

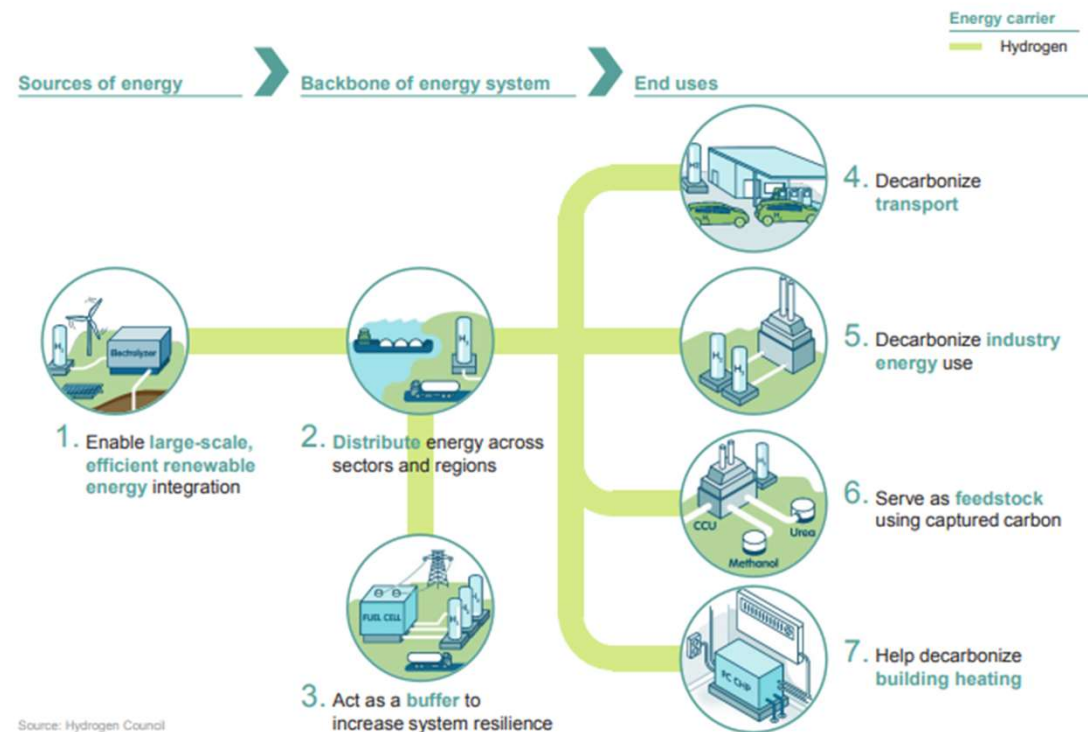


A system perspective on hydrogen

29-4-2021

Prof. Dr. Ad van Wijk

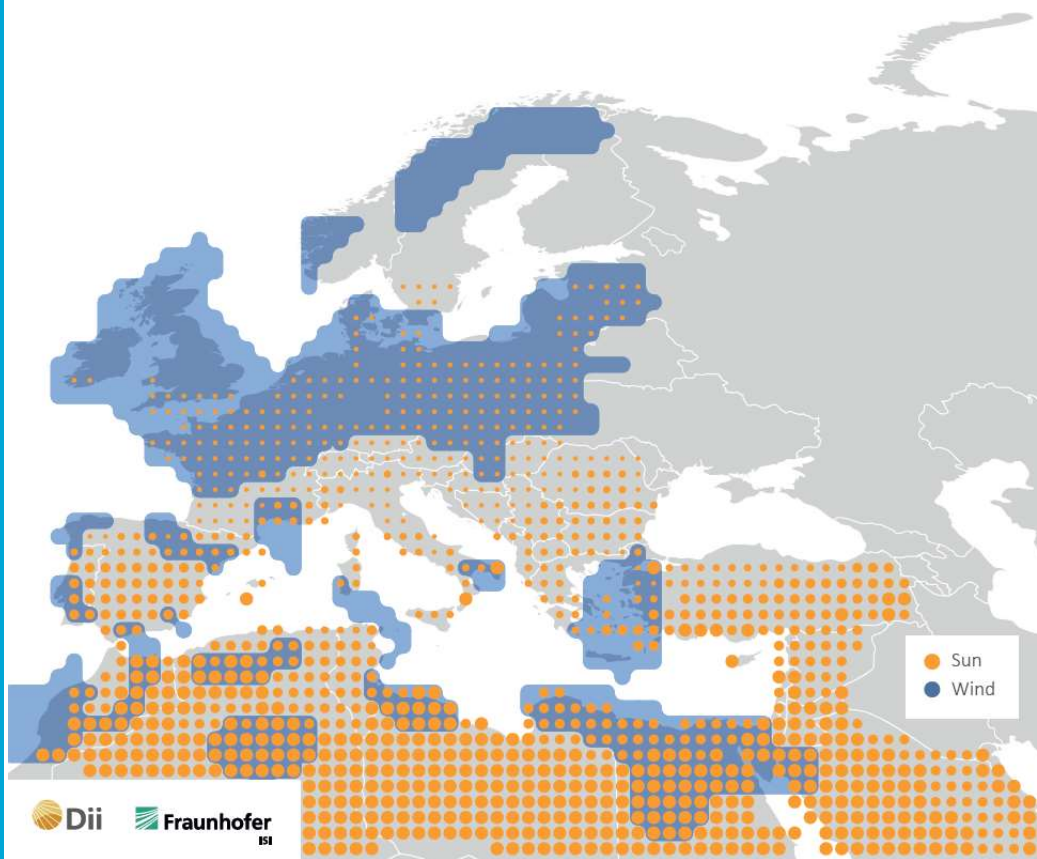
Hydrogen in a carbon-free energy system



Source: Hydrogen Council

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

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

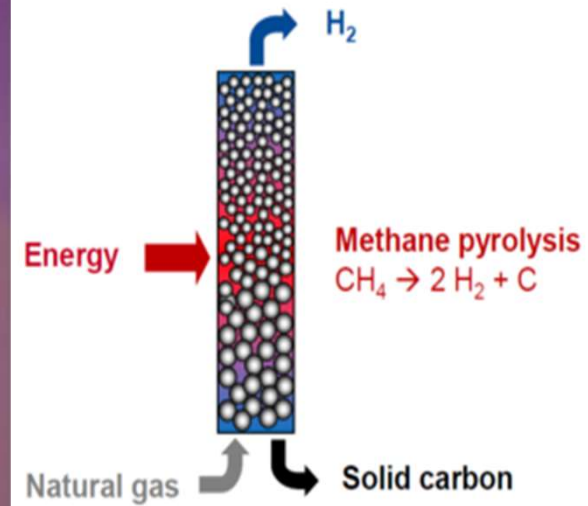
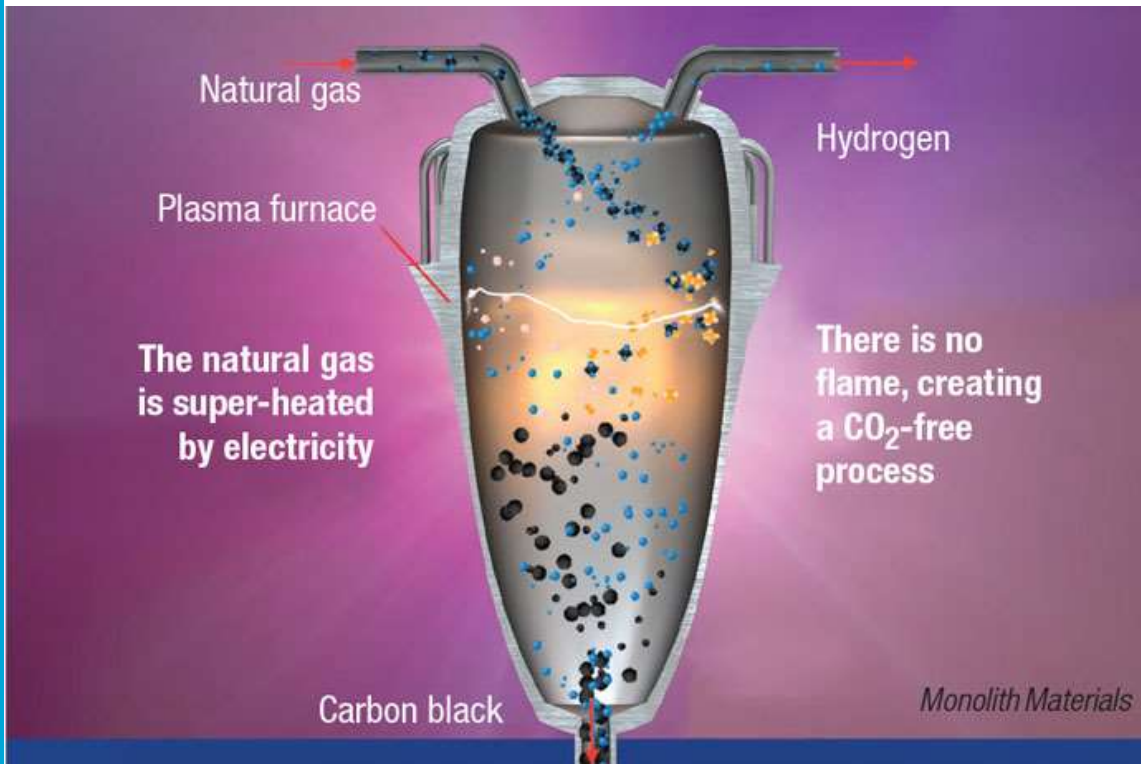
Spain 1.000 MW Wind Farms

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

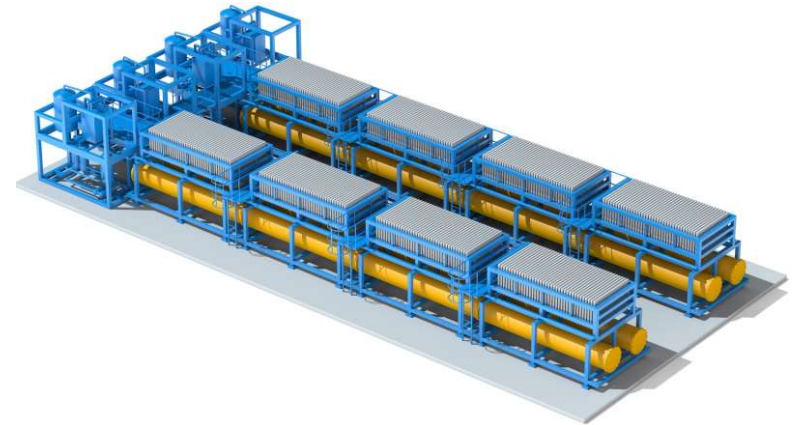
Hydrogen is, like electricity, an energy carrier!

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

Methane Pyrolysis

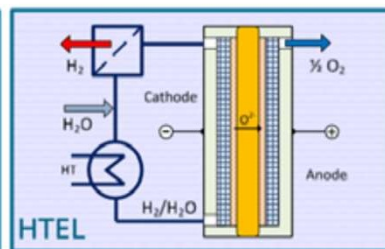
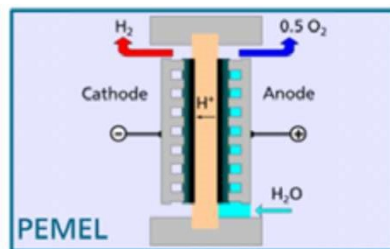
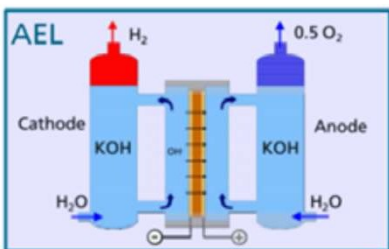


Water Electrolysis



20 MW alkaline electrolyser ThyssenKrupp

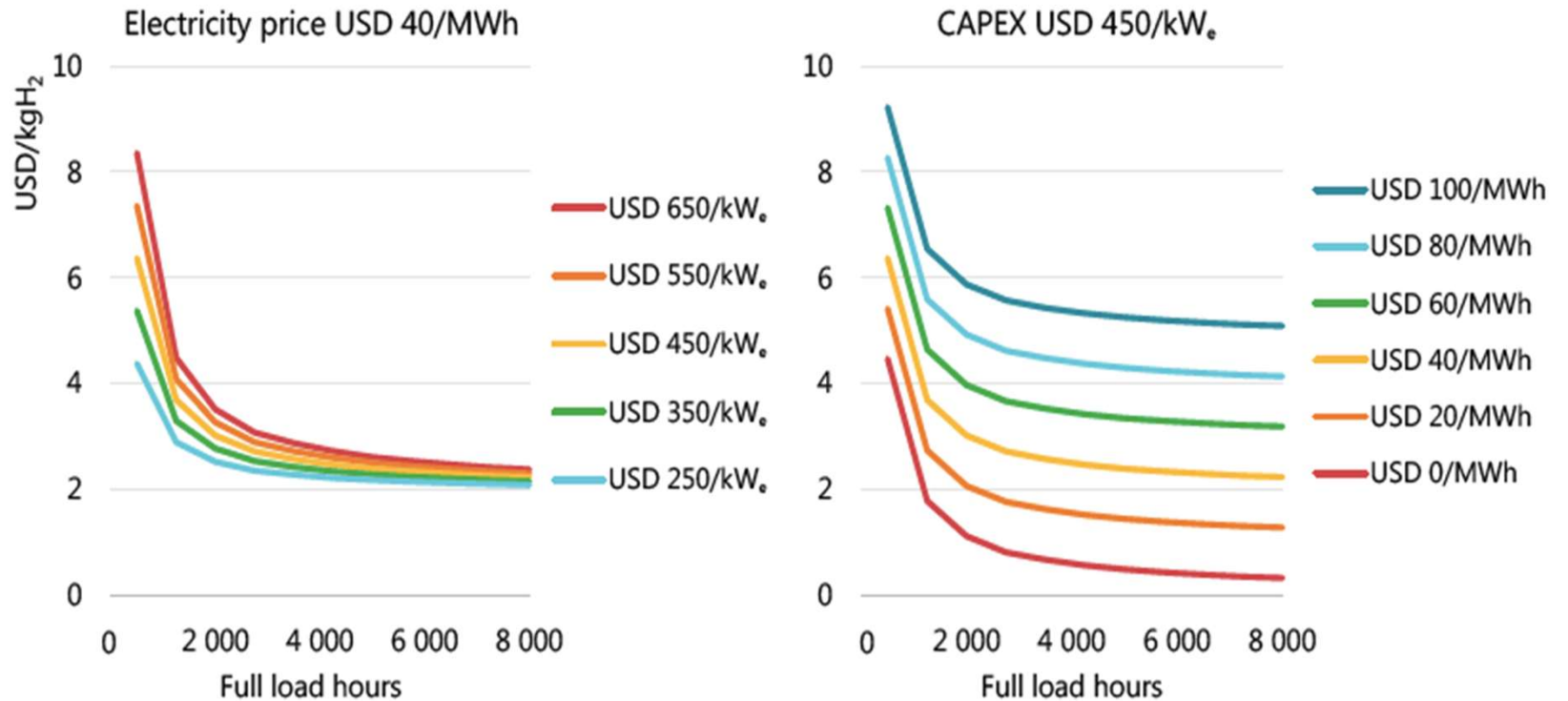
Technology	Temp. Range	Cathodic Reaction (HER)	Charge Carrier	Anodic Reaction (OER)
Alkaline electrolysis	40 - 90 °C	$2H_2O + 2e^- \Rightarrow H_2 + 2OH^-$	OH^-	$2OH^- \Rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$
Membrane electrolysis	20 - 100 °C	$2H^+ + 2e^- \Rightarrow H_2$	H^+	$H_2O \Rightarrow \frac{1}{2}O_2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



	5 MW module	20 MW module
Design capacity H ₂	1000 Nm ³ /h	4000 Nm ³ /h
Efficiency electrolyzer (DC)	> 82% _{HHV} *	> 82% _{HHV} *
Power consumption (DC)	max. 4.3 kWh/Nm ³ H ₂	max. 4.3 kWh/Nm ³ H ₂
Water consumption	<1l/Nm ³ H ₂	<1l/Nm ³ 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.

Hydrogen production cost; LCoH



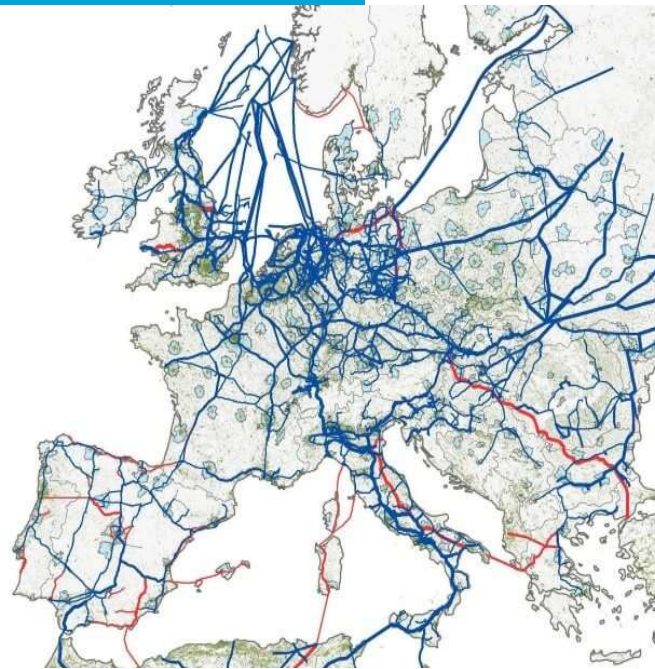
Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

Source: IEA 2019. All rights reserved.

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%)

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

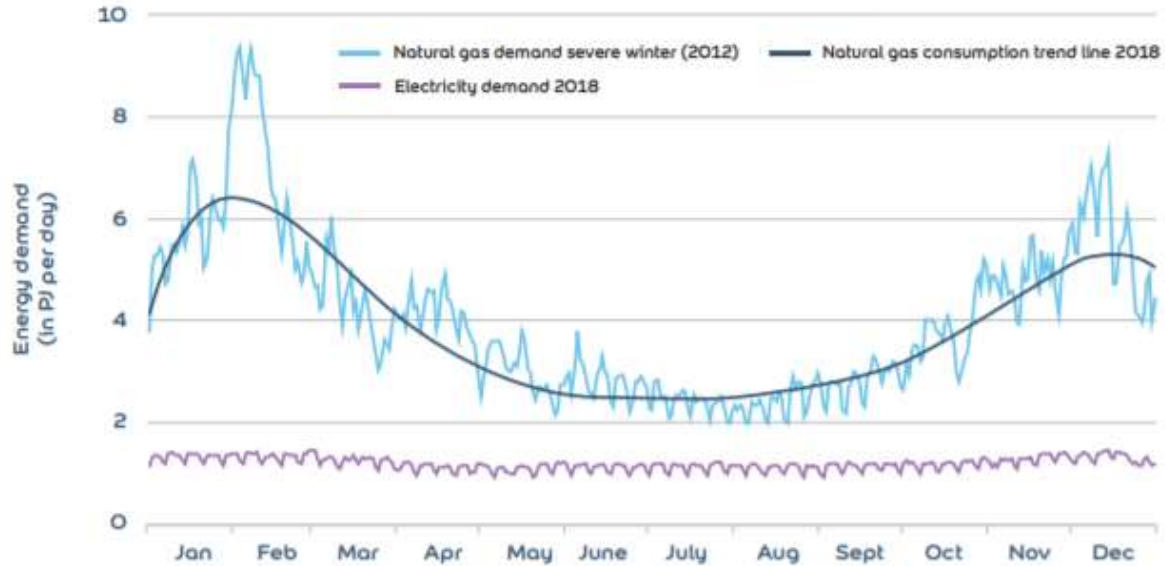
60 GW Natural Gas Pipeline
2x0.7 GW Electricity Cable



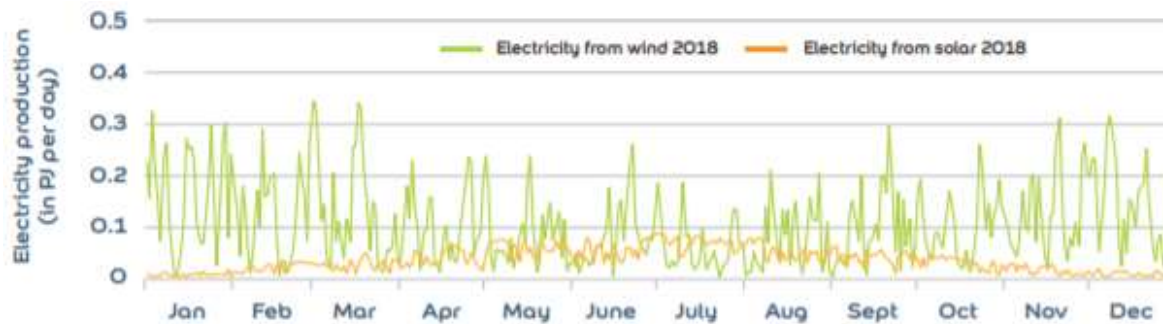
European Hydrogen Backbone

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

Gas and Electricity consumption in the Netherlands 2018

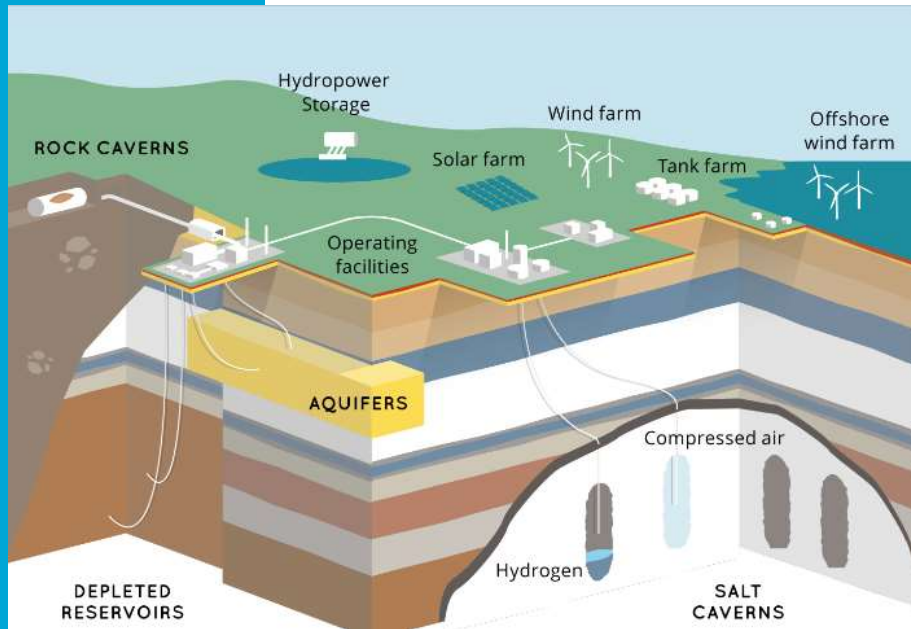


Solar and Wind electricity production in the Netherlands 2018

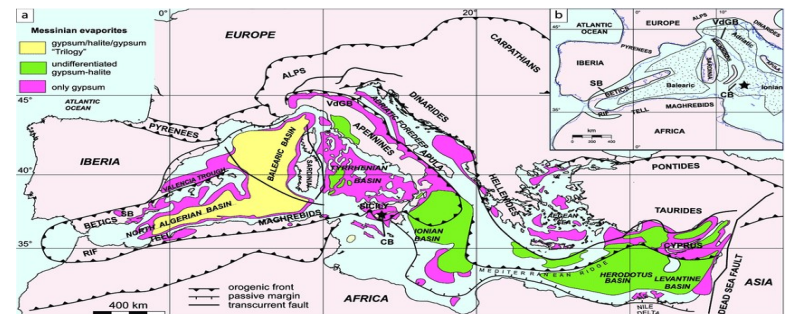
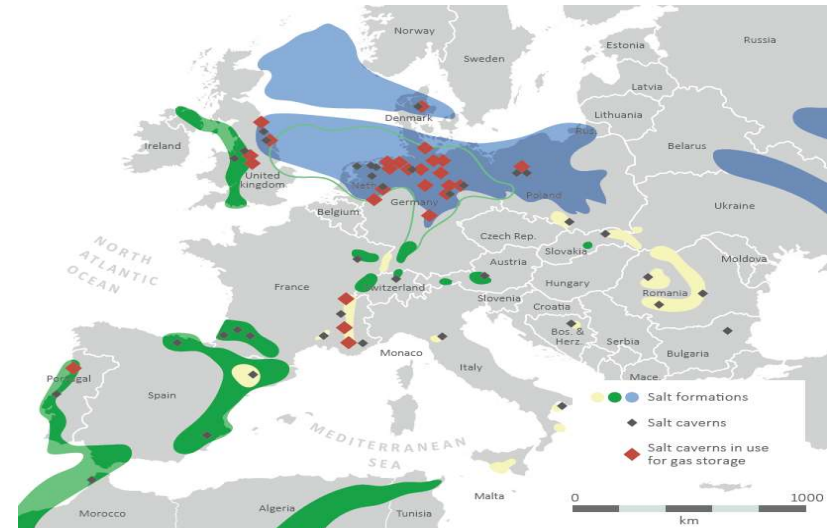


<https://www.energieinederland.nl/wp-content/uploads/2020/02/EBN-INFOGRAPHIC-2020-ENG.pdf>

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

Offshore wind hydrogen



GE Haliade X 12-14 MW



SG 14-222 DD 14-15 MW



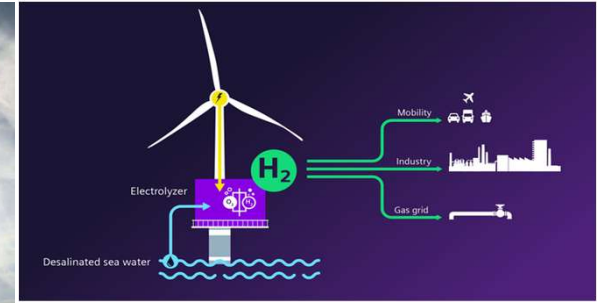
Spar-buoy

Semi-submersible

Tension Leg Platform

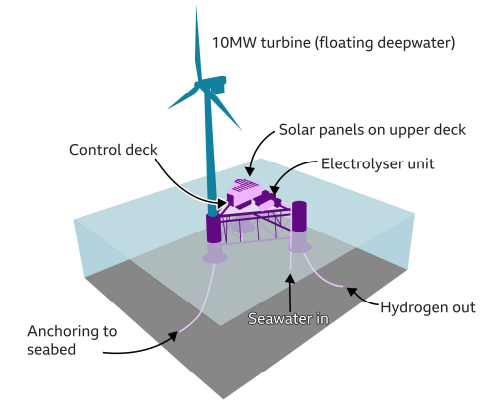
NorthH₂

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

Plan for offshore production of hydrogen



Source: ERM

BIBI

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



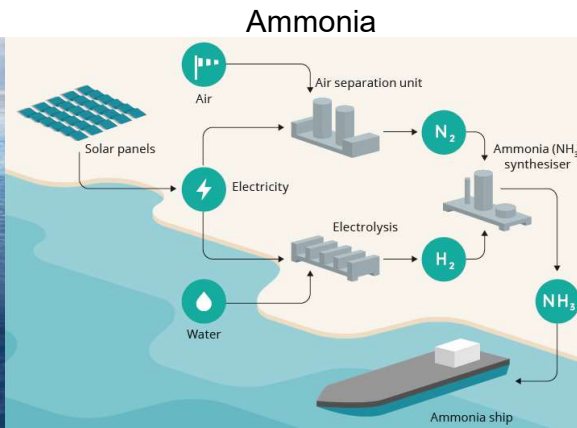
Base load solar hydrogen Morocco to Germany



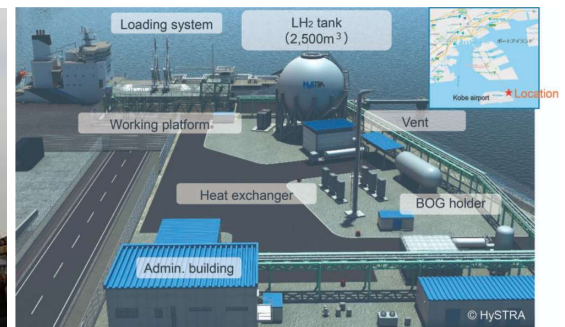
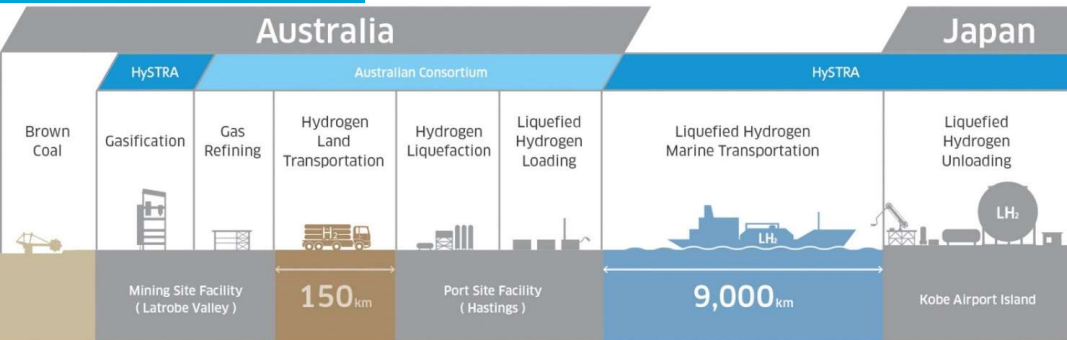
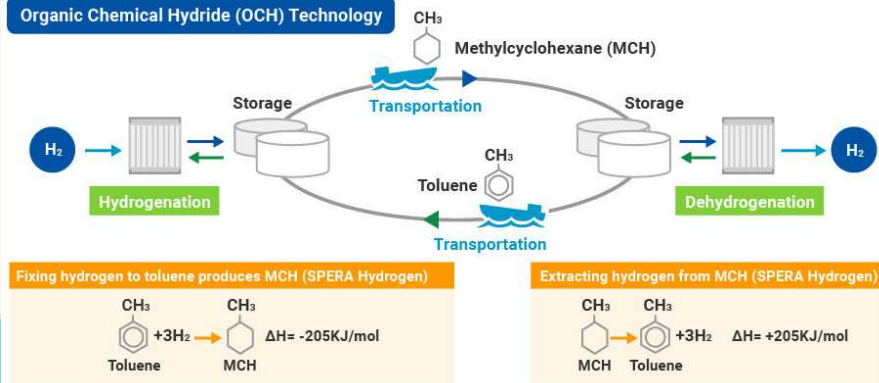
Base load solar H ₂ from Morocco to Germany		LCoH €/kg H ₂
	Assumptions	
Solar-Hydrogen production	Solar electricity cost = 0.01 €/kWh Full load hours = 2,000 hours/yr Electrolyser efficiency = 50 kWh/kg H ₂ 100 GW solar = 4 million ton H ₂ Required surface = 1,800 km ²	1.0
Salt cavern storage	Flexible 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 H₂ =0.04 €/kWh _{H₂(HHV)}

Hydrogen Transport by Ship

Liquid Hydrogen



LOHC Liquid Organic Hydrogen Carrier

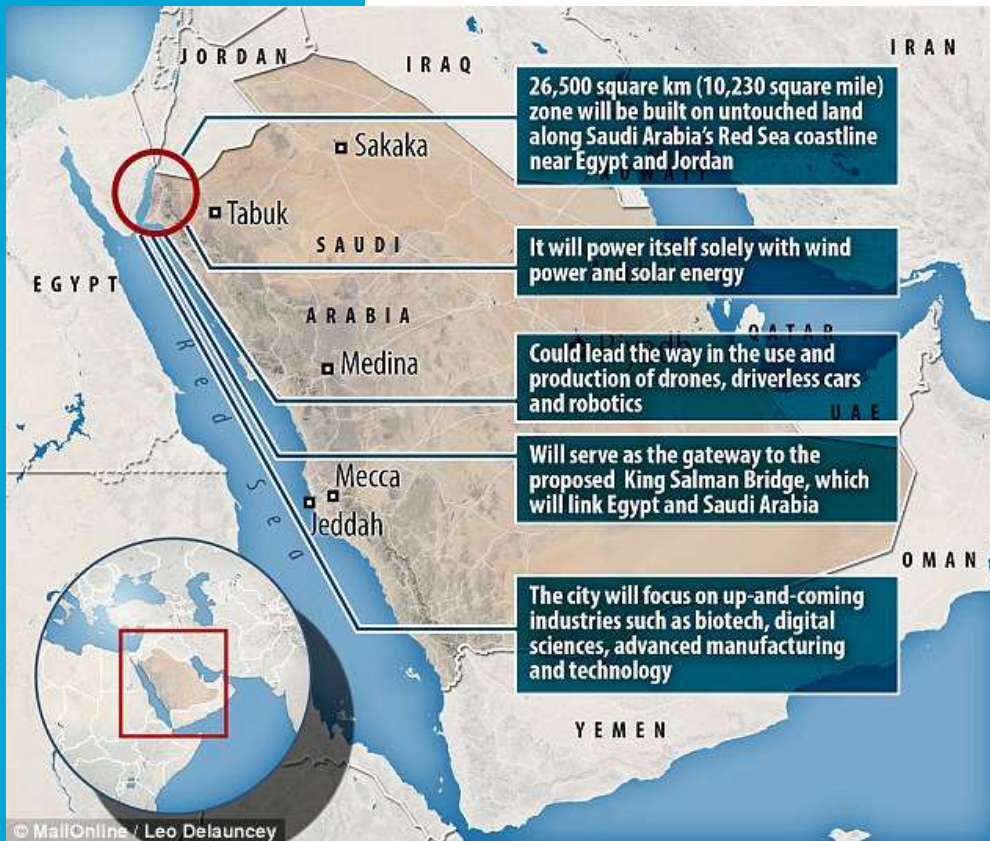


Liquid Hydrogen Supply Chain Australia to Japan

Kawasaki LH₂ tanker launched dec 2019

LH₂ Terminal Kobe Japan Operational Jan 2021

NEOM City; Solar-Wind Hydrogen

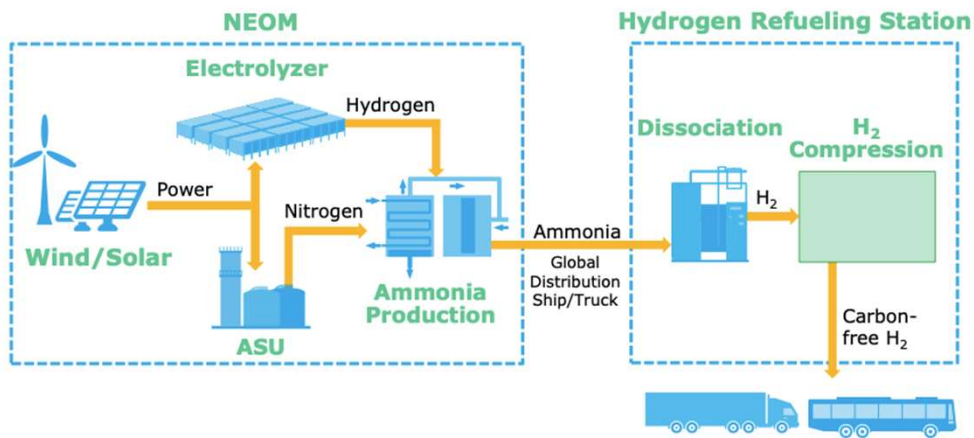


NEOM, ACWA Power, Air Products

Carbon-free hydrogen

Produced and delivered with proven, world-class technology

Moving forward



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

7

Port of Rotterdam Hydrogen Strategy

HYDROGEN ECONOMY IN ROTTERDAM STARTS WITH BACKBONE

PROJECTS

Backbone

The backbone connects production and import (tankers) with clients in the port area. Public infrastructure.

Conversion park

2GW conversion park (industrial estate) for the production of green hydrogen with electrolysis.

Upscaling of electrolyzers

Shell is planning a 150-250 MW electrolyser for the conversion park. Nouryon, BP and the Port of Rotterdam Authority have teamed up in H2-Fifty on the development of a 250 MW electrolyser.

Offshore wind

2 GW Offshore wind energy is linked to the production of green hydrogen.

Import terminals

Large-scale imports of hydrogen compounds are needed to provide Northwest Europe with adequate supplies of sustainable energy. This requires import terminals and pipelines.

Blue hydrogen

H-vision for blue hydrogen production. Natural gas and refinery gas are converted into hydrogen. The released CO₂ is stored in depleted gas fields under the North Sea (Porthos).

Transport

A consortium is being developed with the aim of operating 500 trucks on hydrogen. Under the name H₂NE, 17 parties are collaborating on a climate-neutral transport corridor between Rotterdam and Genoa based on hydrogen.

Eventually, hydrogen can also be used to heat greenhouses and buildings, particularly where heat networks or heat pumps are not a solution.

In addition to the large projects shown here, many smaller ones are in preparation.

TIMETABLE

Backbone and Maasvlakte conversion park operational (investment decision 2022)

2023

Shell goes operational with 150-250 MW electrolyser on conversion park (investment decision 2022)

2023

H2-Fifty's 250 MW electrolyser goes operational (investment decision 2022)

2025

Road transport: 500 hydrogen-powered trucks

2025

Installation of H-vision operational (investment decision 2022)

2026

Import terminal, pipelines to Chemelot and North Rhine-Westphalia operational

2030

Import mainly from South Europe, North Africa and the Middle East.



Connection to national H₂ grid, Chemelot and North Rhine-Westphalia (NRW).



3x

DUTCH ENERGY CONSUMPTION FLOWS THROUGH THE PORT OF ROTTERDAM

20 Mt

TOTAL HYDROGEN FLOW IN ROTTERDAM IN 2050

200 GW

WIND POWER NEEDED TO PRODUCE 20MT OF GREEN HYDROGEN

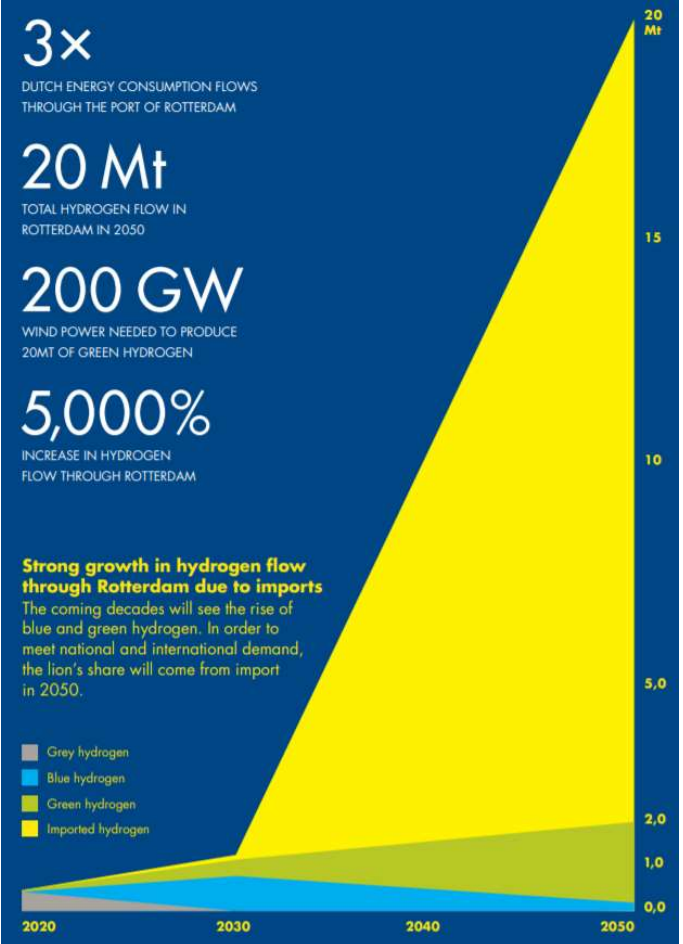
5,000%

INCREASE IN HYDROGEN FLOW THROUGH ROTTERDAM

Strong growth in hydrogen flow through Rotterdam due to imports

The coming decades will see the rise of blue and green hydrogen. In order to meet national and international demand, the lion's share will come from import in 2050.

- Grey hydrogen
- Blue hydrogen
- Green hydrogen
- Imported hydrogen

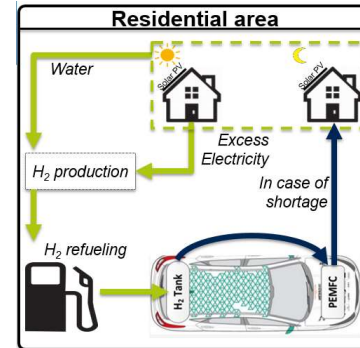


Hydrogen Markets

Industry Feedstock/HT Heat



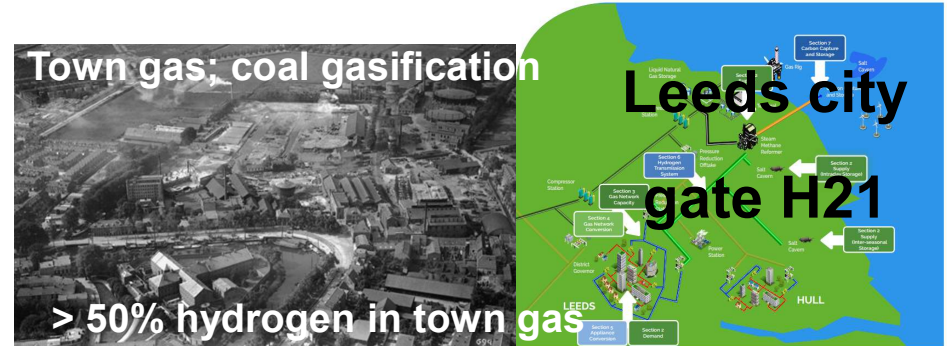
Electricity Balancing



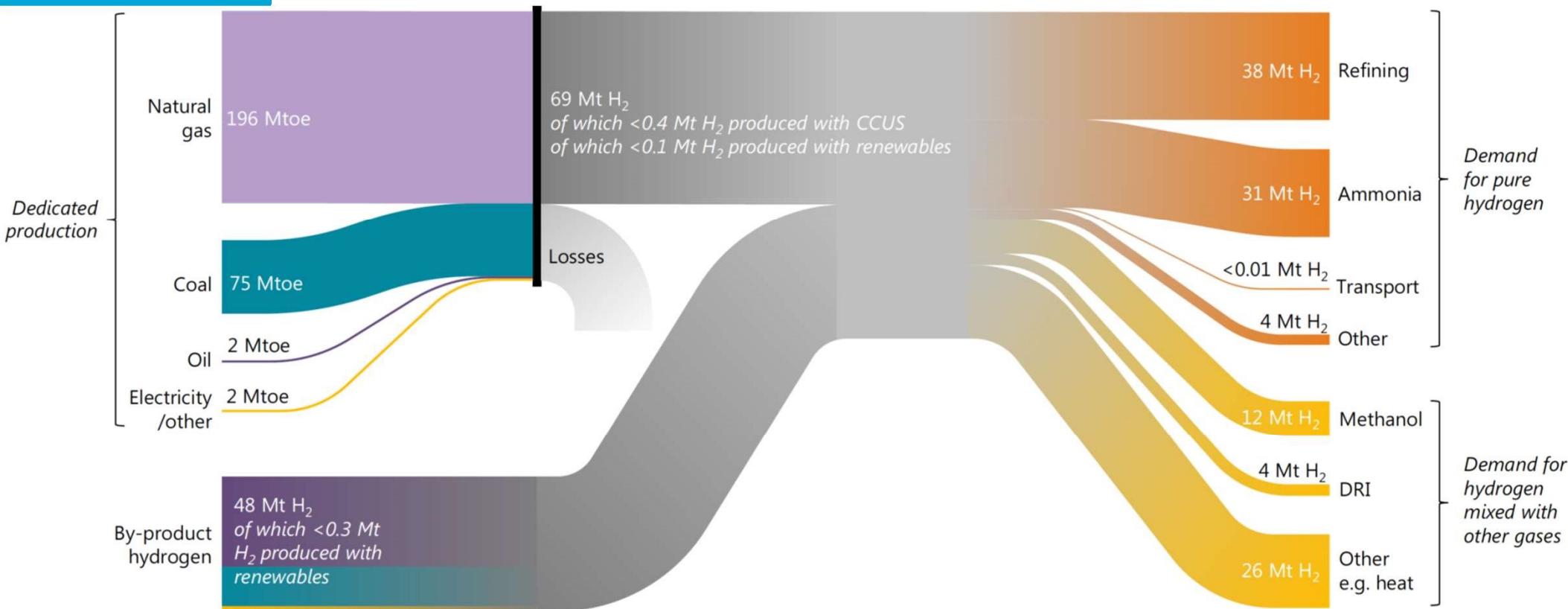
Transport



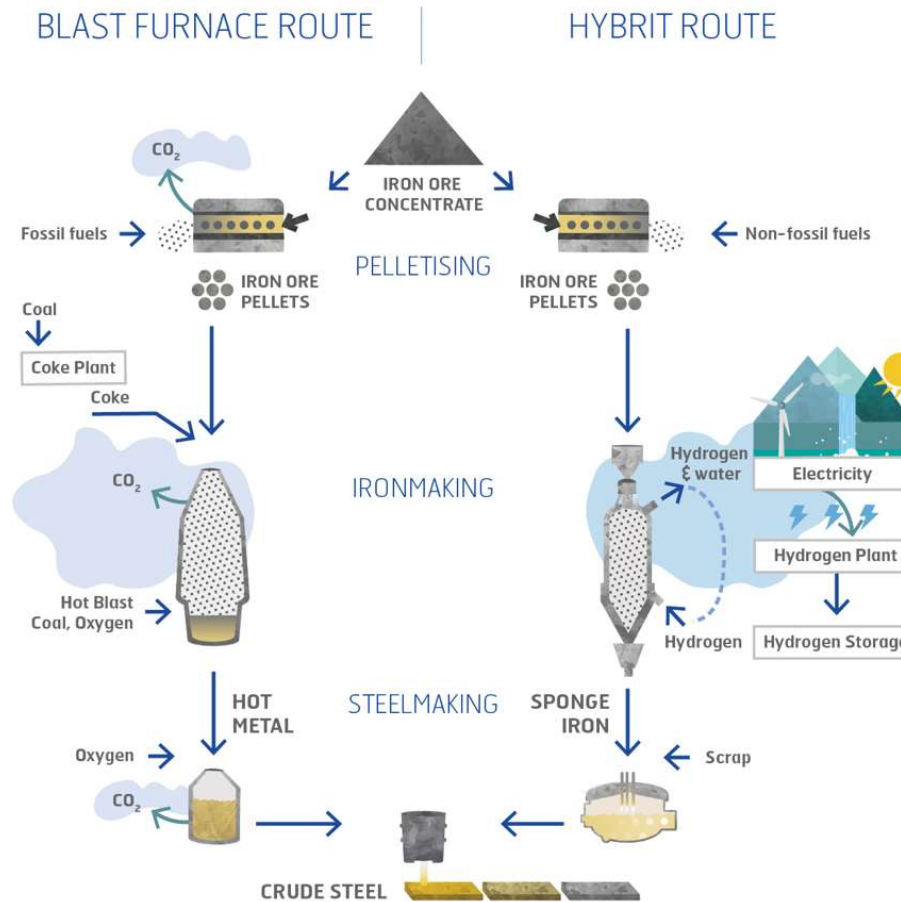
Heating



World Wide H₂ production and use



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



Hydrogen in transport



JosScholman/New-Holland:
Tractor, diesel+H₂



JosScholman:
Holder, diesel+H₂



Airbus: Airplane:
LH₂+Gasturbine



Toyota: Hydrogen Fork Lift



Caetano: Hydrogen bus with
Toyota fuel cell



Hyzon-Holthausen: Production
Hydrogen fuel cell trucks

Hybrid Heat Pump + Boiler

Natural gas shifting to hydrogen



Worcester Bosch, launched 15-11-2019

Panasonic: Home Fuel cell systems Japan

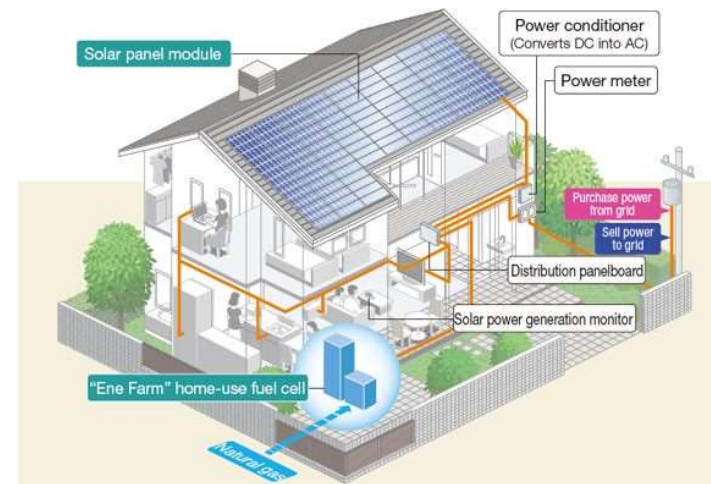
Japan 270.000 sold 2018
Aim 5.3 million end 2025

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

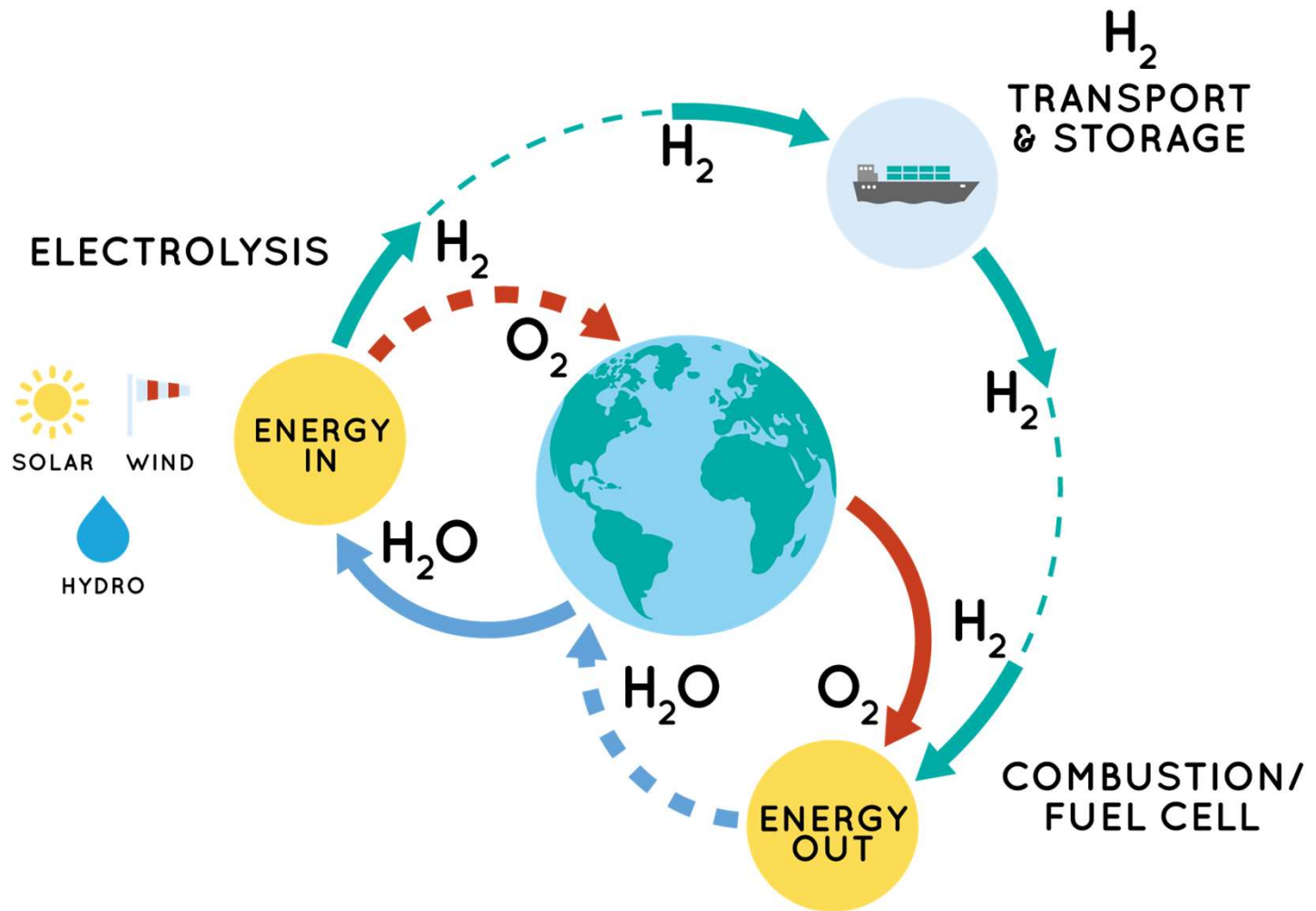


Hot water unit

Fuel cell



The Hydrogen Cycle

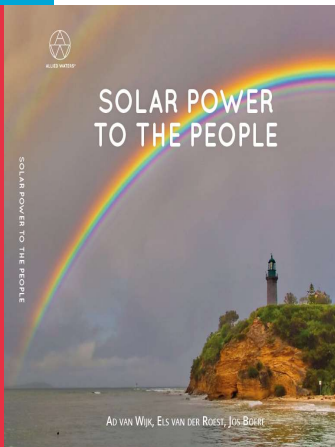


Further Reading

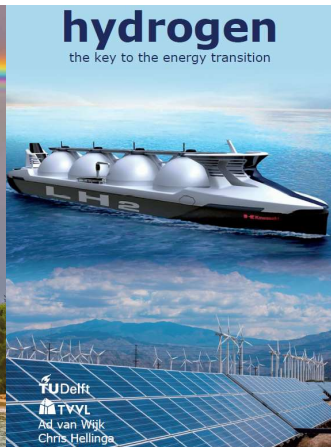
www.profadvanwijk.com



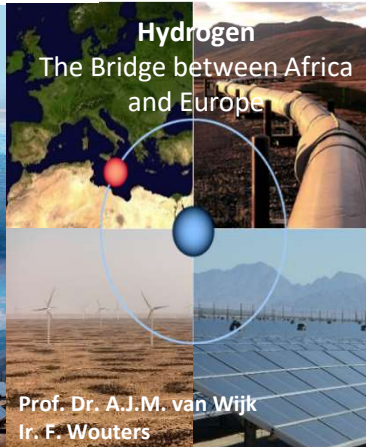
April 2017



November 2017



May 2018



September 2019



April 2020



April 2021