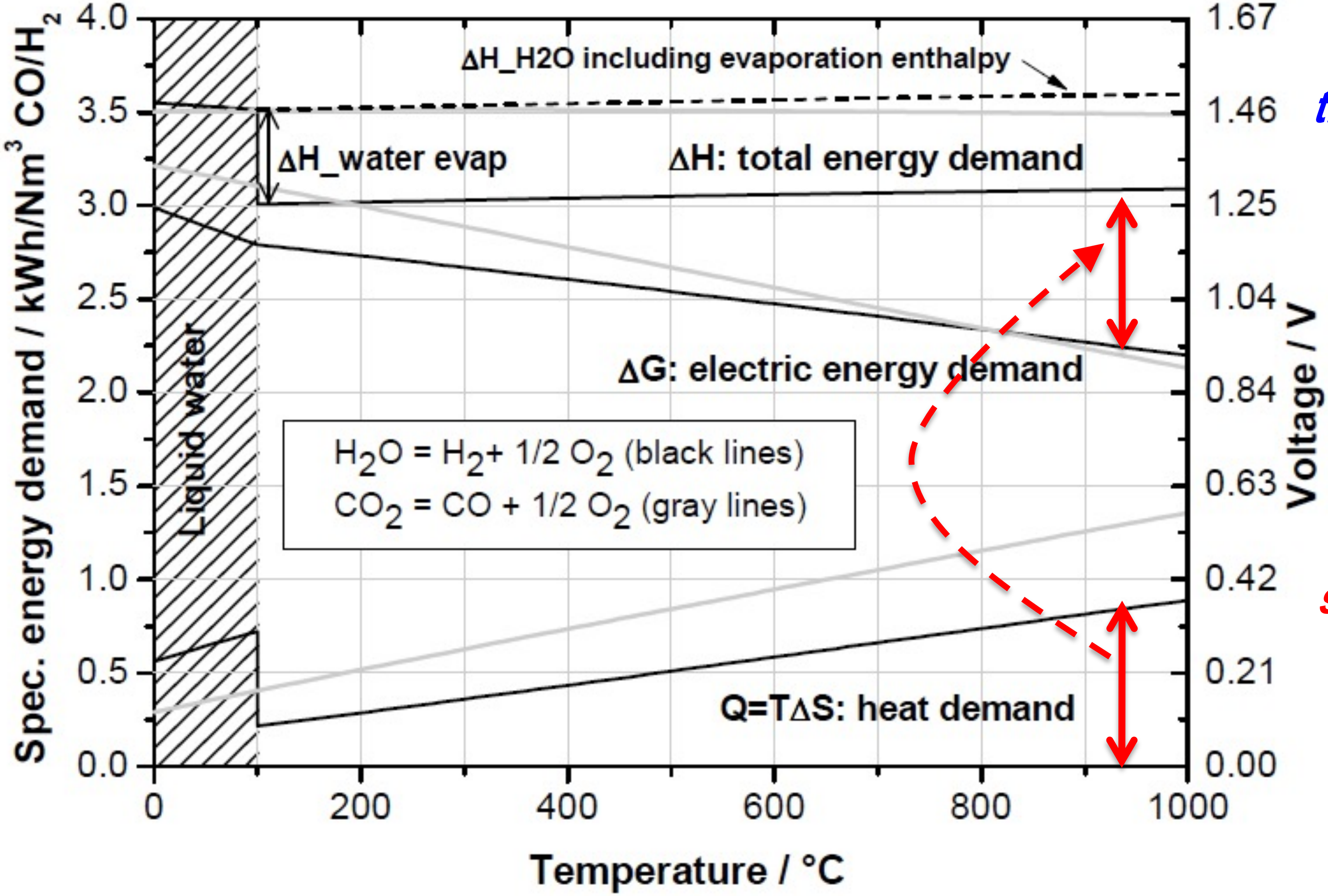
Motivation / Rationale

- tap/store available renewable seasonal/intermittent electricity reserve (hydro, PV, wind)
- chemical fuel storage is long term, high density, versatile
  - esp. mobility fuels are a bottleneck, and imported
- extending the electricity grid is expensive
- the natural gas grid has large capacity reserve and is associated with low distribution losses (1/10th of elec. grid distribution)

Thermodynamics of electrolysis

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



thermoneutral voltage 1.3 V

self-sustained heating from Joule losses

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

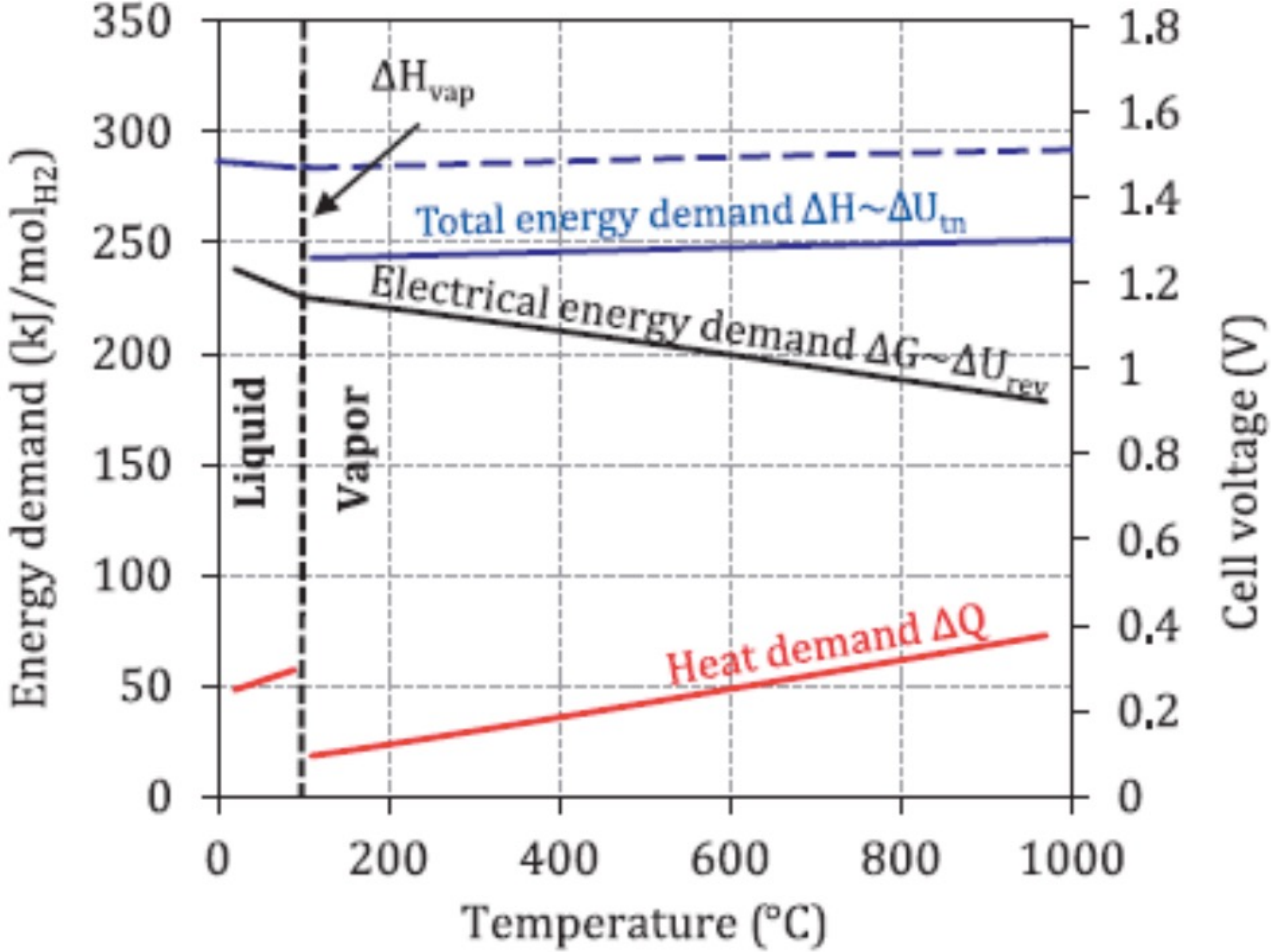
Thermodynamics

	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	$H_2O(g) \Rightarrow H_2 + \frac{1}{2}O_2$	242	10.80	3.00
	$CO_2 \Rightarrow CO + \frac{1}{2}O_2$	283	12.63	3.51

↓ $-\Delta H_{evap}$ (from 286 to 242)

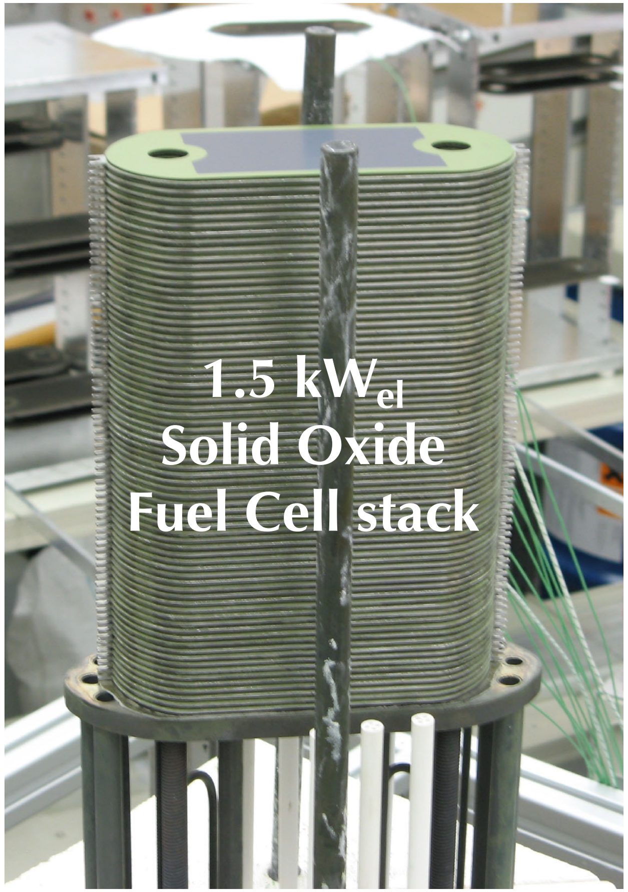
→ *Electrolysis : energy necessary for dissociation*

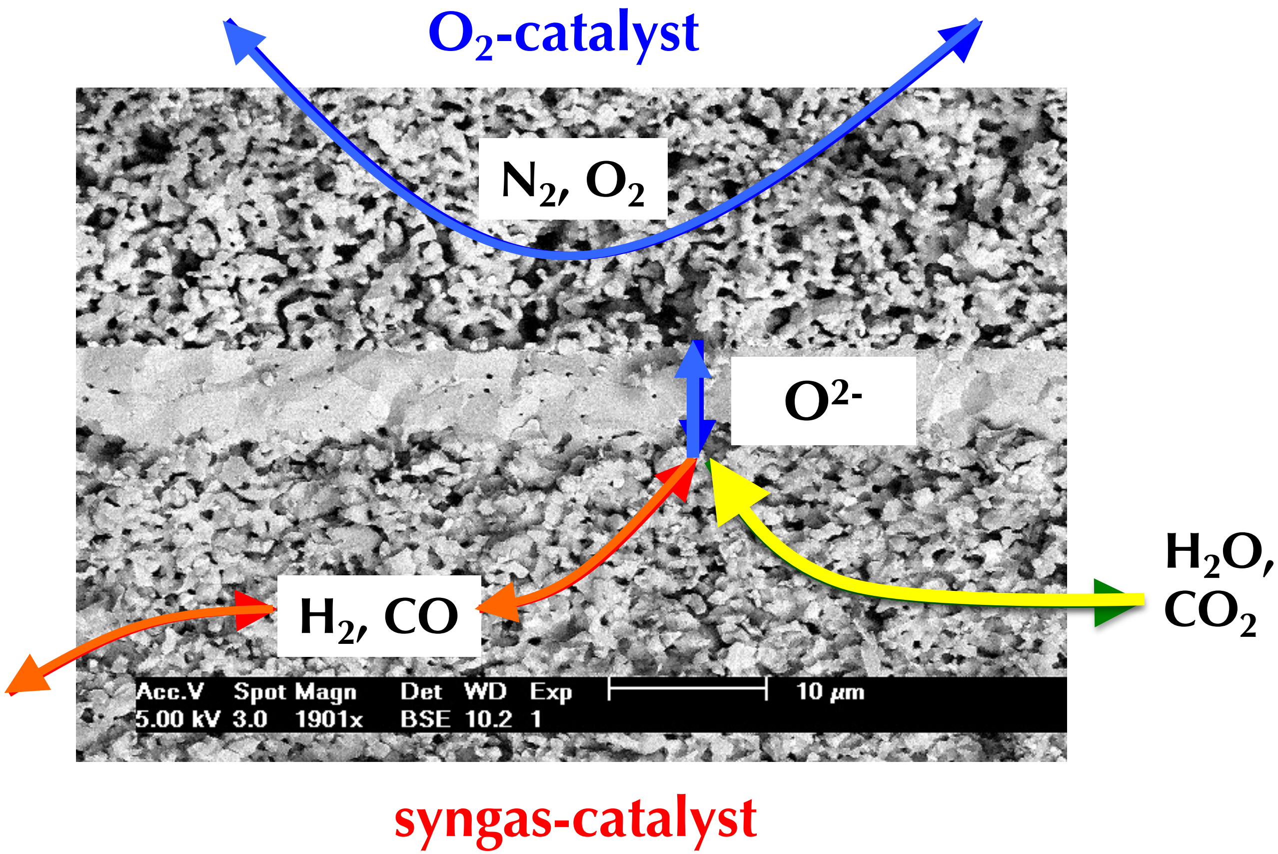
← *Combustion: energy liberated as heat*



Energy demand (kJ/mol$_{H2}$)
Cell voltage (V)
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
350
300
250
200
150
100
50
0
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
200
400
600
800
1000

How is it done? :
as inverse fuel cell

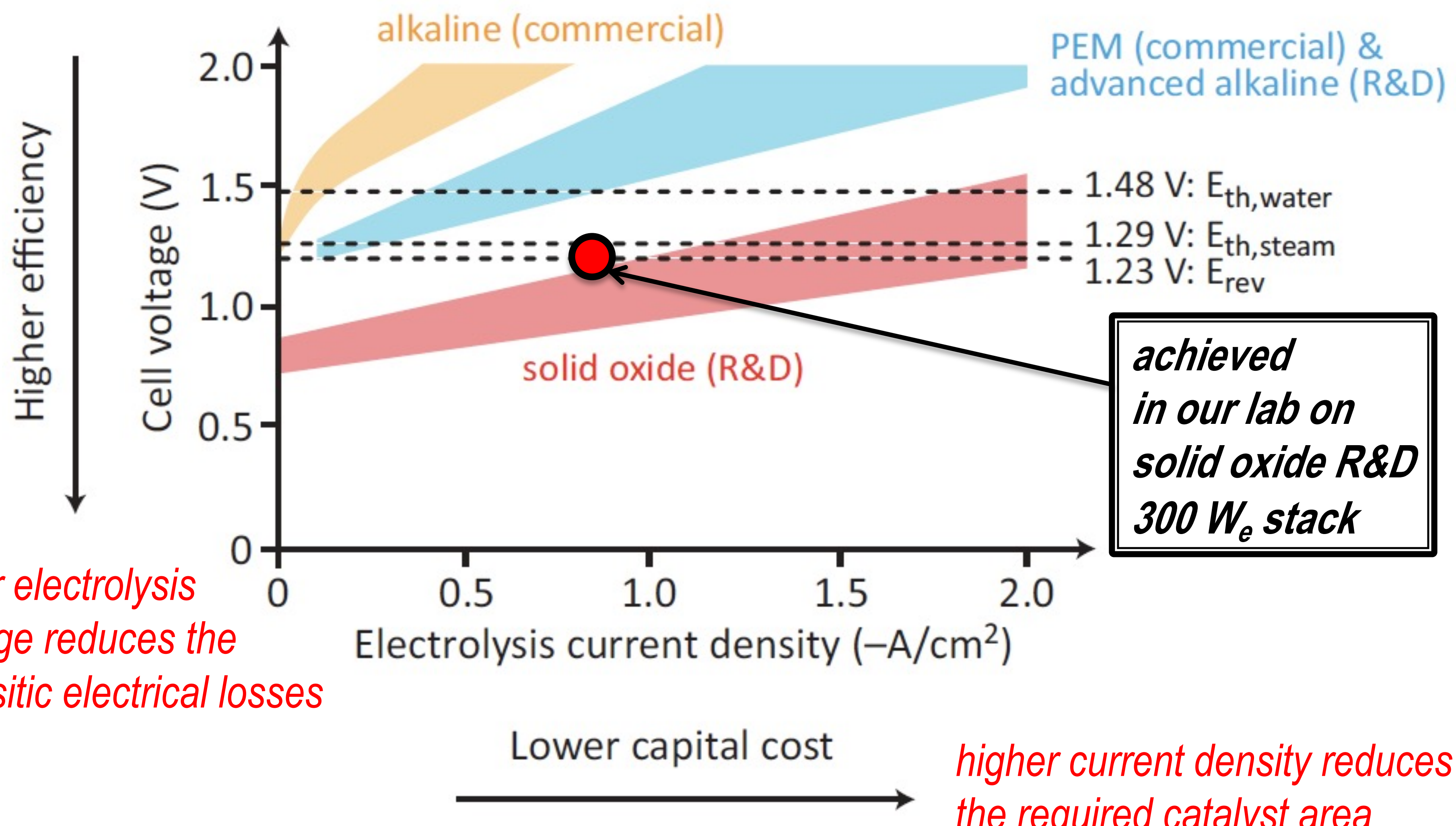




Operating regime :
700-800°C
1 bar (to 5 bar)

FUEL CELL
ELECTROLYSER

Electrolysis technology comparison

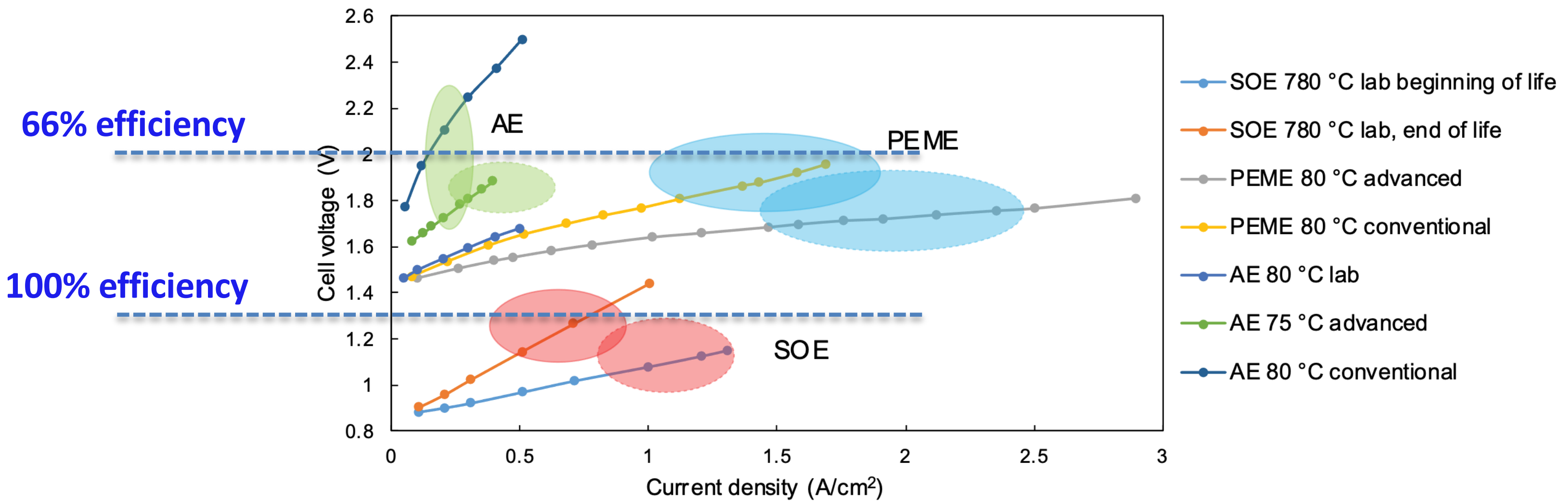


lower electrolysis voltage reduces the parasitic electrical losses

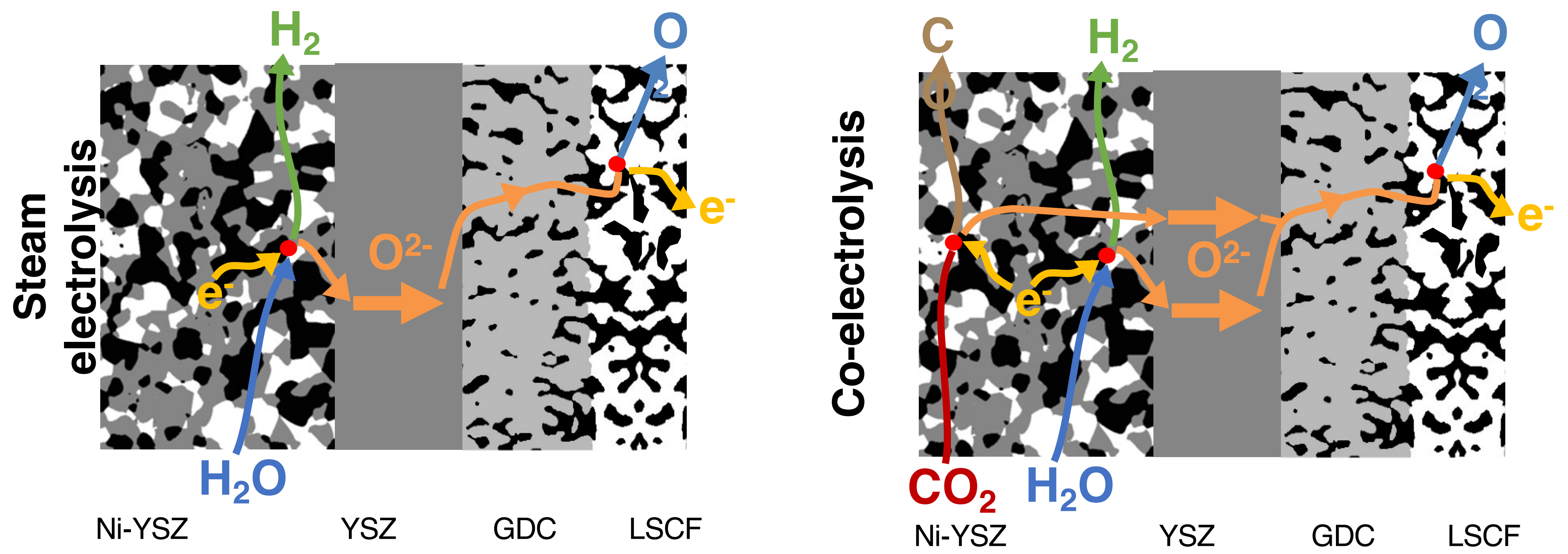
higher current density reduces the required catalyst area

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

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



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



Electrolysis key figures

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

** losses: insulation, compression, inverter*

figures achieved in our lab

Electrolysis efficiencies: lit. data

- theoretical : 39 kWh_{el}/kg H_2 (HHV 142 MJ/kg)
- alkaline electrolysis : 55-69 kWh_{el}/kg (56-73%)
  - 25°C, 30 wt% KOH solution, 2 V, 0.1-0.3 A/cm^2
- polymer membrane electrolysis : 55-70%
  - inverse polymer electrolyte fuel cell
  - 60°C, no separation required, 1.6 V, 1.6 A/cm^2
- ceramic membrane electrolysis (SOEC):
  - inverse solid oxide fuel cell, 800-1000°C, 1.2-1.5 V, 1 A/cm^2
  - 85-90% (electrical only), 60% with external heat source
- cost : alkaline < polymer < SOEC

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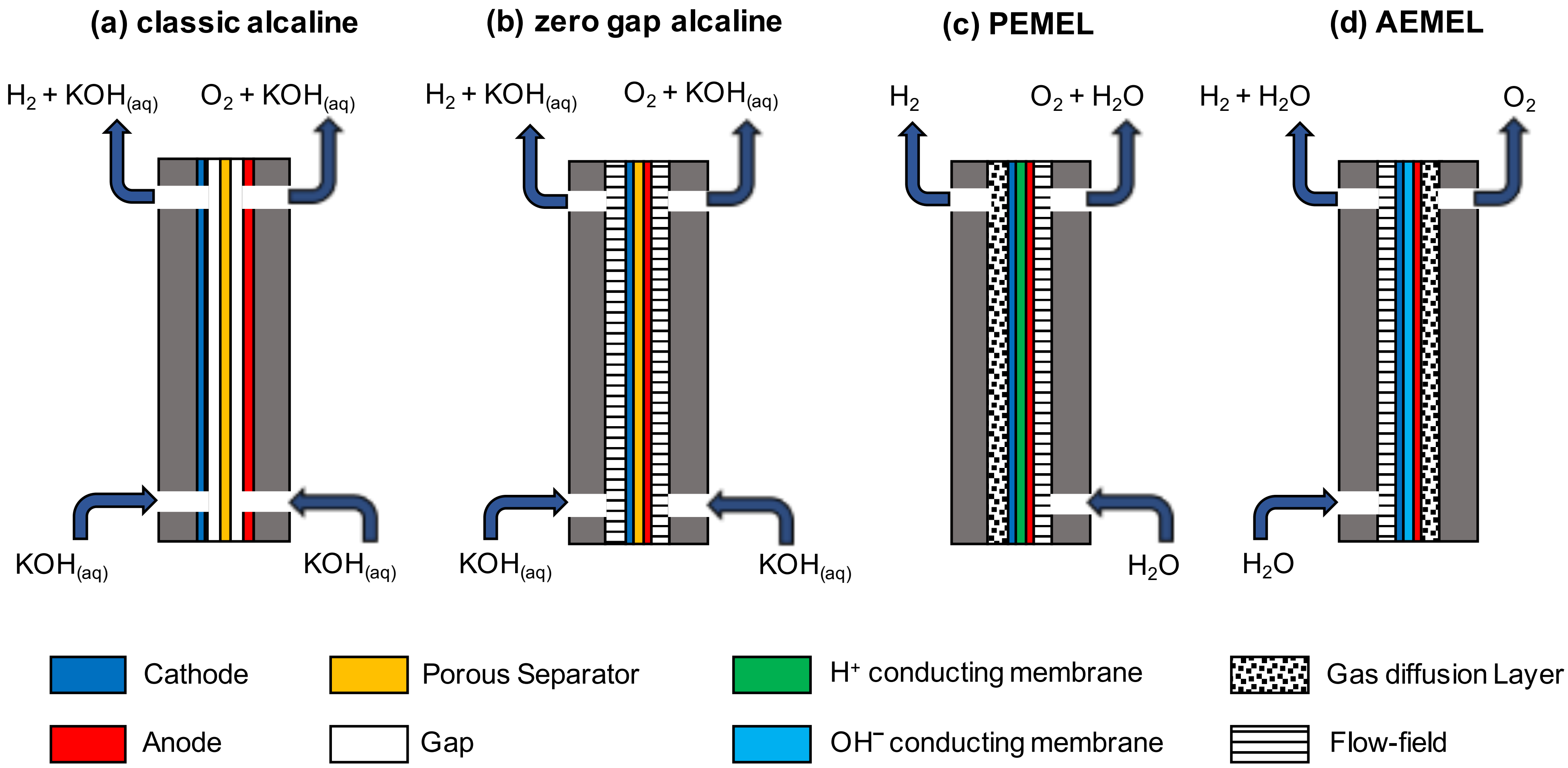
2014 Feb
Development of Water Electrolysis in the European Union

		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm^3_{H2}/h	0.25 – 760	0.01 – 240	0.1 – 1
	kW	1.8 – 5,300	0.2 - 1,150	0.7 – 4.5
Hydrogen purity [6]		99.5% – 99.9998%	99.9% – 99.9999%	99.4%
Indicative system cost	€/kW	1,000-1,200	1,900 – 2,300	N/A

Table 1: Overview of commercially available electrolyser technologies

New technology : AEM
(anionic exchange membrane electrolysis)



(graph : Dr Heron Vrubel)

AEMEL : combination of PEMEL and classical alcaline

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

SOE: better than 'water-only' electrolysis: steam+CO_2 co-electrolysis

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

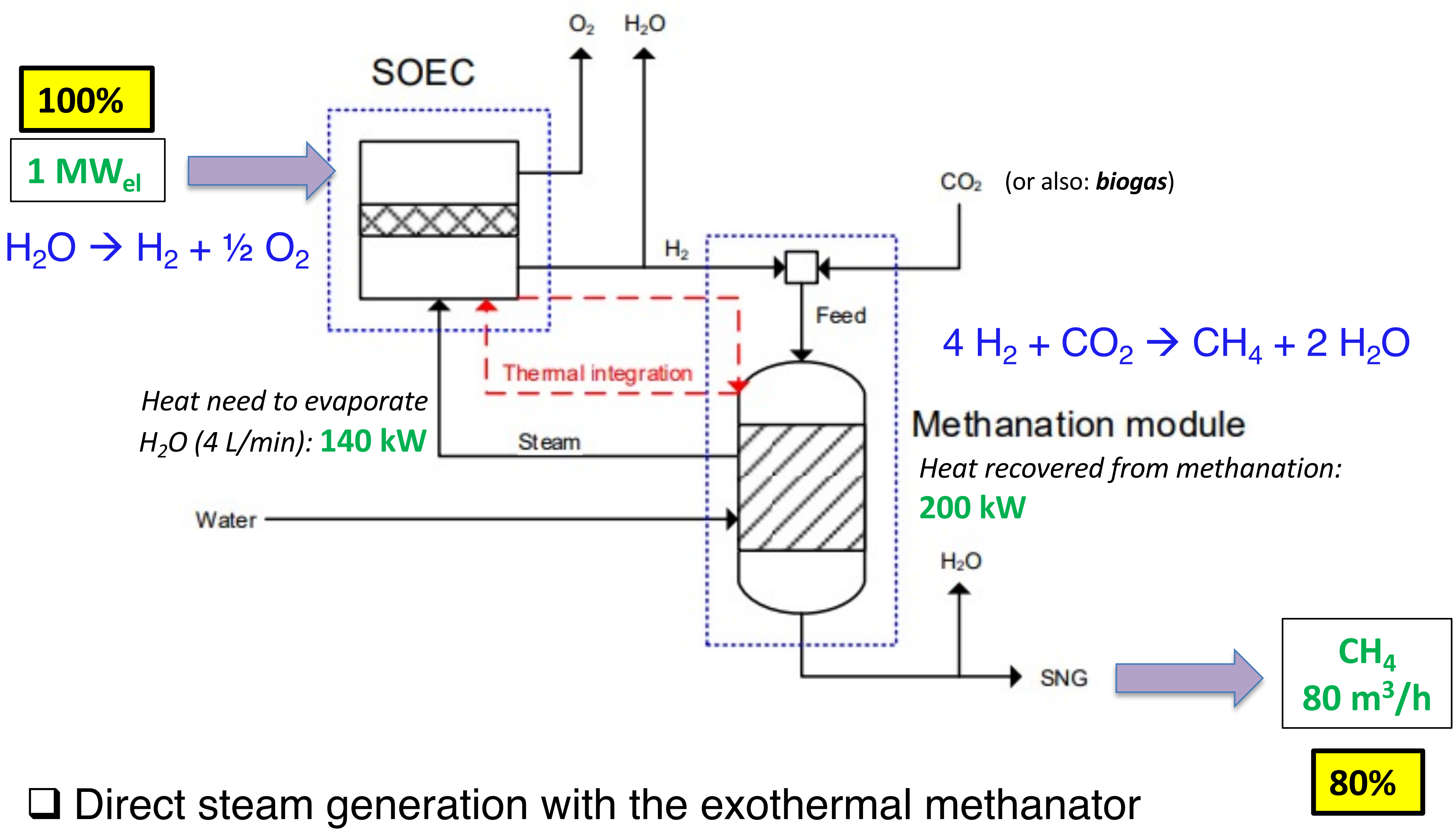
$$CO_2 \Rightarrow CO + \frac{1}{2}O_2$$

→ **SYNGAS**

- syngas is upgradable to CH_4 (→ gas grid), as well as to MeOH, or liquid synfuels
- **no need for extra step** of $H_2 + CO_2 \Leftrightarrow H_2O + CO$
- operation at higher temperature confers:
  - more favorable thermodynamics
  - more favorable kinetics

→ hence less electrical input

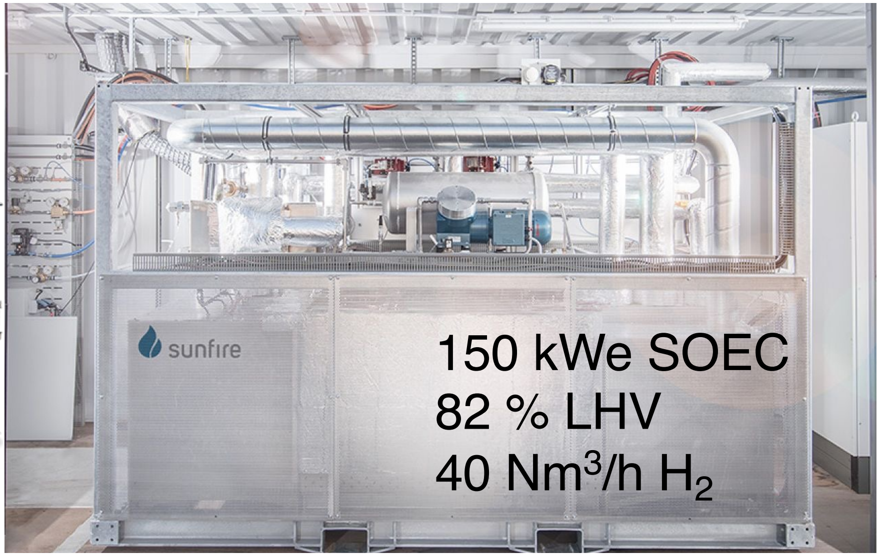
SOE (Solid Oxide Electrolysis) based Power-to-CH_4



- ❑ Direct steam generation with the exothermal methanator

Solid-oxide system development & manufacturers

SUNFIRE
POWERCORE



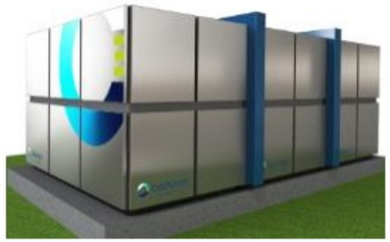
150 kWe SOEC
82 % LHV
40 Nm^3/h H_2

Convion C50
50kW, NG, Biogas

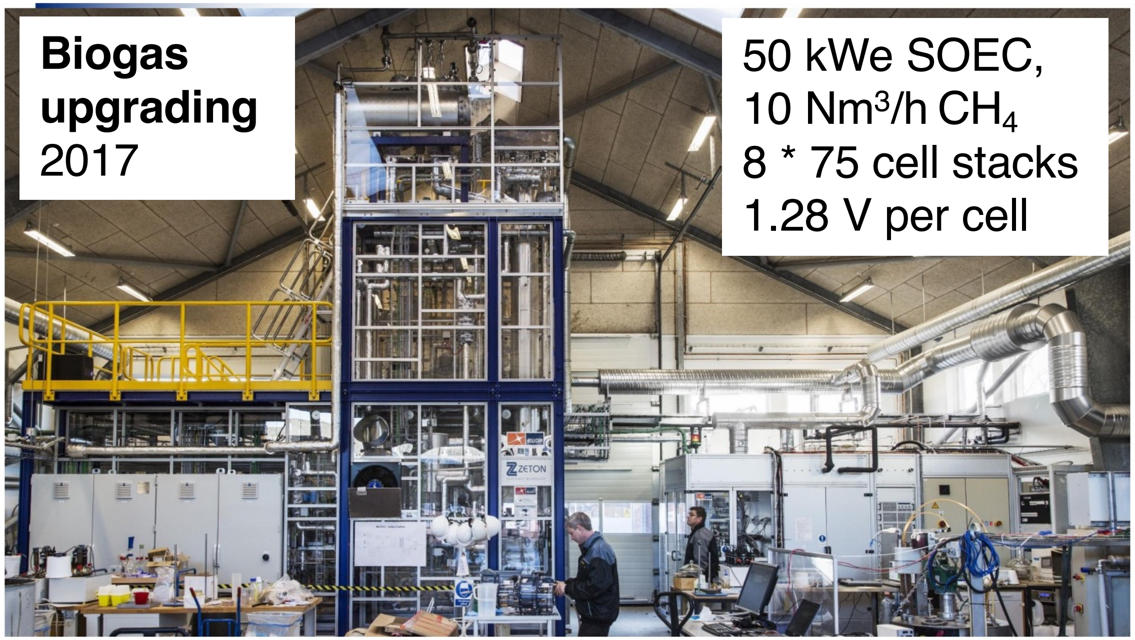
Validation 2015

CONVION SOFC

X00 concept
175 kWe, Biogas
ηe > 53 %
2016



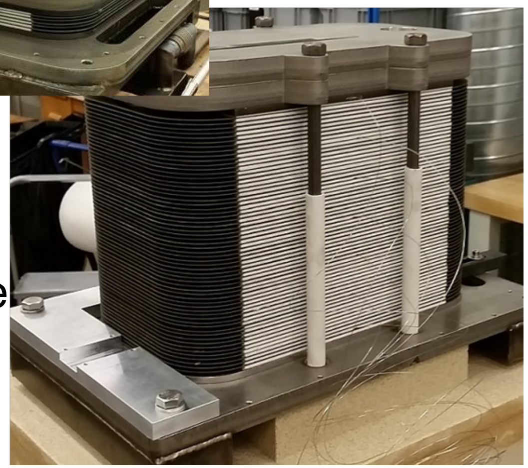
Biogas upgrading
2017



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

HALDOR TOPSØE

SOLIDPower 5-kW SOFC stack

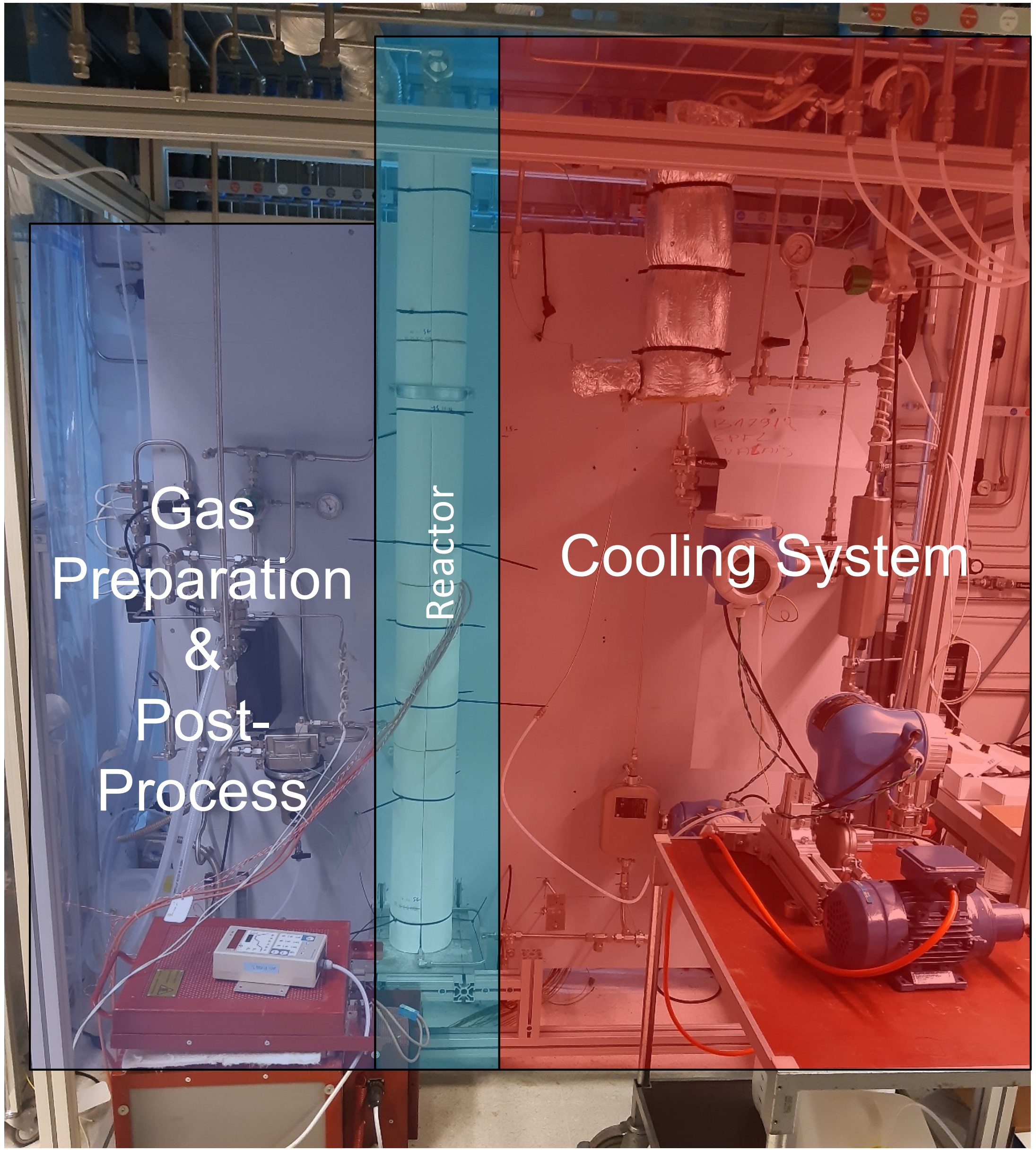


Electrolysis

2019: 20 kWe

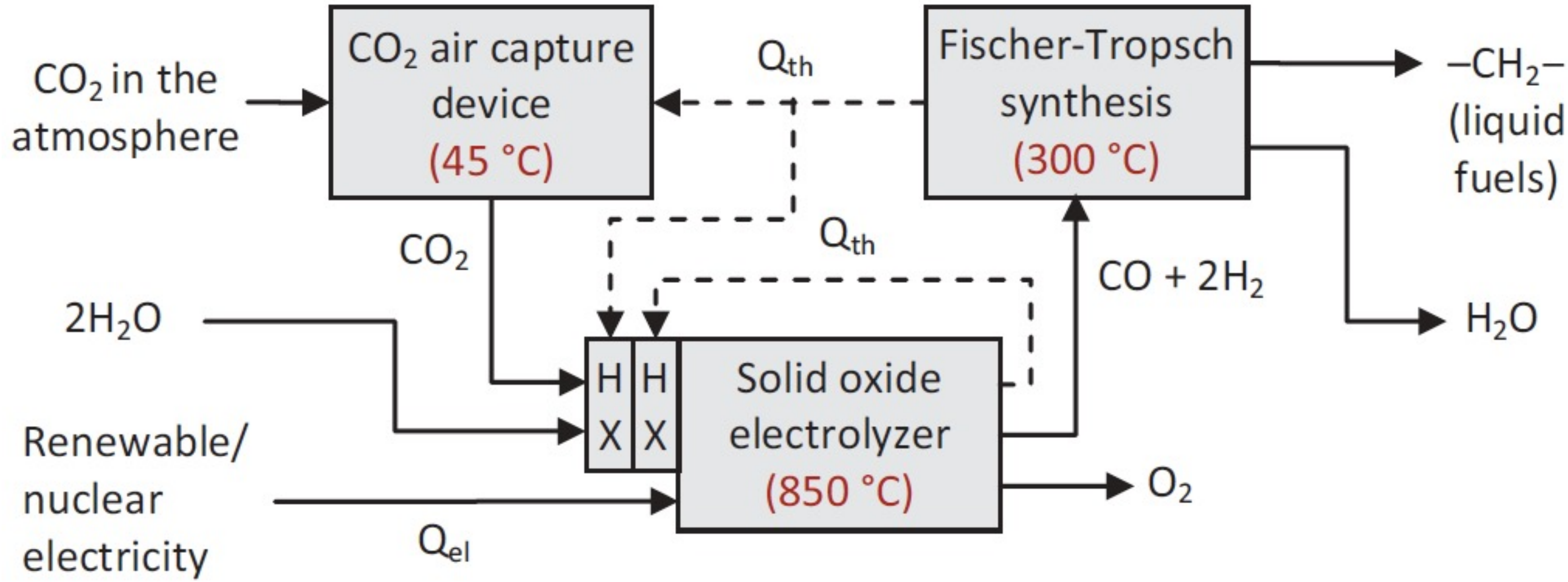
2020: 100 kWe

10 kW_{th} methanator set-up at EPFL-GEM



EPFL

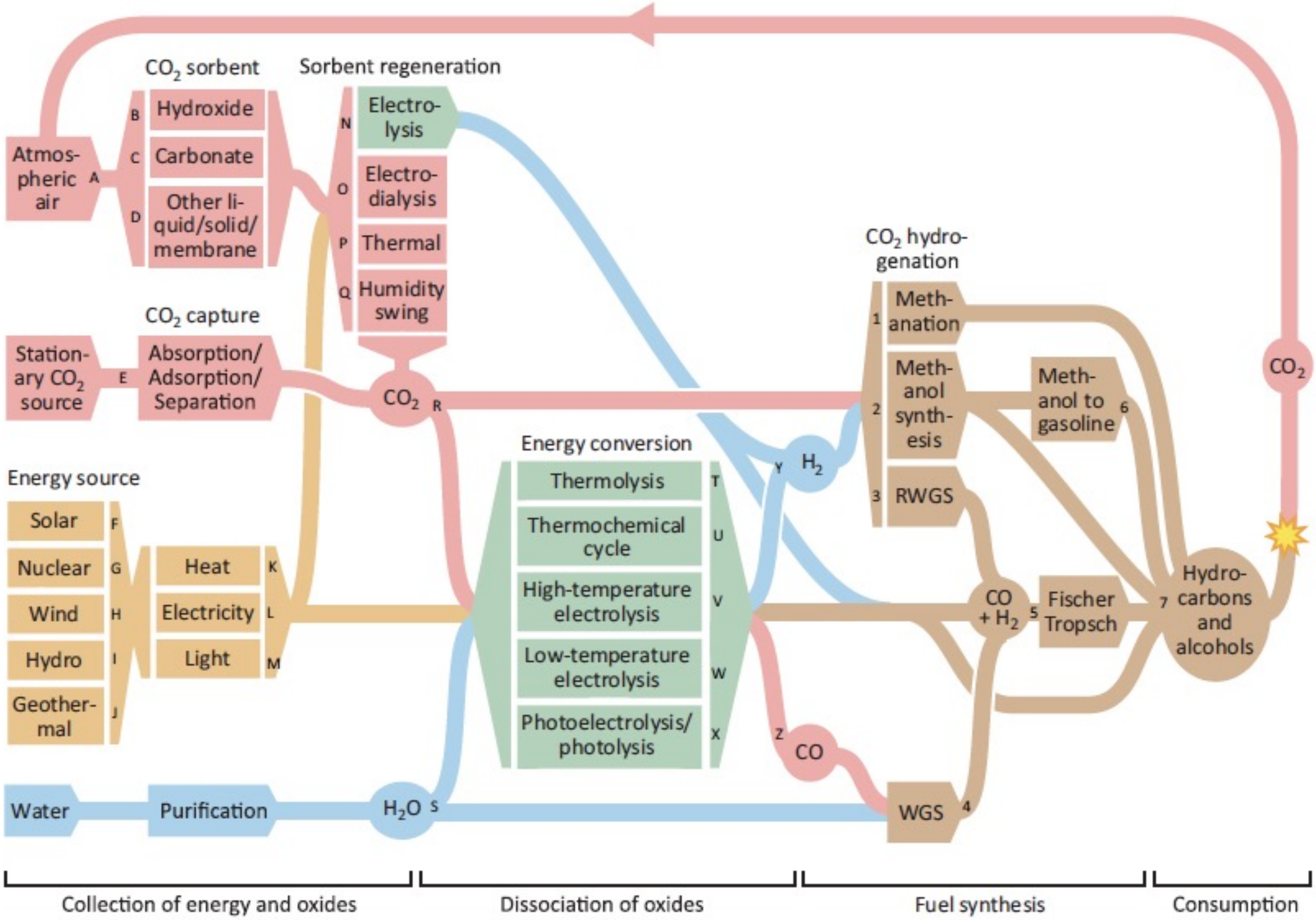
Other downstream thermal process integration example



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

CO_2-to-fuel pathways: general overview

C. Graves et al. / Renewable and Sustainable Energy Reviews 15 (2011) 1–23



Swiss context (gas industry)

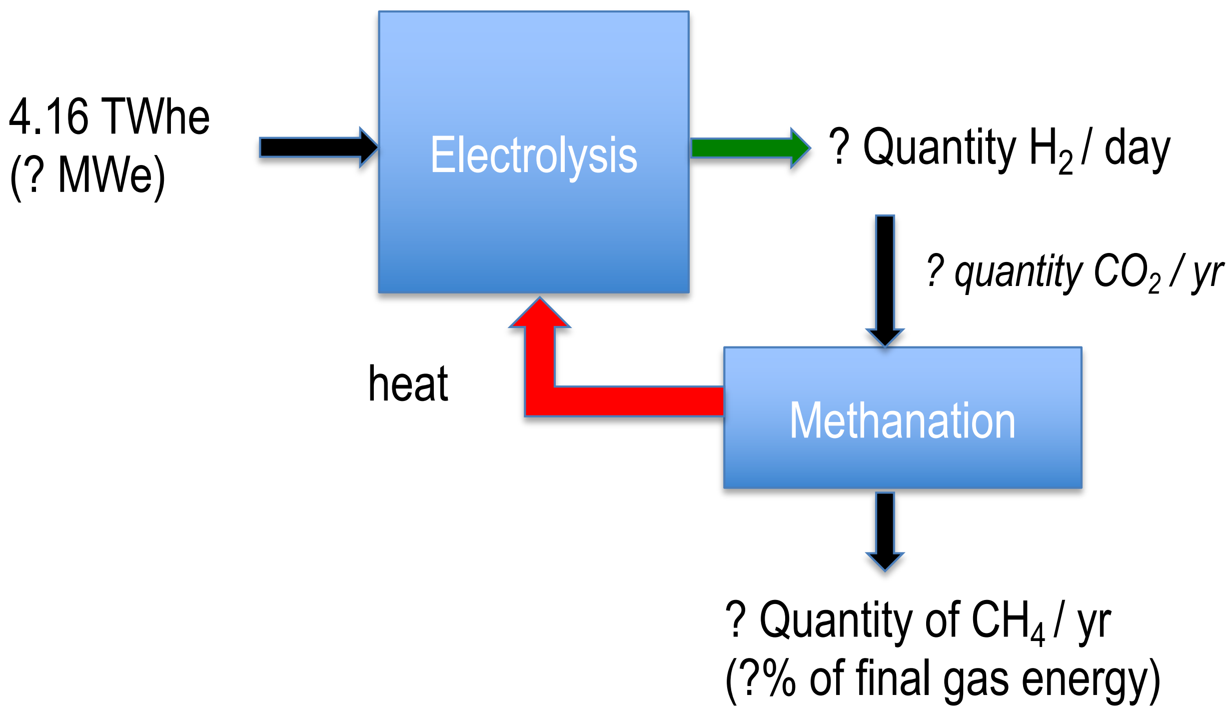
- **Power-to-methane** conversion for storage of renewable electricity
- High **efficiency** electrolysis of steam (H_2O) to H_2
  (>90%, vs. 50-60% for water electrolysis)
- Steam is generated by recovering heat from the downstream exothermal **methanation** process

$$3 \text{ to } 4\ H_2 + CO_2(/CO) \rightarrow CH_4 + 1 \text{ to } 2\ H_2O$$

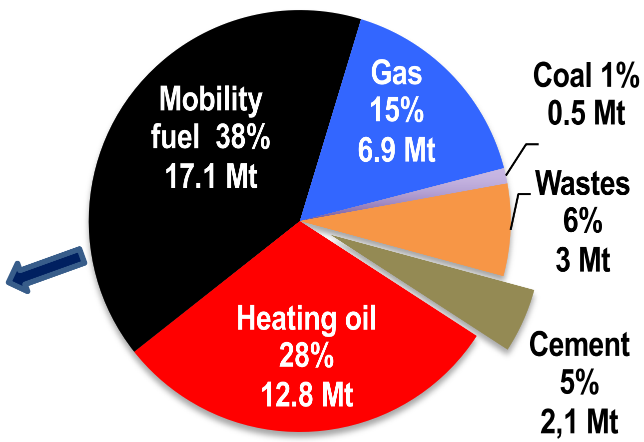
- The integrated process steam electrolysis + methanation can reach **80%** energy **efficiency** from electrical power → to renewable methane CH_4
- The **CO_2 utilisation** can stem from air capture + separation, or from concentrated CO_2 streams, e.g. **biogas**, combustion (wood/waste),…

- « *30% renewable gas in the Swiss gas grid by 2030* » (10.5 TWh):
  - upgrading current Swiss biogas production to bio-methane via SOE can reach ≈**20%** of this target (2.3 TWh)
  - upgrading future potential Swiss biogas production to bio-methane via SOE can reach **100%** of this target (10.9 TWh); this would require ≈800 electrolysers of 1 MW_{el} (800 MWe). This is of the same order as current hydro-pumping storage.

Exercise: P2G instead of hydro-pumping (CH – 2017 data)



Swiss yearly emissions CO_2 (Mt)

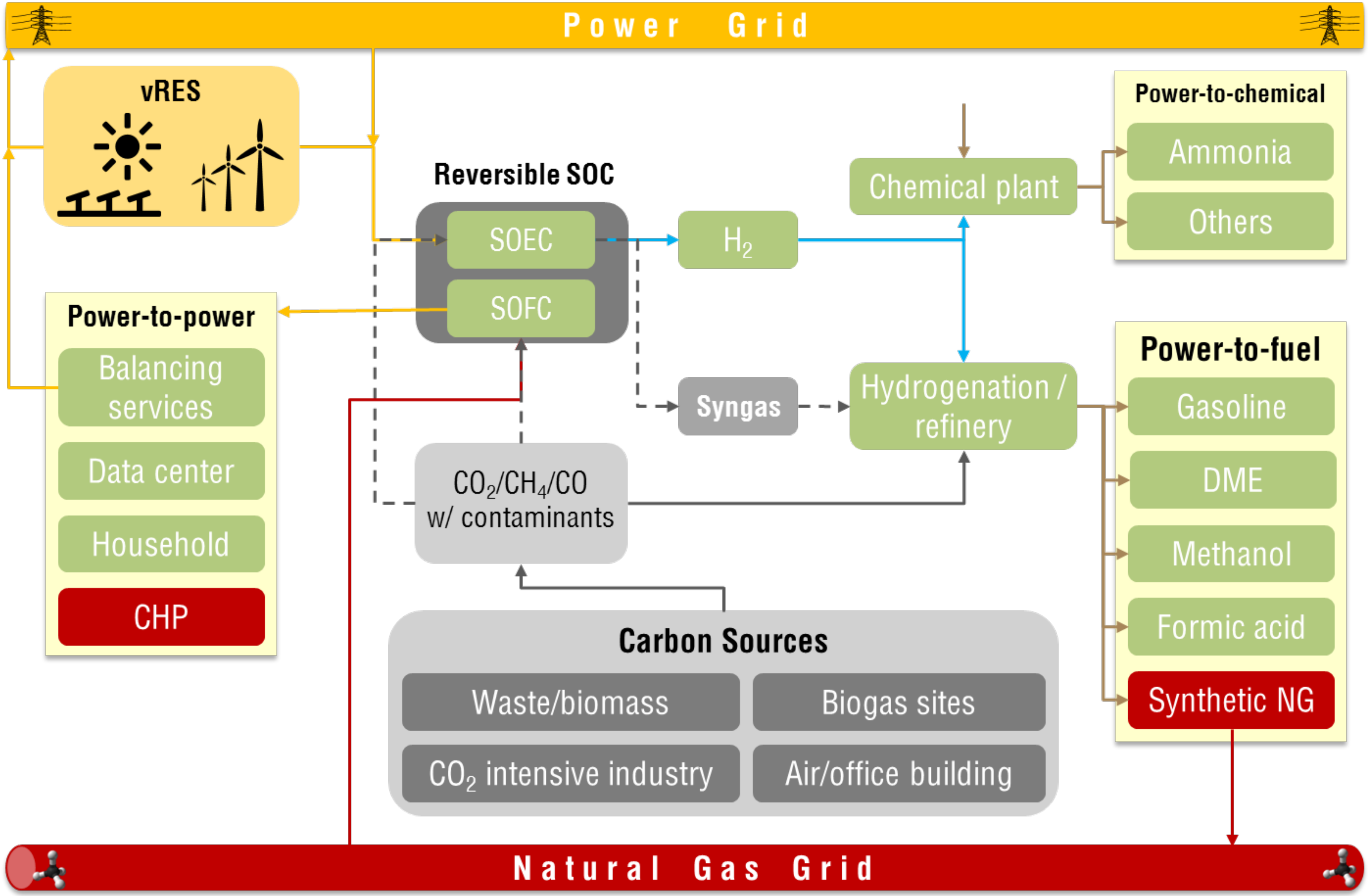


Biogas (2017): 0.185 Mt CO_2

Objective « 30/30 » of Swiss gas industry: 30% of renewable gas in the grid by 2030

Vision

(figure: Dr Ligang Wang)



Electrolyser sizes (1-100 MW)

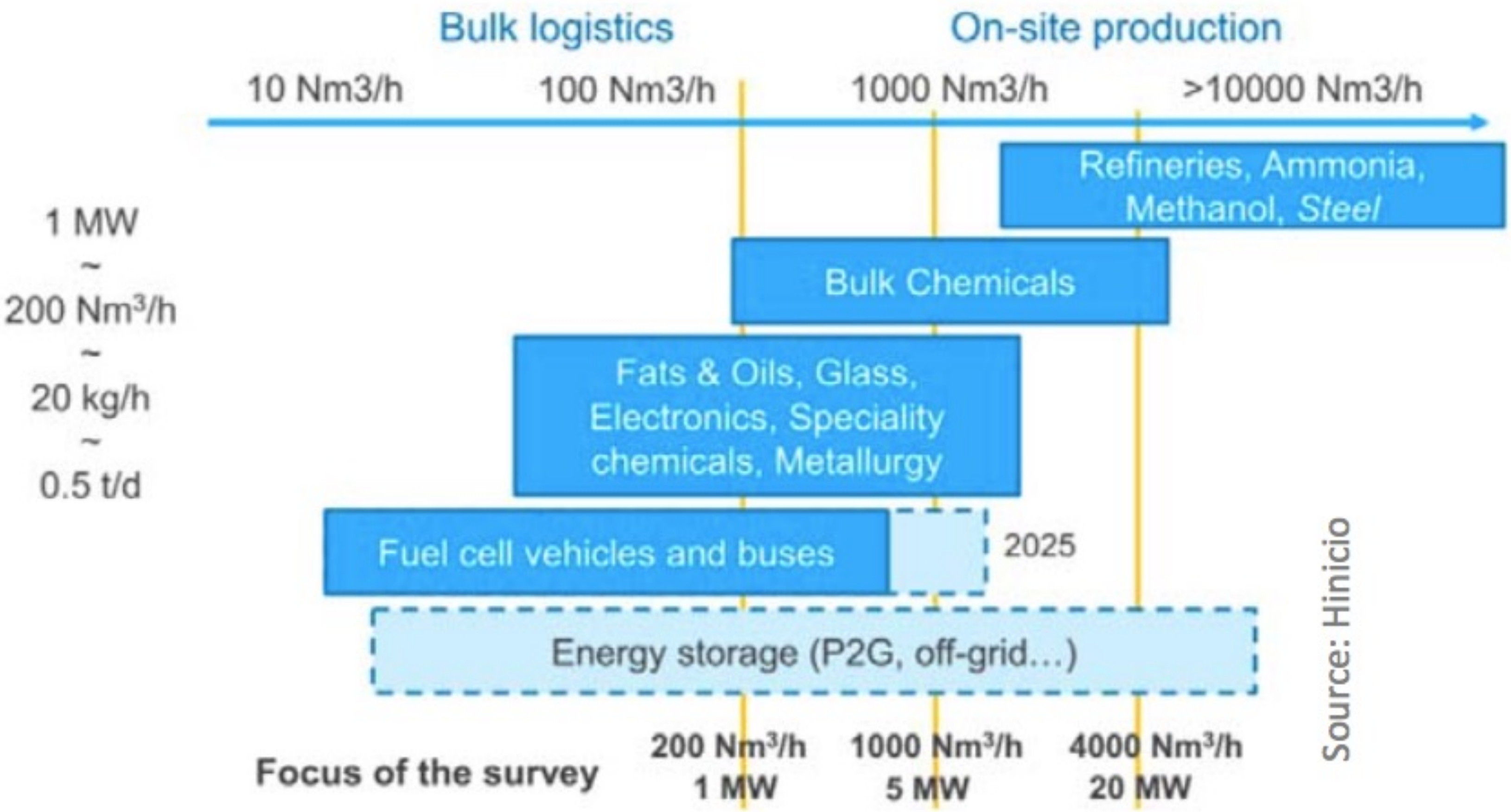


Figure 108: Selection of electrolyser size

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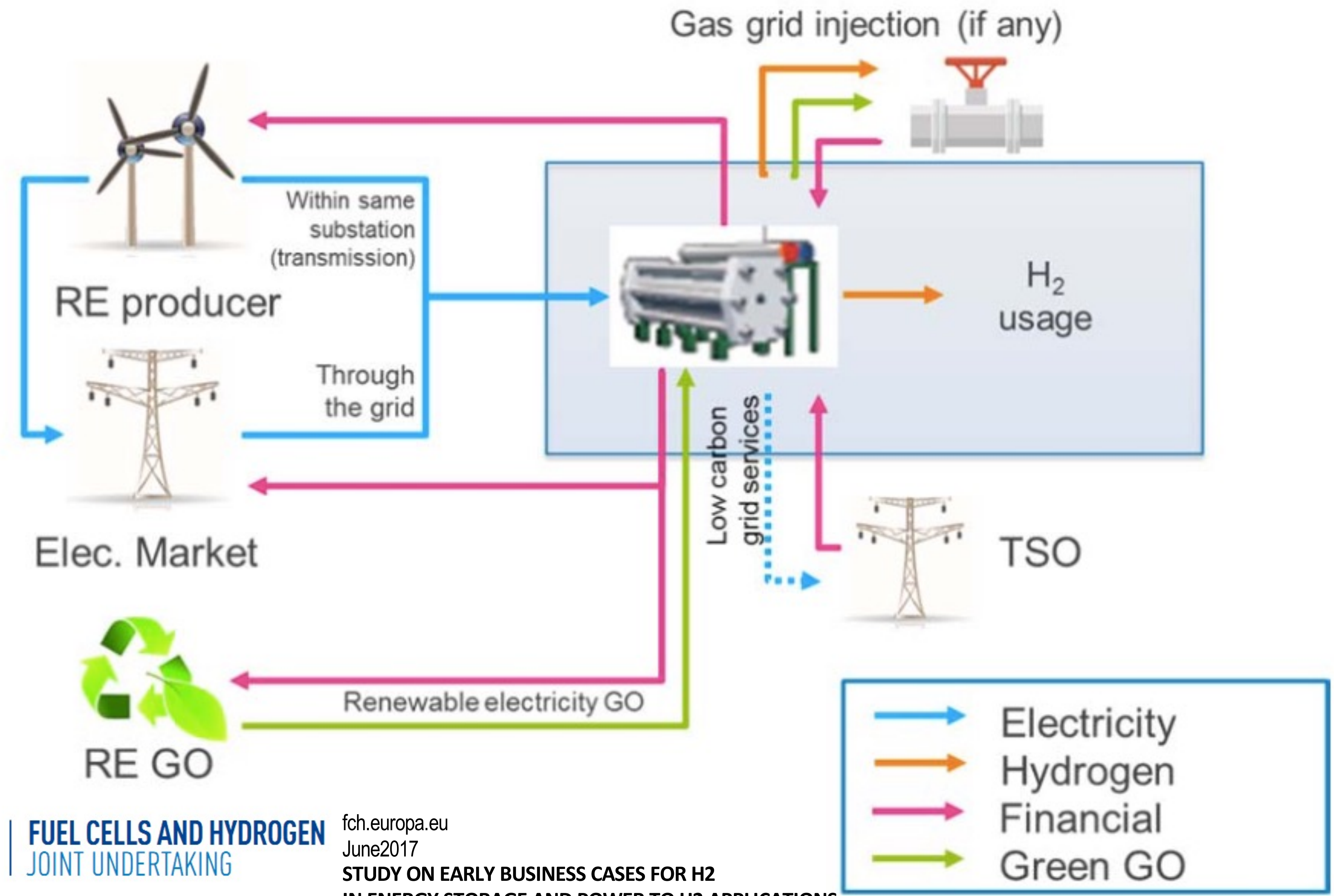
Electrolyser business models



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Storage of hydrogen

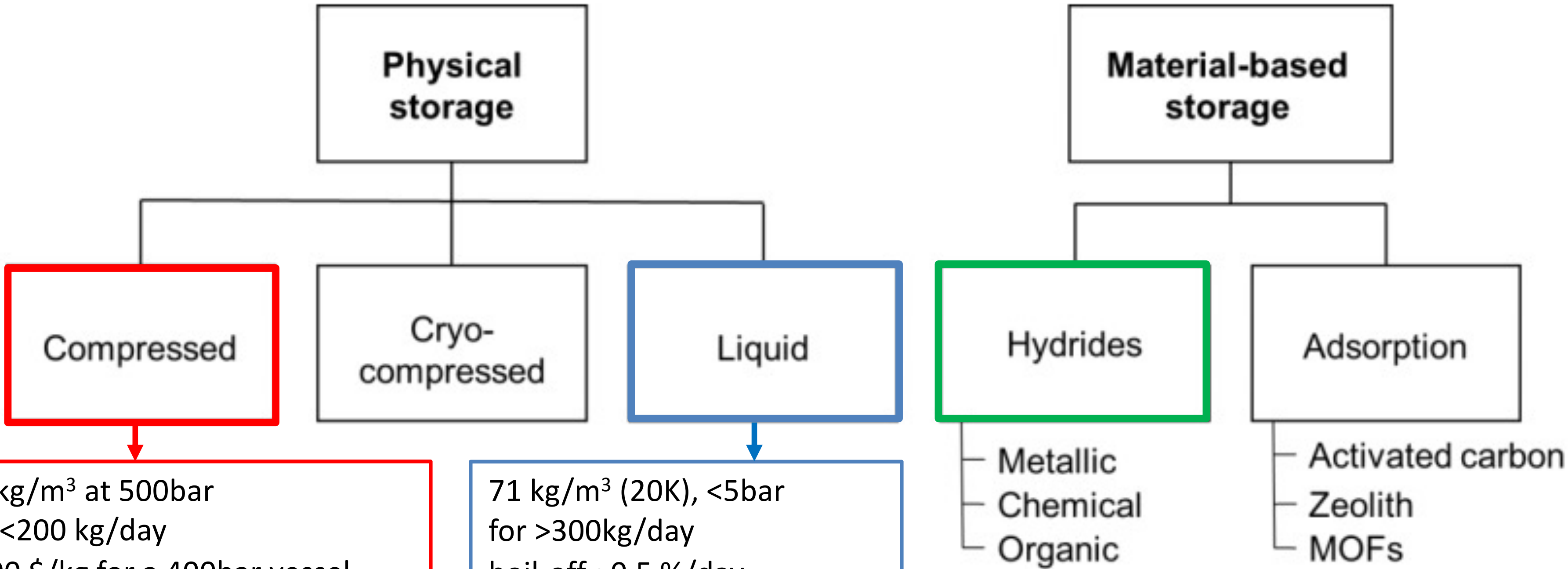
- as compressed gas
- as liquified gas
- as metal hydride
  - physically bound (absorbed, H_2 interstitial)
  - chemically bound (NaH, $NaBH_4$)
- as LHOC (liquid hydrogen organic carrier)
  - e.g. formic acid (H_2+CO_2=>HCOOH), formate

H_2 vs. hydrocarbons: properties

	H_2	Natural gas (CH_4)	Gasoline
Boiling point	-252.7 °C	-160°C	40-200°C
Melting point	-259 °C	-182°C	-40°C
Gas density	0.089 kg/m^3	0.707 kg /m^3	4 kg /m^3
Liquid density	0.071 kg/L	0.41-0.5 kg/L	0.72-0.78 kg/L
Lower HV	120.2 MJ/kg, 8.6 MJ/L as liquid	47 MJ/kg 21 MJ/L as liquid	42 MJ/kg
Higher HV	142 MJ/kg, 12.7 MJ/m^3 10.1 MJ/L as liquid	53 MJ/kg, 40 MJ/m^3 24 MJ/L as liquid	46 MJ/kg 36 MJ/L
Autoignition	585°C	632°C	220°C
Flammability in air	4-75%	5-15%	1-7.6%
Flame temperature	2045°C	1875°C	2200°C

H_2 storage

(figure: Leonardo Gant)



33 kg/m^3 at 500bar
for <200 kg/day
1000 $/kg for a 400bar vessel
energy cost = 5-15% of LHV
40ft container: 1 t H_2, cost 0.9 M$

mature

71 kg/m^3 (20K), <5bar
for >300kg/day
boil-off ≈0.5 %/day
energy cost = 30% of LHV
LH_2 costs 10% more than CH_2

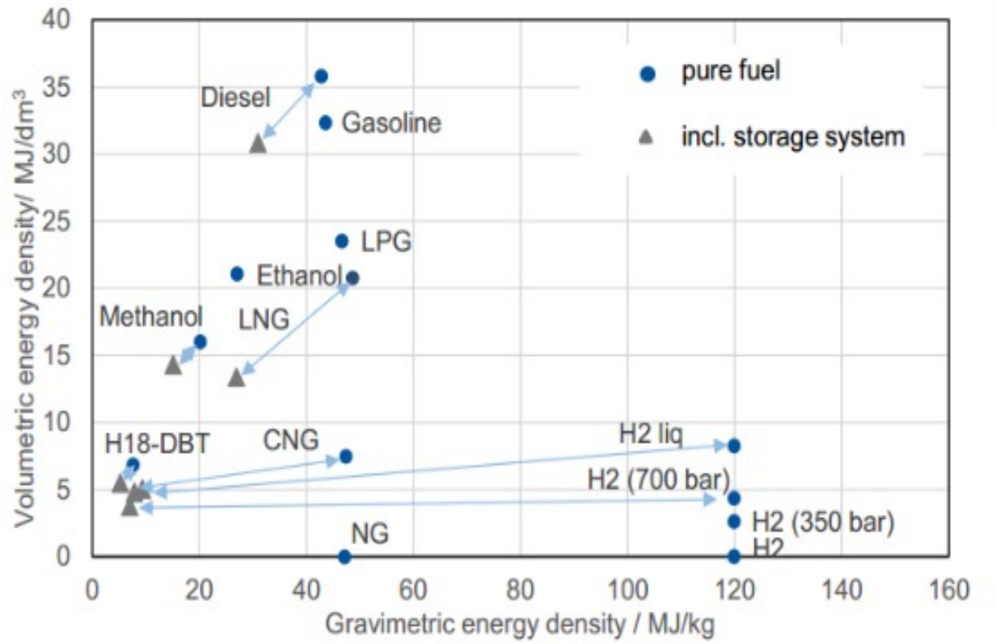
mature

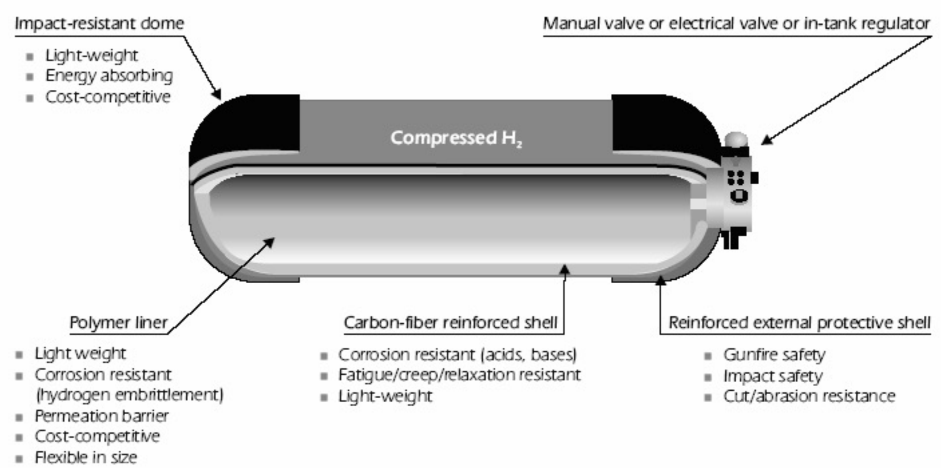
6-8wt%
LOHC : 9 kg/m^3 at 1bar
Hydrides : 40 kg/m^3

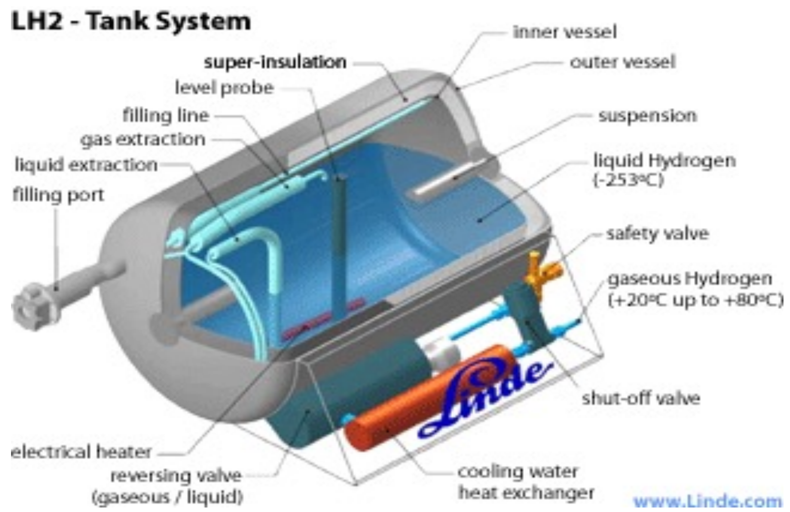
under dvpmt

H_2 storage

1. CH_2
2. LH_2
3. Pipelines
4. Other methods

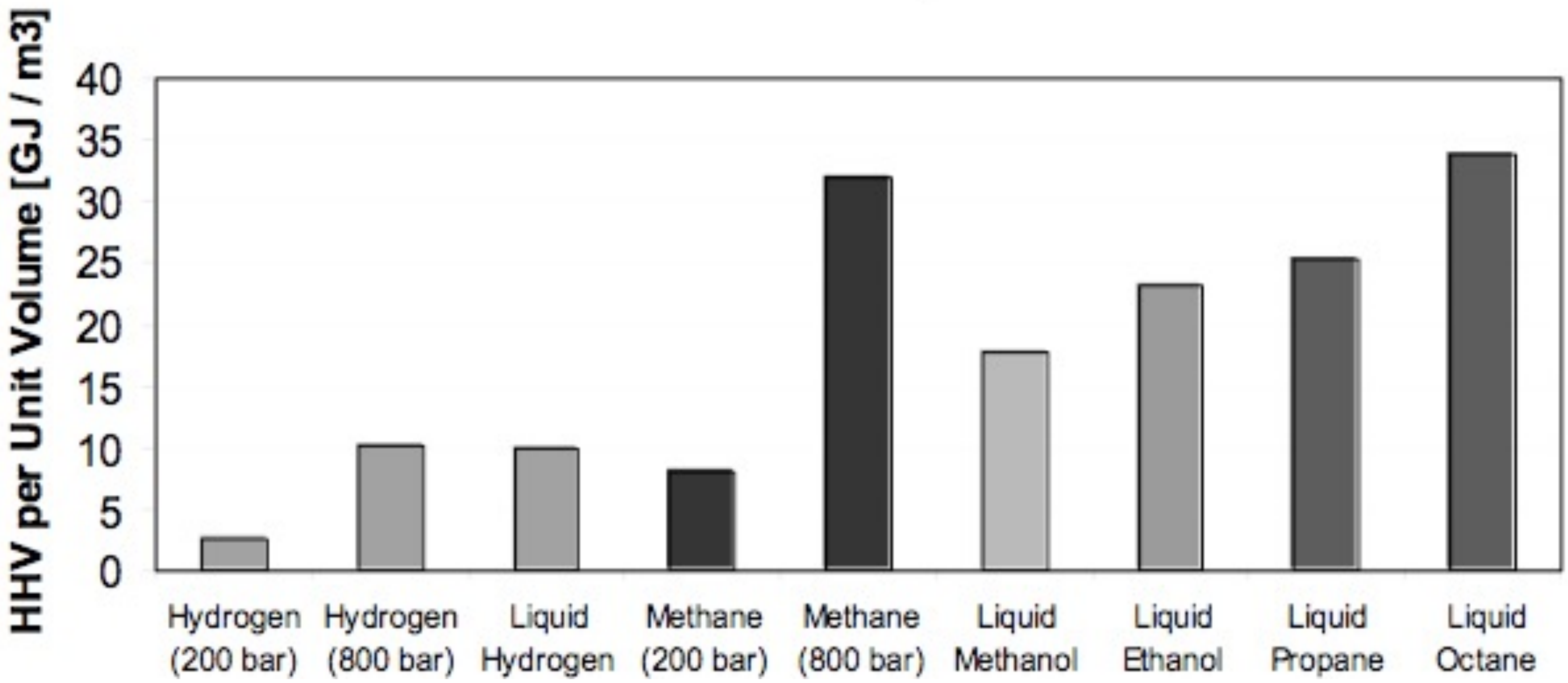






(figures: Leonardo Gant)

HHV by volume



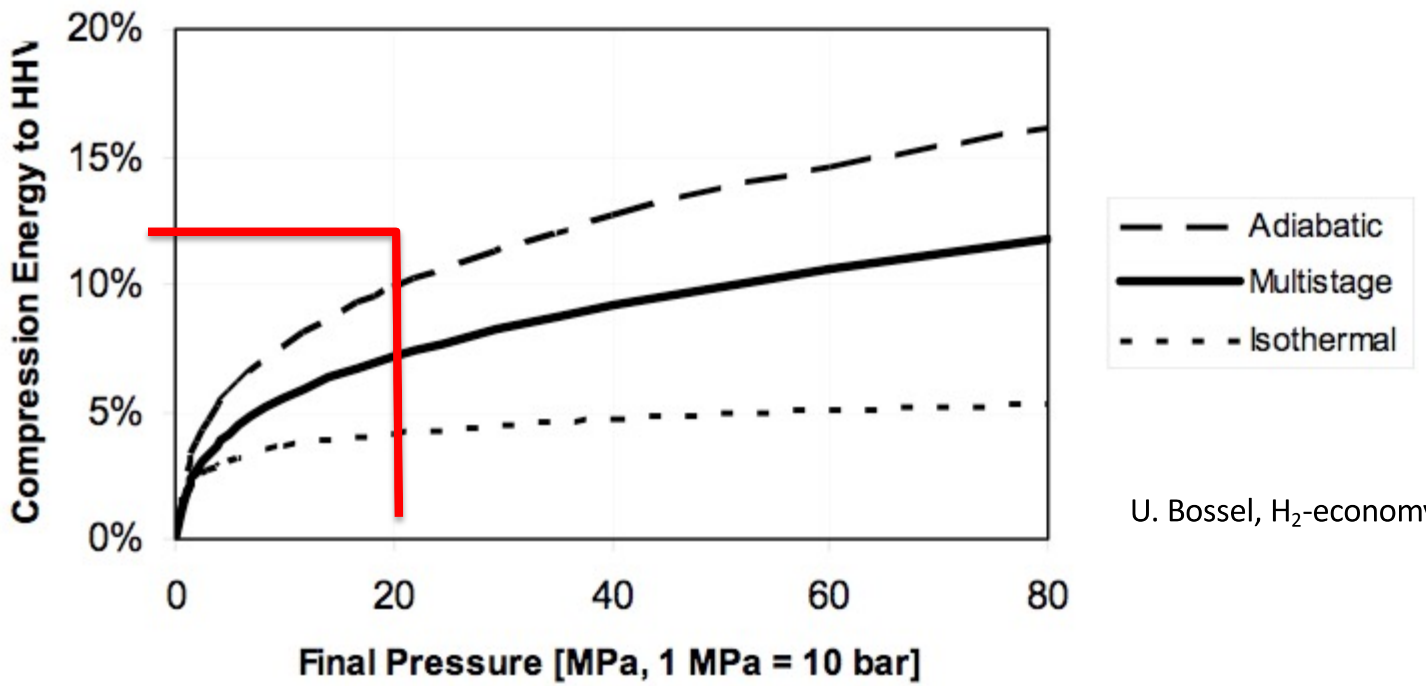
U. Bossel, H_2-economy

Compressed gas energy cost

- ideal isothermal : $work_{id}$ (J/kg) = $p_0V_0 \ln(p_1/p_0)$
- adiabatic : $work_{ad} = (\gamma/\gamma-1)\, p_0V_0\, ((p_1/p_0)^{(\gamma-1)/\gamma}-1)$

  V_o initial volume(m^3/kg) (11.11 m^3/kg for H_2, 1.39 m^3/kg for CH_4)

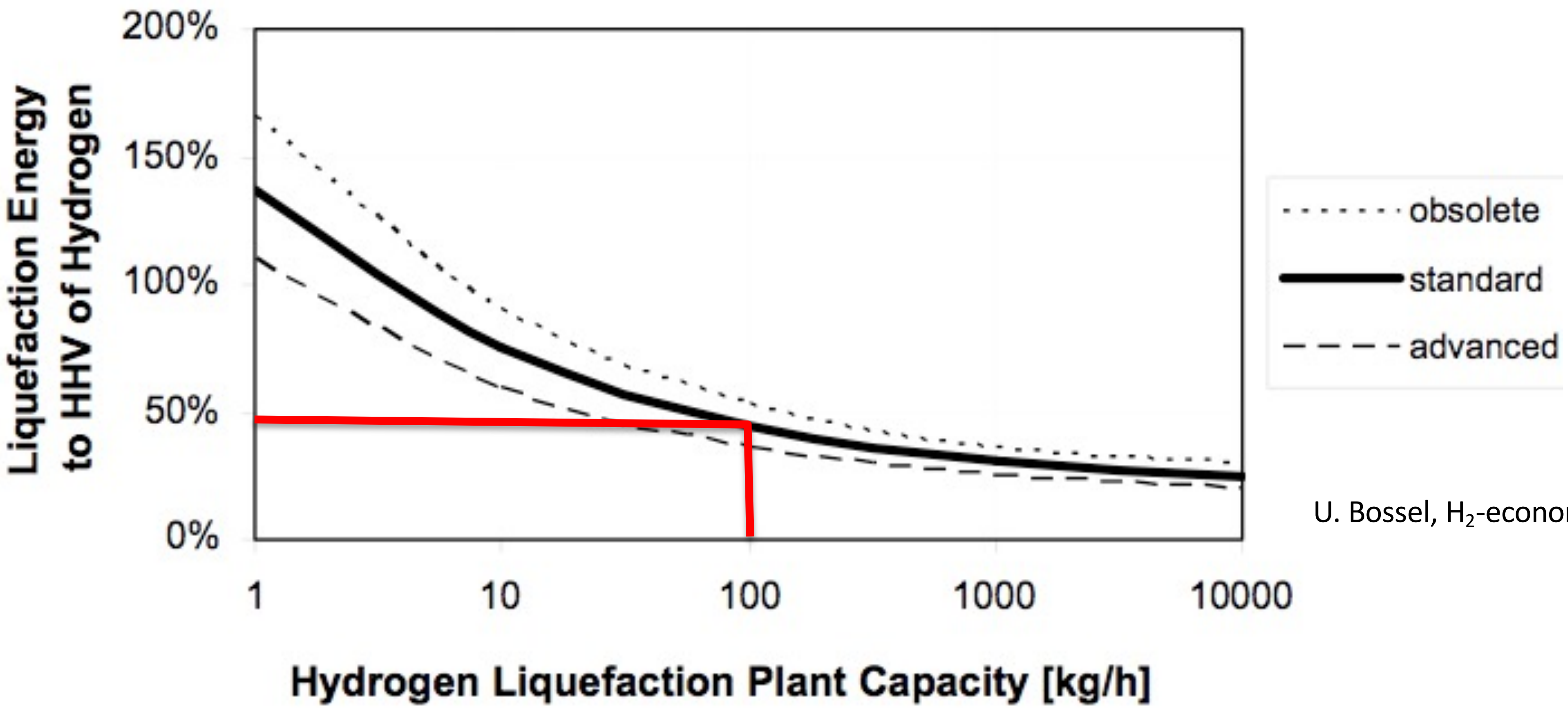
  p_0 initial pressure, p_1 final pressure, $\gamma = C_p/C_v$ (1.41 for H_2, 1.31 for CH_4)
- @200 bar (W_{ad}): for CH_4 2 MJ/kg, for H_2 **14 MJ/kg**



U. Bossel, H_2-economy

H_2 liquefaction

298 K → 20 K	MJ need per kg liquid H_2	Reference
theoretical requirement	14.2 (10% of HHV)	Carnot
usual scale	54	182 kg / h, Linde plant (D)
large scale	36	2000 kg / h, USA
ultimate scale	30-25	12000 kg/h, study case



U. Bossel, H_2-economy

Metal hydride storage
(*physically absorbed*)

- $LaNi_5$, ZrC_2 dissolve H_2 in their crystal structure, under pressure and with heat release
- equivalent to compression at 30 bar
- storage of 55-60 g H_2/L (cf. LH_2 = 70 g/L)
- hydride density = 7 kg/L

→therefore, only 1 kg of H_2 (=1 gallon or 4 L of gasoline) is stored in >100 kg of hydride!

→impossible mobile storage for vehicles

Metal hydride storage
(*chemically bound*)

- LiH, NaH, CaH_2, $LiBH_4$, $NaBH_4$, $LiAlH_4$
- fabrication: $NaCl + ½H_2O \rightarrow NaH + ½Cl_2 + ¼O_2$ 500kJ/mol at high T; then cooled, granulated, packed sealed
- release by hydrolysis: $NaH + H_2O \rightarrow NaOH + H_2$ -85kJ/mol
- in fact, water is the H_2 source
- high energy density (comparable to wood)
- 60% efficiency

Comparison H_2 storage (Linde AG)

	c-H2(g)	LH2	LOHC	MOFS	M-hydride	Complex hydrides	Salt hydrides
ρ (kg /m³)	50bar: 4 700bar:36	71	57	material-dependent	material-dependent	material-dependent	material-dependent
wt% stored	100	100	6.2	5-9 (cryo) 0.5-1 (amb.)	1.4-2 ($LaNi_5$,AB_2)	5.6 ($NaAlH_4$)	7.7 (MgH_2)
T	20°C	-253°C	150-200C ads 300C desorp.	-176°C ads. Des.:vacuum	0-30°C	70-170C ads. (20-150 bar) 100-200C des. (1bar)	250-300C ads. (10-15 bar) 300-350C des. (1bar)
Storage time	unlimited	limited (boil-off)					
Compression as % LHV	6%	22-34%	49% (if no heat avail.)	18% (if no heat avail.)		55% (if no heat avail.)	
Status	commercial	commercial	emerging	R&D		R&D	
Challenge	transport limited (low ρ)	boil-off	purity, stability weight	T_adsorpt P_desorb weight		T ads/des. P_desorb weight	
TRL	9	9	4	3	7	3-4	3-4

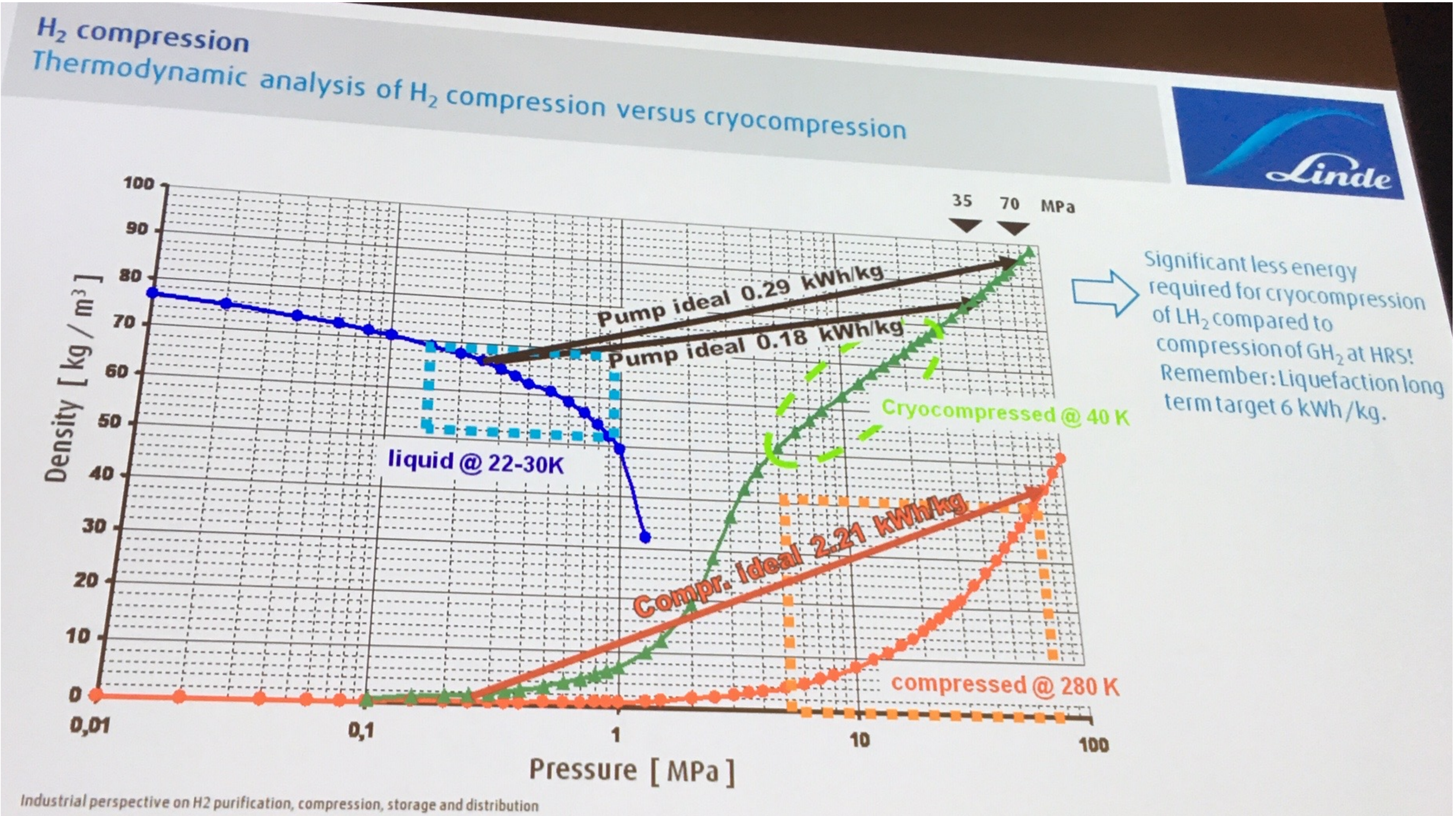
Linde AG presentation EFCF July 2019: Industrial perspective on H_2 purification, compression, storage and distribution

H_2 compression overview (Linde AG)

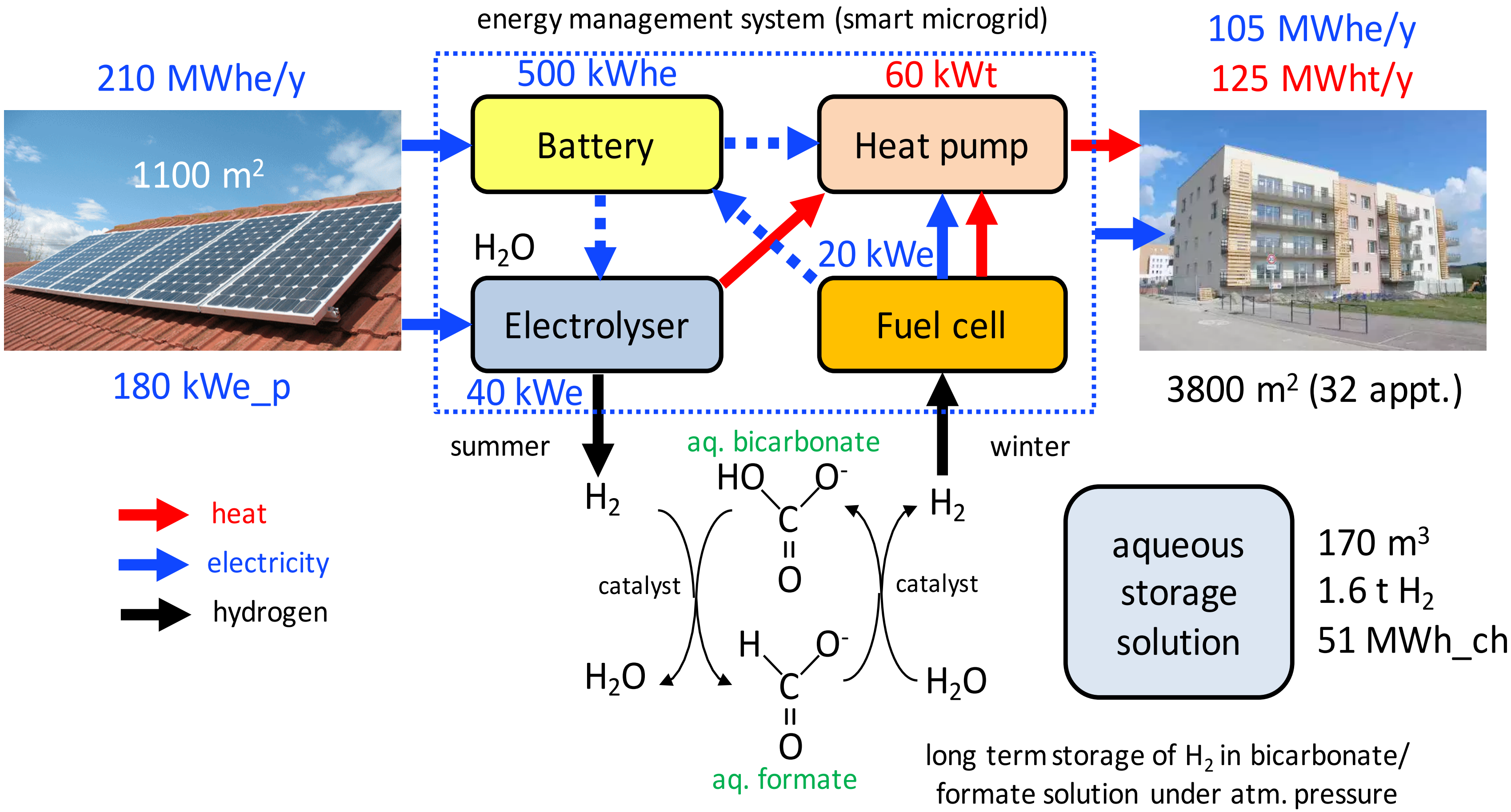
	Piston	Membrane	Screw	Electro-chemical	Metal-hydride	Ionic compressor	Turbo-compressor
Scale Nm^3/h	10 - 115000	1 - 4000	200 - 100000	5 - 280	1 - 12	750	>1000
Max P (bar)	1300	3000	55	950	250	1000	<50
TRL (H_2)	9	9	commercial	7	5-6	8	low
Advant.	availability	availability no contamination	availability low maintenance	no moving parts low OPEX	thermal no contamin. no mov. parts	efficiency no contamination	availability low mainten. high vol. flow
Disadvant.	contamination maintenance	lim. suction maintenance	contamination H2 backflow	low vol. flow R&D	low vol. flow R&D	maintenance	Δp depends on mol weight

Linde AG presentation EFCF July 2019: Industrial perspective on H_2 purification, compression, storage and distribution

New: Cryocompression (Linde AG)



Seasonal H_2 storage via formate cycle



Hydrogen Distribution

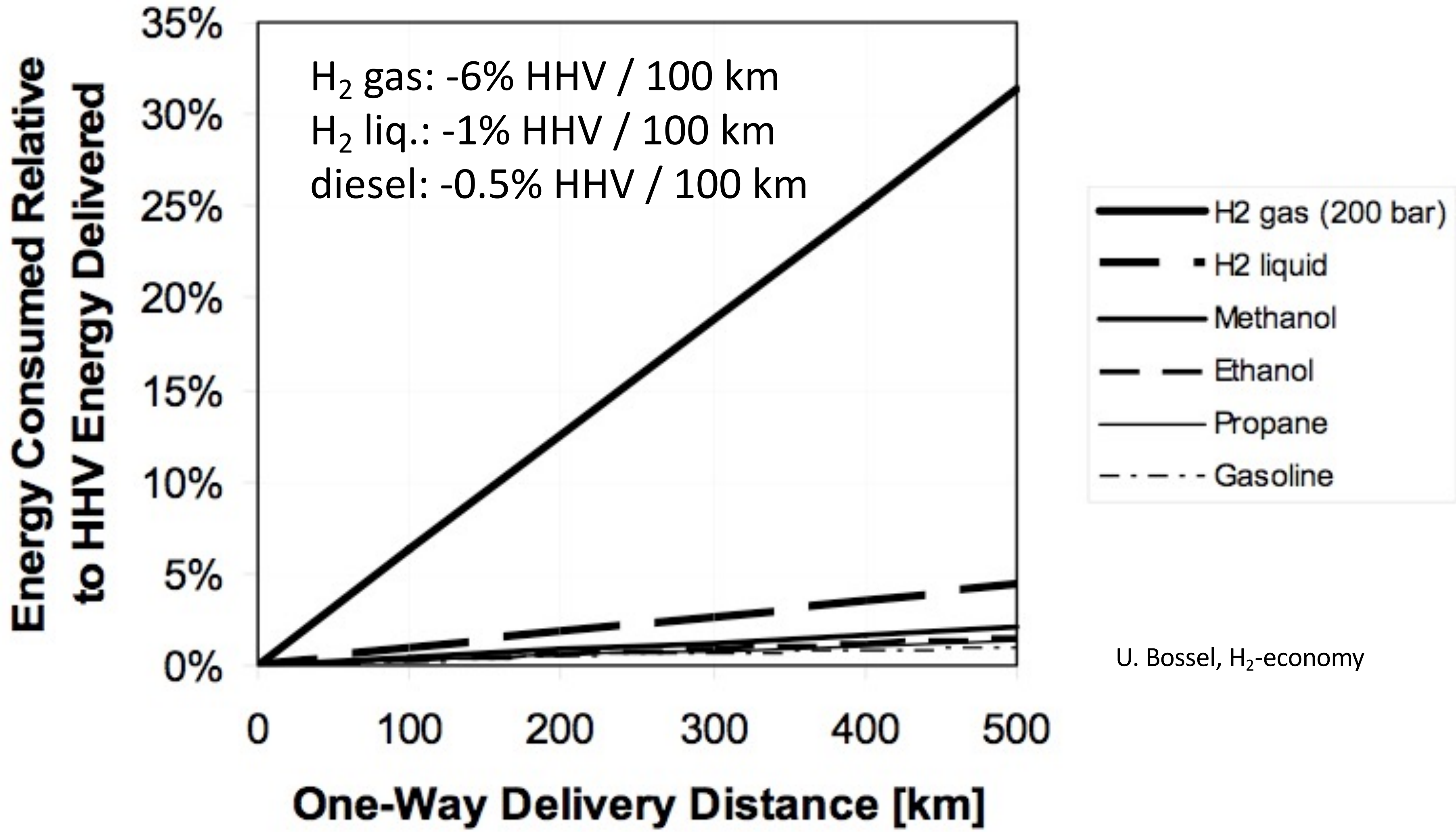
1. by road (delivery trucks)
2. by pipeline
3. by on-site generation (electrolysis) at filling station

H_2 distribution – vehicles (Linde AG)

Vehicle	H_2 kg/day	Number of vehicles supplied			
		$cH_2(g)$ truck	LH_2 truck	LH_2 plant 5 tpd	LH_2 plant 50 tpd
car	0.4	2500	8750	12500	125000
bus	30	33	117	167	1667
truck	100	10	35	50	500
train	250	4	14	20	200
ship	2000	0.5	1.75	2.5	25
large ship	10000	0.1	0.35	0.5	5

Linde AG presentation EFCF July 2019: Industrial perspective on H_2 purification, compression, storage and distribution

1. By road transport



U. Bossel, H_2-economy

2. Onsite electrolysis => exercise

- Q: How big an electrolyser is needed to produce the daily amount of H_2 for a filling station (HRS), under the following assumptions?:
  - 1000 cars/day, equivalent of 50 L gasoline/car (LHV_gasoline: 33MJ/L
  - car average consumption : 7L/100km
  - a FCEV consumes 1 kg H_2/100km (HHV_H_2 : 142 MJ/kg)
  - electrolyser efficiency 78% HHV
  - compression energy needed to 400 bar
  - the electrolyser operates 50% of the time

3. By pipeline

- NG pipelines are **<u>not</u>** fully **<u>compatible</u>** for H_2 use (diffusion loss, brittleness, compressor,…)
- energy carried: $Q(W) = V(m^3/s).\rho(kg/m^3).HHV(MJ/kg) =$ section $A (m^2)$*flow $f(m/s).\ \rho(kg/m^3).HHV(MJ/kg)$
- with $\rho_{CH4}=0.71$ vs $\rho_{H2}=0.09$, and $HHV_{H2}=142$ vs $HHV_{CH4}=53$, the H_2-velocity has to be 3.1 times higher
- pumping power $P(W)=A.f.\Delta p=A.f.½(L/D)\rho f^2\zeta$
- ratio $P_{H2}/P_{CH4}=(\rho_{H2}/\rho_{CH4}).(f_{H2}/f_{CH4})^3=(0.09/0.71).(3.1)^3 = 3.85$
- $f_{CH4}=10m/s$, one compressor every 150 km consumes ca. 0.3% of the passing energy stream

  → for H_2,ca. 0.3%*3.85 = 1.16%

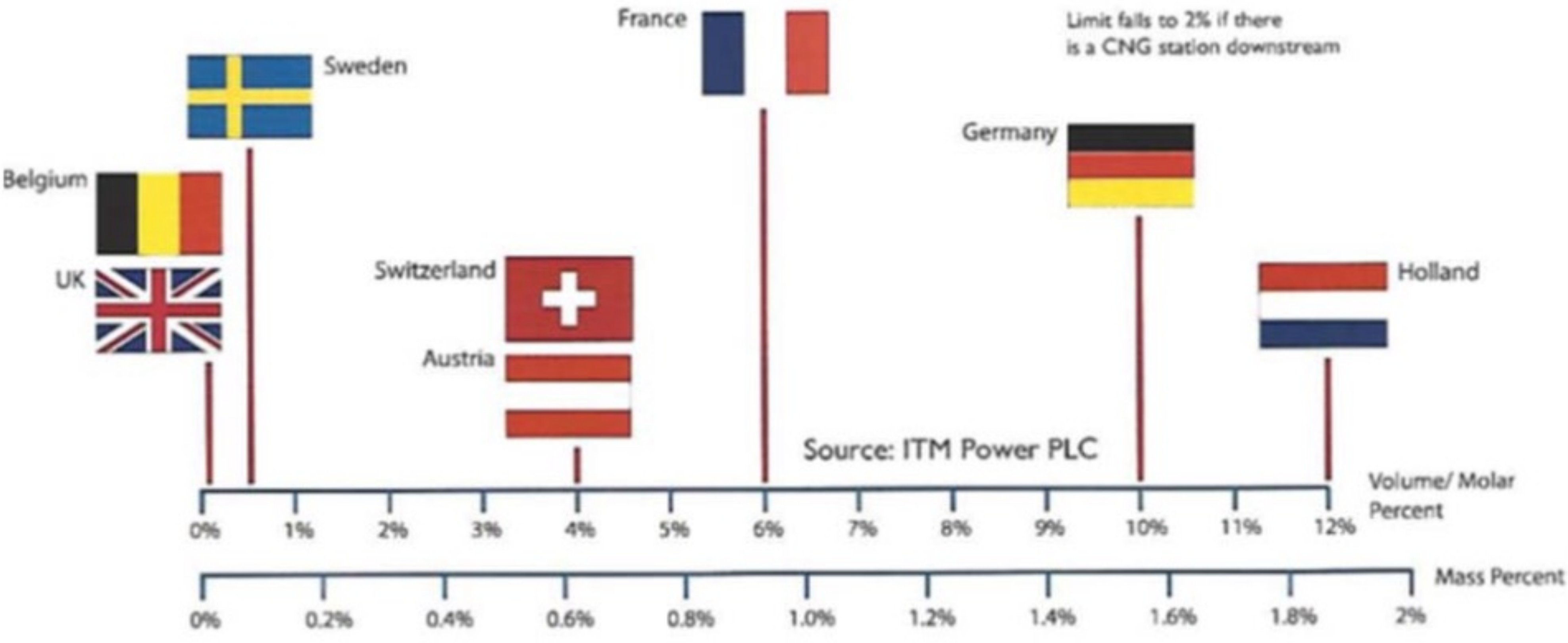


Figure 34: Hydrogen injection limit in national gas networks [71]

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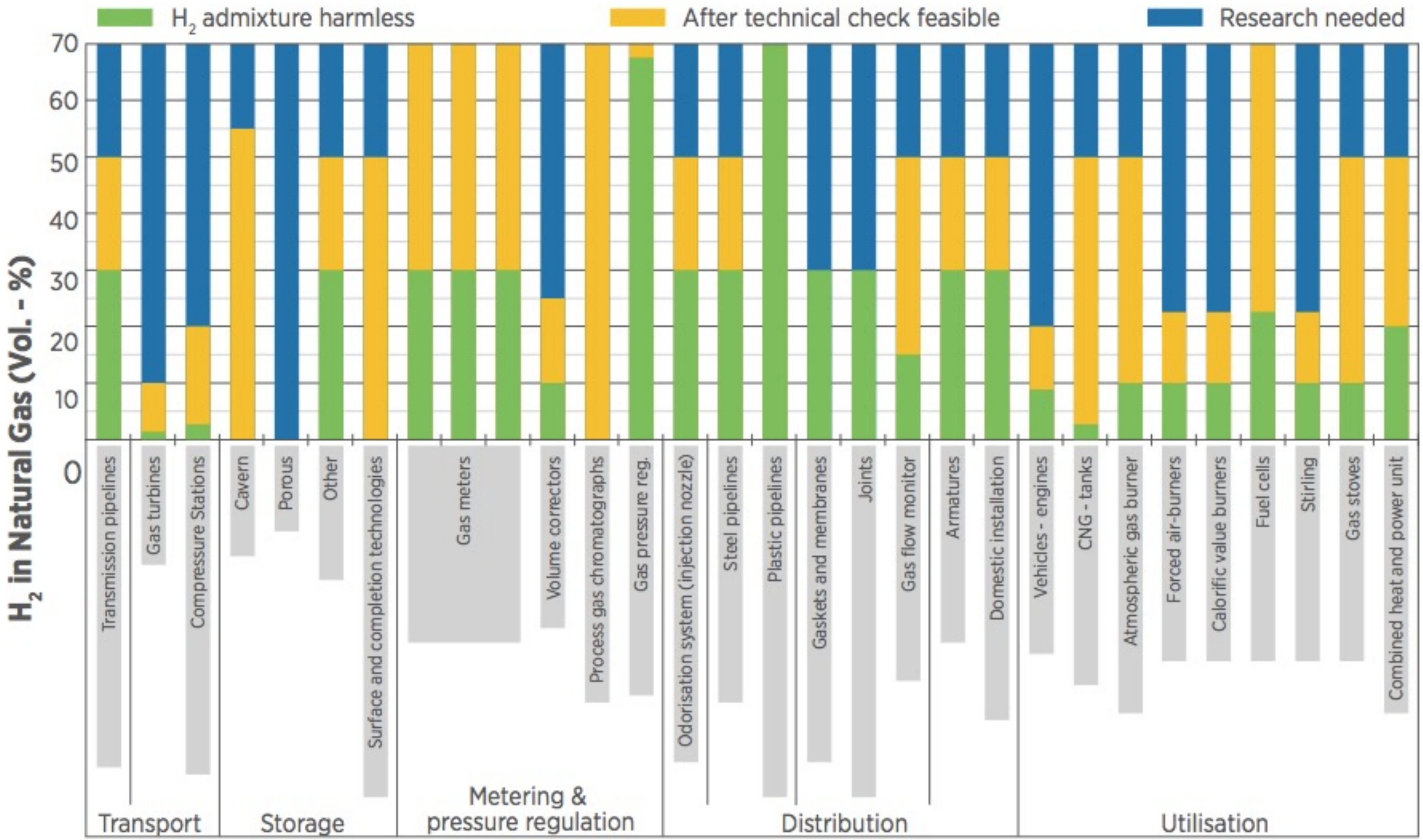
Figure 16: Hydrogen tolerance of gas infrastructure components

IRENA Report 2018 p39



European Gas network

Vested infrastructure
42% of buildings heated by NG
112 million households

<u>Consumption</u>: 5375 TWh
(23% of energy)
<u>Storage</u>: 1200 TWh

= large reserve for injection of
H_2 (and green methane)

Eurogas Statistical Report 2018

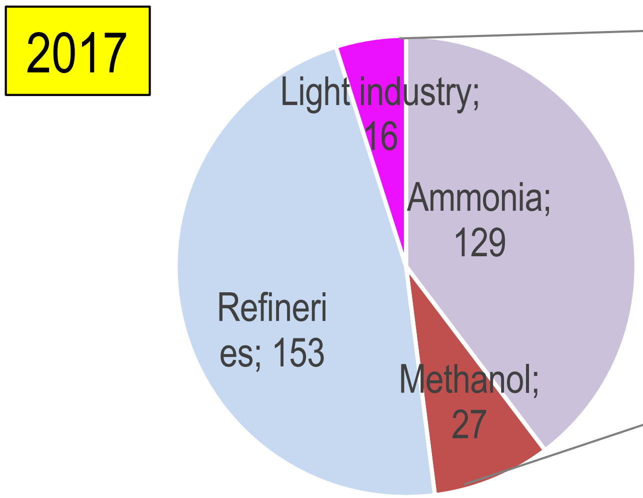
Green Hydrogen for a European Green Deal : 2x40 GW Initiative (January 2020, FCHJU)

- H_2 transport by pipeline (15-30 GW) is 10-20x cheaper than electricity transport by cable (1-2 GW); a pipeline adds only 0.2€/kgH_2 to the cost
- Capacity of the gas grid is >10x larger than of the electricity grid
  - e.g. NG pipeline Libya-Algeria-Italy-Spain = 60 GW
  - e.g. electricity line Morocco-Spain = 0.7 GW
- Natural gas is stored in large quantities in empty gas fields, porous rock formations and salt caverns (200bar). About 15-20% of the total gas consumption is stored to balance gas production and consumption
- 40 GWe H_2 in EU 2030 = 4.4 MtH_2 = 173 TWh
- Additional 100-150GWe in PV/wind are expected

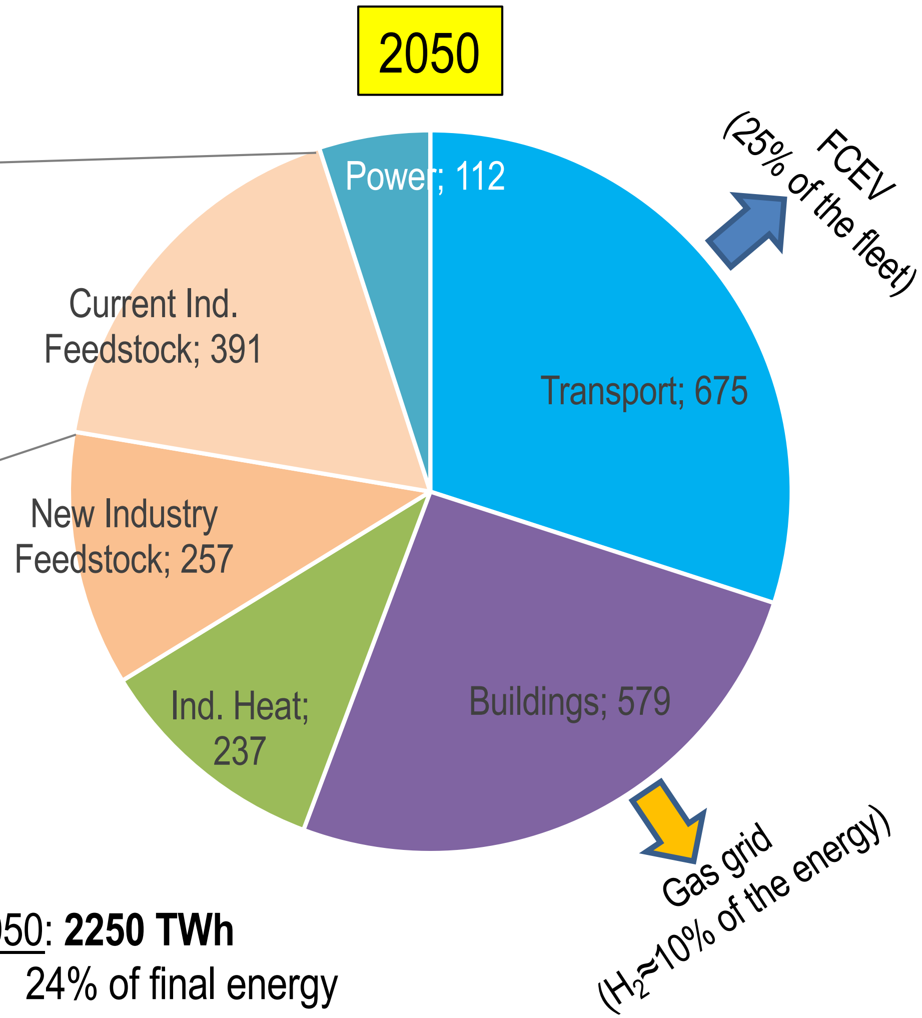
Green Hydrogen for a European Green Deal :
2x40 GW Initiative (January 2020, FCHJU)

Figure 7 *European Transnational Hydrogen Backbone - The natural gas infrastructure in Europe (blue and red lines) and an outline for a hydrogen backbone infrastructure (orange lines). The main part of the hydrogen backbone infrastructure consists of re-used natural gas transport pipelines with new compressors. A "new" hydrogen transport pipeline must be realised from Italy to Greece and from Greece to the Black See, also along the South Coast of the Iberian Peninsula a dedicated hydrogen pipeline has to be realised.*

H_2 roadmap (EU) - TWh



Investment:
8 b€ / yr



x 7

Production H_2 in 2017: **325 TWh**

- 2% of final energy
- only in industry (chemical, petro)
- H_2 from fossil sources

(electrolysis would need 55 GWe equivalence)

2050: **2250 TWh**

- 24% of final energy
- multiple uses

(equivalent electrolysis : **385 GWe)**

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

fch.europa.eu - January 2019

Example: oil refinery

https://refhyne.eu/

Rheinland refinery (Shell) (D)

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

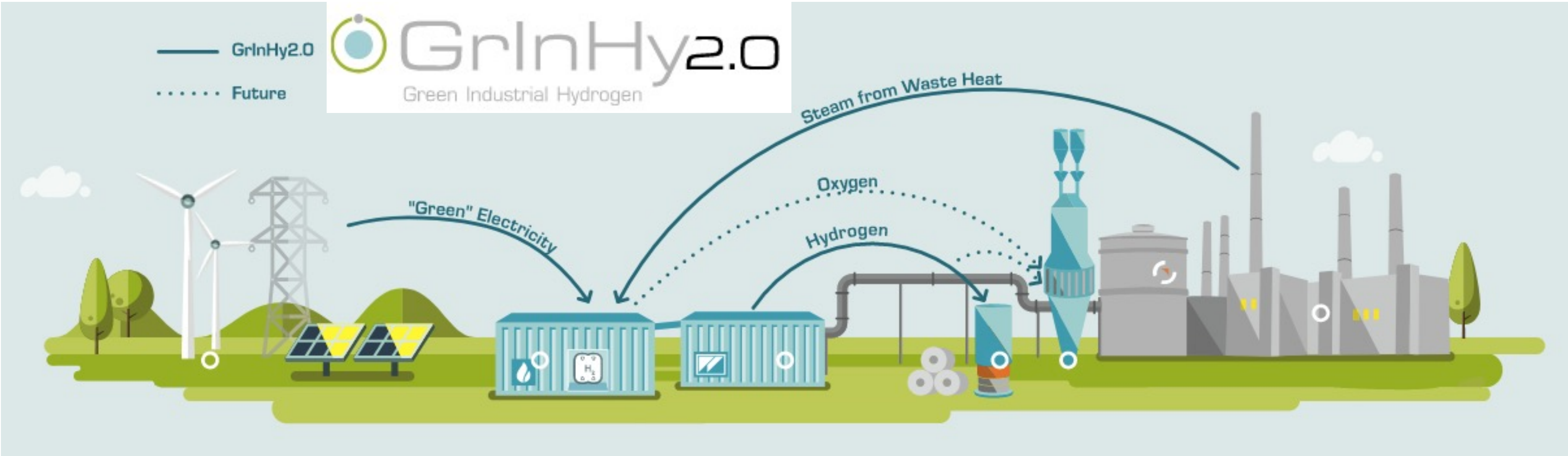
10 MWe PEM-electrolyser:
=> supplies **1300 t H_2** / yr (<1% !!)

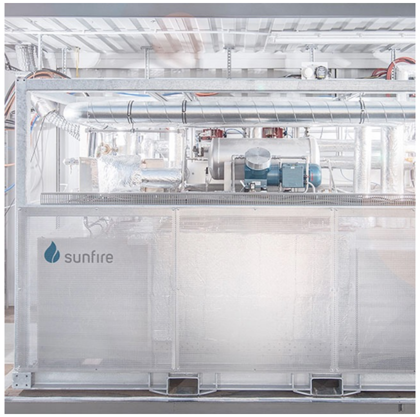
REFHYNE CLEAN REFINERY HYDROGEN FOR EUROPE 2018-2022

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING 10 M€

Example: steel industry

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





2016 - 2022

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

4.5 M€

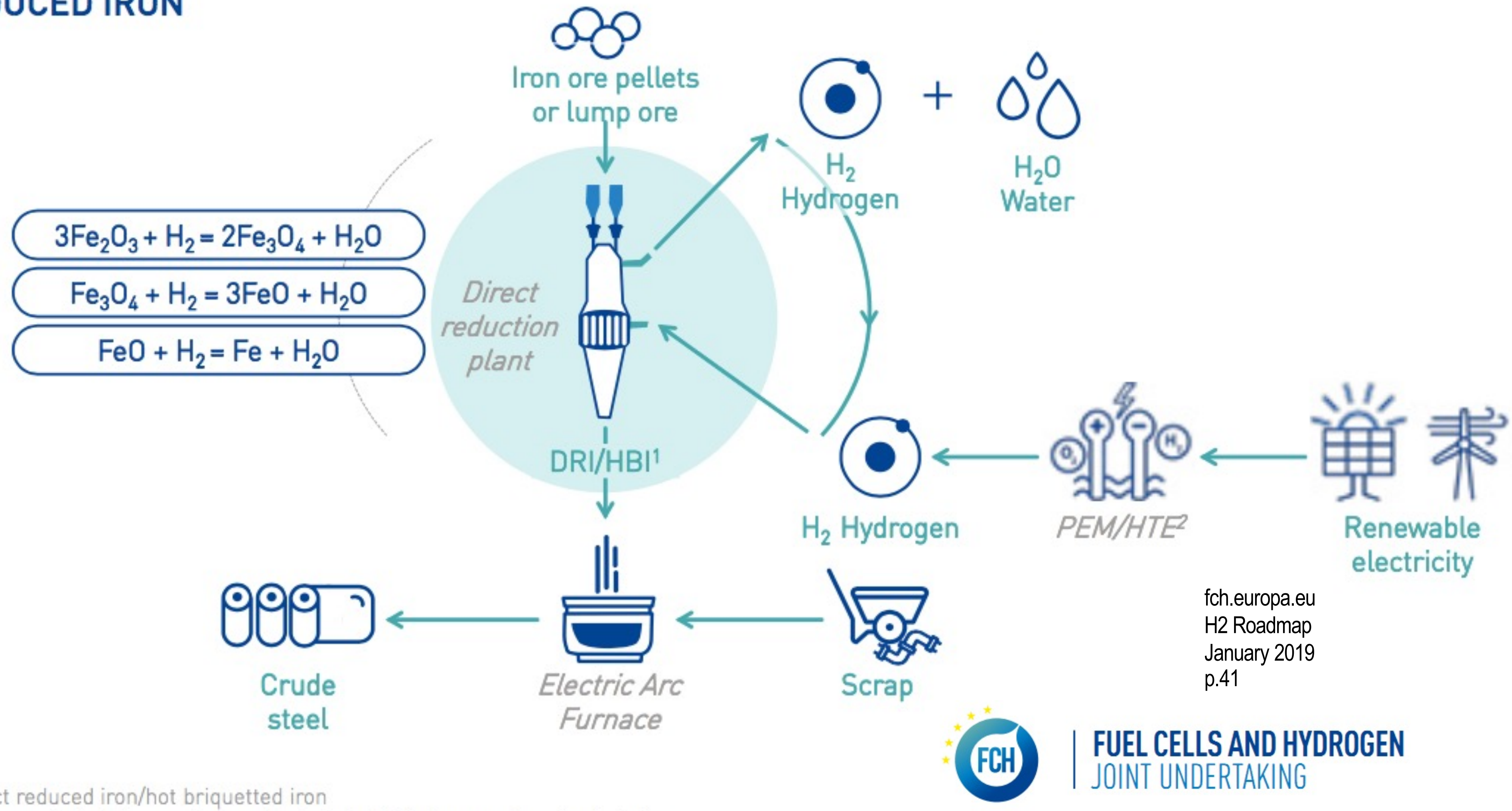
720 kWe solid oxide steam electrolyser

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

100 t H_2 @ < 7€/kg

H_2 for steel making : DRI

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



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1 Direct reduced iron/hot briquetted iron
2 Polymer electrolyte membrane electrolysis/high temperature electrolysis

H_2 and electric mobility

- **Mobility** consumes ⅓ of primary energy and is a bigger bottleneck (fossil resource: gasoline, diesel, kerosene) than **electricity** demand (¼ of primary energy), for which many renewable sources exist, and **heating** demand (≈40% of primary energy), which has enormous saving potential
- biofuels cannot cover, by far, the current demand

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

Fuel Cell Electric Vehicle: battery car with H_2 range extension

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

More remarks on E-mobility

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

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

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

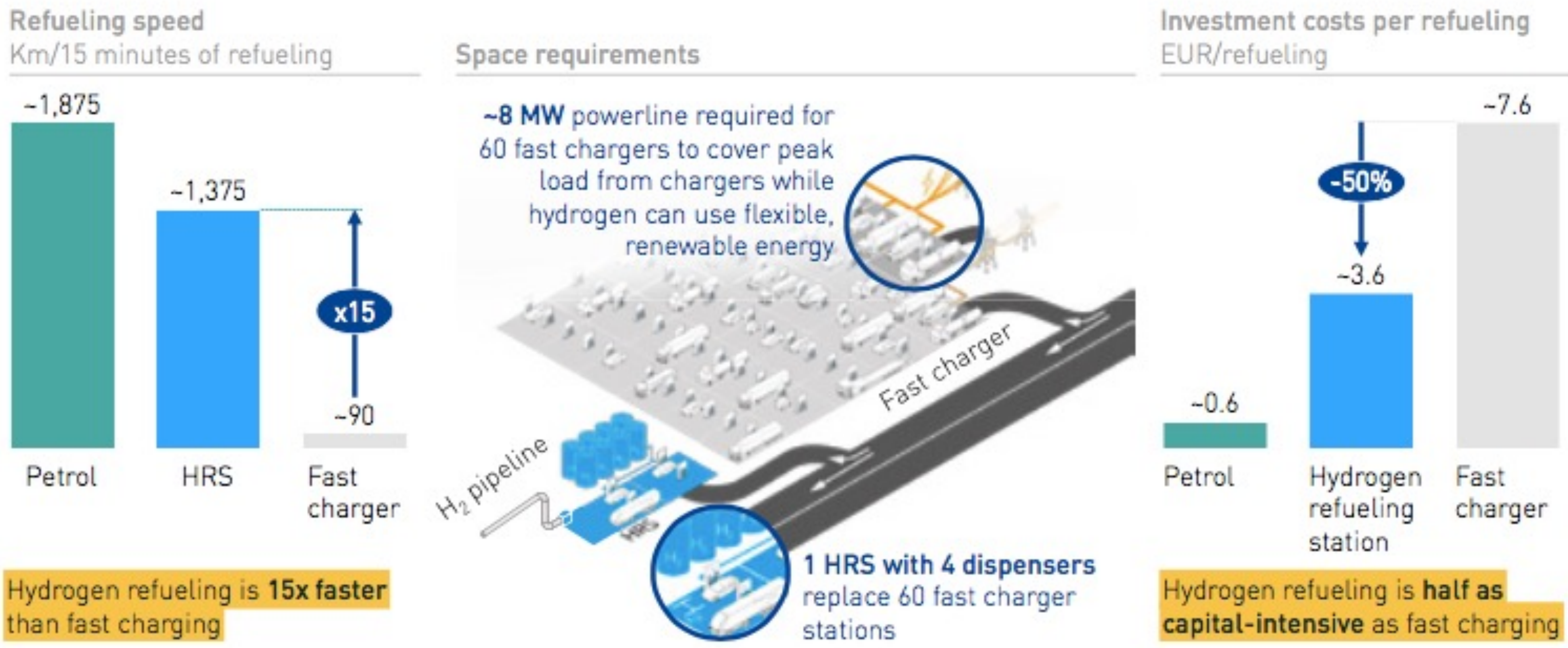
HRS discharge the electrical grid when needed (electrolysis of exces renewables); fast battery charge stations always increase the demand on the grid.

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

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

Supply infrastructure: H_2 vs. battery

EXHIBIT 11: IMPLICATIONS OF REFUELING SPEED ON SPACE REQUIREMENTS AND INVESTMENTS



Assumptions: Average mileage of passenger car = 24,000 km; number of PCs in EU in 2050: ~180 million; ICE: range = 750 km/refueling, refueling time = 3 minutes; FCEV: range: 600 km/refueling, refueling time = 5 minutes, fast charger = 1,080 km²; BEV: range = 470 km/refueling, refueling time = 75 min, gas station = 1,080 m²; WACC 8%; fast charger: hardware = USD 100,000, grid connection = USD 50,000, installation costs = USD 50,000, lifetime = 10 years; HRS: capex (1,000 kg daily) = EUR 2,590,000, lifetime = 20 years, refueling demand/car = 5 kg; gas: capex = EUR 225,750, lifetime = 30 years, 1 pole per station

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Future H_2 refueling stations (HRS)

EXHIBIT 21: FUTURE HRS REQUIREMENT

Required large HRS[1], number

AMBITIOUS SCENARIO

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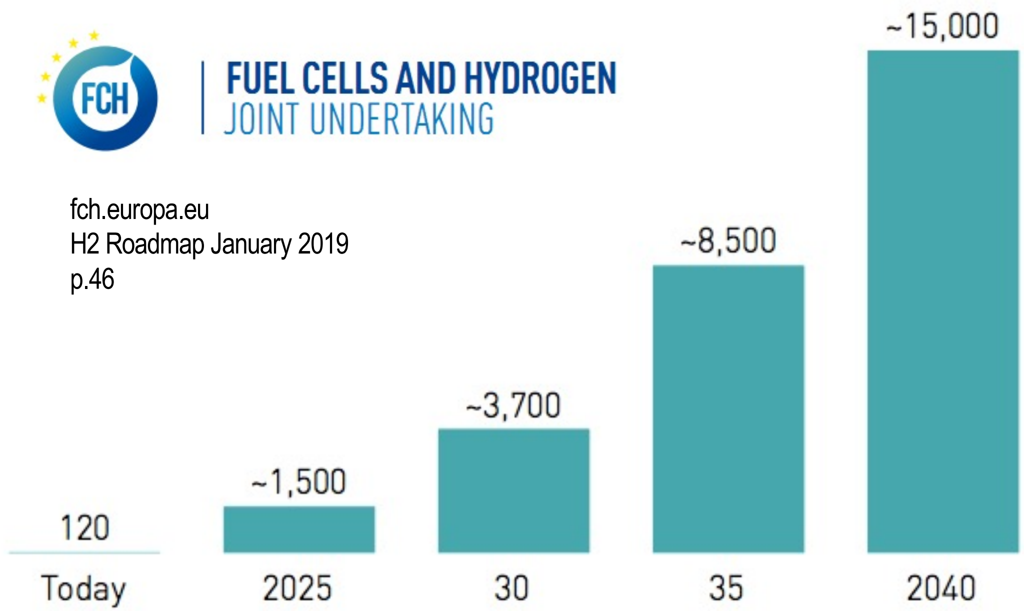
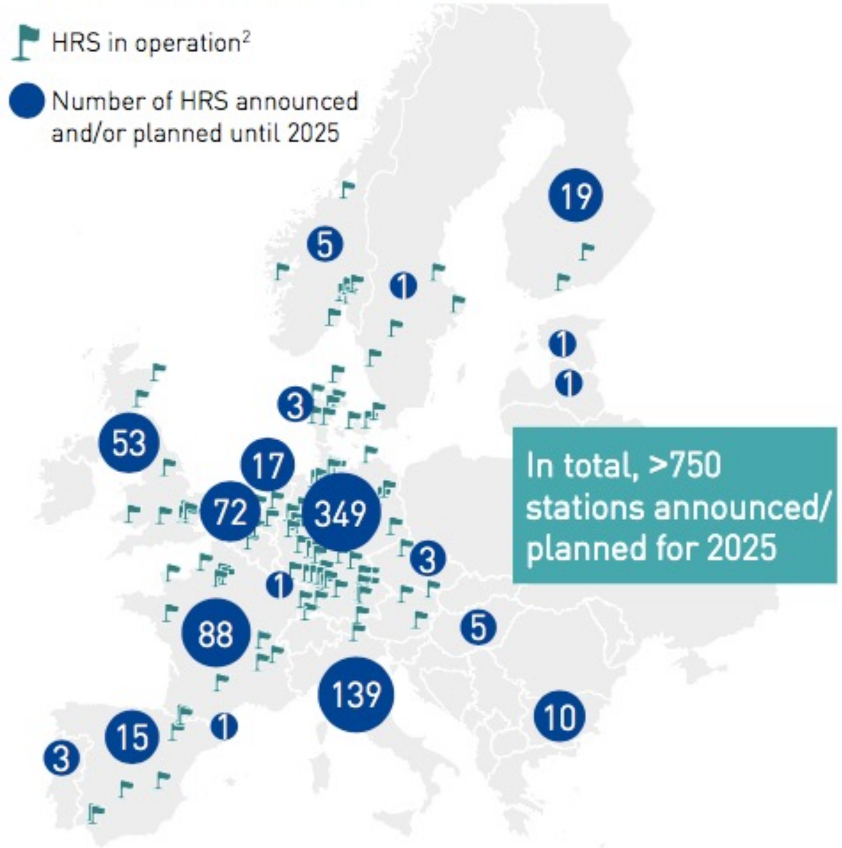


Cumulative investment need, EUR billions

	3.5	8.2	17.0	27.5

Current and planned HRS in Europe



1 Equivalents of medium HRS (1,000kg daily capacity); utilization relative to steady-state 2 Indicative position

Status of H_2 fuel cell vehicles

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

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

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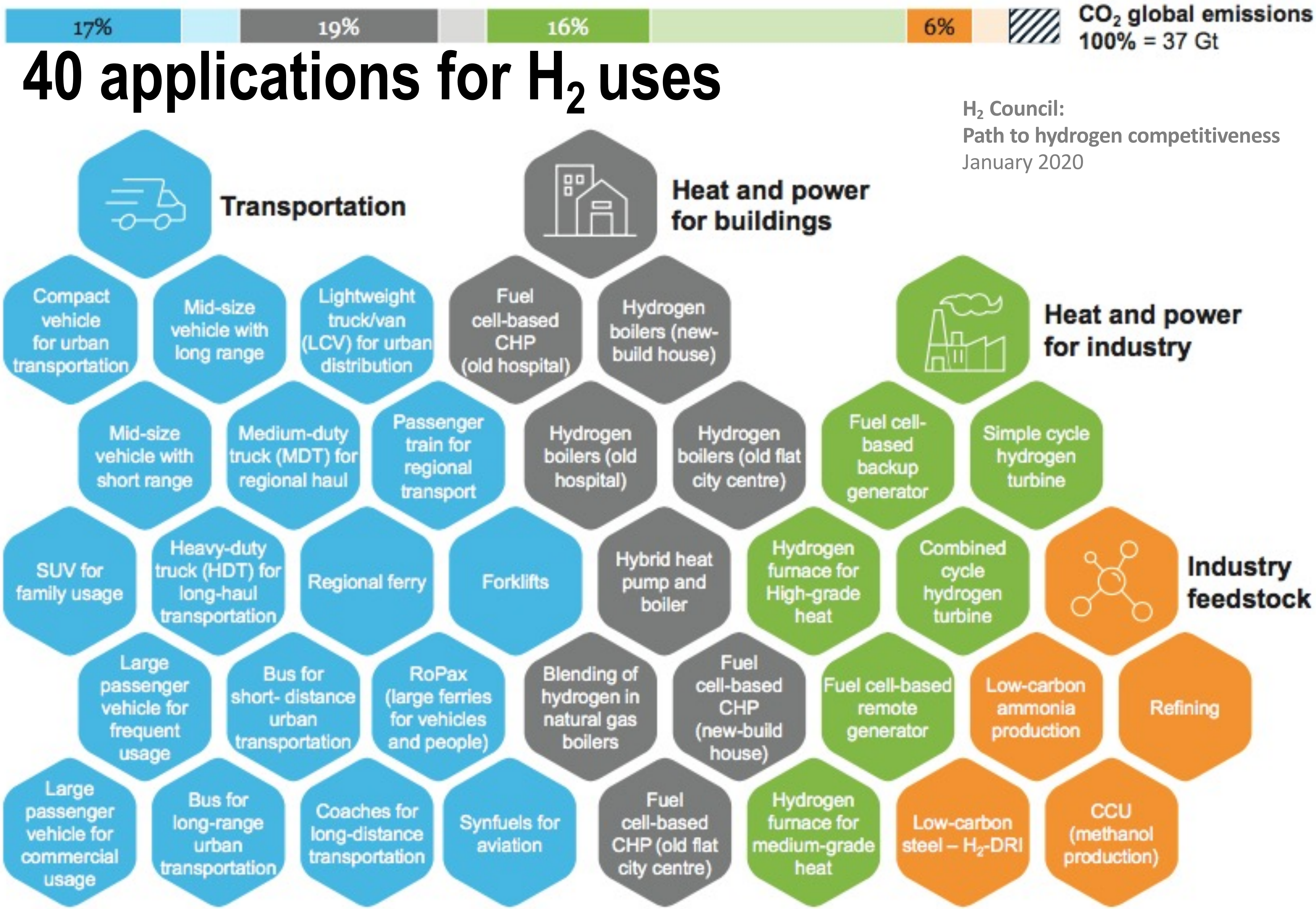
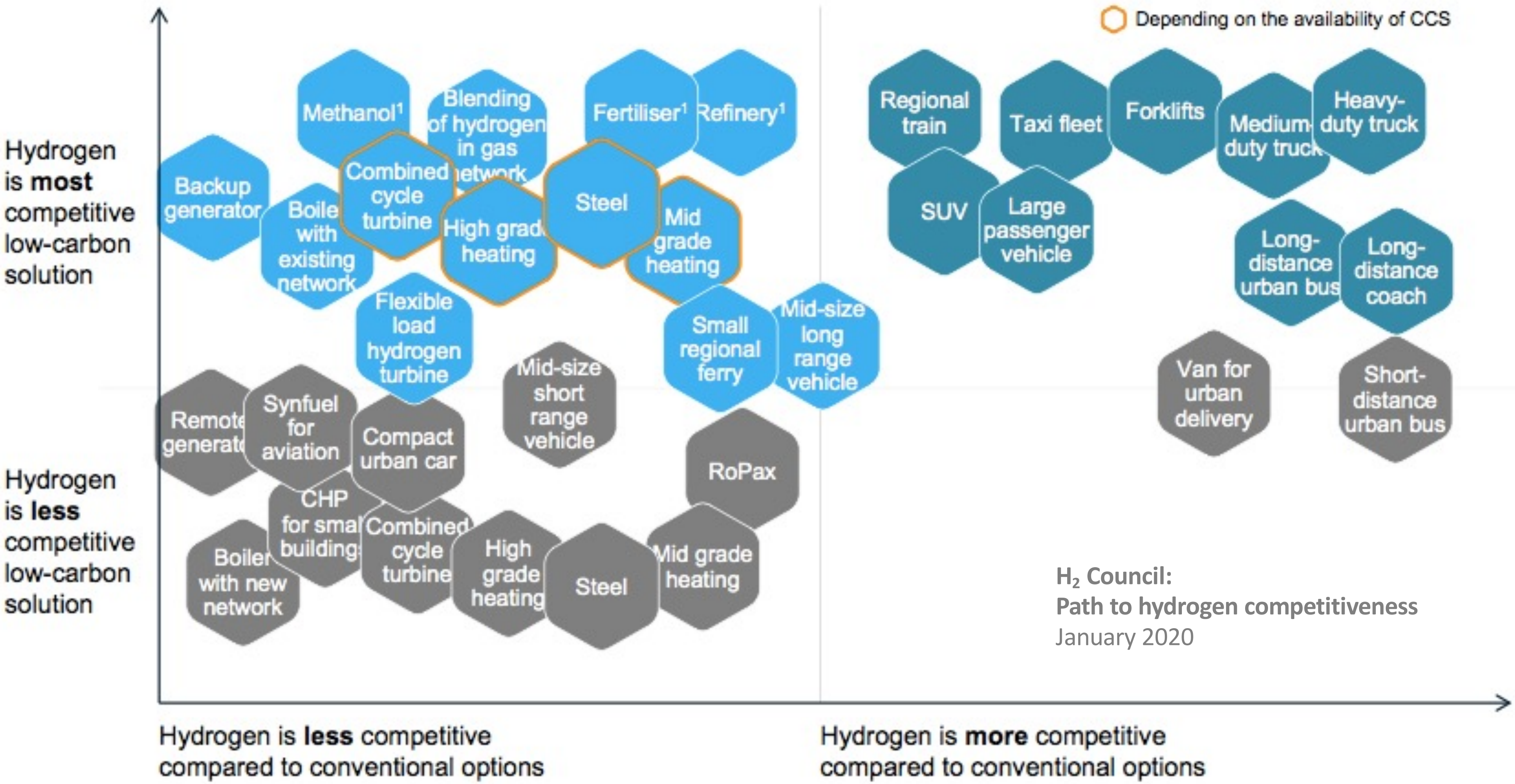
40 applications for H_2 uses

H_2 **Council:**
Path to hydrogen competitiveness
January 2020



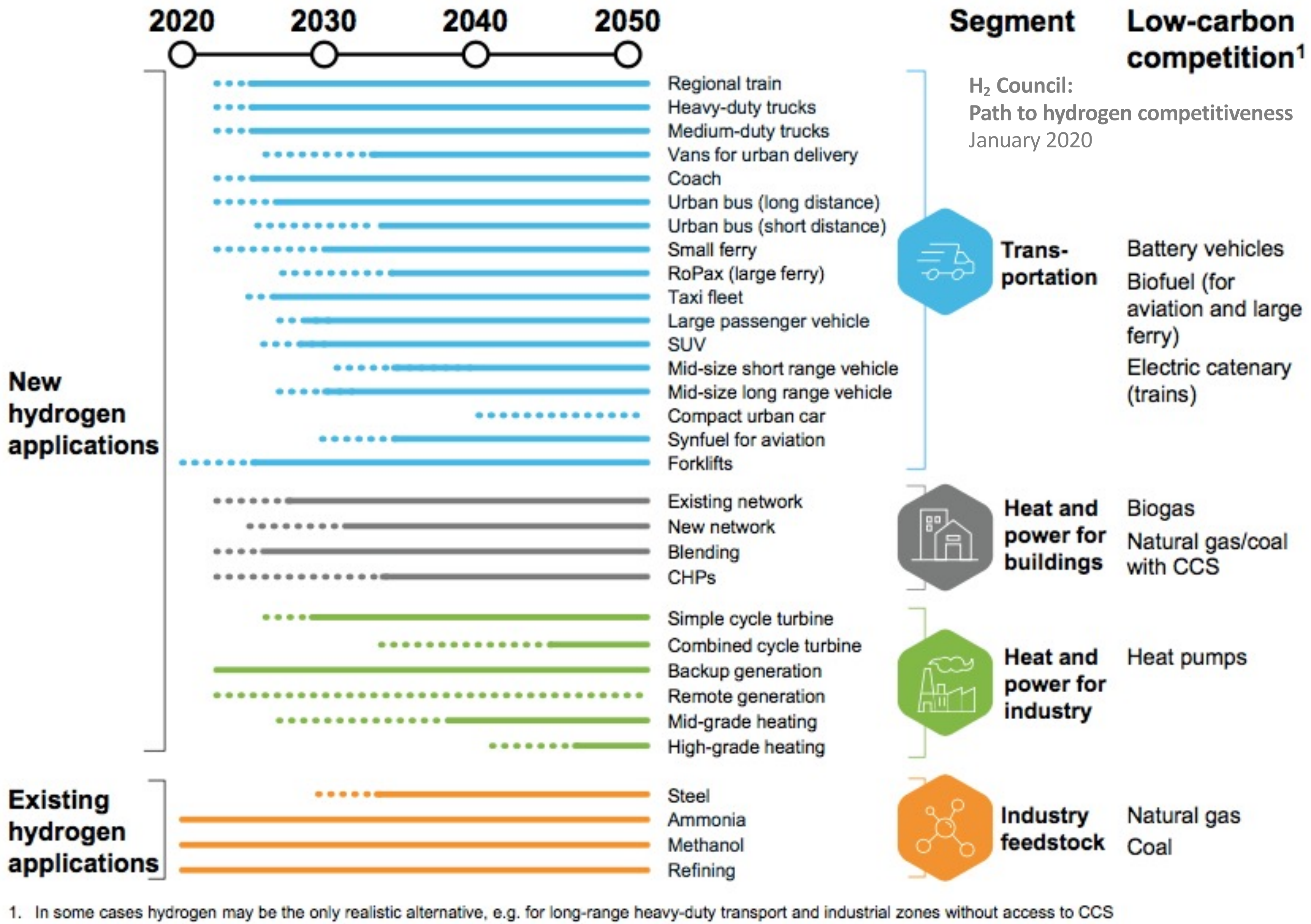
Competitiveness of H_2 as low-carbon solution



H_2 Council:
Path to hydrogen competitiveness
January 2020

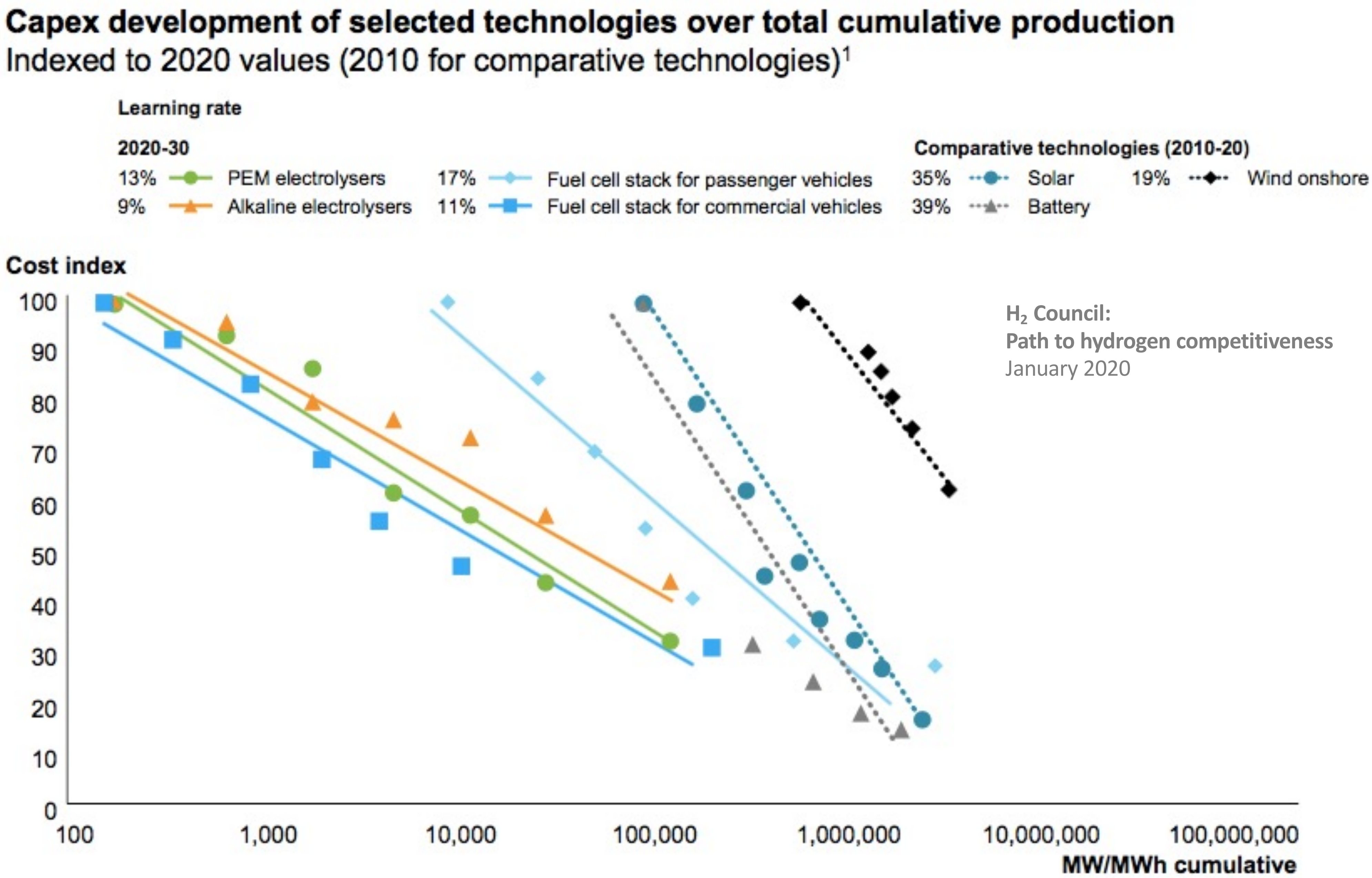
1. Hydrogen is the only alternative and low-carbon/renewable hydrogen competing with grey (optimal renewable or low-carbon shown)

Timeline



H_2 Council:
Path to hydrogen competitiveness
January 2020

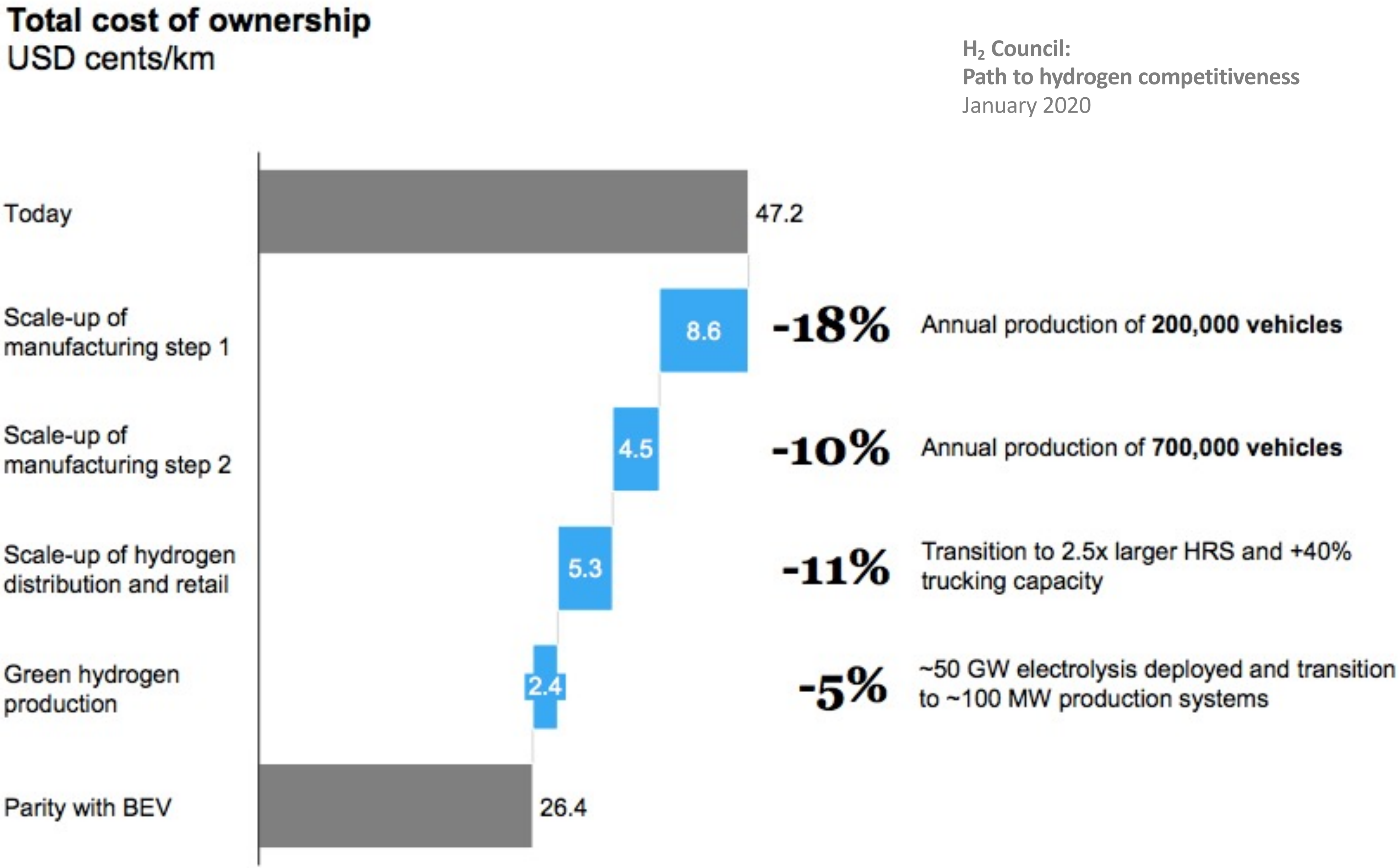
Massive scaling is key. Learning curves.



H_2 Council:
Path to hydrogen competitiveness
January 2020

Parity of FCEV with battery-EV

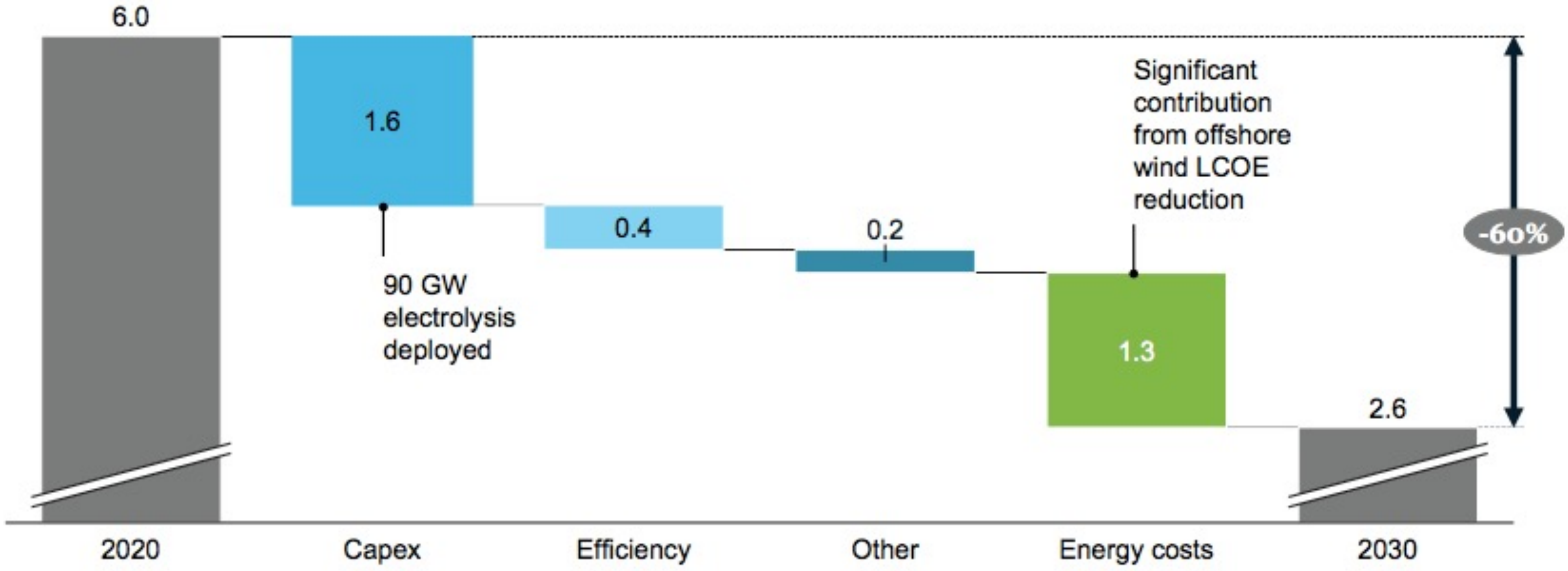
H$_2$ Council:
Path to hydrogen competitiveness
January 2020



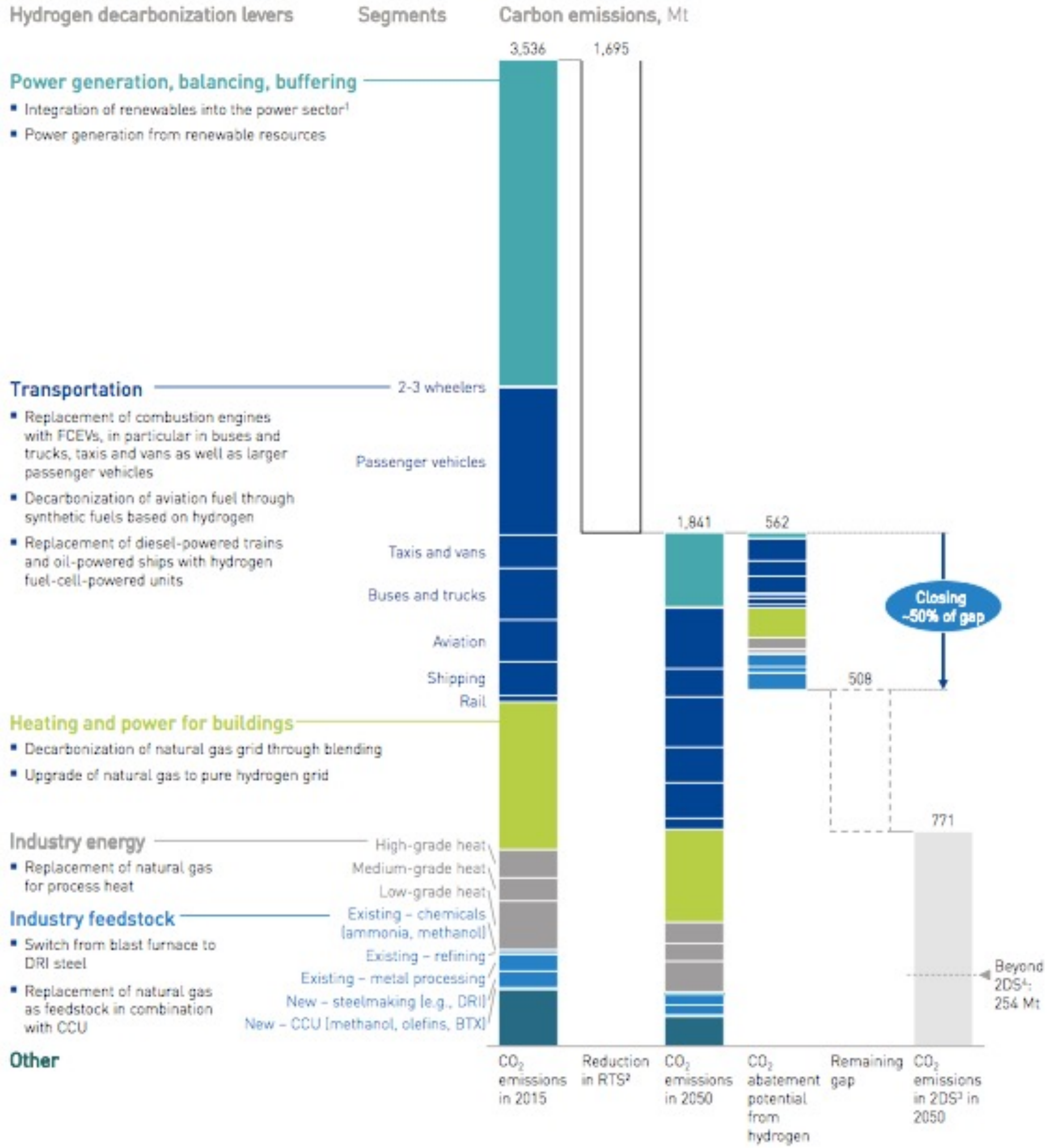
H_2 cost reduction path from 6$/kg → 2.6 $/kg

Cost reduction lever for hydrogen for electrolysis[1] connected to dedicated offshore wind in Europe (average case)
USD/kg hydrogen

H_2 Council:
Path to hydrogen competitiveness
January 2020



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

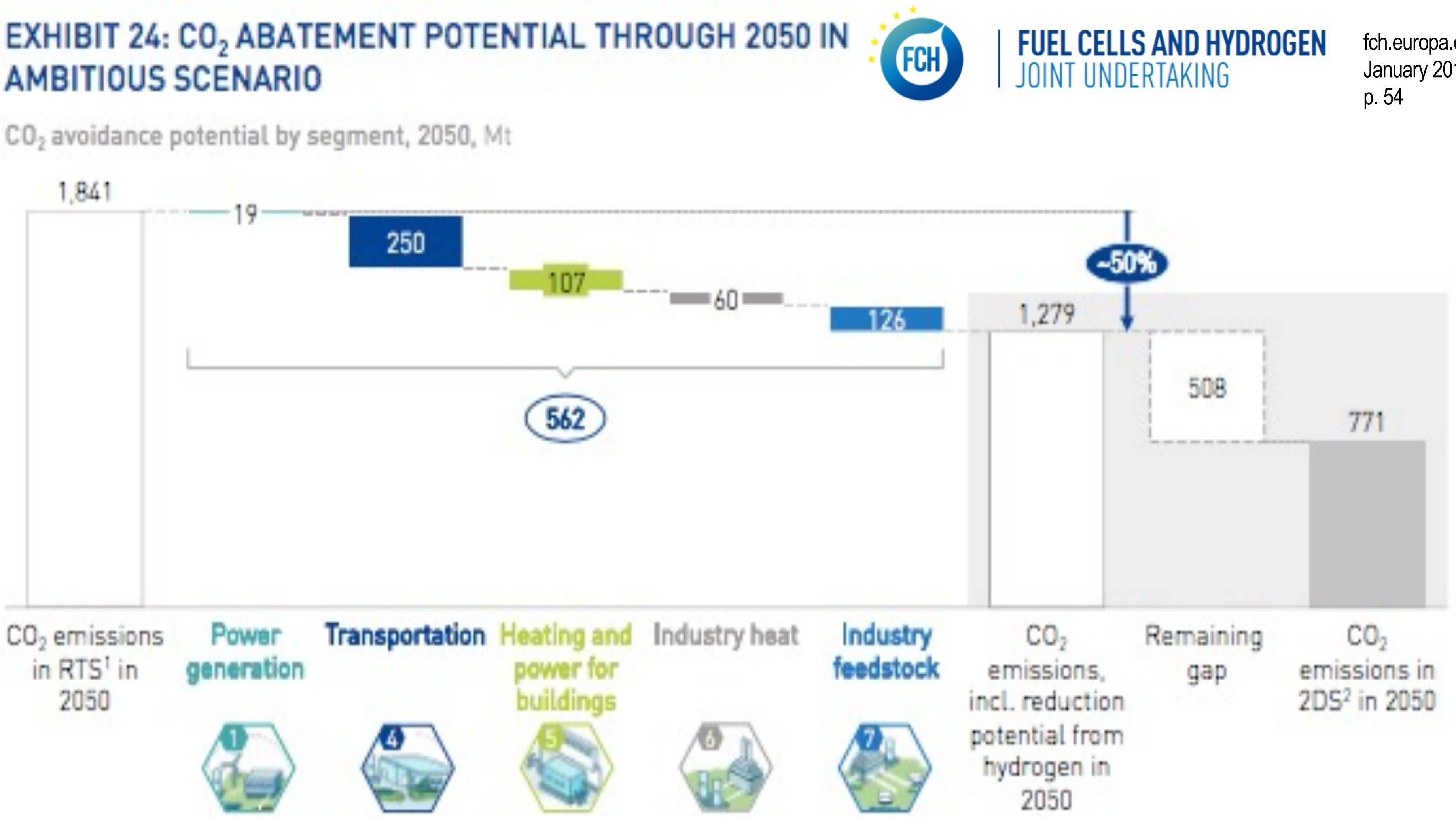


Associated CO_2 emissions reduction

fch.europa.eu
January 2019

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Associated CO_2 emissions reduction



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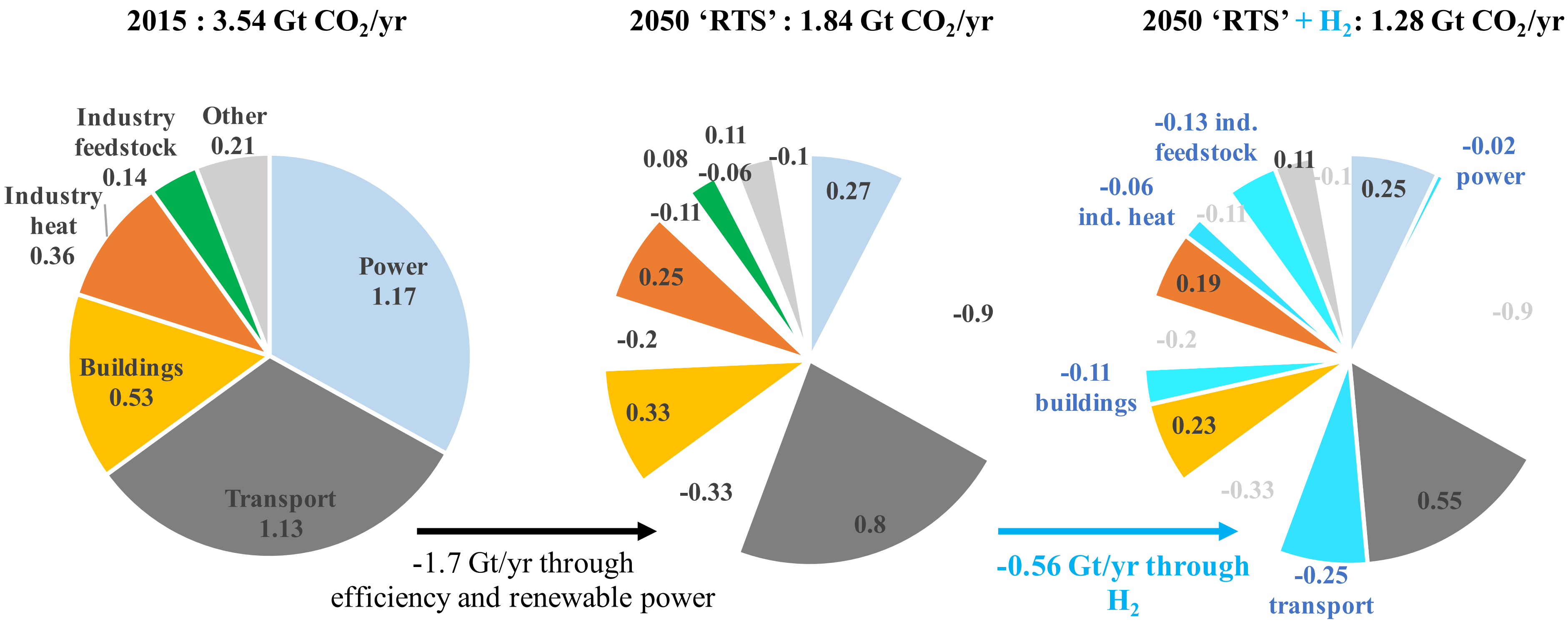
H_2 will decarbonize energy supply and heavy industry



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

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

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

- existing (EU): ≈2 GWe
- 66.7% efficiency = **1.88V** electrolysis voltage (100% = 1.25 V)
- suppose: **1A/cm²** current density
  => 1.88 W/cm² absorbed electroc power density
- for 385 GWe we then need 385.10⁹ W / 1.88 Wcm⁻² = 205.10⁹ cm² = 20.5 km² membrane surface ; 0.6 km³ water consumption
- *Swiss Lake of Murten : 22.8 km²; 0.6 km³ volume*
- membrane of 50 μm thick, density ≈ 1 => 20. 10⁶ m² x 50. 10⁻⁶ m = 1000 m³ = 1000 tons
- compare this to the annual plastics production (polymers) = 330 Mtonnes / yr

Example from the aluminium-industry

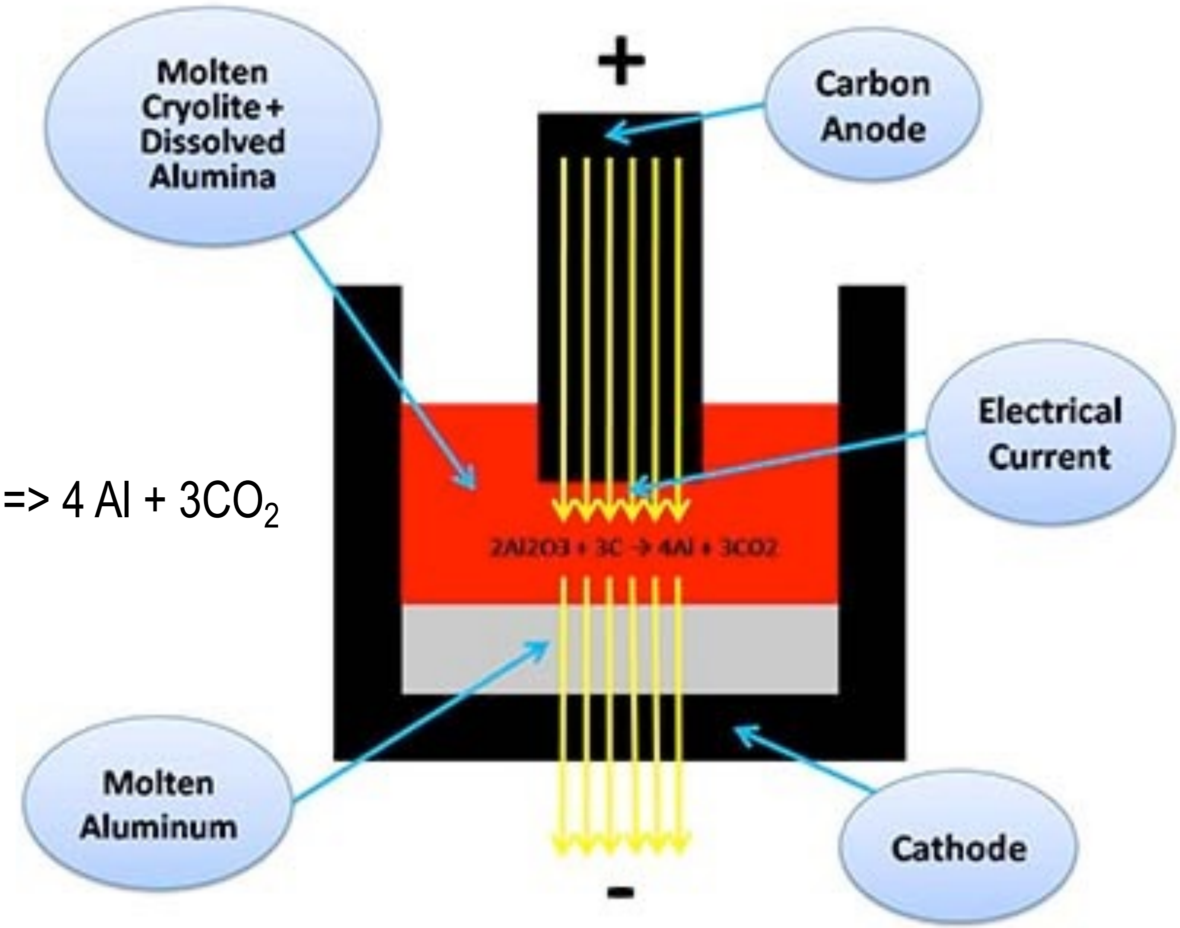
Hall-Héroult Process (1886)

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

=> 960 TWhe (≈ 110 GWe)

(≈4% of world electricity)

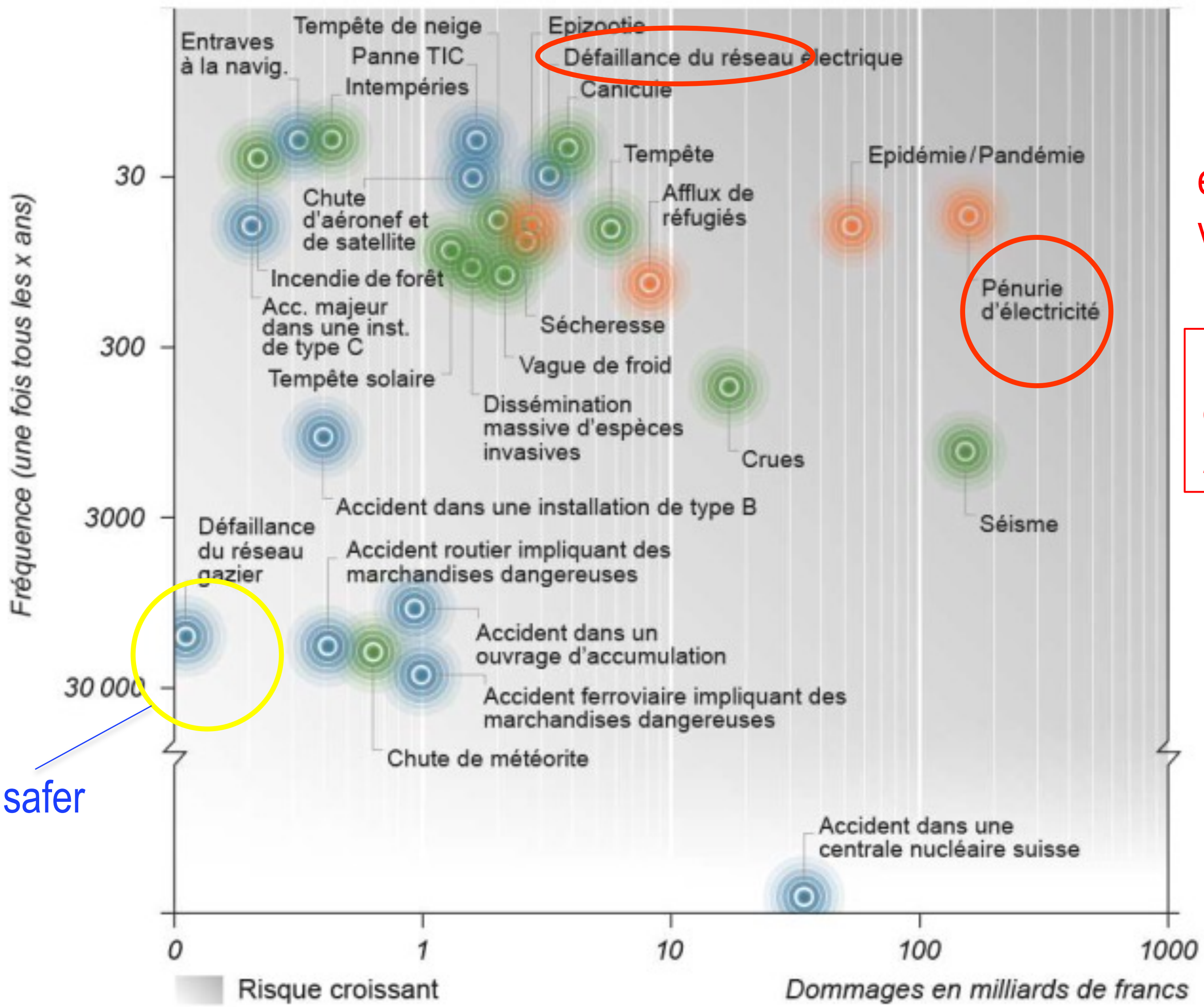
$2\,Al_2O_3 + 3C \Rightarrow 4\,Al + 3CO_2$



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

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

=> Strategic vision:

Electrolysis from hydro-power plants (Switzerland: 600 installations > 300kWe and 180 installations >10MWe)

This vision applies to:

⇒ PV + electrolysis

⇒ Wind + electrolysis

⇒ Biogas + electrolysis

⇒ compatible with H_2 mobility