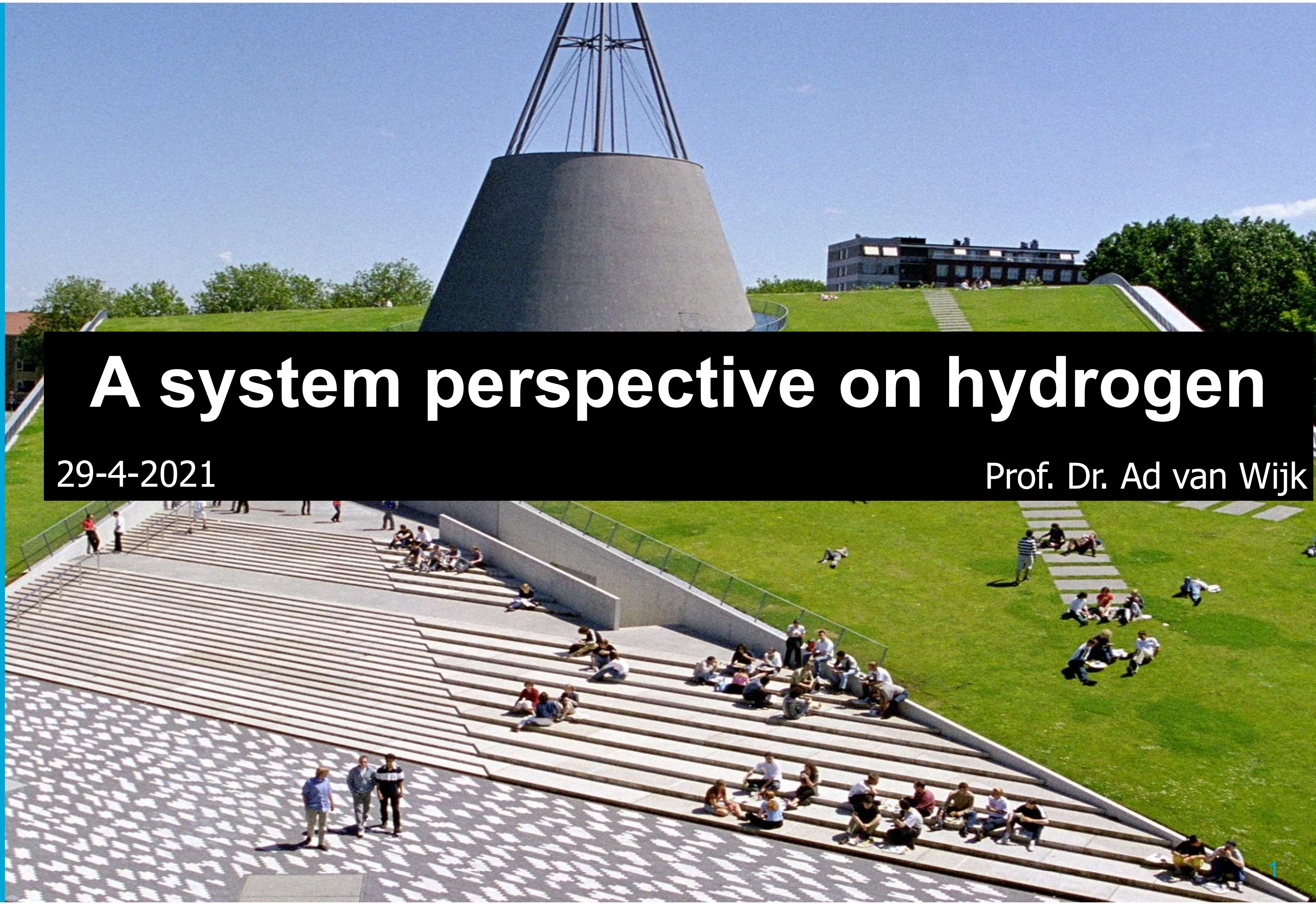

A system perspective on hydrogen

29-4-2021

Prof. Dr. Ad van Wijk

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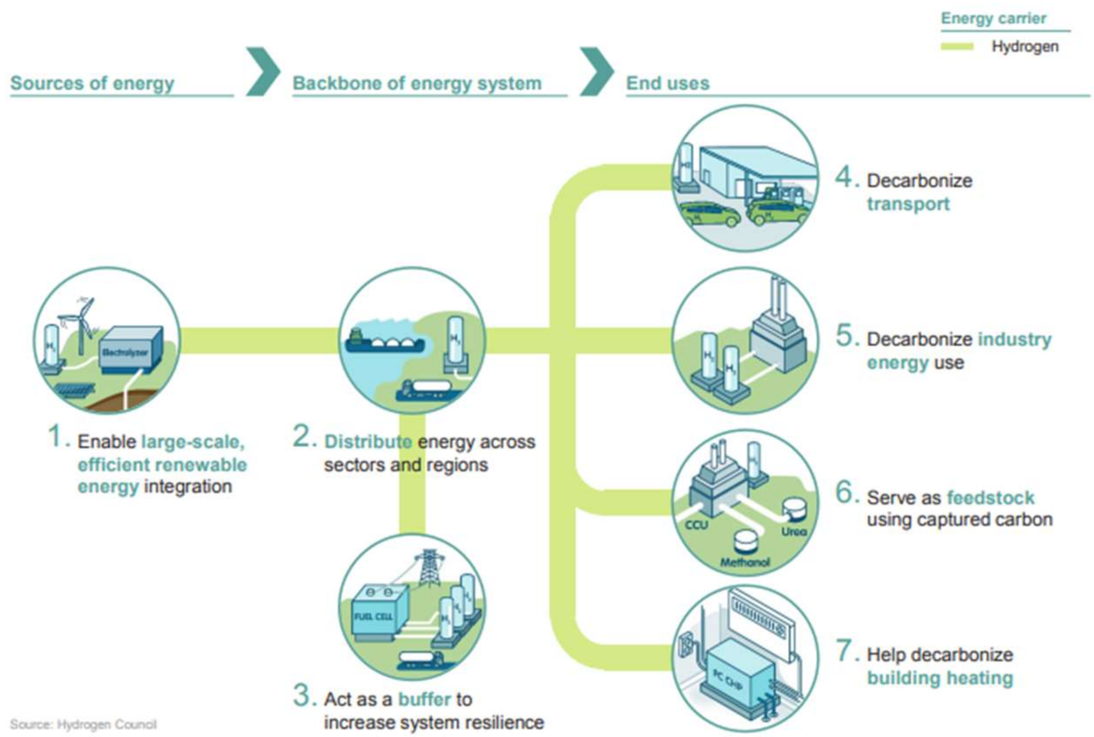
Hydrogen in a carbon-free energy system



https://hydrogencouncil.com/wp-content/uploads/2017/06/Hydrogen-Council-Vision-Document.pdf

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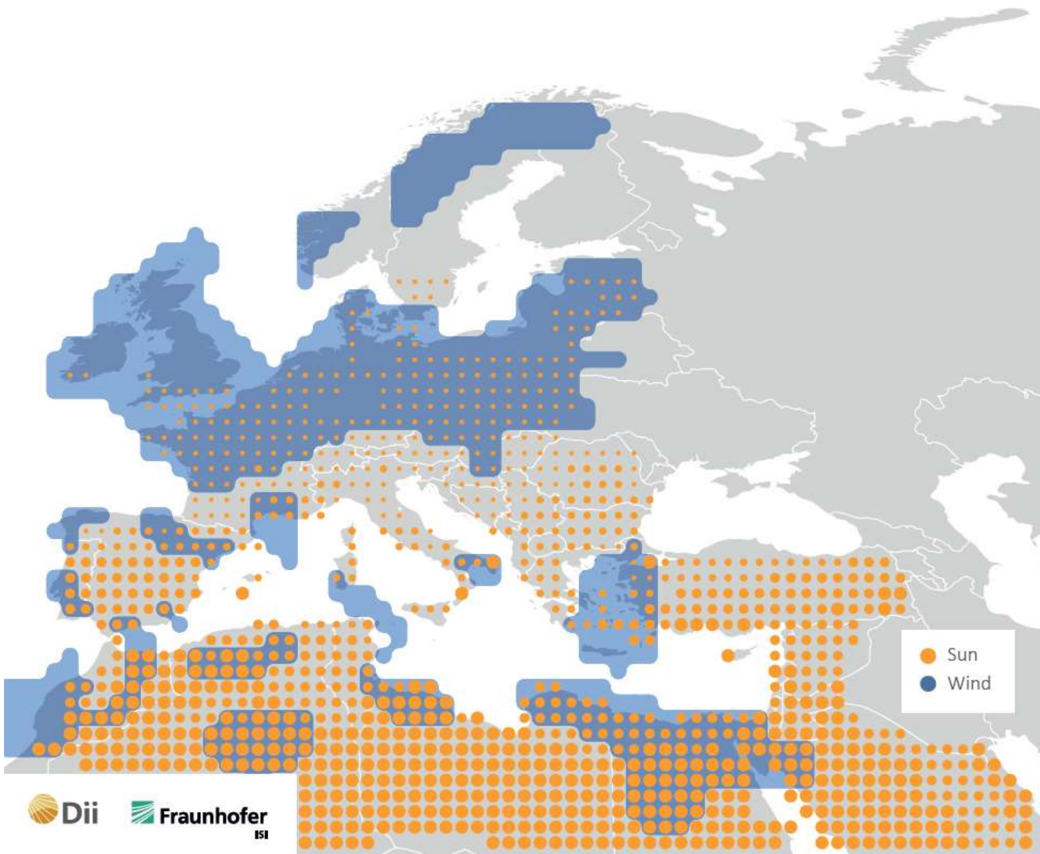
Solar and wind electricity becomes cheap, but only at good resource sites



Abu Dhabi 2.000 MW Solar Farm

€ 1.25 ct/kWh July 2020

Portugal 700 MW Solar Farm

€ 1.12 ct/kWh August 2020

Saudi Arabia 600 MW Solar Farm

€ 0.87 ct/kWh April 2021

Spain 1.000 MW Wind Farms

Range from € 2 ct/kWh to € 2.9 ct/kWh January 2021

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Hydrogen is, like electricity, an energy carrier!

Source	Process/Technology	Maturity	Output	'Colour' of Hydrogen
Natural gas	Steam methane reforming Auto-thermal reforming Thermal Pyrolysis	Mature Mature First plant 2025	$H_2 + CO_2$ $H_2 + CO_2$ $H_2 + C$	**Grey or blue**, 50-90% of CO_2 can be captured + stored **Turquoise**, CO_2 emissions depend on the source for electricity production
Coal	Gasification Underground coal gasification	Mature Projects exist	$H_2 + CO_2 + C$ $H_2 + CO_2$	**Brown or blue**, 50-90% of CO_2 can be captured + stored
Solid Biomass, Biogenic waste	Gasification Plasma gasification	Near Maturity First Plant 2023	$H_2 + CO_2 + C$ $H_2 + CO_2$	**Green** Negative CO_2 emissions possible
Wet Biomass, Biogenic waste	Super critical water gasification Microbial Electrolysis Cell	First Plant 2023 Laboratory	$H_2 + CH_4 + CO_2$ $H_2 + CH_4$	**Green** Negative CO_2 emissions possible
Electricity + Water	Electrolysis Alkaline PEM SOEC	 Mature Near Maturity Pilot Plants	 $H_2 + O_2$ $H_2 + O_2$ $H_2 + O_2$	**Shades of grey to green and pink** depend on the source for electricity production
Sunlight+Water	Photoelectrochemical	Laboratory	$H_2 + O_2$	**Green**

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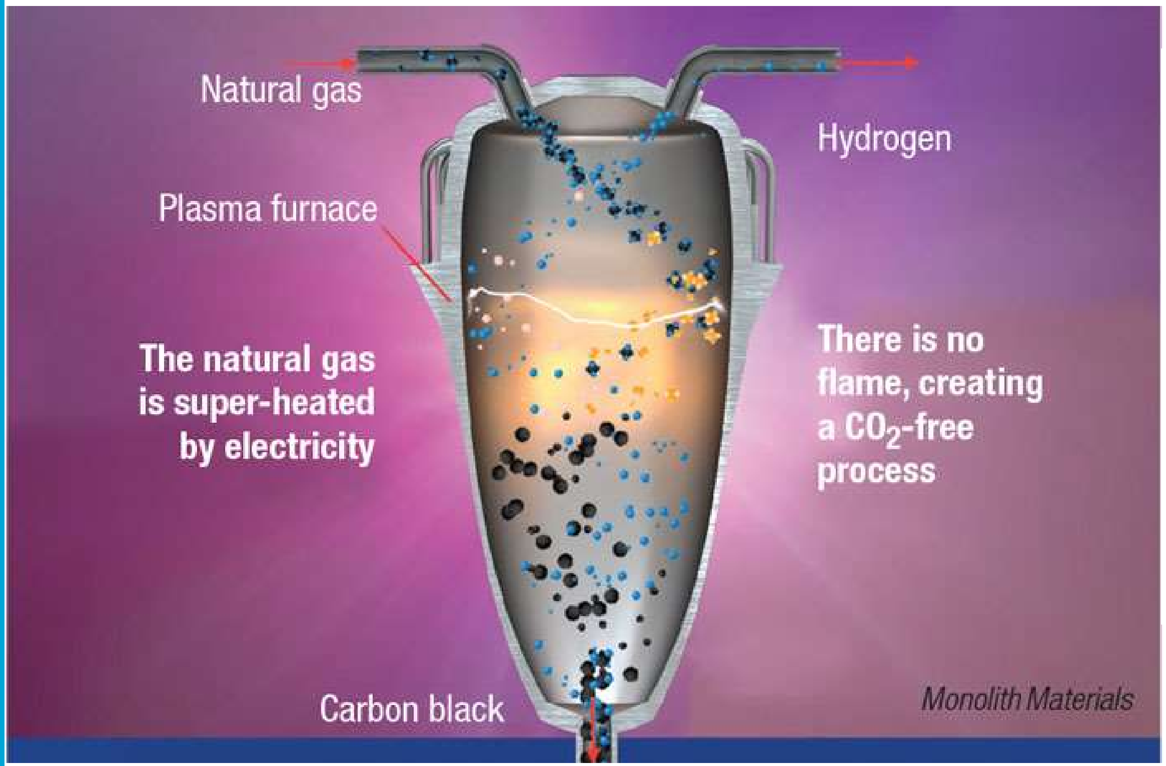
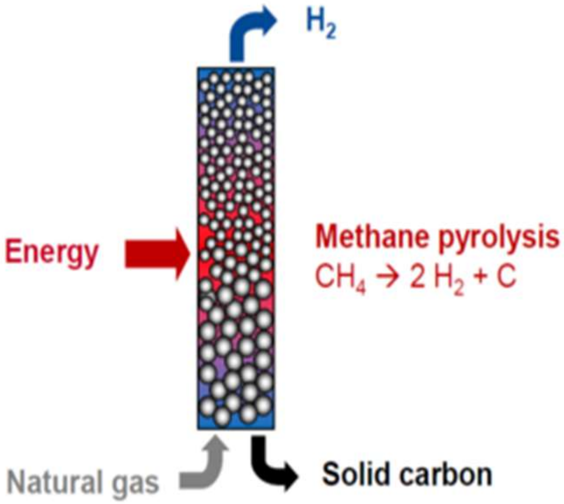
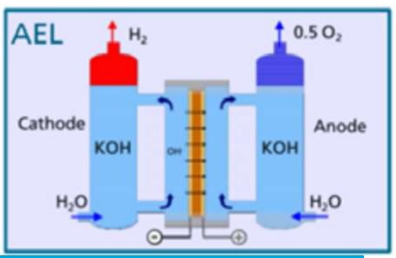
Methane Pyrolysis

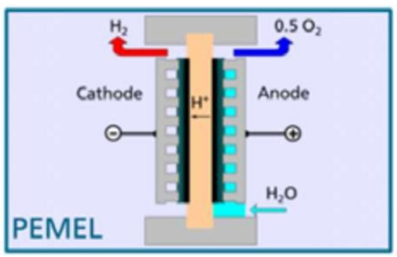


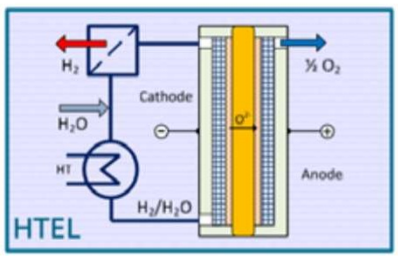


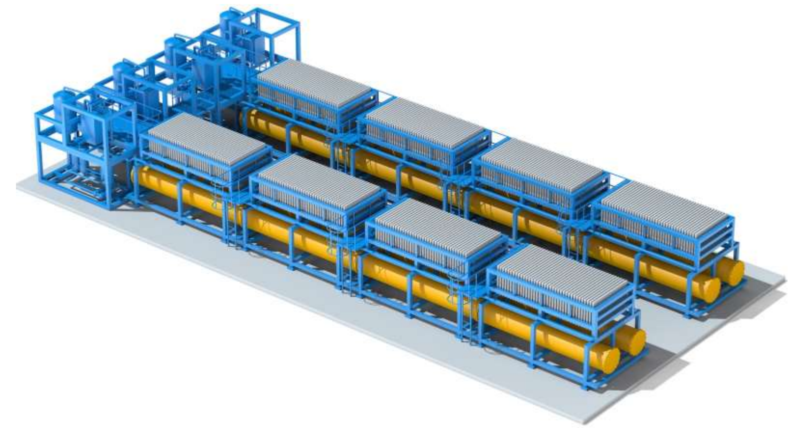
Water Electrolysis

Technology	Temp. Range	Cathodic Reaction (HER)	Charge Carrier	Anodic Reaction (OER)
Alkaline electrolysis	40 - 90 °C	$2H_2O + 2e^- \Rightarrow H_2 + 2OH^-$	OH^-	$2OH^- \Rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$
Membrane electrolysis	20 - 100 °C	$2H^+ + 2e^- \Rightarrow H_2$	H^+	$H_2O \Rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$
High temp. electrolysis	700 - 1000 °C	$H_2O + 2e^- \Rightarrow H_2 + O^{2-}$	O^{2-}	$O^{2-} \Rightarrow \frac{1}{2}O_2 + 2e^-$









20 MW alkaline electrolyser ThyssenKrupp

	5 MW module	20 MW module
Design capacity H_2	1000 Nm³/h	4000 Nm³/h
Efficiency electrolyzer (DC)	> 82%$_{HHV}$*	> 82%$_{HHV}$*
Power consumption (DC)	max. 4.3 kWh/Nm³ H_2	max. 4.3 kWh/Nm³ H_2
Water consumption	<1l/Nm³ H_2	<1l/Nm³ H_2
Standard operation window	10% - 100%	10% - 100%
H_2 product quality at electrolyzer outlet	> 99.95% purity (dry basis)	> 99.95% purity (dry basis)
H_2 product quality after treatment (optional)	as required by customer, up to 99.9998 %	as required by customer, up to 99.9998 %
H_2 product pressure at module outlet	~300 mbar	~300 mbar
Operating temperature	up to 90 °C	up to 90 °C

* HHV = calculated with reference to higher heating value of hydrogen.
All values may vary depending on operating conditions.

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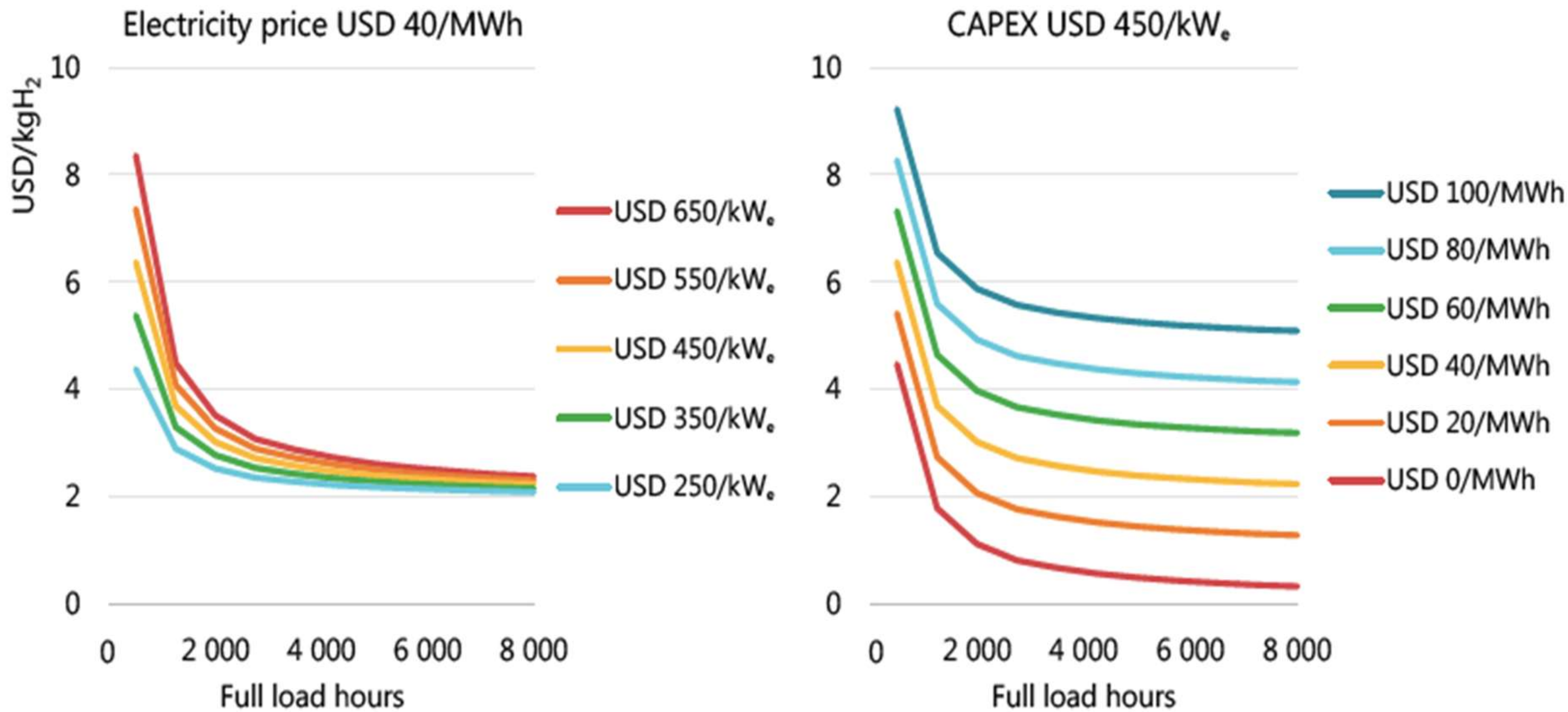
Hydrogen production cost; LCoH



Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

Source: IEA 2019.

Future levelized cost of hydrogen production by operating hour for different electrolyser investment costs (left) and electricity costs (right), from *The Future of Hydrogen (IEA 2019)* (LHV efficiency 69% is HHV efficiency 81%)

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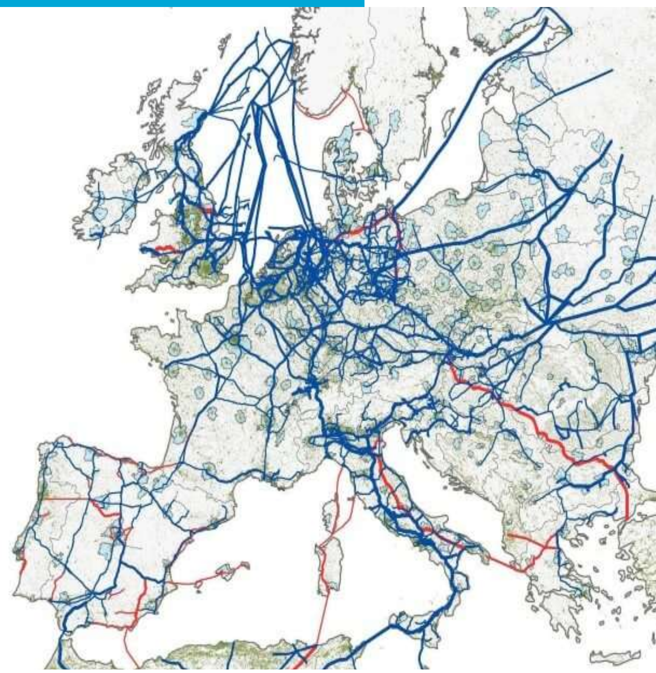
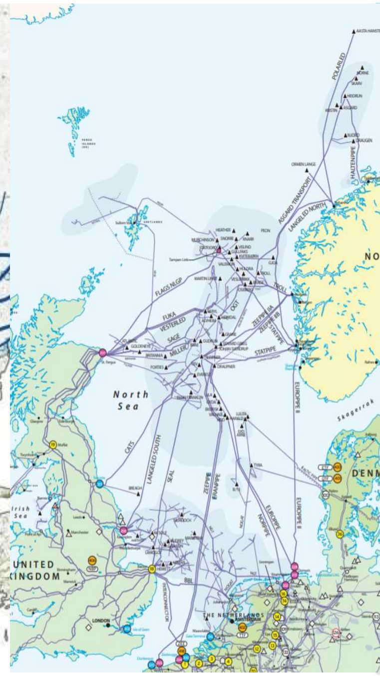
Hydrogen can be transported through re-used gas infrastructure

Gas pipeline capacity 10-20 GW,
Electricity cable capacity 1-2 GW

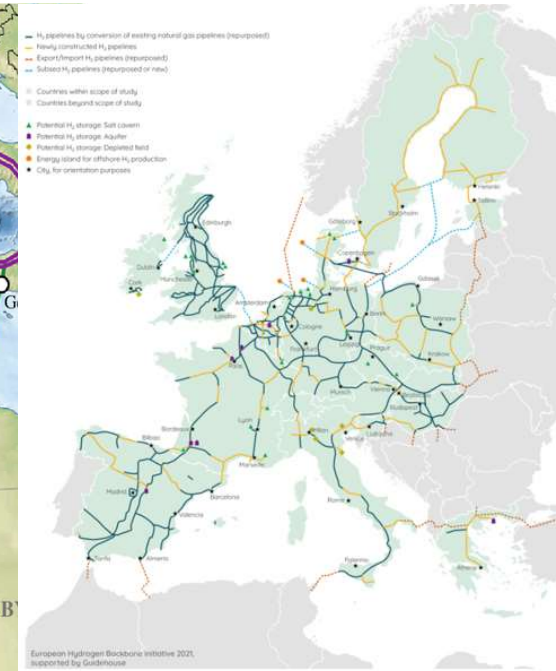


Gas Pipelines Europe
Transporting gas from gas fields at North Sea, Norway, Russia, Algeria, Libya to Europe



Gas from North-Sea
2017 production
190 bcm = 1.900 TWh

Gas from North-Africa
60 GW Natural Gas Pipeline
2x0.7 GW Electricity Cable



European Hydrogen Backbone
75% re-used gas pipelines
25% new hydrogen pipelines
40.000 km pipelines

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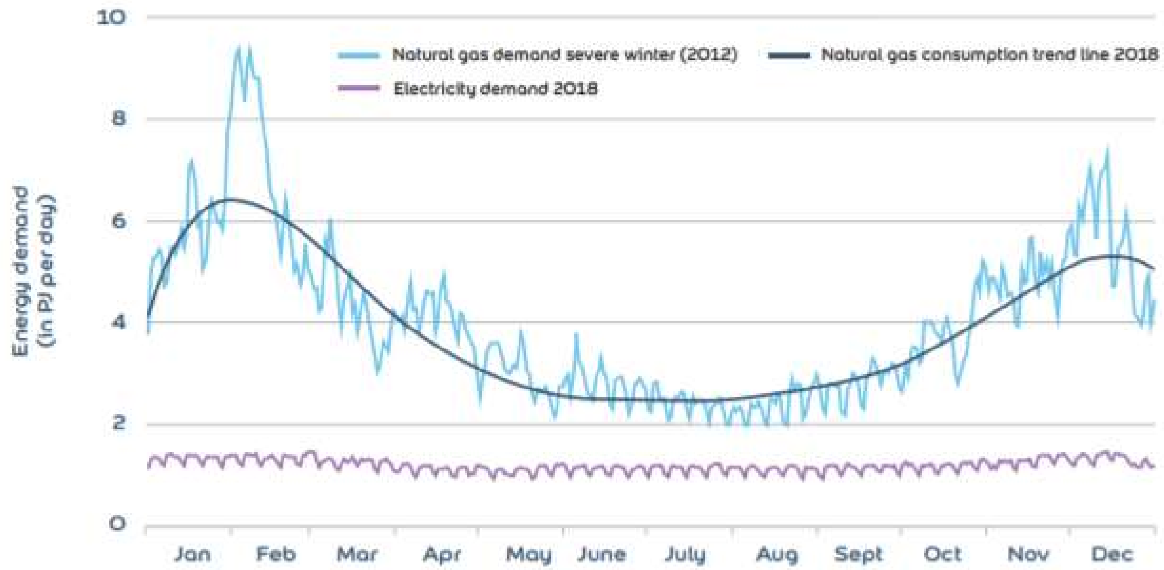
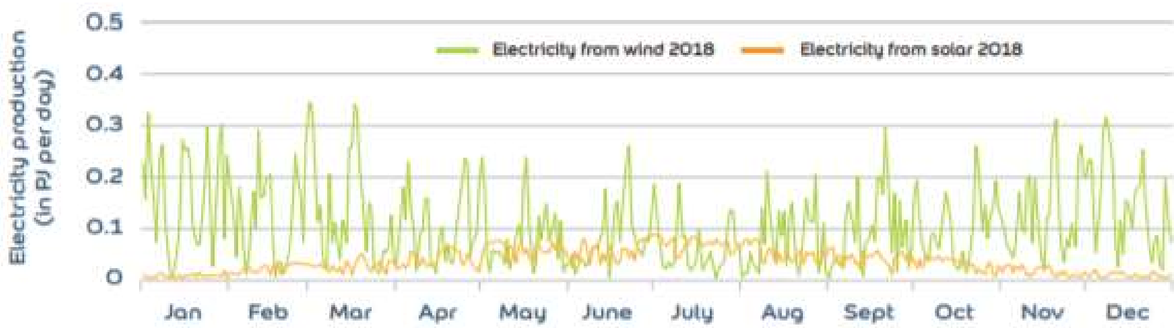
Gas and Electricity consumption in the Netherlands 2018



Solar and Wind electricity production in the Netherlands 2018



https://www.energieinnederland.nl/wp-content/uploads/2020/02/EBN-INFOGRAPHIC-2020-ENG.pdf

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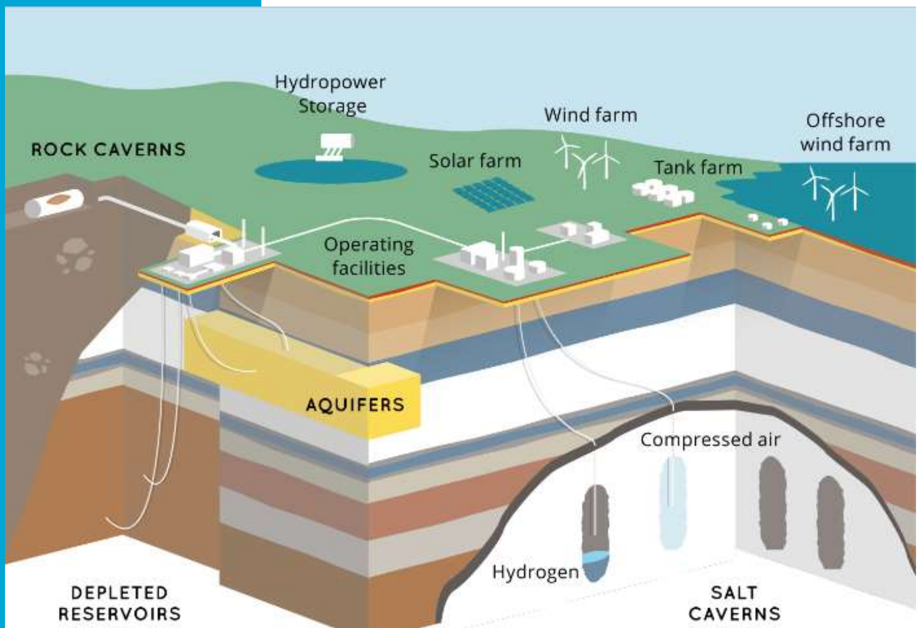
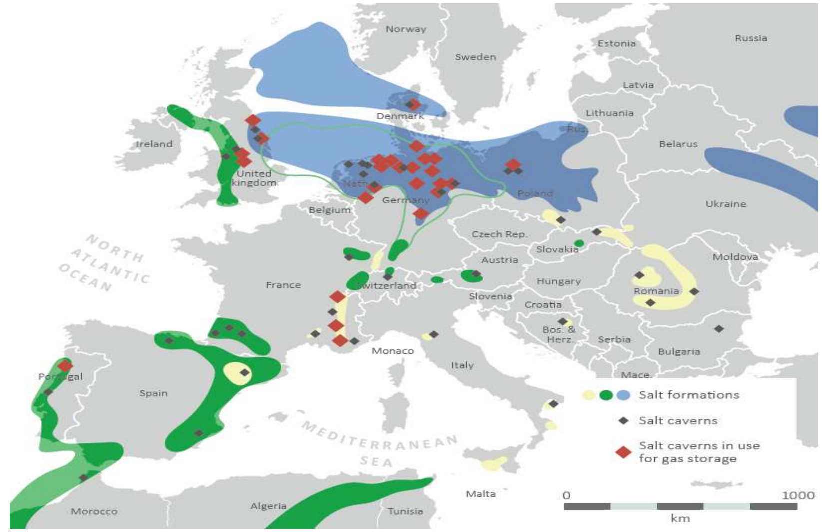
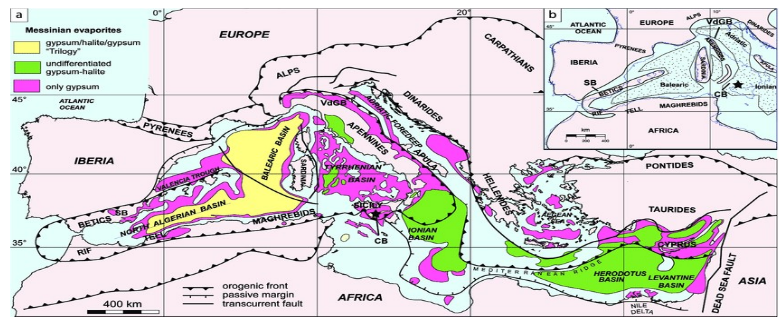
Hydrogen storage in Salt Caverns



Salt formations and caverns in Europa





1 salt cavern can contain up to 6,000 ton (= 236.4 GWh HHV) hydrogen, Salt Cavern CAPEX 100 million Euro
For comparison, with 100 Euro per kWh battery storage CAPEX, Total battery CAPEX would be 23.6 billion Euro

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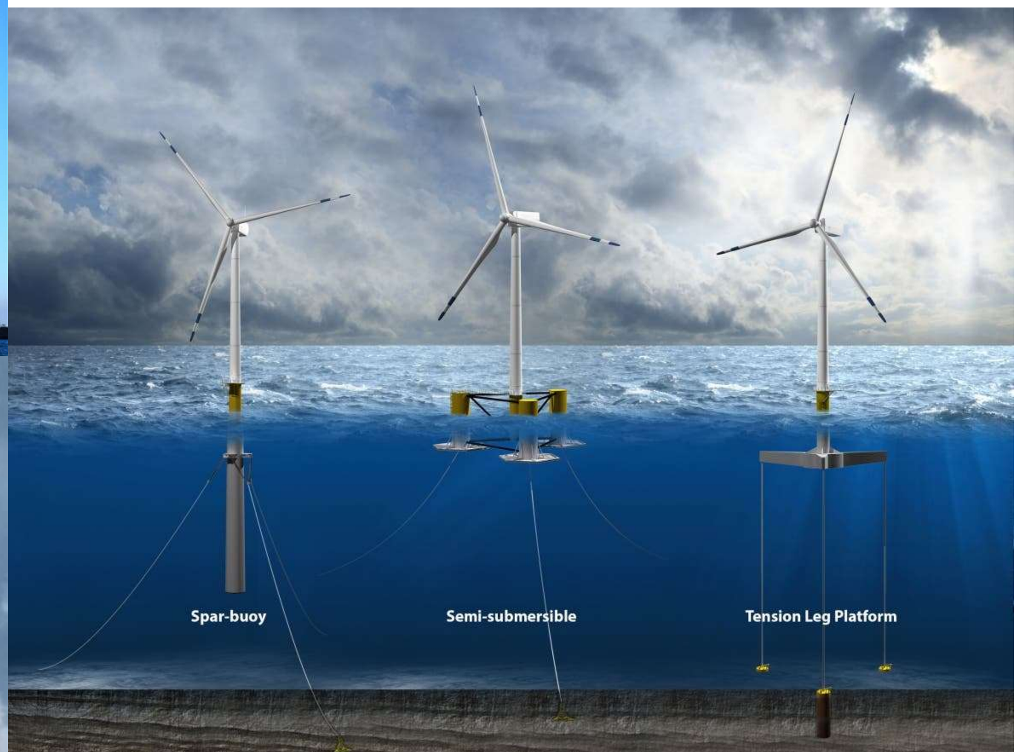
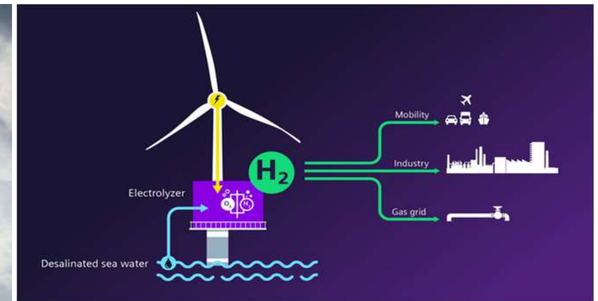
Offshore wind hydrogen

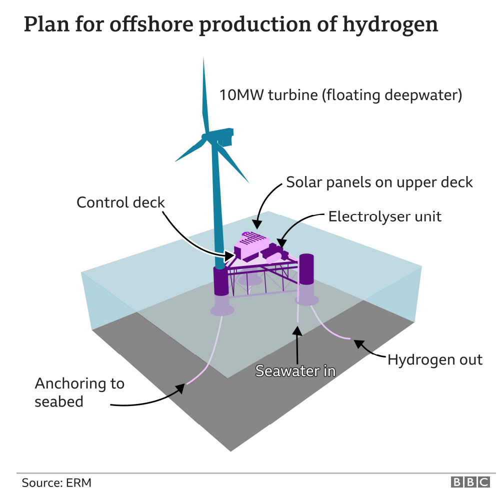


NorthH$_2$

Shell, Gasunie, Groningen Seaports, RWE, Equinor
10.000 MW offshore wind-hydrogen



SiemensGamesa SG 14-222 DD offshore wind turbine 15 MW with electrolyser in mast



ERM UK, 10 MW floating offshore wind turbine with electrolyser at platform

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Base load solar hydrogen Morocco to Germany

Base load solar H_2 from Morocco to Germany		LCoH €/kg H_2
	Assumptions	
Solar-Hydrogen production	Solar electricity cost = 0.01 €/kWh Full load hours = 2,000 hours/yr Electrolyser efficiency = 50 kWh/kg H_2 100 GW solar = 4 million ton H_2 Required surface = 1,800 km^2	1.0
Salt cavern storage	Flexible production to base load; daily cycles	0.1-0.2
Pipeline Transport	Pipeline capacity = 20 GW Full load hours = 8,000 hours/yr Pipeline length = 3,000 km	0.3
TOTAL		**1.5 €/kg H_2** =0.04 €/kWh$H_{2(HHV)}$

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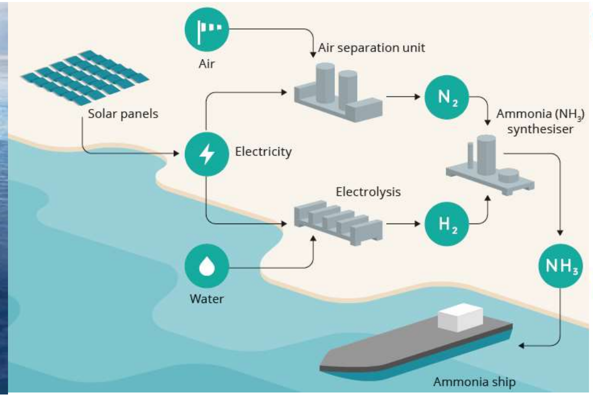
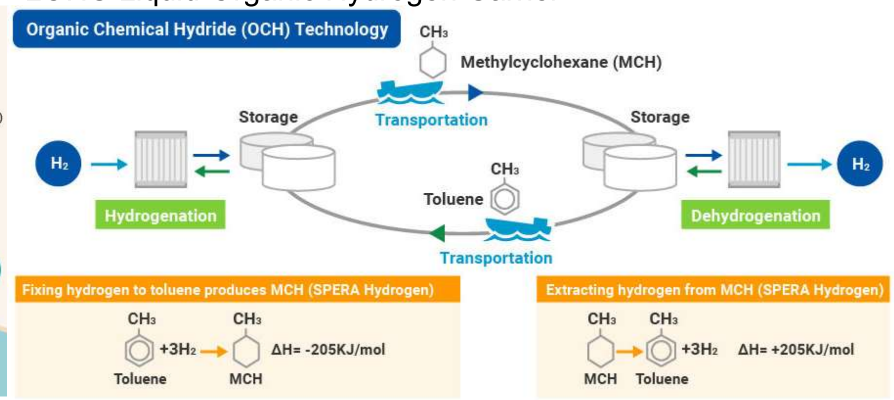
Hydrogen Transport by Ship

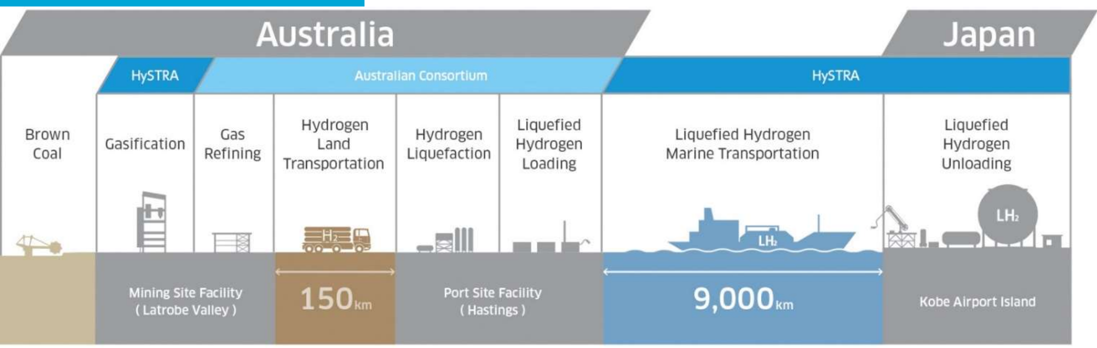
Liquid Hydrogen

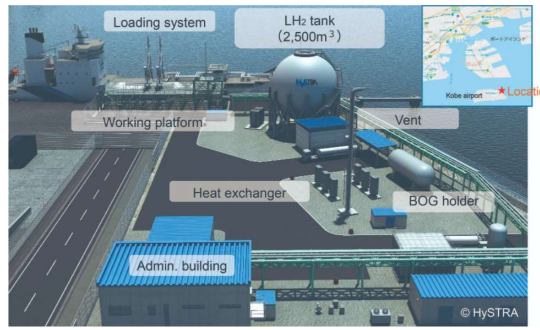
Ammonia



LOHC Liquid Organic Hydrogen Carrier





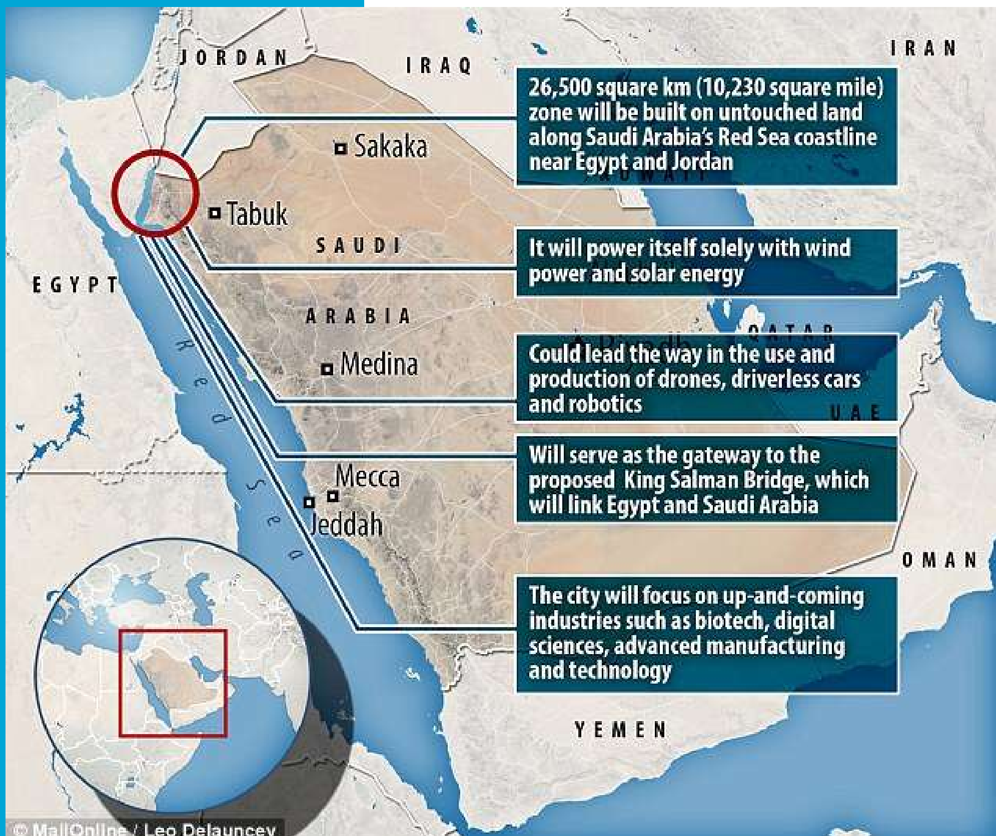


Liquid Hydrogen Supply Chain Australia to Japan

Kawasaki LH_2 tanker launched dec 2019

LH_2 Terminal Kobe Japan Operational Jan 2021

NEOM City; Solar-Wind Hydrogen



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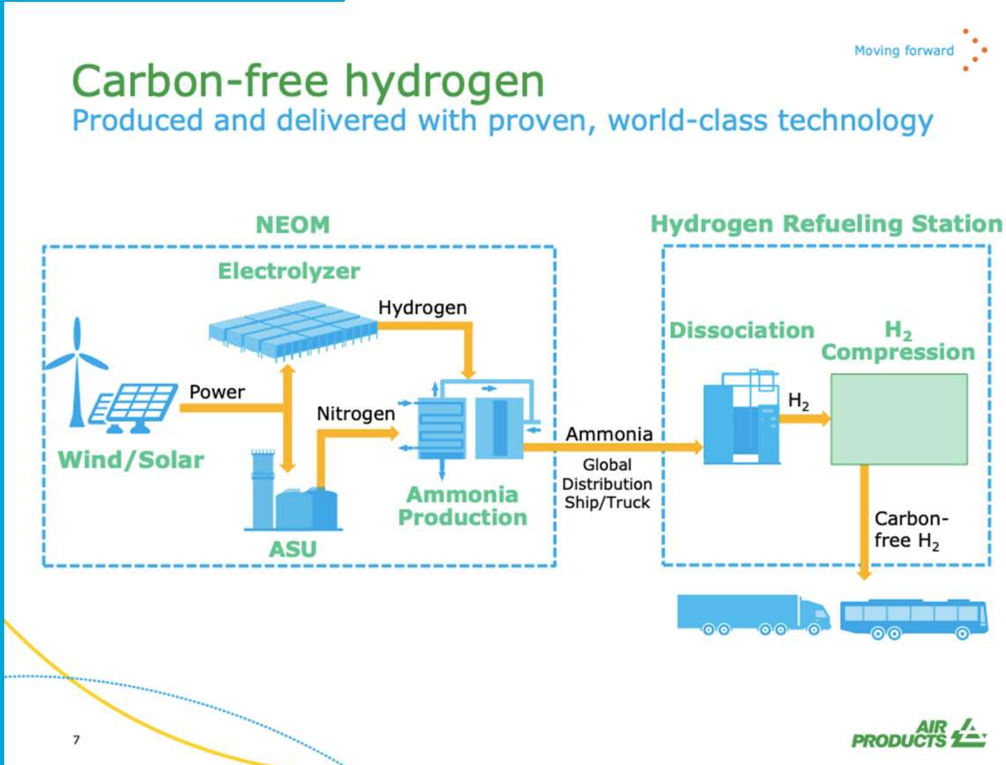
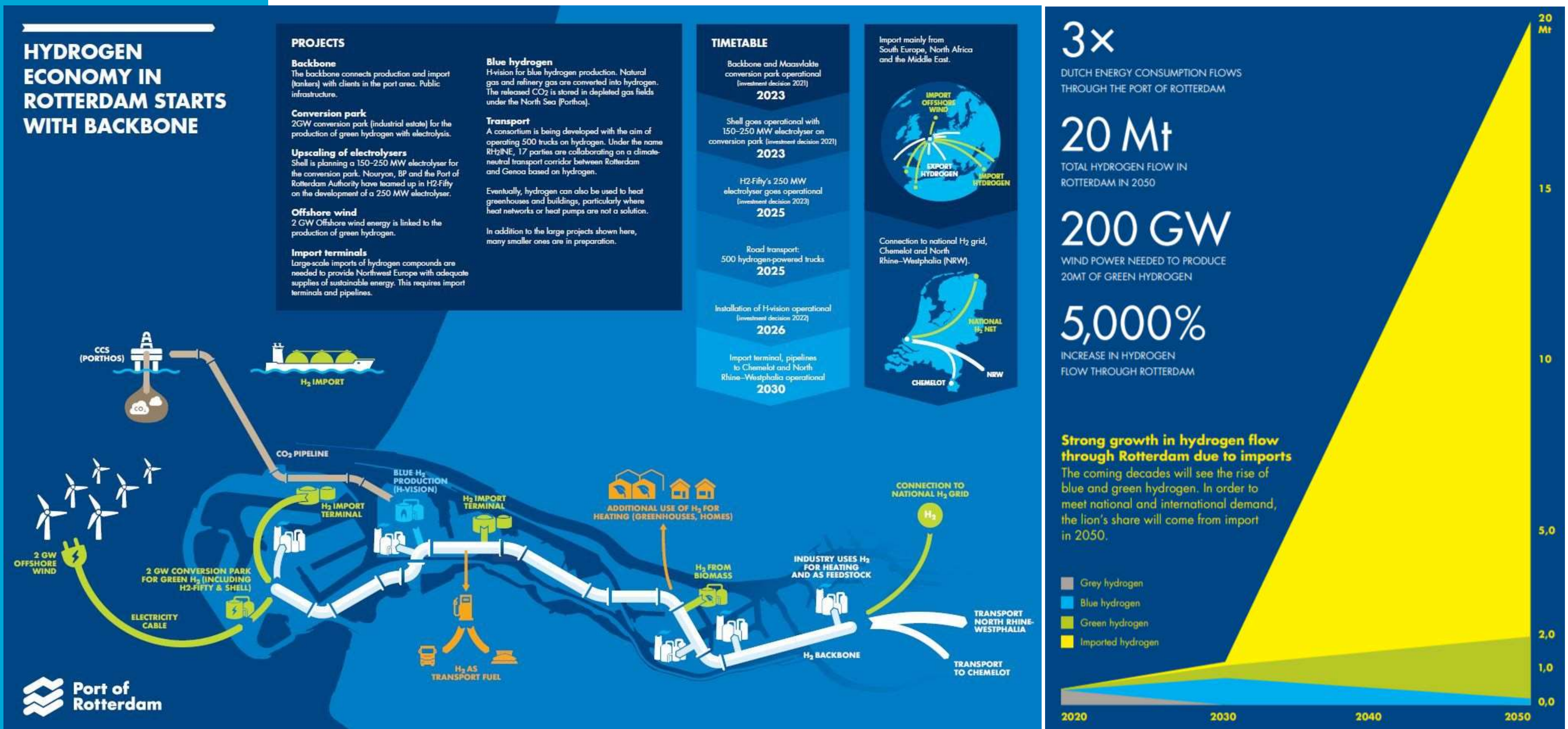
NEOM, ACWA Power, Air Products



- Announced 7 July 2020
- 5 billion dollar investment
- 2025 Operational
- 4 GW Solar, Wind, Storage
- Wind speed 10.3 m/s
- 650 ton Hydrogen per day
- 1.2 million ton Ammonia per year = 7.5 TWh Ammonia

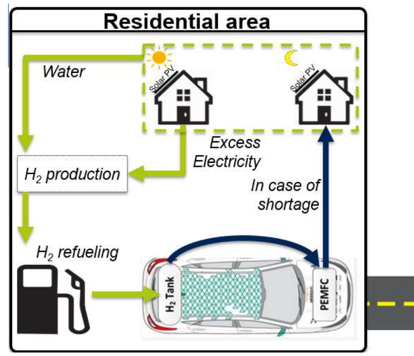
Port of Rotterdam Hydrogen Strategy



Hydrogen Markets

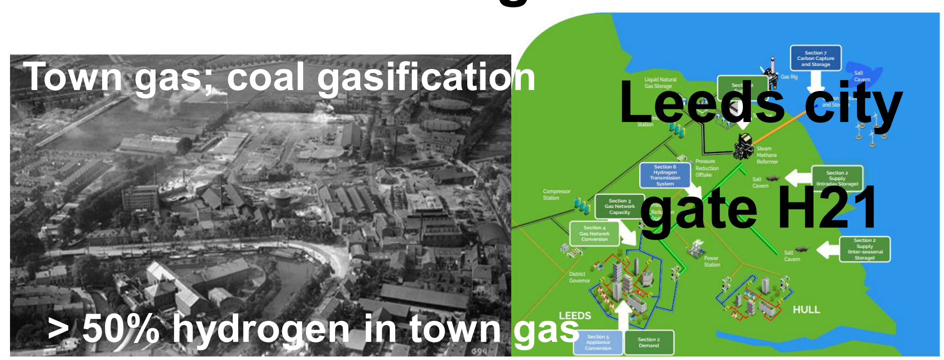
Industry Feedstock/HT Heat

Electricity Balancing



Transport

Heating



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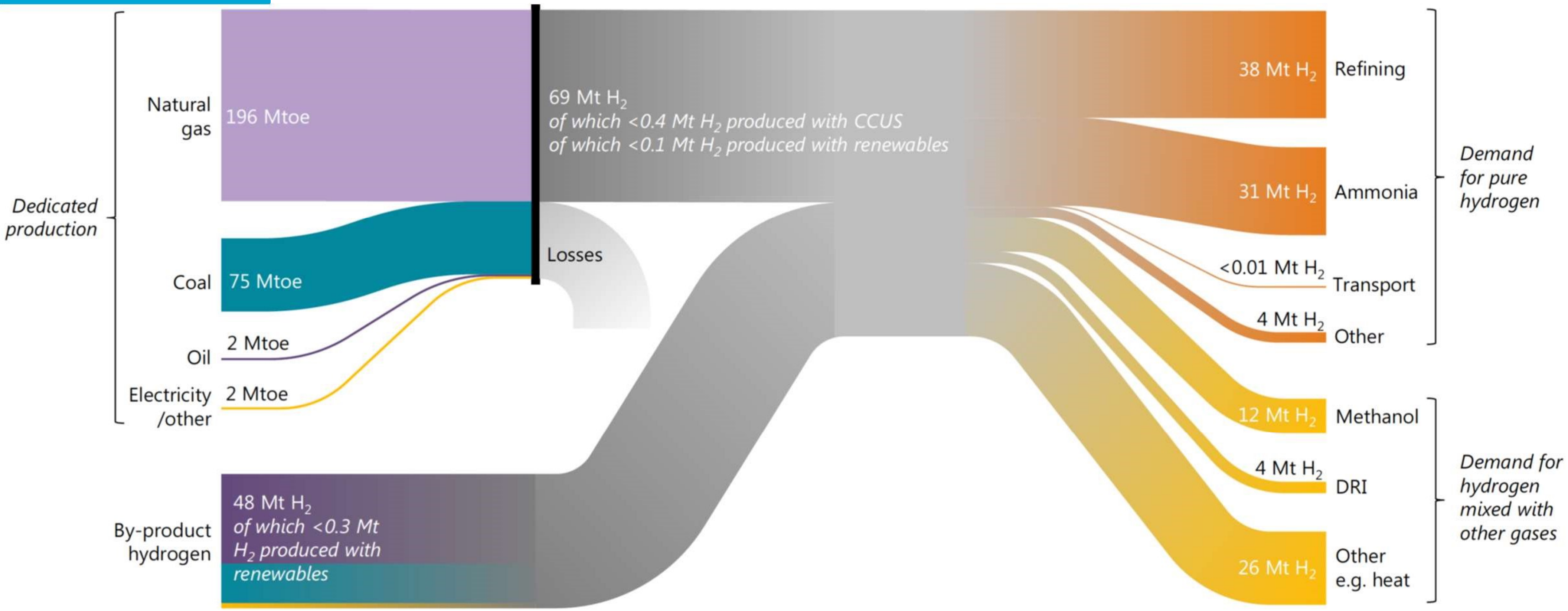
World Wide H_2 production and use



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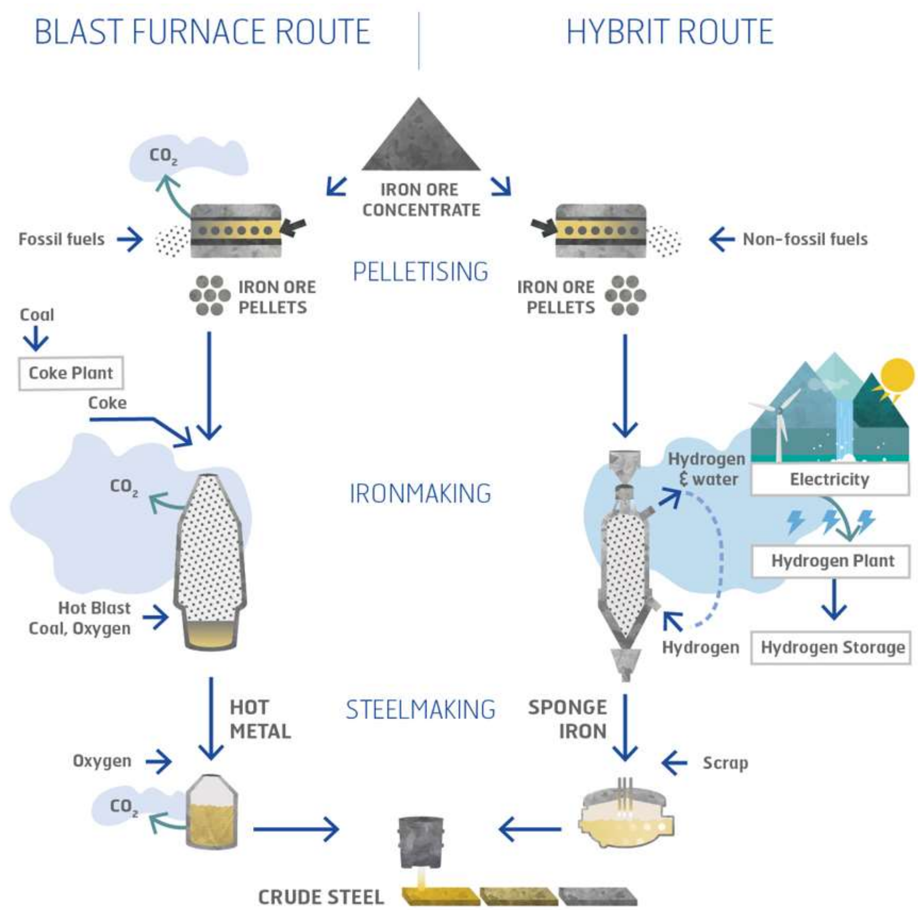
Steel making with Hydrogen SSAB



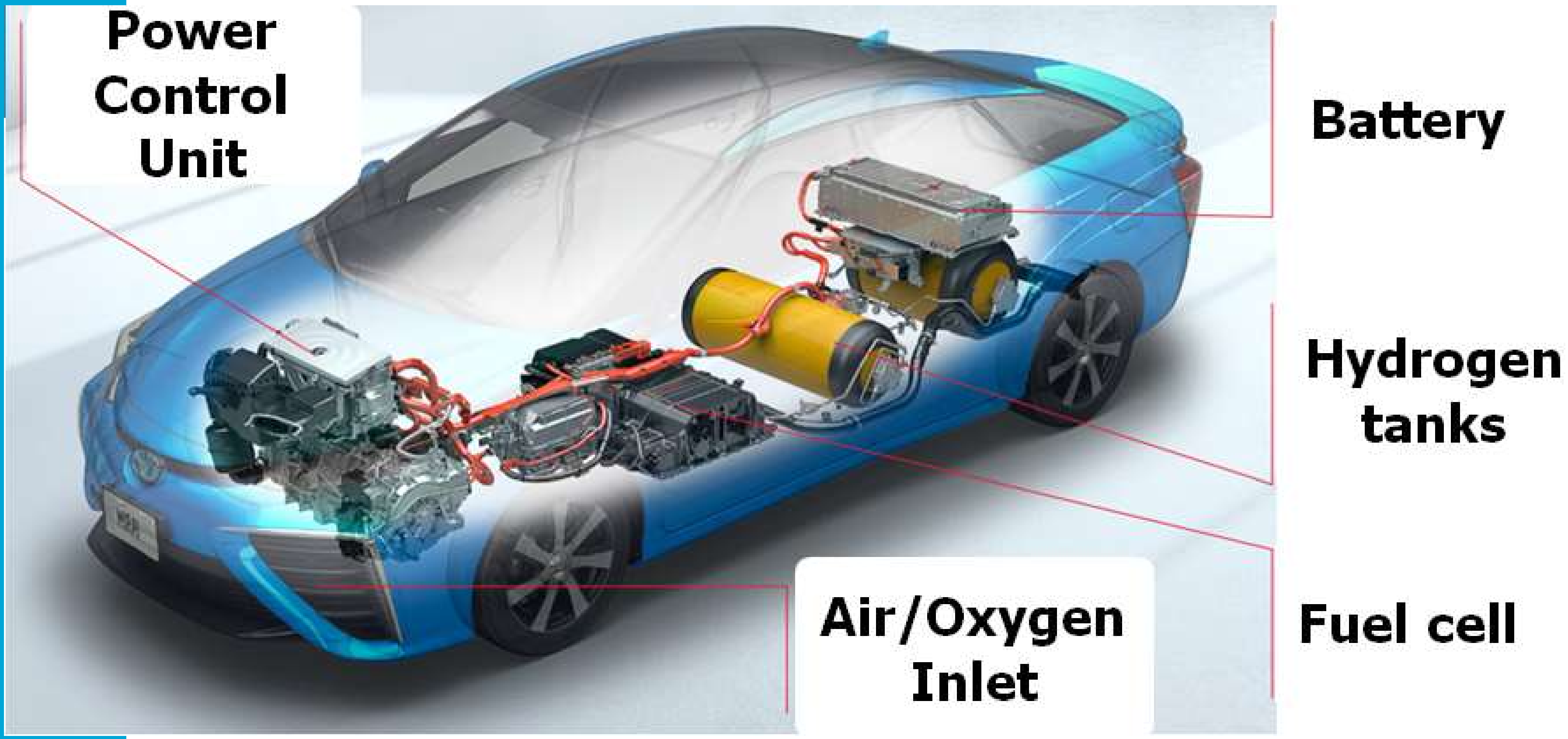
http://www.hybritdevelopment.com/steel-making-today-and-tomorrow

The Future is Electric!

Tesla Model S

Toyota Mirai

Toyota Mirai; Fuel cell car



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AVW1

Hydrogen in transport

JosScholman/New-Holland: Tractor, diesel+H_2

JosScholman: Holder, diesel+H_2

Airbus: Airplane: LH_2+Gasturbine

Toyota: Hydrogen Fork Lift

Caetano: Hydrogen bus with Toyota fuel cell

Hyzon-Holthausen: Production Hydrogen fuel cell trucks

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Slide 22

AVW1 Ad Van Wijk, 08-Nov-20

Hybrid Heat Pump + Boiler
Natural gas shifting to hydrogen

Worcester Bosch, launched 15-11-2019

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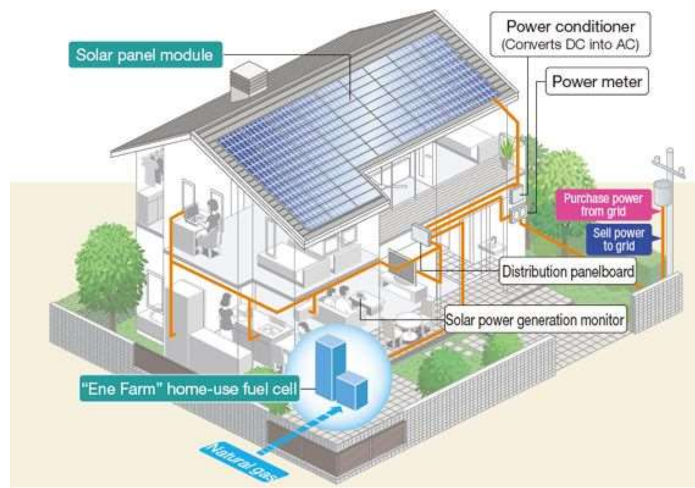
Panasonic: Home Fuel cell systems Japan

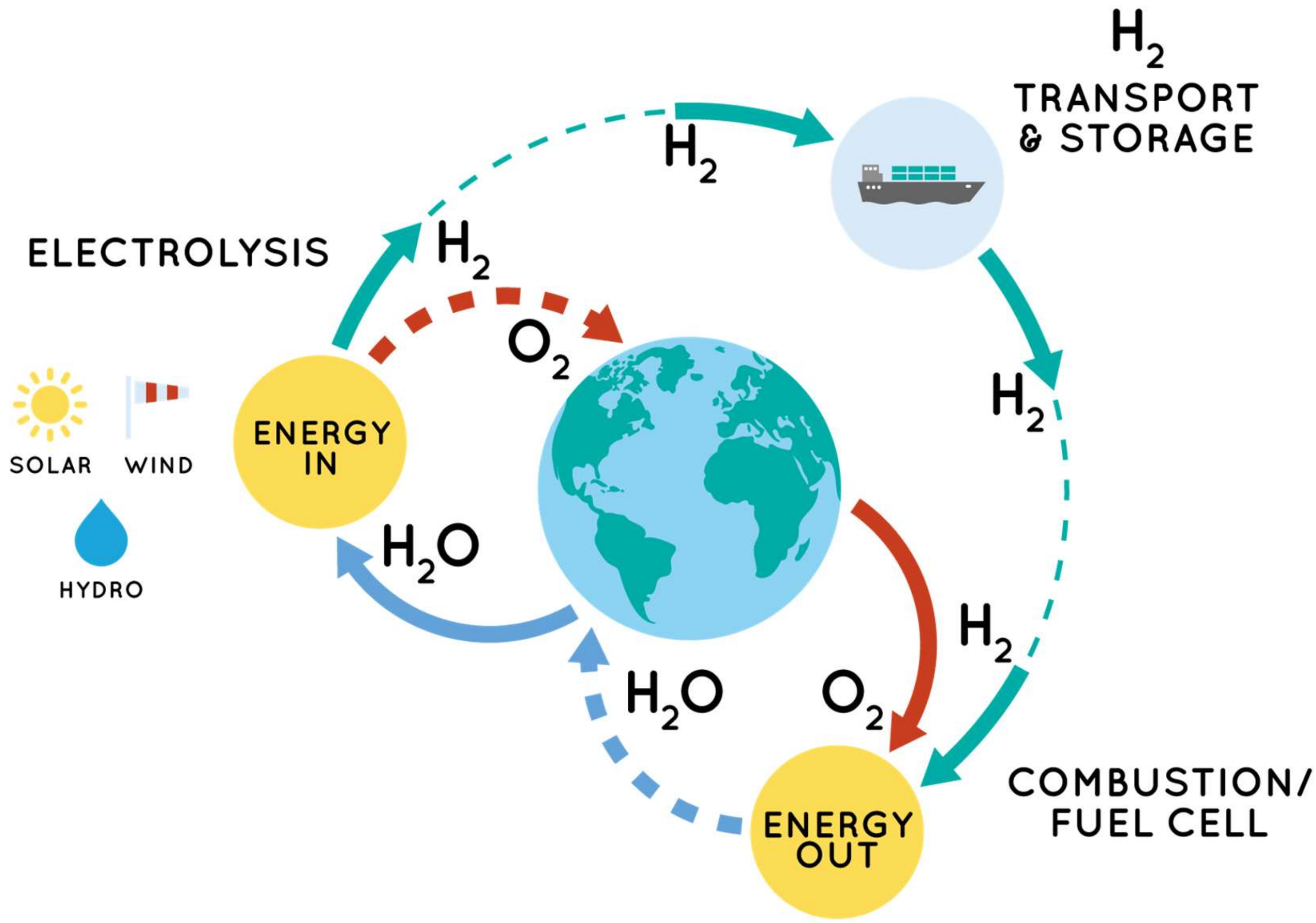
Japan 270.000 sold 2018
Aim 5.3 million end 2025

Reforming natural gas to H_2 + CO_2 and heat
<1 kW fuel cell converts H_2 in electricity and heat

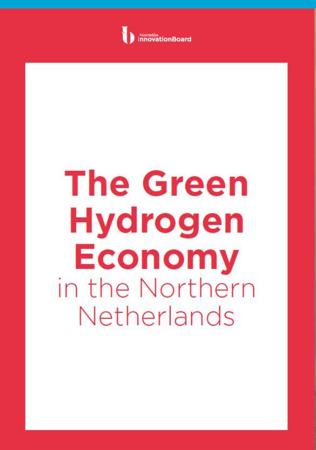
Hot water unit Fuel cell



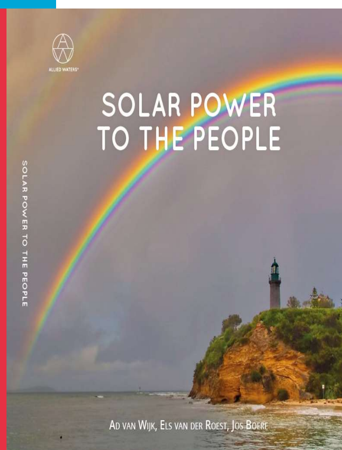
The Hydrogen Cycle



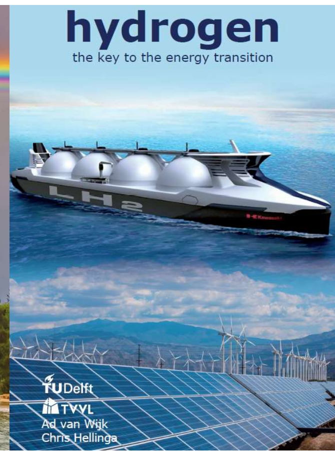
Further Reading
www.profadvanwijk.com



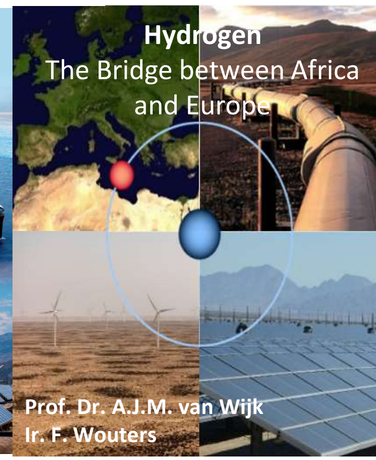
April 2017



November 2017

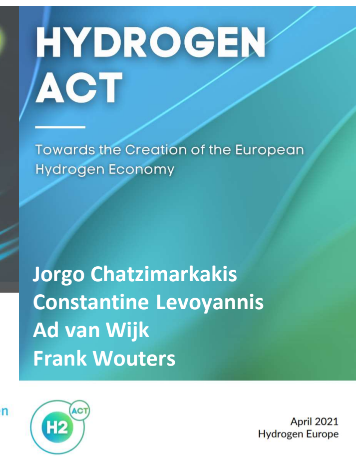


May 2018



September 2019

April 2020



April 2021