The role of hydrogen in the energy transition:

Technological options, costs and the role for a carbon neutral energy system

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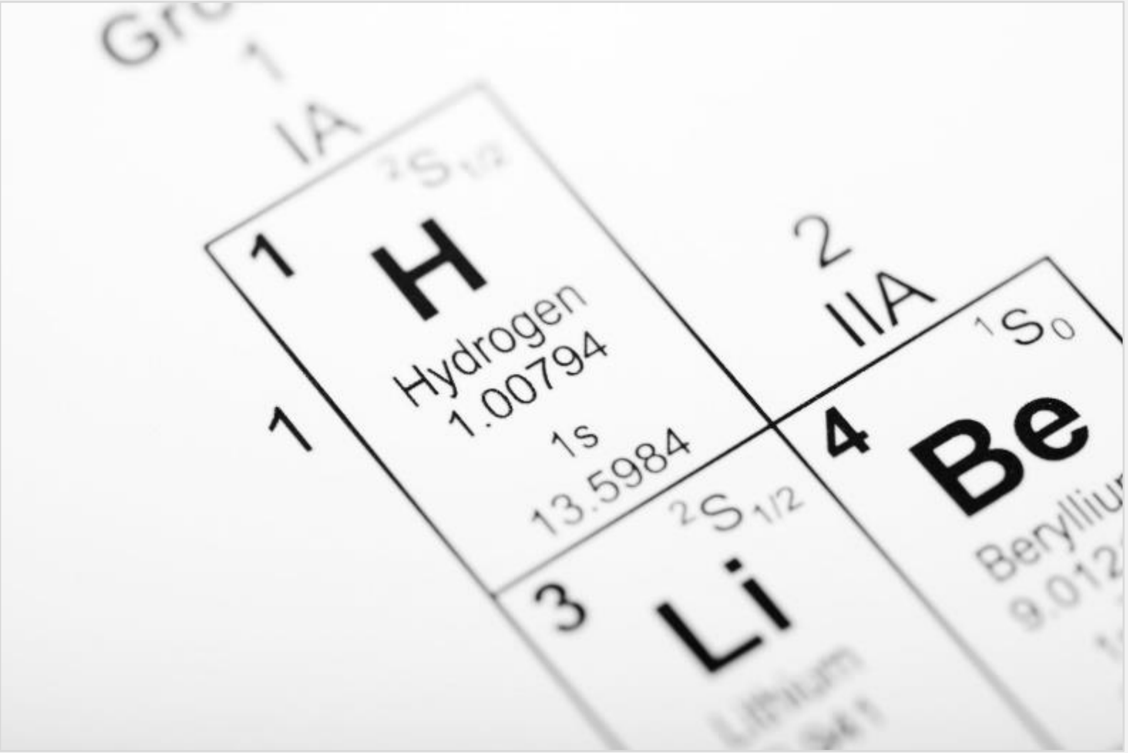
Outline

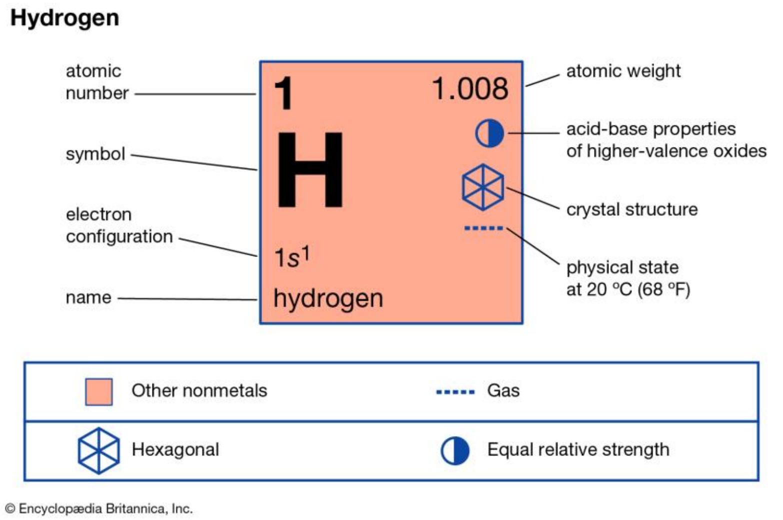


What is Hydrogen?

> The most abundant chemical substance in the Universe.

> The lightest element in the periodic table.

> Contains more energy per unit of mass than natural gas or gasoline (3X) – lower energy per volume (1/10 of natural gas)



larger volumes of hydrogen are needed to meet identical energy demands as compared with other fuels

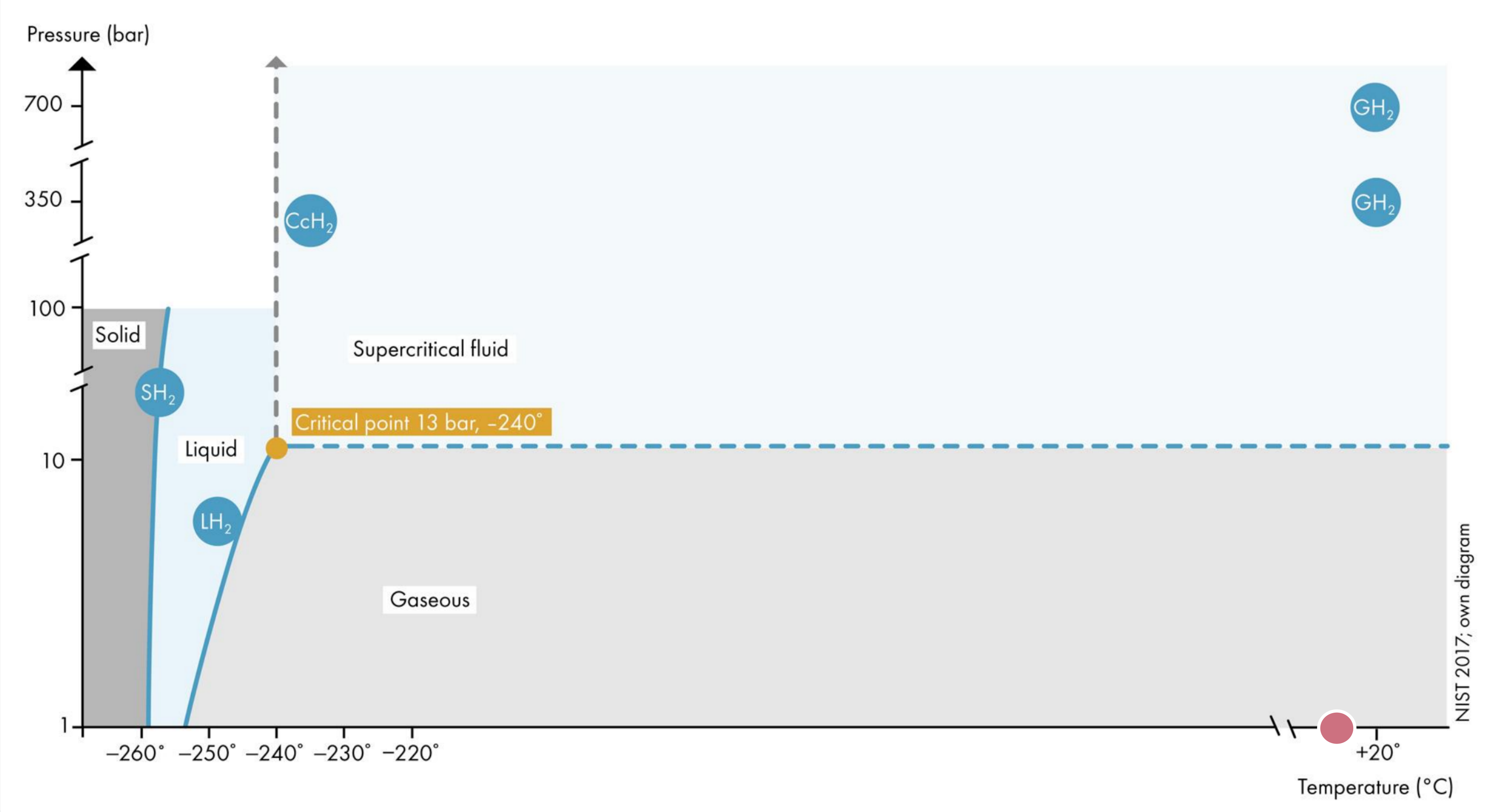
Physical properties of hydrogen

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/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Source: IEA, 2019a

Phase H_2 diagram



Source: Shell, 2017

The early entrance of H2 in the energy system

- In the begging of the XIX century H_2 was incorporated in street lighting in Europe and USA as town gas (produced trough coal gasification)
- H_2 was around 50% of town gas
- Why town gas?
  - Economic: Cheaper than whale oil
  - Quality of services: Brighter and safer flame

- Widespread adoption of town gas in UK around 1820

- In Lisbon the public lighting trough town gas started in 1848 (Chiado)

- When electricity (and in some countries natural gas) appeared, town gas started to disappear
- In Portugal for example the first eletric lighting appearred in 1878 and the town gas continue in the streets of Lisbon up to 1965 (Bairro Alto and Santa Catarina).

Is H_2 safe?

1. H_2 is **not toxic**, unlike conventional fuels.

2. H_2 is **14X lighter than air and 57X lighter** than gasoline vapor. When released, hydrogen will typically rise and disperse rapidly, reducing the risk of ignition at ground level..

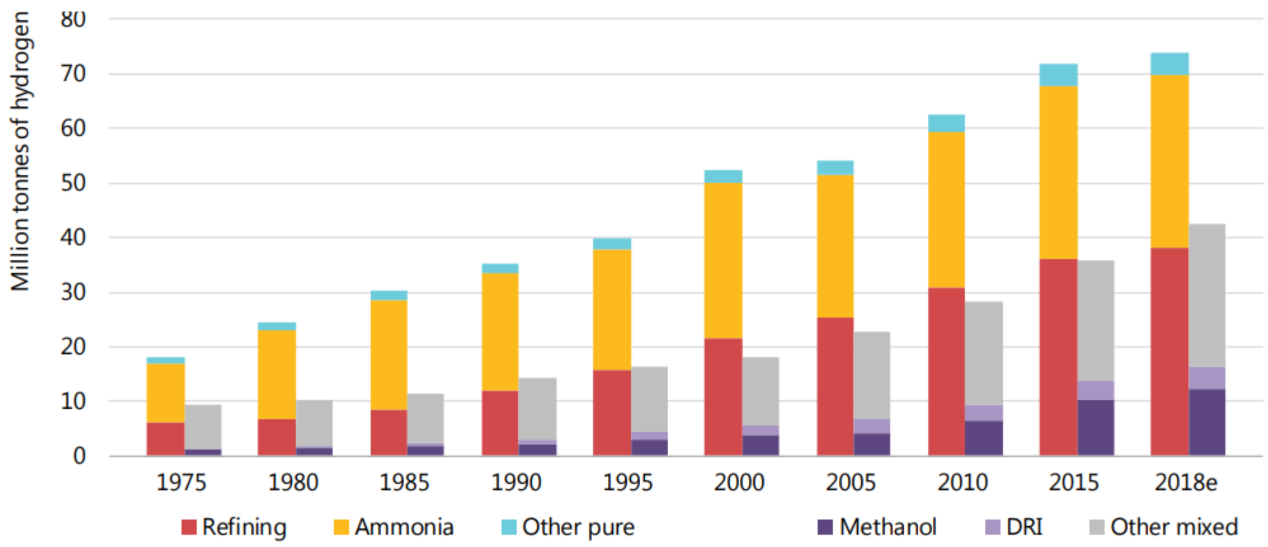
3. H_2 has a **lower radiant heat than conventional gasoline**, meaning the air around the flame of hydrogen is not as hot as around a gasoline flame.

4. H_2 has a **higher oxygen requirement for explosion than fossil fuels**. Ii can be explosive with oxygen concentrations between 18-59% while gasoline can be explosive at oxygen concentrations between 1-3%.

***Hindenburg* disaster 1937**

What is the current role of H_2?

Global annual demand for hydrogen since 1975



Notes: DRI = direct reduced iron steel production. Refining, ammonia and "other pure" represent demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock.

Source: IEA 2019.

Around 70 MtH_2/yr is used today in pure form, mostly for oil refining and ammonia manufacture for fertilisers; a further 45 MtH_2 is used in industry without prior separation from other gases.

Current H_2 uses:

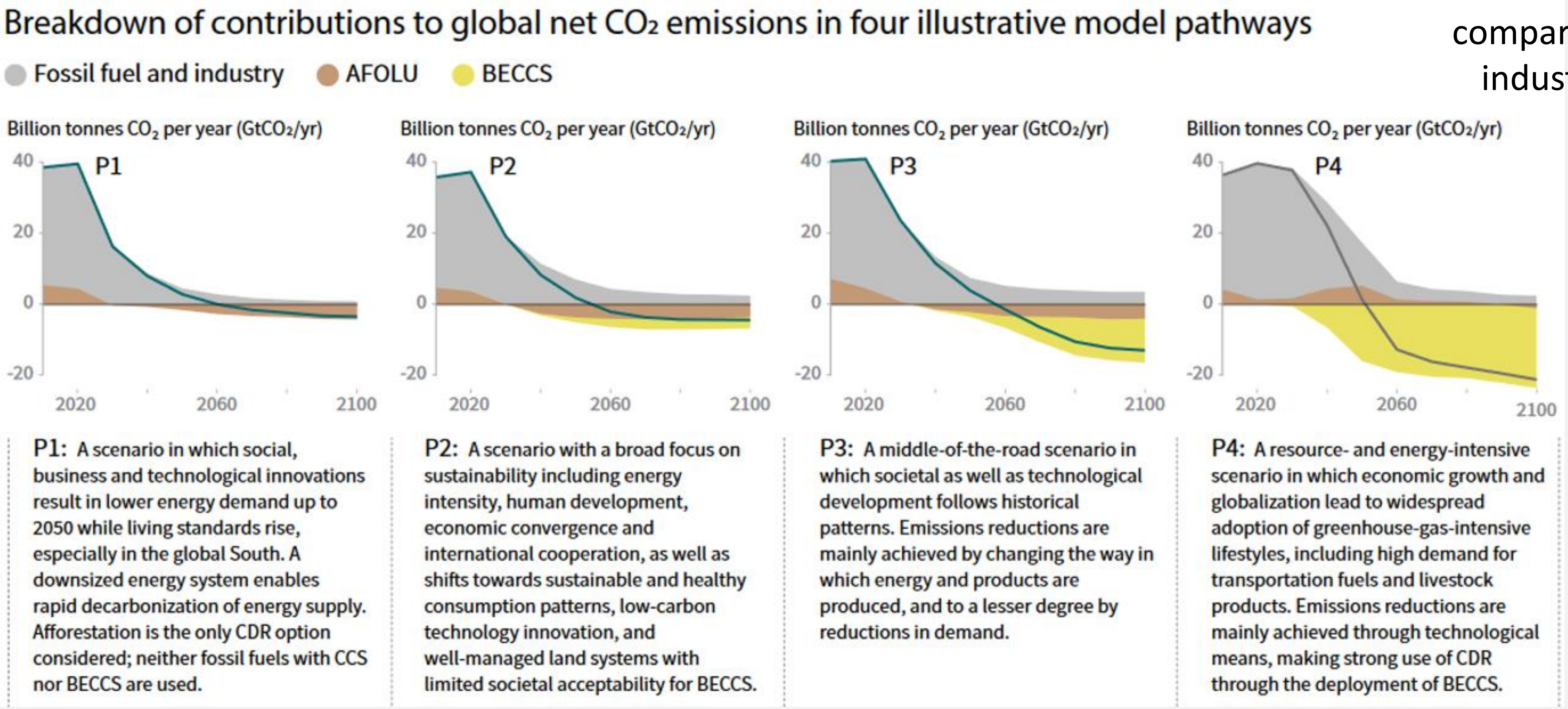
> refining petroleum (e.g., lower the sulfur content of diesel fuel),

> producing fertilizer (ammonia)

Source: IEAa, 2019

Why are we talking so much about H_2?

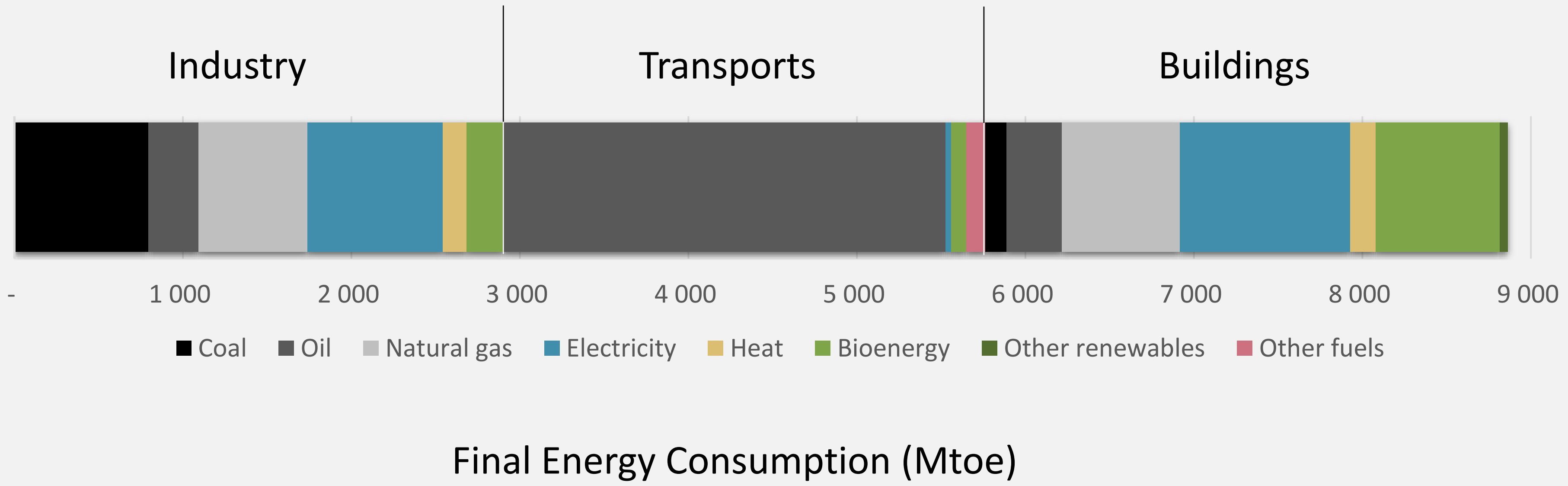
Climate Change - Limiting global warming to 1.5◦C compared to pre-industrial levels



Source: IPCC, 2018

Why are we talking so much about H_2?

> H_2 can be an alternative energy vector to lower the carbon intensity of transport (and heating)

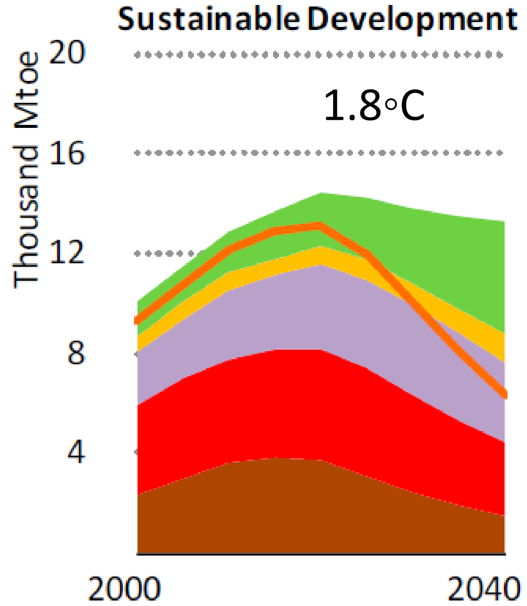


17 809 Mt CO_2 (54% of energy-related CO_2 emissions)

Source: IEAb, 2019

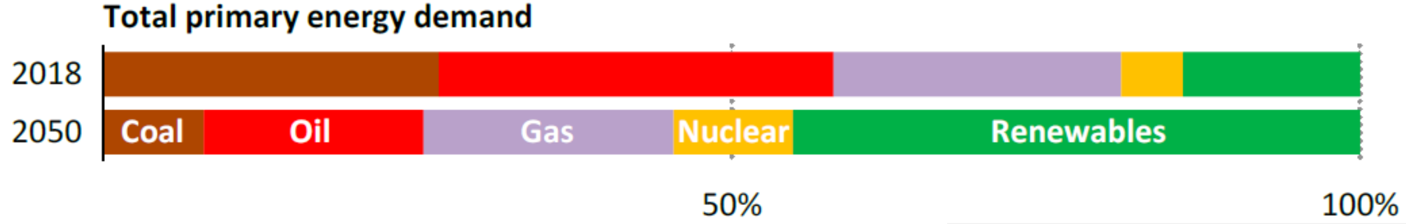
Why are we talking so much about H_2?

▻ **World primary energy demand by fuel and related CO_2 emissions by scenario**



Coal Oil Gas Nuclear Renewables CO_2 emissions (right axis)

▻ **Primary energy mix and fuel use by sector in the Sustainable Development Scenario, 2018 and 2050**



Existing policies and announced targets slow growth in global emissions to 2040, but they are not strong enough to force a peak in an expanding energy system

Energy system transformation

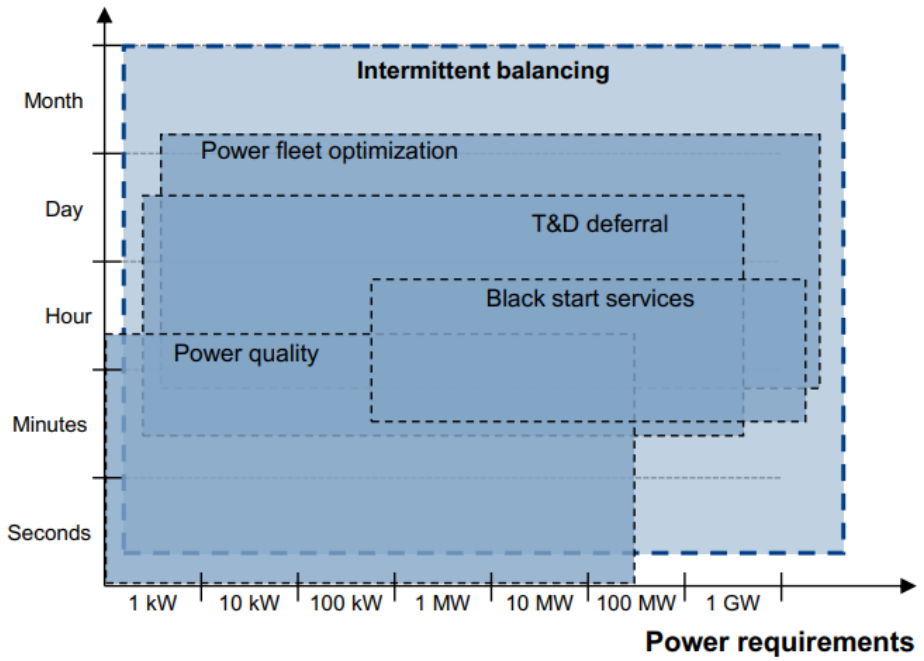
> Renewable energy sources (RES) will have a major contribution in reduction GHG

> Most of RES are intermittent

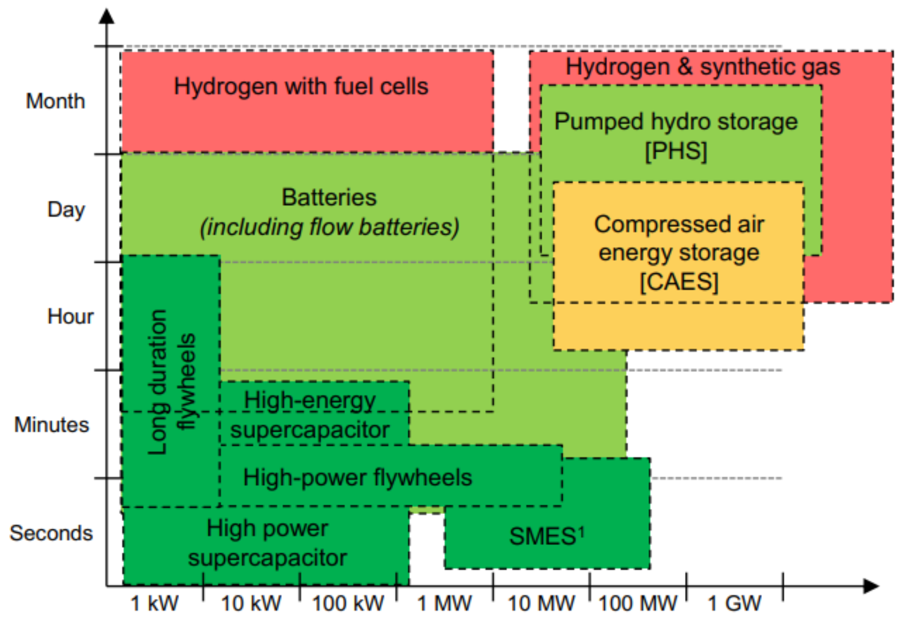
Source: IEAb, 2019

Why are we talking so much about H_2?

Storage Applications Requirements[2]
Discharge time vs. power requirements (MW)



Electricity storage technollogies' features
Discharge time *vs.* power requirements (MW)



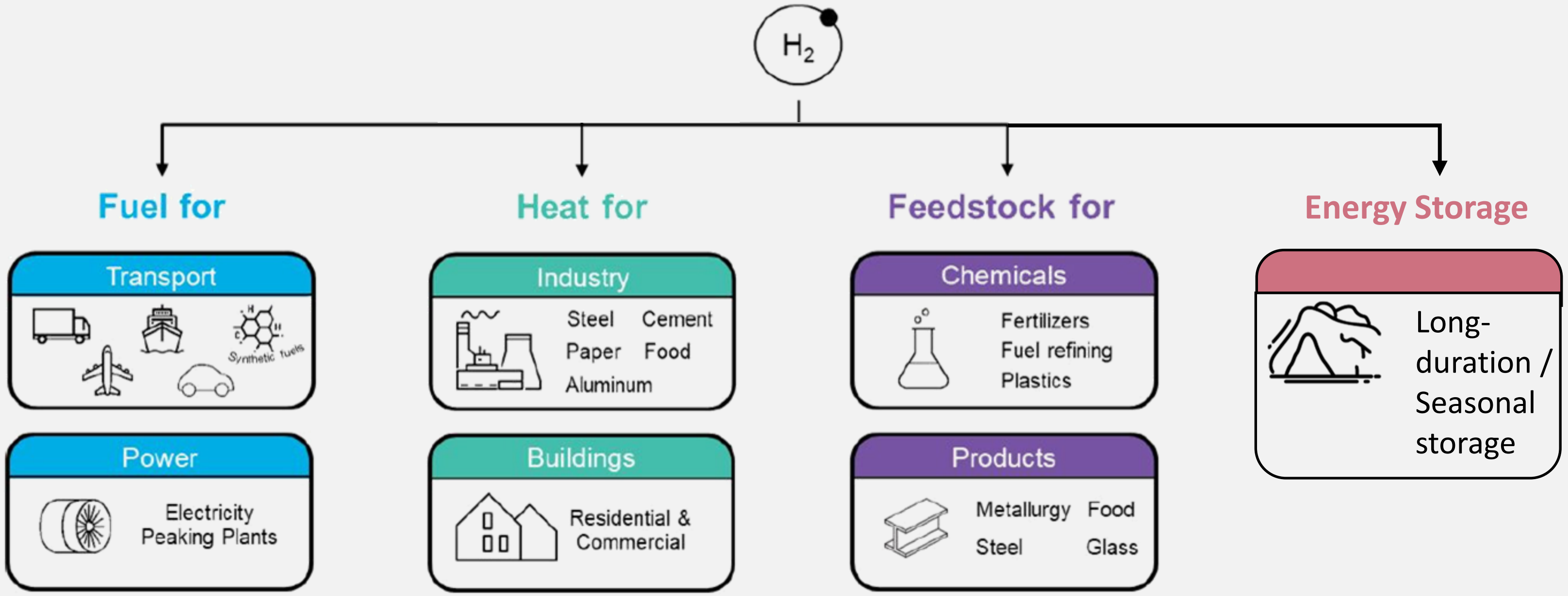
1. SMES: superconducting magnetic energy storage; 2. For more information on storage applications, please refer to the Hydrogen FactBook; 3. T&D for transmission & distribution
Source: A.T. Kearney Energy Transition Institute based on US DoE (2011), "Energy Storage Program Planning Document".
Hydrogen-based energy conversion

Electricity Storage

- H_2 can be storage at large scale
- Allows a seasonal storage

Source: AT Kearney Energy Transition Institute, 2014.

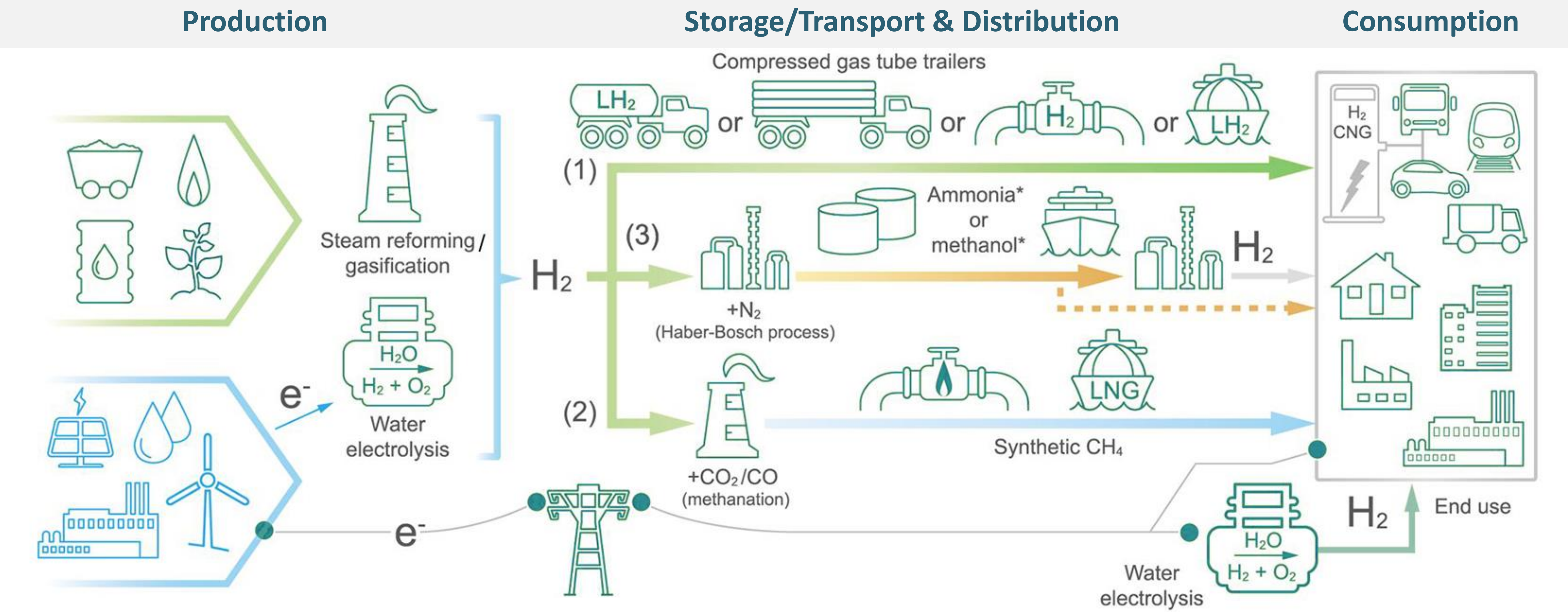
Why are we talking so much about H_2?



Source: Adapted fromBloomberg NEF

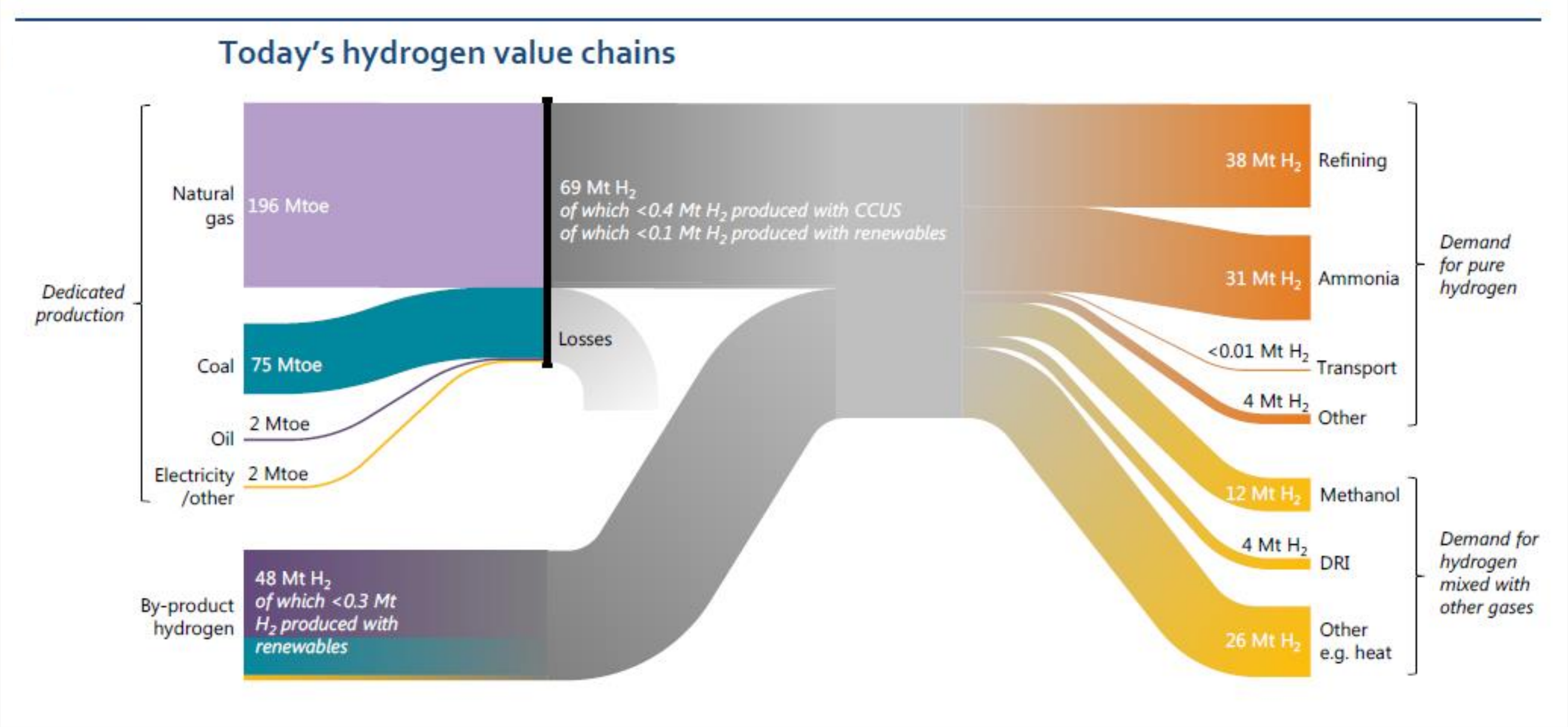
H2 can play a key role in many economic sectors/uses

What is H_2 economy? | H_2 chain



Hydrogen value chains can follow many different paths

The production of H_2 today



IEA, 2019a

The majority of H2 produced is from fossil fuels - 60% is from "dedicated" hydrogen production facilities

Most is produced from natural gas

Small fraction comes from water electrolysis (water + electricity).

Less than 0.7% of H2 production is from RES or from fossil fuel plants with CCUS (2018)

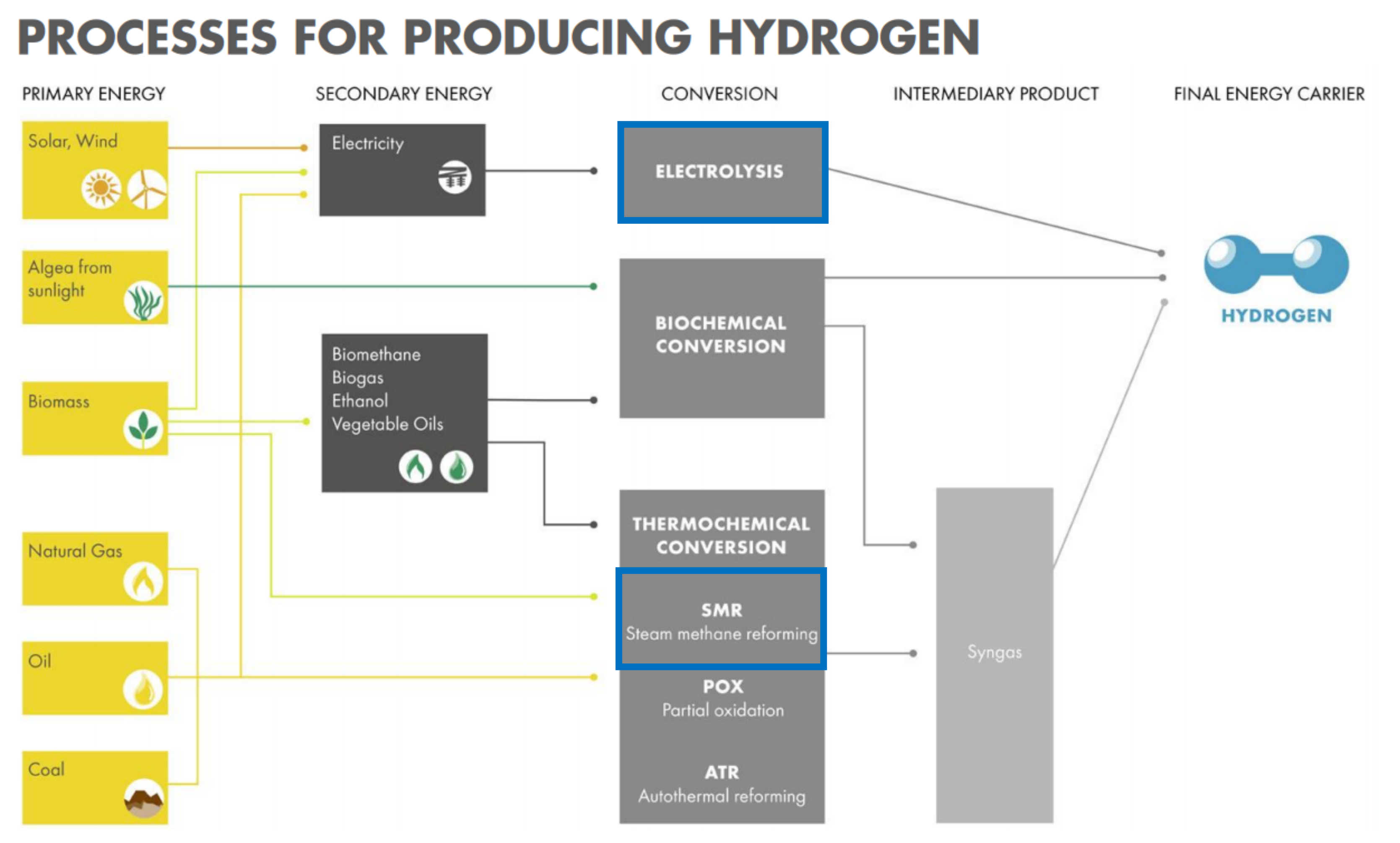
H2 production is responsible for 830 MtCO2/yr

H_2 production

Green H2

Grey/Blue (CCS) H2

Black H2



Source: Shell, 2017

Hydrogen 101 short film

STUDENT ENERGY
Student Energy
53,1 mil subscritores

https://www.youtube.com/watch?v=Kv8WT3-7ZHE

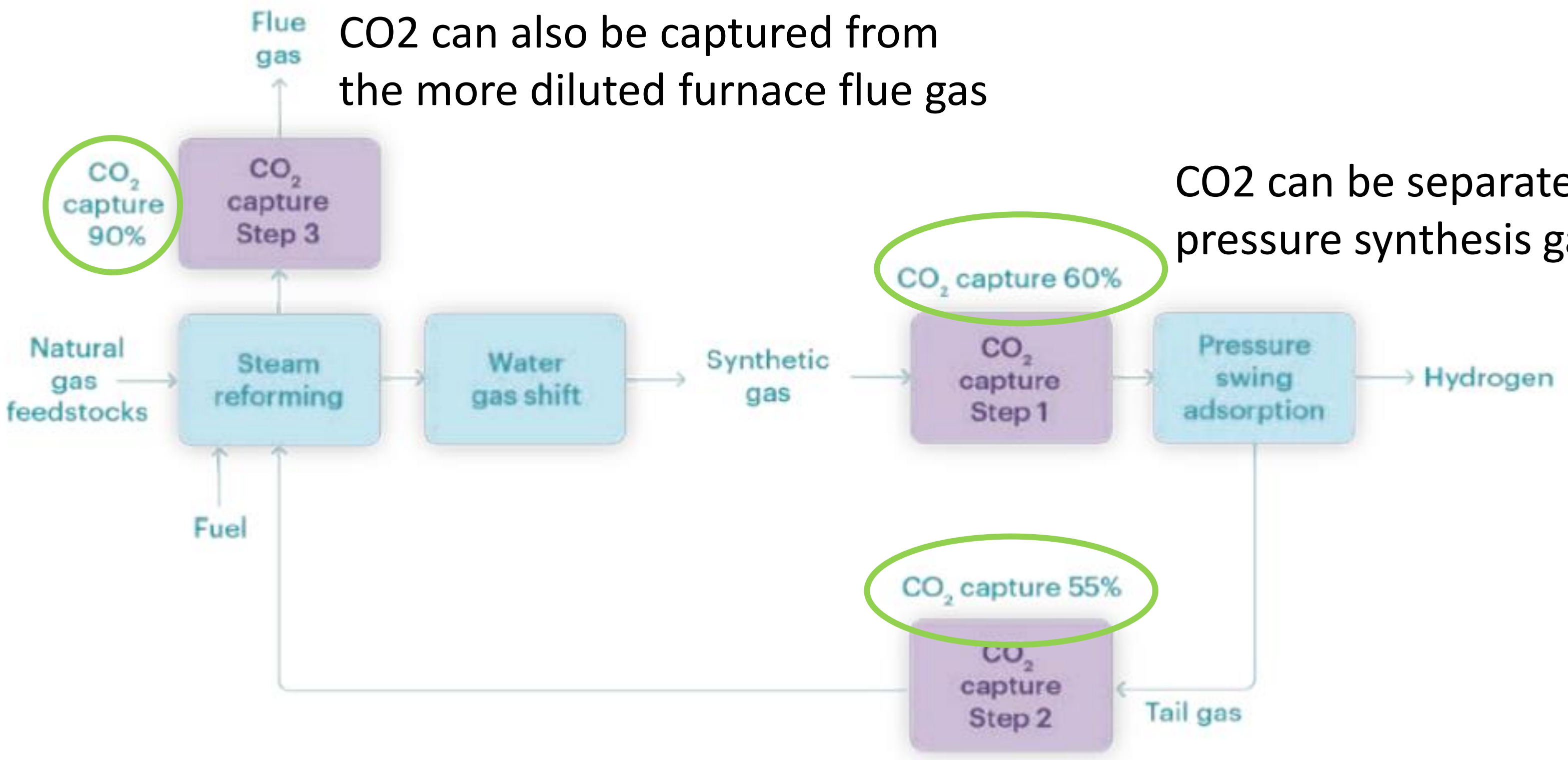
BLUE hydrogen

SRM with carbon capture and utilization

Figure 8. Production process of hydrogen from gas with CCUS

CO2 can also be captured from the more diluted furnace flue gas

CO2 can be separated from the high-pressure synthesis gas stream



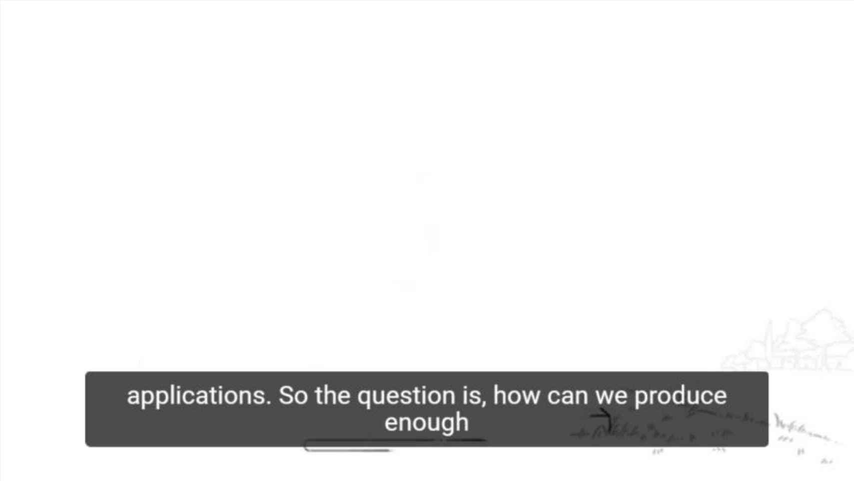
Source: IEAGHG (2017a), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS".

Source: IEA, 2019a

Electron to hydrogen

H_2 Production | Water electrolysis

- Electrochemical reaction that splits water into H_2 and Oxygen, using electricity.
- It is a 100% emission free and carbon-free process



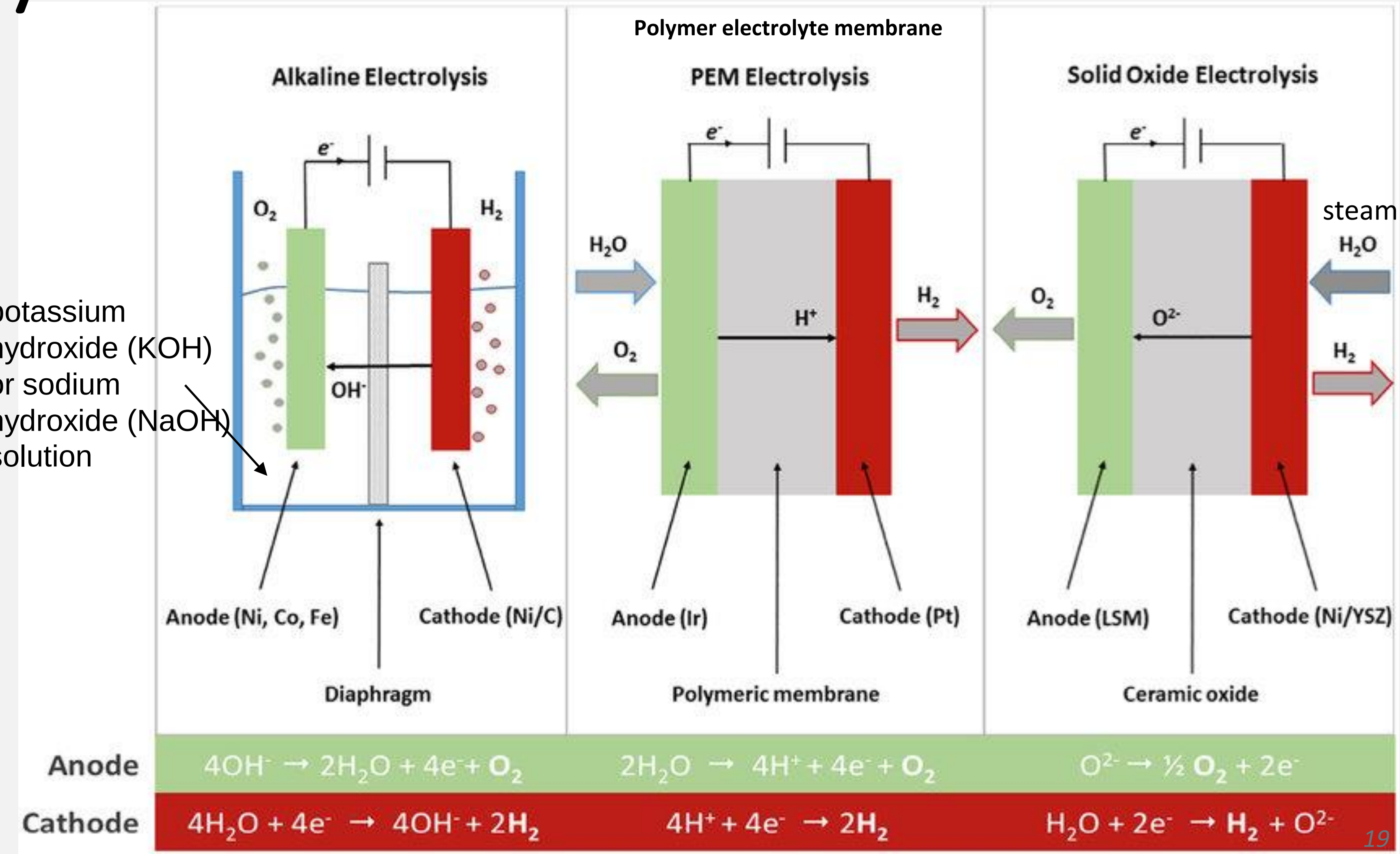
https://youtu.be/ZLf1cOWsefU

Power: 1 MW electrolyser ⟷ ± 18 kg/h H_2
Energy: +/- 55 kWh of electricity →1 kg H_2 ⟷ ± 9 liters demineralized water

Electron to hydrogen

Water electrolysis

potassium hydroxide (KOH) or sodium hydroxide (NaOH) solution



Electron to hydrogen

Water electrolysis

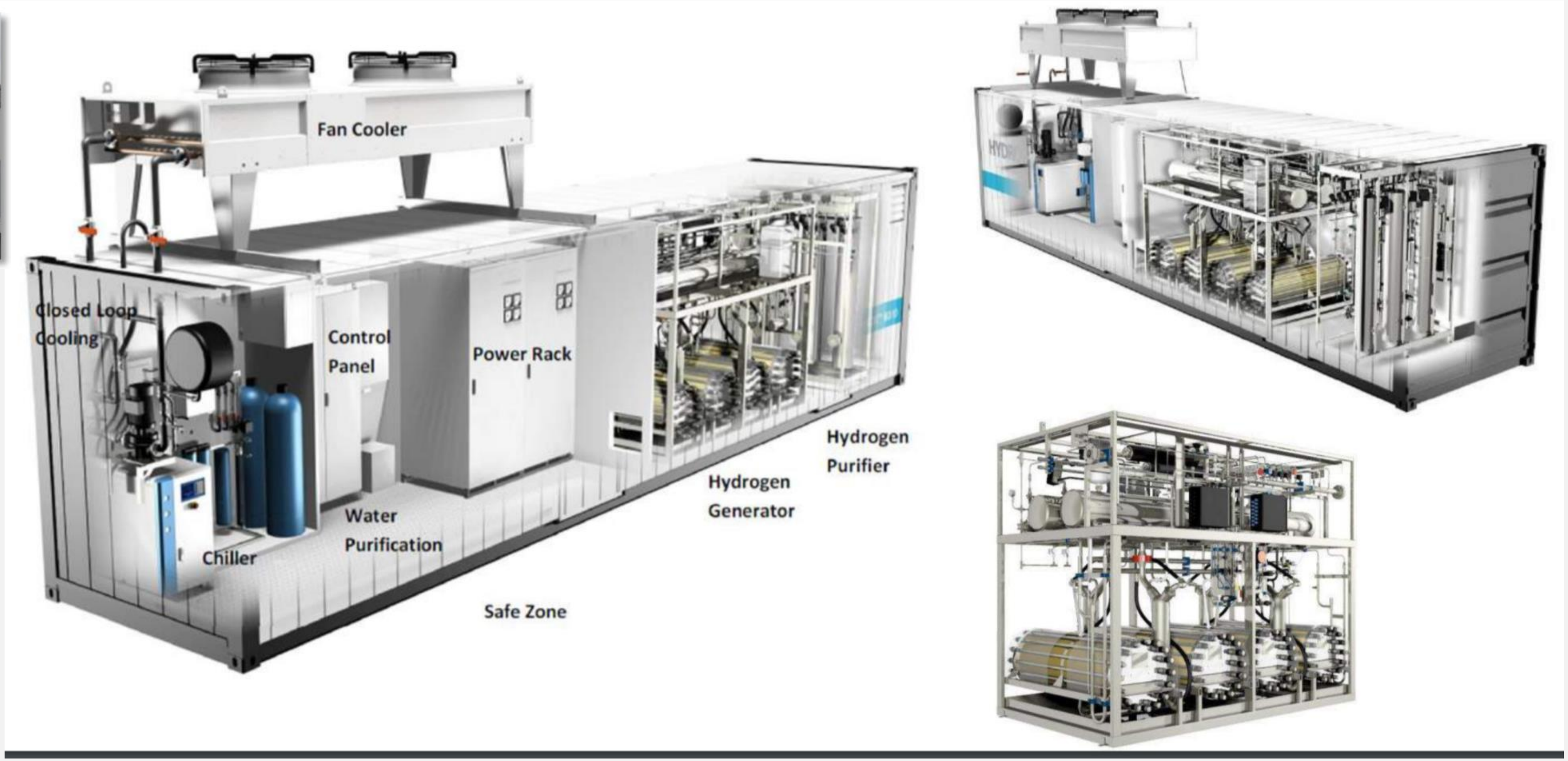
- Alkaline electrolyser
  - Mature and commercial technology
  - Do not operate on zero load
  - Do not produce highly compressed H2 – needs additional compression
  - Needs the recovery and recycling of the potassium hydroxide electrolyte solution
- PEM
  - Produce highly compressed H2
  - Operating range can go from zero load
  - Need expensive electrode catalysts (platinum, iridium) and membrane materials
- SOEC
  - Have not yet been commercialized
  - Need a heat source (nuclear, solar thermal, geothermal)
  - It is possible to operate in reverse mode

	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
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					
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

Source: IEA, 2019a

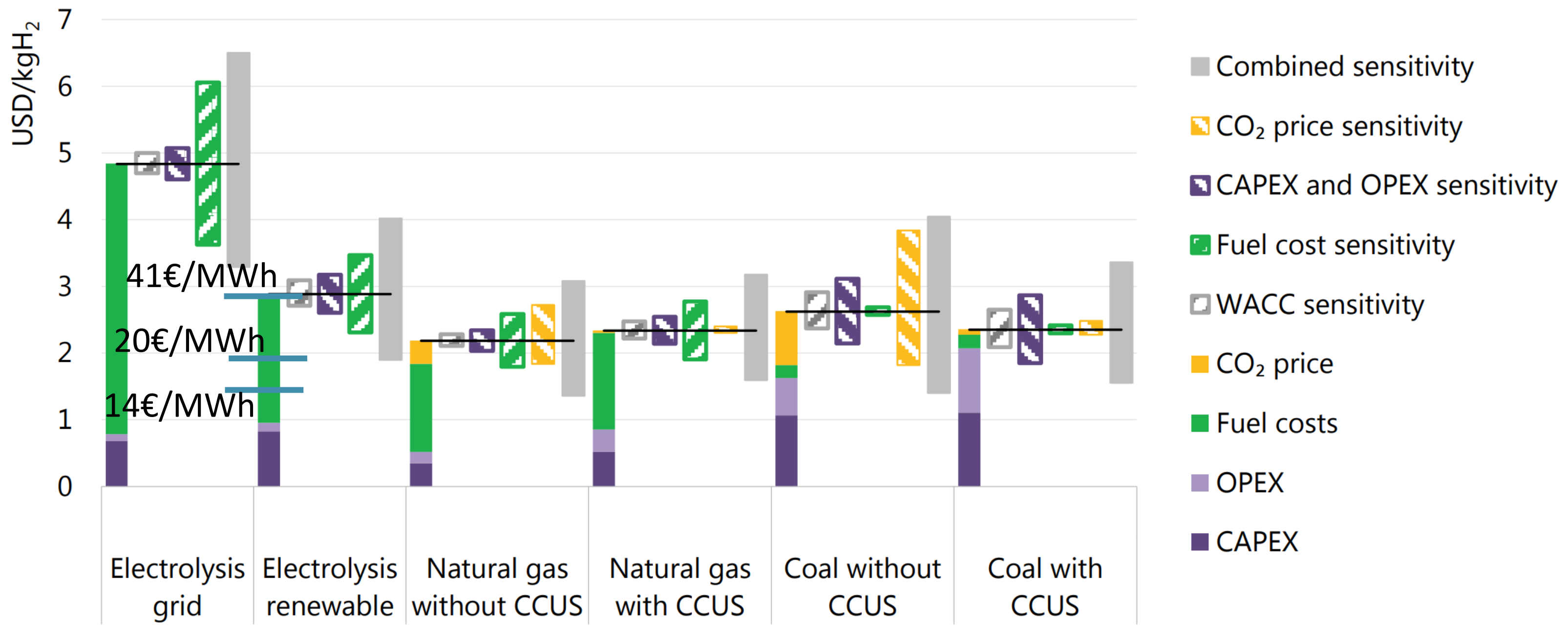
Studies indicate PEM as the main electrolyser technology in the future

How does an electrolyser (alkaline) looks like?



Source:
https://hydrogeneurope.eu/sites/default/files/2018-06/2018-06_Hydrogenics_Company%20presentation.compressed.pdf

H_2 production costs

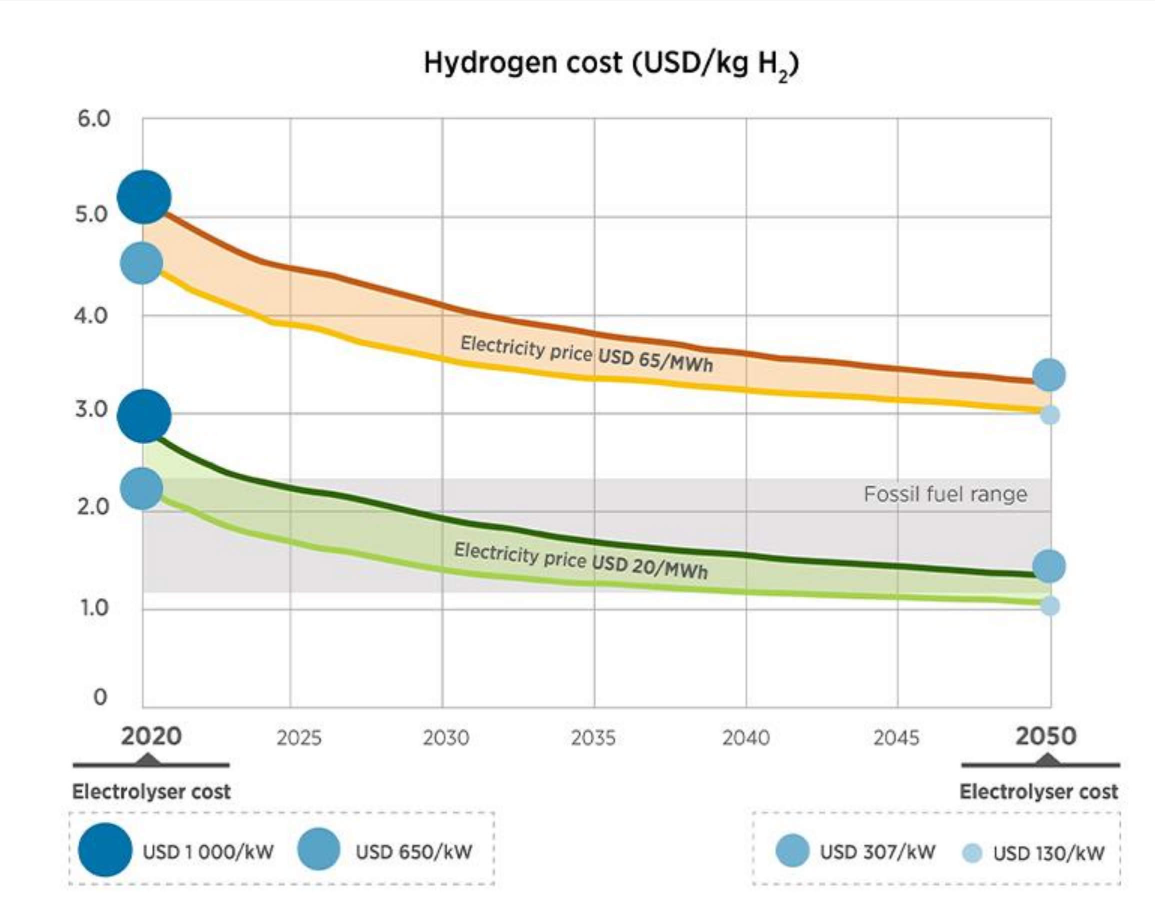


Notes: WACC = weighted average cost of capital. Assumptions refer to Europe in 2030. Renewable electricity price = USD 40/MWh at 4 000 full load hours at best locations; sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs; +/-3% change in default WACC of 8% and a variation in default CO_2 price of USD 40/tCO_2 to USD 0/tCO_2 and USD 100/tCO_2. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA, 2019a

- Steam Methane Reforming from Natural Gas is the cheapest way to produce H2
- Electricity price is the biggest component of H2 production price (Renewable electricity price around 41€/MWh)
- The 1st solar auction in Portugal has awarded at an average tariff of 18,4 €/MWh, with a lot awarded at 14,7 €/MWh, the lowest price in the world at the time. In the 2nd auction the lolowest output price was broken once again with a bid of 11.2€/MWh

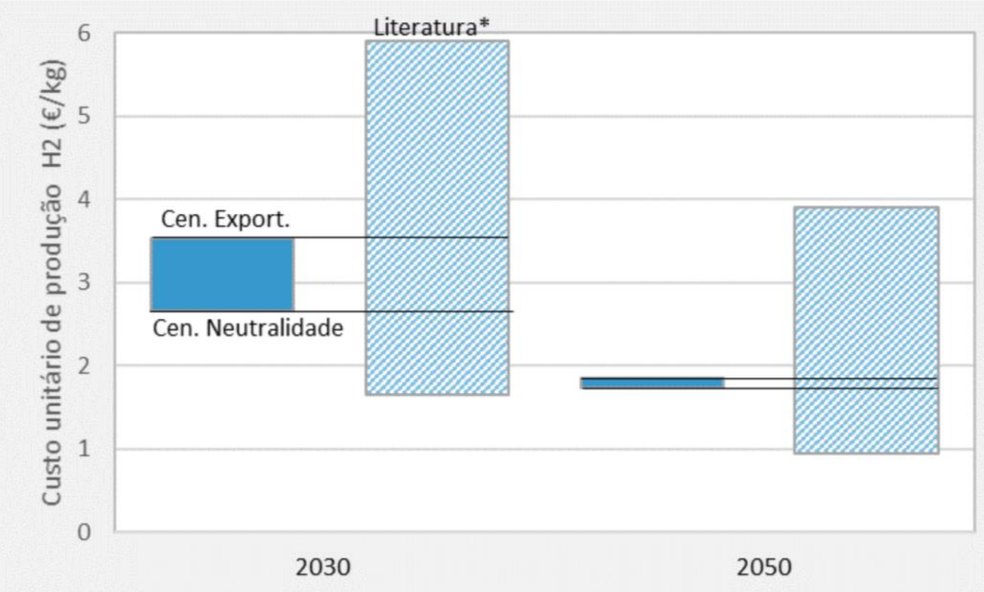
Electrolysis and H_2 cost evolution



Source: IRENA, 2020

> Electrolysers are expected to reduce its cost between 65-80% from 2020 to 2050

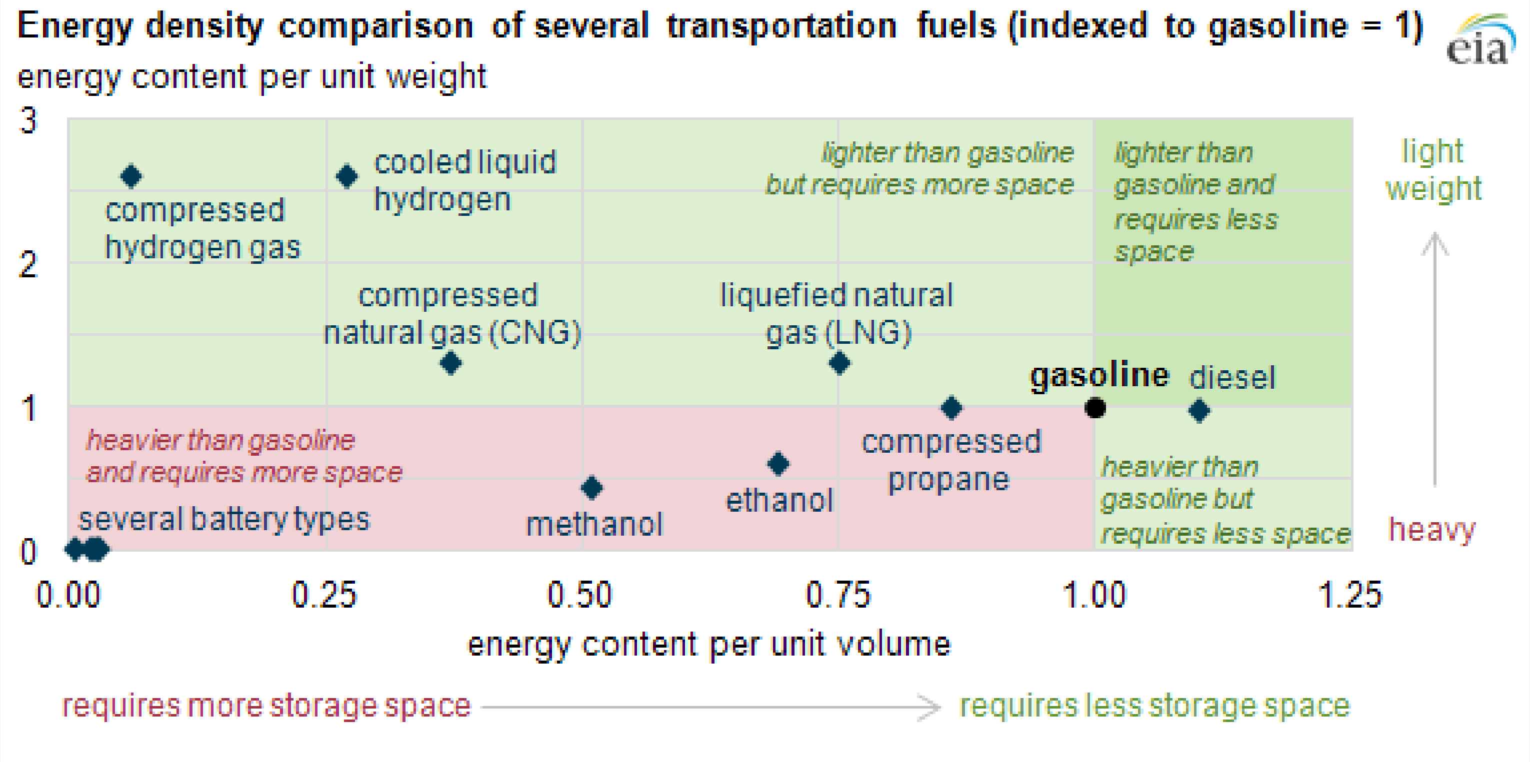
H2 production cost in Portugal



Source: NOVA-FCT, 2020

H_2 Storage

- H2 low volumetric energy density at ambient conditions makes it considerably harder to store than fossil fuels – compressions, liquefaction or absorption
- If hydrogen replace natural gas in the global economy today would need 3-4 times more storage infrastructure



Source: https://www.eia.gov/todayinenergy/detail.php?id=9991

H_2 Storage

$CO_2 + 2H_2 \rightarrow CH_3OH$ (methanol)

$3H_2 + N_2 \rightarrow 2NH_3$

Cool it down H2 further, to its melting point (-260◦C)

Table 1: Hydrogen storage options

	Gaseous state				Liquid state			Solid state
	Salt caverns ●	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen ●	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.

- ● High energy lost (24-45%)
- ● Energy lost (5-10%)

Source; BloombergNEF, 2020

LOHC – Liquid Organic H2 Carriers, e.g., methanol, dibenzyltoluene and toluene

Note: Salt caverns are the only type of geological formation successful used to storage H2 underground to date. Other alternatives are under research to test leaks and reactivity with the host rock

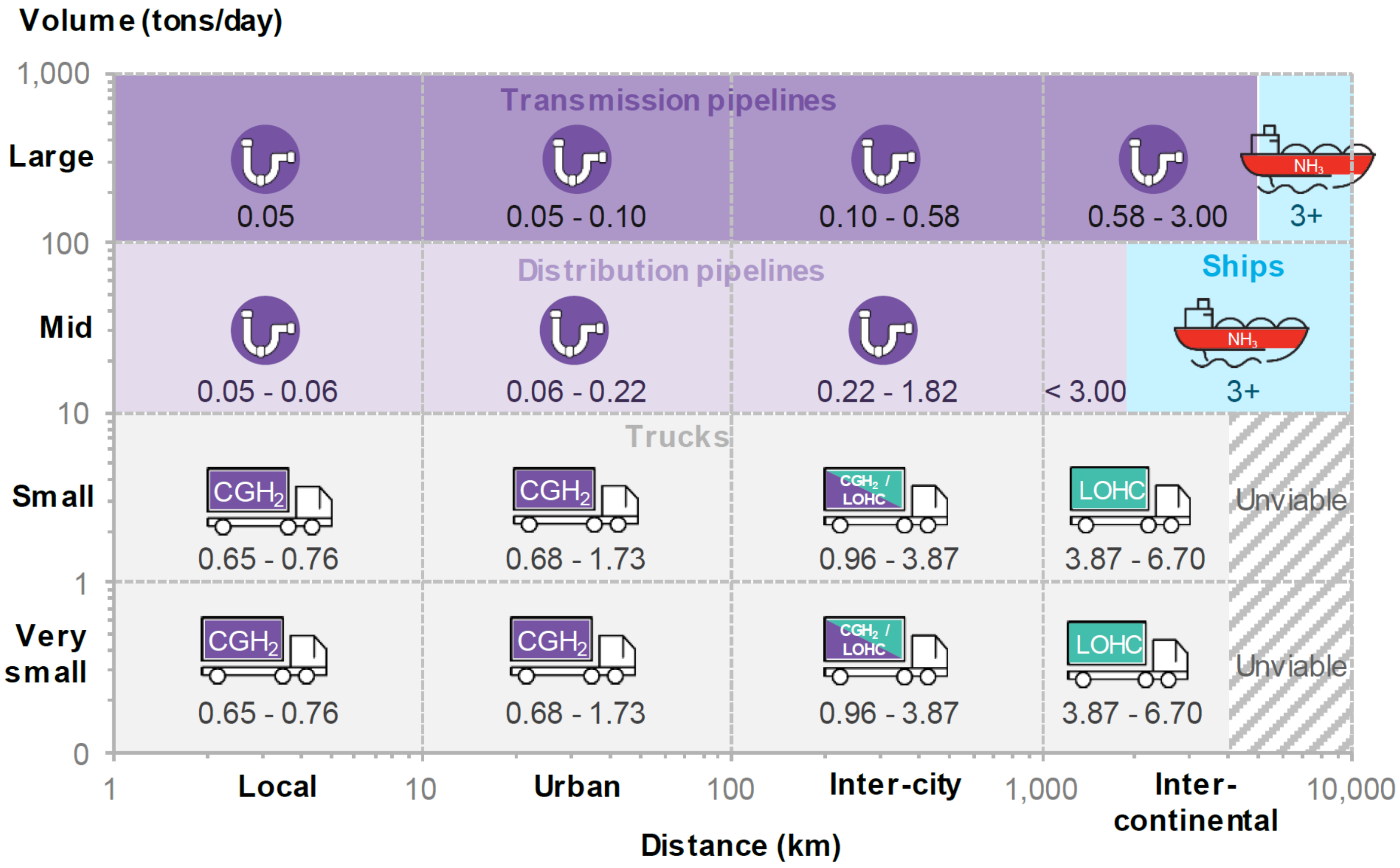
H_2 Transport & Distribution

- > The low energy density of hydrogen means that it can be very expensive to transport over long distances

- > The best option: **blending in the natural gas grid, dedicated grid, trucks or shipping** will vary according to geography, distance, amount of H2 and the required end use of the hydrogen

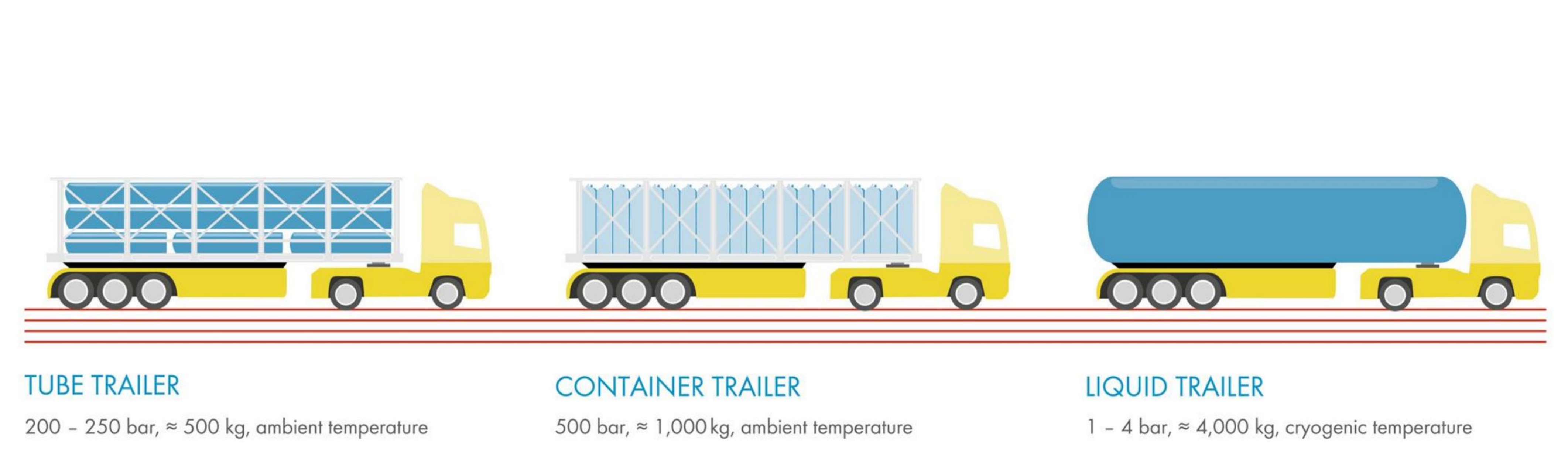
Source; BloombergNEF, 2020

Figure 4: H_2 transport costs based on distance and volume, $/kg, 2019



Legend: Compressed H2 Liquid H2 Ammonia Liquid Organic Hydrogen Carriers

H_2 Road Transport

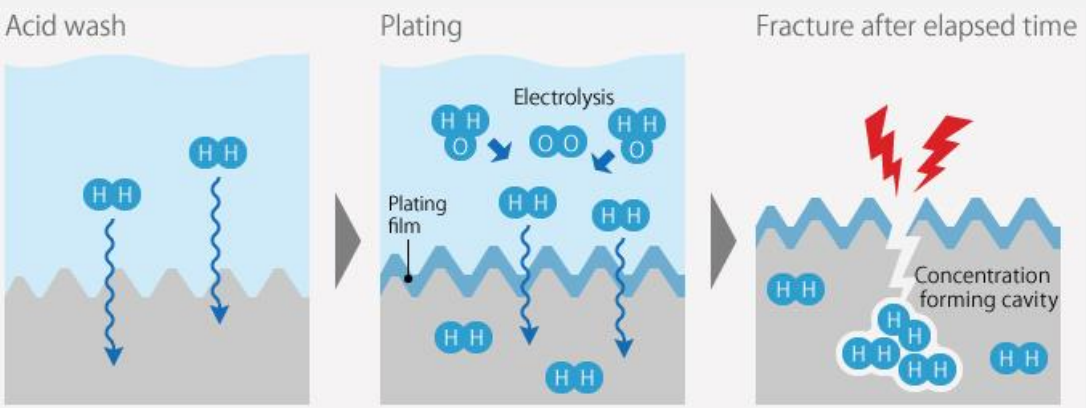


Source: Shell, 2017

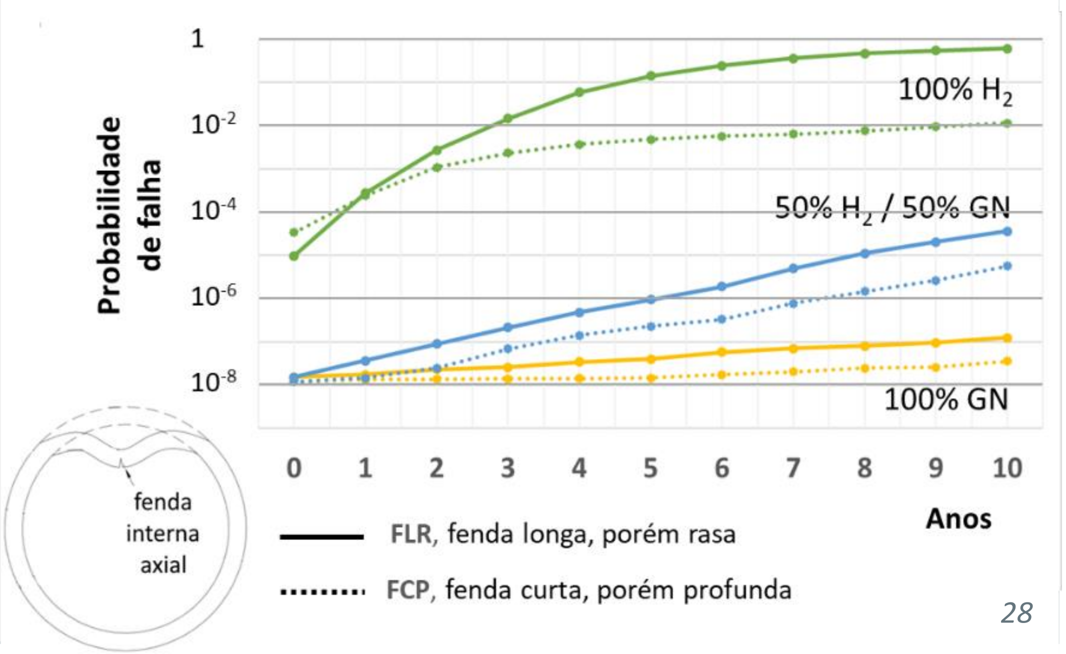
Blending H_2 in the natural gas grid

Limitations

- The material of the pipeline limits the amounts of H2:
  - polyethylene distribution pipelines can handle up to 100% hydrogen
  - some metal pipes can degrade when exposed to hydrogen over long periods, particularly with H2 in high concentrations and at high pressures – ***embrittlement*** - *Literature suggests a maximium of 20% blending without major transformations of the natural gas grid*
- Energy density of hydrogen is around 1/3 of that of natural gas and so a blend reduces the energy content of the delivered gas – more volume needed
- *Even a 20% blending of H2 only reduce natural gas emissions in 7%*

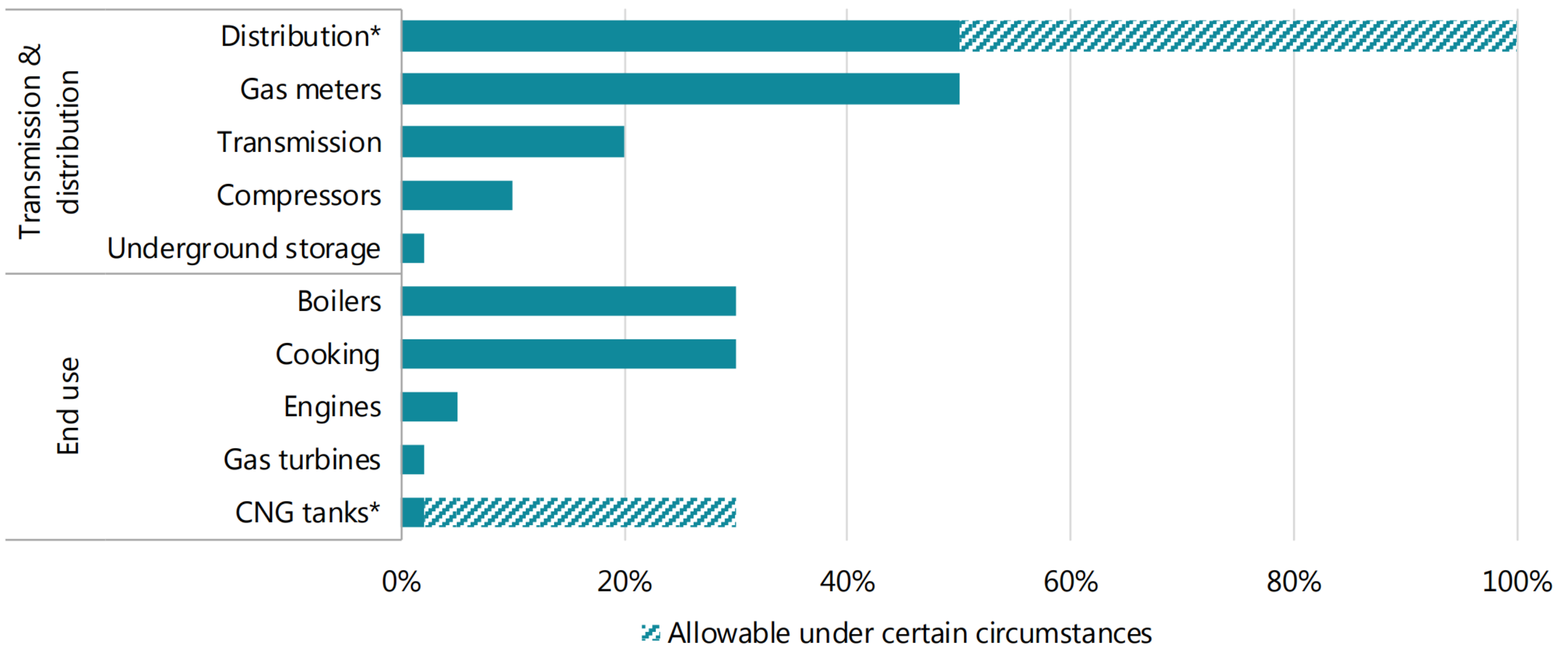


Fonte: Nabeya Bi-tech Kaisha (NBK®)



H_2 Blending in the natural gas grid

Tolerance of selected existing elements of the natural gas network to hydrogen blend shares by volume



> There are 37 demonstration projects studying H2 blending in the gas grid.

> The Ameland project in the Netherlands did not find that blending hydrogen up to 30% posed any difficulties for household devices, including boilers, gas hobs and cooking appliances

Source: IEA, 2019a

Dedicated H_2 pipelines

- Dedicated H2 pipeline already exist mostly associated with refineries/industry

Source: Shell, 2017

Green Pipeline Project (Portugal – Seixal)

> Project leader: Galp Gás Natural Distribuição, Partners: PRF, Gestene, ISQ, Vulcano/Bosch

> Starting: first half of 2020

> Duration: 2 years

> Budget: 0.5 M€

> Goal: Mixing H_2 in the natural gas distribution network (polyethylene) starting with 2% and then increase to a maximum of 20% (v/v).

> H_2 produced through Solar PV

> 80 Consumers: 70 residential, one industrial and remaining tertiary

Overall H_2 economy

> Production represents is the principal driver in H2 costs

> The higher the RES potential de lower the H2 costs

Figure 5: Estimated delivered hydrogen costs to large-scale industrial users, 2030

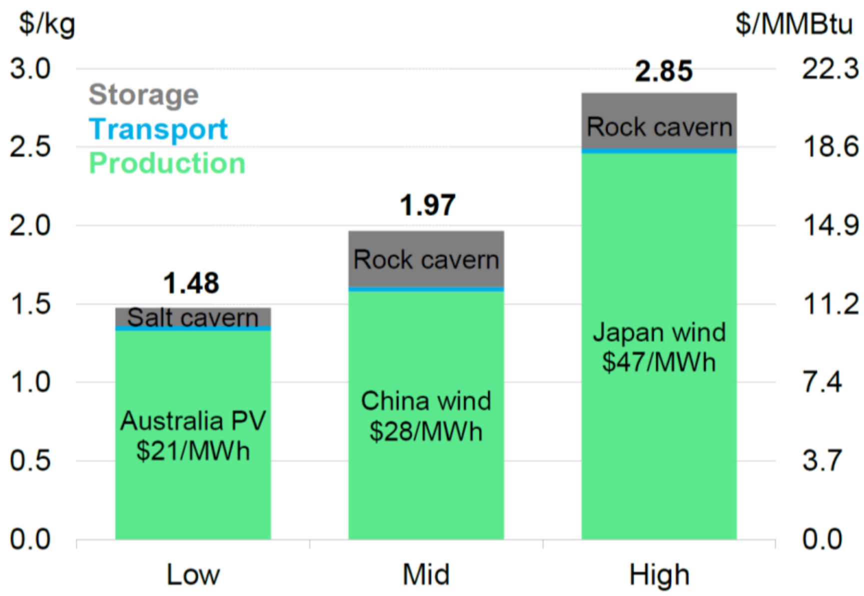
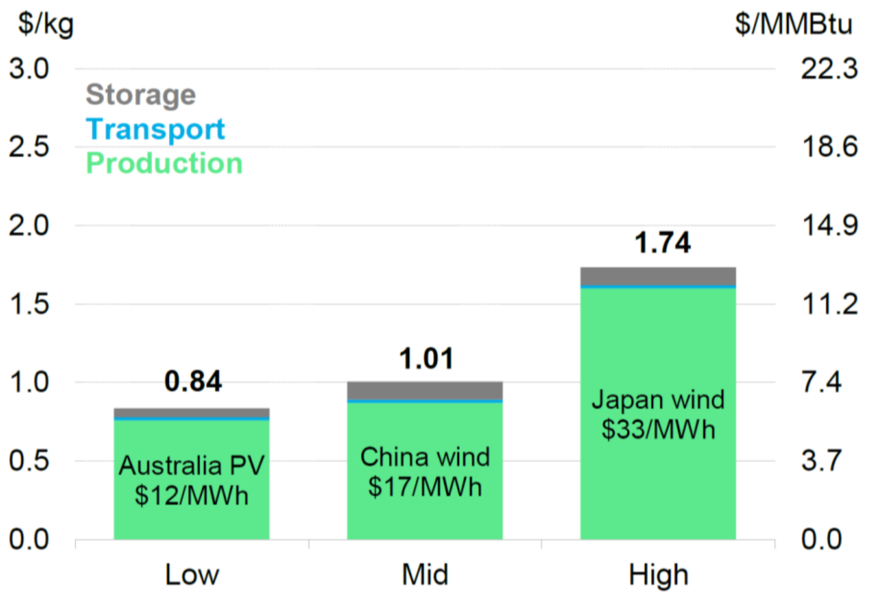


Figure 6: Estimated delivered hydrogen costs to large industrial users, 2050



Assuming the current costs of electricity from solar PV (last auction) Portugal will have a H2 cost close to Australia

Transport costs represent 50km transmission pipeline

H_2 -based energy conversion solutions

Charge

1 Hydrogen production

Extraction of green energy from variable renewables and **conversion** to a new carrier by means of water electrolysis[1]

Electron-to-hydrogen

Store

2 Hydrogen storage & transport

Time and spatial **decoupling** of production and consumption

Hydrogen state

Discharge

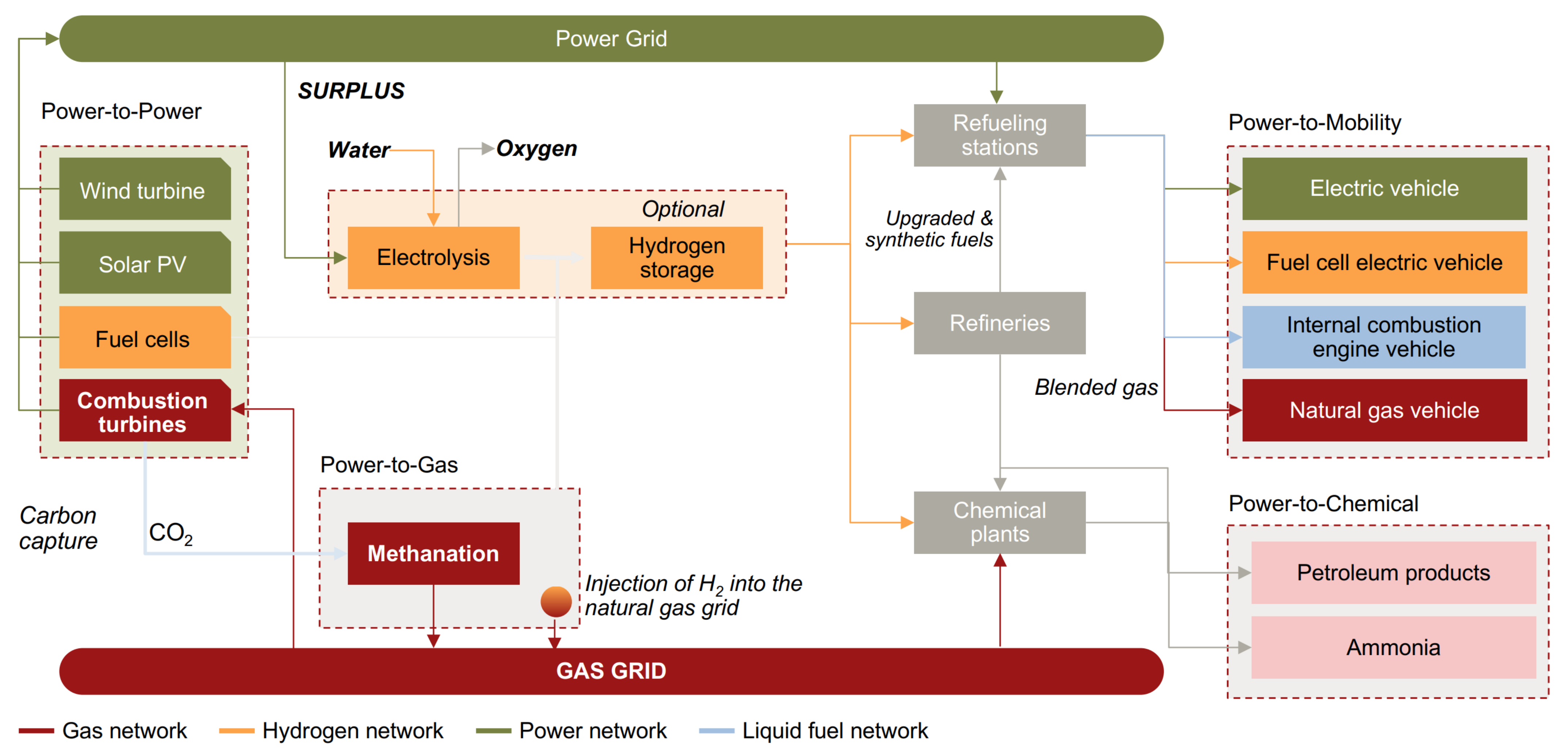
3 Hydrogen use

Valorization of the energy where and when it is needed **with or without conversion** to a new carrier

- Hydrogen-to-electron — Power to Power (fuel cells)
- Hydrogen-to-gas — Power to gas (methane CH_4)
- Hydrogen-to-motion — (fuel cells)
- Hydrogen-to-chemical — (Ammonia)
- Hydrogen-to-liquid fuels[2] — Synthetic fuels
- Hydrogen to heat

Source: AT Kearney Energy Transition Institute, 2014.

H_2 -based energy conversion solutions

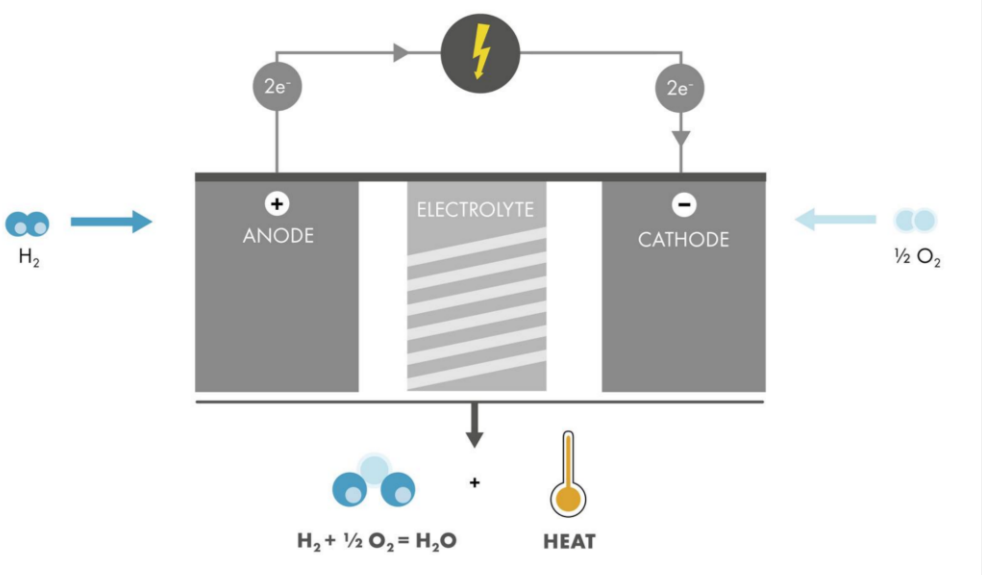


Source: AT Kearney Energy Transition Institute, 2014.

Fuel Cell

Power production from a hydrogen PEM fuel cell from hydrogen (+/- 50% efficiency)

Energy: 1 kg H2 → 16 kWh

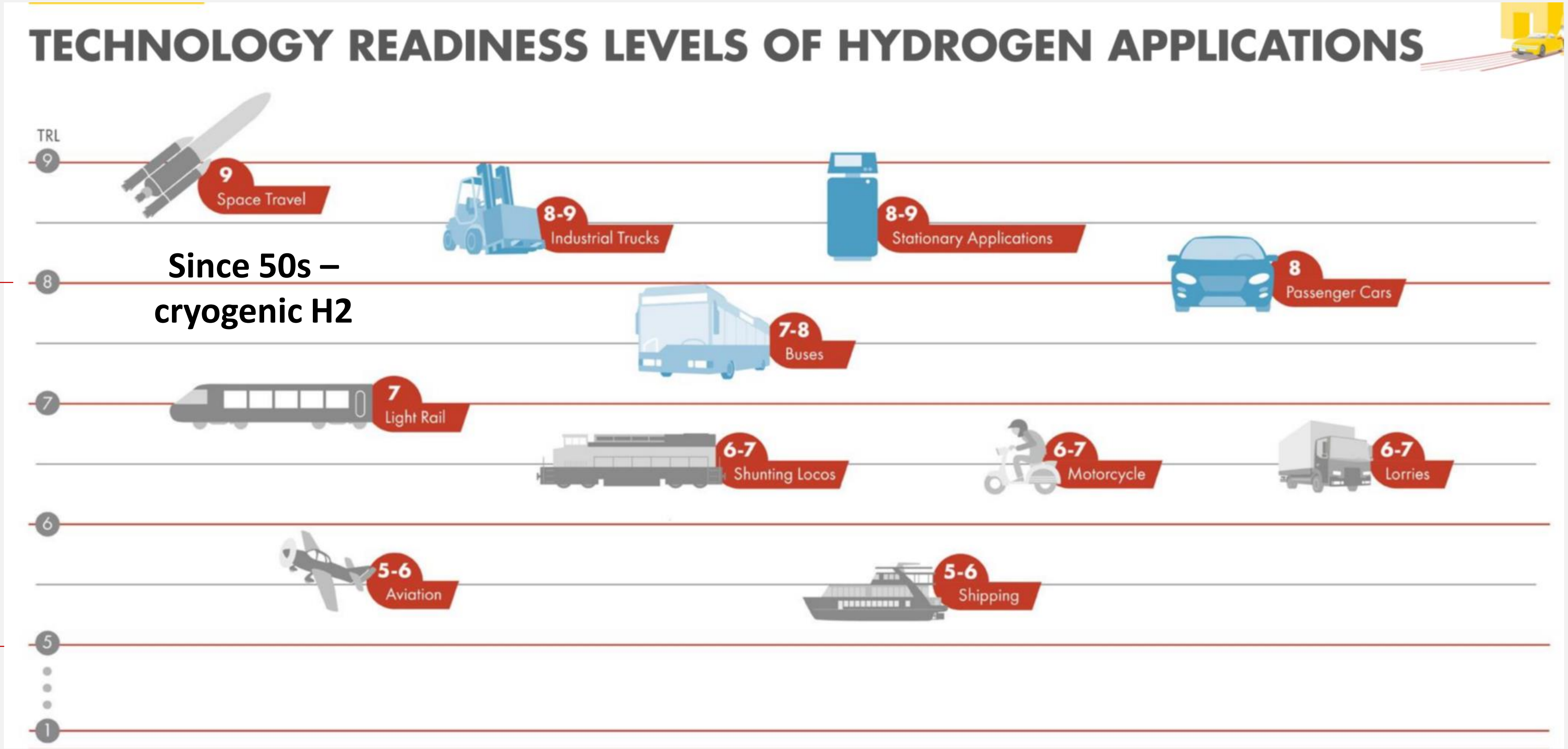


https://www.youtube.com/watch?v=bXHwnKMchkk

H_2 Uses – Transport Sector

System complet and quaified

Technology validated in relevant environment



Since 50s – cryogenic H2

Source: Shell, 2017

Transport by H2 Fuel Cells – First Movers

- H_2 Fuel Cell bus trials began in many countries as long ago as the 1990's; substantial developments in 2000-2010.
- Feb, 2017: Toyota sells first FC bus to Tokyo Metropolitan Govt.; > 100 buses by 2020 Olympics*.

*https://global.toyota/en/detail/15160167

- 100km track between Cuxhaven and Buxtehude, Nth Germany; the train runs for 1,000km on one tank of H_2.
- France, Germany, Holland, Scandanavia and United Kingdom are first-movers with FC trains.
- JR East, Japan plans to test fuel cell trains in 2021.

- Nicola Motors aims at 700 refuelling truck stops in USA by 2028
- Claims 12-15 mpg compared with 6 mpg for diesel
- Anglo-American partner with Williams Engineering to build hydrogen powered ultra-class electric mining haul truck.

https://energypost.eu/hydrogen-fuel-cell-trucks-can-decarbonise-heavy-transport/
Australian Mining, February 2020

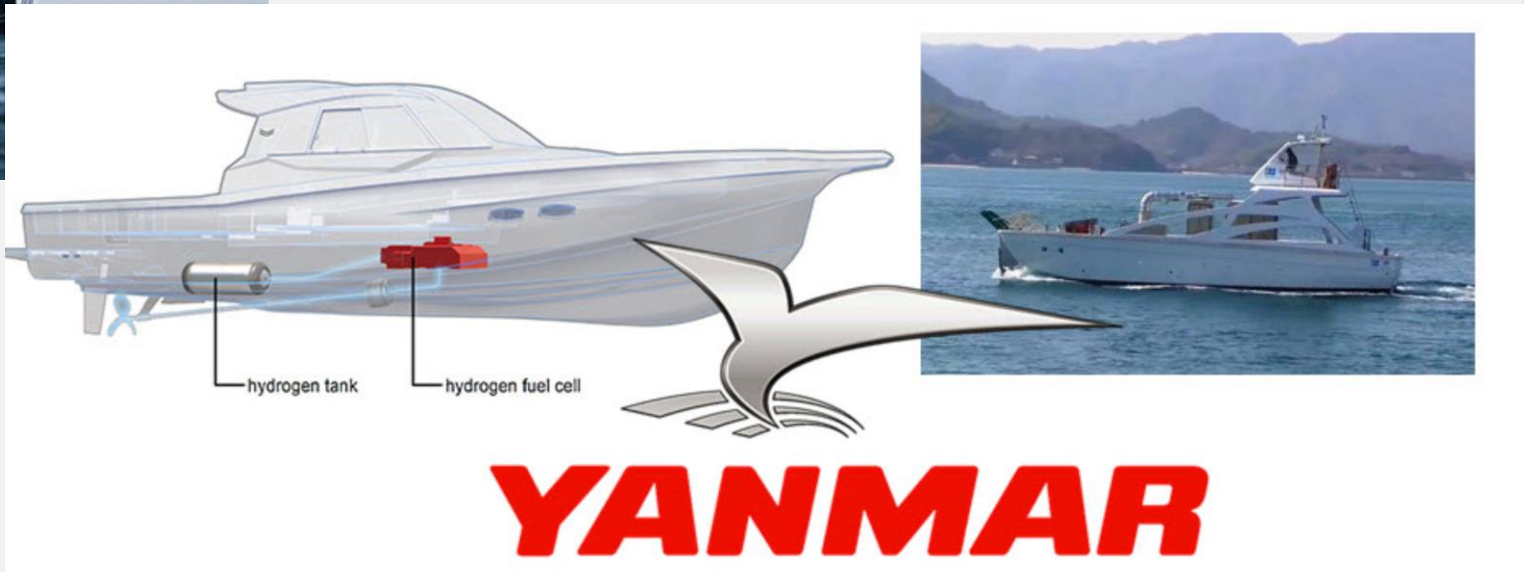
Source: http://www.dsdmip.qld.gov.au/resources/presentations/cq-hydrogen-presentation-2.pdf

Fuel cell electric vehicle (FCEV) in Portugal

> Caetano Bus (*fuel cell* Toyota) manufacture the H2.City Gold

Navigation

Source: https://www.energy-reporters.com/



Source: https://fuelcellsworks.com/

H_2 in aviation (2035)

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