UCLouvain

Waterstof en (grootschalige) energie-opslag

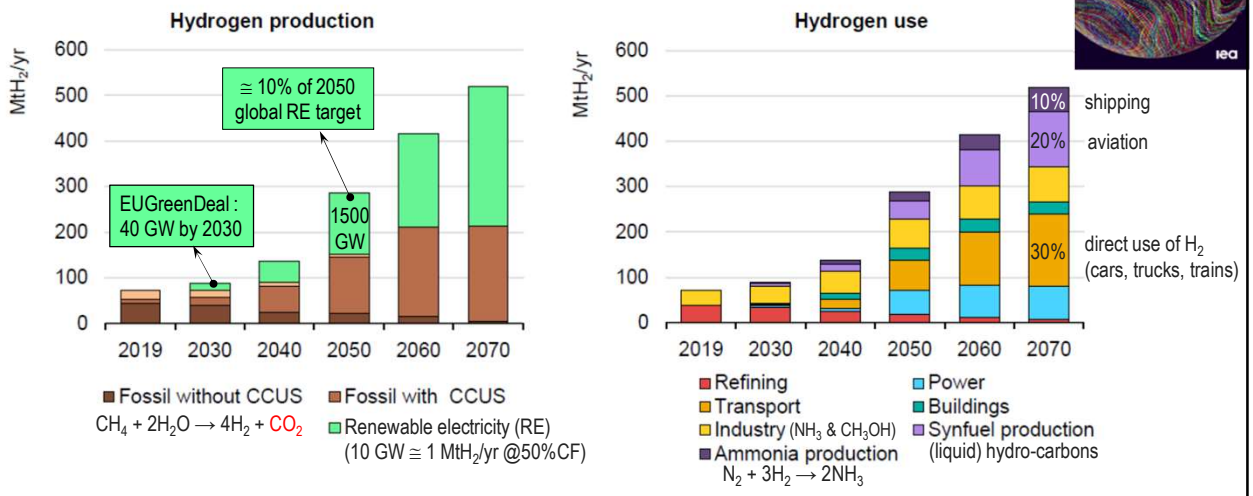
een nuchtere kijk op de zaak ...

Prof. Joris Proost

joris.proost@uclouvain.be

The big(ger) picture ...

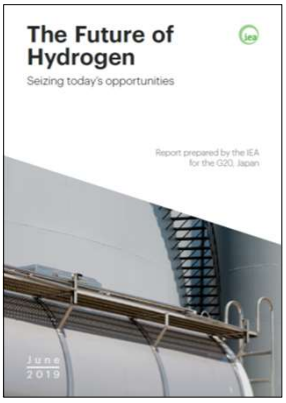
Figure 2.15 Global hydrogen production by fuel and hydrogen demand by sector



Review and analysis of demonstration projects on power-to-X pathways in the world

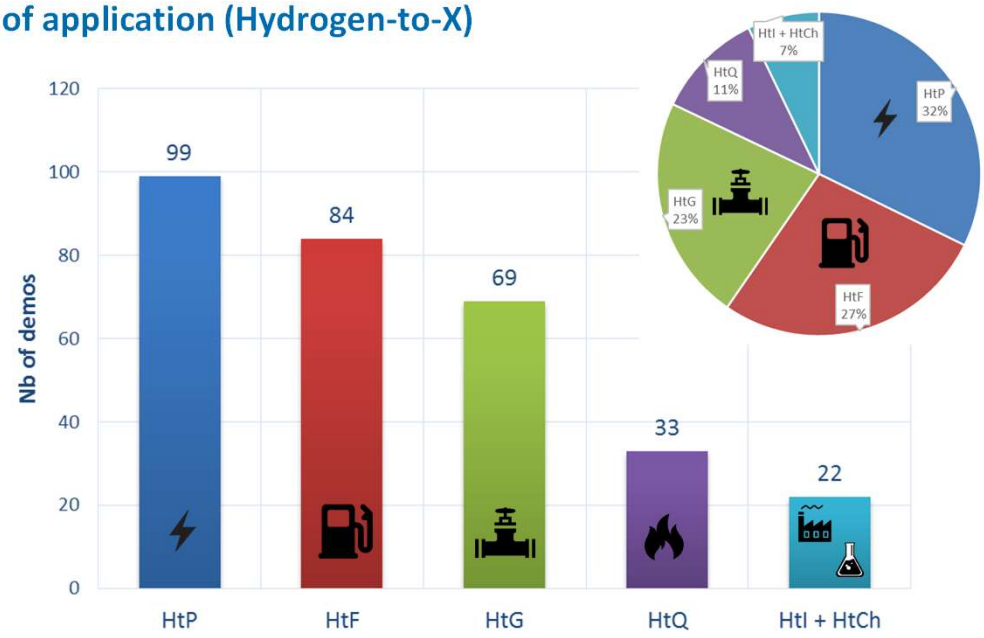
Hydrogen-to-X : Definitions

Category		Acronym	
Hydrogen-to-Power		HtP	Supply of electricity to the grid from hydrogen with a fuel cell or a gas turbine
Hydrogen-to-Fuel		HtF-H2	Hydrogen in a vehicle to be injected in a fuel cell
		HtF-S	Hydrogen for liquid synfuel applications : liquid biofuels, synthetic liquid fuels
		HtF-G	Hydrogen for mobility through gas fuels : Hythane®, biogas, synthetic methane
Hydrogen-to-Gas		HtG-H2	Hydrogen injection in the natural gas grid
		HtG-M	synthetic methane injection in natural gas grid, synthetic methane is obtained from Hydrogen from PtH through methanation processes
Hydrogen-to-Heat		HtQ	Hydrogen-to-heat via H_2-fired boilers; Hydrogen-to-heat and power via CHPs (fuel cells, turbine etc.)
Hydrogen-to-Industry		HtI	Hydrogen from PtH and for industrial applications (e.g. Refinery)
Hydrogen-to-Chemicals		HtCh	Other pathways to industrial chemical intermediates from hydrogen : 1. H_2 to methanol to C2, C3 olefins 2. H_2 to syngas to C2, C3 olefins 3. Methanol/syngas to >C1 hydrocarbons and >C1 alcohols 4. H_2 to ammonia and formic acid (which could also be used as alternative renewable energy storage)

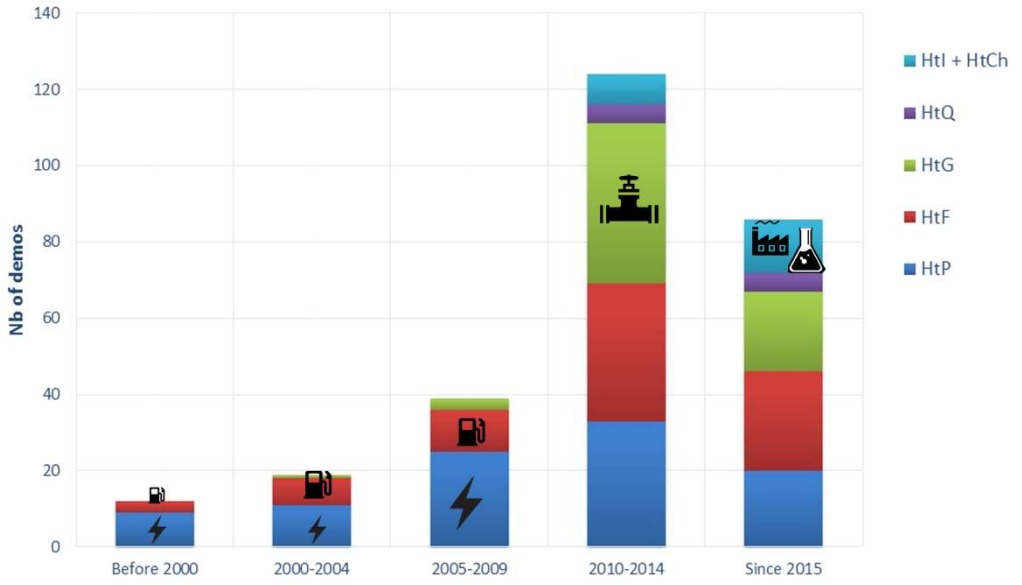


J. Proost *et al.*, International Journal of Hydrogen Energy 44 (2019) 27637

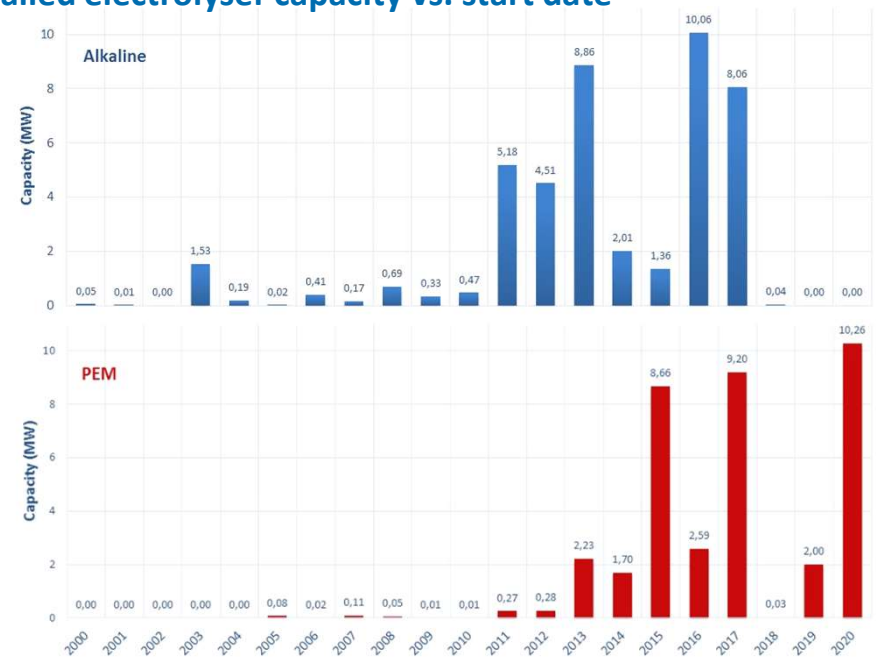
Type of application (Hydrogen-to-X)



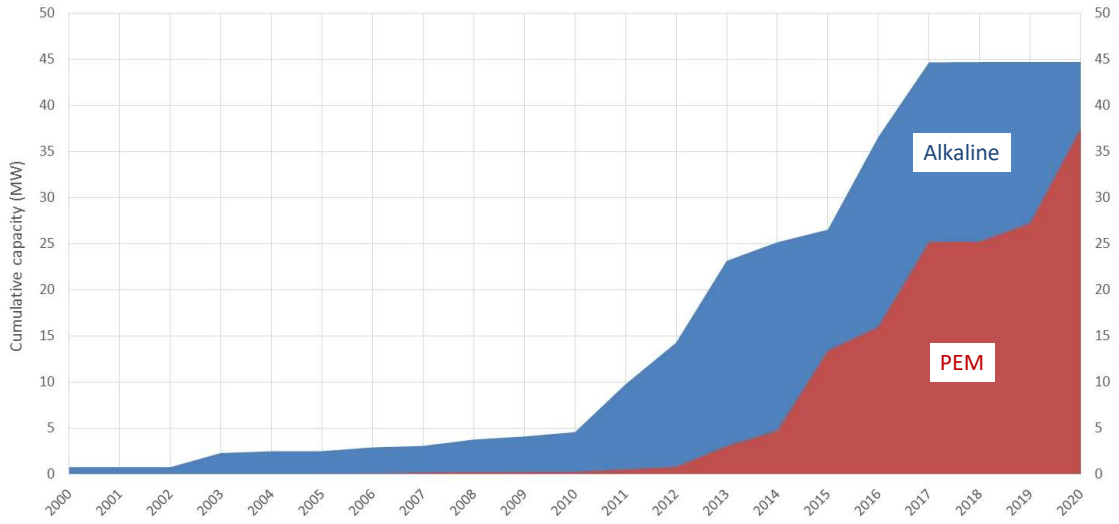
Temporal progression of HtX



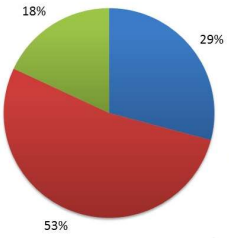
PtH installed electrolyser capacity vs. start date

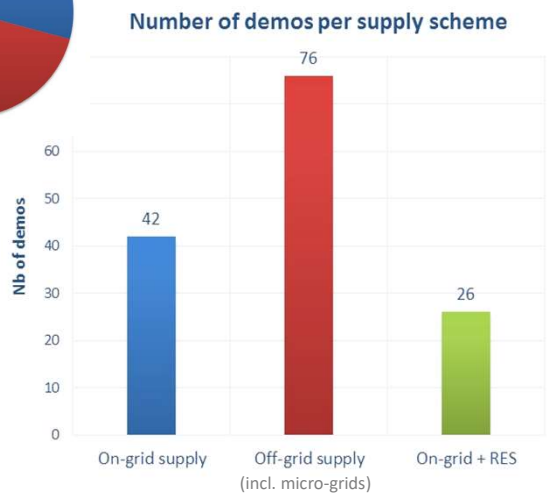


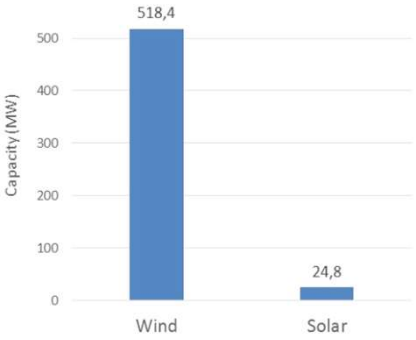
PtH cumulative installed capacity



Type of Power-to-Hydrogen : grid services



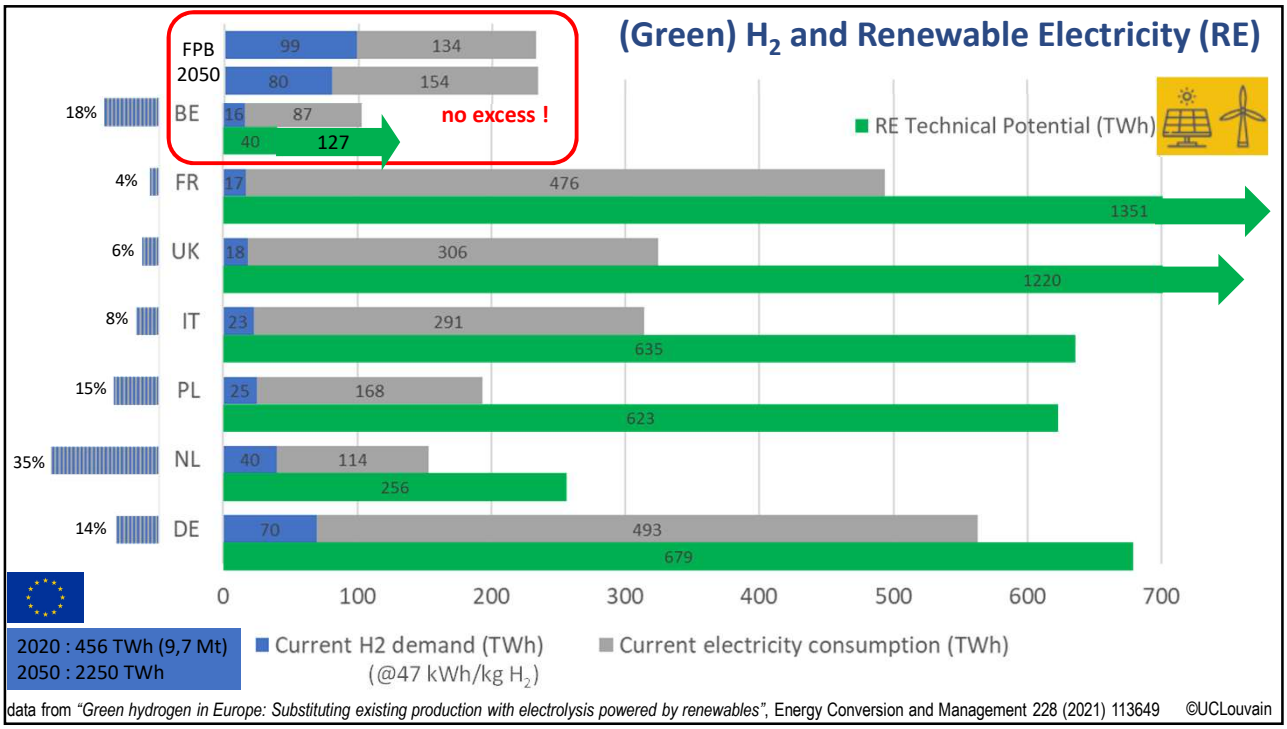




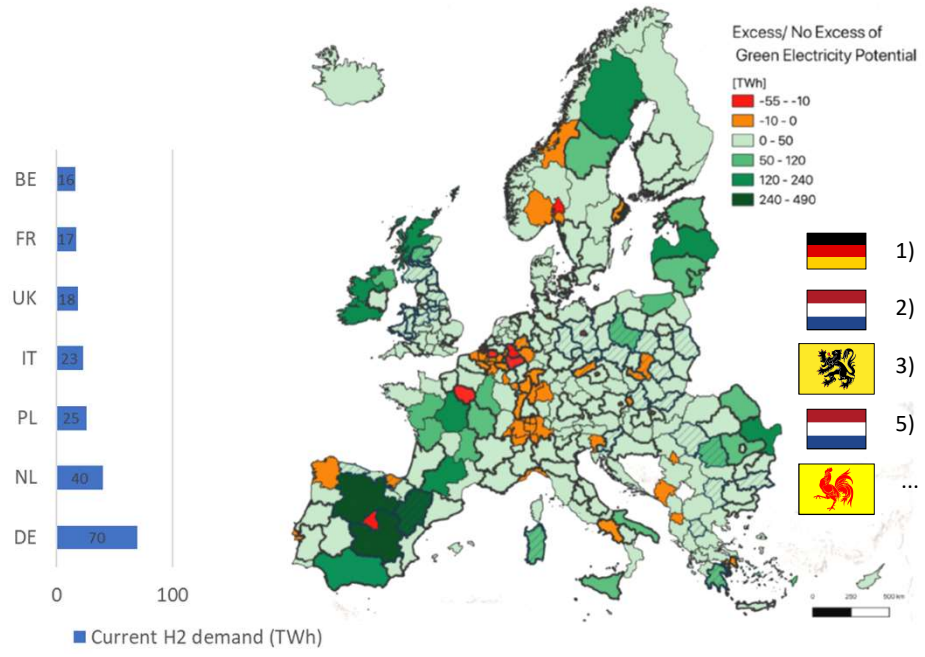
Green H_2 or Blue H_2

1) **price**

2) scale



data from *"Green hydrogen in Europe: Substituting existing production with electrolysis powered by renewables"*, Energy Conversion and Management 228 (2021) 113649



1) 20.34 TWh (Sachsen-Anhalt)

2) 18.18 TWh (Zeeland)

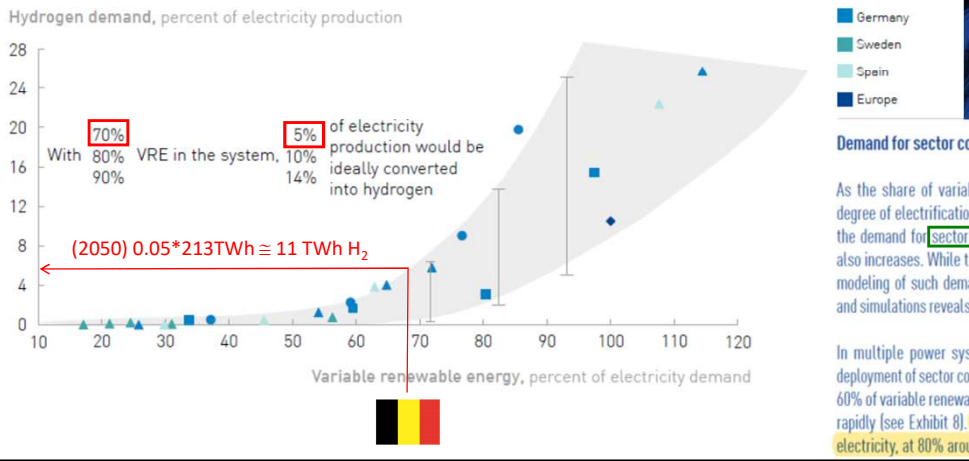
3) 9.87 TWh (Antwerp – 1.1 GW)

5) 9.63 TWh (NL Limburg)

... 5.98 TWh (Wallonia – 0.7 GW)

data from *"Green hydrogen in Europe: Substituting existing production with electrolysis powered by renewables"*, Energy Conversion and Management 228 (2021) 113649 ©UCLouvain

Green H_2 and Variable Renewable Electricity (VRE)

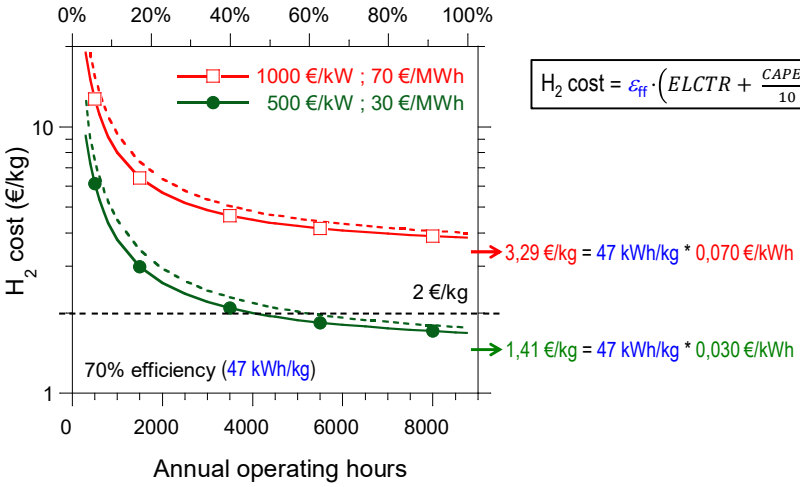


Demand for sector coupling

As the share of variable renewable sources and the degree of electrification increases in an energy system, the demand for sector coupling and long-term storage also increases. While there is no comprehensive view or modeling of such demand, a review of existing studies and simulations reveals that the relationship is nonlinear.

In multiple power system simulations,[12] the optimal deployment of sector coupling grows steadily until roughly 60% of variable renewable sources and then accelerates rapidly (see Exhibit 8). At 70%, around 5% of produced electricity, at 80% around 10% is converted

Green H_2 production price curves



J. Proost, *"State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings"*, Int. J. Hydrogen Energy 44 (2019) 4406

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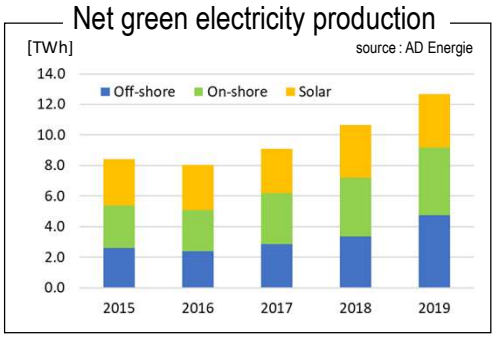

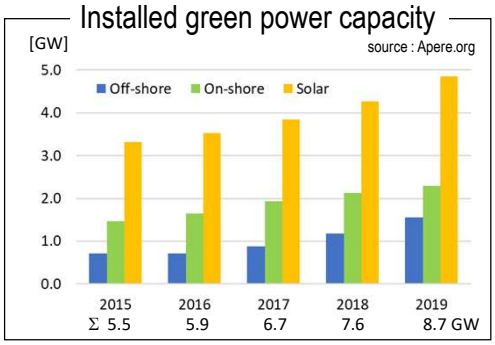

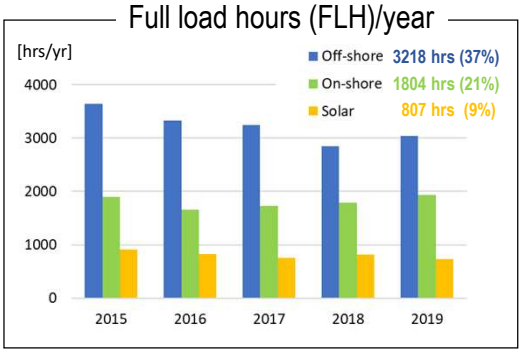

courtesy D. Devogelaer (FPB)

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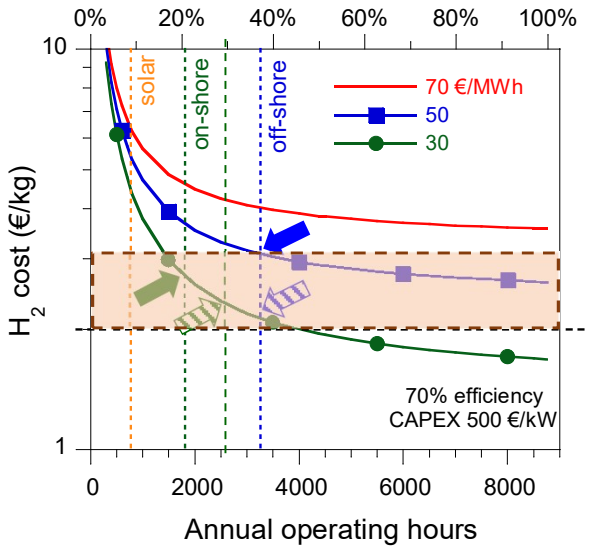

Fuel for the future

More molecules or deep electrification of Belgium's energy system by 2050

Average System Marginal Costs, Belgium and its neighbouring countries

(2050, €/MWh)	Diversified Energy Supply				
	BE	DE	FR	GB	NL
TC0	30.9	23.8	30.1	62.1	16.2
TC1	85.7	60.0	85.5	85.9	31.5
TC2	107.6	121.0	78.2	78.0	59.4

Source: Artelys, FPB own calculations.

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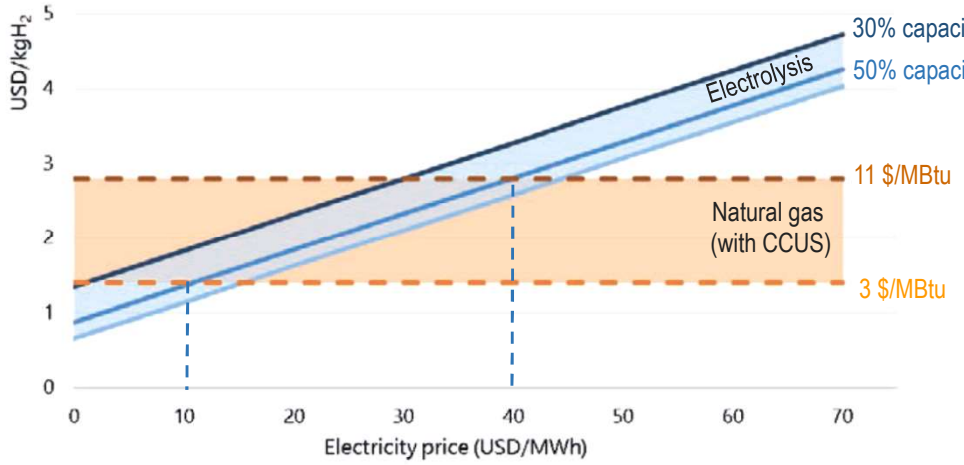
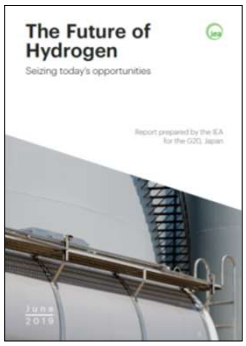
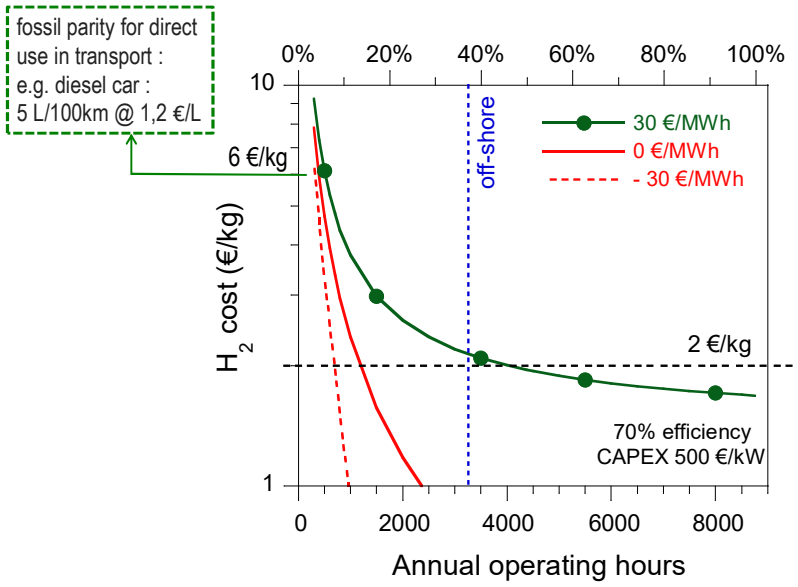
Figure 18. Comparison of hydrogen production costs from electricity and natural gas with CCUS in the near term





Depending on local gas prices, electricity at USD 10- 40/MWh and at full load hours of around 4 000 hours are needed for water electrolysis to become cost-competitive with natural gas with CCUS.

Excess renewable electricity ?



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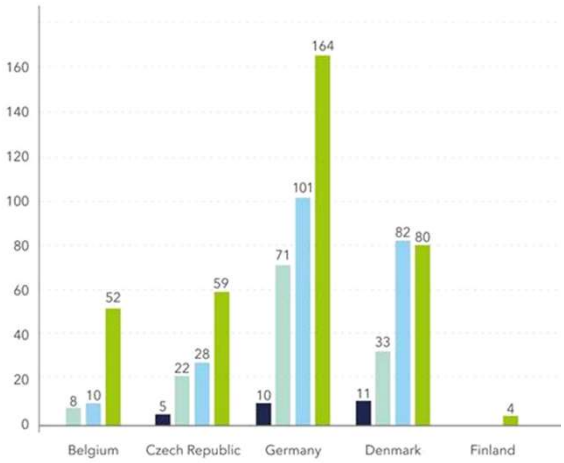
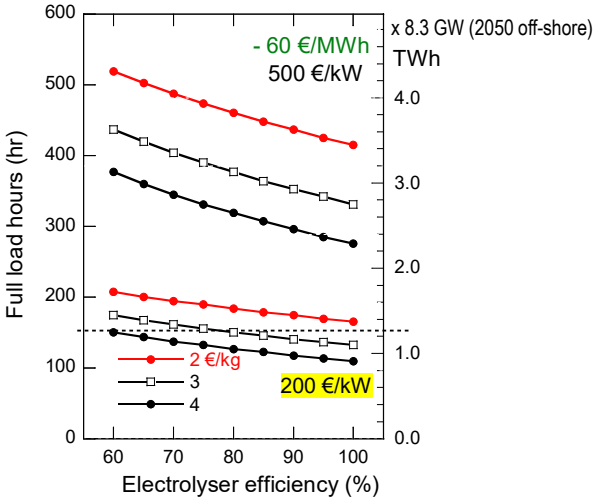
Number of Hours with Negative Electricity Prices in Selected Countries in Europe





courtesy D. Devogelaer (FPB)

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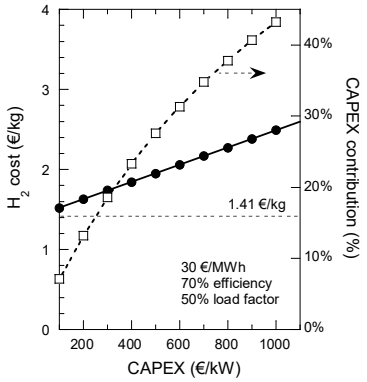
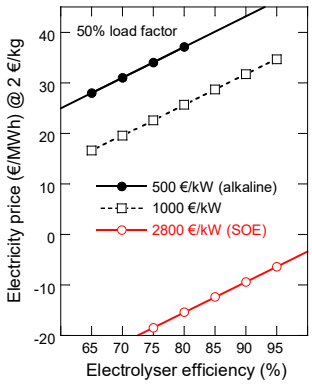
Table 3. Techno-economic characteristics of different electrolyser technologies

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
CAPEX (USD/kW_e)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000





J. Proost, *"Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen"*, Int. J. Hydrogen Energy 45 (2020) 17067

Electrolytic H_2 is already (cost-)competitive today !

TCO examples for on-site hydrogen production

GREENHYDROGEN.DK

- Continuous reduction of TCO (CAPEX and OPEX) for electrolysers is required to support different hydrogen business cases as the market develops towards multi MW applications
- GreenHydrogen delivers modular, scalable solutions at lowest TCO for on-site hydrogen generation – to fit the needs and business case of most applications
- Current price/kW (**CAPEX/kW**) for HyProvide™ A60 (incl. electrolyser and inverter) is app. 1.000 €
- The cost of electricity corresponds to app. 70% (average) of the OPEX for electrolysers -> high efficiency is a must
- HyProvide™ A60 (**kW power/ Nm³ H_2**) efficiency is 4.2 kWh/Nm³ - 46,7 kWh/kg at 100% load.

10 years' Total Cost of Ownership for complete, containerised HyProvide A-series electrolyser solution			
(@ 35 bar) Nm³ H_2 / hr	kW	Kg H_2/day	40 €/MWh €/kg H_2
30	135	65	3,81
60	270	130	3,14
90	405	194	2,84
180	810	390	2,79
270	1215	583	2,78
360	1620	777	1.6 MW 2,77

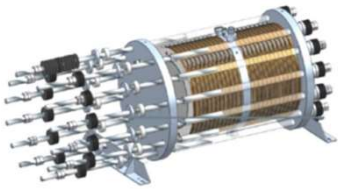
Prices based on 10 years operation, linear depreciation. Complete turnkey, containerized HyProvide™ electrolyzer unit including inverter and water treatment. Delivered and installed in Europe, including 10 years' Service & Maintenance agreement, electricity, water and nitrogen (for purge). Electricity price set at 40 €/MWh.

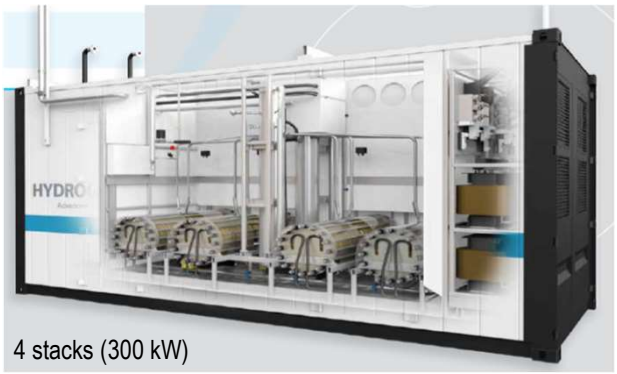
Green H_2 or Blue H_2

1) price

2) scale

Water electrolysis : intrinsically small-scale & ultra-high purity (99,998%)





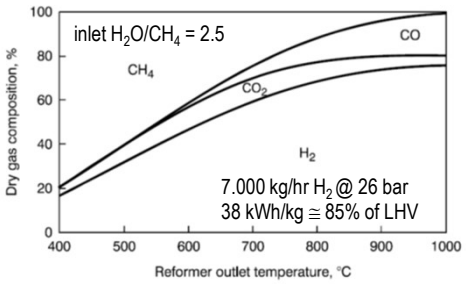
SMR : intrinsically large-scale & (much) less pure (95-98%)

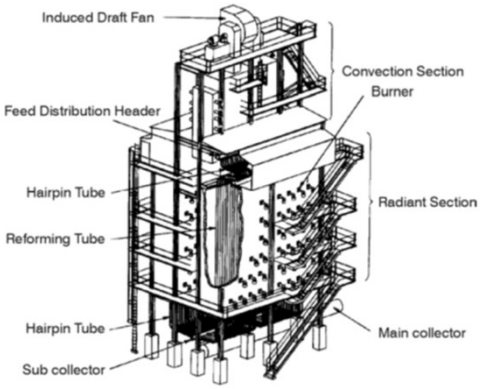
Steam methane reforming (SMR)

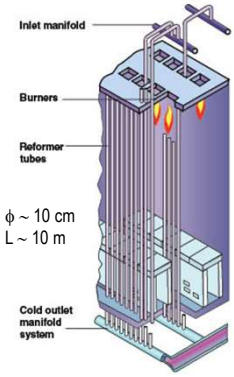
reformer $CH_4 + H_2O \rightarrow 3H_2 + CO$ (endo : T↑, p↓)

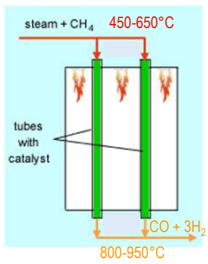
water gas shift $CO + H_2O \rightarrow H_2 + CO_2$

$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$ (8 tons/ton H_2)









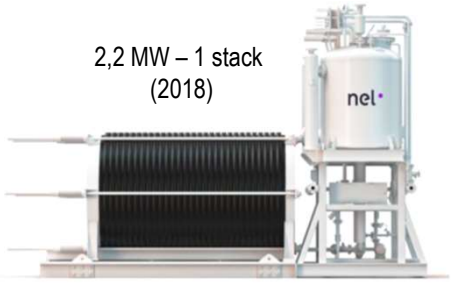
courtesy Prof. J. De Wilde (UCLouvain)

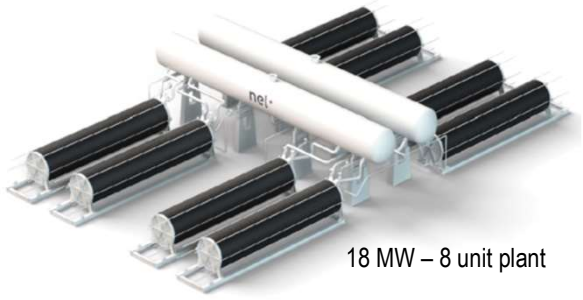
SMR : centralised production ⇒ distribution logistics needed

Water electrolysis : scale-up (only) for decentralised production

2 MW ≅ 6 x 300 kW (2013)

2,2 MW – 1 stack (2018)





18 MW – 8 unit plant

Hydrogen market **today** (~70 Mton/yr)

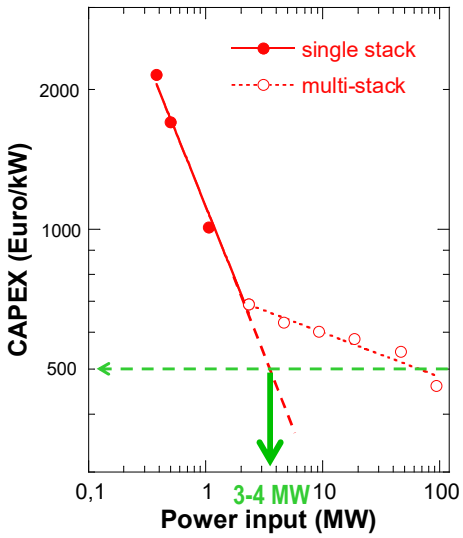
INDUSTRY SECTOR	UNIT REACTOR/PROCESS SIZE	PERCENTAGE OF GLOBAL H_2 DEMAND	ELECTROLYSER CAPACITY (50 kWh/kg @100% CF)
CHEMICAL	• Ammonia & Methanol • Polymers NH_3 8.000 kg/h • Resins CH_3OH 1.000 kg/h	65 %	NH_3 400 MW CH_3OH 50 MW
REFINING	• Hydrocracking • Hydrotreating	25 %	
IRON & STEEL	• Annealing • Blanketing gas • Forming gas 40 kg/h + 40.000 kg/h (H_2 reduction)		2 MW (+ 2000 MW)
GENERAL INDUSTRY	• Semiconductor • Propellant fuel • Glass production • Hydrogenation of fats • Cooling of generators 5 kg/h + 300 kg/h (H_2 combustion)	10 %	0,25 MW (+ 150 MW)

40 kg/h

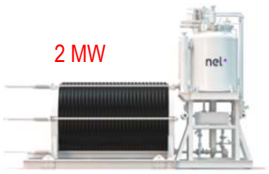
2 MW

(non-stop delivery during 15-20 years !!!)

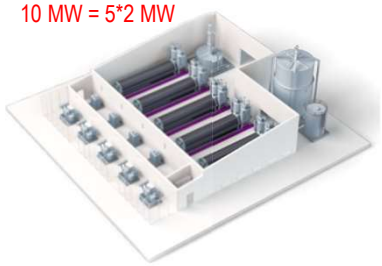
Green H_2 for small-scale fossil parity



2 MW



10 MW = 5*2 MW



J. Proost, *"Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen"*, Intern. J. Hydrogen Energy 45 (2020) 17067

Electrolytic H_2 for small-scale fossil parity

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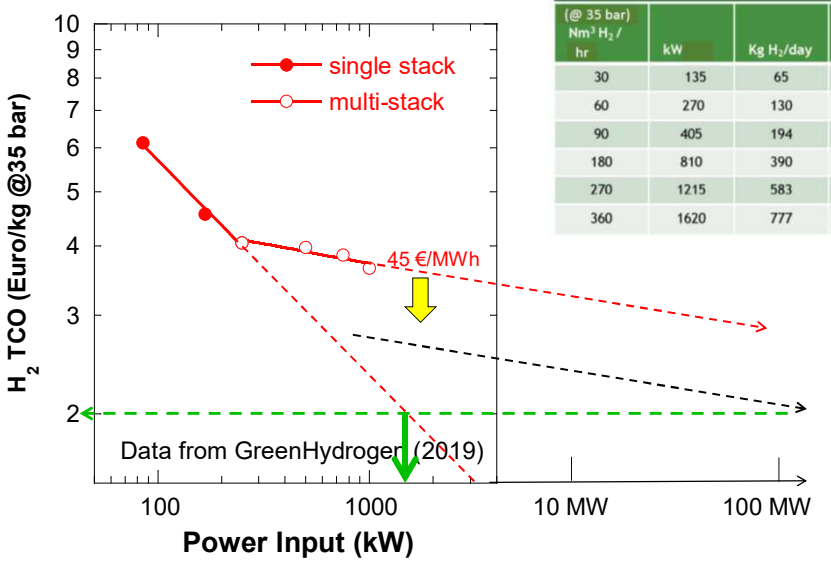

10 years' Total Cost of Ownership for complete, containerised HyProvide A-series electrolyser solution			
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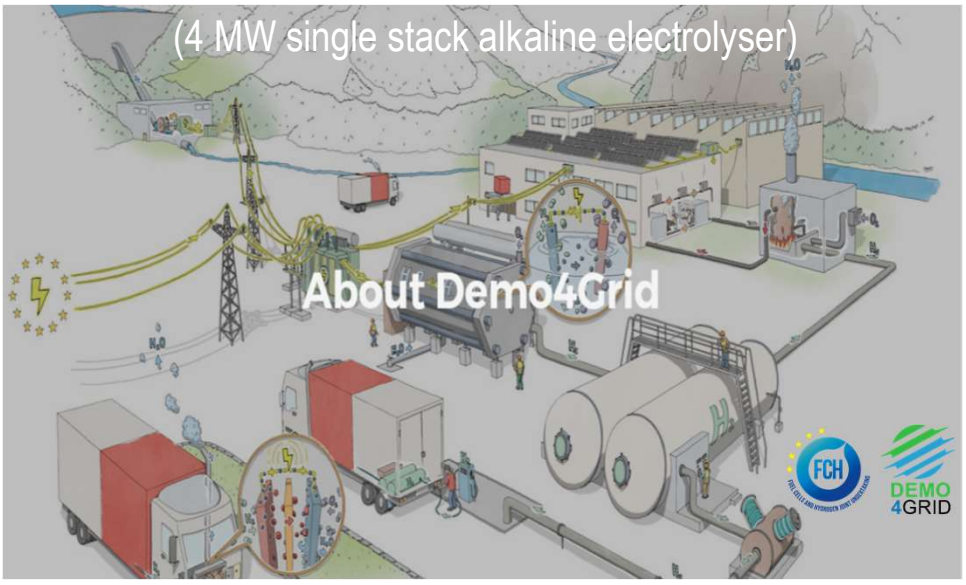
60	270	130	3,14
90	405	194	2,84
180	810	390	2,79
270	1215	583	2,78
360	1620	777	2,77

Small-scale fossil parity ...
... also opens new small-scale markets for Green H_2



Large-scale electrolytic H_2

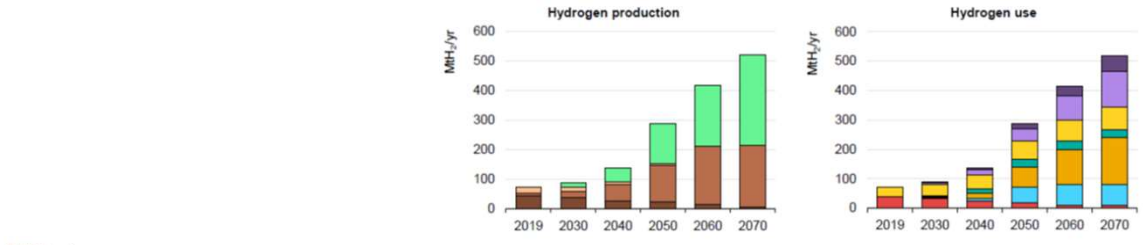
THE Biggest Plant in Operation (NH_3 production)

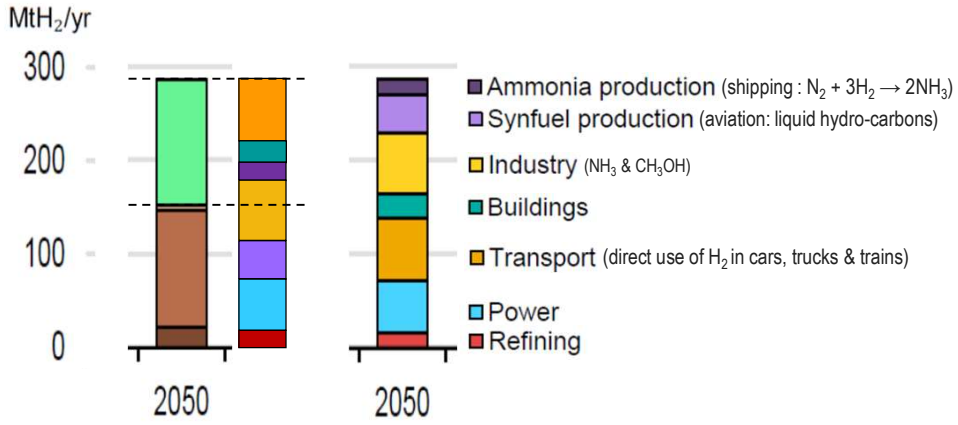
25MW/5'500Nm³/h – Hydroelectricity → Green H_2

25 MW

nel

Green H_2 or Blue H_2





Technology Collaboration Programme

by iea

Hydrogen TCP

For a rapid deployment of carbon-free hydrogen worldwide: Advocacy for a "rainbow" hydrogen