The role of hydrogen in the energy transition:

*T*echnological options, costs and the role for a carbon neutral energy system

Patrícia Fortes

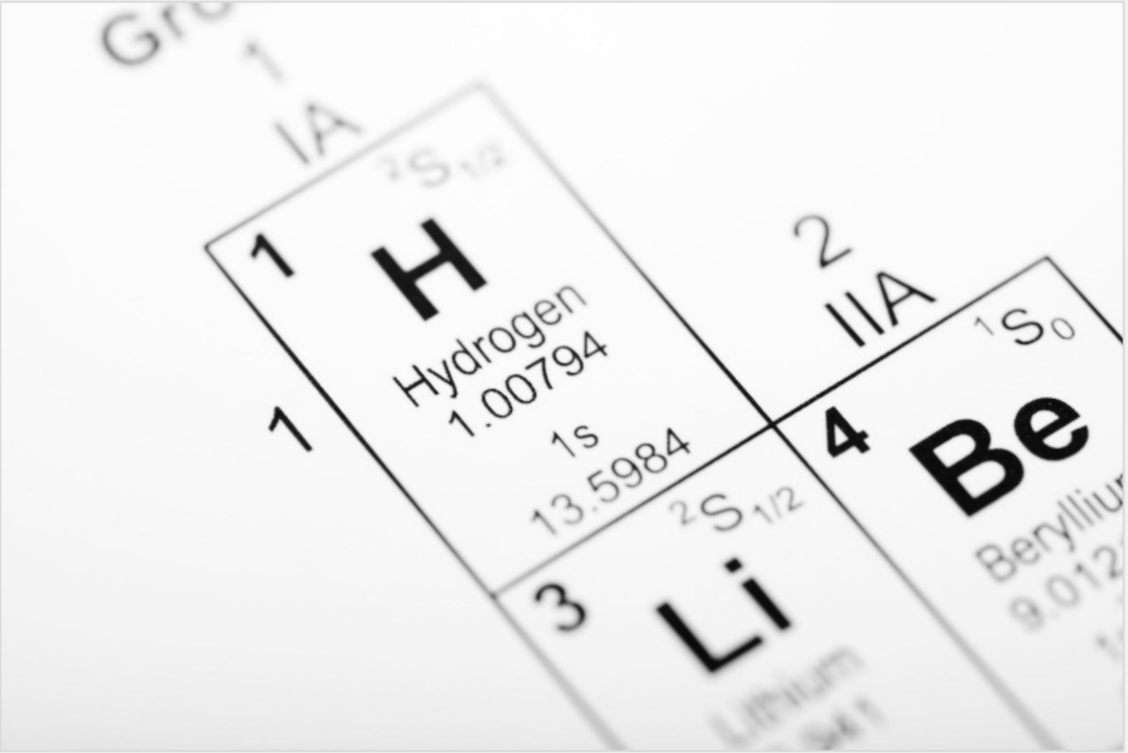
CENSE
center for environmental and sustainability research

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

UNIVERSIDADE NOVA DE LISBOA

Outline

1. What is Hydrogen (H_2)?
2. What is current role of H_2?
3. Why we are talking so much about H_2?
4. What is the H_2 economy?
   - H_2 production
   - H_2 storage
   - H_2 transport & distribution
   - H_2 utilization
5. What is the role of H_2 in a carbon neutral economy (European case)?
6. What is Portugal saying about H_2?



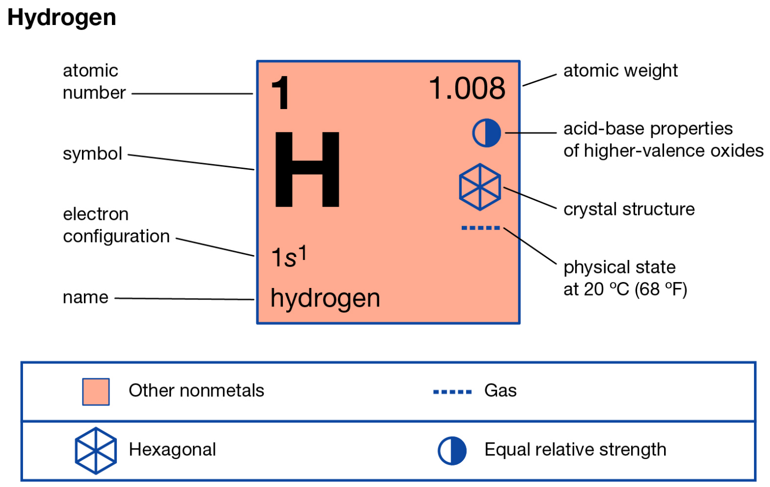
What is Hydrogen?

> 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



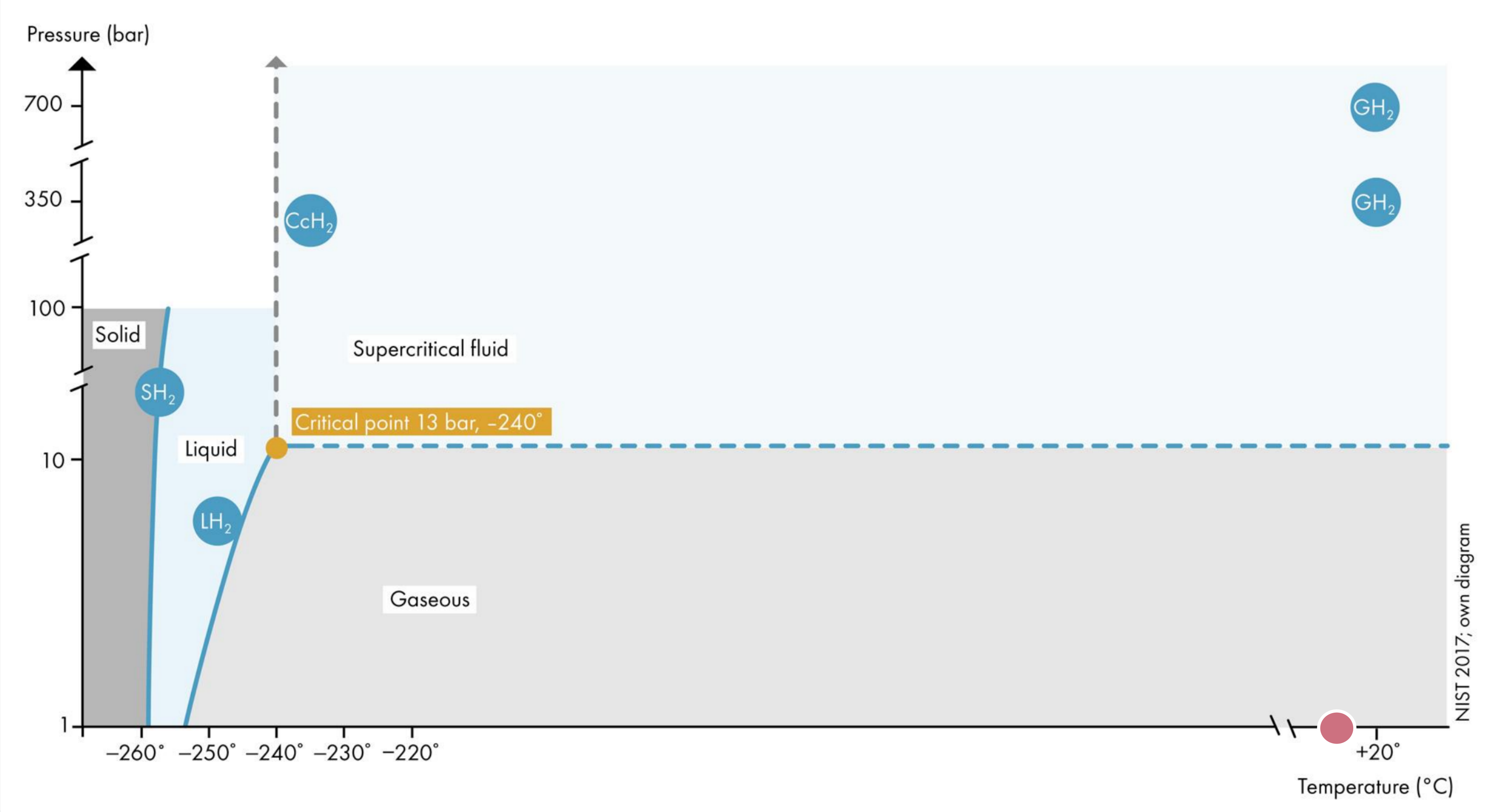
Physical properties of hydrogen

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

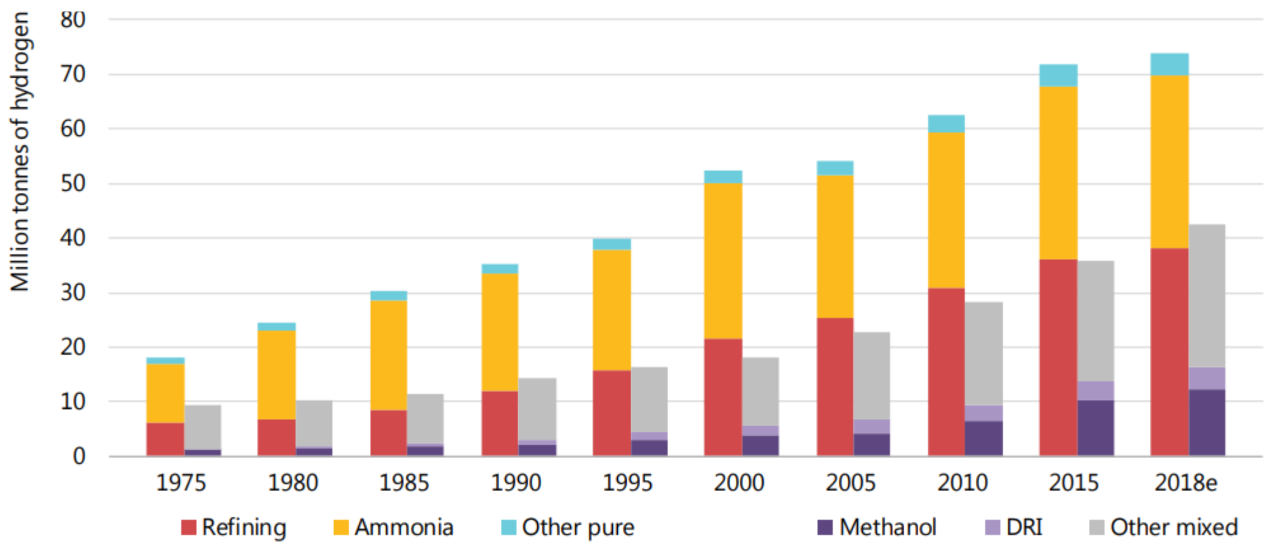
- Widespread adoption of town gas in UK around 1820

- 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).

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:

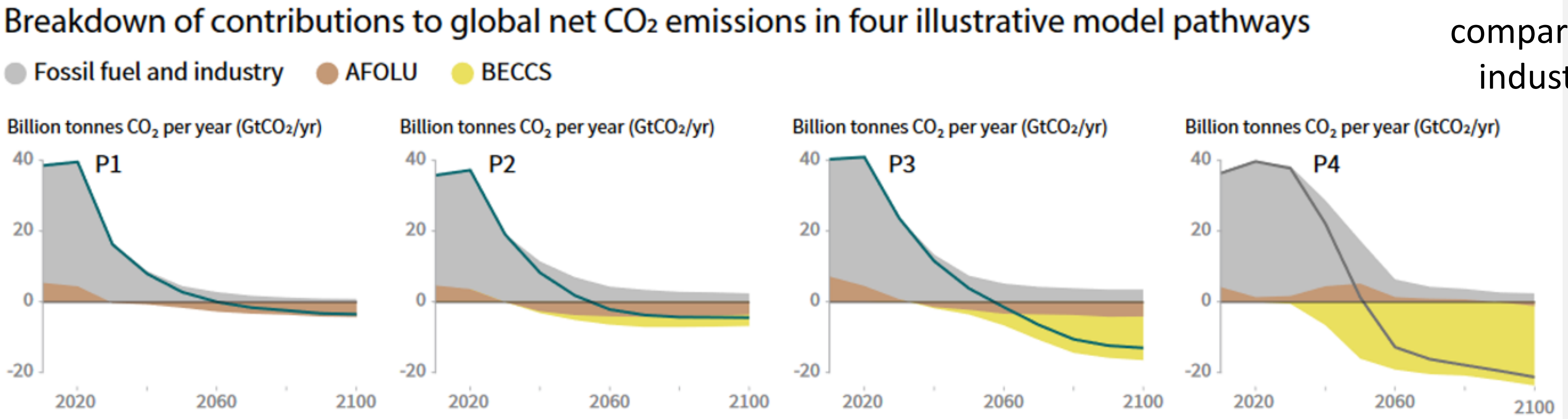
> refining petroleum (e.g., lower the sulfur content of diesel fuel),

> producing fertilizer (ammonia)

Source: IEAa, 2019

Why we are talking so much about H_2?

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



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

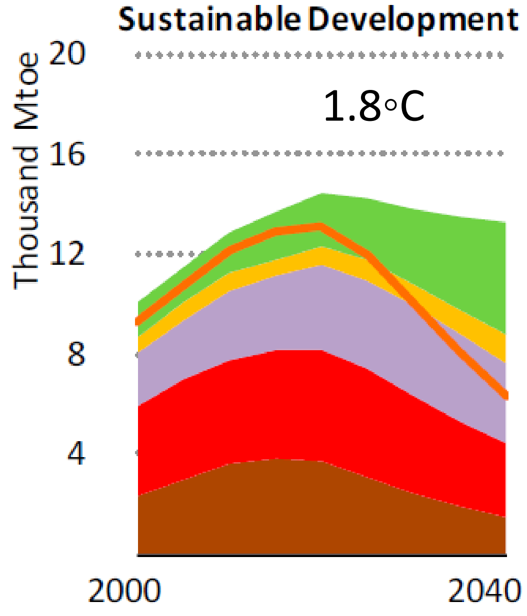
P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

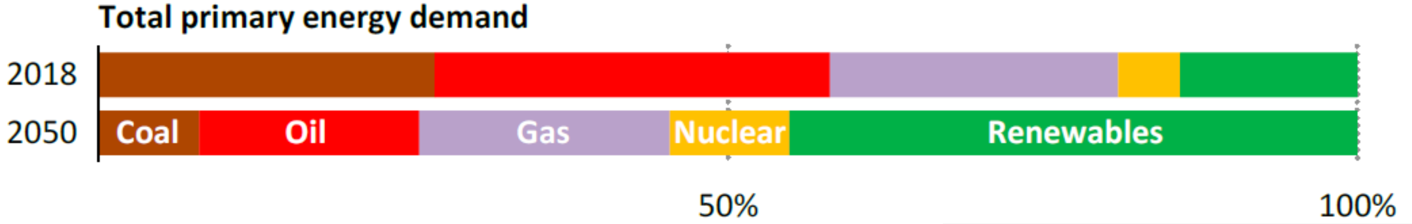
Source: IPCC, 2018

Why we are talking so much about H_2?

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



▻ **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

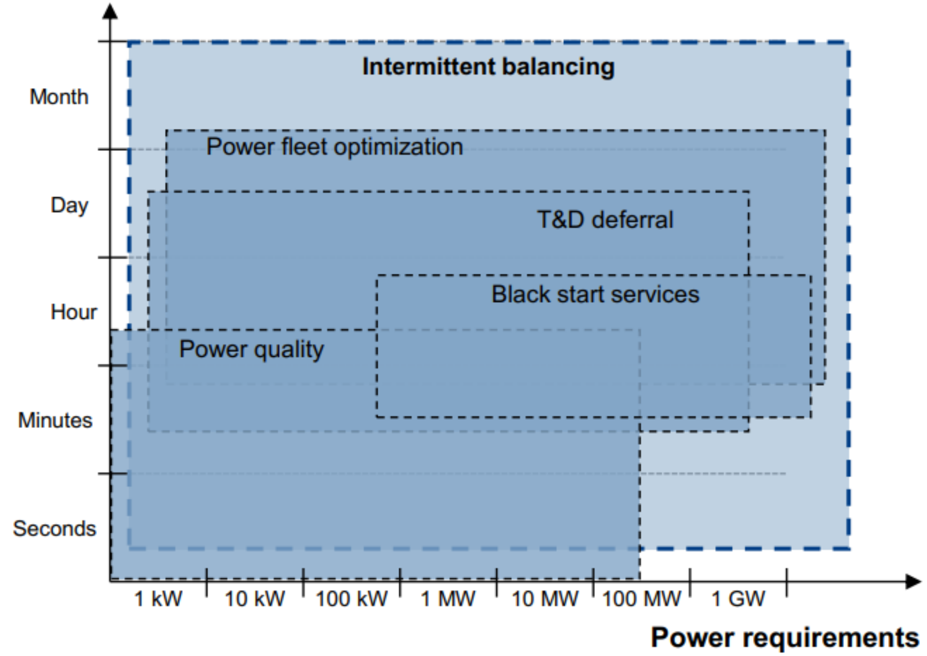
> Renewable energy sources (RES) will have a major contribution in reduction GHG

> Most of RES are intermittent

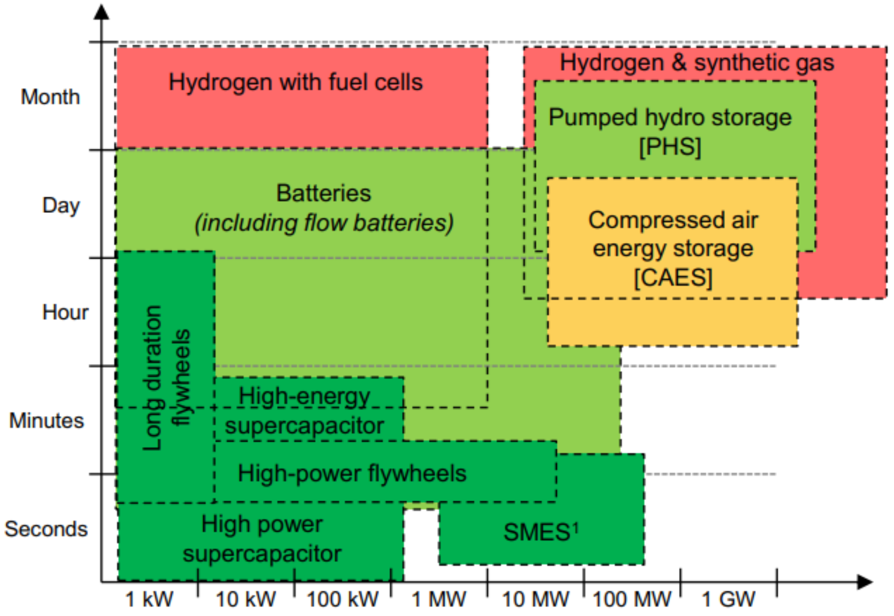
Source: IEAb, 2019

Why we are 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

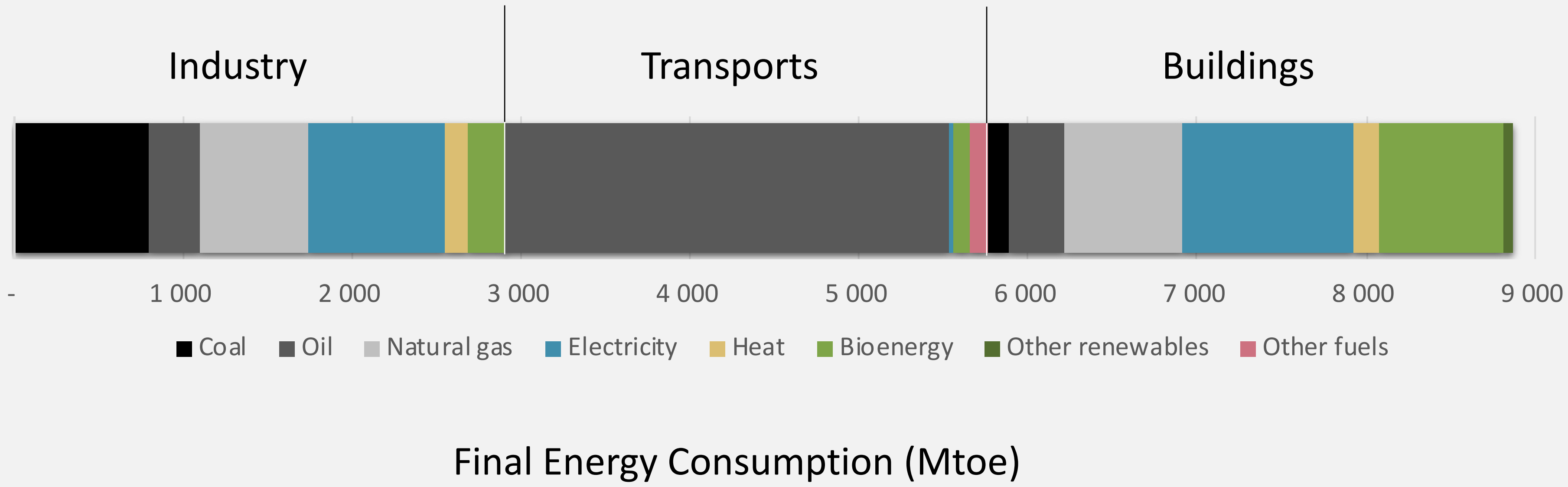
Electricity Storage

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

Source: AT Kearney Energy Transition Institute, 2014.

Why we are talking so much about H_2?

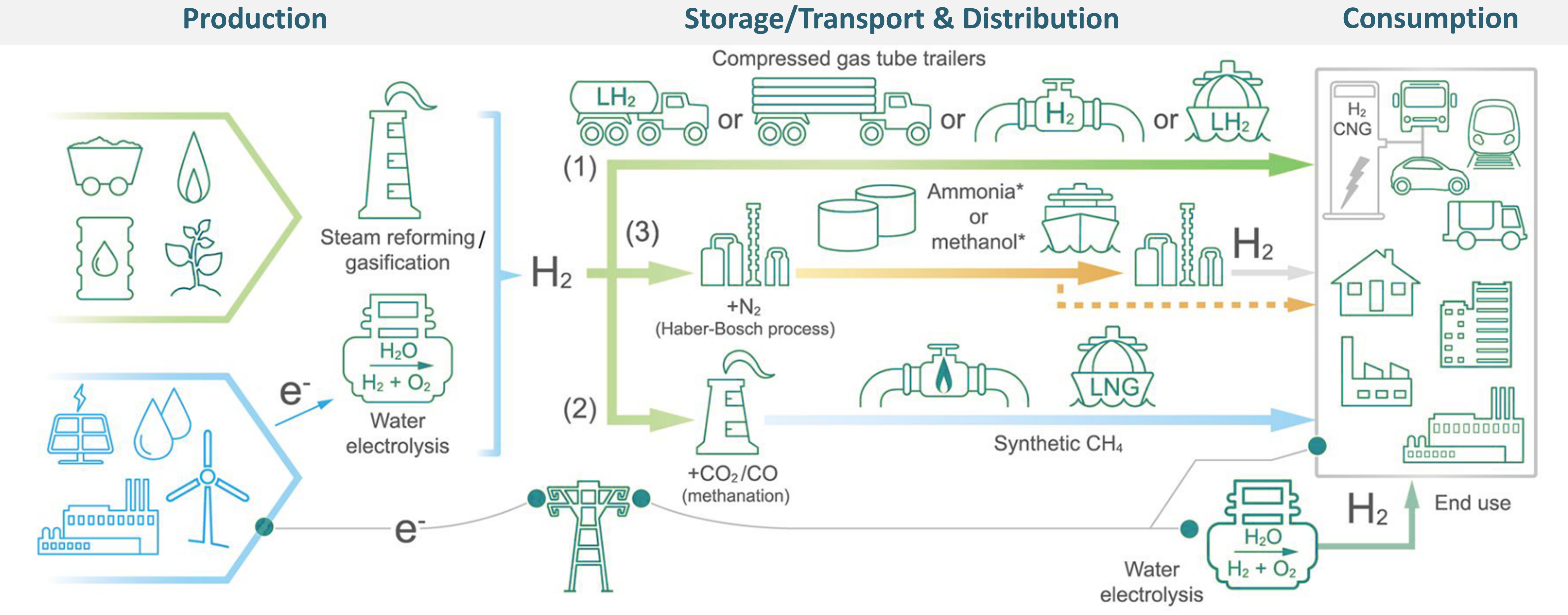
> H2 can be an alternative energy vector to lower the carbon intensity of transport (and heating)



17 809 Mt CO2 (54% of energy-related CO2 emissions)

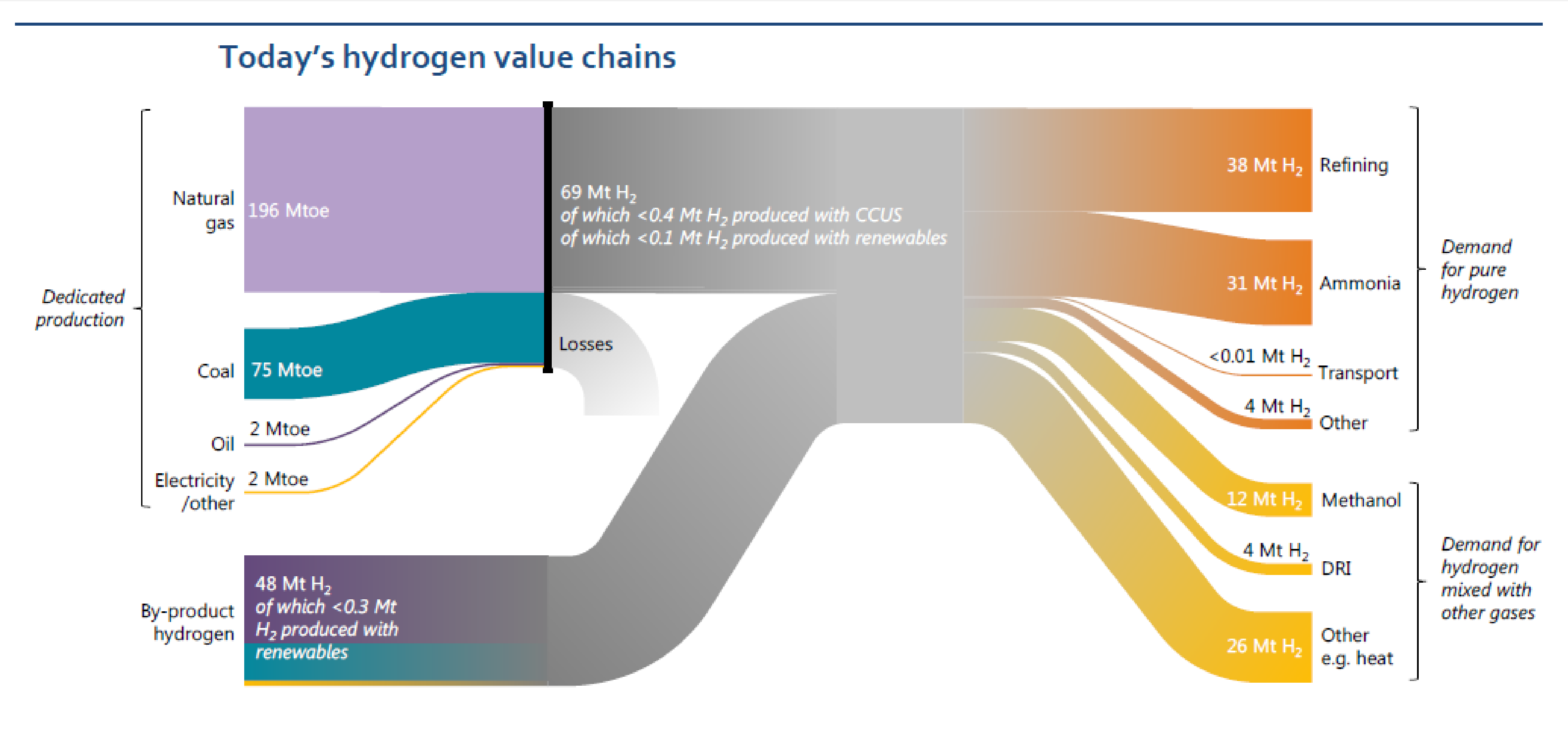
Source: IEAb, 2019

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

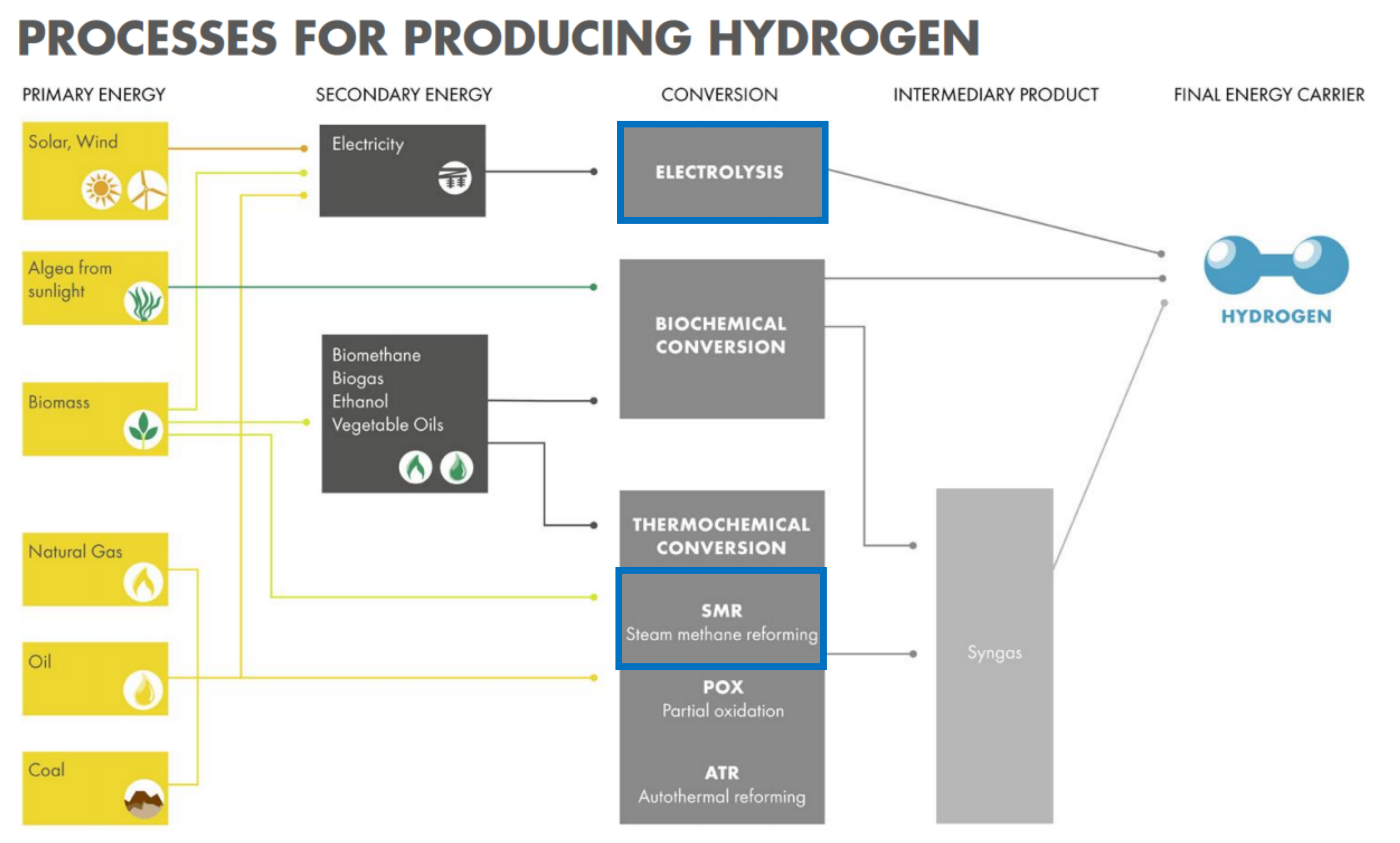
830 MtCO2/yr

H_2 production

Green H2

Grey/Blue (CCS) H2

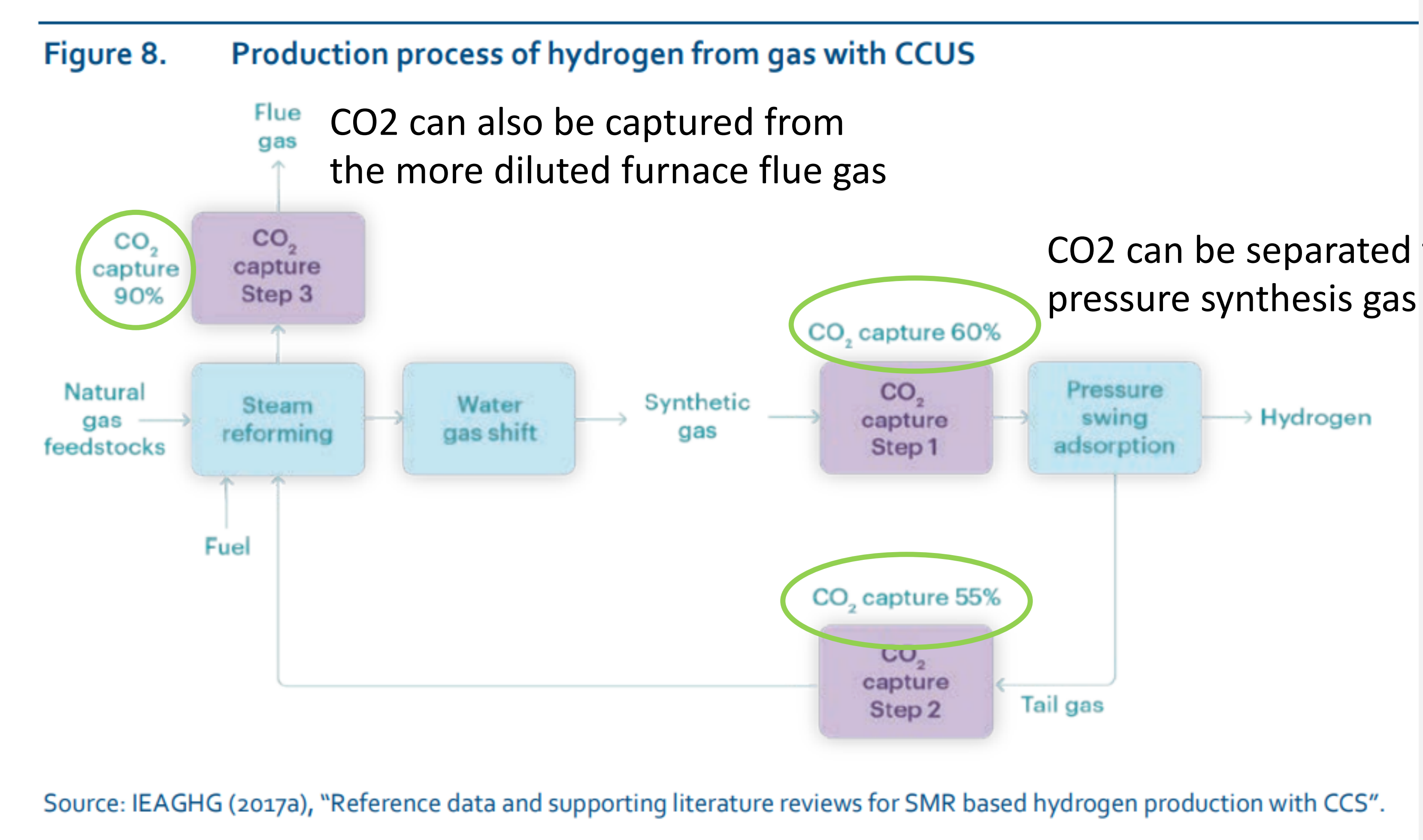
Black H2



Source: Shell, 2017

SRM with carbon capture and utilization

BLUE hydrogen



CO_2 can also be captured from the more diluted furnace flue gas

CO_2 can be separated from the high-pressure synthesis gas stream

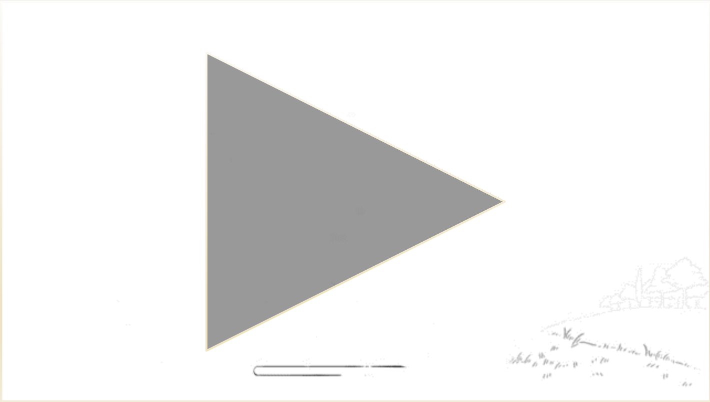
Source: IEA, 2019a

Electron to hydrogen

H_2 Production | Water electrolysis

> Electrochemical reaction that splits water into H2 and Oxygen, using electricity.

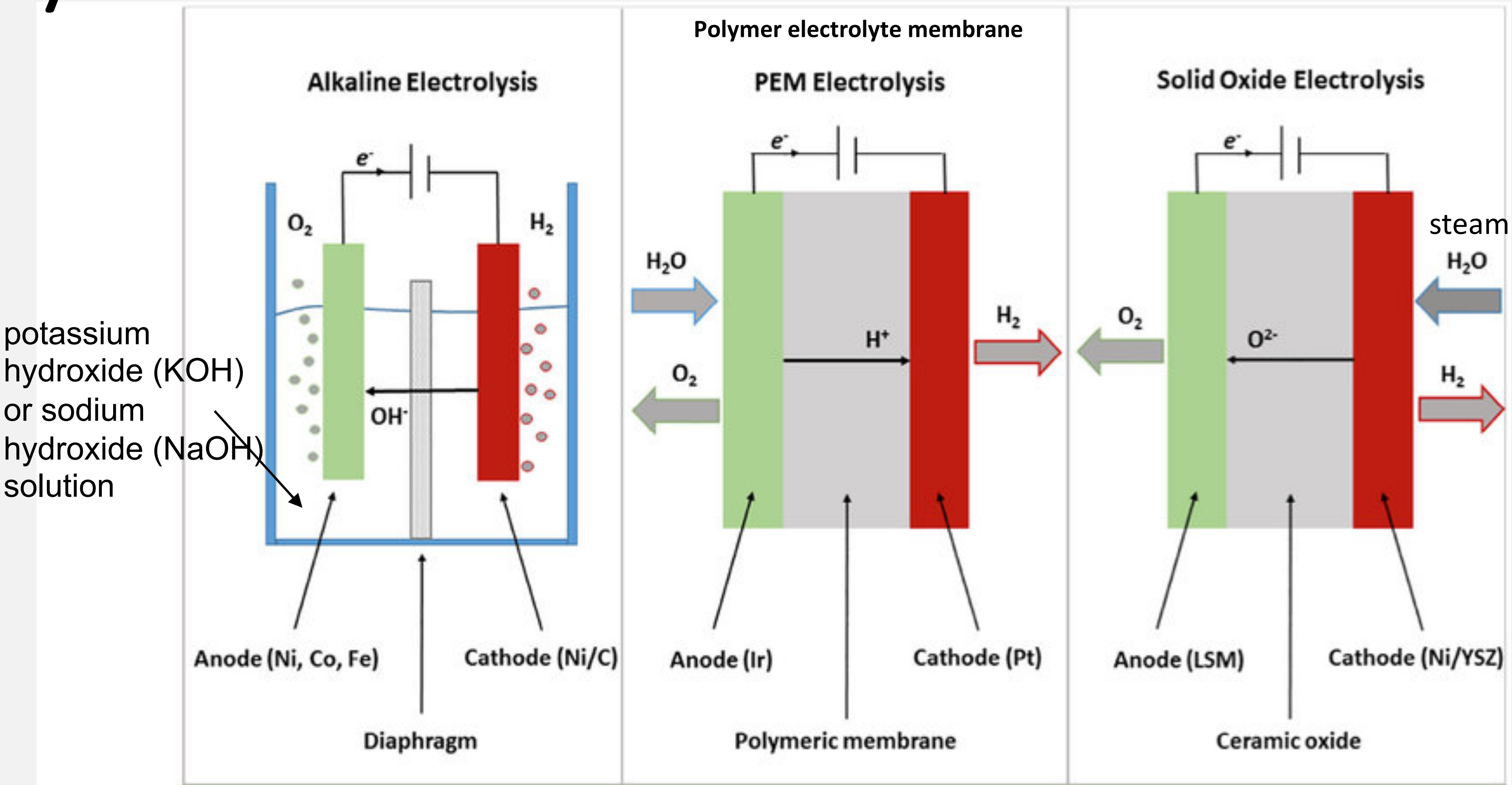
> It is a 100% emission free and carbon-free process



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



	Alkaline Electrolysis	PEM Electrolysis	Solid Oxide Electrolysis
Anode	$4OH^- \rightarrow 2H_2O + 4e^- + \mathbf{O_2}$	$2H_2O \rightarrow 4H^+ + 4e^- + \mathbf{O_2}$	$O^{2-} \rightarrow \frac{1}{2}\mathbf{O_2} + 2e^-$
Cathode	$4H_2O + 4e^- \rightarrow 4OH^- + 2\mathbf{H_2}$	$4H^+ + 4e^- \rightarrow 2\mathbf{H_2}$	$H_2O + 2e^- \rightarrow \mathbf{H_2} + O^{2-}$

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

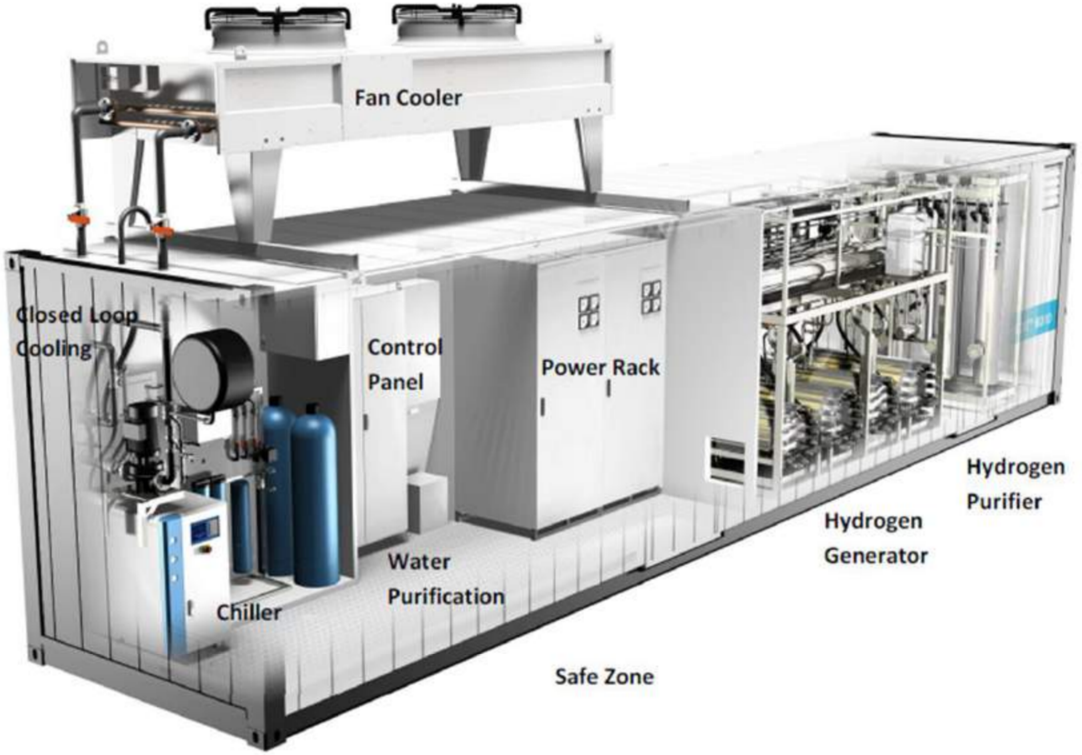
- > Have not yet been commercialized (–)
- > Need a heat source (nuclear, solar thermal, geothermal) (–)
- > It is possible to operate in reverse mode (+)

	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

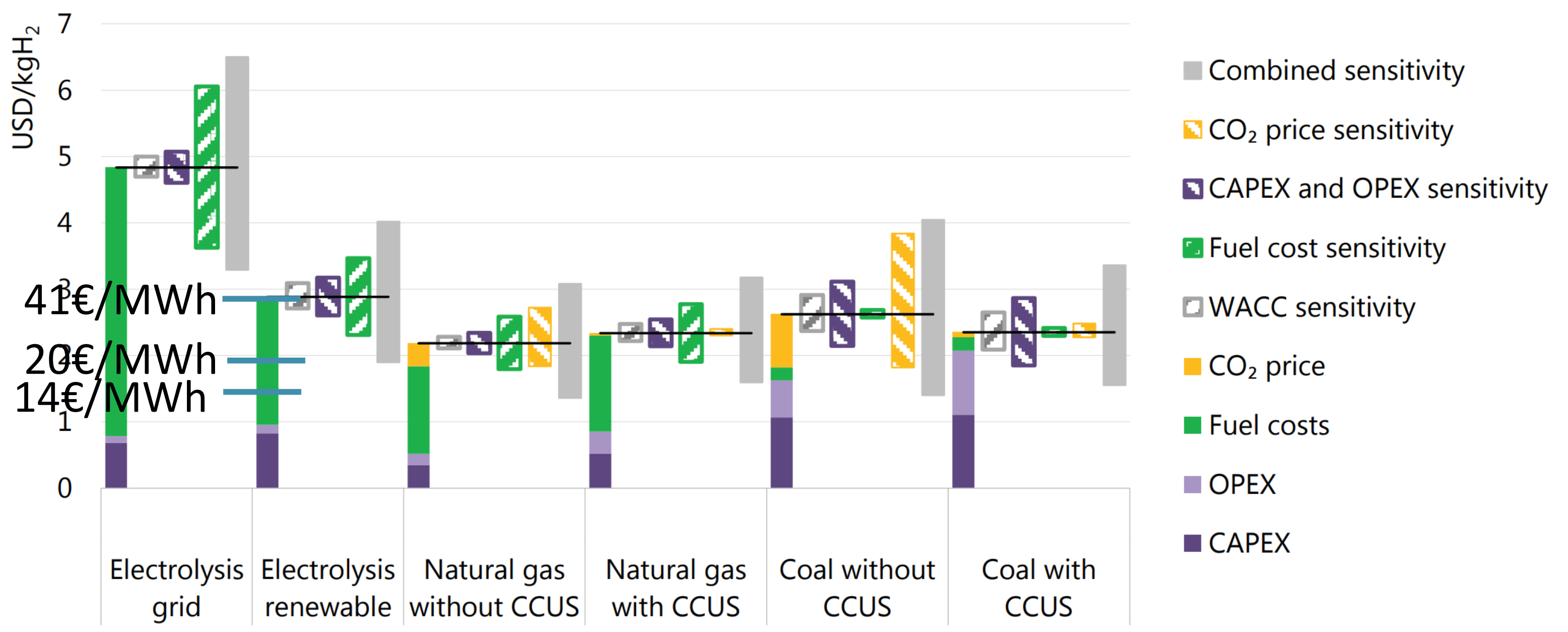
Studies indicate PEM as the main electrolyser technology in the future

How does an electrolyser (alkaline) look 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.

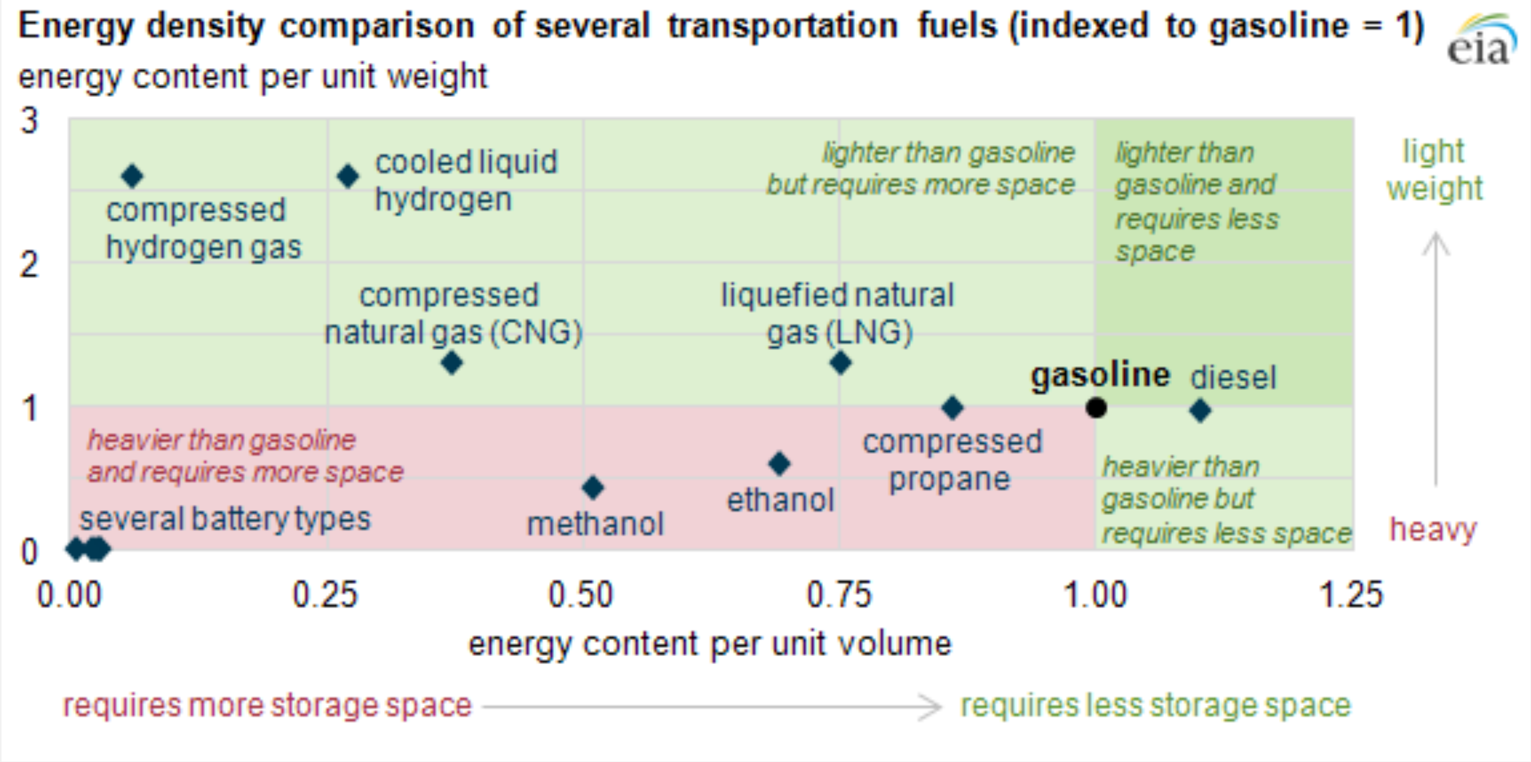
Source: IEA 2019.

- 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 around 1.4 GW, at an average tariff of 20,4 €/MWh, with a lot awarded at 14,7 €/MWh, the lowest price in the world at the time

Source: IEA, 2019a

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)

$3H_2 + N_2 \rightarrow 2NH_3$

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.

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

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

Source; BloombergNEF, 2020

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

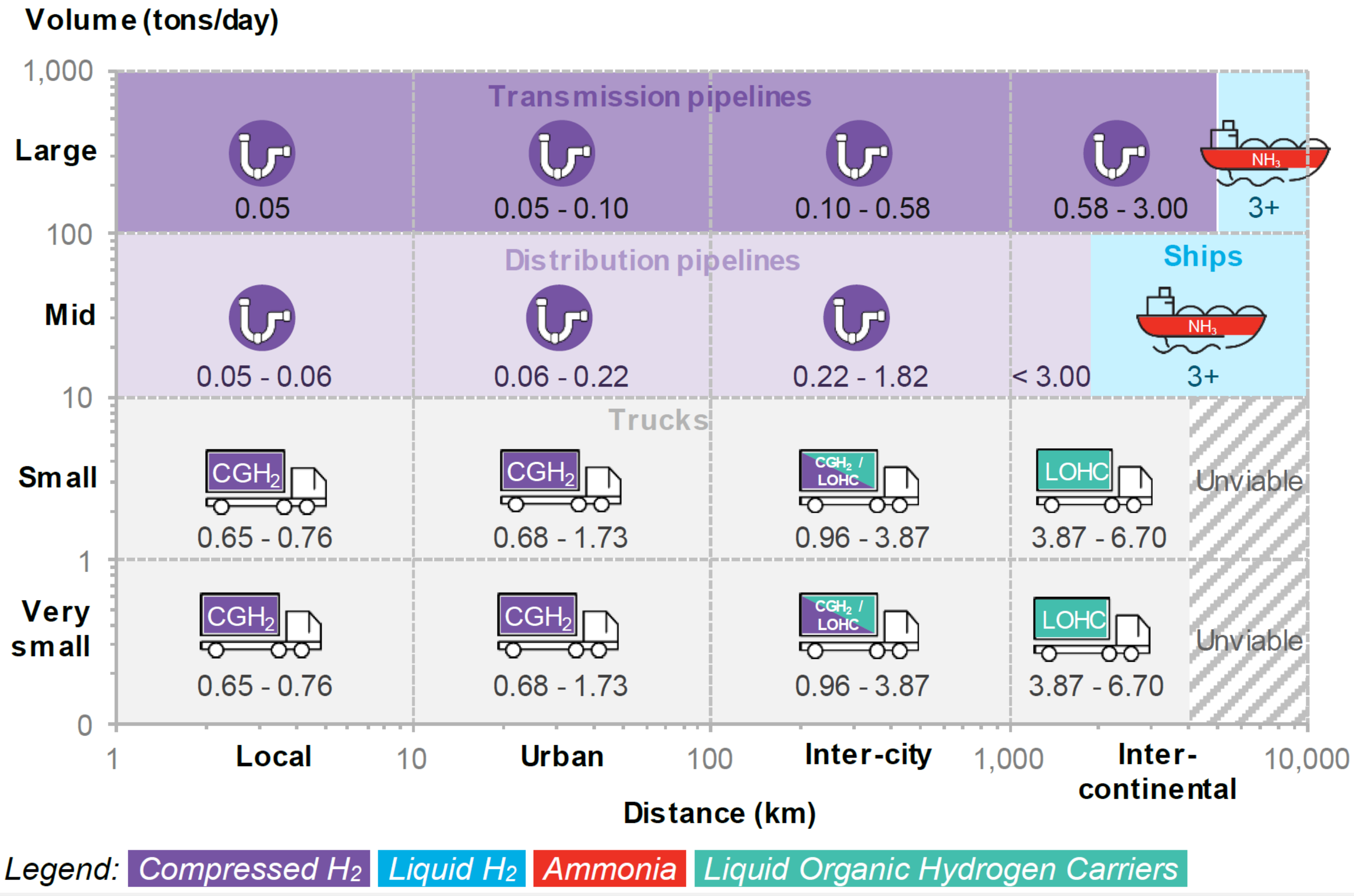
Note: Salt caverns are the only type of geological formation successful used to storage H2 underground to date. Other alternatives are under research to test leaks and reactivity with the host rock

H_2 Transport & Distribution

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

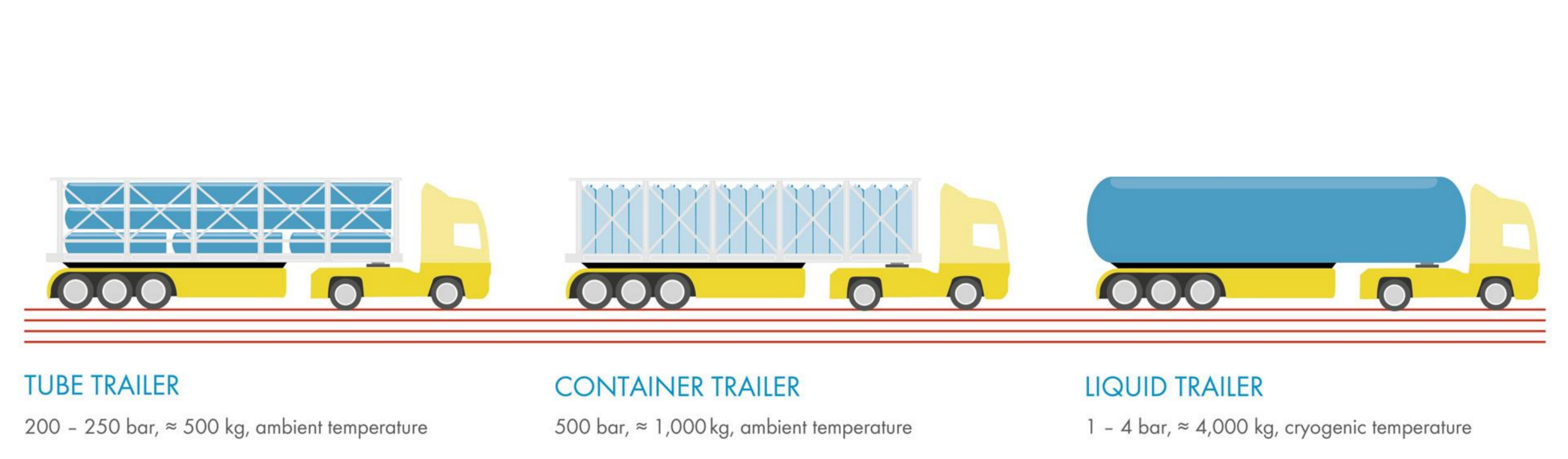
> The best option: **blending in the natural gas grid, dedicated grid, trucks or shipping** will vary according to geography, distance, amount of H2 and the required end use of the hydrogen

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



Source; BloombergNEF, 2020

H_2 Road Transport

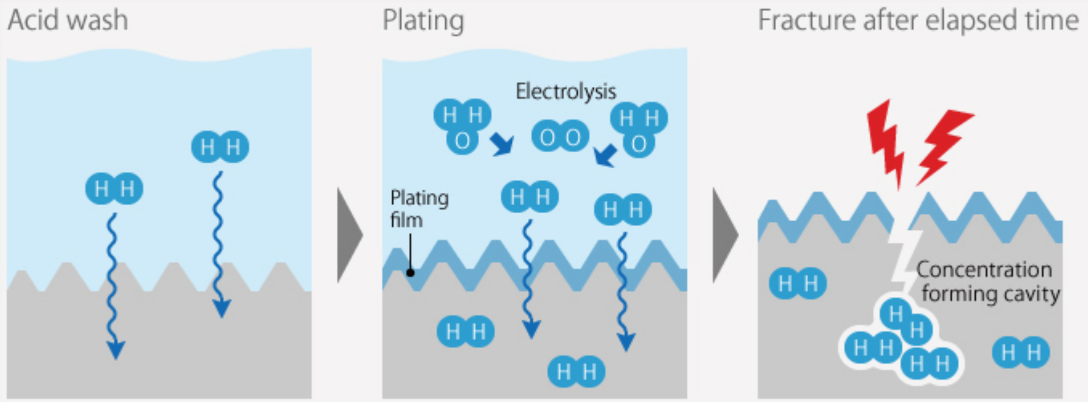


Source: Shell, 2017

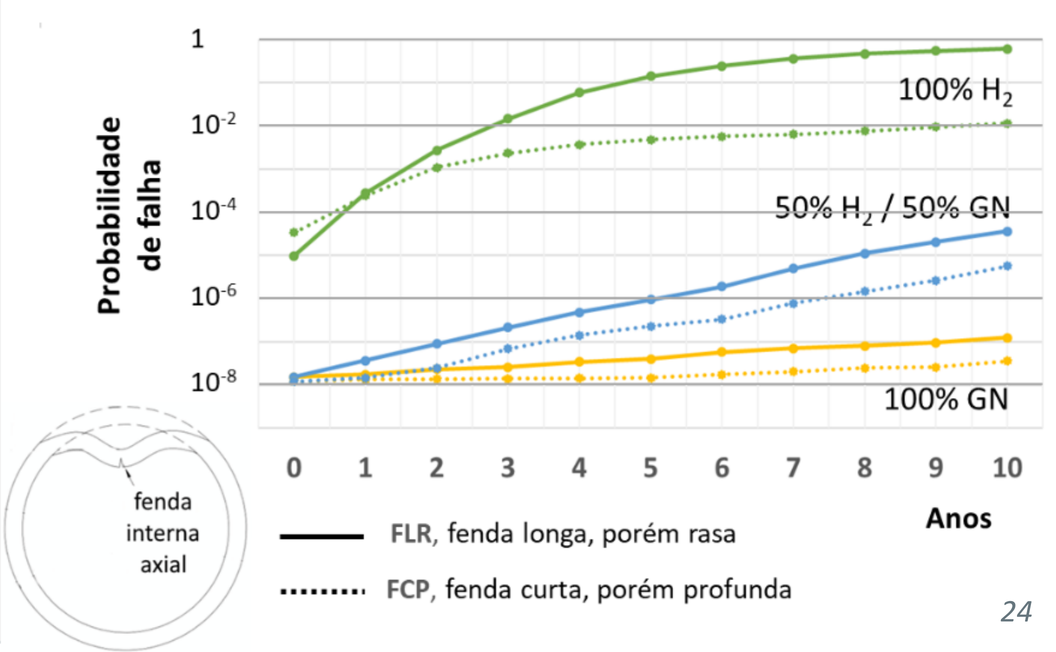
Blending H_2 in the natural gas grid

Limitations

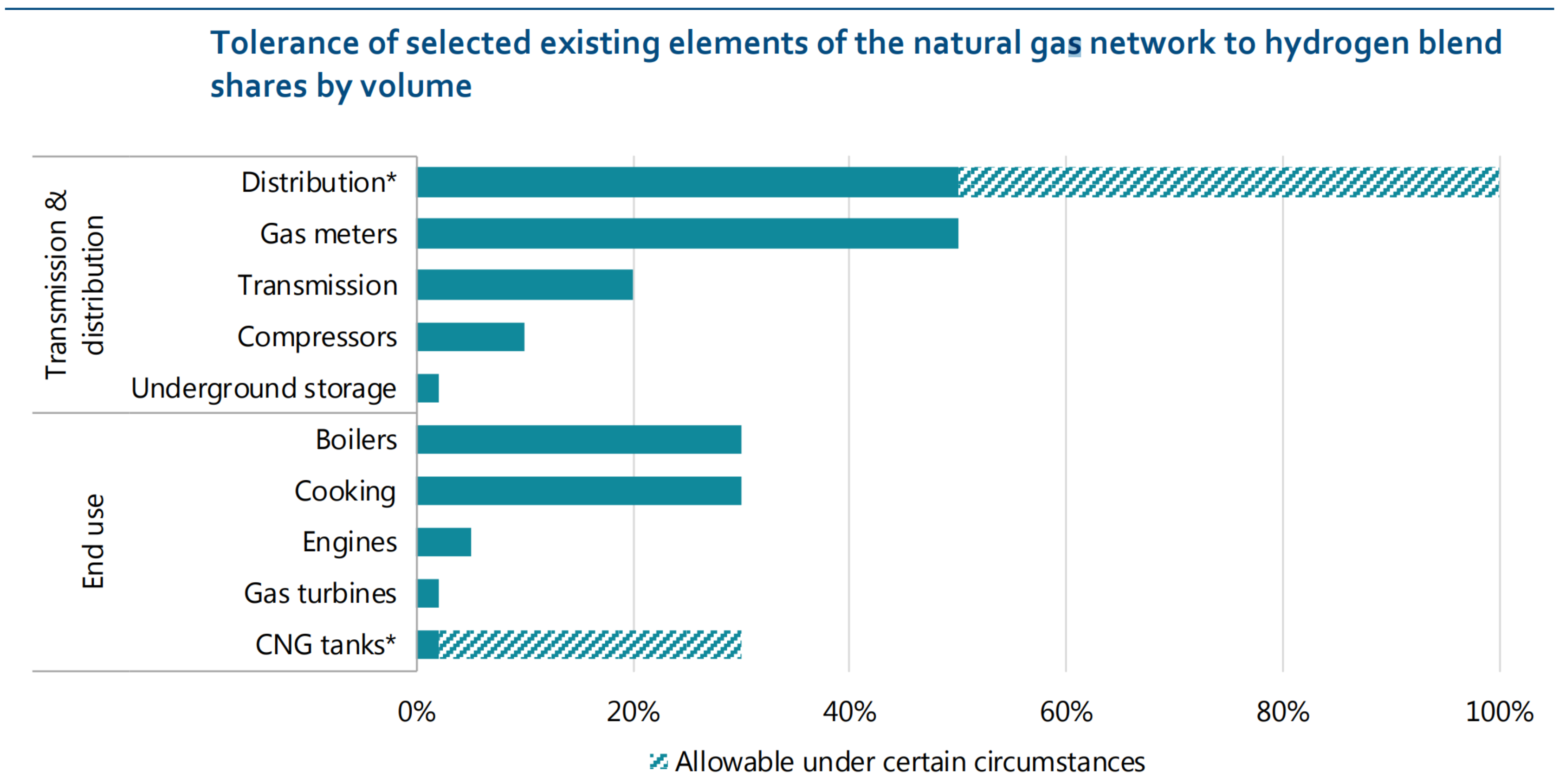
- The material of the pipeline limits the amounts of H2:
  - polyethylene distribution pipelines can handle up to 100% hydrogen
  - some metal pipes can degrade when exposed to hydrogen over long periods, particularly with H2 in high concentrations and at high pressures – ***embrittlement*** *- Literature 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



> 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

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

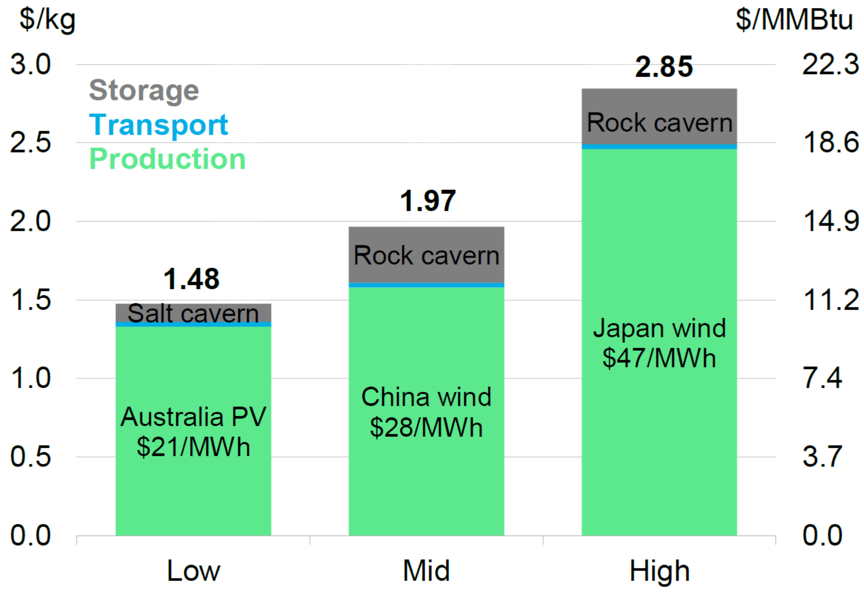
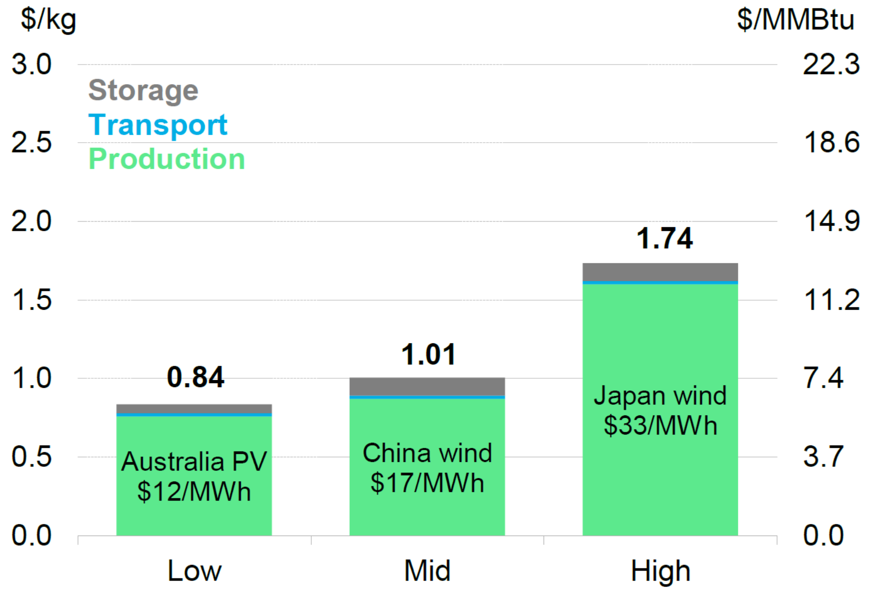


Figure 6: Estimated delivered hydrogen costs to large industrial users, 2050



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

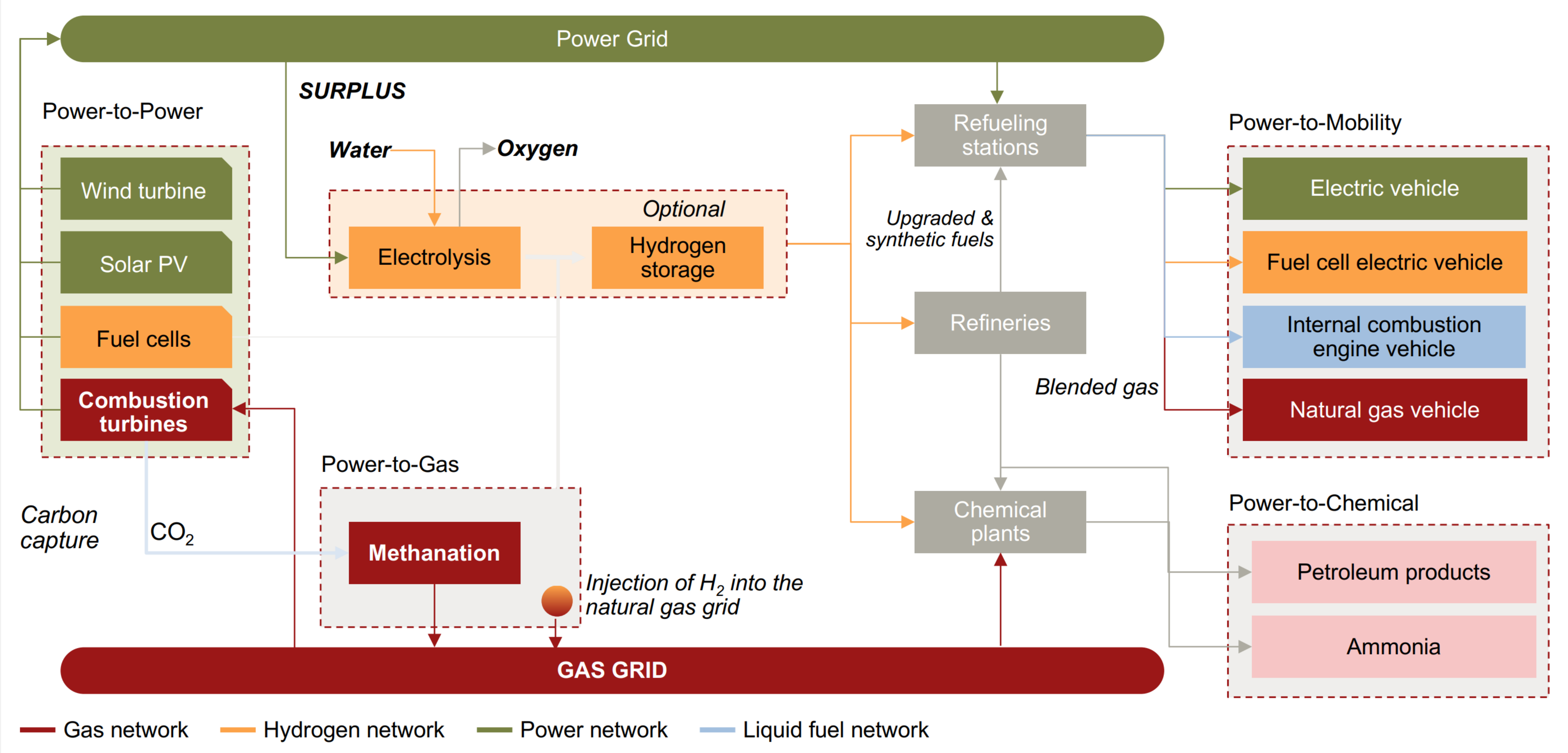
3 Hydrogen use

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 CH4)
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

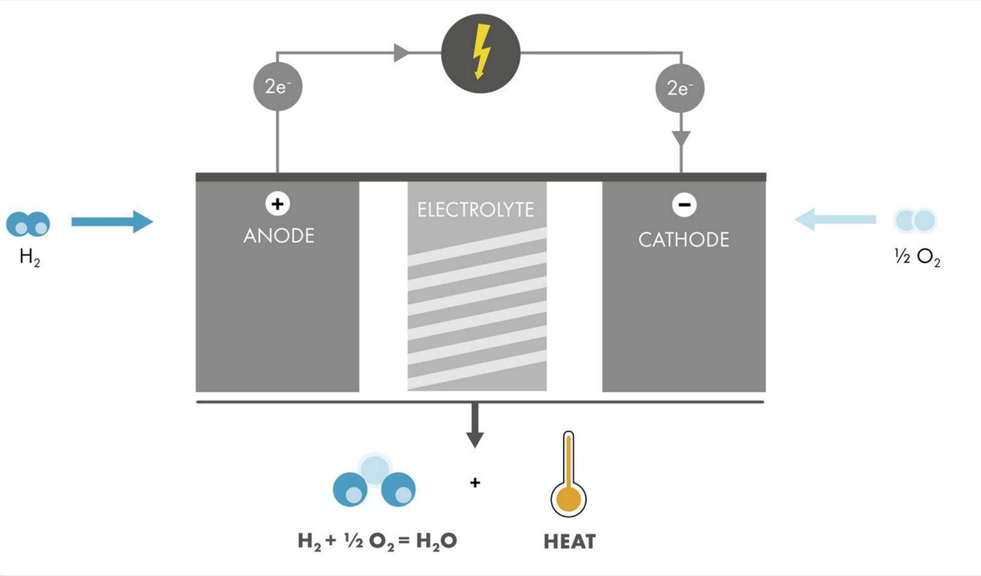


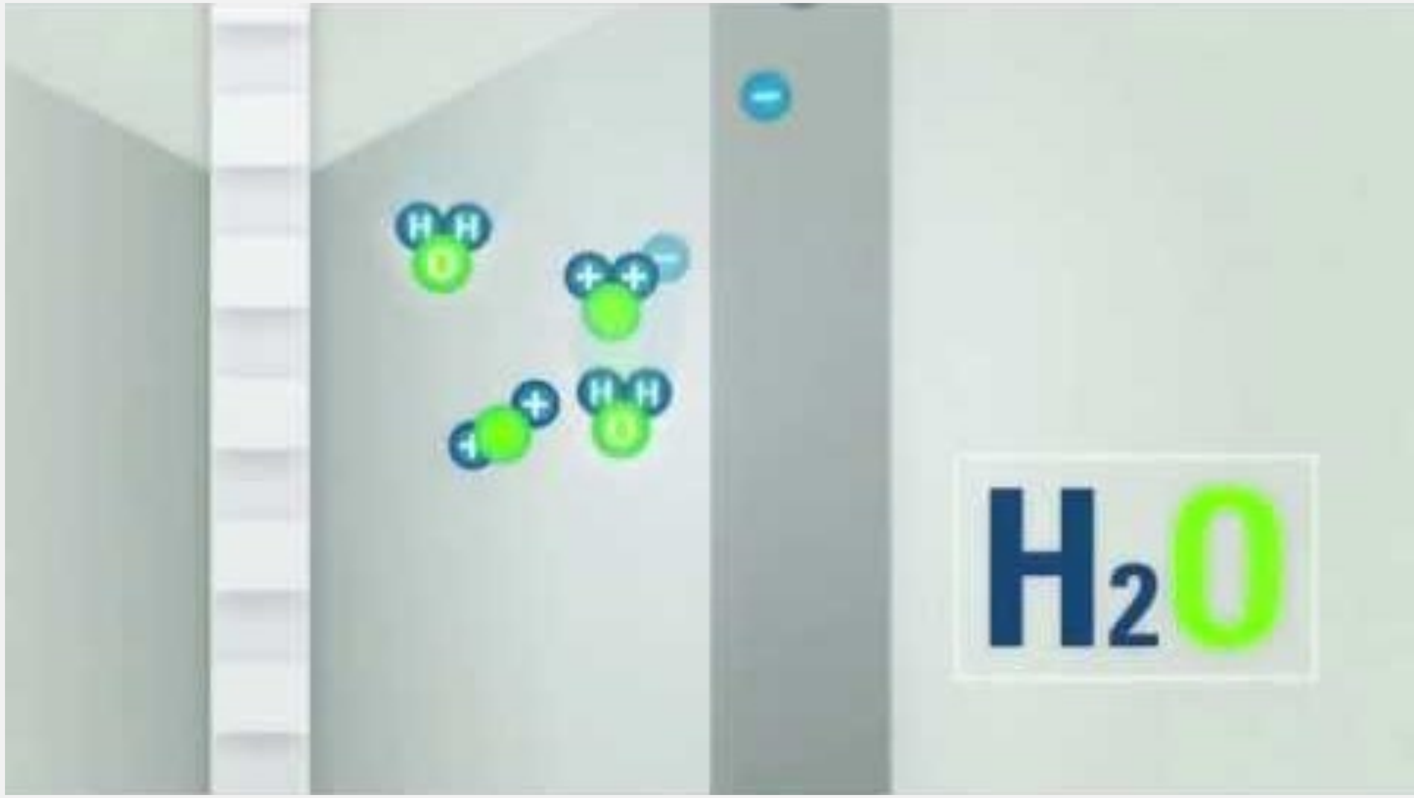
Source: AT Kearney Energy Transition Institute, 2014.

Fuel Cell

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

Energy: 1 kg H2 → 16 kWh

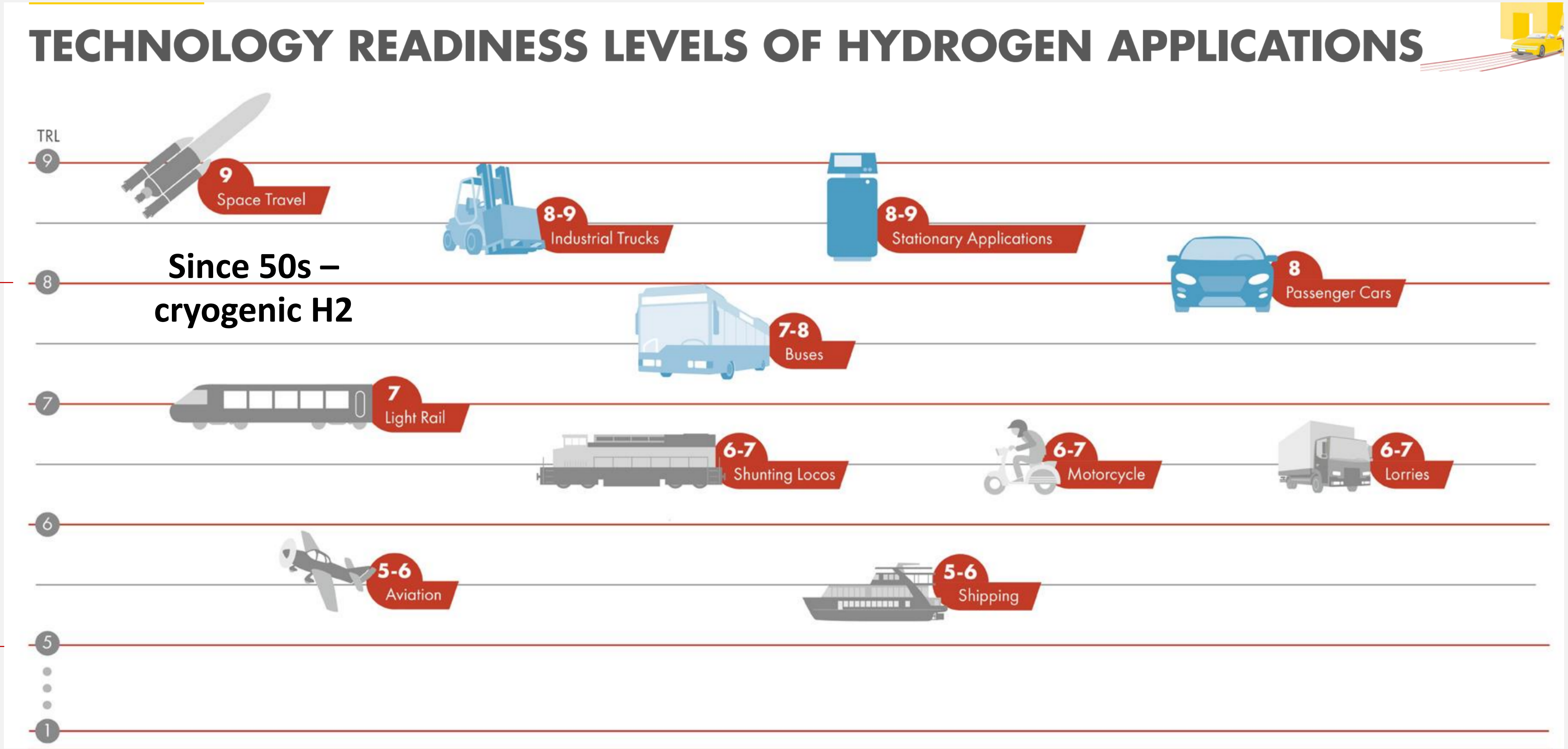




H_2 Uses – Transport Sector

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

FCEV | Private Cars

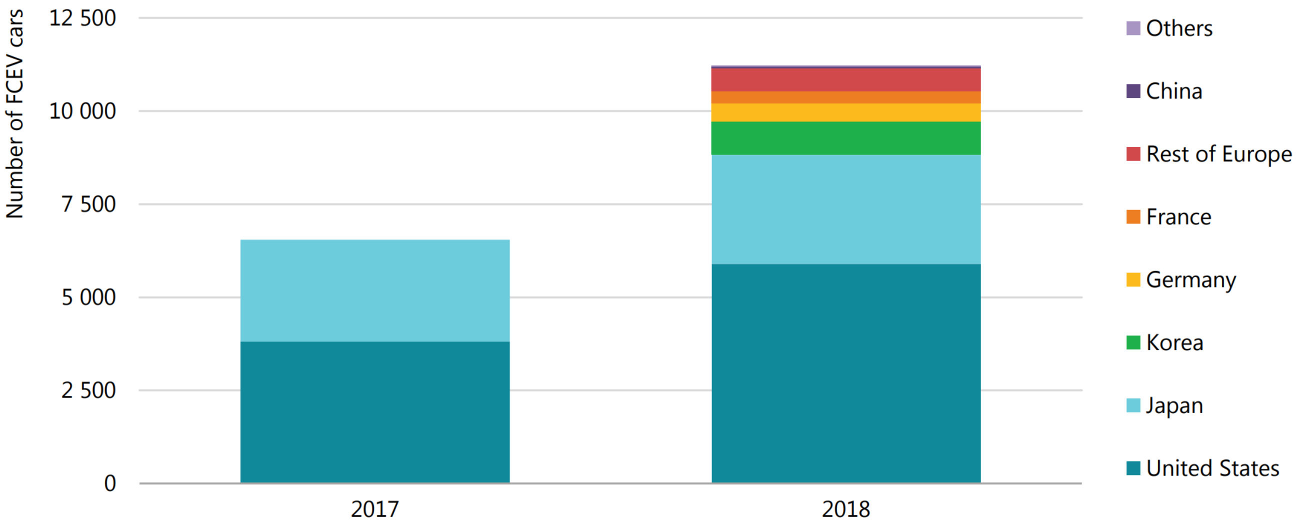
FCEV is a type of electric vehicle, but instead of storing electricity, a FCEV stores H_2 and a fuel cell acts as micro power plant to generate electricity on board

Table 1. Fuel cell vehicles available on the automotive market

	Toyota Mirai	Hyundai ix35 Fuel Cell	Honda Clarity Fuel Cell
			
Acceleration 0-60 mph	9.6 s	12.5 s	11 s
Fuel Cell power	113 kW	100 kW	103 kW
Engine power	113 kW	100 kW	130 kW
Top speed	179 km/h	161 km/h	200 km/h
Range	ca. 550 km (NEDC test)	594 km	482 km
H_2 storage	70 MPa	70 MPa	70 MPa

Source: Pielecha et al., 2018

Fuel cell electric cars in circulation, 2017–18



Source: AFC TCP (2019), *AFC TCP Survey on the Number of Fuel Cell Electric Vehicles, Hydrogen Refuelling Stations and Targets*.

2018:
FC total stock: 11 200 units
BEV total stock: 5.1 million

Source: IEA, 2019a

FCEV vs other technologies

Hydrogen fuel cell vehicle

Starts at: €60,000

Range: 320-405km/200-250 miles

Time to refuel: 3-4 minutes

Electric vehicle

Starts at: €21,000

Range: 160-500km/100-310 miles

Time to refuel: 30 minutes to 12 hours

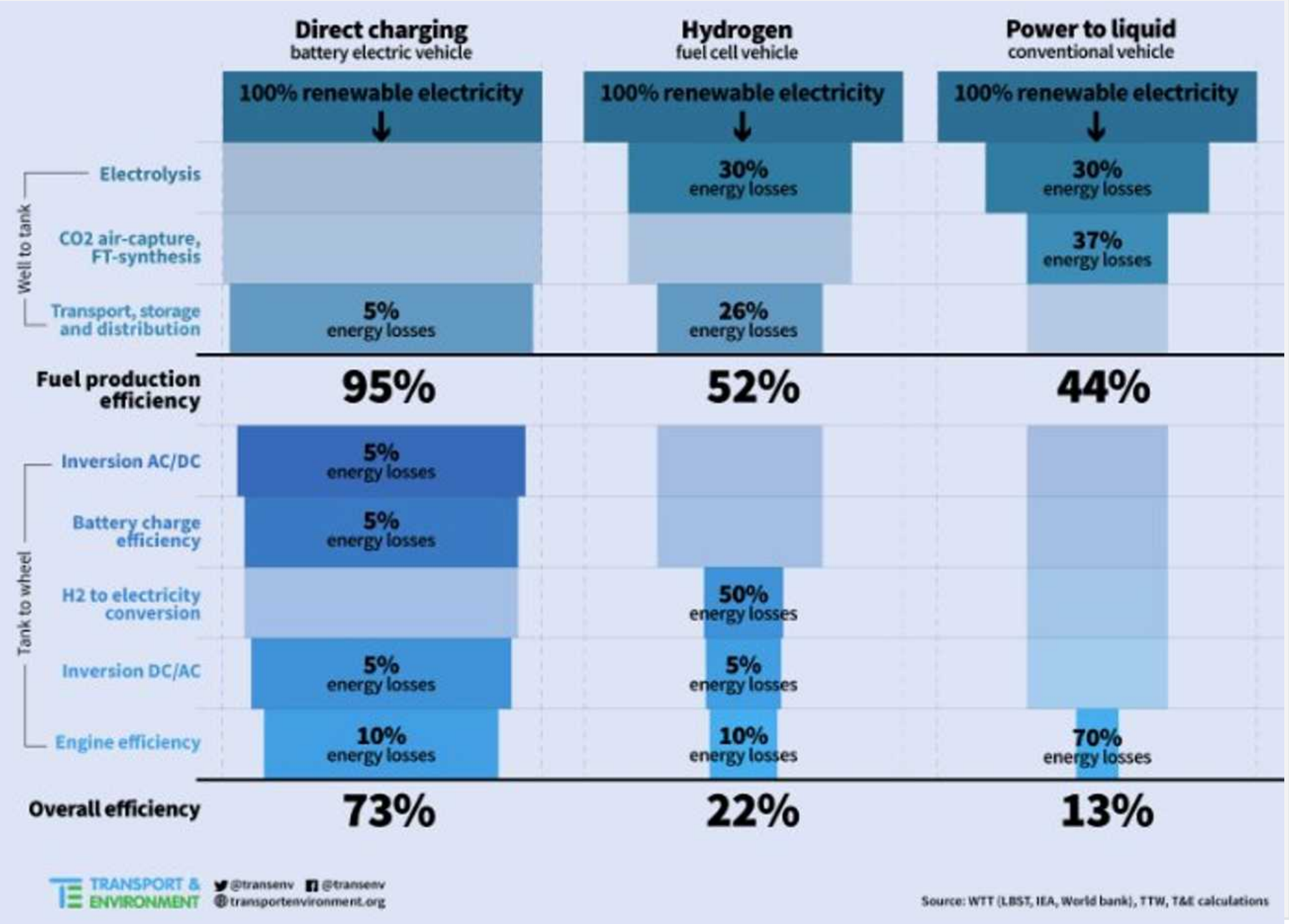
Petrol or diesel vehicle

Starts at: €8,000

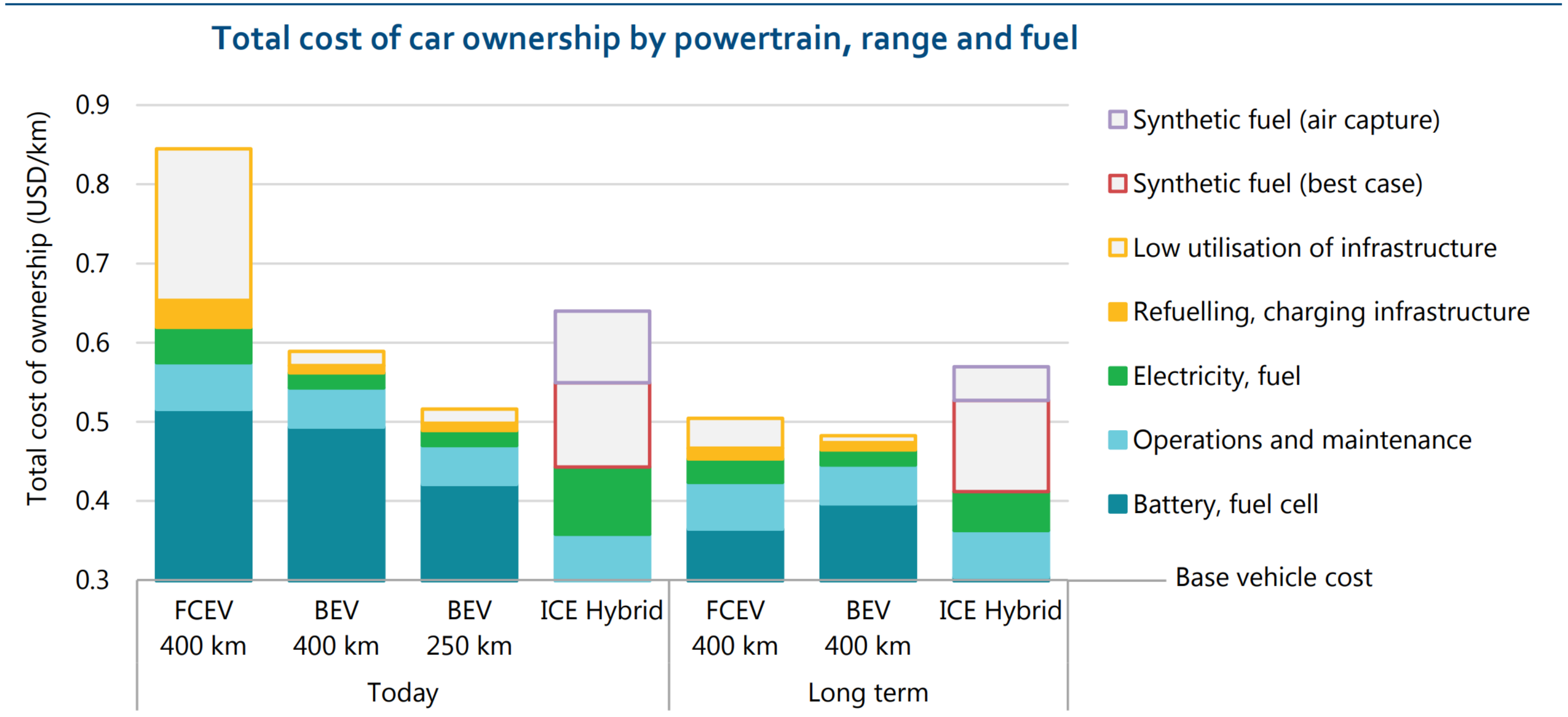
Range: 480-640km/300-400 miles

Time to refuel: 2-3 minutes

Source: https://www.euronews.com/living/2020/02/13/hydrogen-fuel-cell-vs-electric-cars-what-you-need-to-know-but-couldn-t-ask



FCEV vs other technologies



Notes: ICE = internal combustion engine. The y-axis intercept of the figure corresponds to base vehicle "glider" plus minor component costs, which are mostly invariant across powertrains. More information on the assumptions is available at www.iea.org/hydrogen2019.

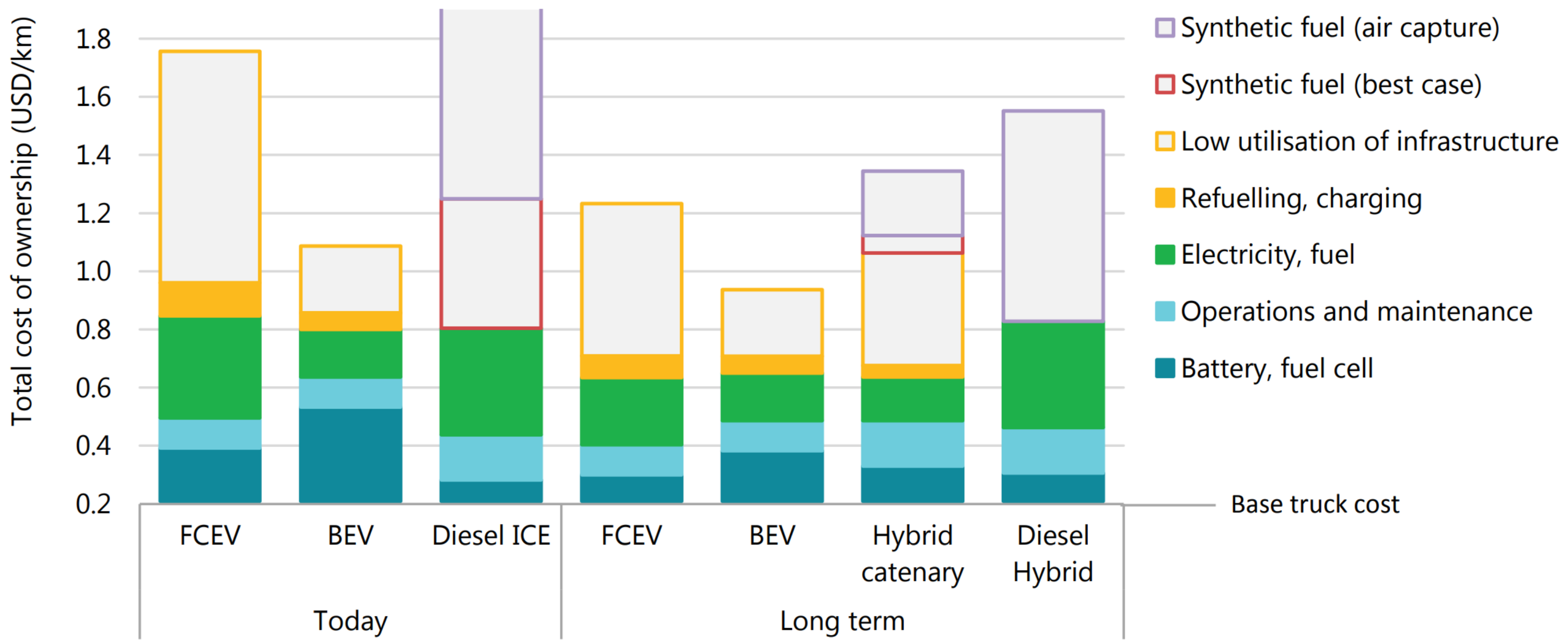
Source: IEA 2019.

- > FCEV costs could break even.
- > Cost reductions in fuel cells and storage tanks, together with high utilization of stations, are the keys to achieving competitiveness.
- > Refueling infrastructure is determinant of the future competitiveness of FCEVs

Source: IEA, 2019a

Heavy-duty (trucks and intercity buses) FCEVs

Current and future total cost of ownership of fuel/powertrain alternatives in long-haul trucks



Notes: The y-axis intercept of the figure corresponds to base vehicle "glider" plus minor component costs. Infrastructure covers stations, charging points and catenary lines. More information on the assumptions is available at www.iea.org/hydrogen2019.

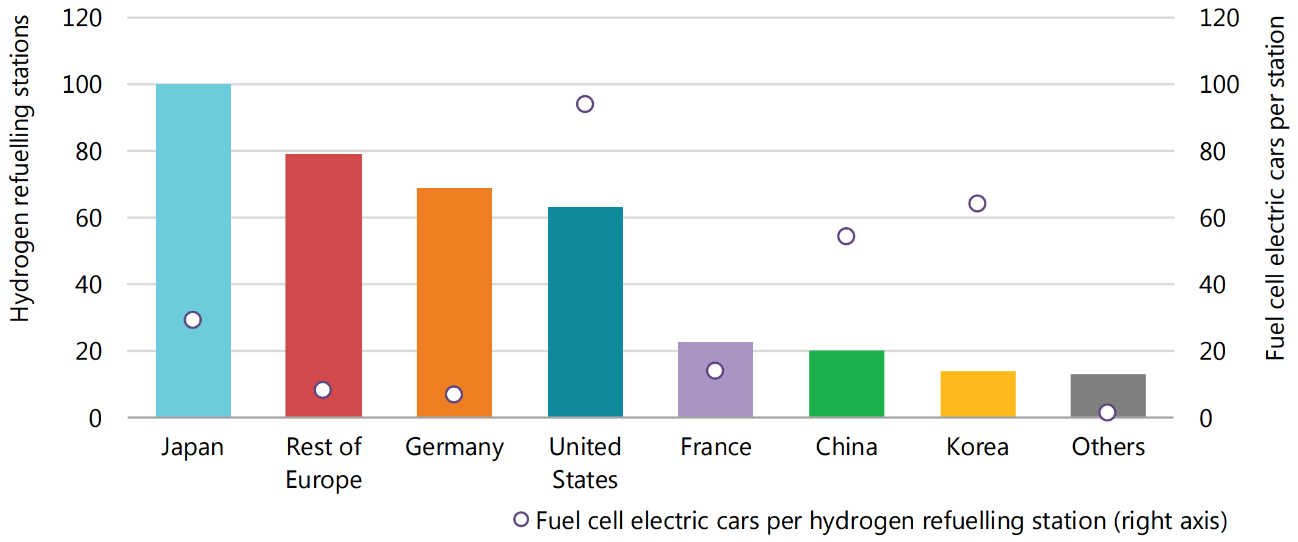
Source: IEA 2019.

- Heavy-duty FCEVs tend to be more immediately competitive against BEVs
- H_2 < USD 7/kgH2 in the long term makes FCEVs competitive in relation with IC
- The limited size of the truck market may limit the fuel cell price reduction (economies of scale). Price will rely on substantial deployment of fuel cells in cars.

Source: IEA, 2019a

H_2 refueling stations

Hydrogen refuelling stations and utilisation, 2018



Notes: Hydrogen station numbers include both publicly available and private refuelling units. The number of FCEVs used to estimate the ratio includes only light-duty vehicles, and so does not reflect utilisation of stations by other categories of road vehicles.

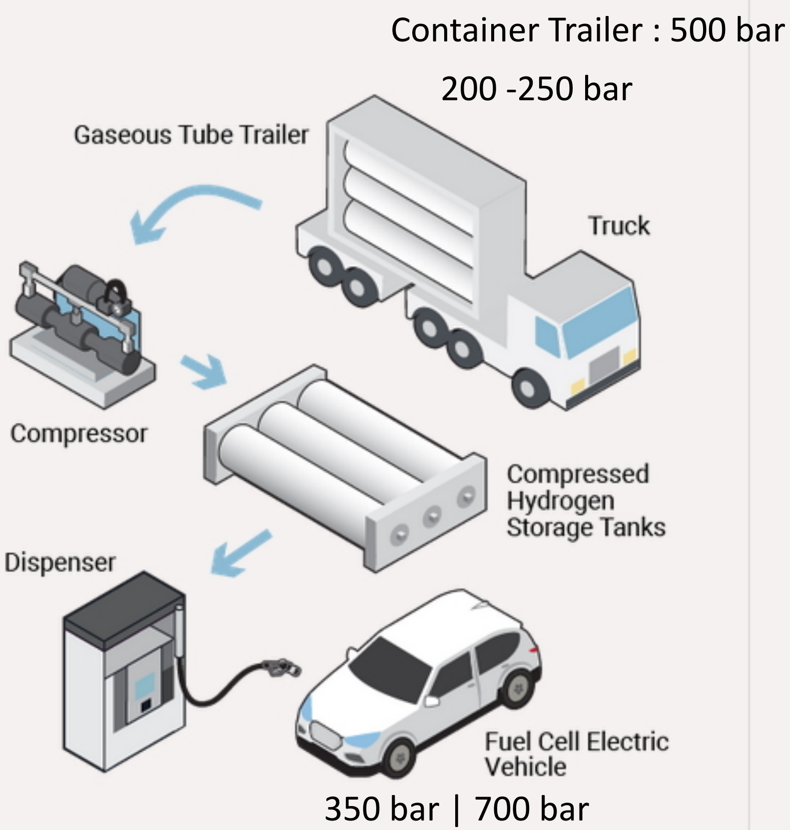
Source: AFC TCP (2019), *AFC TCP Survey on the Number of Fuel Cell Electric Vehicles, Hydrogen Refuelling Stations and Targets*.

Source: http://www.flanderstoday.eu/business/first-public-hydrogen-fuel-station-opens-flanders

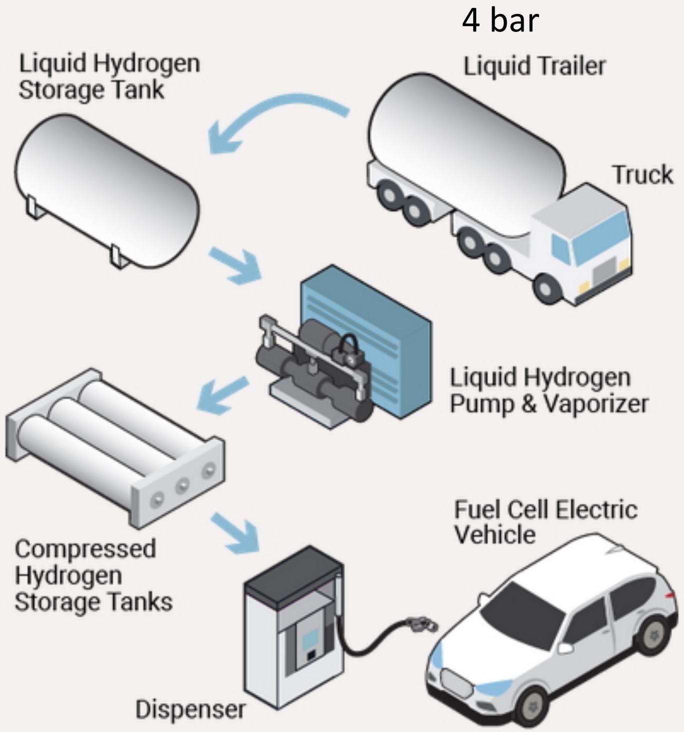
Source: IEA, 2019a

Refueling Stations

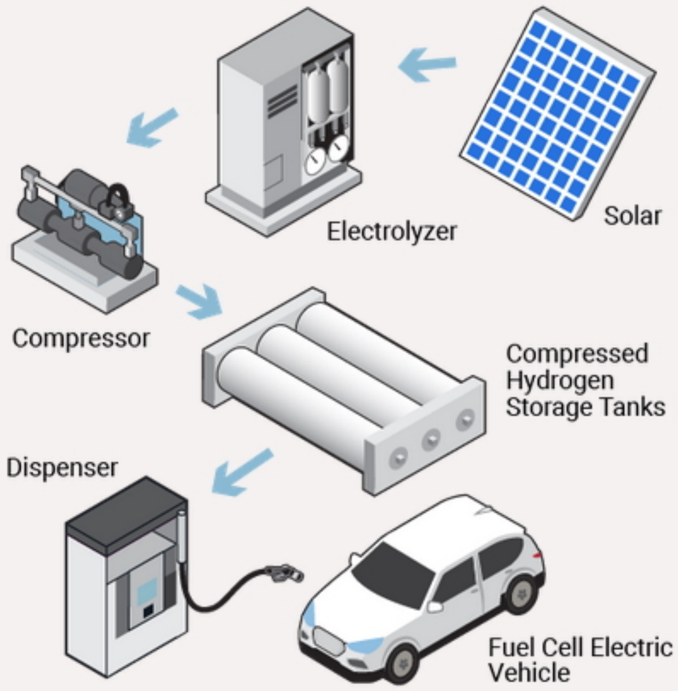
Gaseous Delivery



Liquid Delivery

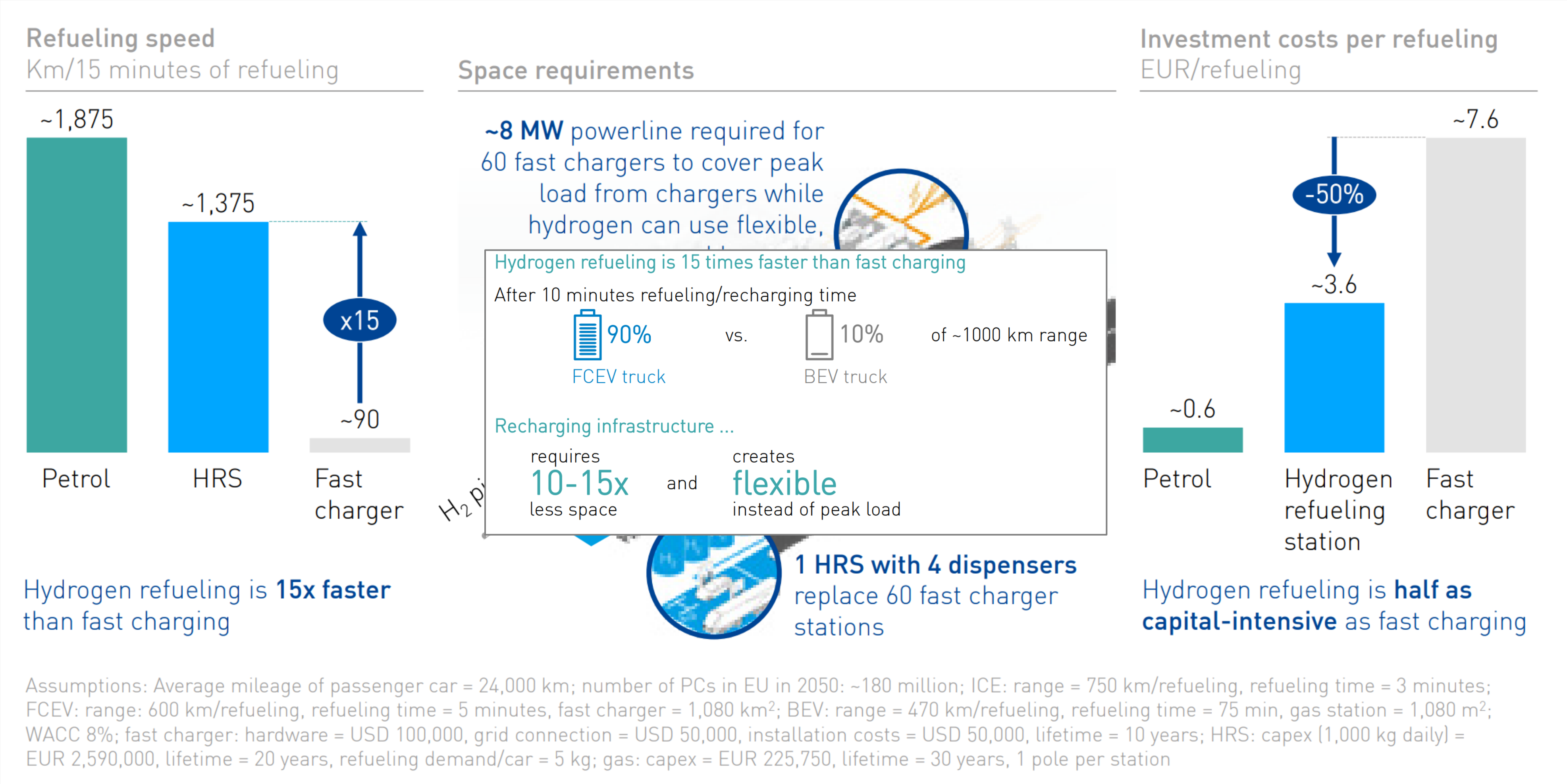


Onsite Production



Source: https://h2stationmaps.com/

Refueling Stations

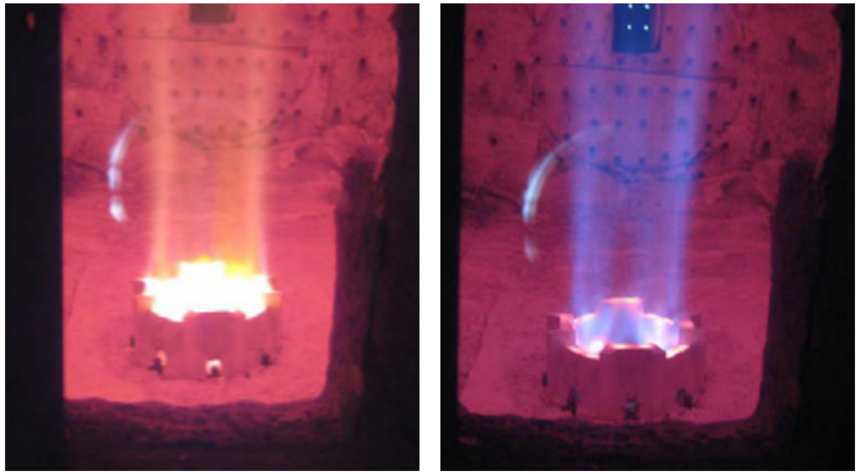


Source: FCH, 2019

H_2 use for heating (Industry and Buildings)

- H_2 can be used in 3 forms:
  - Fuel-cell (H_2 to produce electricity) – lower efficiency than direct use of electricity, higher control of power supply load curves
  - Blended in natural gas (the % of blending depend on the equipment – due to *embrittlement factor*)
  - 100% H_2
    - Lower flame brightness affect some industrial sectors – e.g., glass, ceramic
    - Higher production of NOX (additional control measures) and H2O steam
    - H2 higher volatility and requires additional security measures to detect leakages

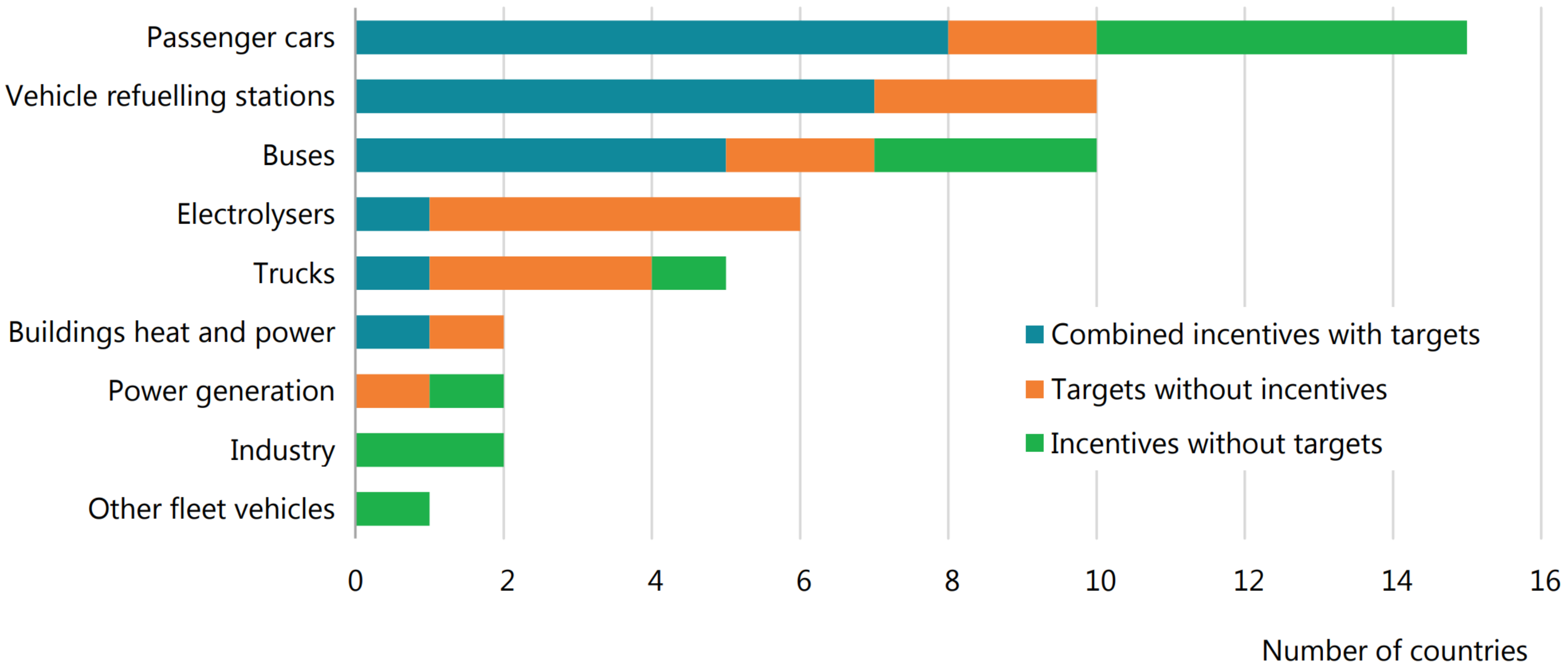
with H_2 without H_2



Sources:
“Heat Transfer in Industrial Combustion” , Charles E. Baukal
“Computational modelling of turbulent flow, combustion and heat transfer in glass furnaces”, Hoogendoorn et al (1994)
Stig Stenström (2019): Drying of paper: A review 2000–2018, Drying Technology

The growing interest on H_2

Figure 2. Policies directly supporting hydrogen deployment by target application



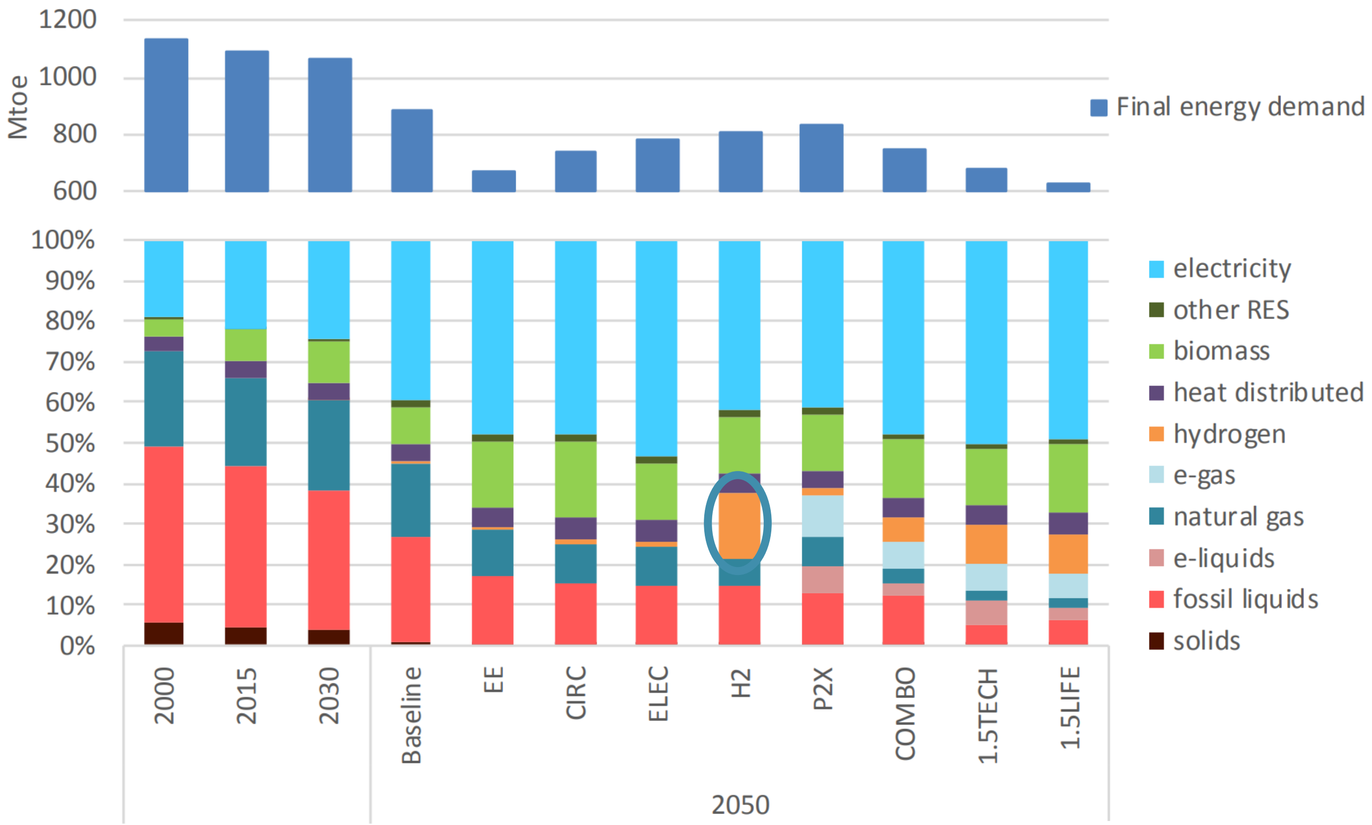
Note: Based on available data up to May 2019.

Source: IEA analysis and government surveys in collaboration with IEA Hydrogen Technology Collaboration Programme; IPHE (2019), *Country Updates*.

- The number of countries with polices that directly support investment in hydrogen technologies is increasing – **16 countries by May 20109** (Portugal not included)
- Over the past few years, global spending on hydrogen energy research, development and demonstration (RD&D) by national governments has risen

What is the role of H_2 in carbon neutrality?

Figure 20: Share of energy carriers in final energy consumption



Source: EC, 2018

A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

> Hydrogen can gradually replace natural gas as an energy fuel per se (often with energy efficiency losses) for heating purposes or in transport (used with fuel cells) and as feedstock for industrial applications (e.g. steel industry, refineries, fertilisers)

> H2 is consumed directly or is used to generate e-fuels

H2 scenario

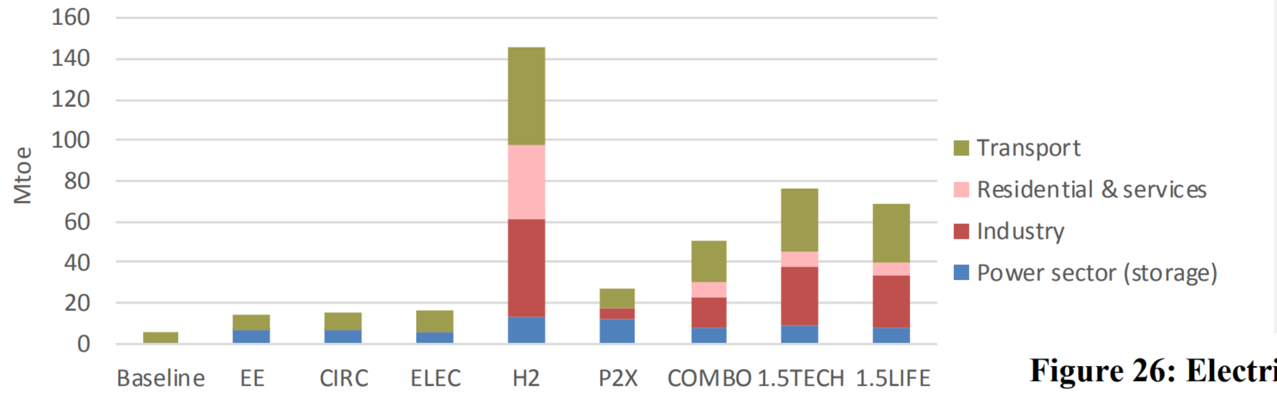
> H_2 represents to a maximum of 20% of final energy consumption

> H_2 with a mix up to 50% in gas distribution in 2050

What is the role of H_2 in carbon neutrality?

Figure 32: Consumption of hydrogen by sector in 2050

Direct use of H2

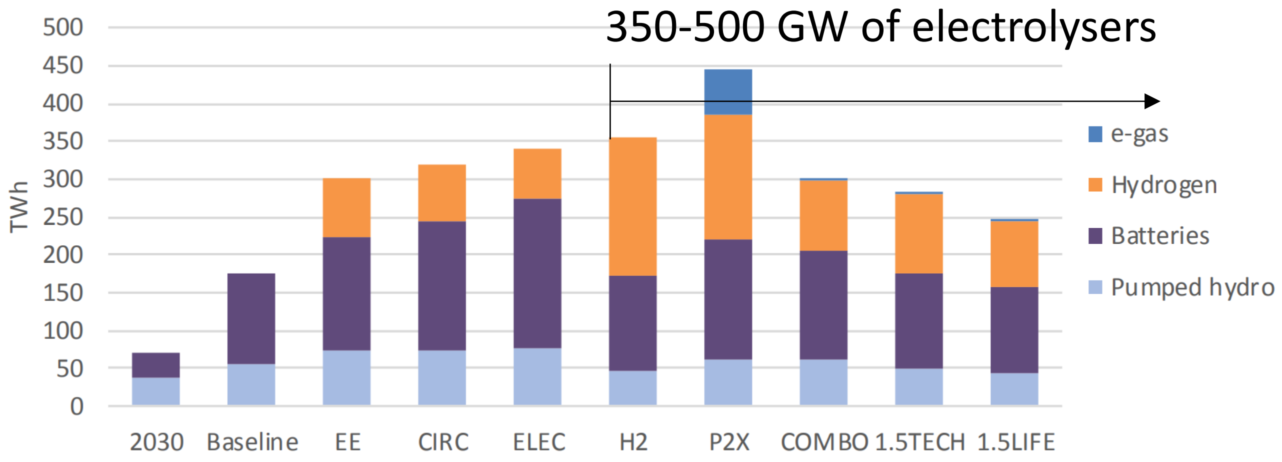


Note: "Residential & services" also includes agriculture.

Source: EC, 2018

Hydrogen is projected to have the highest share in transport energy demand in the H2 scenario (21% in 2050) - mostly for heavy duty vehicles

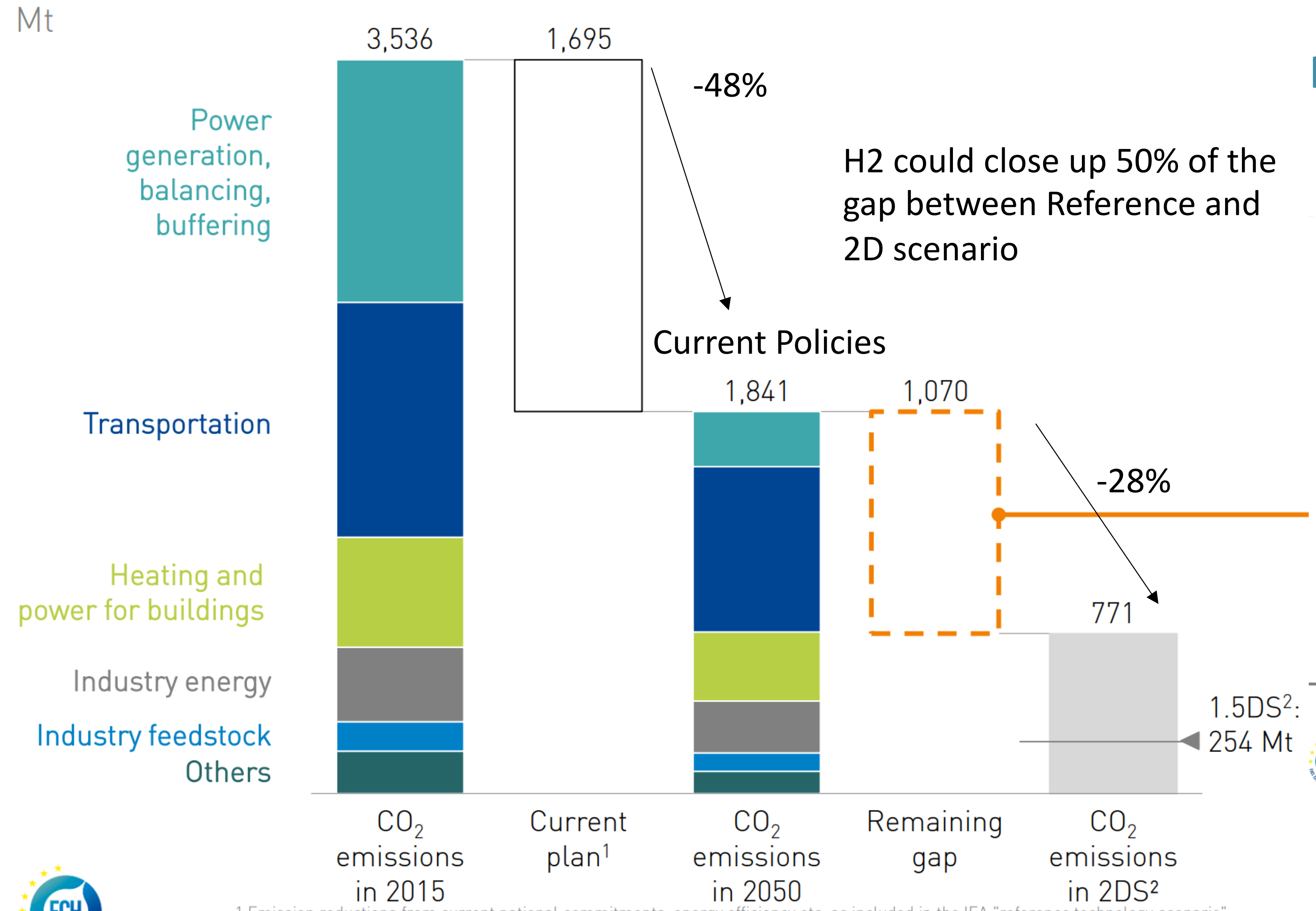
Figure 26: Electricity storage in 2050



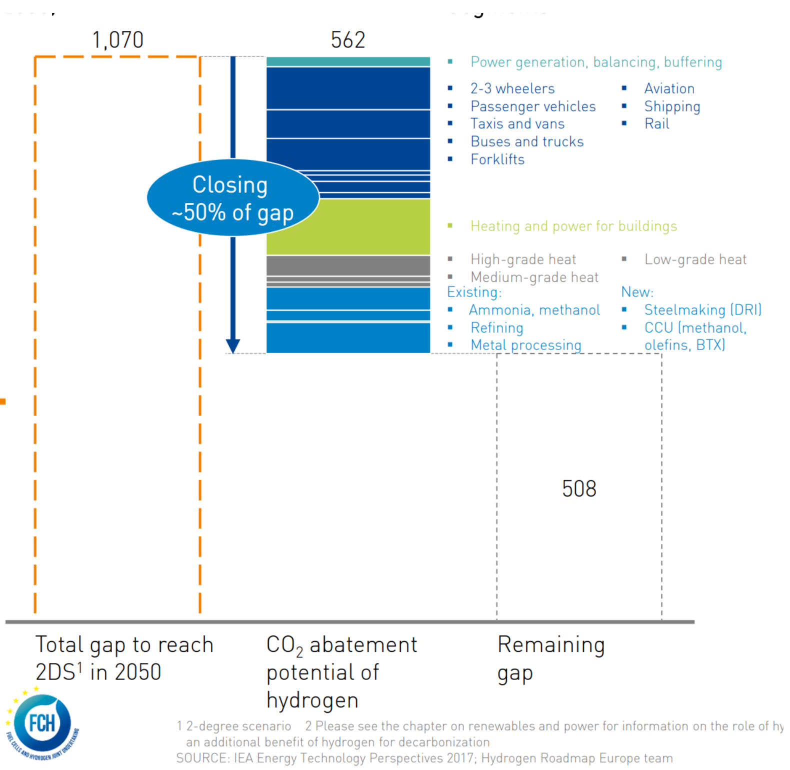
Source: PRIMES.

Source: EC, 2018

Hydrogen Roadmap Europe



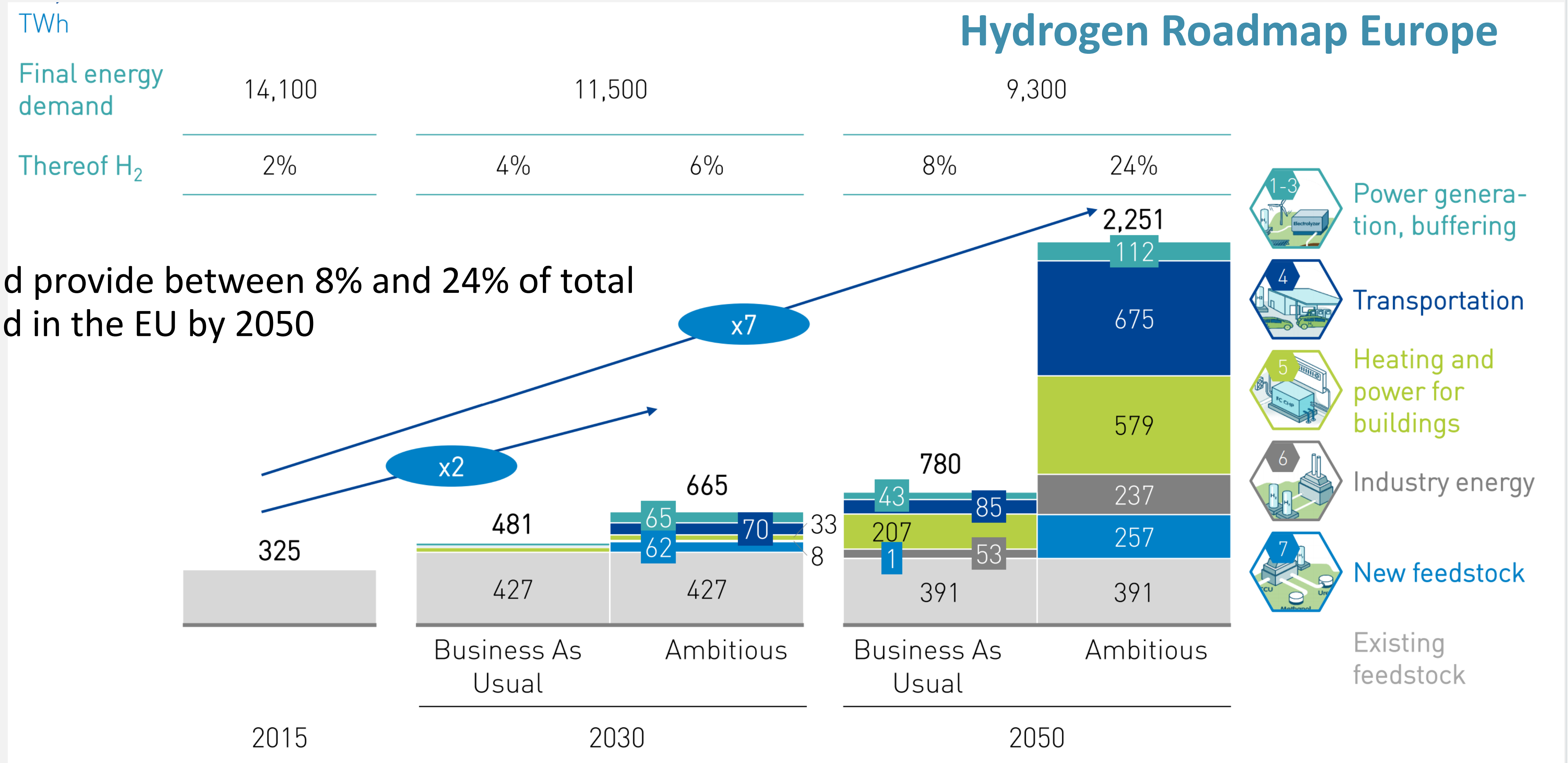
1 Emission reductions from current national commitments, energy efficiency etc. as included in the IEA "reference technology scenario"
2 DS = degree scenario
SOURCE: IEA Energy Technology Perspectives 2017; Hydrogen Roadmap Europe team



Source: FCH, 2019

What is the role of H_2 in carbon neutrality?

Hydrogen could provide between 8% and 24% of total energy demand in the EU by 2050



Source: FCH, 2019

Segments	Key subsegments	Relative importance by 2050[1]	Complementary decarbonization solutions
4 Transportation	▪ Large cars (fleets) and taxis ▪ Trucks and buses ▪ Light commercial vehicles ▪ Trains	39% 22% 30% 9%	▪ Battery-electric vehicles ▪ Plug-in hybrid electric vehicles ▪ Electrified trains
5 Heating and power for buildings	▪ Hydrogen blending for heating ▪ Pure hydrogen grids for heating	2% 16%	▪ Electrification of heating via heat pumps ▪ Energy efficiency measures ▪ Biogas/biomass
6 Industry energy	▪ High-grade heat	23%	▪ Demand side and energy efficiency measures ▪ Electrification ▪ Biogas/biomass ▪ Carbon capture
7 Industry feedstock	▪ Ultra-low-carbon hydrogen as feedstock for – Ammonia, methanol – Refining ▪ Feedstock in steelmaking (DRI) ▪ Combined with CCU in production of olefins and BTX	 100% 80% 20% 30%	*For steel:* ▪ Coke from biomass ▪ CCS on blast furnace *For CCU:* ▪ Carbon storage
1 Power generation	▪ Power generation from hydrogen ▪ Flexible power generation from hydrogen	2% 55%	▪ Biogas ▪ Post-combustion CCS ▪ Batteries

1 In transportation: percent of total fleet; in heating and power for buildings: percent of total heating demand; in industry energy: percent of final energy demand; in industry feedstock: percent of total feedstock for production; in power generation: percent of total power generation and percent of power generated from natural gas

SOURCE: Hydrogen Roadmap Europe team

Source: FCH, 2019

What is the role of H_2 in carbon neutrality?

EXHIBIT 3: BENEFITS OF HYDROGEN FOR THE EU

Hydrogen Roadmap Europe

Ambitious scenario
2050 hydrogen vision

~24%
of final energy demand[1]

~560 Mt
annual CO_2 abatement[2]

~EUR 820 bn
annual revenue (hydrogen and equipment)

~15%
reduction of local emissions (No_x) relative to road transport

~5.4 m
jobs (hydrogen, equipment, supplier industries)[3]

1 Incl. feedstock
2 Compared to the Reference Technology Scenario
3 Excl. indirect effects

Source: FCH, 2019

H_2 Strategy for Portugal

EN-H_2

HIDROGÉNIO

ESTRATÉGIA NACIONAL PARA O HIDROGÉNIO

	2025	2030	2040	2050
H_2 NA REDE DE TRANSPORTE DE GÁS NATURAL[20]	1% - 5%	10% - 15%	40% - 50%	75% - 80%
H_2 NA REDE DE DISTRIBUIÇÃO DE GÁS NATURAL[21]	1% - 5%	10% - 15%	40% - 50%	75% - 80%
H_2 NO CONSUMO DA INDÚSTRIA[22]	0,5% - 1%	2% - 5%	10% - 15%	20% - 25%
H_2 NO CONSUMO DO TRANSPORTE RODOVIÁRIO	0,1% - 0,5%	1% - 5%	5% - 10%	20% - 25%
H_2 NO TRANSPORTE MARITIMO DOMÉSTICO	0%	3% - 5%	10% - 15%	20% - 25%
H_2 NO CONSUMO TOTAL FINAL DE ENERGIA	1% - 2%	2% - 5%	7% - 10%	15% - 20%
H_2 NAS CENTRAIS TERMOELÉTRICAS A GÁS NATURAL	1% - 5%	5% - 15%	40% - 50%	75% - 80%
CAPACIDADE PARA PRODUÇÃO DE H_2	250 - 500 MW	1,75 - 2 GW	3 GW	5 GW
CAPACIDADE PARA PRODUÇÃO DE H_2 UPP[23] (<5 MW)	50 MW	100 MW	250 MW	500 MW

Mostly PV
& Onshore Wind

Exportação de H2 para a Holanda

Summary

1 What is Hydrogen (H_2)?

H2 is the simplest and most abundant element on earth. H2 is a flexible energy carrier, i.e., can store and deliver usable energy, but it doesn't typically exist by itself in nature and must be produced from compounds that contain it.

2 What is current role of H_2?

H2 is mostly used as a feedstock in petroleum refining and fertilizer (ammonia) production. Today 95% of H2 is produced from fossil fuels, mostly from natural gas with consequent CO2 emissions.

3 Why we are talking so much about H_2?

H2 can be produced from clean energy sources (e.g., renewables) and may deliver or store a tremendous amount of energy*, without CO2 emissions supporting the decarbonization of economy. H2 can store electricity (chemical storage) for higher periods of time than batteries (seasonal vs daily) and deliver this energy to different uses, for example, can be used in fuel cells to generate electricity to transports or to stationary uses, can be used directly to decarbonize industry heating

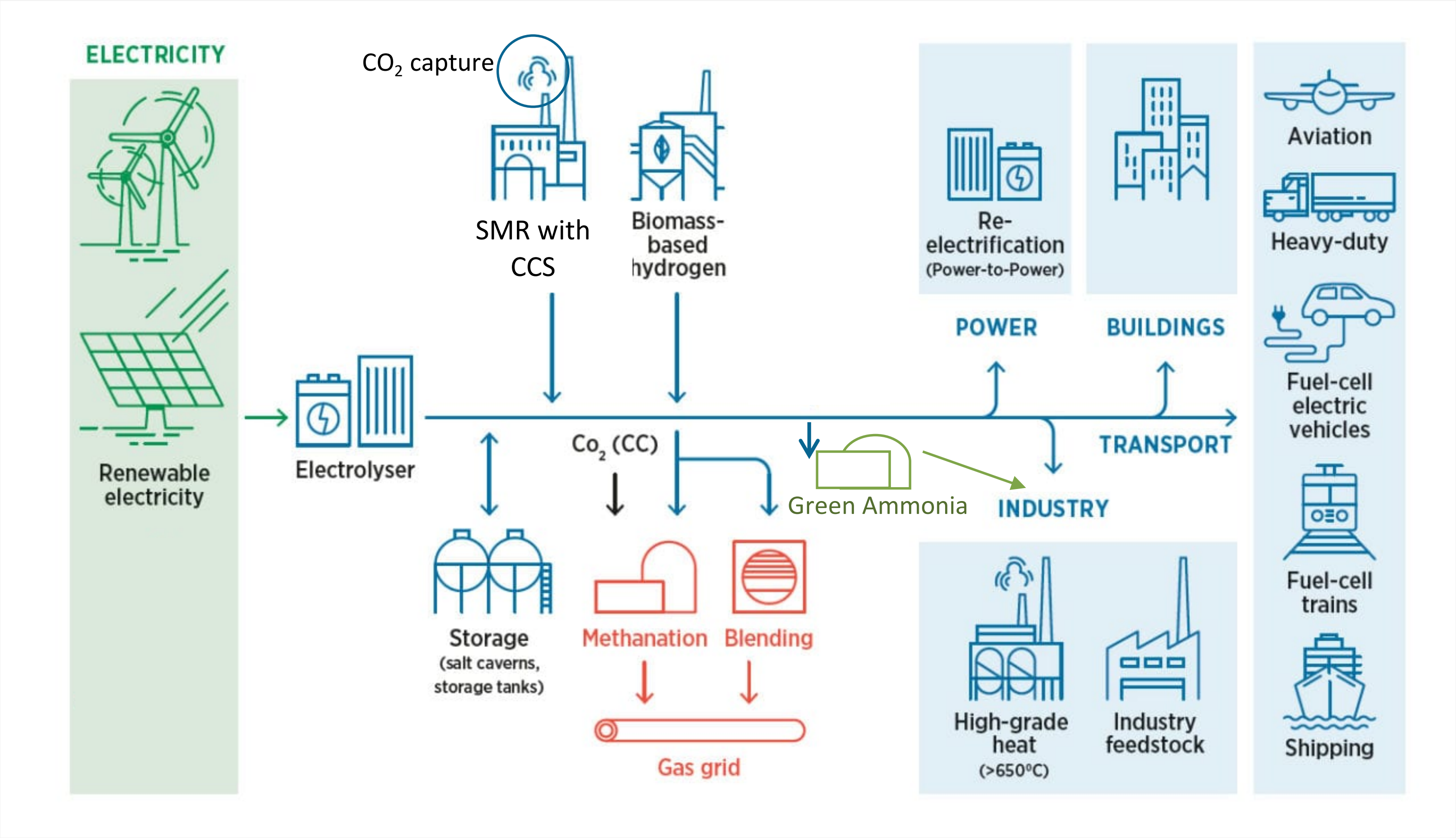
***It has 2 and 3 times more energy per unit of mass than natural gas and gasoline.**

Summary

4 What is the H_2 economy?

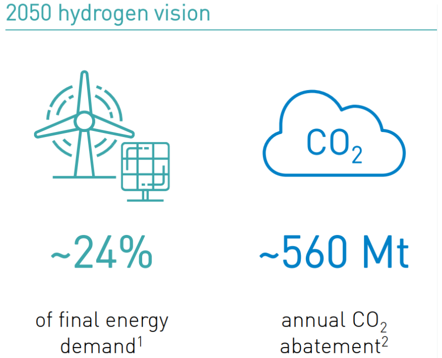
- H_2 production
- H_2 storage
- H_2 transport & distribution
- H_2 utilization

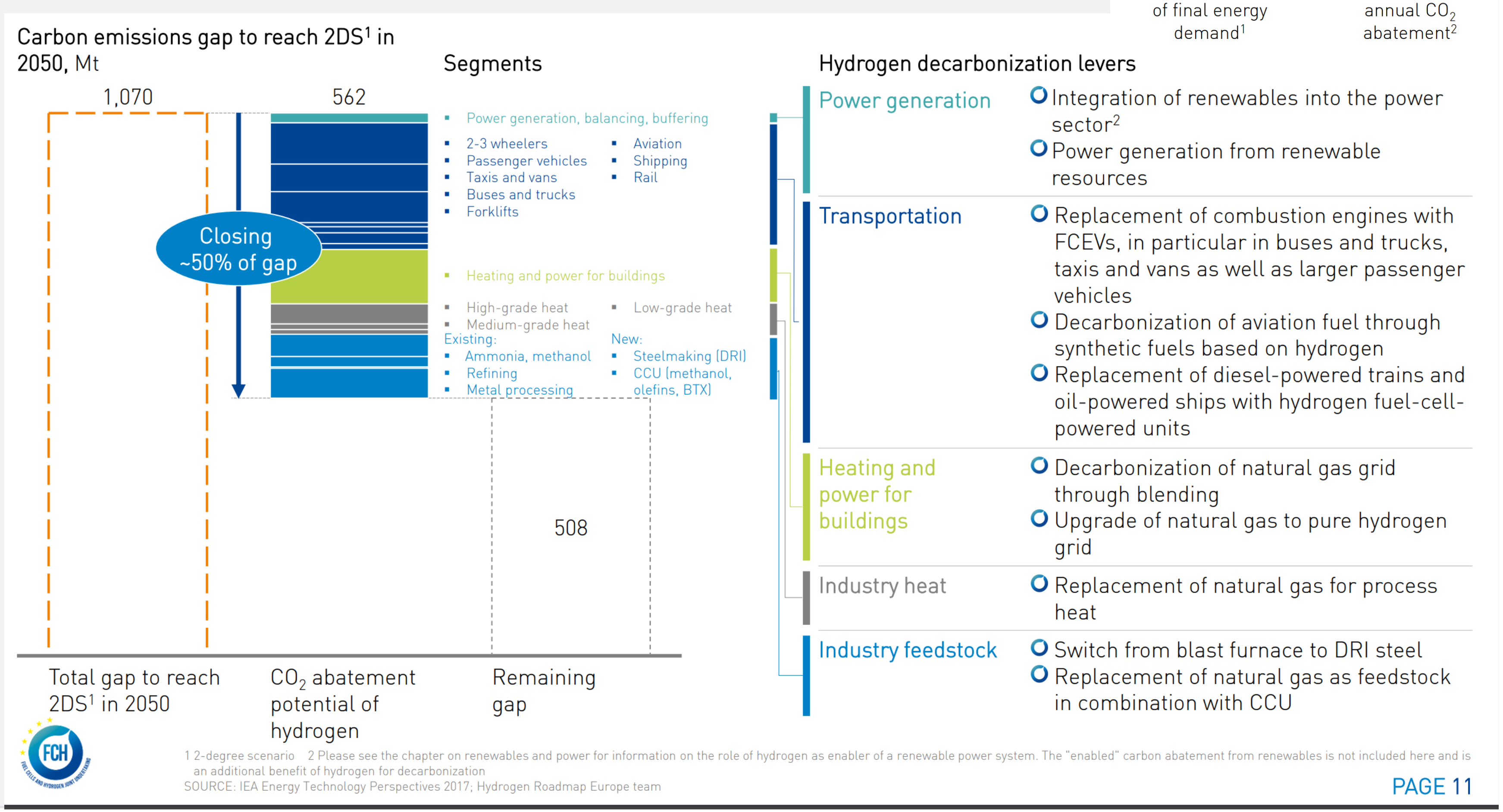
Example of Hydrogen "green" and "blue" economy



Summary

5 What is the role of H_2 in a carbon neutral economy (European case)?





6 What is Portugal saying about H_2?

2050 | 5 GW electrolyser for
75%/80% in natural gas grid
15%/20% of H2 in final energy

Patrícia Fortes
p.f@fct.unl.pt

References

- BloombergNEF, 2020. Hydrogen Economy Outlook: Key messages
- EC 2018. A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773. European Commission Brussels, 28 November 2018. https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf
- FCH, 2019. Hydrogen Roadmap Europe. Fuel Cells and Hydrogen, Joint Undertaking
- IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press. https://www.ipcc.ch/sr15/
- IEA, 2019a. The future of hydrogen - Seizing today's opportunities. International Energy Agency. Paris
- IEA, 2019b. World Energy Outlook 2019. International Energy Agency. Paris
- AT Kearney Energy Transition Institute, 2014. More than storage: system flexibility. Hydrogen-based energy conversion. https://www.energy-transition-institute.com/_/media/Files/ETI/Hydrogen%20Based%20Energy%20Conversion%20Presentation.pdf
- Pielecha, Ireneusz & Cieslik, Wojciech & Andrzej, Szałek. (2018). The use of electric drive in urban driving conditions using a hydrogen powered vehicle-Toyota Mirai. Combustion Engines. 172. 51-58. 10.19206/CE-2018-106.
- Shell Deutschland Oil, 2017. Shell Hydrogen Study: Energy of the Future? Hamburg. https://www.shell.com/energy-and-innovation/new-energies/hydrogen/_jcr_content/par/keybenefits_150847174/link.stream/1496312627865/6a3564d61b9aff43e087972db5212be68d1fb2e8/shell-h2-study-new.pdf