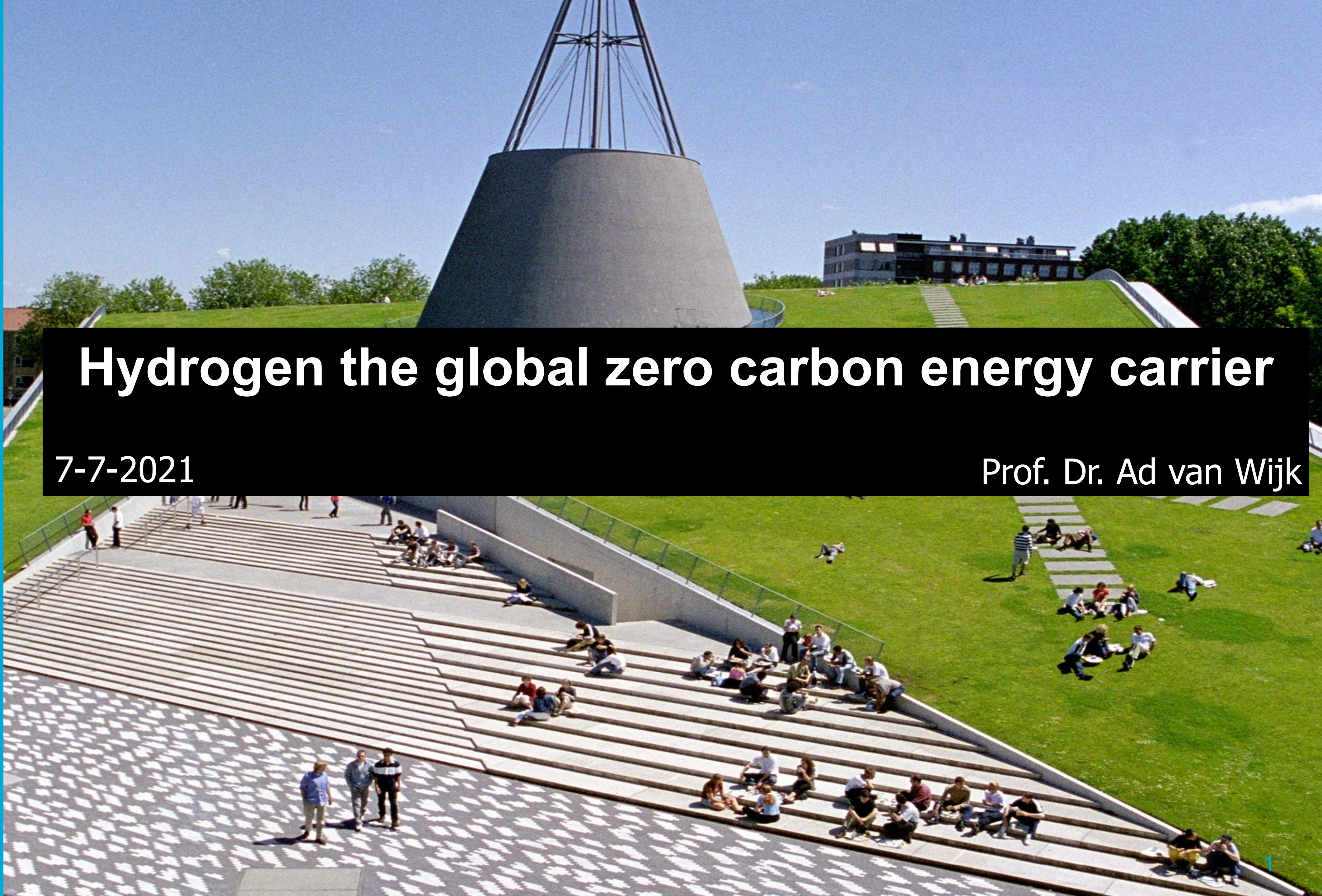


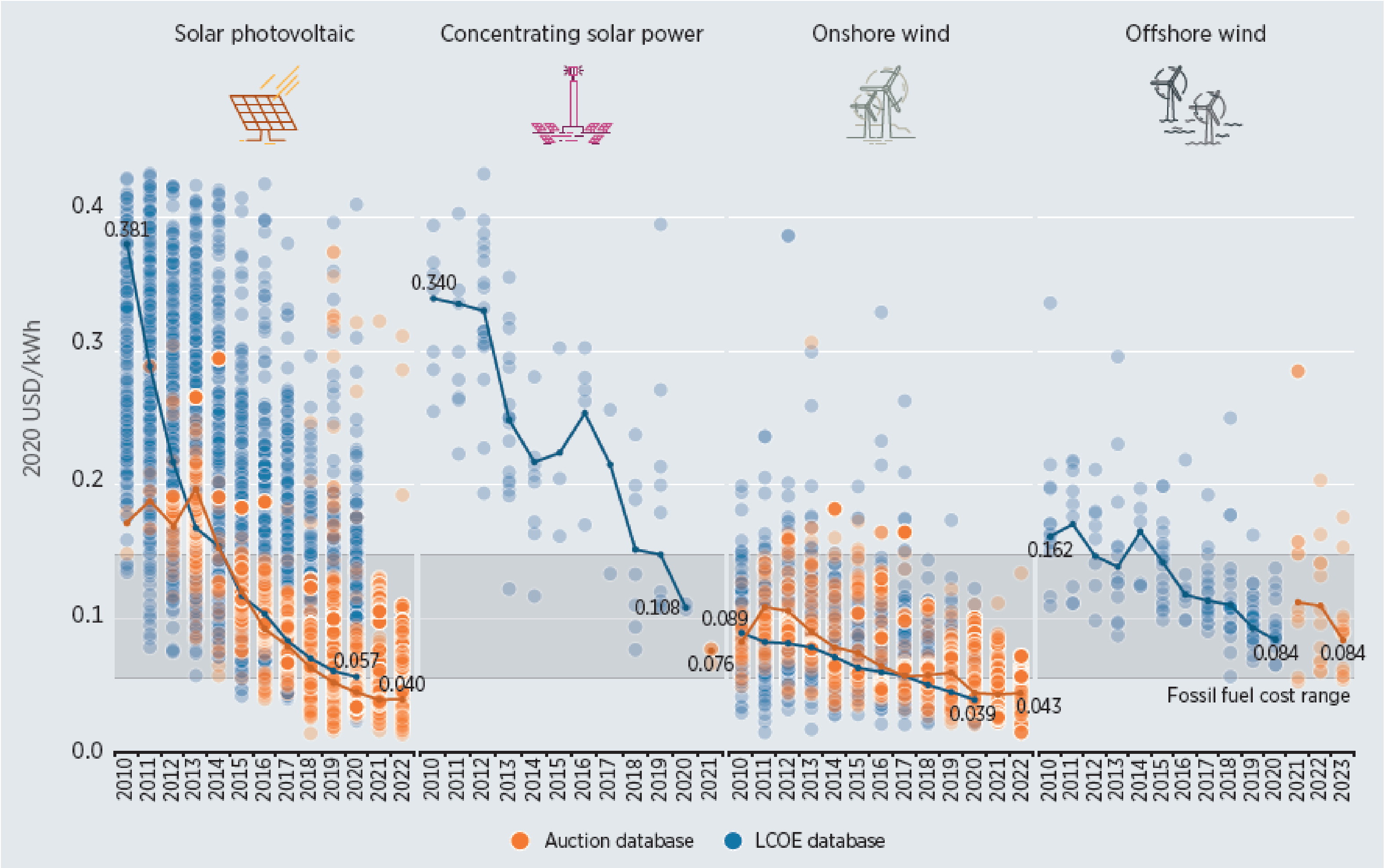
Hydrogen the global zero carbon energy carrier

7-7-2021

Prof. Dr. Ad van Wijk

TU Delft

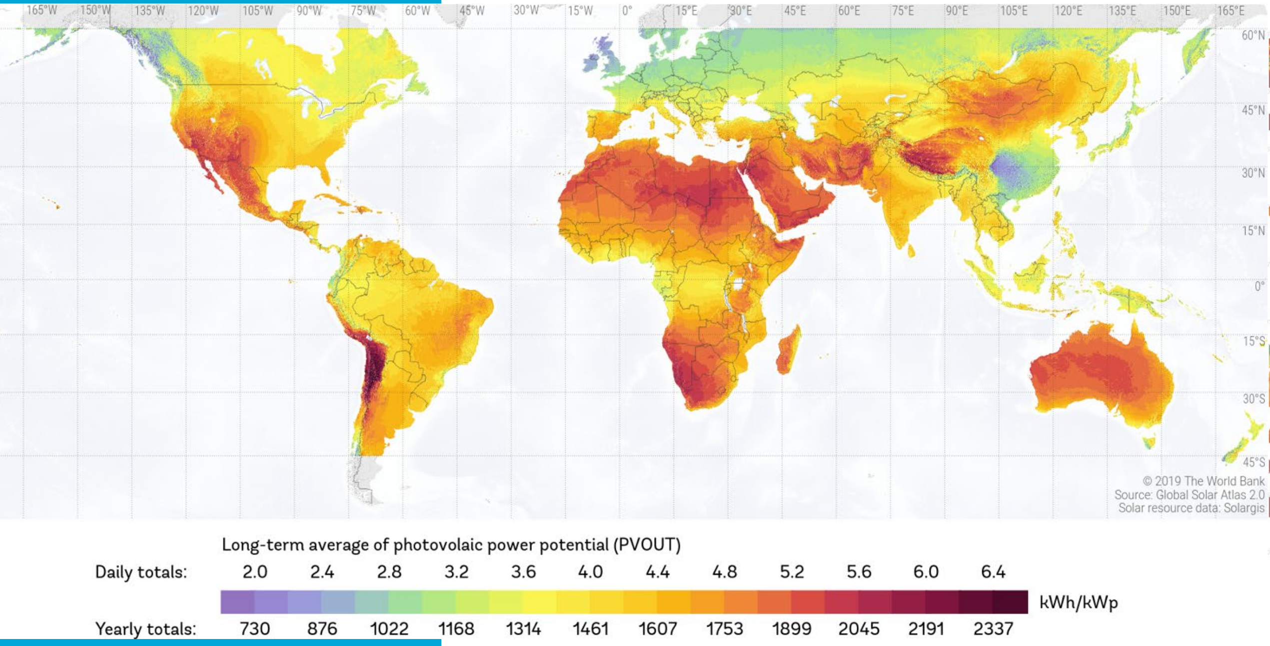
Electrification energy system both in supply and demand
Important Key driver is low cost renewable electricity

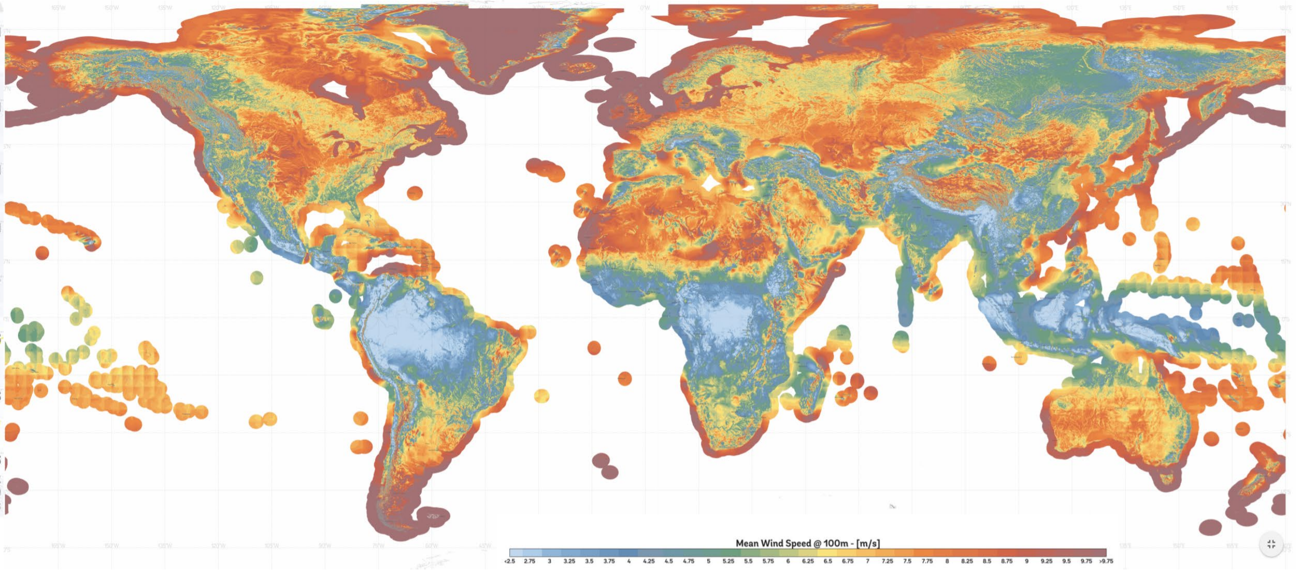


Source: IRENA Renewable Cost and Auction and PPA Databases

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

Low cost solar and wind electricity at good solar and wind resources sites, often far from energy demand

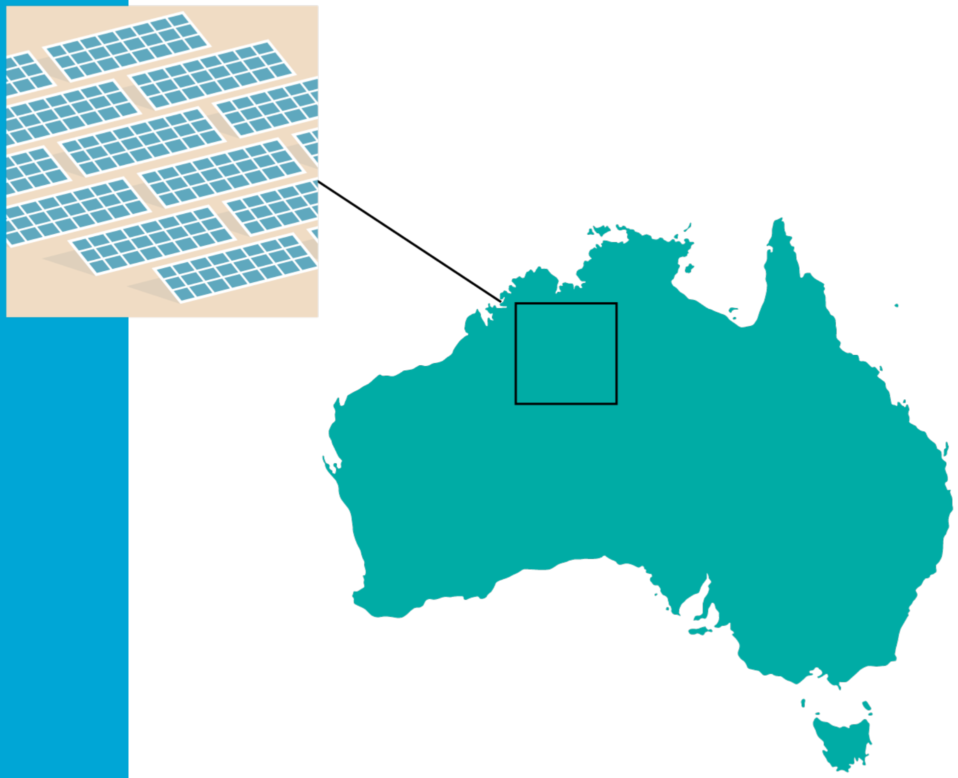




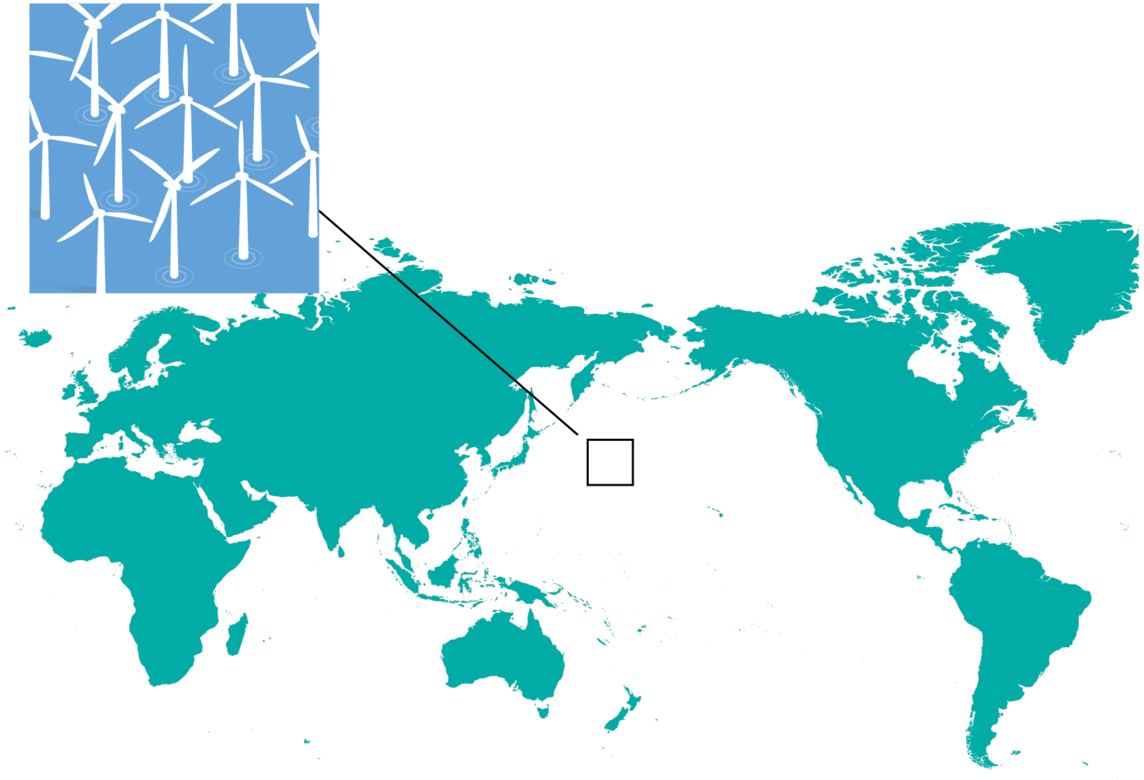
Solar Resources Map

Wind Speed at 100 meter height Map

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

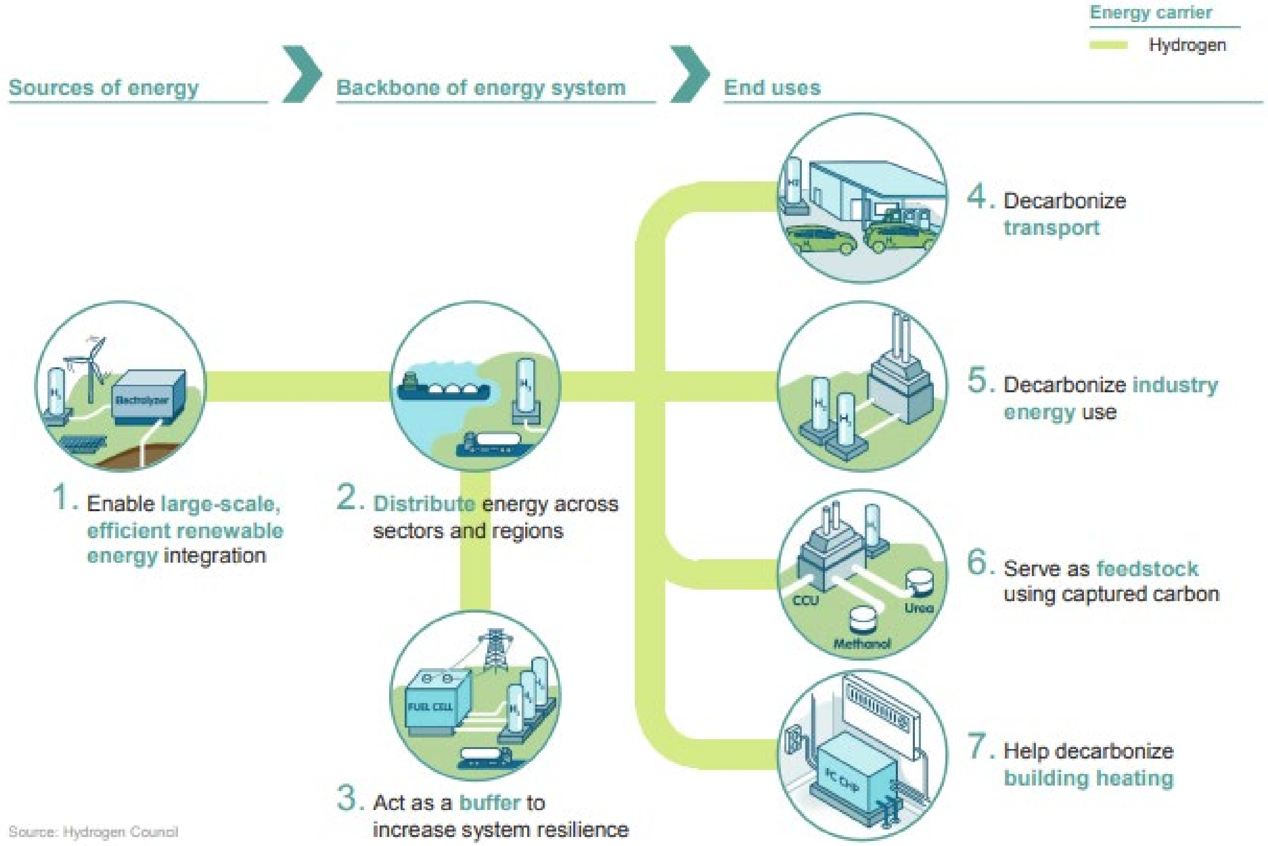
TU Delft

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

TU Delft

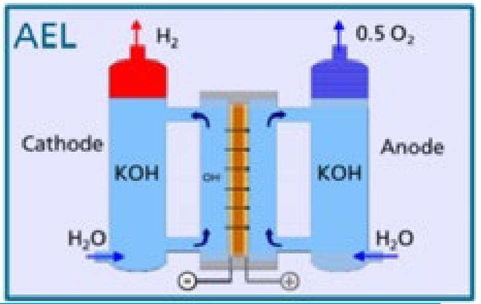
Hydrogen like electricity is an energy carrier

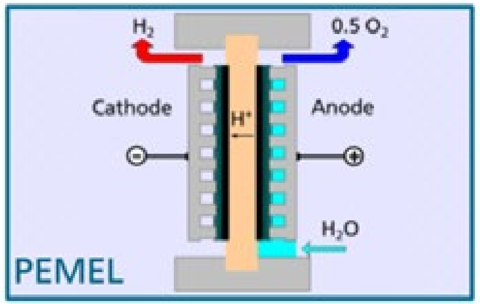
Source	Process/Technology	Maturity	Output	'Colour' of Hydrogen
Natural gas	Steam methane reforming Auto-thermal reforming Thermal Pyrolysis	Mature Mature First plant 2025	$H_2 + CO_2$ $H_2 + CO_2$ $H_2 + C$	**Grey or blue**, 50-90% of CO_2 can be captured + stored **Turquoise**, CO_2 emissions depend 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**

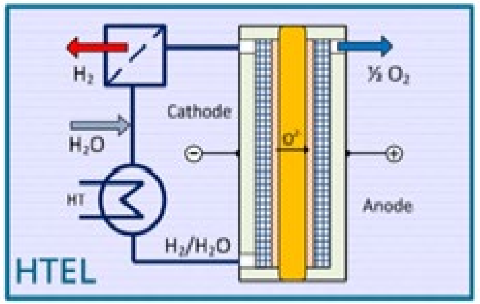
TU Delft

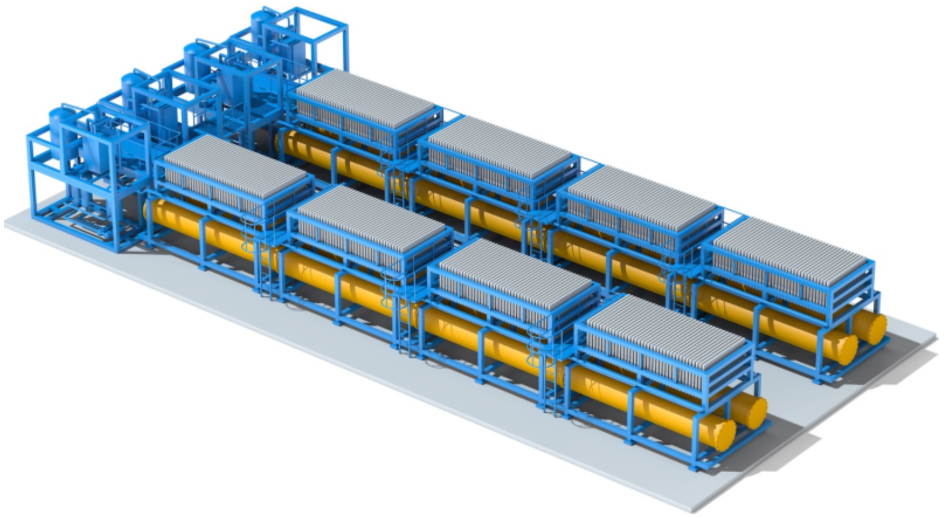
Power to hydrogen technology: Water Electrolysis

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-}	$O^{2-} \Rightarrow \frac{1}{2}O_2 + 2e^-$









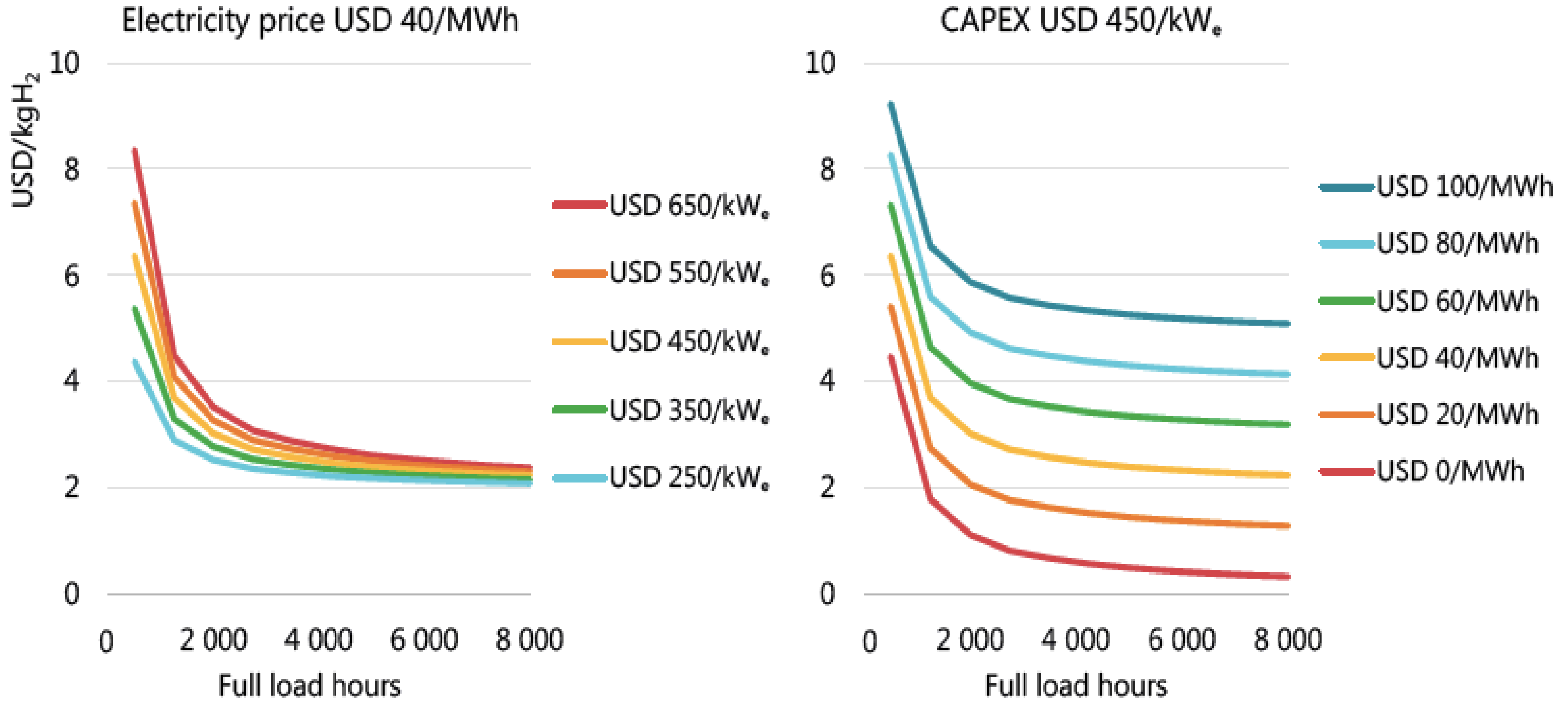
20 MW alkaline electrolyser ThyssenKrupp

	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.

Power to Hydrogen production cost; LCoH

Electricity cost dominant in hydrogen cost; every 10 USD/kWh electricity = 0.5 USD/kg H_2 (at 80% efficiency HHV)



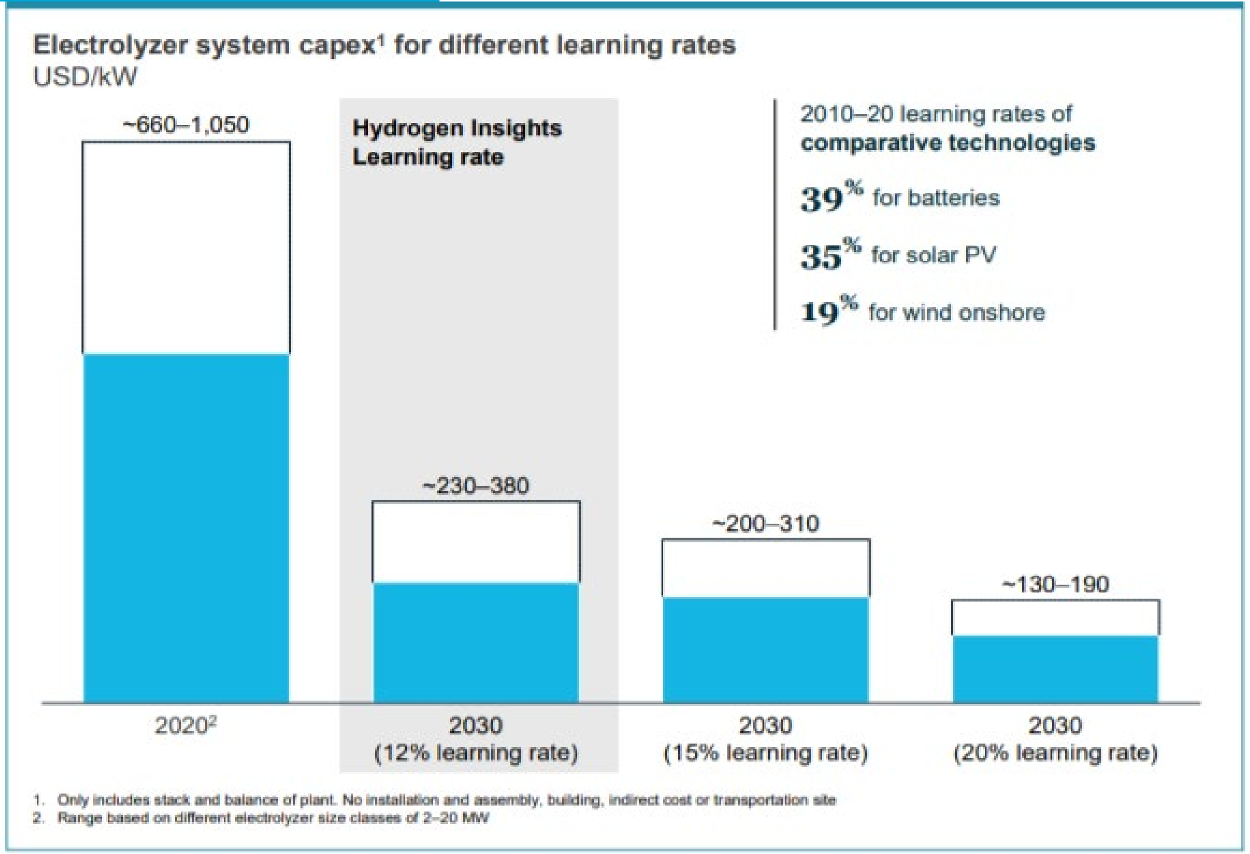
Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

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%)

TU Delft

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

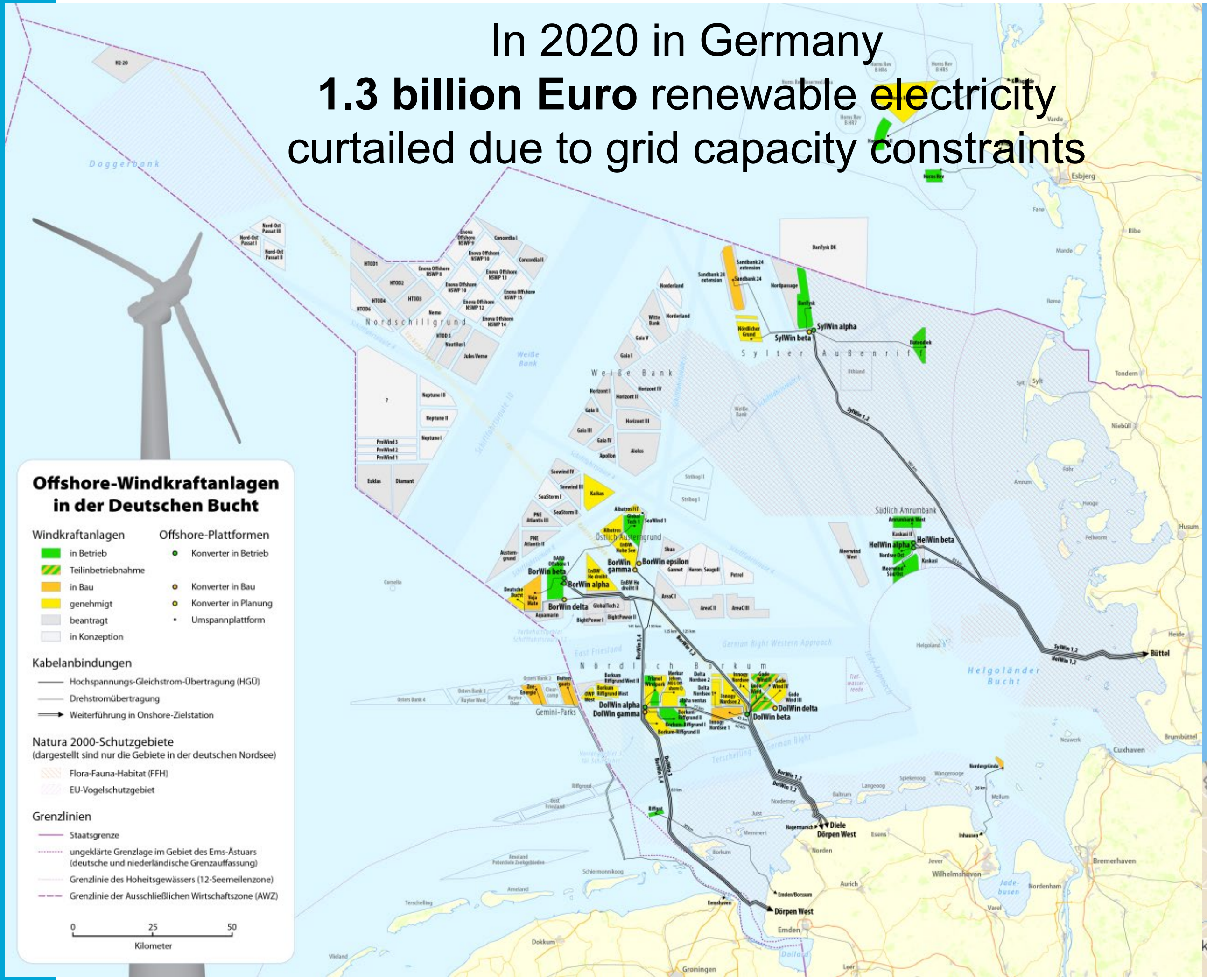
Characteristics current gas, electricity and hydrogen systems

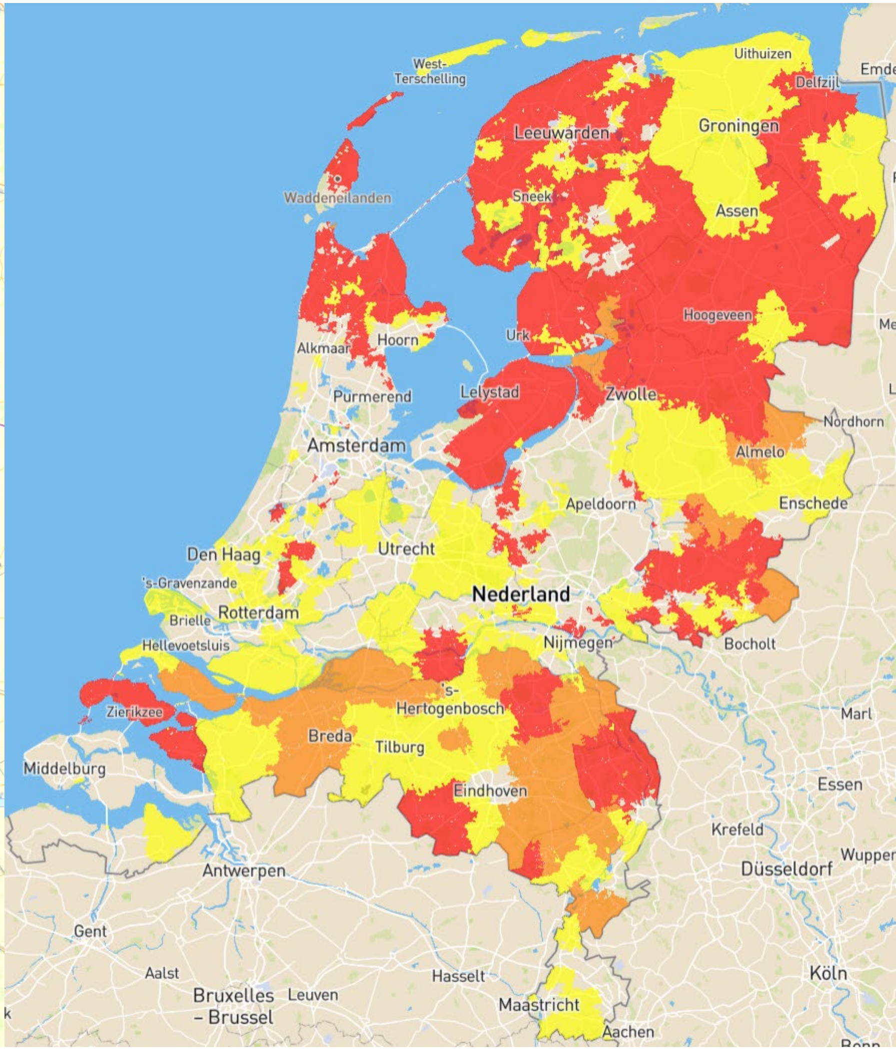
	Gas system	Electricity system	Hydrogen system
Production volume per location	10-1,000 TWh/yr Gas field	1-30 TWh/yr Power Plant	0.1-4 TWh/yr SMR plant
Distance between production location and demand centres	Up to 5.000 km Pipeline Worldwide Shipment	Up to 1.000 km Cable	'Captive' production for demand on location
Capacity Transport Pipeline/Cable	5-35 GW Pipeline	1-4 GW Cable (HVDC)	Some small pipeline infrastructure on and between industrial sites
Infrastructure ownership	Public and Private	Mainly Public	Private
Storage Capacity	200-500 GWh Salt cavern Natural Gas Empty Gas field storage capacity factor 10 larger then salt caverns	5-25 GWh Pumped hydro-power 0.73 GWh Largest battery storage system announced	100-250 GWh Salt cavern Hydrogen Today salt caverns are in use for H_2 storage

TUDelft

High penetration solar and wind in electricity system leads to grid congestion and electricity balancing challenges

In 2020 in Germany
1.3 billion Euro renewable electricity curtailed due to grid capacity constraints

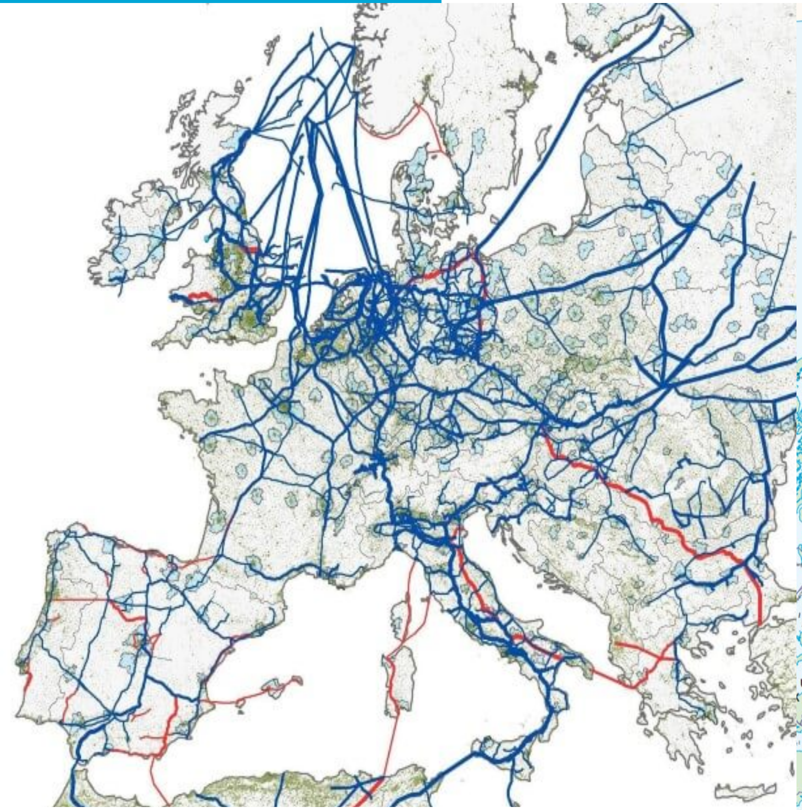




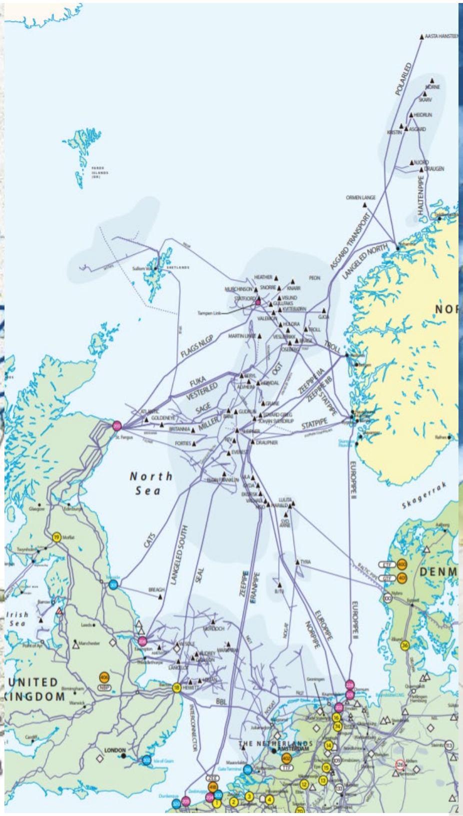
Gas Infrastructure in Europe can be reused for hydrogen

Gas Pipeline Capacity 5-20 GW, Electricity cable capacity 0.5-2 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

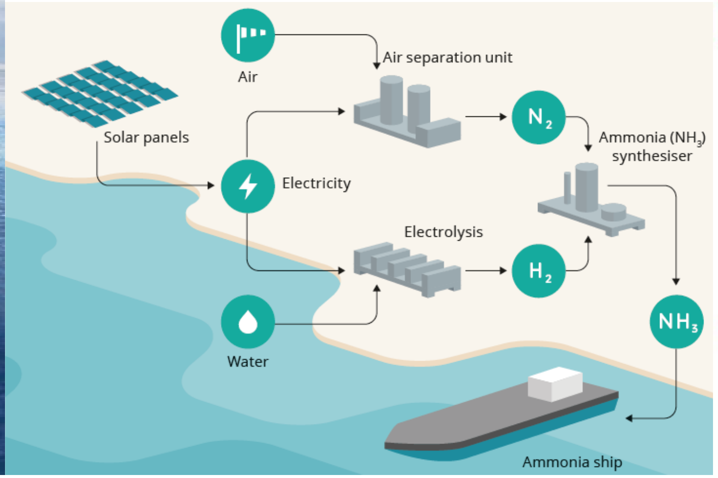
European Hydrogen Backbone
75% re-used gas pipelines
25% new hydrogen pipelines
40.000 km pipelines

TU Delft

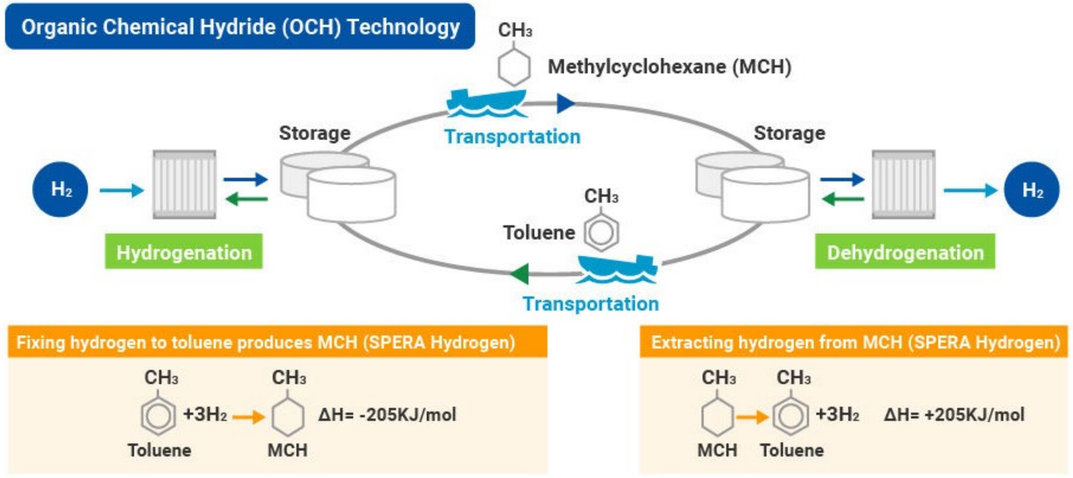
Hydrogen transport by ship

Liquid Hydrogen

Ammonia

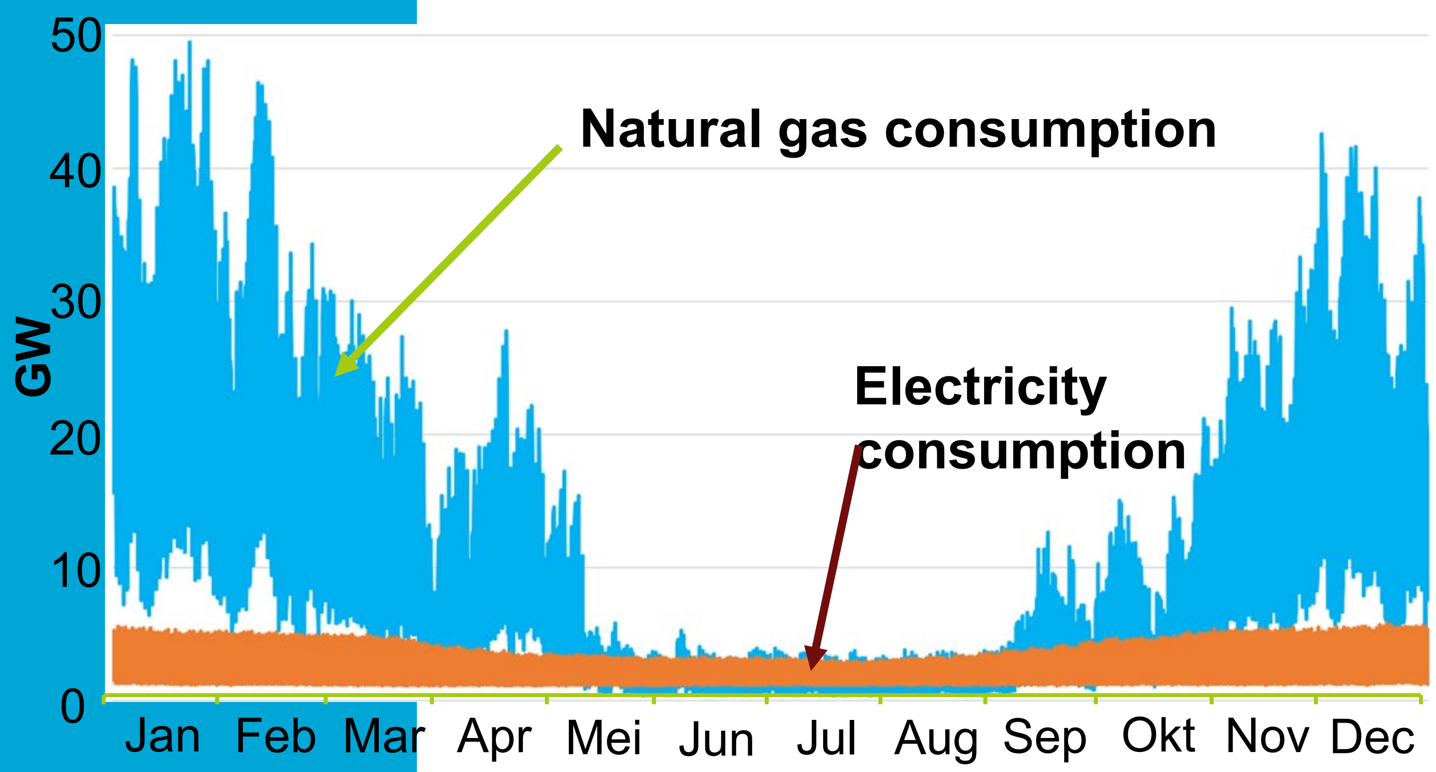


LOHC Liquid Organic Hydrogen Carrier



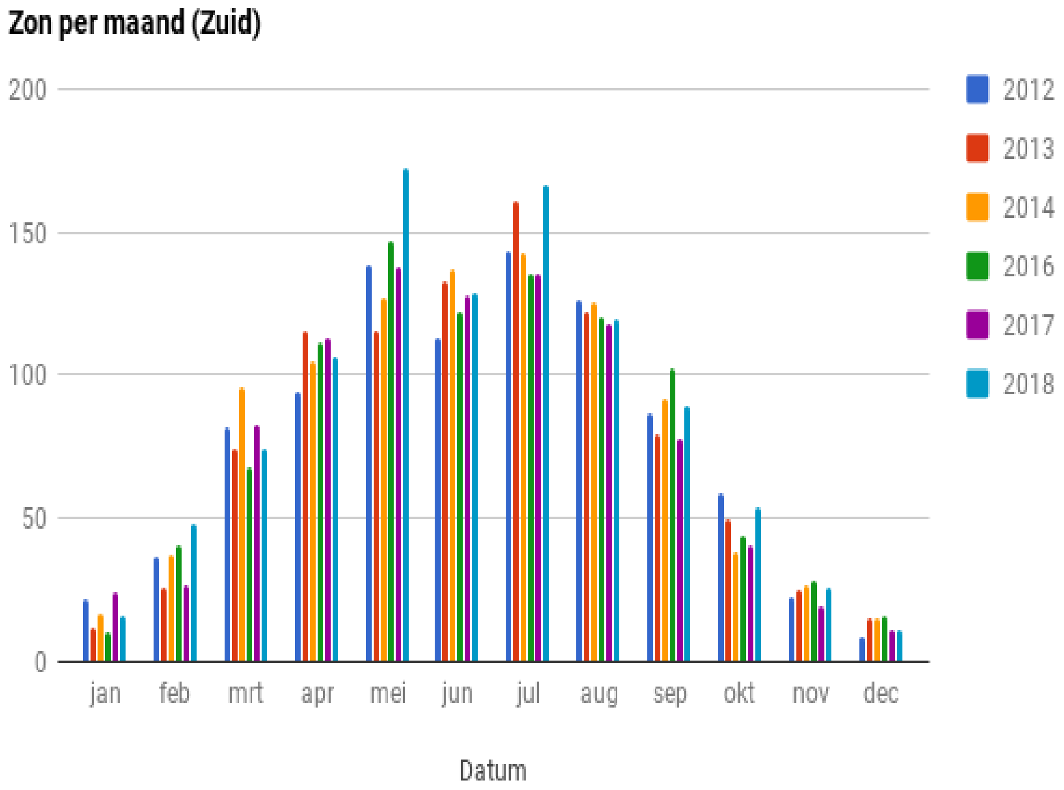
Storage needed to balance supply and demand today

100 TWh gas storage capacity in the Netherlands
= 1 billion Tesla cars with a 100 kWh battery



7,8 million Dutch houses (2017)

Source: Kellner, 2018



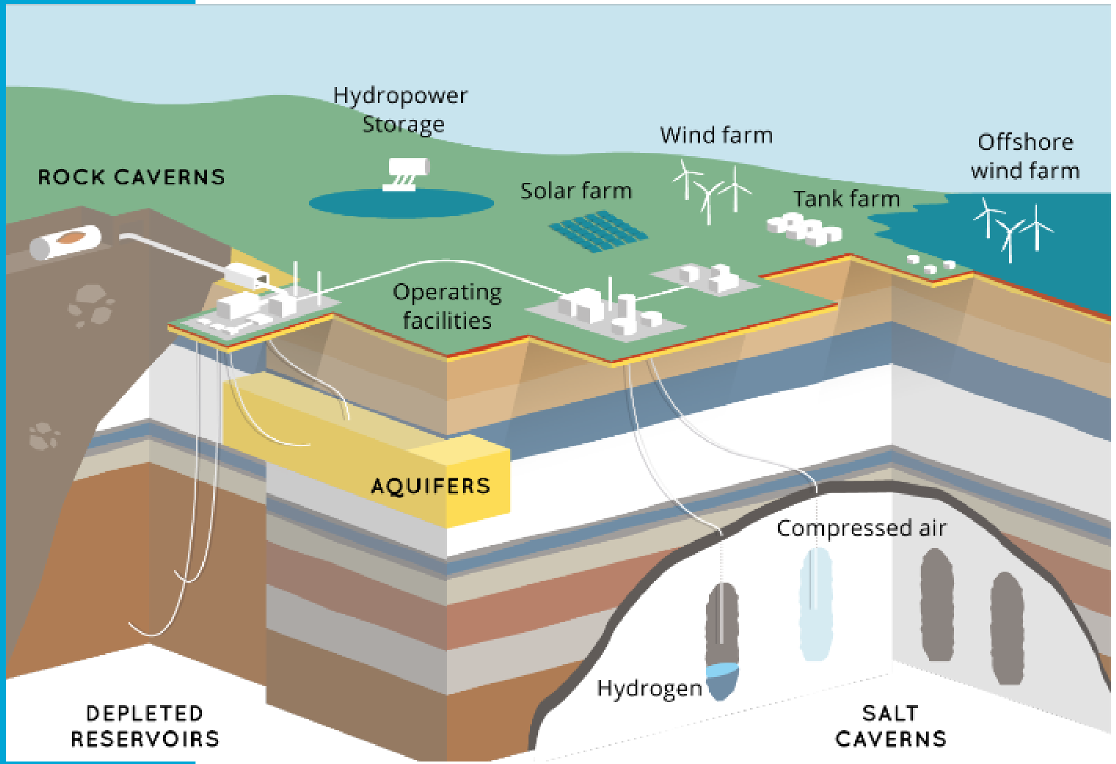
https://thuiszonnepanelen.nl/opbrengst-van-onze-zonnepanelen/

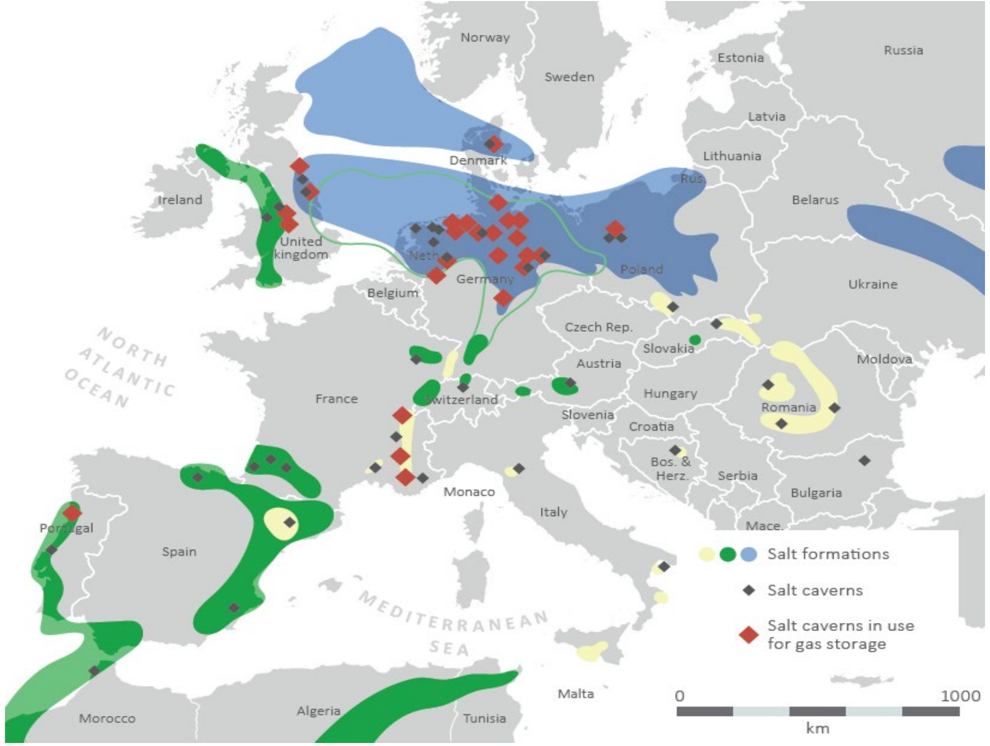
TU Delft

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

Hydrogen storage in Salt Caverns

Salt formations and caverns in Europa





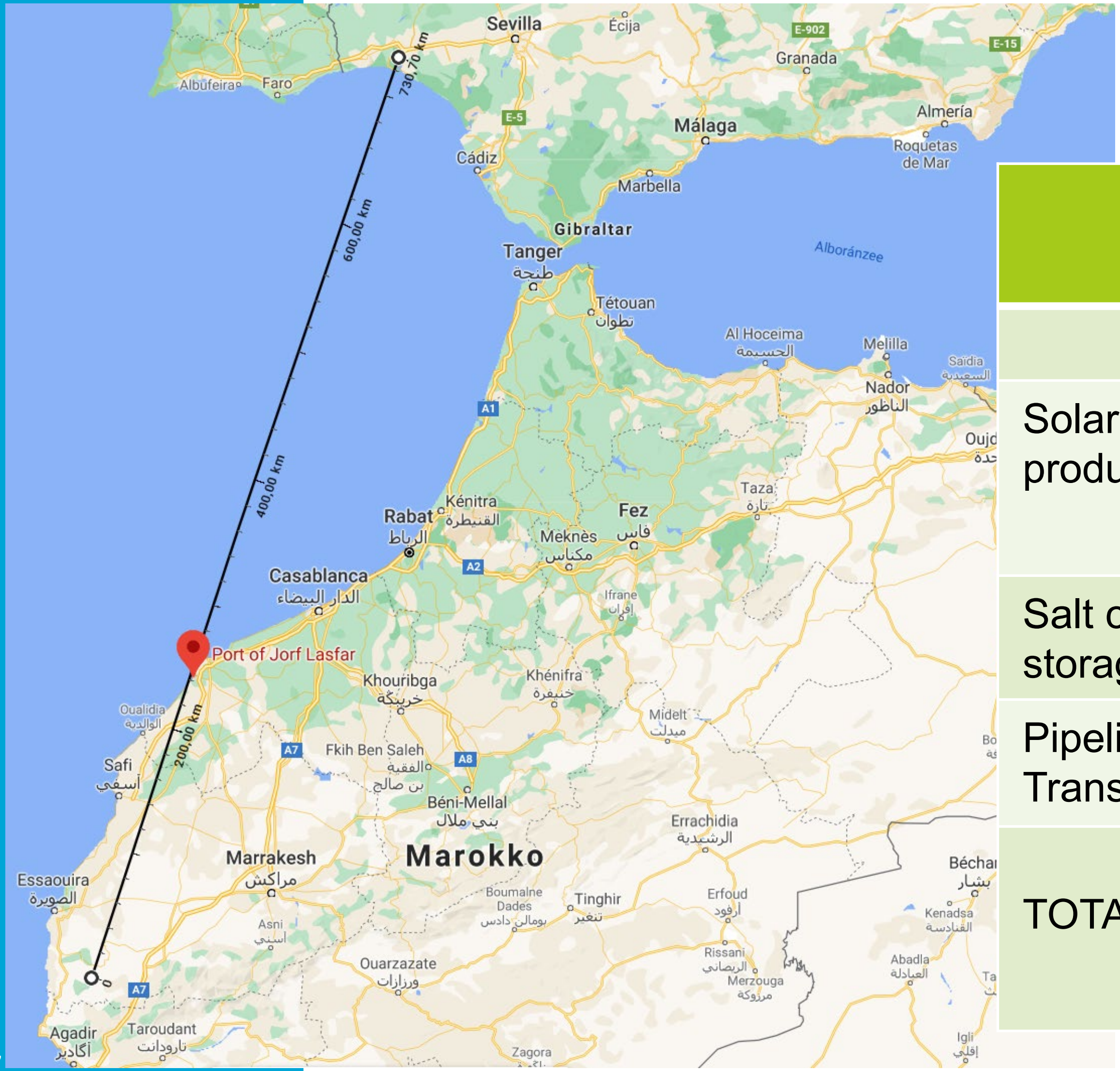
1 salt cavern can contain up to 6,000 ton (= 236.4 GWh HHV) hydrogen, Salt Cavern CAPEX 100 million Euro

Salt Cavern Capex cost less than 0.5 Euro/kWh$_{(HHV)}$ H_2

Battery Capex cost in future 50 Euro/kWh?

TU Delft

Base load solar hydrogen Morocco to Germany

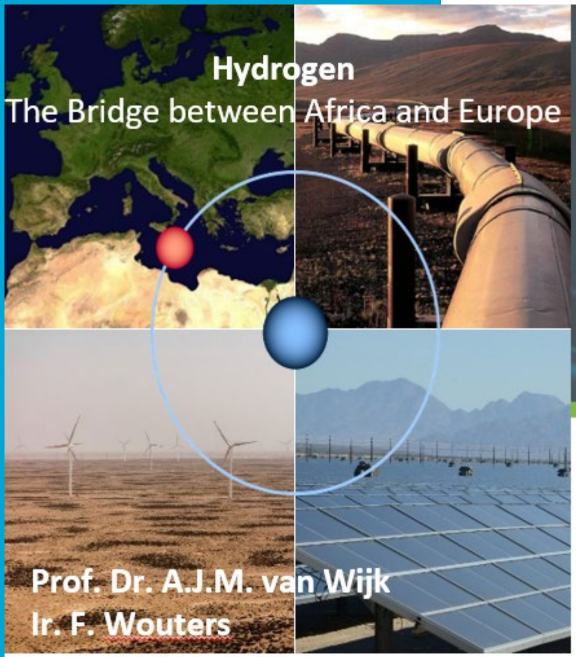


Base load solar H_2 from Morocco to Germany		LCoH €/kg H_2
	Assumptions	
Solar-Hydrogen production	Solar electricity cost = 0.01 €/kWh Full load hours = 2,000 hours/yr Electrolyser efficiency = 50 kWh/kg H_2 100 GW solar = 4 million ton H_2 Required surface = 1,800 km^2	1.0-1.5
Salt cavern storage	Flexible 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		**1.5-2.0 €/kg H_2** =0.038-0.051 €/kWh$H_{2(HHV)}$

TU Delft

Worldwide over 40 countries have released hydrogen strategies

EU Hydrogen strategy for a climate-neutral Europe (8 July2020)



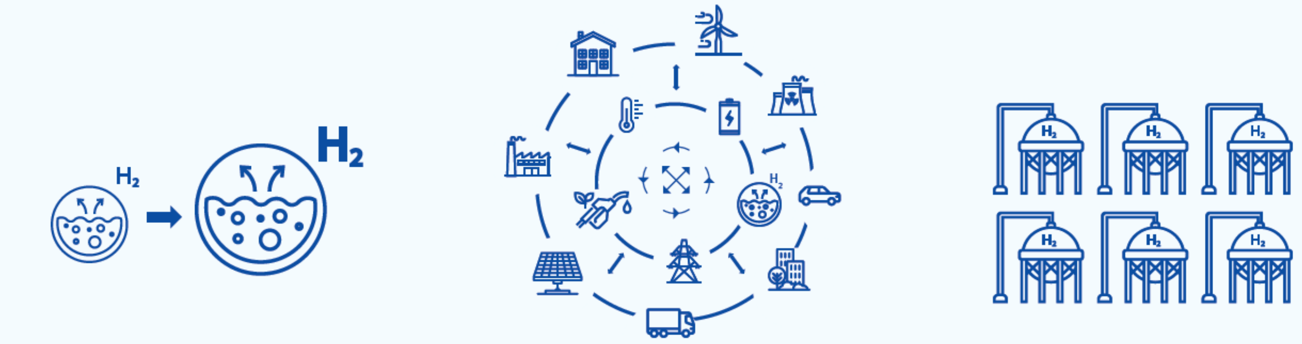
September 2019

March 2020

http://profadvanwijk.com/hydrogen-the-bridge-between-africa-and-europe/

https://hydrogeneurope.eu/sites/default/files/Hydrogen%20Europe_2x40%20GW%20Green%20H2%20Initative%20Paper.pdf

The path towards a European hydrogen eco-system step by step :



Today - 2024

From now to 2024, we will support the **installation of at least 6GW of renewable hydrogen electrolysers in the EU**, and the production of **up to 1 million tonnes** of renewable hydrogen.

2025 - 2030

From 2025 to 2030, hydrogen needs to **become an intrinsic part of our integrated energy system**, with at least 40GW of renewable hydrogen electrolysers and the production of **up to 10 million tonnes** of renewable hydrogen in the EU.

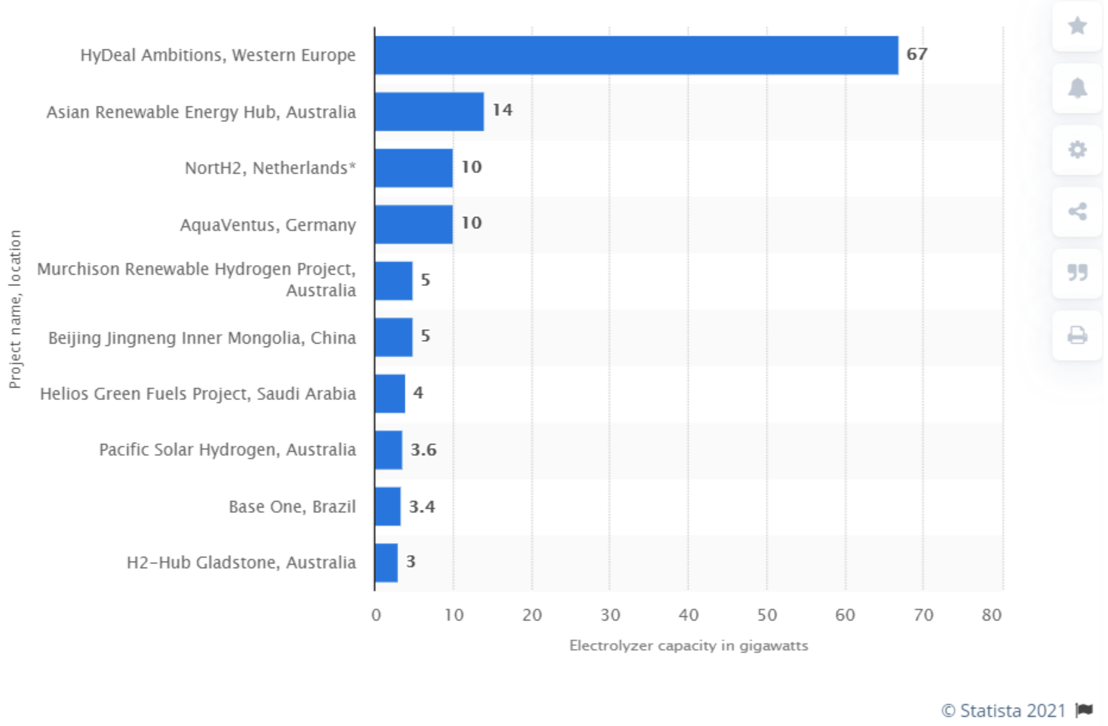
2030 -

From 2030 onwards, **renewable hydrogen will be deployed at a large scale** across all hard-to-decarbonise sectors.

https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

TU Delft

Large scale power to hydrogen projects worldwide develop at an ever increasing pace



The global green hydrogen pipeline of large-scale projects has a combined capacity of nearly 140 GW, April 2021

https://www.statista.com/statistics/1011849/largest-planned-green-hydrogen-projects-worldwide/

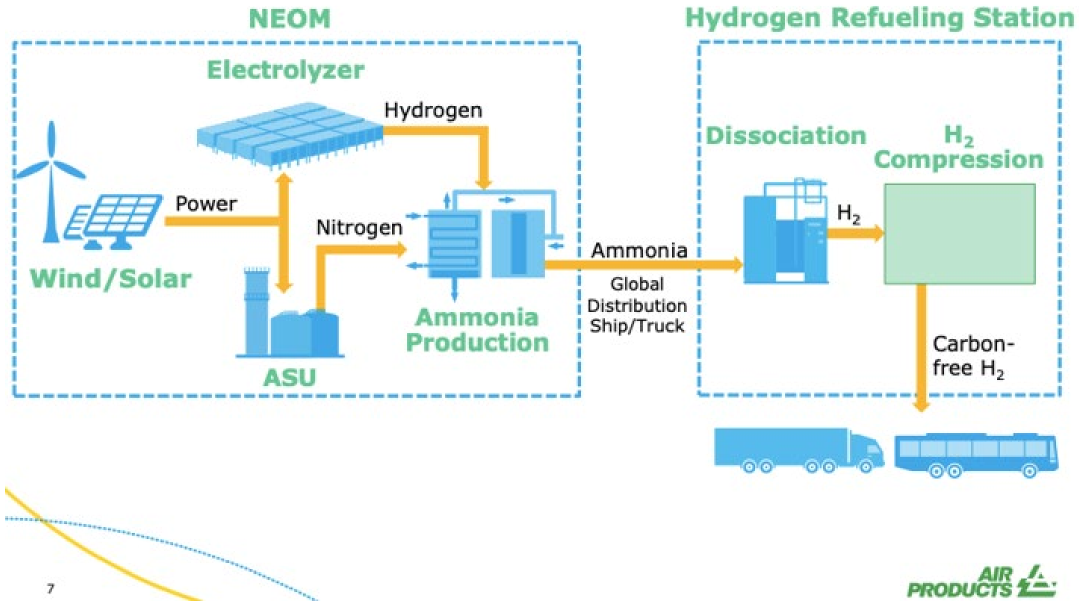
End of June 2021, the gigawatt-scale pipeline alone adds up to about 207GW across 24 projects

https://www.rechargenews.com/energy-transition/global-green-hydrogen-pipeline-exceeds-200gw-heres-the-24-largest-gigawatt-scale-projects/2-1-933755

TU Delft

NEOM Solar-Wind Hydrogen-Ammonia

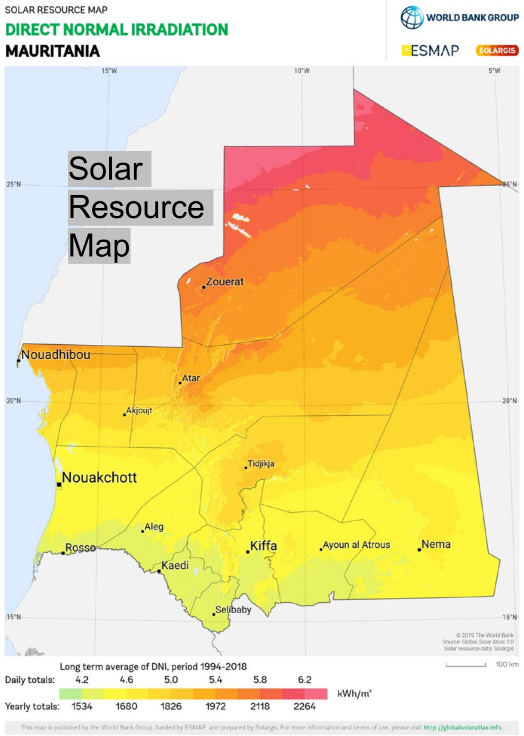
- Consortium: NEOM, ACWA Power, Air Products
- Announced 7 July 2020
- 5 billion dollar investment
- 2025 Operational
- 4 GW Solar, Wind, Storage, 2 GW Electrolyser
- Wind speed 10.3 m/s
- 650 ton Hydrogen per day
- 1.2 million ton Ammonia per year

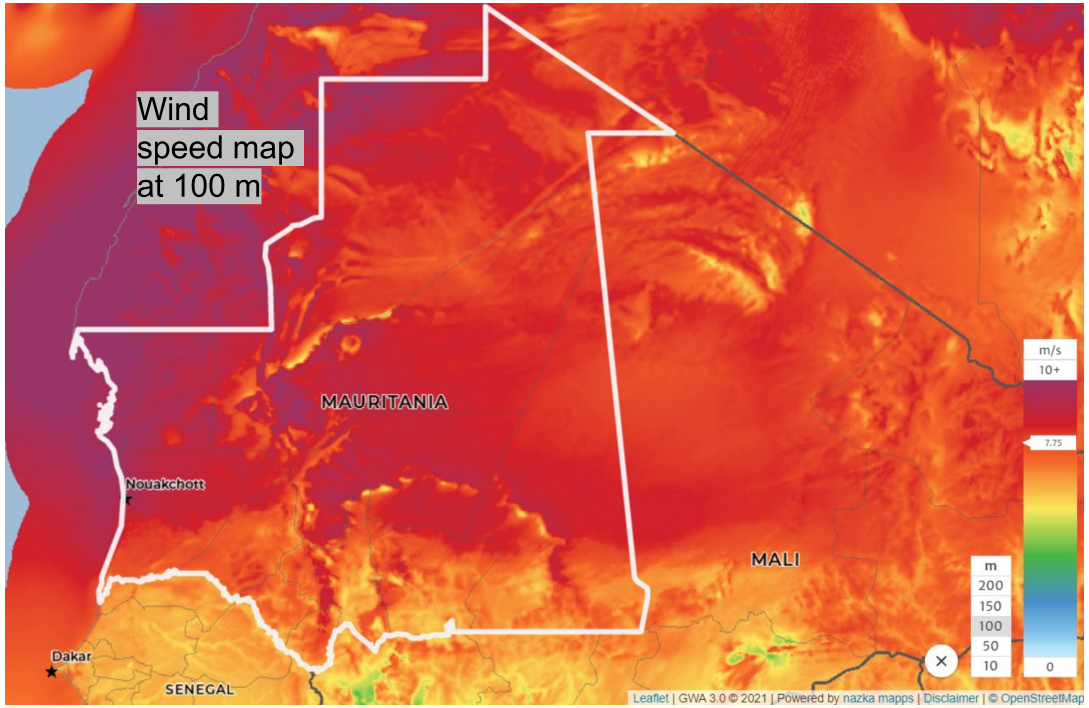


TU Delft

Mauritania and CWP Global sign MoU for a US$40 Billion Green Hydrogen project (30-5-2021)

- Project ‘AMAN’
- 30 GW Solar and Wind Power to hydrogen
- North of Mauritania excellent solar and wind resources
- Desert size 8,500 km^2, 0,8% Mauritania (20% the Netherlands, 2,4% Germany)
- Production of electricity and drinking water for local market
- Production of hydrogen and ammonia for global market





Kazahkstan 45 GW wind/solar to power 30 GW electrolysers

- 45 GW Solar and Wind
- 30 GW electroloysers
- 3 million ton Hydrogen per year
- Export to EurAsia
- Local use for production of ‘high value green products’ such as Ammonia.

- German company Svevind Energy, investor and project developer, signed MoU with Kazakh Invest National Company
- Signed 28 June 2021

TU Delft

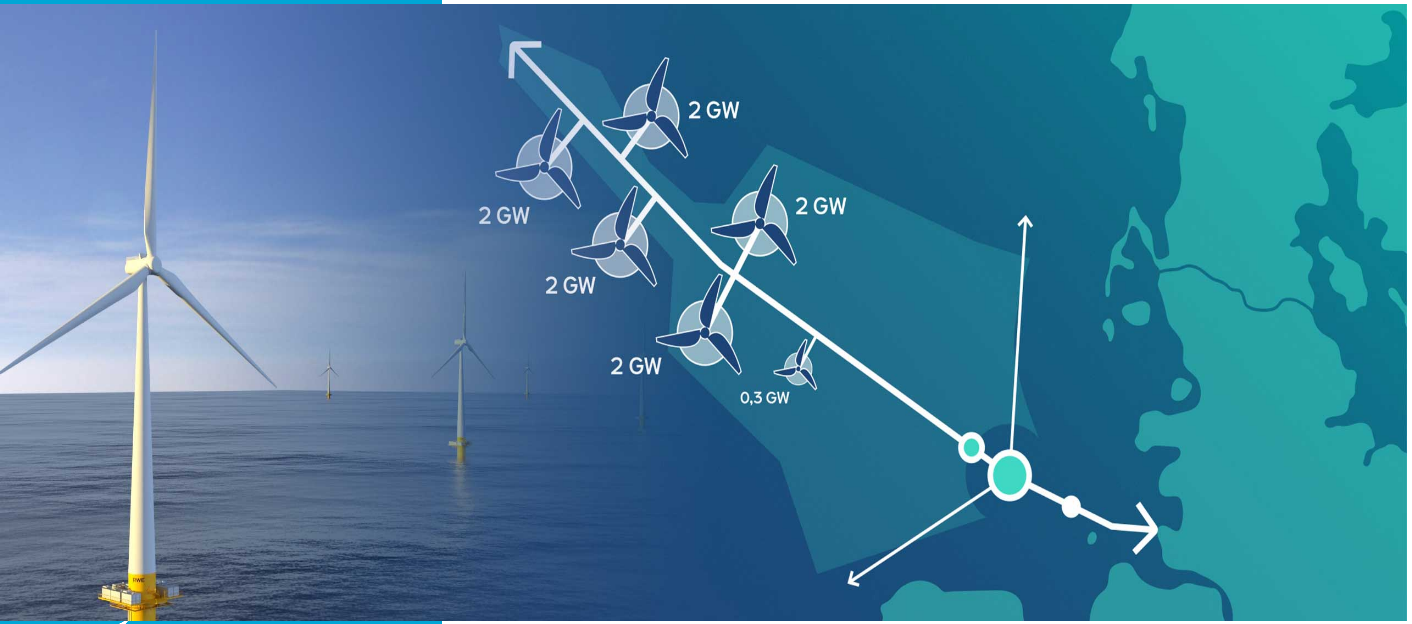
Offshore wind hydrogen projects starting off

Aquaventus and Aquaductus (Germany)

- 10 GW offshore wind Hydrogen
- 1 million ton hydrogen (= 5.000 full load hours)
- Operational 2035
- RWE, Equinor, Orsted, Boskalis + others
- Pipeline: Gascade, Gasunie, RWE, Shell

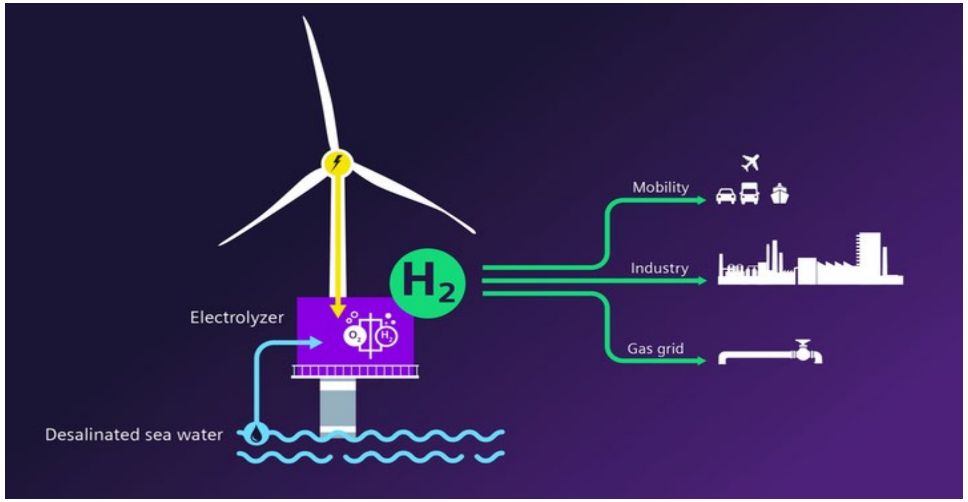
NortH2 (Netherlands)

- 10 GW offshore wind Hydrogen
- 1 million ton hydrogen (= 5.000 full load hours)
- 3-4 GW onshore electrolyser 2030 in Eemshaven
- 6-7 GW offshore electrolyser <2040
- Shell, Gasunie, Groningen Seaports, Equinor, RWE+ others
- Pipeline: Connect to Hydrogen backbone + salt cavern storage



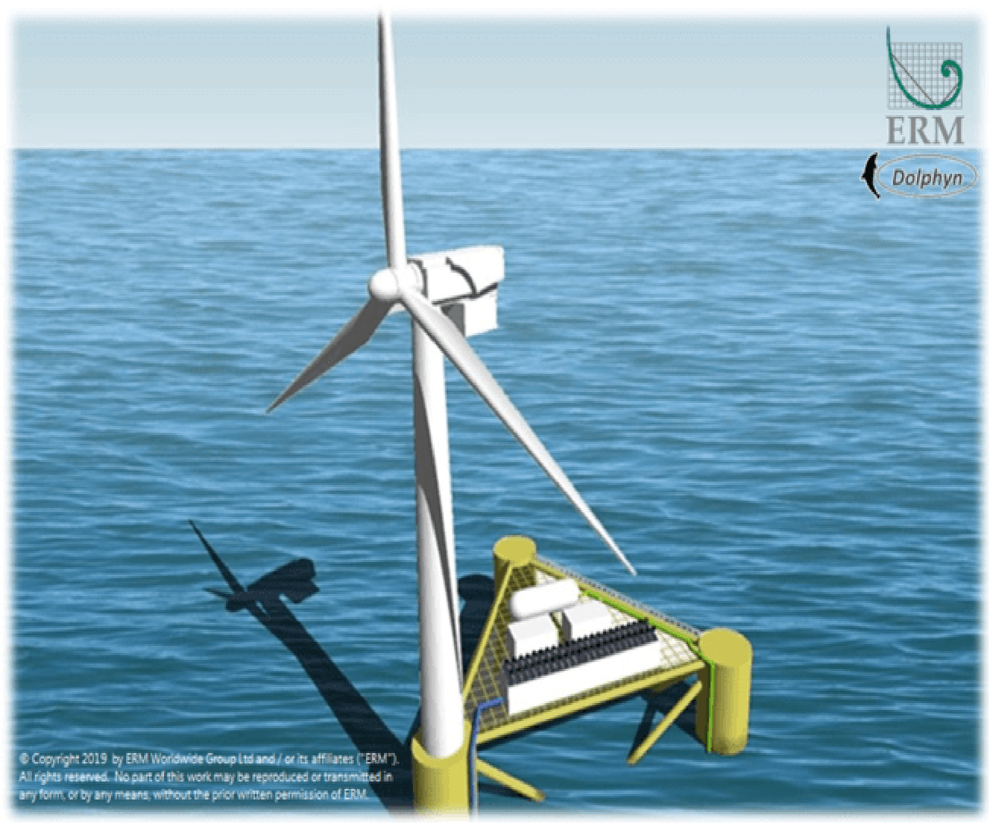
TU Delft

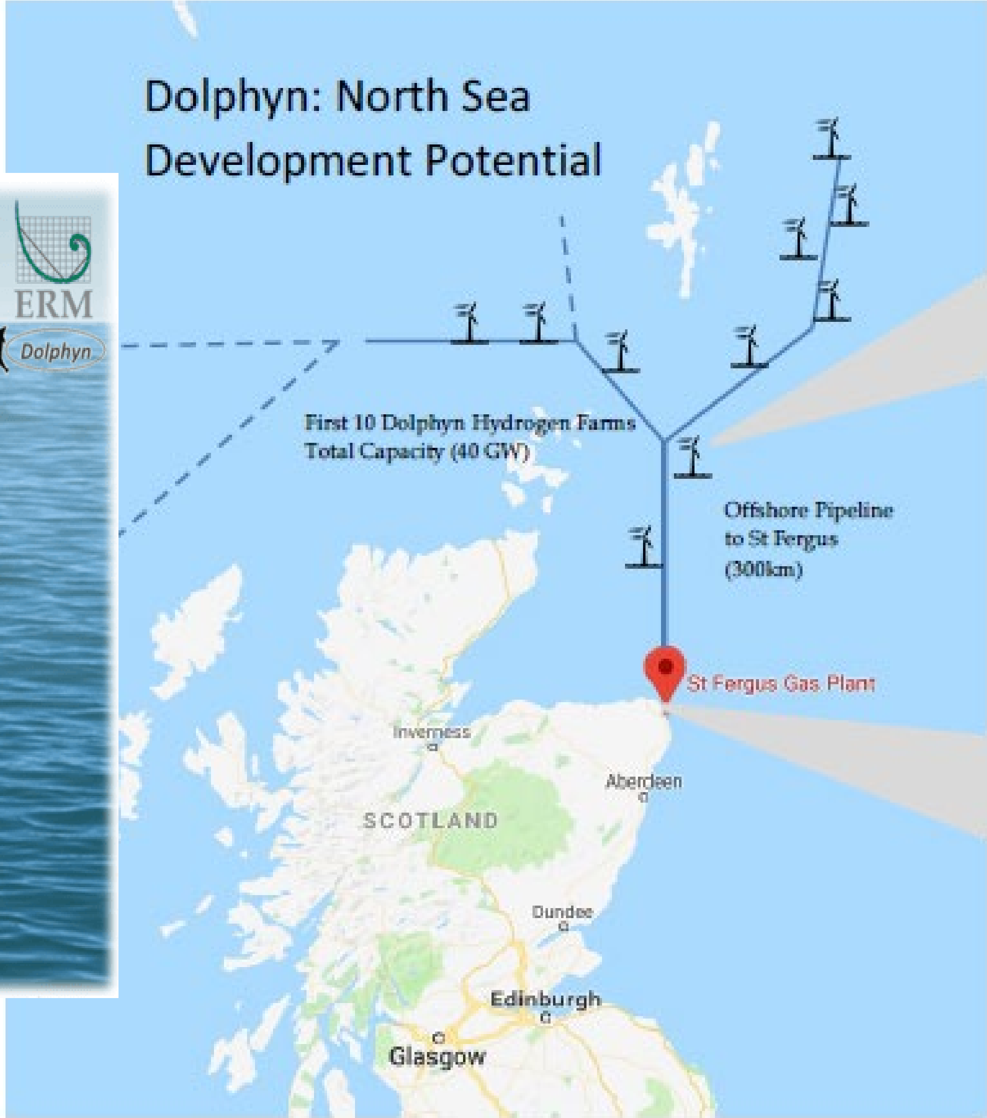
Offshore wind hydrogen



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

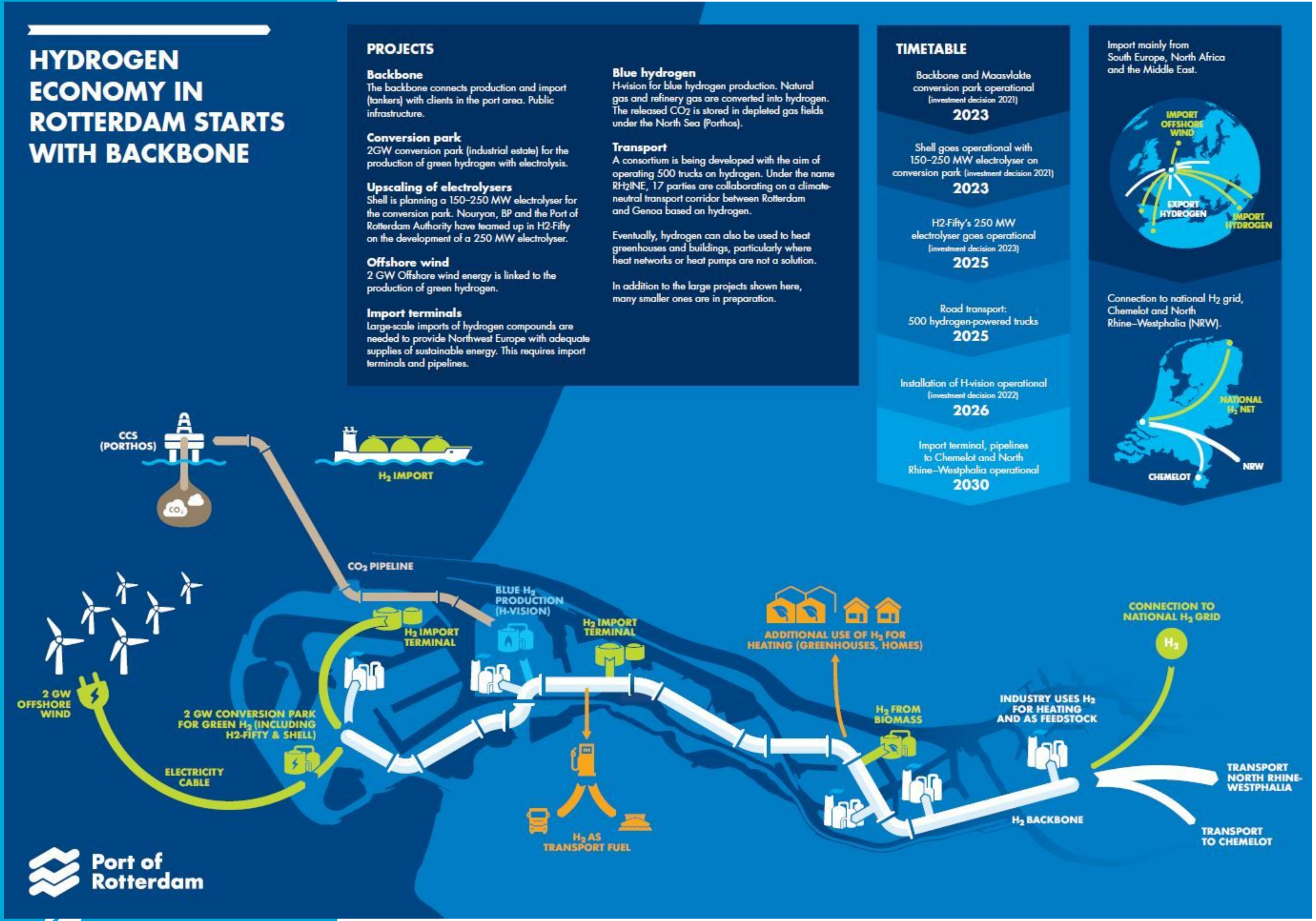
Dolphyn North Sea Offshore wind Hydrogen 10x4GW

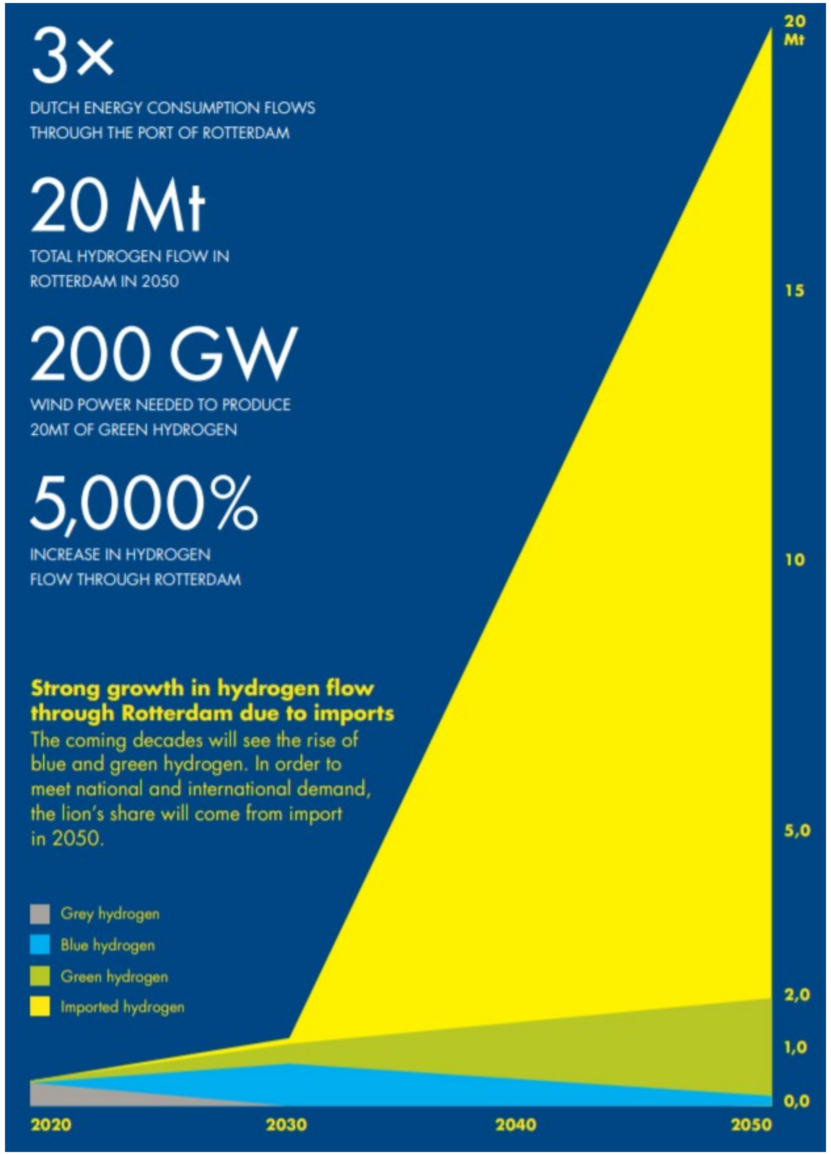




ERM; David Caine, Molly Iliffe, Kevin Kinsella, Widya Wahyuni, Laura Bond
Dolphyn Hydrogen; Phase 1 - Final Report,
9 October 2019
UK Department for Business, Energy and Industrial Strategy

Port of Rotterdam Hydrogen Strategy

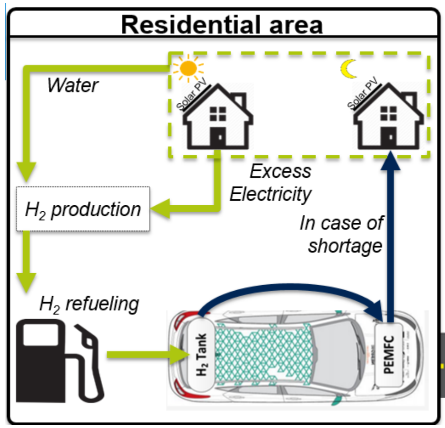




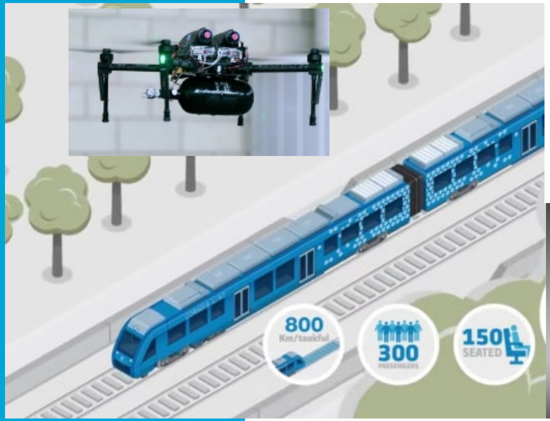
Hydrogen Markets

Industry Feedstock/HT Heat

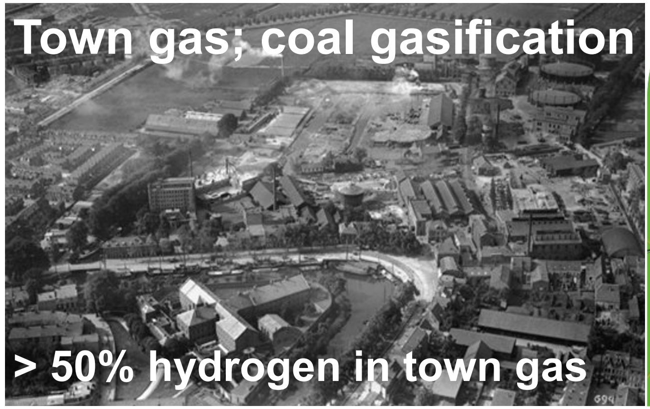
Electricity Balancing



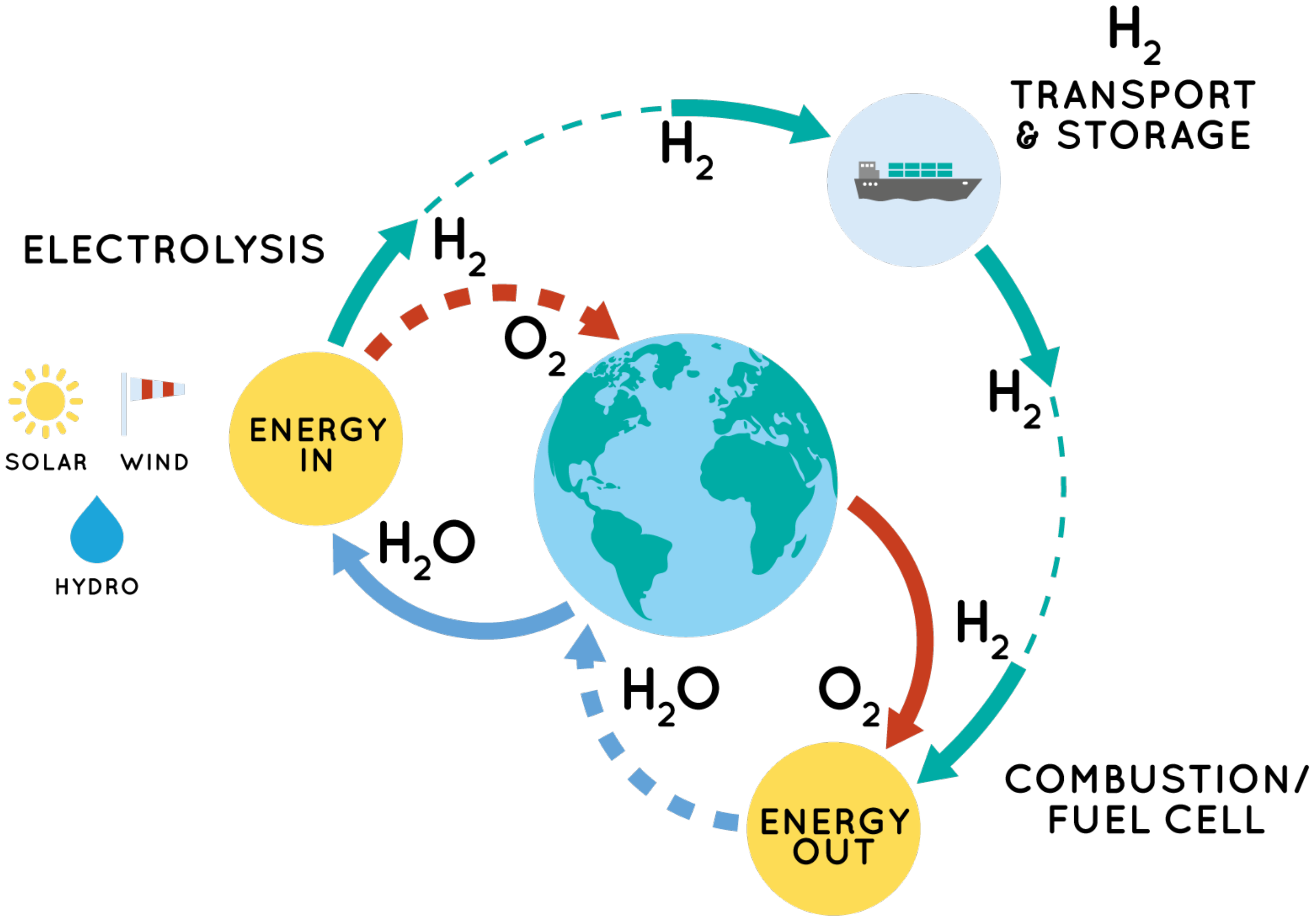
Transport



Heating

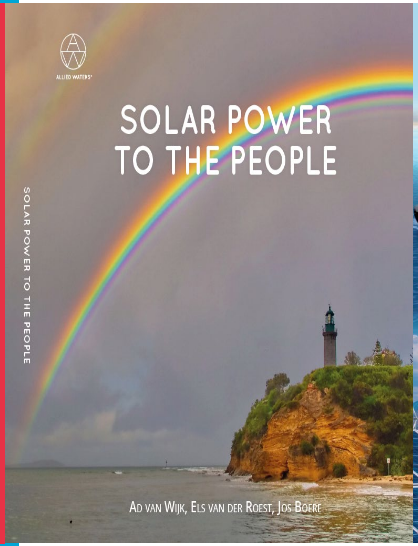


The Hydrogen Cycle

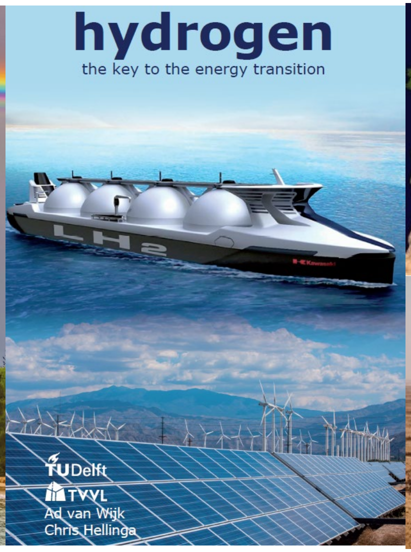


Further Reading
www.profadvanwijk.com

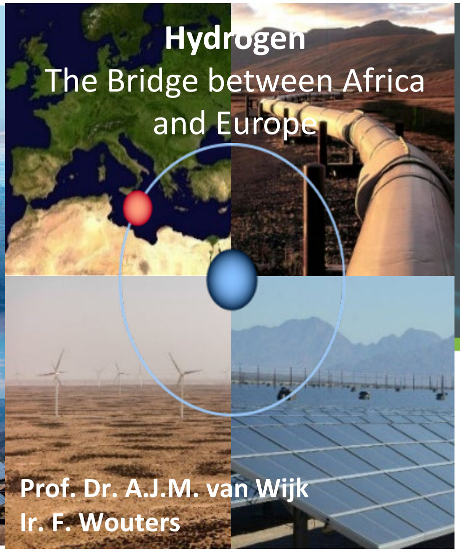
April 2017



November 2017



May 2018



September 2019

April 2020

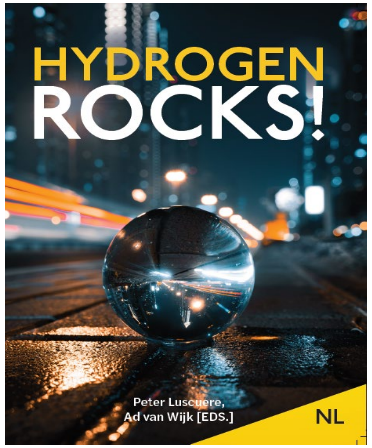
April 2021

Waterstof voor gebouwverwarming

Naar 500.000 woningen op waterstof in 2030

Chris Hellinga
Ad van Wijk

May 2021



July 2021

TUDelft