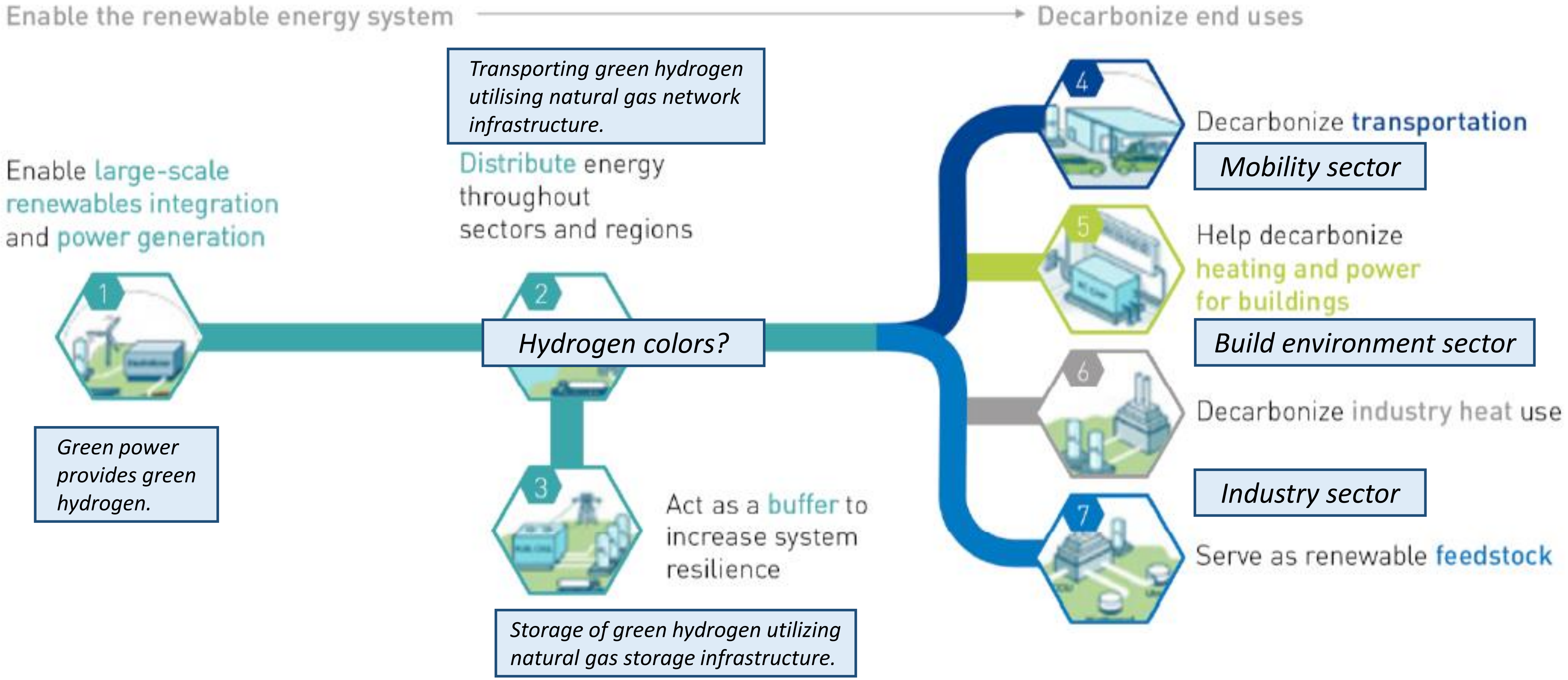
Hydrogen, a multisector promise in the energy transition, current status and developments

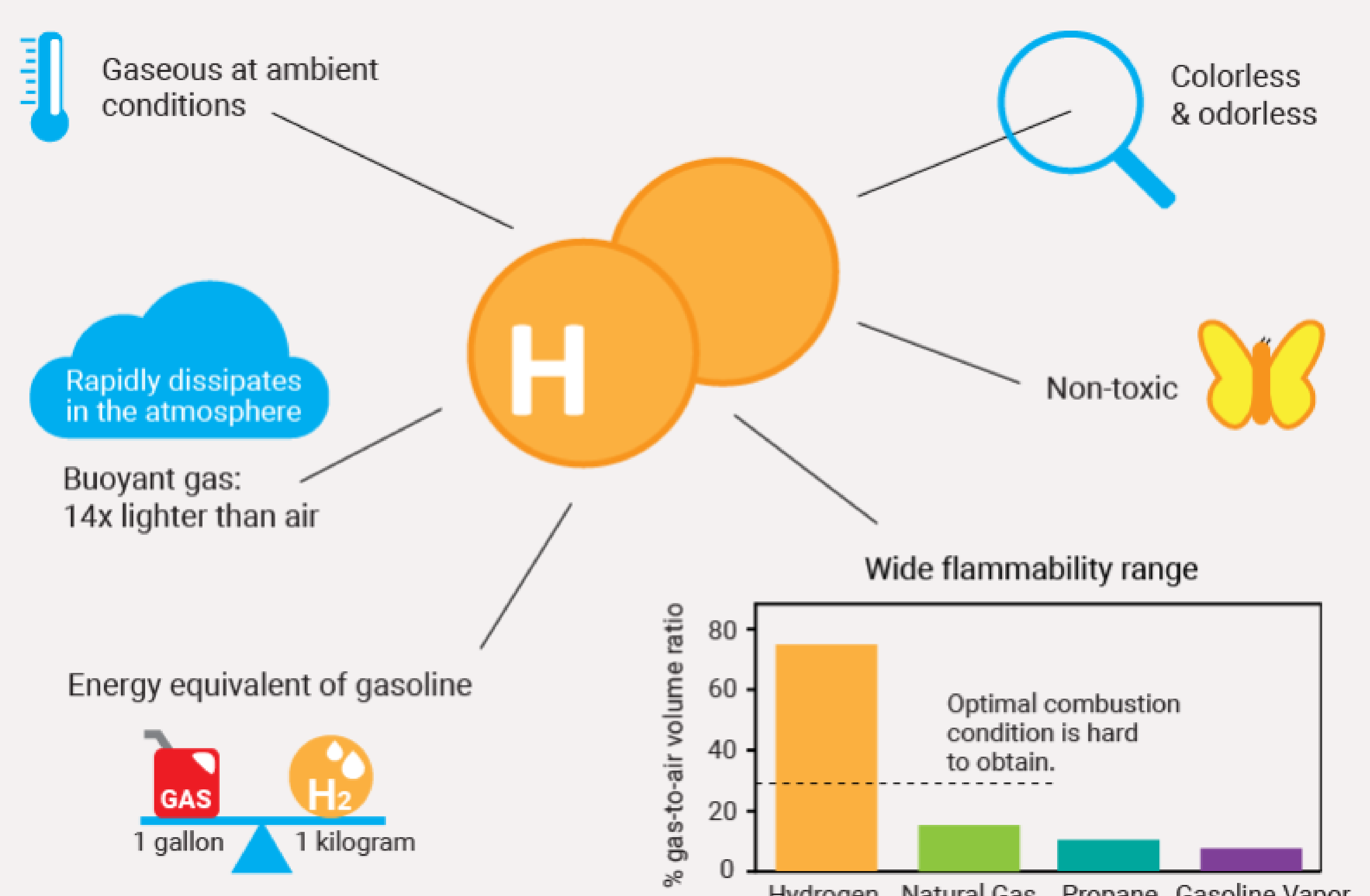
Theo Fens
Delft University of Technology
PEP2040, May 2023

Hydrogen as an enabler for the energy transition



Source: FCH JU 2019
https://www.fch.europa.eu/publications

Hydrogen safety and handling



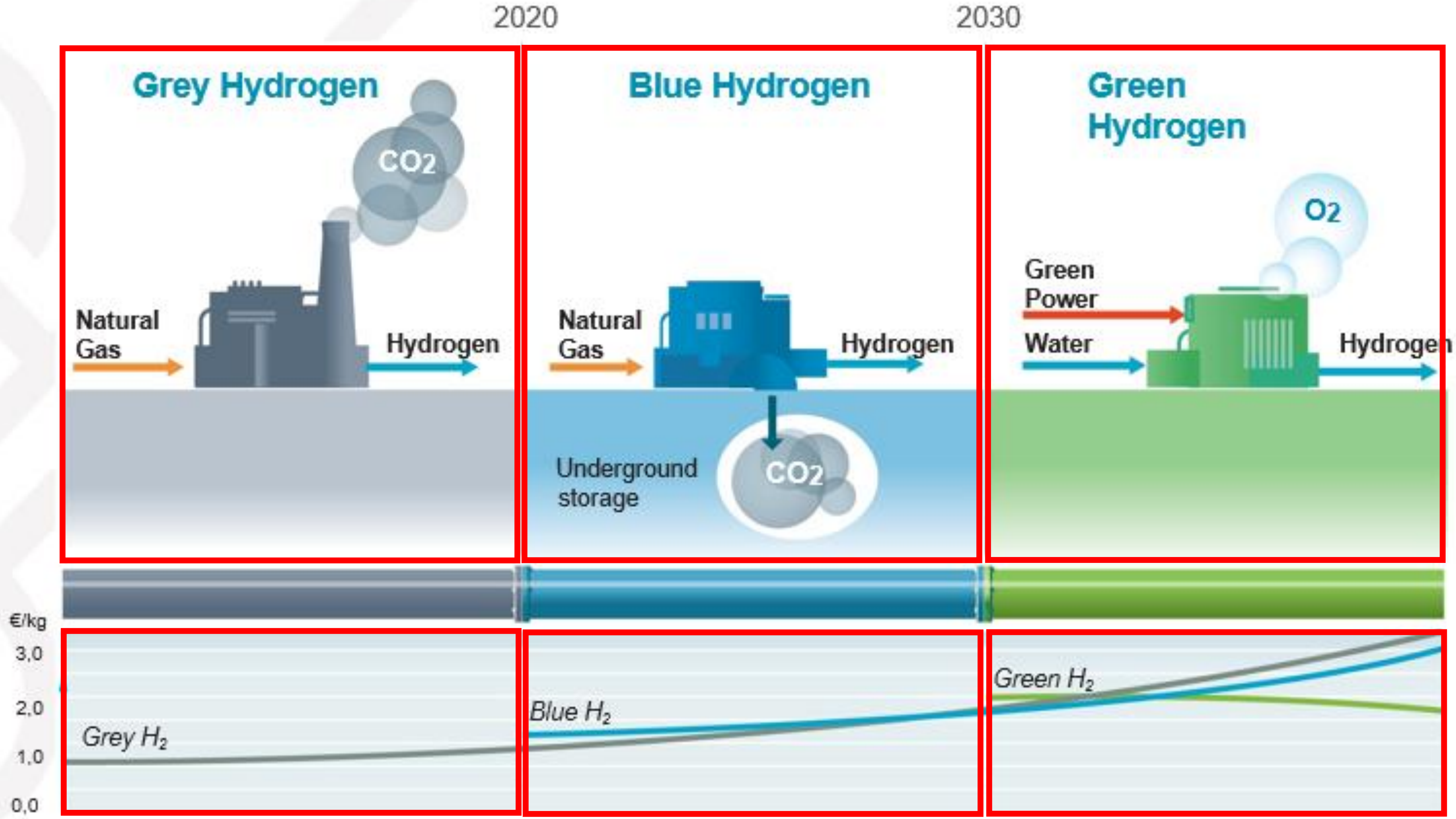
Remarks:
When a conventional hydrocarbon fuel burns, it produces hot ash from the oxidation of carbon, creating radiant heat.

This is not the case with hydrogen because it does not contain carbon. In its pure form, hydrogen burns and produces no hot ash and very little radiant heat.

However, a hydrogen flame is nearly invisible compared to a natural gas flame.

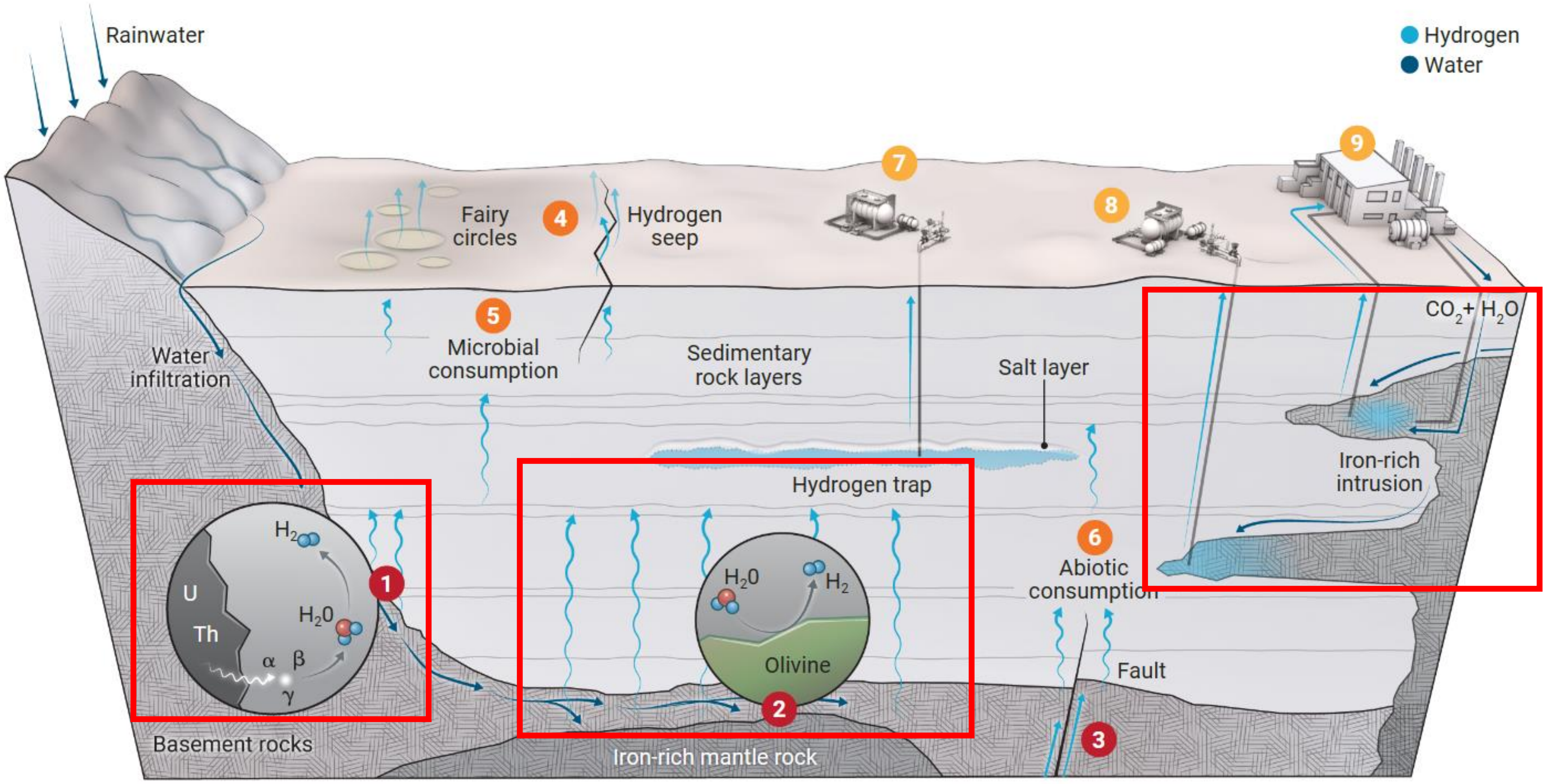
Source: Hydrogen station maps 2020
https://h2stationmaps.com/hydrogen-stations#safety

Hydrogen colours, from Grey to Green, the economics



Source: ECN/TNO 2019
https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-fuels-and-feedstock/hydrogen-for-a-sustainable-energy-supply/

White hydrogen from geological formations?



Source: Science 2023

[Hidden hydrogen: Earth may hold vast stores of a renewable, carbon-free fuel | Science | AAAS]

Green hydrogen: electrolysers and fuel cells

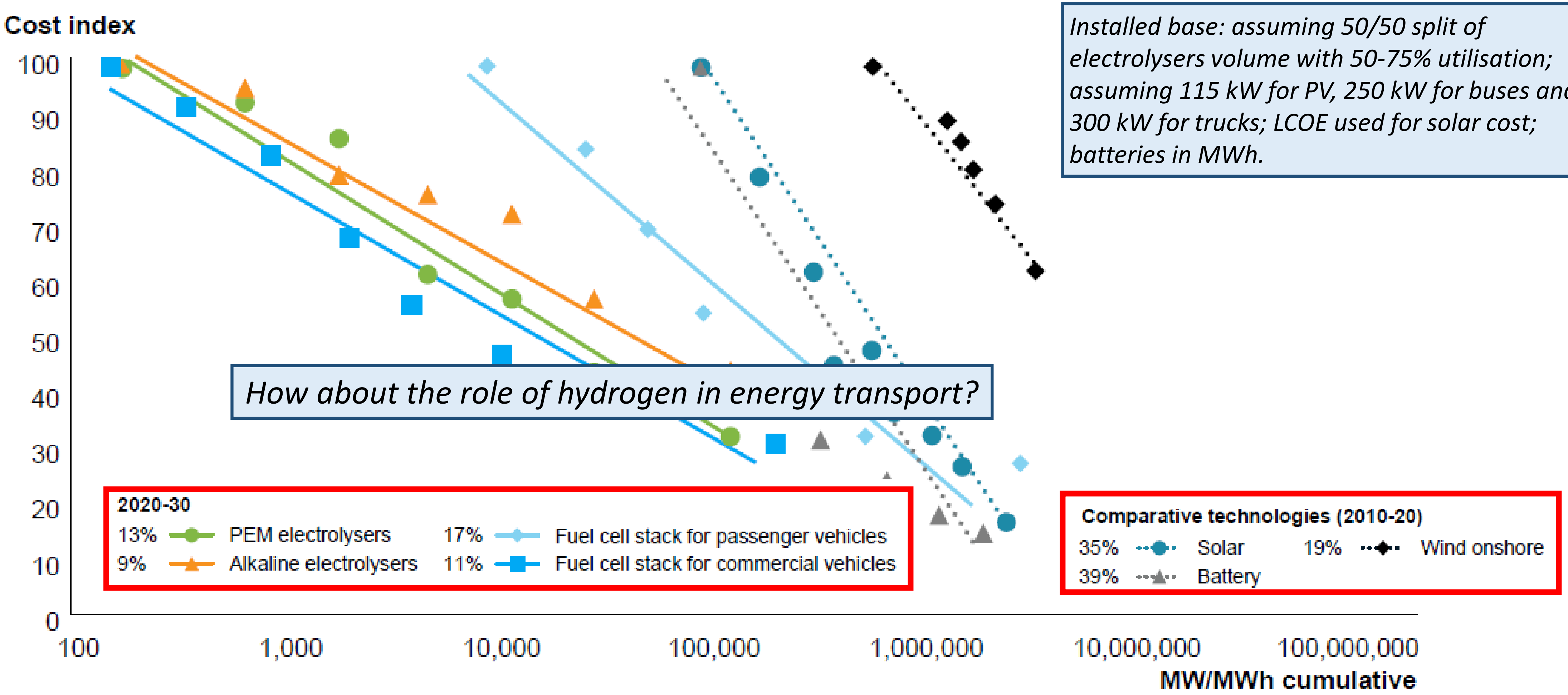
WATER (H_2O) + **POWER** — Electrolyzer → **HYDROGEN (H_2)** + OXYGEN (O_2)

← Fuel Cell

Source: Hydrogenics 2019
https://www.hydrogenics.com/

Learning rates for hydrogen generation and applications

Installed base: assuming 50/50 split of electrolysers volume with 50-75% utilisation; assuming 115 kW for PV, 250 kW for buses and 300 kW for trucks; LCOE used for solar cost; batteries in MWh.



How about the role of hydrogen in energy transport?

Capex development of selected technologies over total cumulative production, indexed to 2020 values (2010 for comparative technologies).

Source: Hydrogen Council, Path-to-Hydrogen-Competitiveness _Full-Study-1 2019
https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/

Transport of gas is much cheaper and more efficient than transport of electricity

Power *Unavoidable physical losses*

BritNed

- 260 km
- € 600 mio
- 1 GW capacity
- € 230/kW/100 km

Gas *Leak-free: no losses*

bbl company

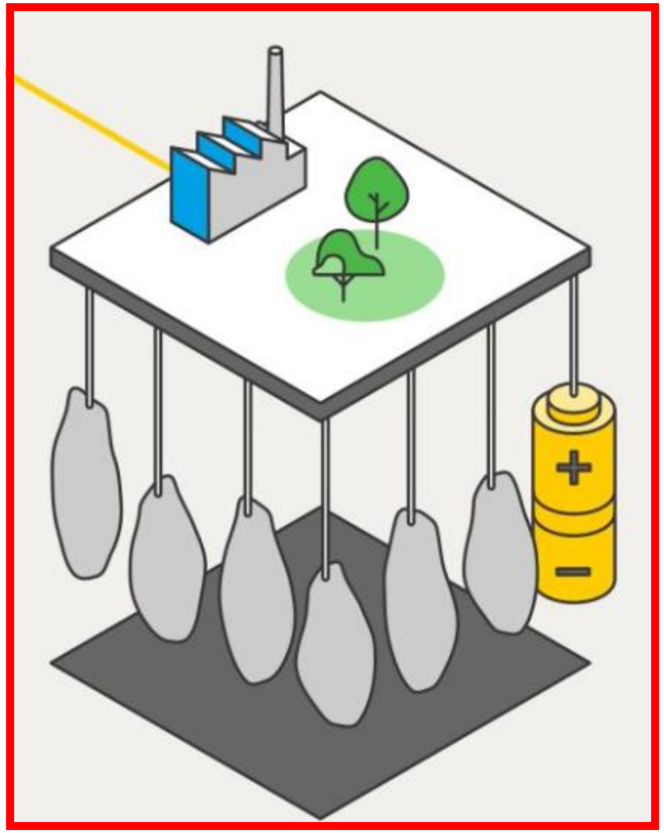
- 230 km
- € 500 mio
- 20 GW capacity
- € 11/kW/100 km

Nord Stream

- € 9/kW/100 km

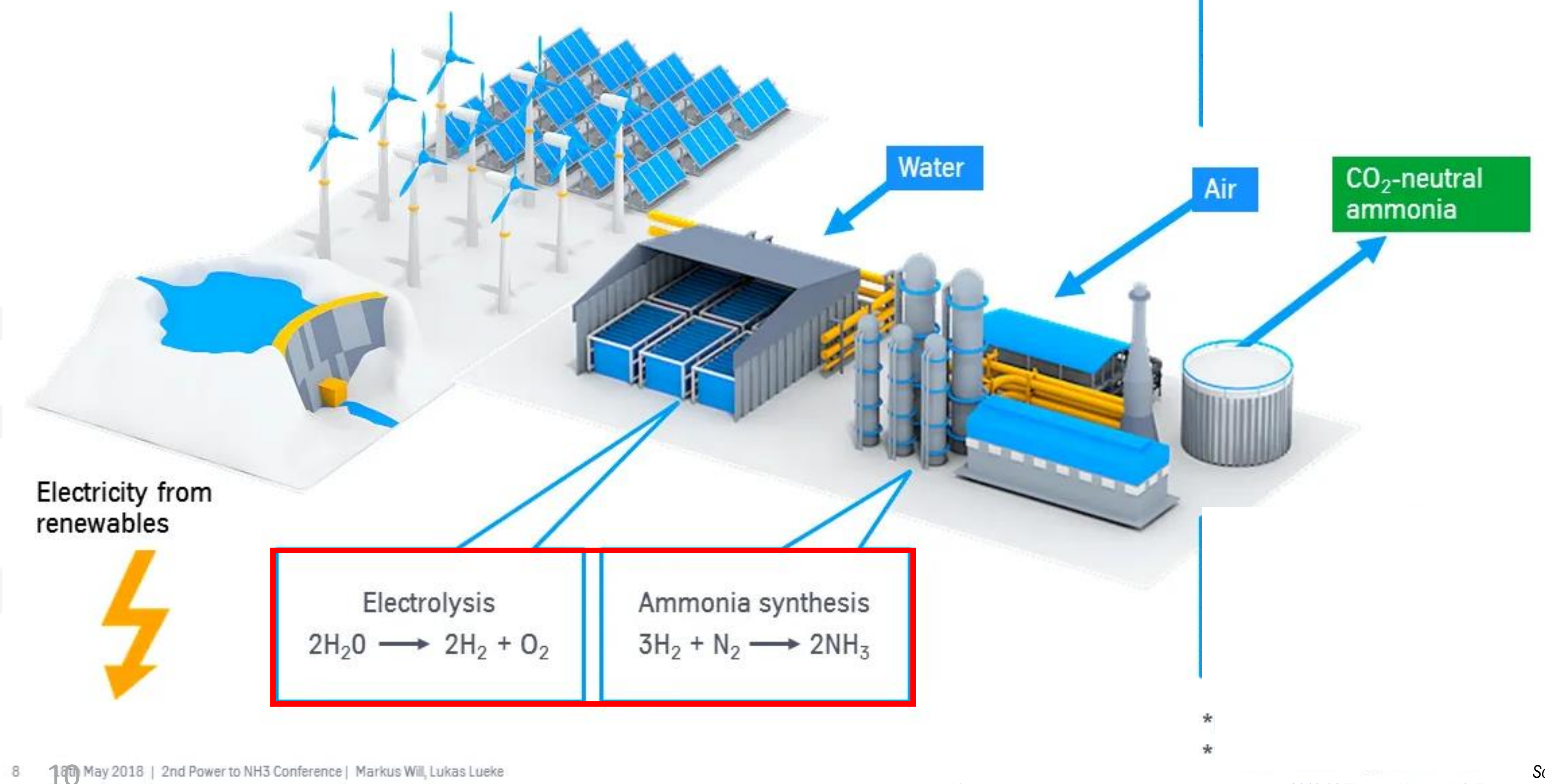
Offshore wind farms at GW scale: the combination of local conversion of power to hydrogen + a pipeline system may well be cheaper than a GW scale cable….certainly when current gas infrastructure is used.

Hydrogen storage in salt caverns



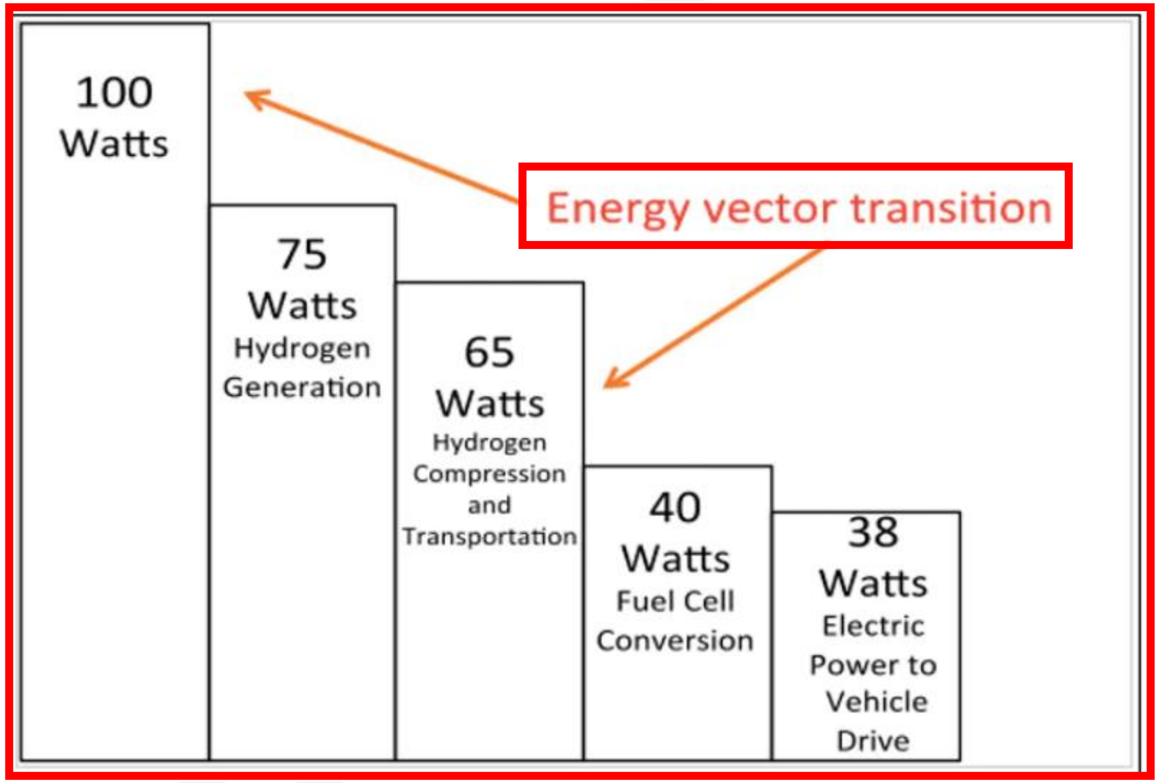
Source: Gasunie 2023
https://www.hystock.nl/waterstof/opslag-in-zoutcavernes

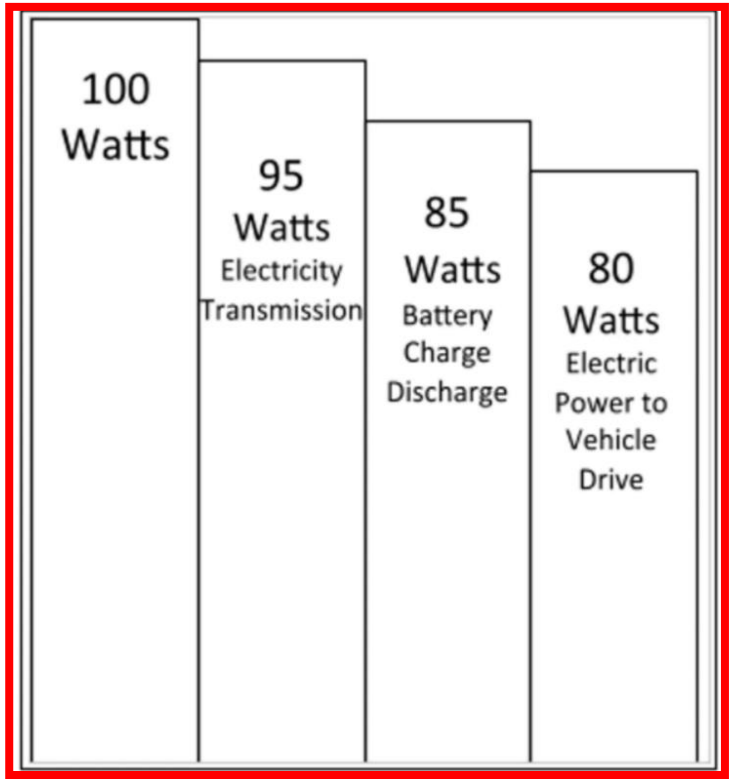
Renewable Ammonia



Source: ThyssenKrupp 2018
https://i1.wp.com/ammoniaindustry.com/wp-content/uploads/2018/06/ThyssenKrupp-NH3-Event-renewable-ammonia.png?ssl=1

Fuel cell cars versus battery electric vehicle

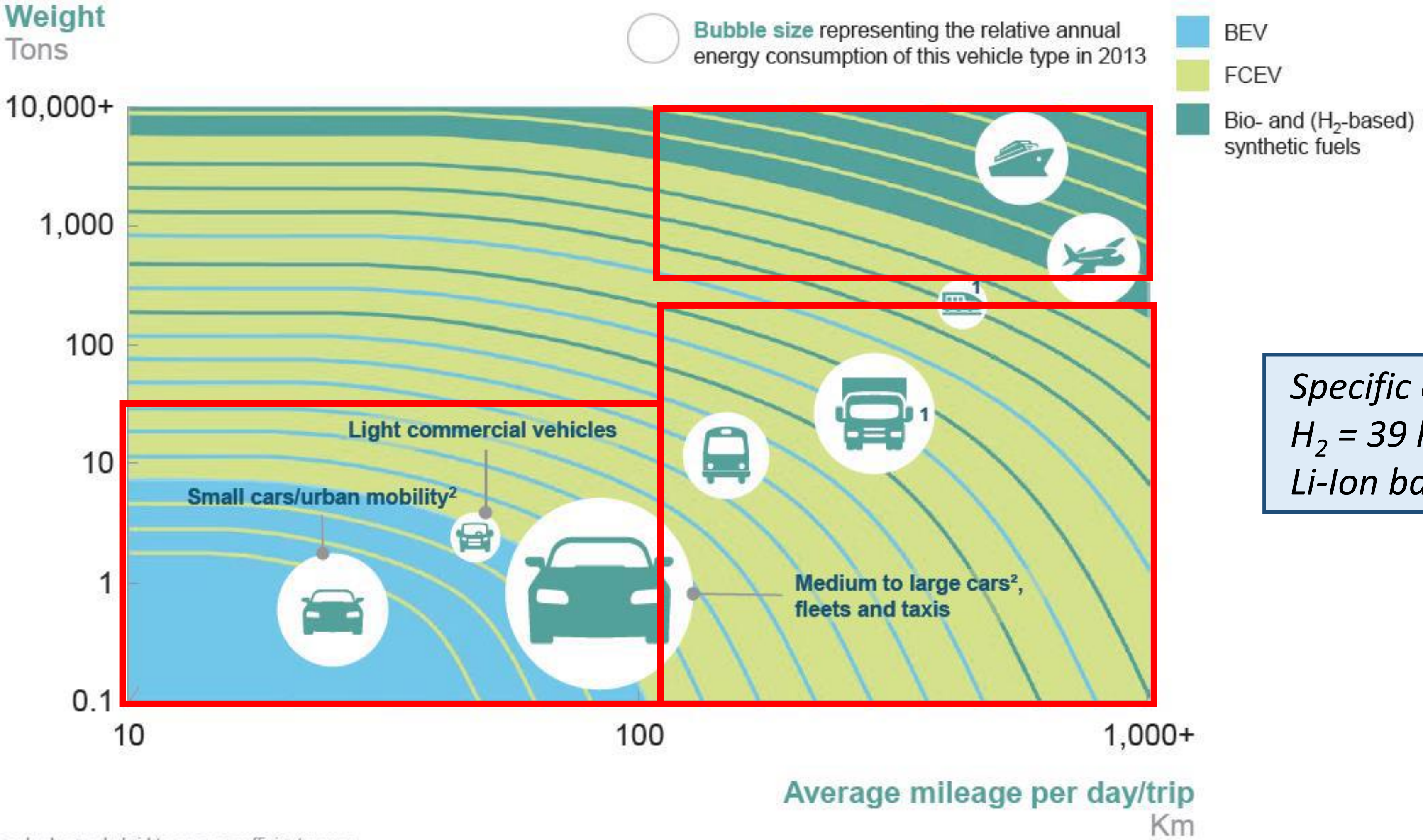




For comparison, a gasoline or diesel car with an internal combustion engine has an overall efficiency of some 25%.

Source: Energy Post 2020
https://energypost.eu/energy-conversion-for-hydrogen-cars-is-only-half-that-for-bevs/

Mobility: battery or fuel cell? Or both?



1 Battery-hydrogen hybrid to ensure sufficient power
2 Split in A- and B-segment LDVs (small cars) and C+-segment LDVs (medium to large cars) based on a 30% market share of A/B-segment cars and a 50% less energy demand

Source: Toyota, Hyundai, Daimler

Specific energy
H_2 = 39 kWh/kg
Li-Ion battery = 0.1-0.25 kWh/kg

Source: Hydrogen Europe 2020
https://hydrogeneurope.eu/zero-emission-mobility

Stad aan 't Haringvliet, Het Innovathuis

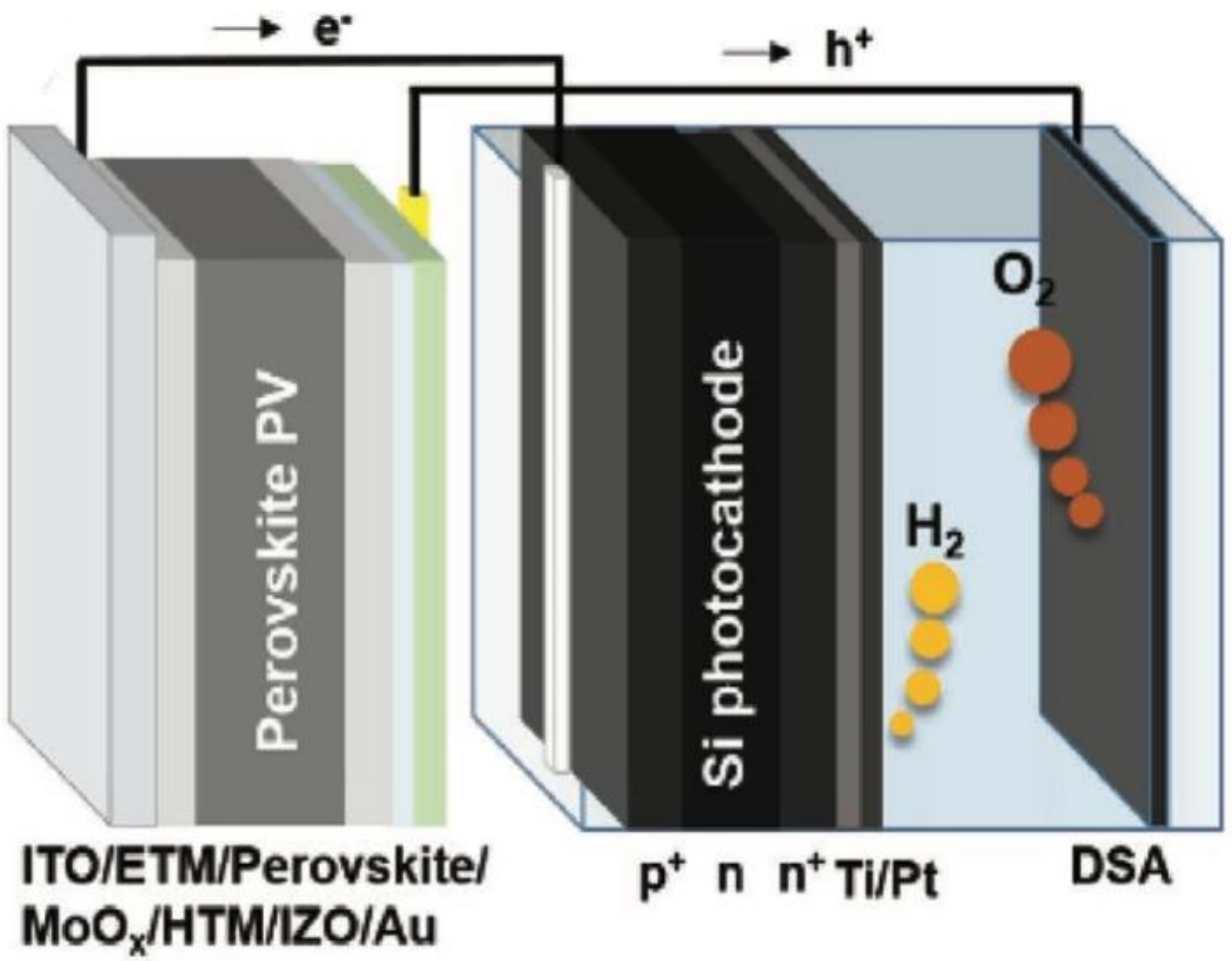
Source: https://wonenopflakkee.nl/initiatieven/het-innovathuis/ , 2019

Hydrogen directly from solar panels

Bioscience engineers from KU Leuven have designed a hydrogen panel that converts 15 per cent of the sunlight straight into hydrogen gas – a world record.

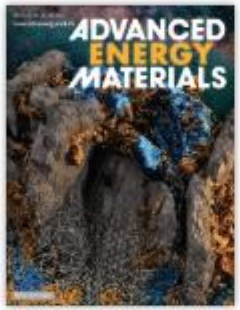
Source: KU Leuven 2019
https://nieuws.kuleuven.be/en/content/2019/belgian-scientists-crack-the-code-for-affordable-eco-friendly-hydrogen-gas

Hydrogen directly from solar panels, using water splitting



Australian researchers have claimed a new world efficiency record of 17.6% for solar panels that can directly split water using sunlight. They use a photoelectrochemical (PEC) solar-to-hydrogen (STH).

The low-cost layered perovskite is combined with a convectional Si solar cell should lead to low cost hydrogen.



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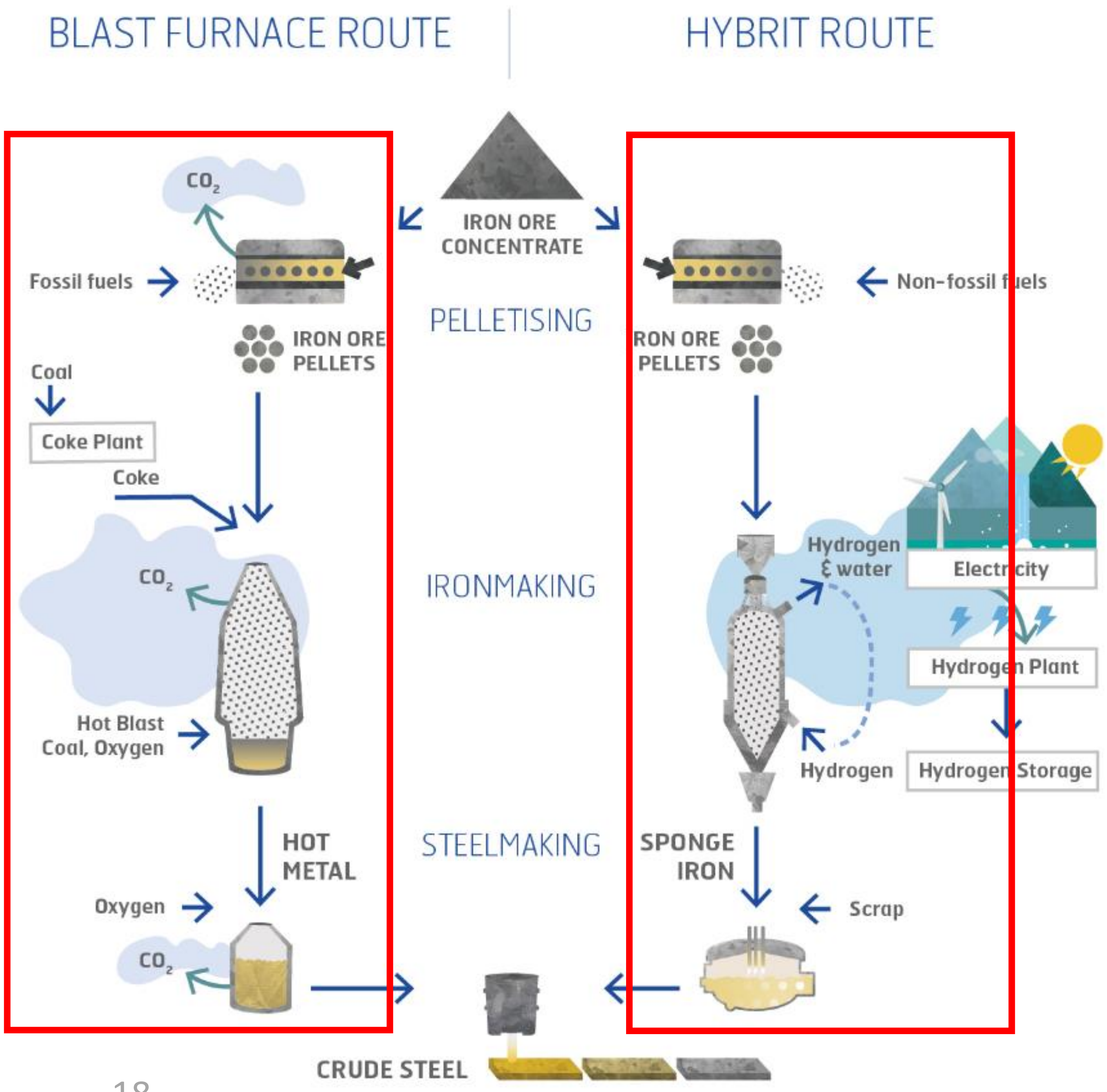
2000772

Source: Australian National University 2020
https://onlinelibrary.wiley.com/doi/epdf/10.1002/aenm.202000772

Thank you for your attention

Backup sheets

Direct Reduction of Iron in steel making with hydrogen



Source: Hybrit fossil free steel 2020
https://www.hybritdevelopment.com/

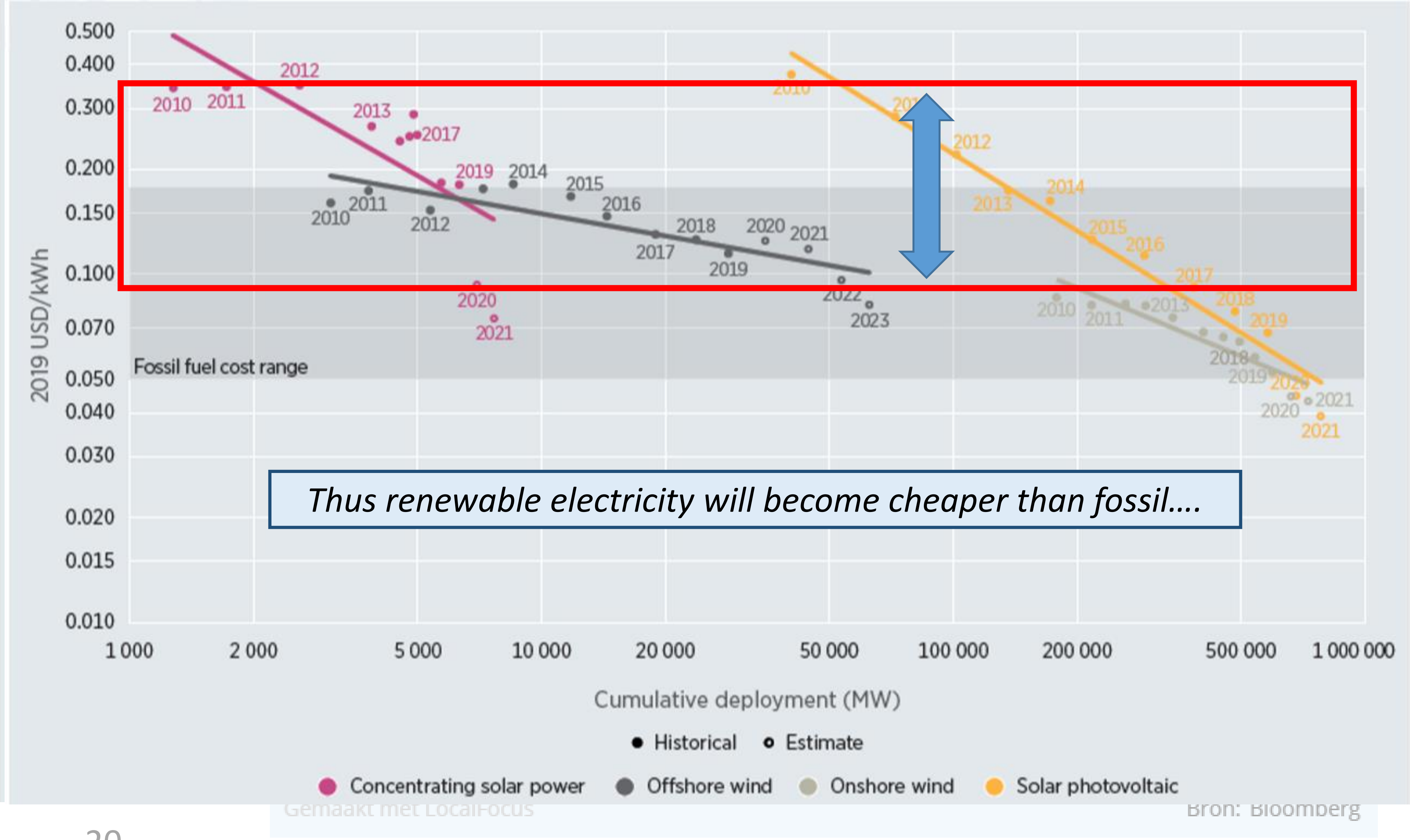
Characteristics hydrogen compared to natural gas

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Source: EIA 2019
https://www.iea.org/reports/the-future-of-hydrogen

Levelised cost of renewable electricity in $/kWh



Learning rates:

- Utility-scale solar PV:
  36% for 2010 – 2019
  40% for 2010 - 2021
- Concentrating solar power:
  23% for 2010 - 2019
  38% for 2010 - 2021
- Onshore wind:
  23% for 2010 - 2019
  29% for 2010 - 2021
- Offshore wind:
  10% for 2010 - 2023

Source: Irena June 2020

https://www.irena.org/-/media/Files/IRENA/Agency/Webinars/2020/Jun/IRENAinsight-webinar_RPGC-in-2019-Overview.pdf?la=en&hash=80A08A29C8807989DC9DBA8E78E55B6124DC5E42

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Levelised cost of green hydrogen from electrolysers

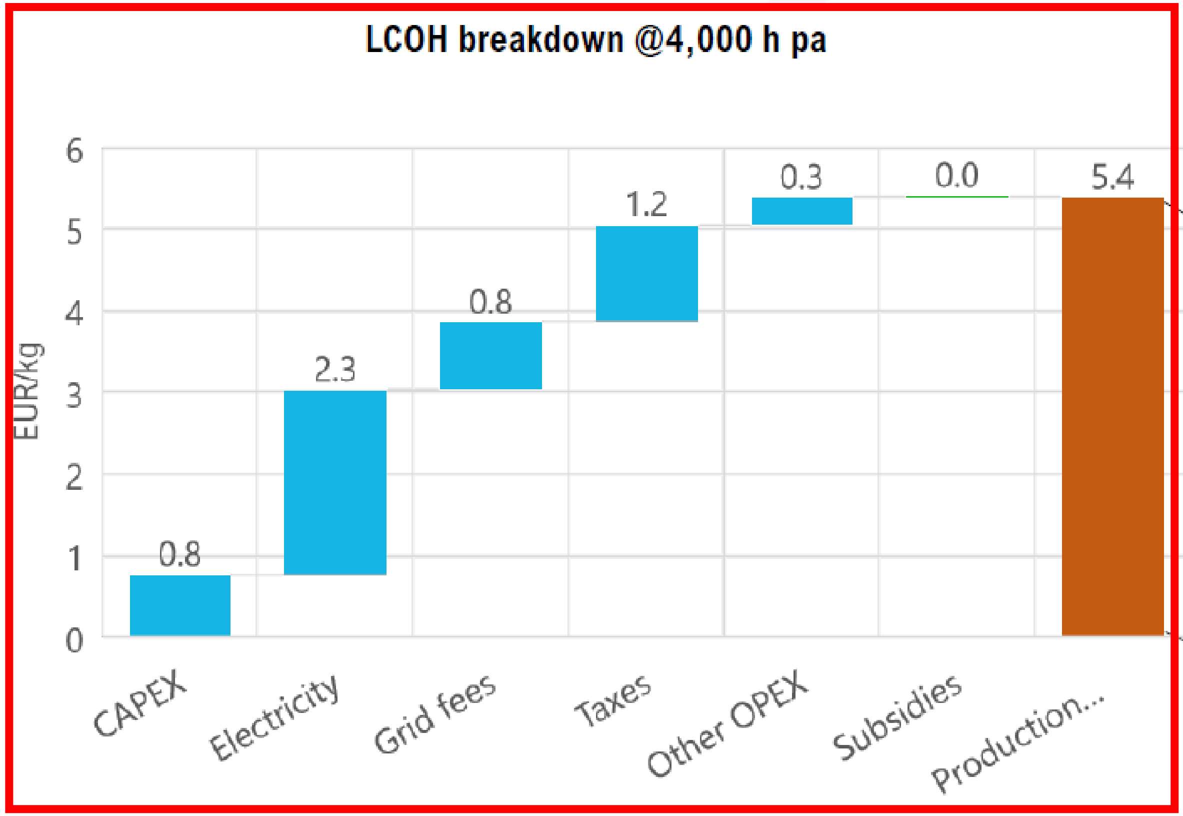
$$LCOH = \frac{LCCO}{Util} + LCOE * Eff$$

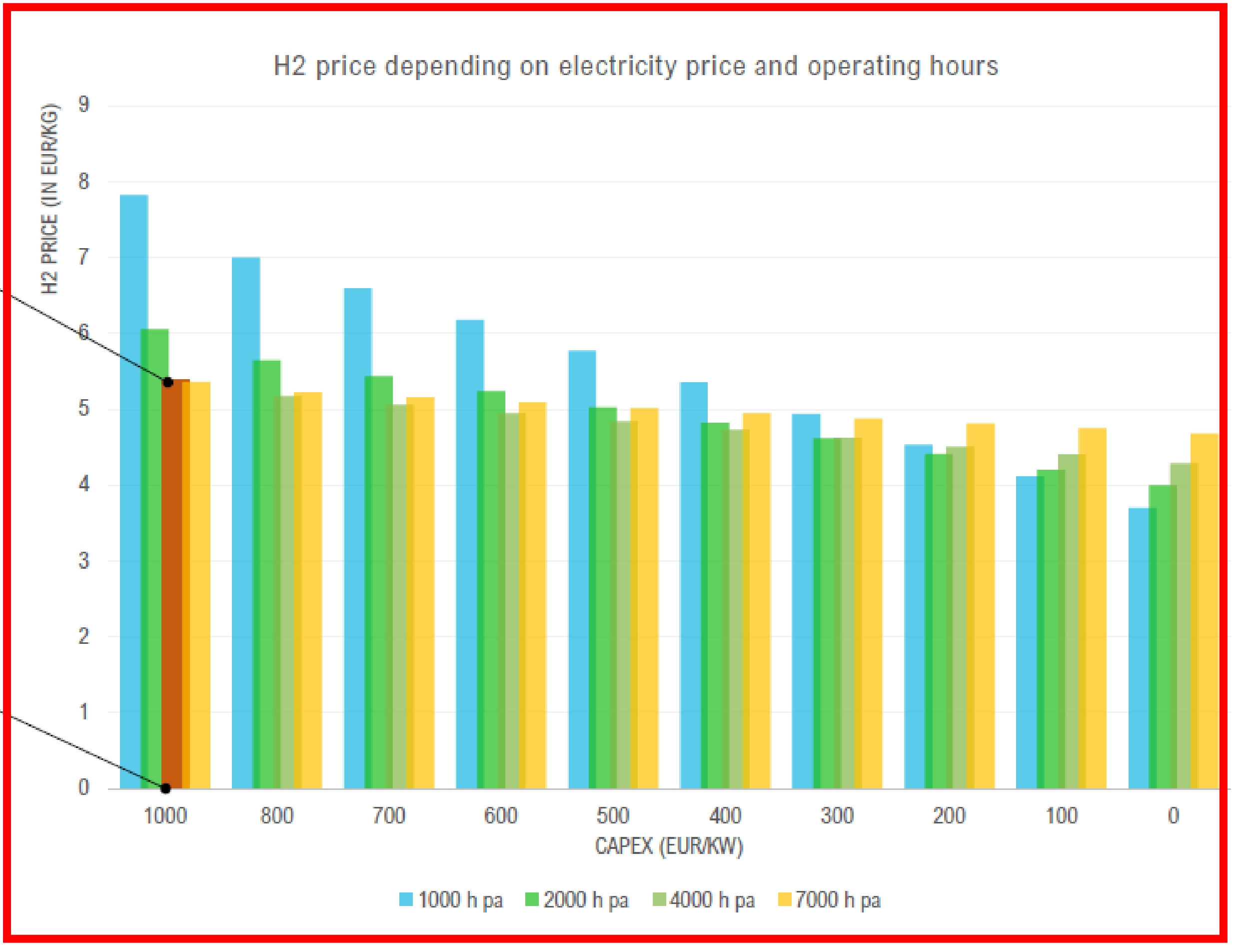
Symbol	Definition	Unit
LCOH	Levelized Cost of Hydrogen	€/kg H_2
LCCO	Levelized cost of Capital and fixed Opex at 100% utilization	€/kg H_2
Util	Utilization rate of the electrolyser	% of the time
LCOE	Levelized cost of electricity	€/kWh$_e$
Eff	Efficiency of the electrolyzer	kWhe/kg H_2

Cost components of green hydrogen?

Source: Hydrogenics 2019
https://www.hydrogenics.com/

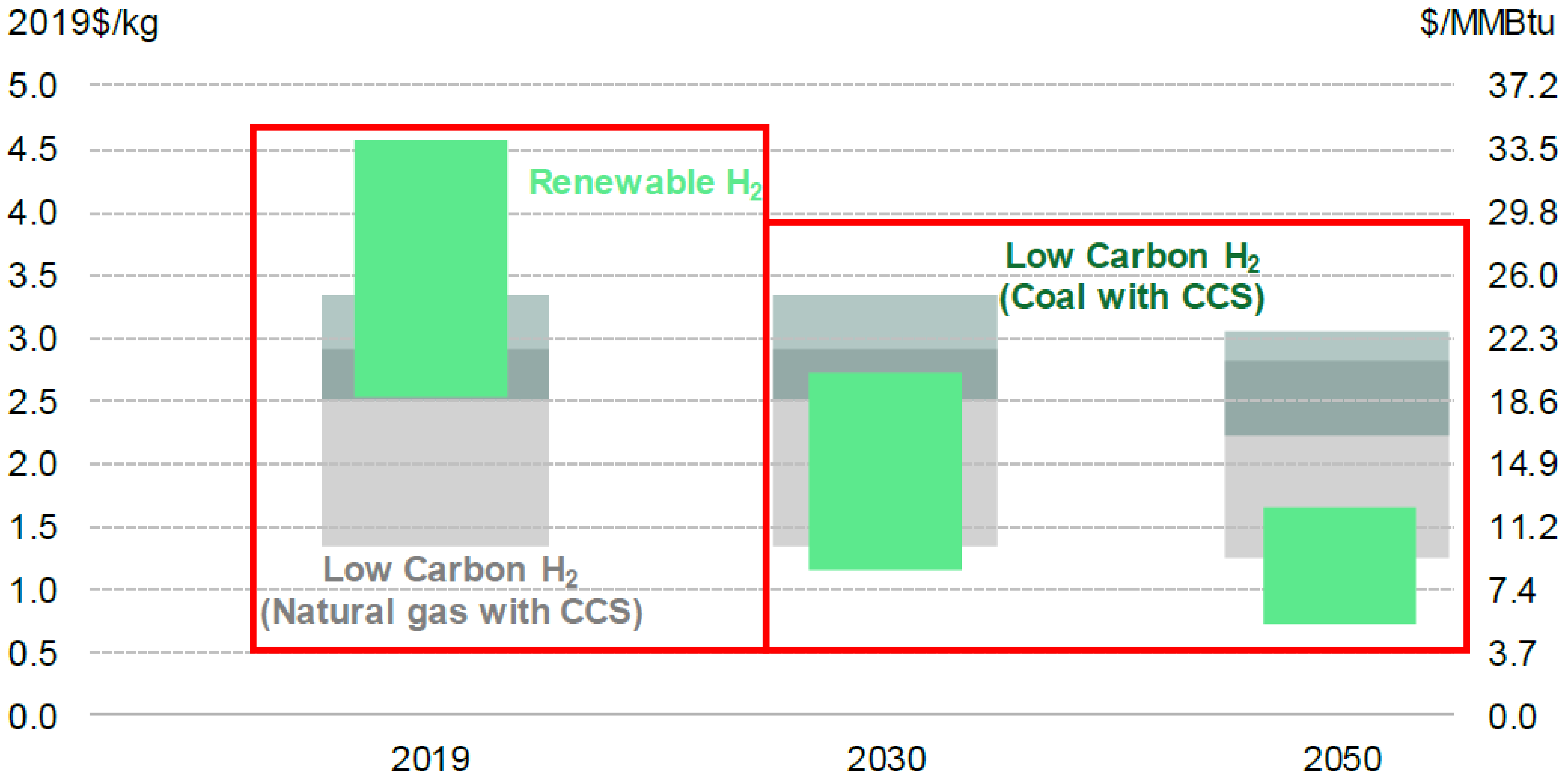
Hydrogen production cost breakdown





Source: Hydrogen Europe 2021
https://hydrogeneurope.eu

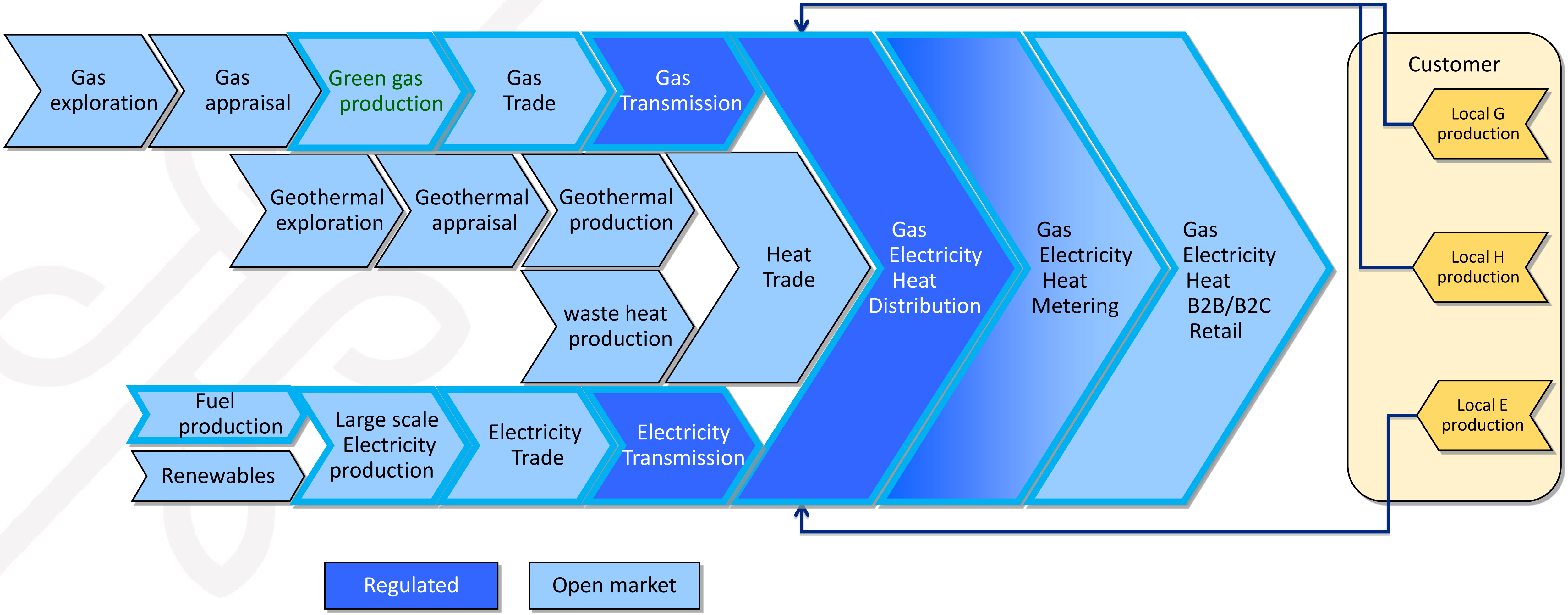
Forecast global range of levelized cost of hydrogen production from large projects



Natural gas seems the best candidate to support the transition towards a green gas economy via the blue hydrogen route.

Source: Bloomberg, May 2020
https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

End use applications, energy value chain ---> hydrogen NL example



Government roles: policy maker, regulator, share holder, taxes, governance subsidies, dividend receiver