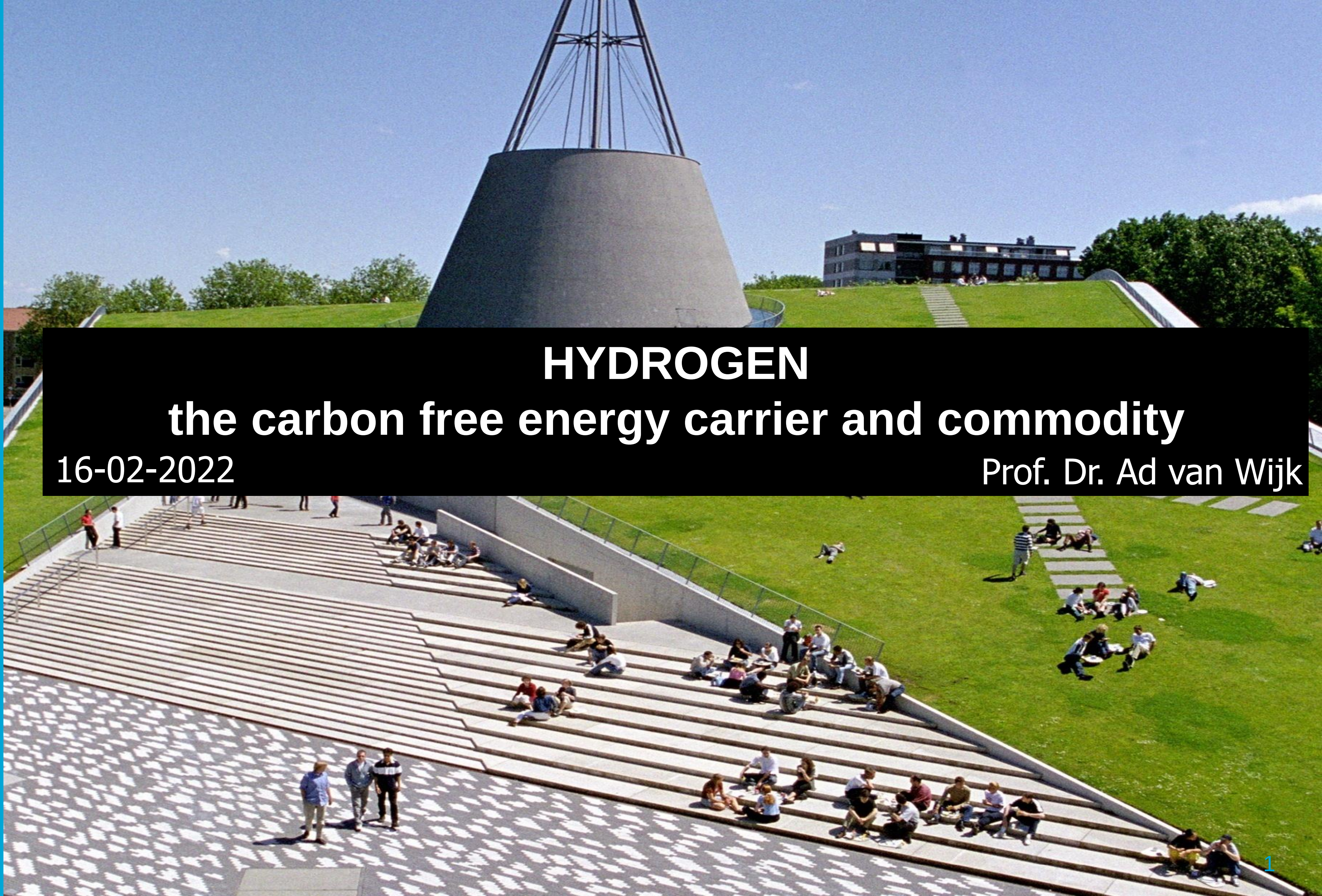


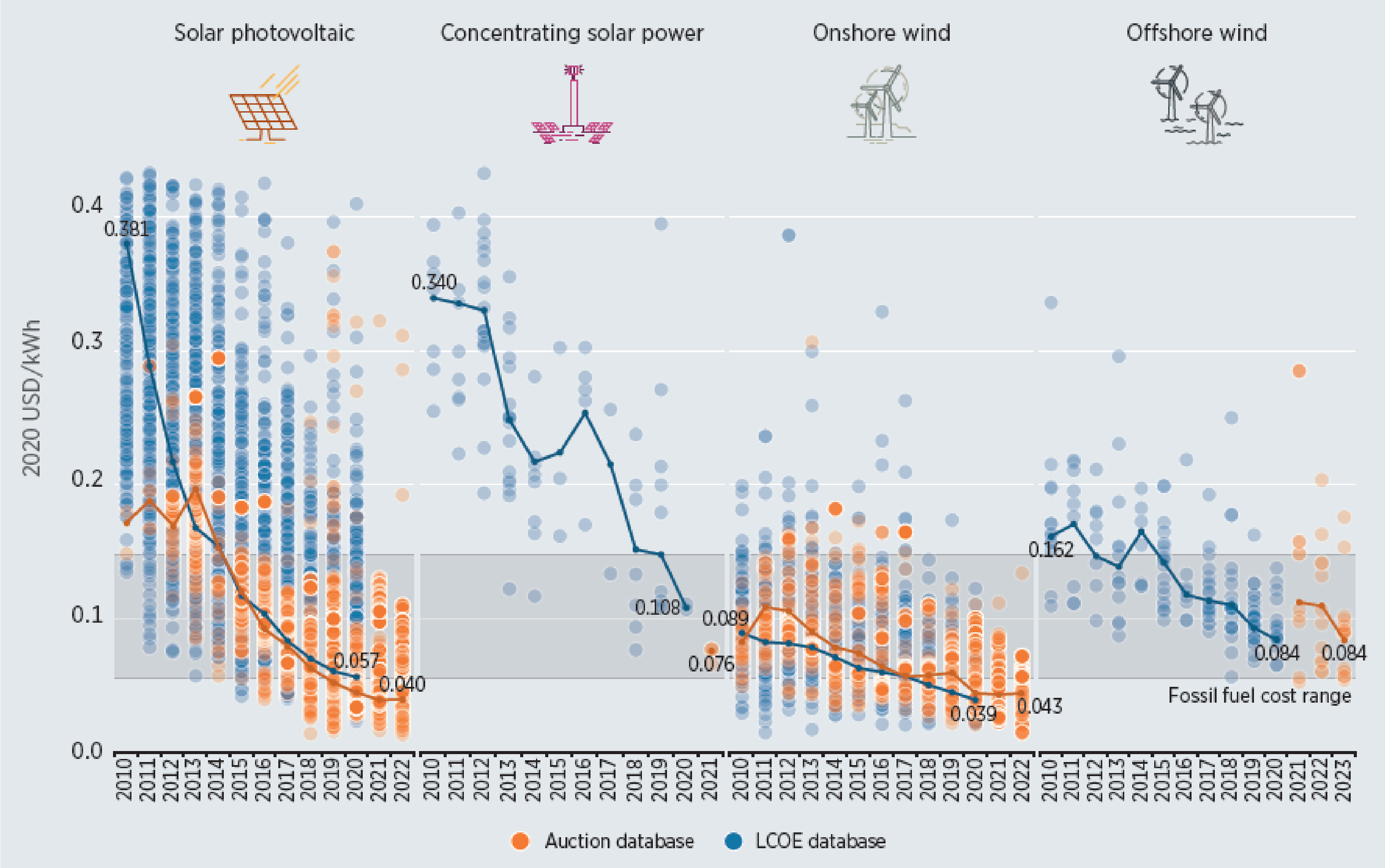
HYDROGEN
the carbon free energy carrier and commodity

16-02-2022

Prof. Dr. Ad van Wijk

TU Delft

Electrification energy system is the trend, both for production as well as demand. ‘Key driver’ is low solar and wind electricity production cost



Source: IRENA Renewable Cost and Auction and PPA Databases

IRENA, "Renewable power generation costs in 2020,“ https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

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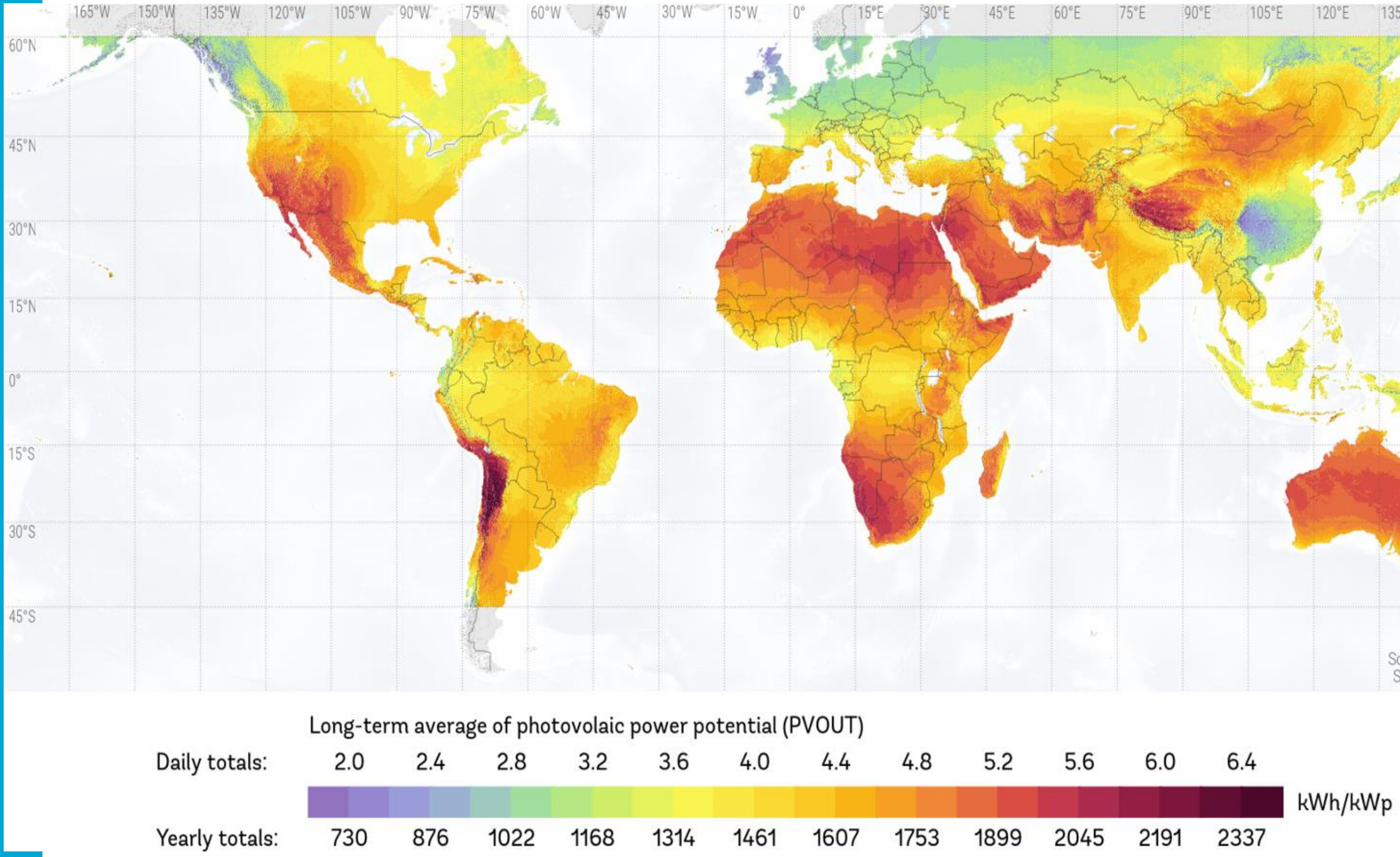
Low cost solar electricity at good solar resources sites, often in desert areas far from energy demand



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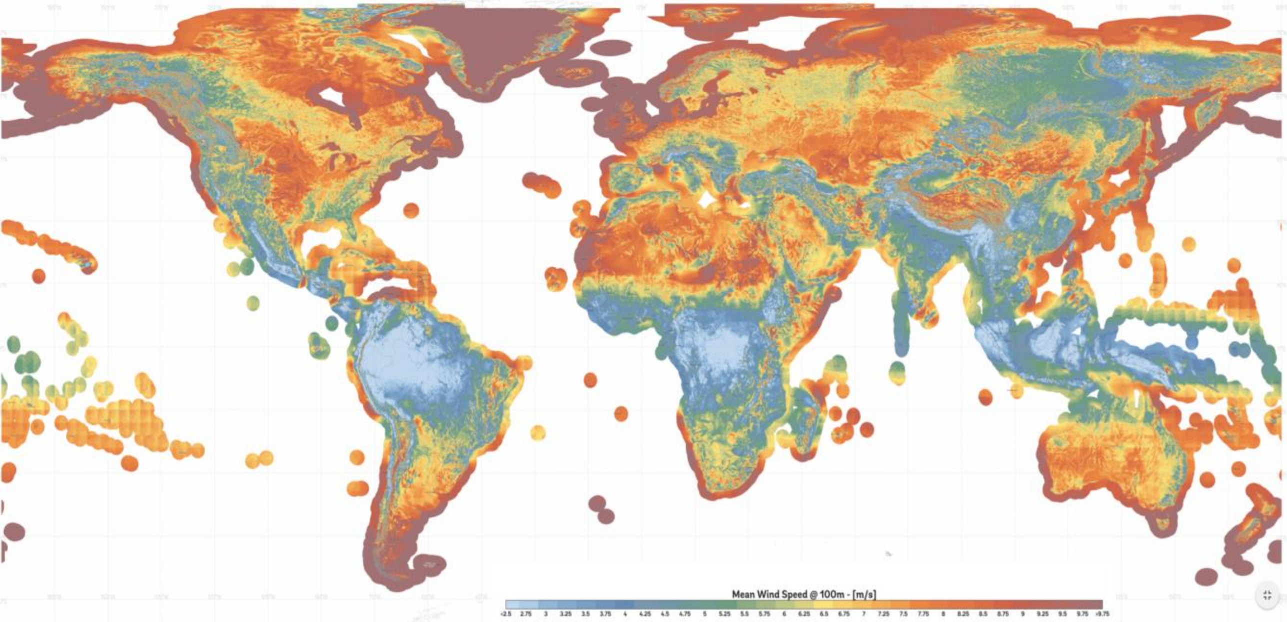
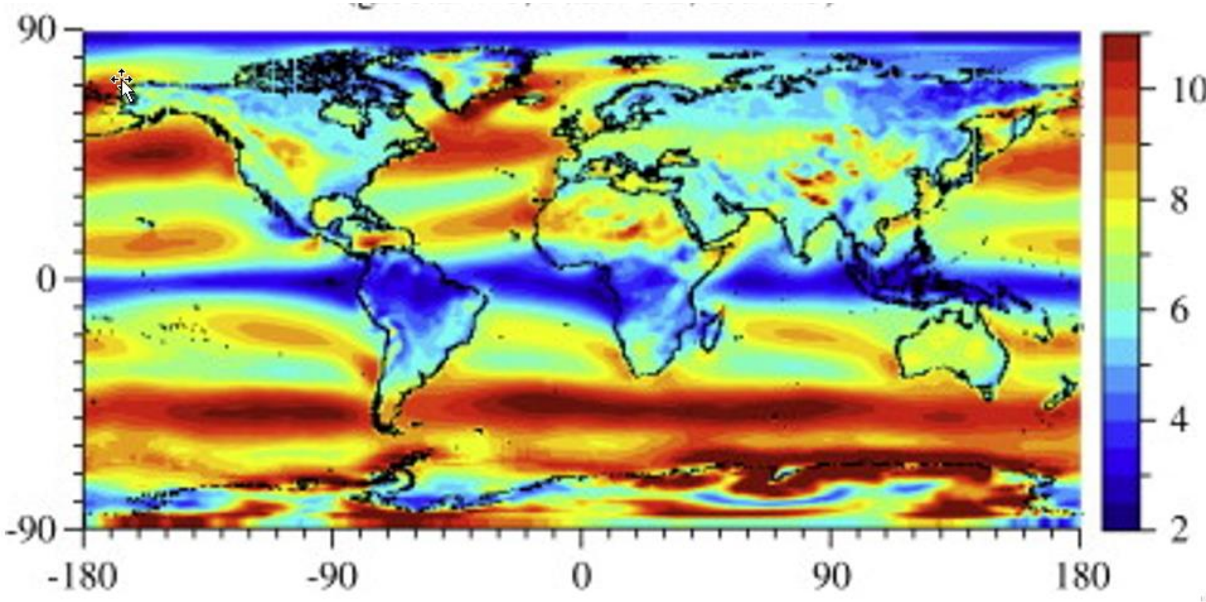
Low cost wind electricity at good wind resources sites, often at the oceans far from energy demand





Annual wind speed at 100 meter height

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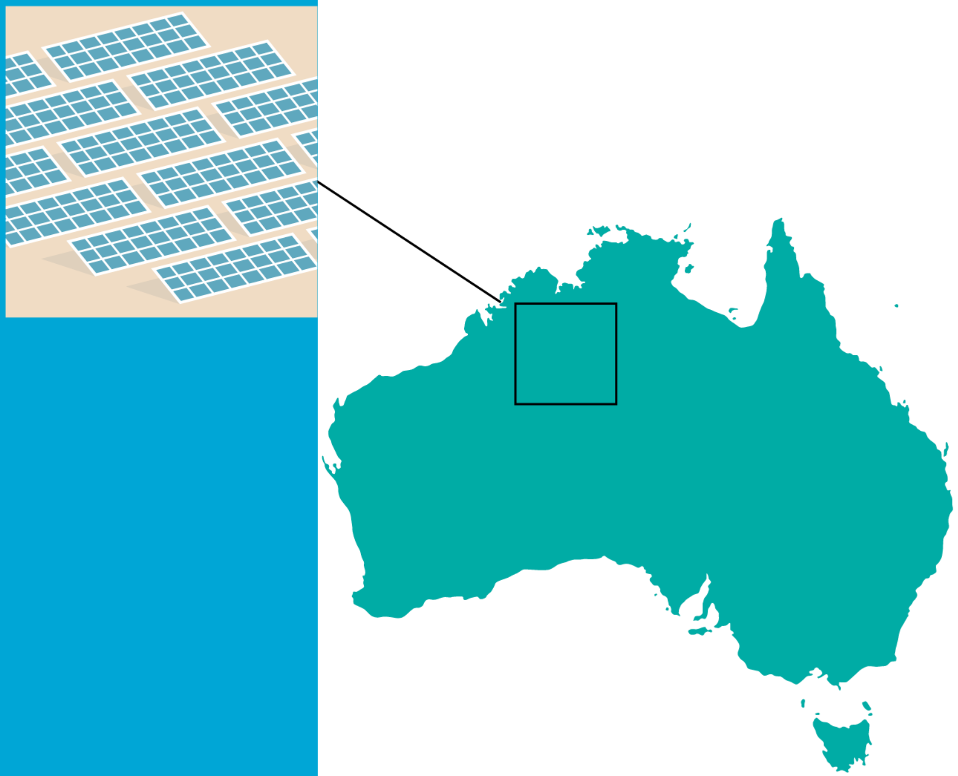
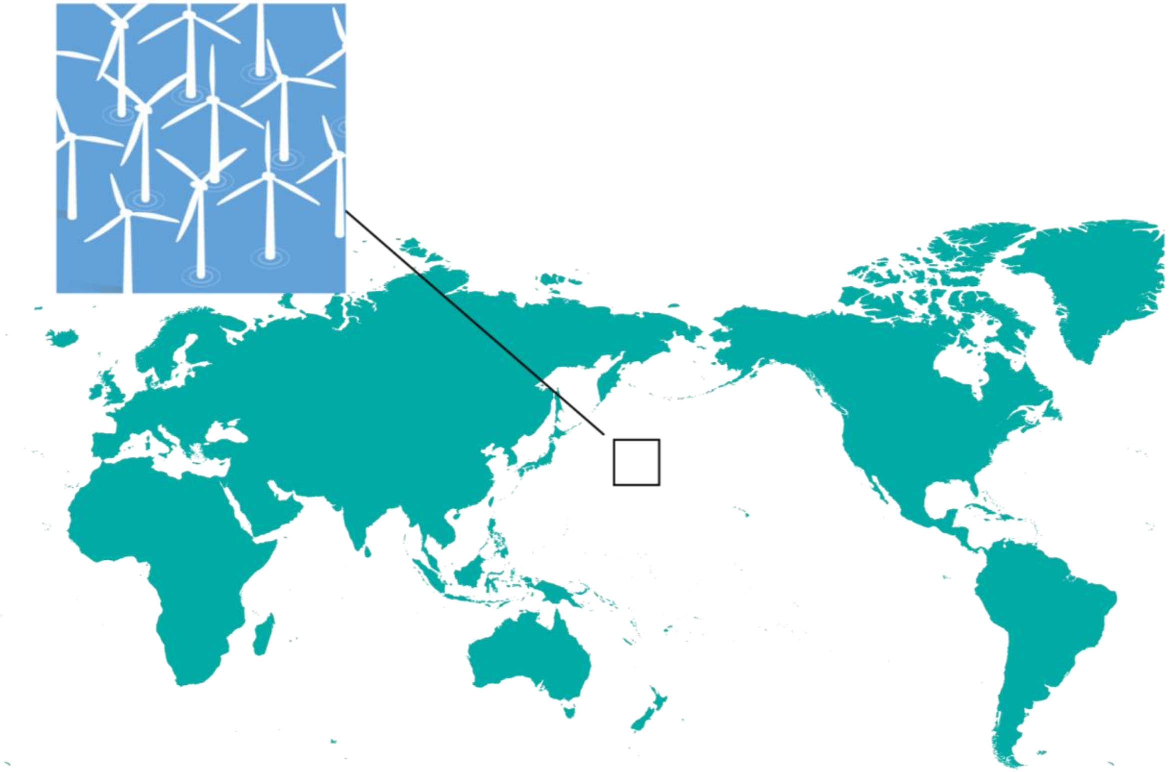
Surface needed to produce all the world's energy
556 EJ = 155.000 TWh



10% SOLAR AUSTRALIA

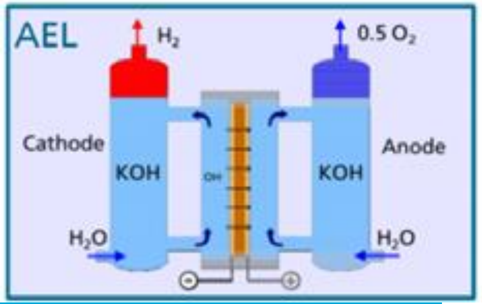


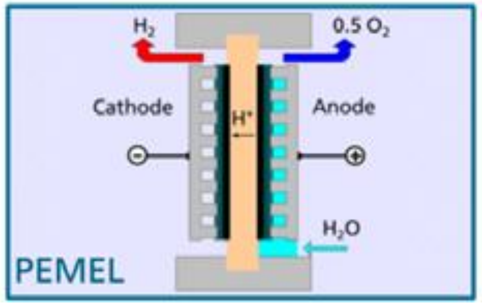
1.5% WIND PACIFIC OCEAN

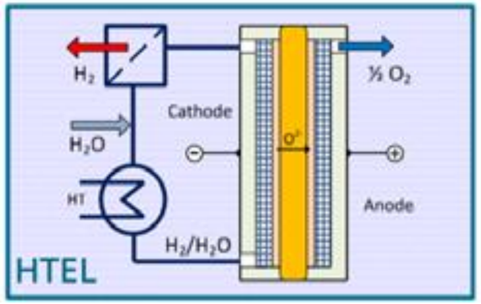
A. van Wijk, E. van der Roest and J. Boere, Solar Power to the People, Nieuwegein-Utrecht: Allied Waters, 2017

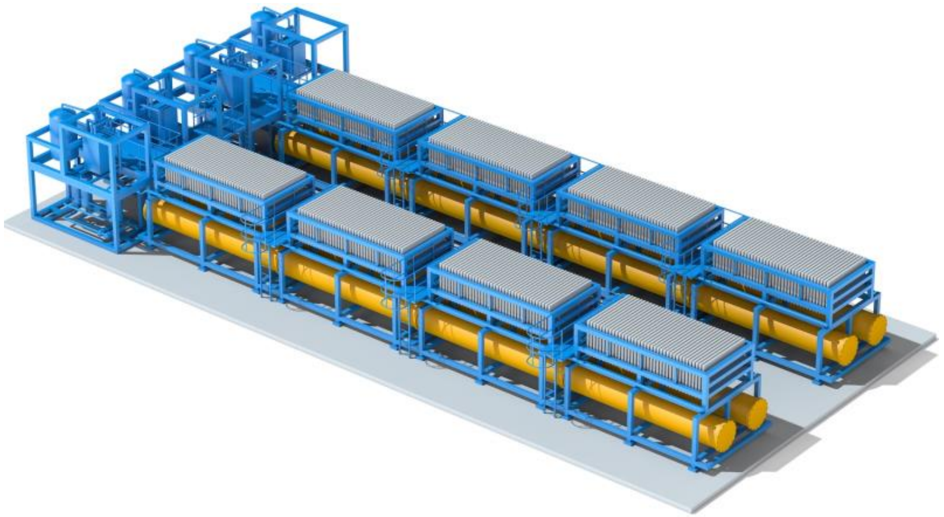
Water Electrolysis

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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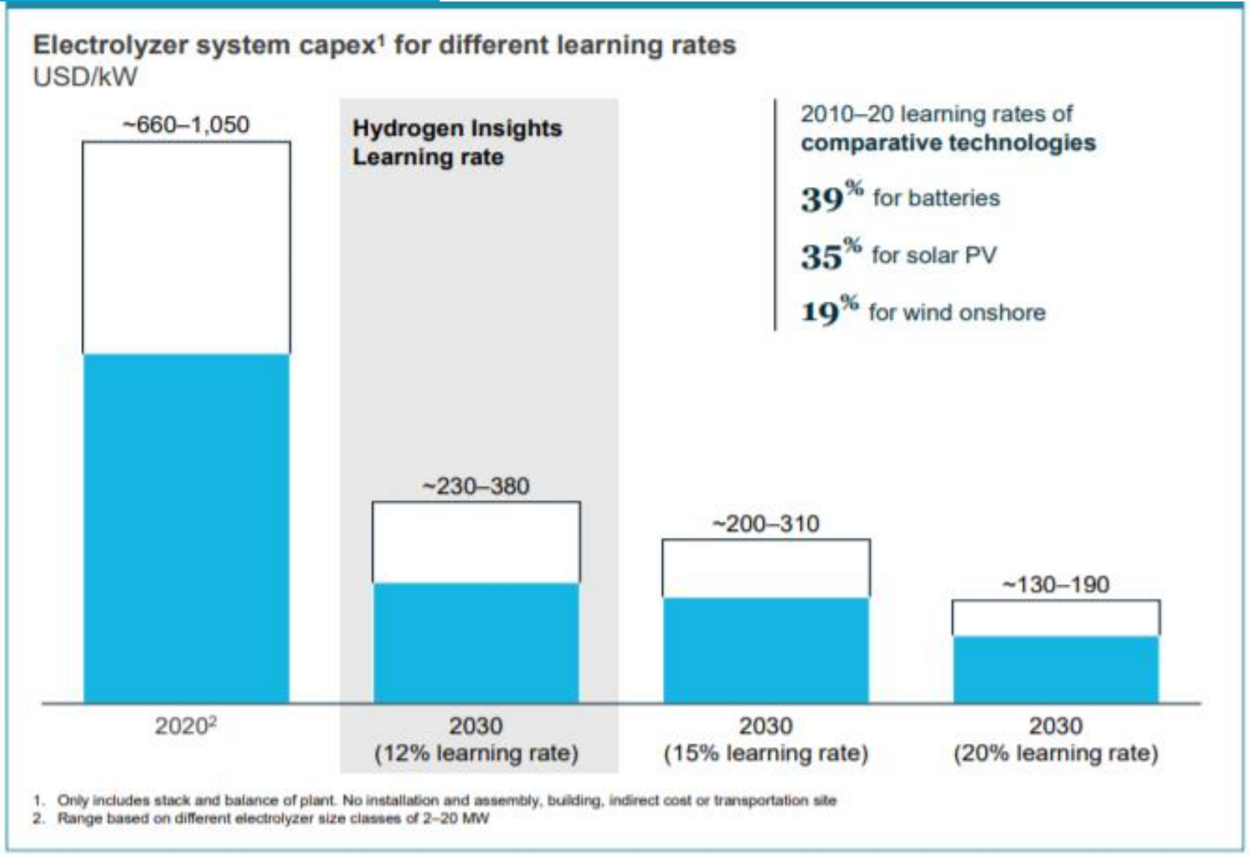
Technology structure electrolysers similar to solar PV, batteries, fuel cells



https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

Technology structure:

- Cells as the fundamental production unit
- Cells are grouped or stacked together in modules or stacks as a physical production unit.
- A number of modules/stacks together with balance of plant equipment is the system production unit.
- These technologies do not have mechanical components and operates at low temperatures.
- Only balance of plant cost scale with system size, but module/stack or cell cost do not scale with system size.

Electrolyser learning rates expected in same range as solar PV and batteries
Mass production of cells and stacks will bring down Capex cost rapidly

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Hydrogen, like electricity, is an energy carrier

Source	Process/Technology	Maturity	Main output	Colour of Hydrogen
Natural gas	Steam methane reforming (SMR)	Mature	$H_2 + CO_2$	**Grey/Blue**, depending on the capture technology and the process input energy 50-90% of CO_2 can be captured and stored.
	Auto-thermal reforming (ATR)	Mature	$H_2 + CO_2$	**Grey/Blue**, with ATR using part of the produced H_2 as energy for process heat, 100% CO_2 emission capture and storage is possible
	Methane Pyrolysis	Small plants operational	$H_2 + C$	**Turquoise**, indirect CO_2 emissions are zero if green electricity or part of the produced hydrogen is used as process energy
Coal	Partial Oxidation/Gasification	Mature	$H_2 + CO_2 + C$	**Brown/Blue**,
	Underground coal gasification	Projects exist	$H_2 + CO_2$	depending on the CCS technology 50-90% of CO_2 can be captured and stored.
Solid Biomass, Biogenic waste	Gasification	Near Maturity	$H_2 + CO_2 + C$	**Green**
	Plasma gasification	First Plant 2023	$H_2 + CO_2$	Negative CO_2 emissions possible
Wet Biomass, Biogenic waste	Super critical water gasification	First Plant 2023	$H_2 + CH_4 + CO_2$	**Green**
	Microbial Electrolysis Cell	Laboratory	$H_2 + CH_4$	Negative CO_2 emissions possible
Electricity + Water	Electrolysis			All shades of **grey to green** and **pink** depending on the source for electricity production.
	Alkaline	Mature	$H_2 + O_2$	
	PEM	Near Maturity	$H_2 + O_2$	With electricity from renewable resources, green H_2 and from nuclear, pink H_2 is produced, both with zero CO_2 emissions
	SOEC	Pilot Plants	$H_2 + O_2$	
Sunlight + Water	Photoelectrochemical	Laboratory	$H_2 + O_2$	**Green**

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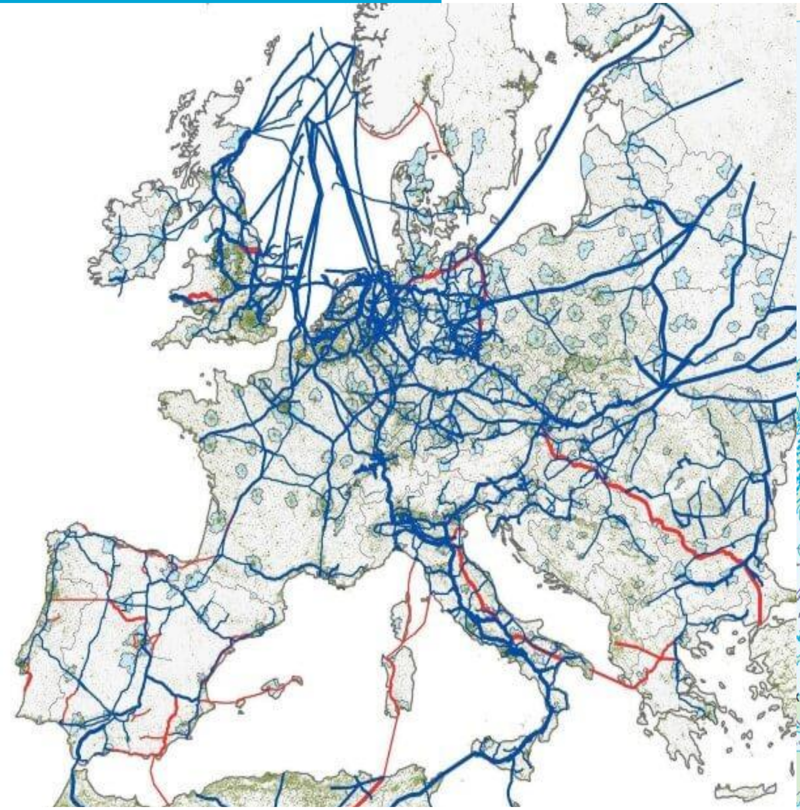
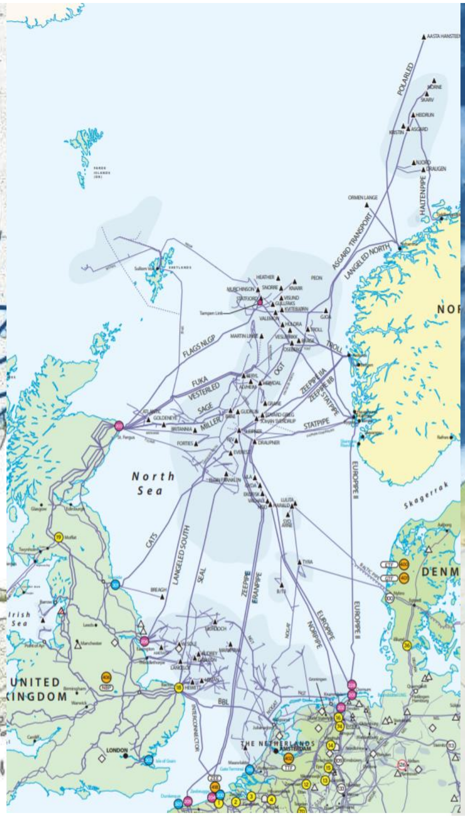
Gas Infrastructure can be reused for hydrogen

Gas Pipeline Capacity 10-20 GW, Electricity cable capacity 1-2 GW

Gas transport cost roughly a factor 10 cheaper than electricity transport



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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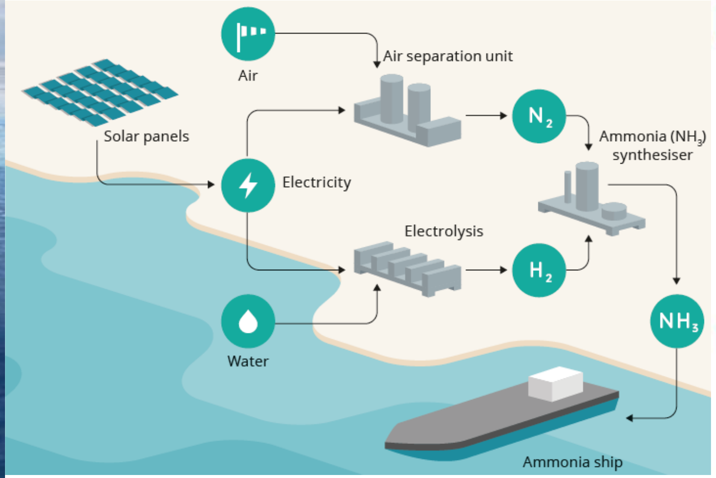
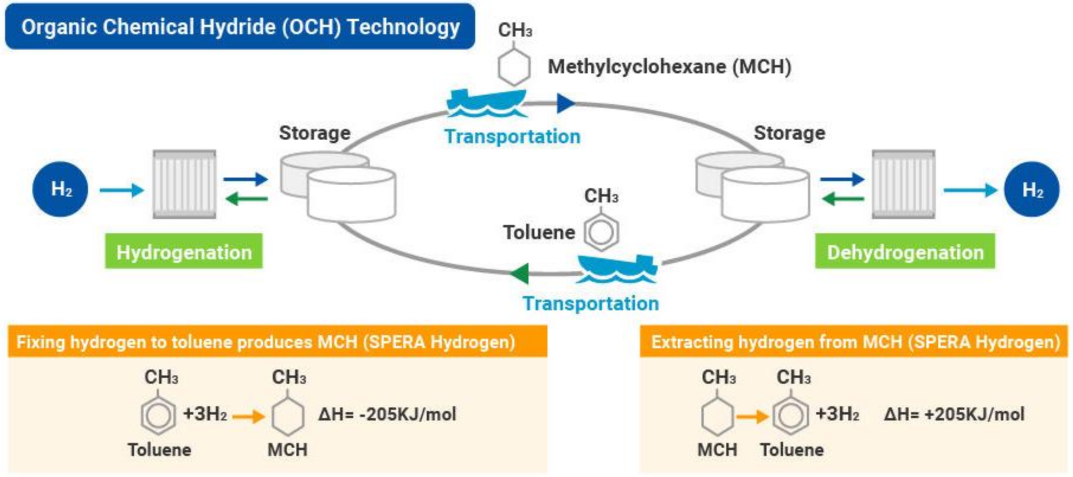
Hydrogen Transport by Ship

Liquid Hydrogen

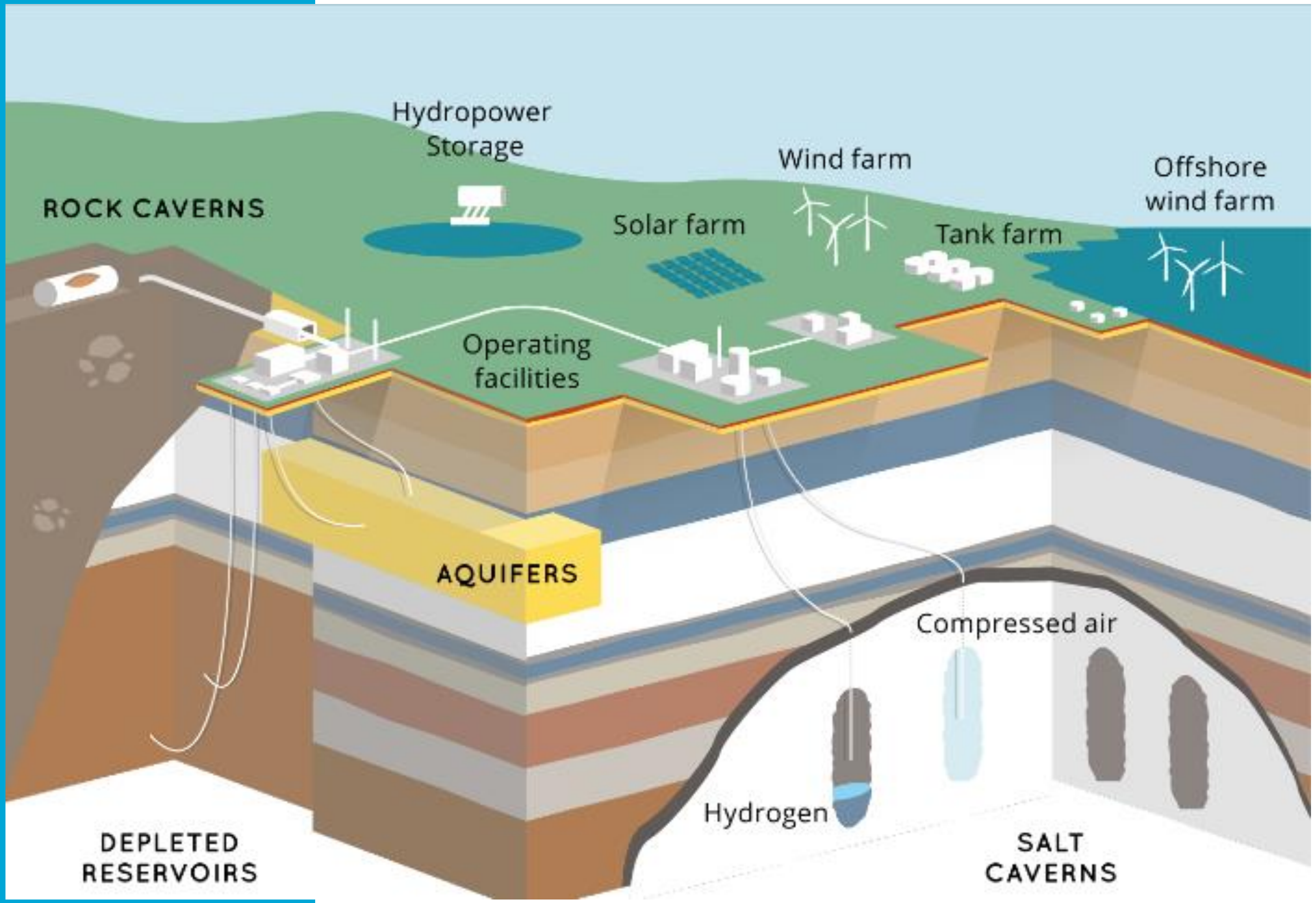


Ammonia

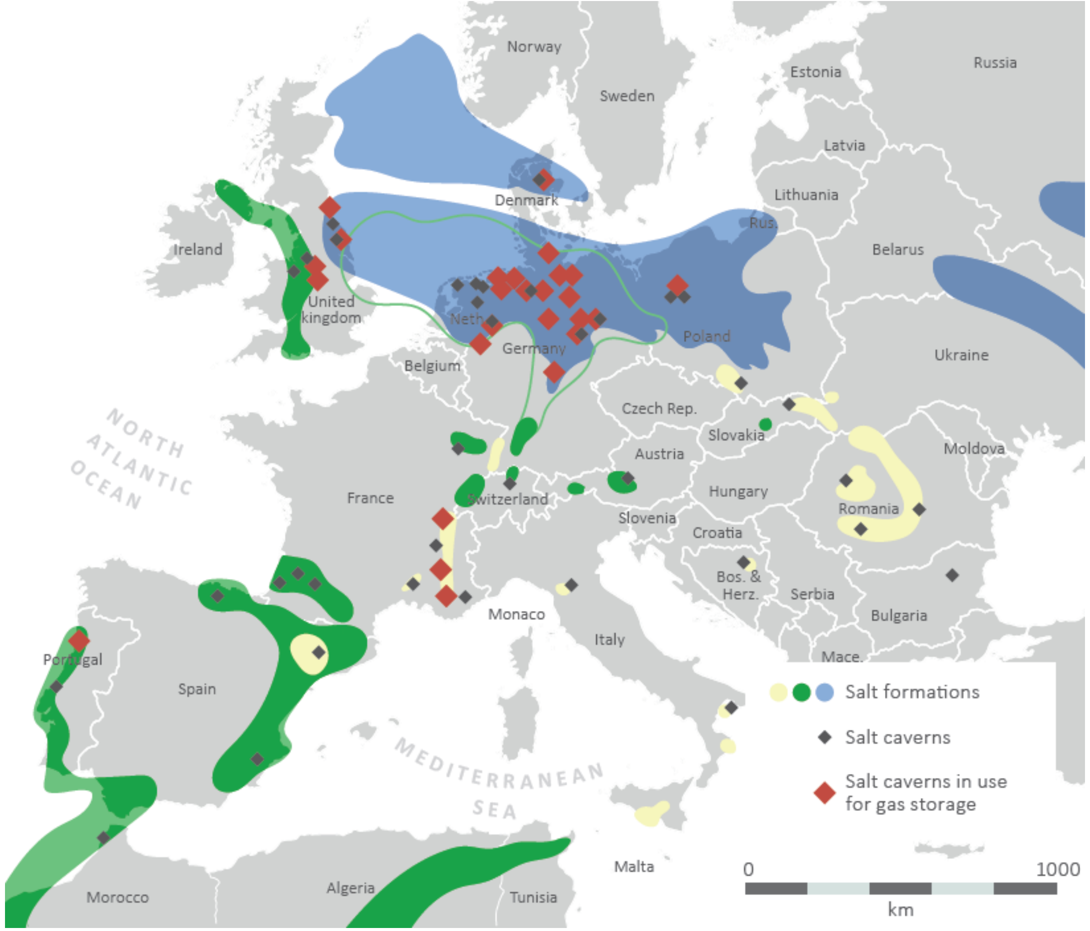


LOHC
Liquid Organic Hydrogen Carrier

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 = 0.5 Euro per kWh, Total Salt cavern CAPEX is 100 million Euro

For comparison, Battery CAPEX = 100 Euro per kWh, Total battery CAPEX would be 23.6 billion Euro

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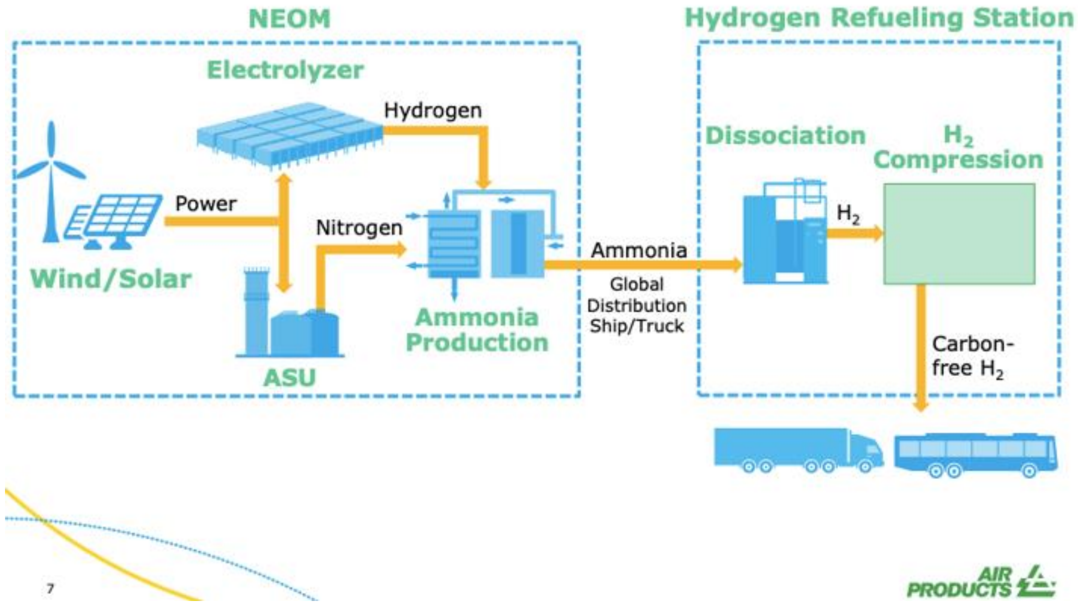
NEOM Solar-Wind Hydrogen-Ammonia

- Consortium: NEOM, ACWA Power, Air Products
- Announced 7 July 2020
- 5 billion dollar investment
- 2025 Operational
- 4 GW Solar, Wind, Storage, 2 GW Electrolyser
- Wind speed 10.3 m/s
- 650 ton Hydrogen per day
- 1.2 million ton Ammonia per year

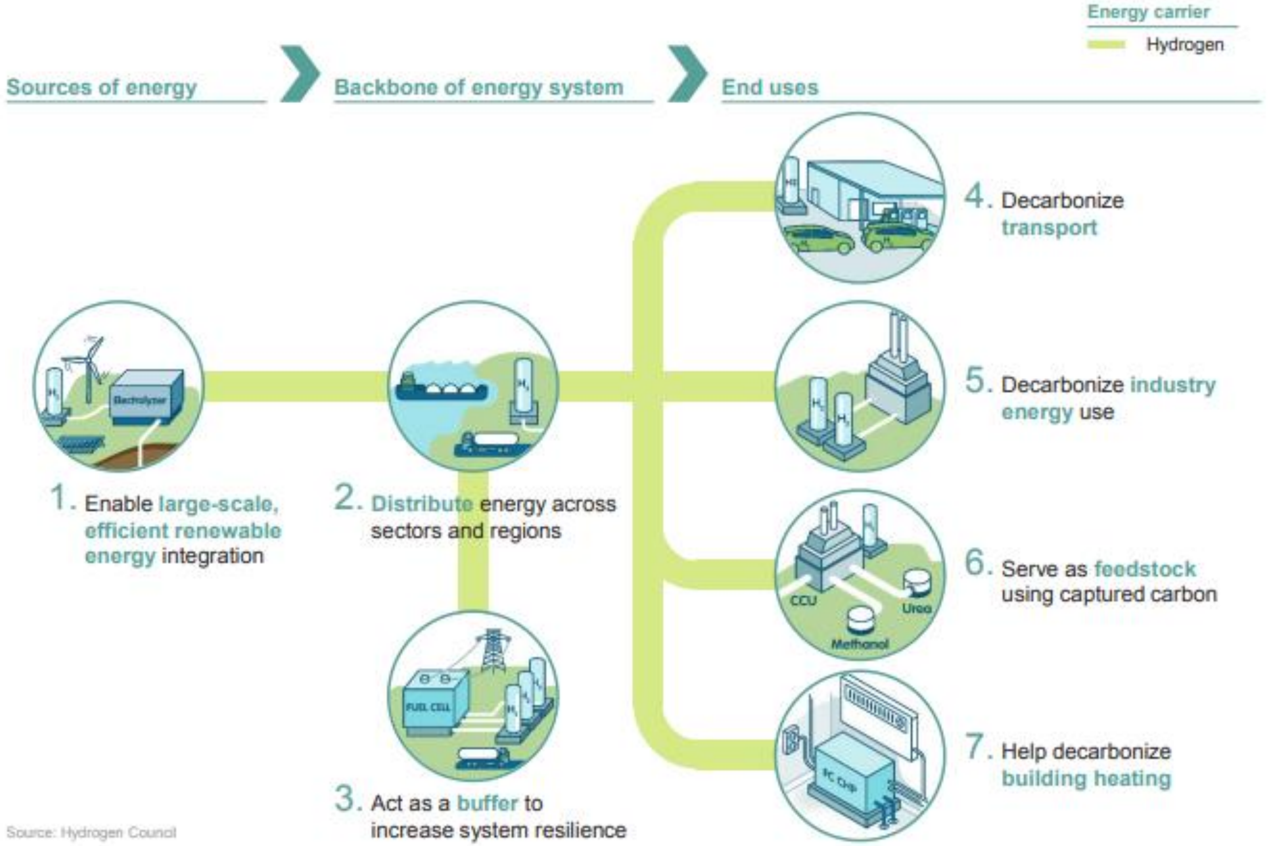


Hydrogen in a carbon-free energy system

1. To deliver cheap solar and wind energy cost-effectively at the right time and place (transport and storage)

2. To decarbonize hard to abate energy use (industry, feedstock, mobility, heating and balancing electricity system)

Finally cost competition between imported hydrogen with regionally produced hydrogen and electricity



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

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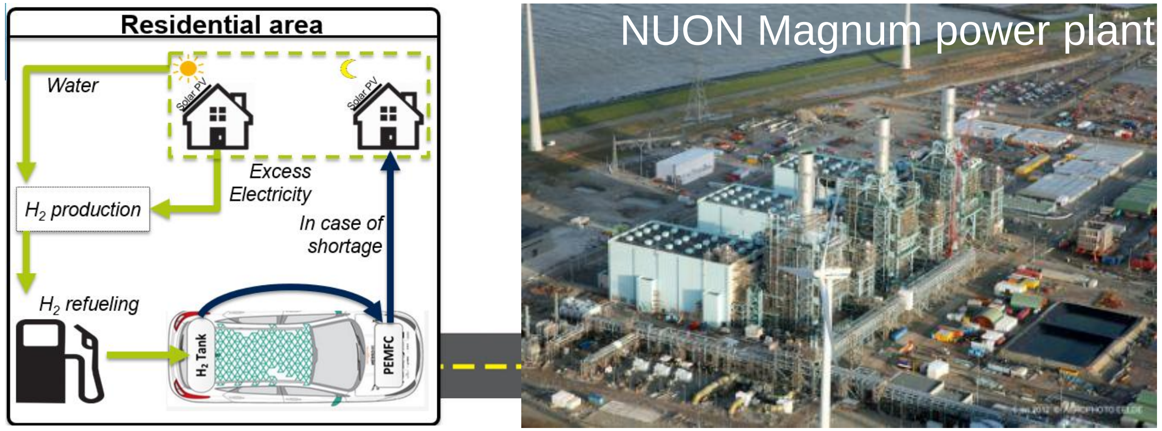
Hydrogen Markets

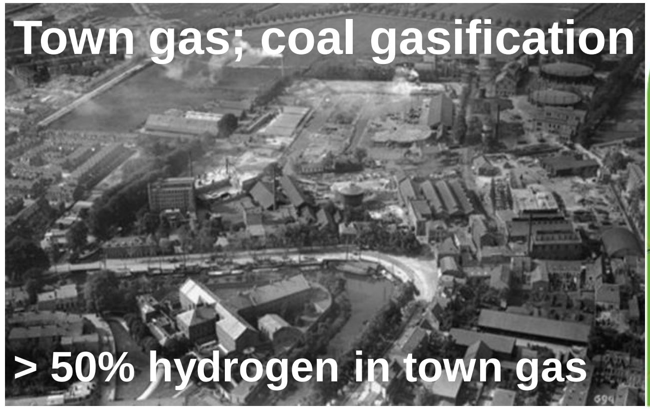
Industry Feedstock/HT Heat

Electricity Balancing



Transport

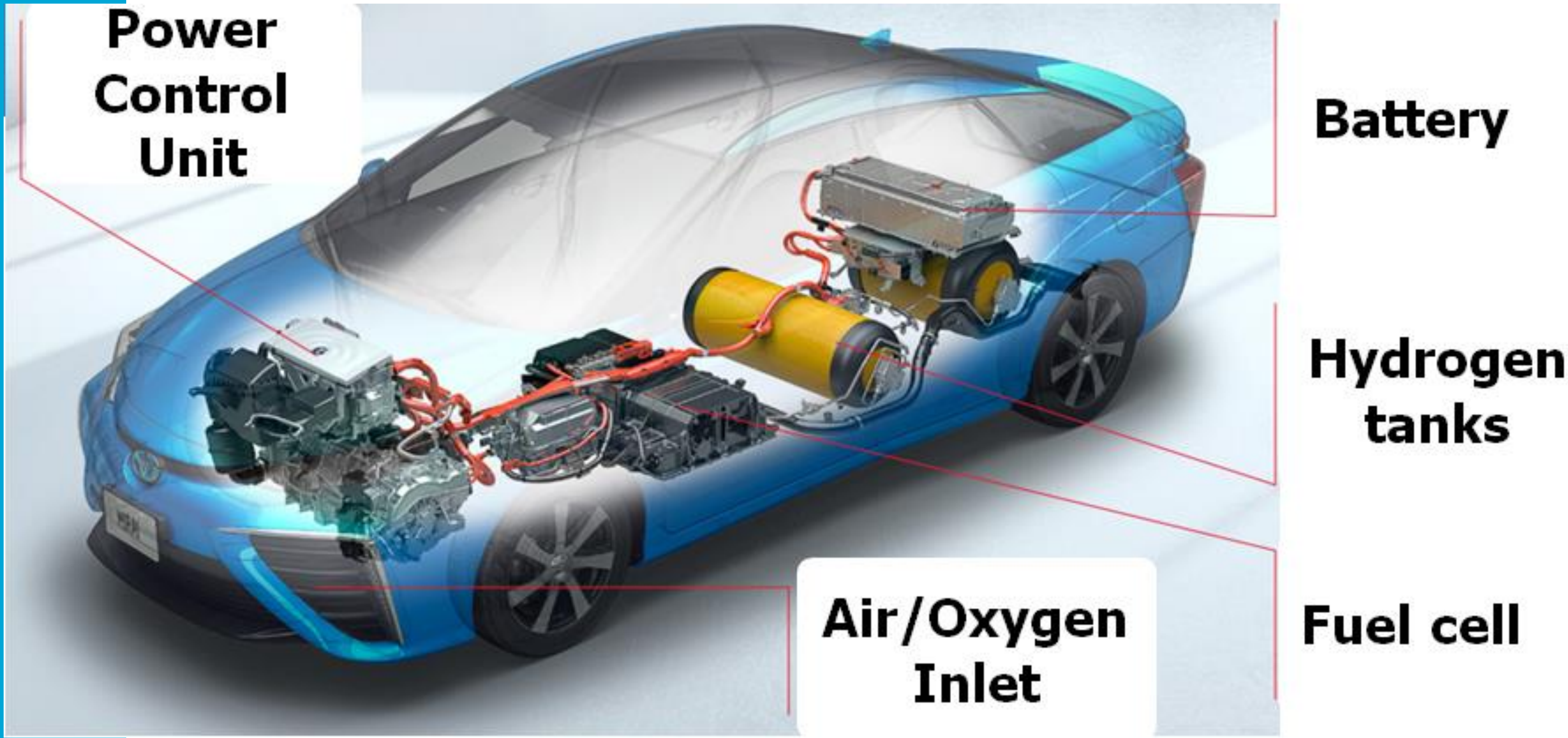
Heating



The future for mobility is electric!

Tesla Model S **Toyota Mirai**

Toyota Mirai; Fuel cell car



New Holland; Diesel/hydrogen dual fuel tractor
Hydrogen injection in air inlet diesel engine
Hydrogen replaces 60%-80% diesel

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Hyundai, autonomous driving fuel cell electric truck on hydrogen, driving range 1000 km

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24 Hours LeMans in 2024 on hydrogen

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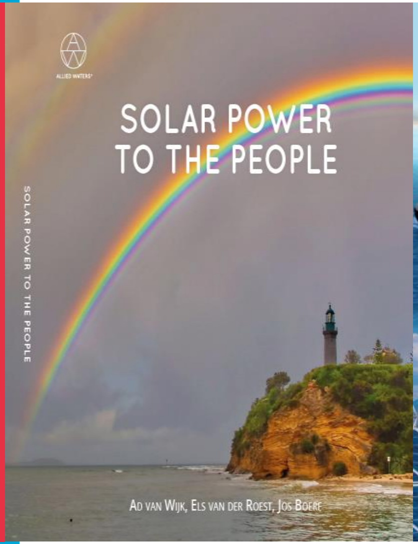
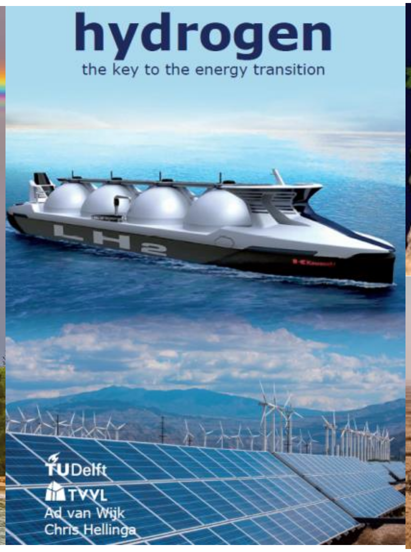
Further Reading
www.profadvanwijk.com

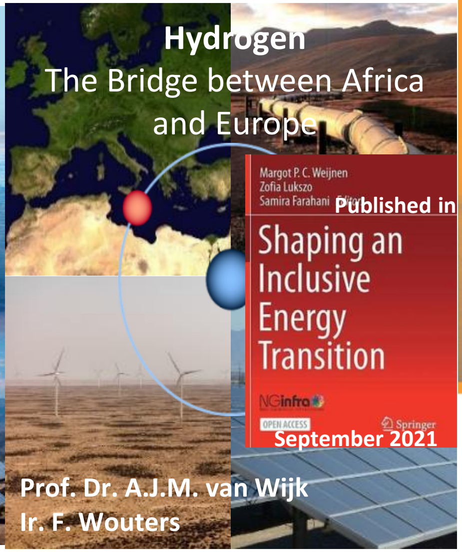
April 2017



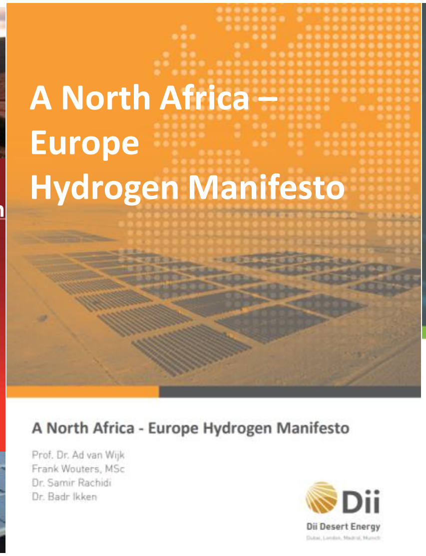
November 2017



May 2018



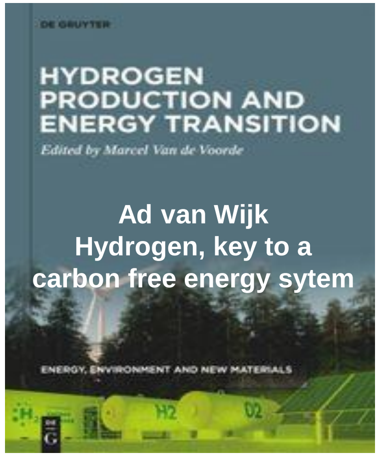
September 2019



November 2019

April 2020

April 2021



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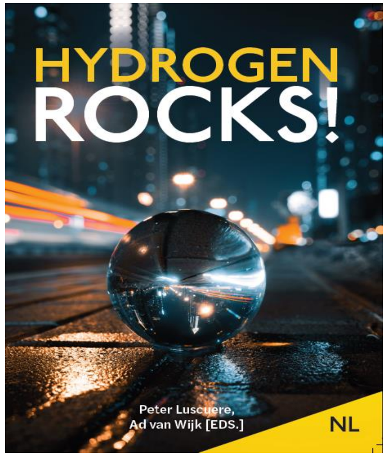

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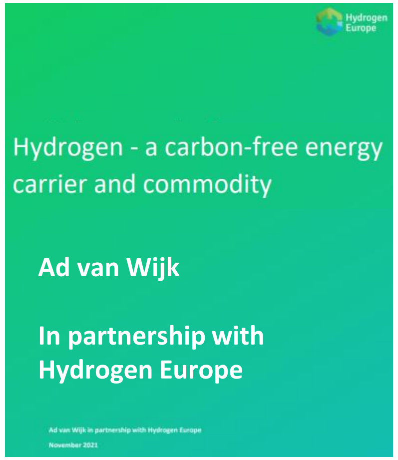

November 2021

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