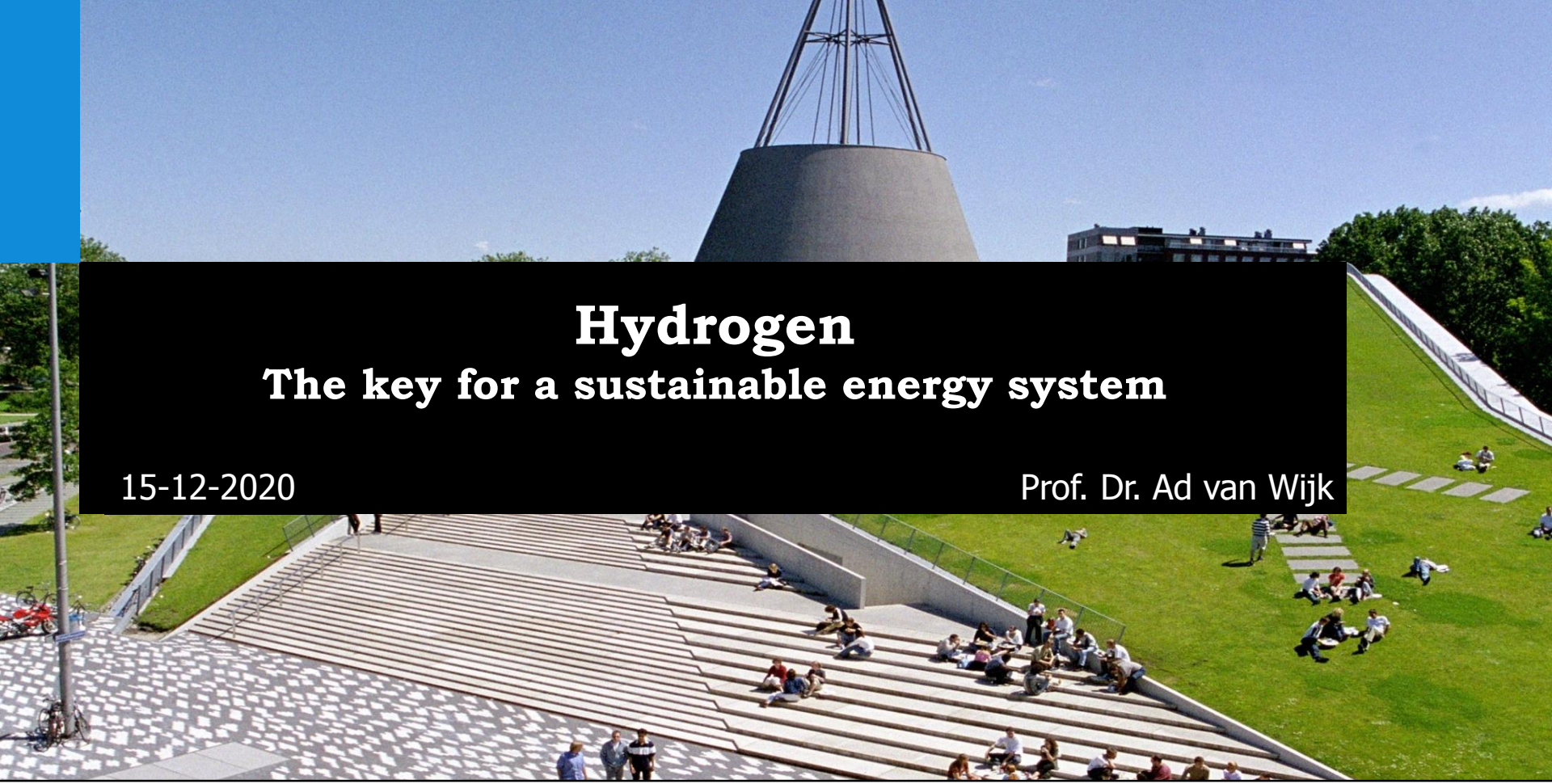


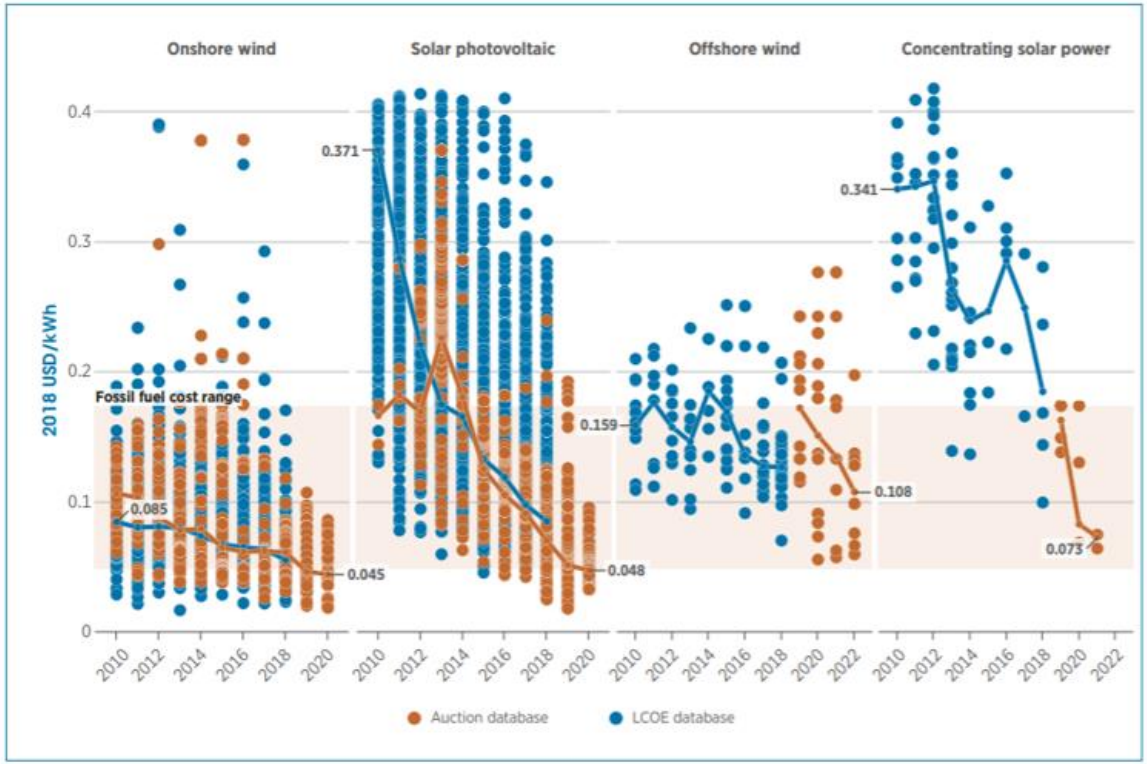
Hydrogen

The key for a sustainable energy system

15-12-2020

Prof. Dr. Ad van Wijk

Levelized Cost of Electricity Solar and Wind

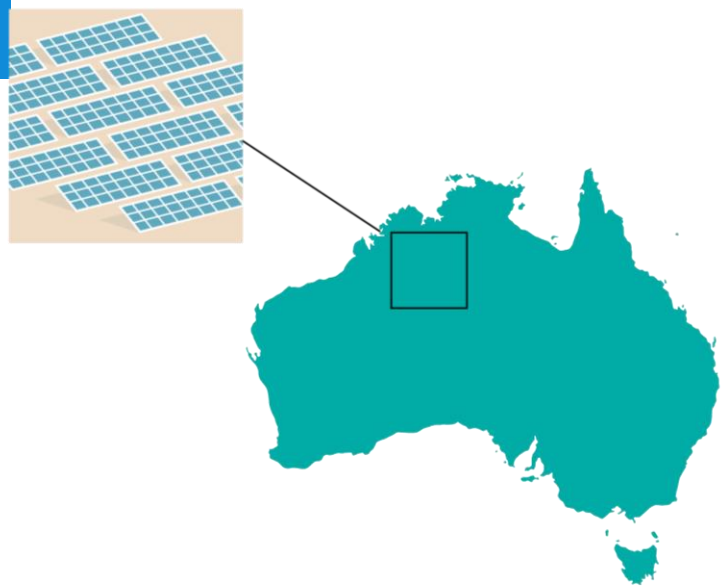


Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted-average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

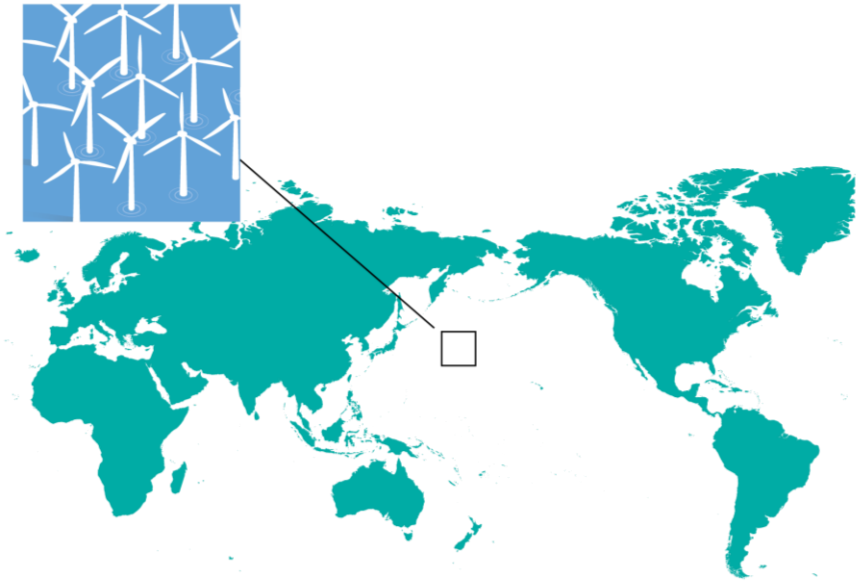
IRENA, "Renewable power generation costs in 2018," https://www.irena.org/

Mohammed Bin Rashid Al Maktoum Solar Park in Dubai; 2 GW ready expanding to 5 GW

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



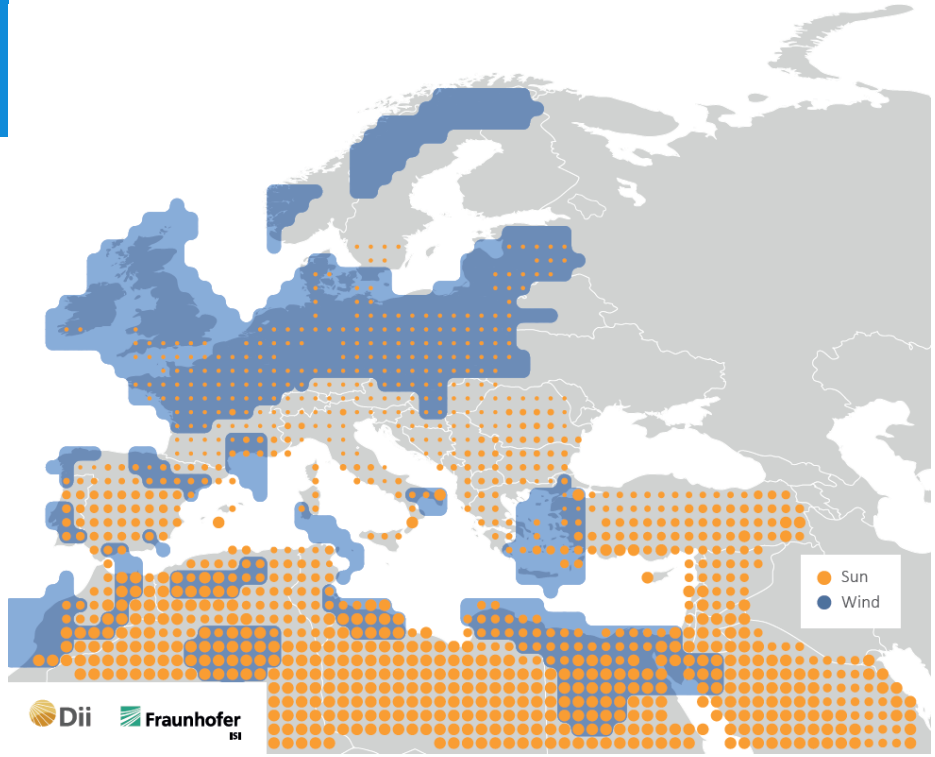
10% SOLAR AUSTRALIA



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

Renewable Energy Resources; Europe, North Africa and Middle East

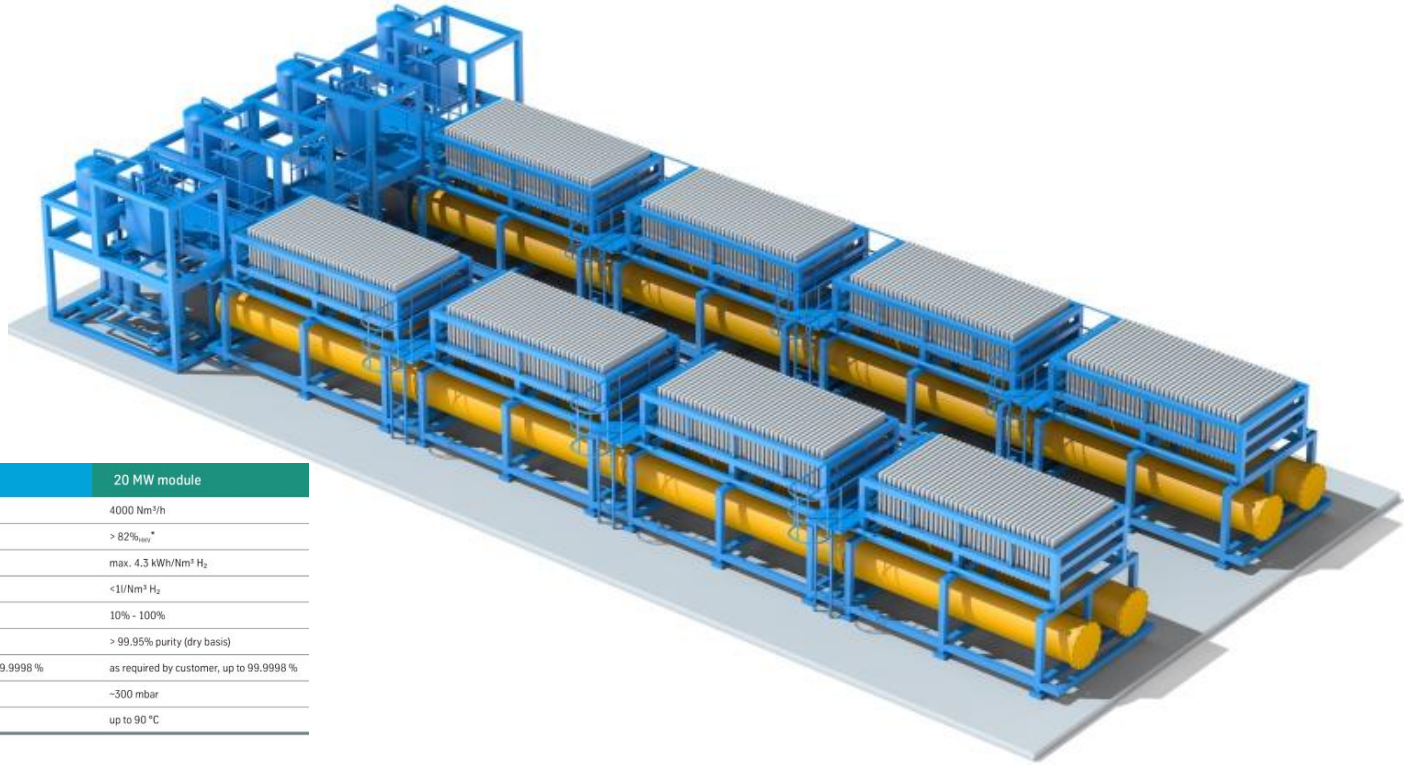


Abu Dhabi
2 GW Solar PV July 2020
Lowest bid USD 1.35 cents/kWh

Portugal
0.7 GW Solar PV August 2020
Lowest bid Euro 1.12 cents/kWh

20 MW Alkaline Electrolyser

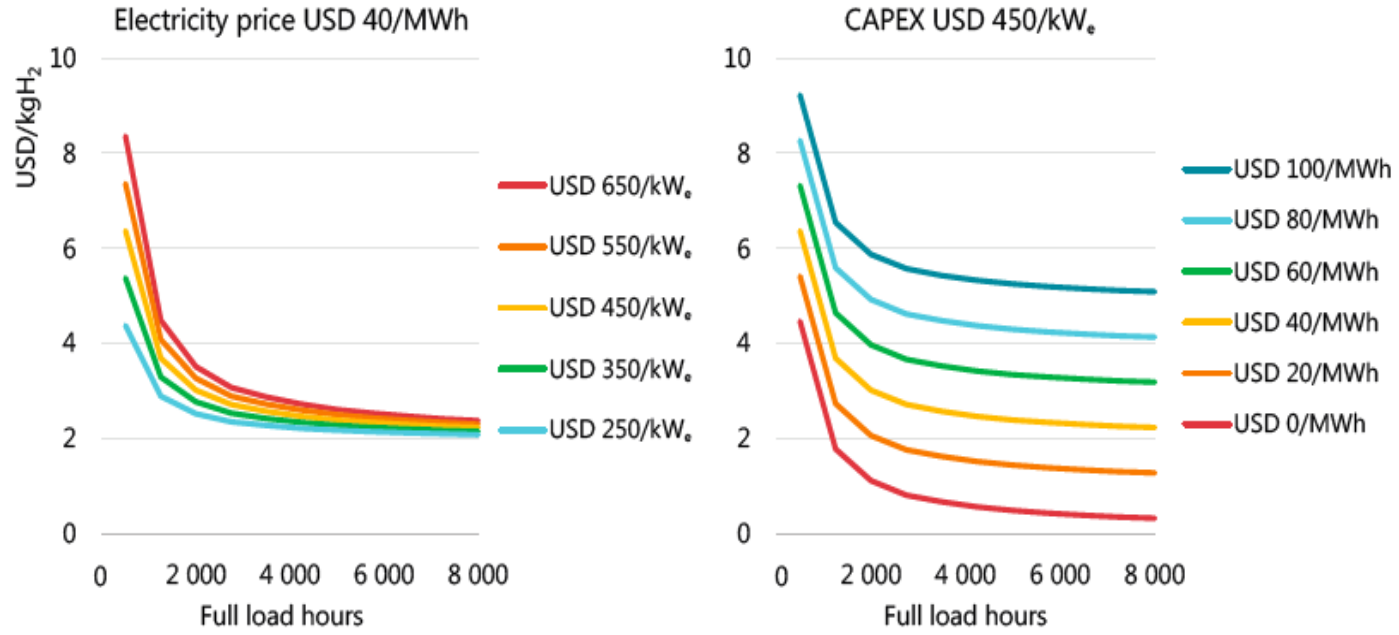
ThyssenKrupp



	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%.

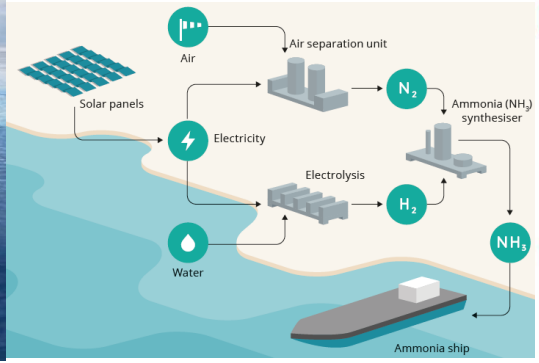
Future levelized cost of hydrogen production by operating hour for different electrolyser investment costs (left) and electricity costs (right), from *The Future of Hydrogen (IEA 2019)* (LHV efficiency 69% is HHV efficiency 81%)

Hydrogen, like electricity, is an energy carrier

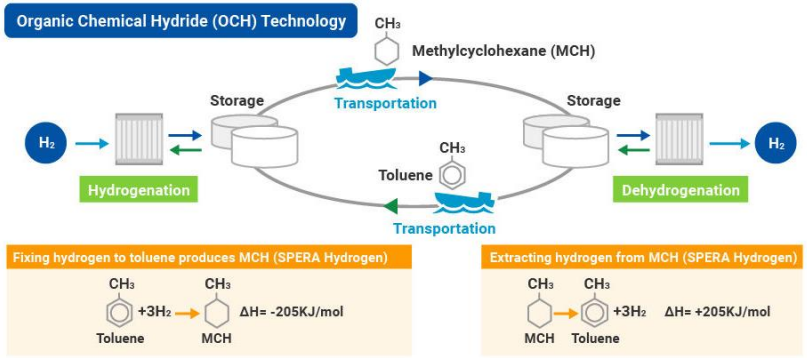
Source	Process/Technology	Maturity	Output	'Colour' of Hydrogen
Natural gas	Steam methane reforming	Mature	$H_2 + CO_2$	**Grey or blue**,
	Auto-thermal reforming	Mature	$H_2 + CO_2$	50-90% of CO_2 can be captured + stored
	Thermal Pyrolysis	First plant 2025	$H_2 + C$	**Turquoise**, CO_2 emissions depend on the source for electricity production
Coal	Gasification	Mature	$H_2 + CO_2 + C$	**Brown or blue**,
	Underground coal gasification	Projects exist	$H_2 + CO_2$	50-90% of CO_2 can be captured + 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			
	Alkaline	Mature	$H_2 + O_2$	**Shades of grey to green** depend on the source for electricity production
	PEM	Near Maturity	$H_2 + O_2$	
	SOEC	Pilot Plants	$H_2 + O_2$	
Sunlight+Water	Photoelectrochemical	Laboratory	$H_2 + O_2$	**Green**

Hydrogen Transport by Ship

Liquid Hydrogen



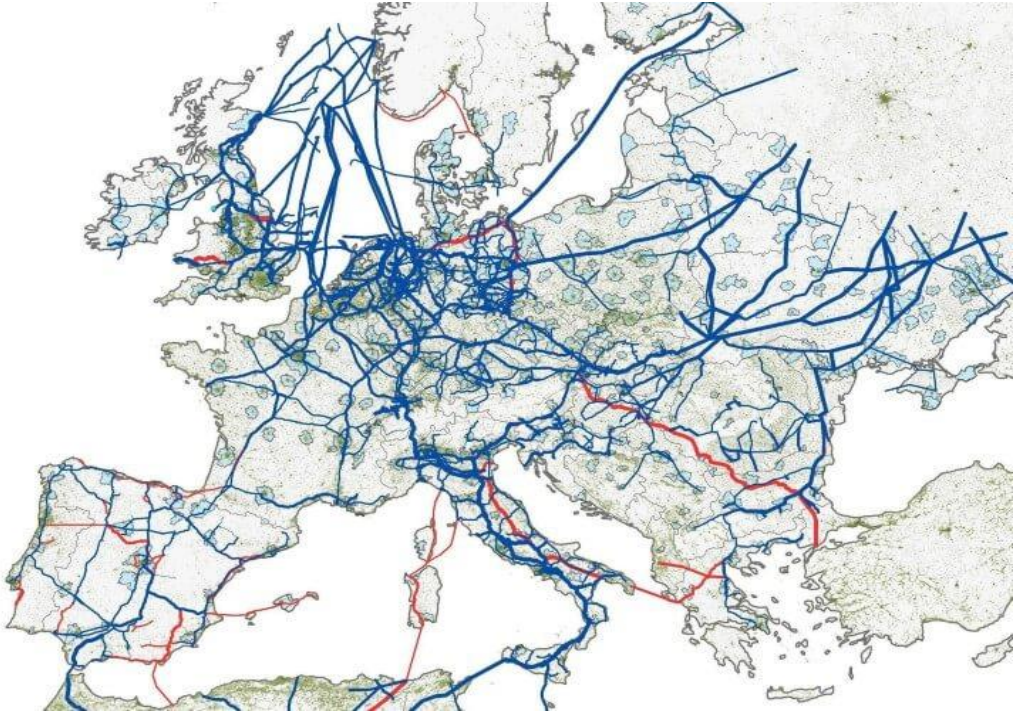
Ammonia



LOHC
Liquid Organic Hydrogen Carrier

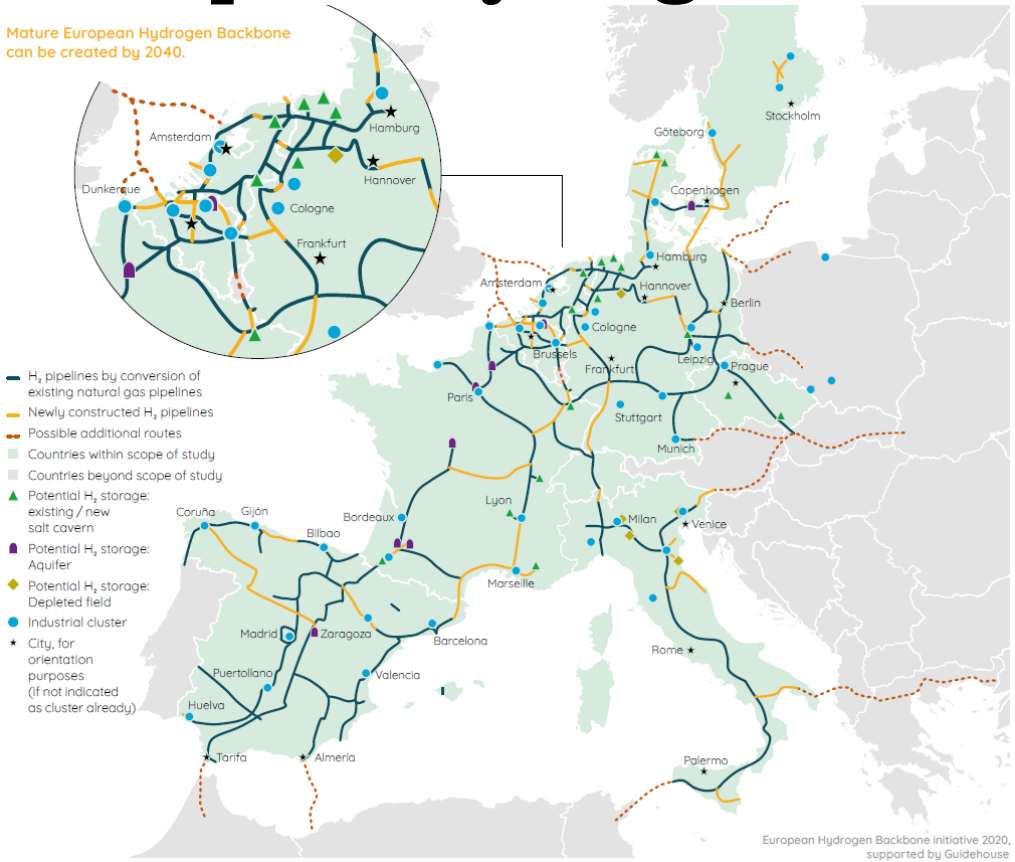
Gas Infrastructure in Europe and from North-Africa

Transport pipeline capacity 15-25 GW



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

European Hydrogen Backbone



Proposed by 11 Gas TSO's July 2020

Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga

Pipeline capacities: 5-15 GW

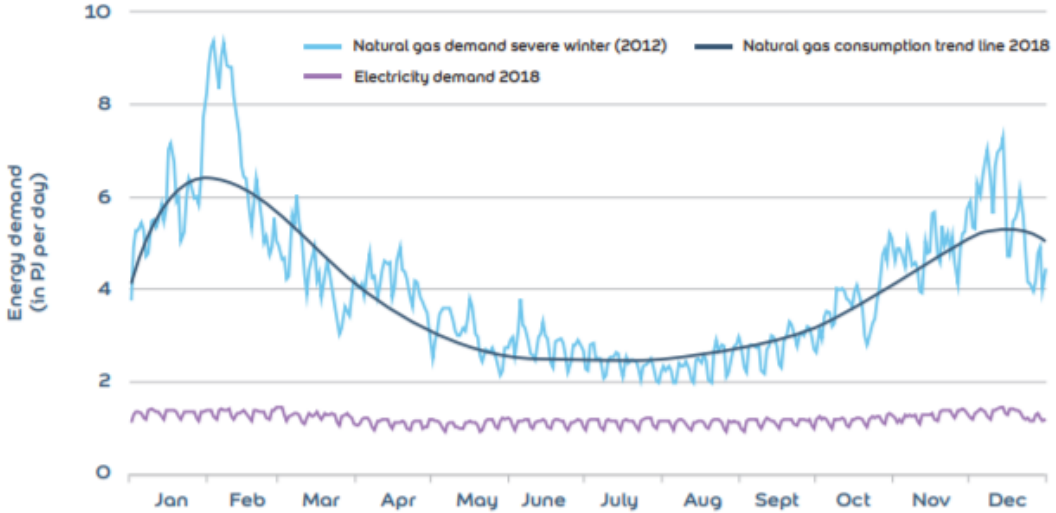
Transport cost:

Euro 0.13 per kg H_2 per 1,000 km

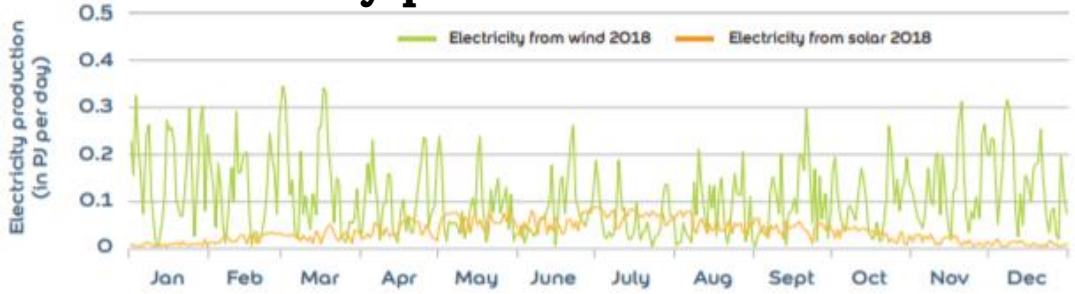
= Euro 0.0033 per kWh H_2 per 1,000 km

https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/

Gas and Electricity consumption in the Netherlands 2018

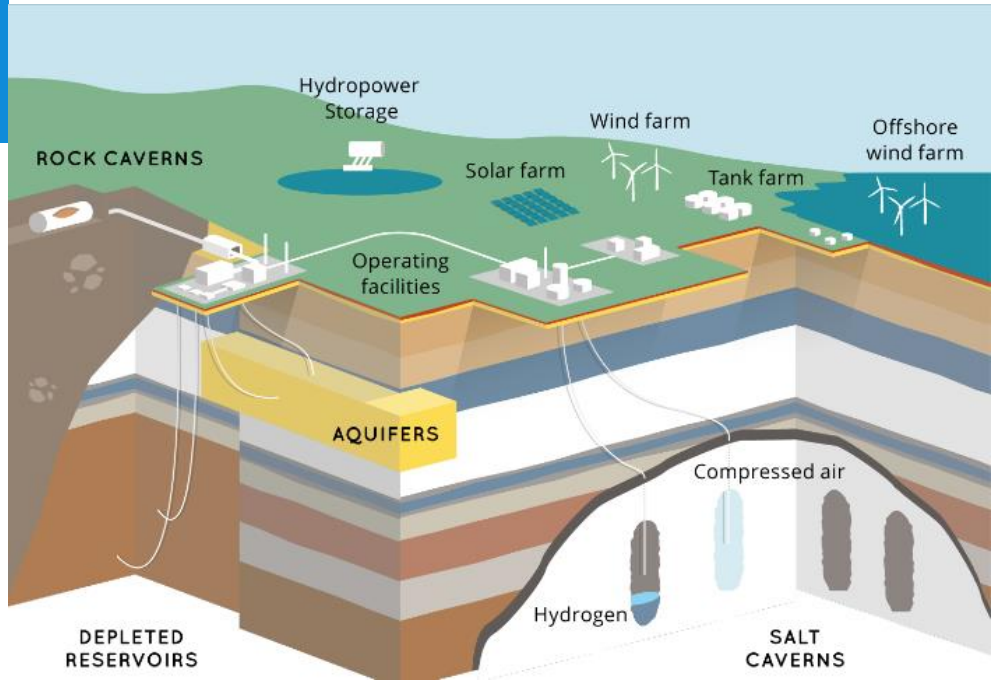


Solar and Wind electricity production in the Netherlands 2018

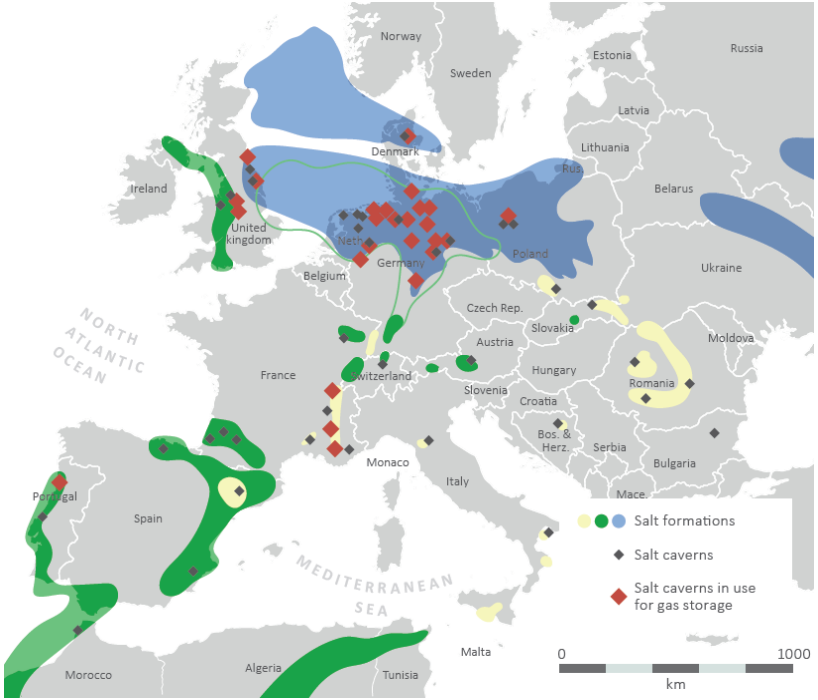


https://www.energieinnederland.nl/wp-content/uploads/2020/02/EBN-INFOGRAPHIC-2020-ENG.pdf

Hydrogen storage in Salt Caverns



Salt formations and caverns in Europa

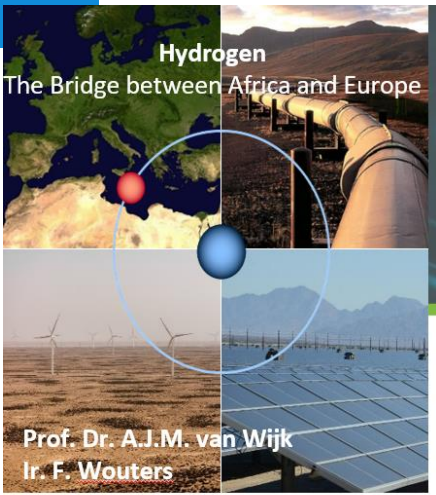


1 salt cavern can contain up to 6,000 ton (= 236.4 GWh HHV) hydrogen, Salt Cavern CAPEX 100 million Euro
For comparison, with 100 Euro per kWh battery storage CAPEX, Total battery CAPEX would be 23.6 billion Euro

Characteristics for 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	10-35 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

A Hydrogen strategy for a climate-neutral Europe (8 July 2020)



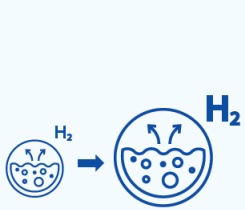
September 2019

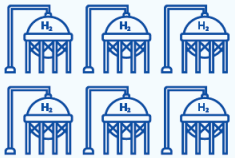
http://profadvanwijk.com/hydrogen-the-bridge-between-africa-and-europe/

March 2020

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.

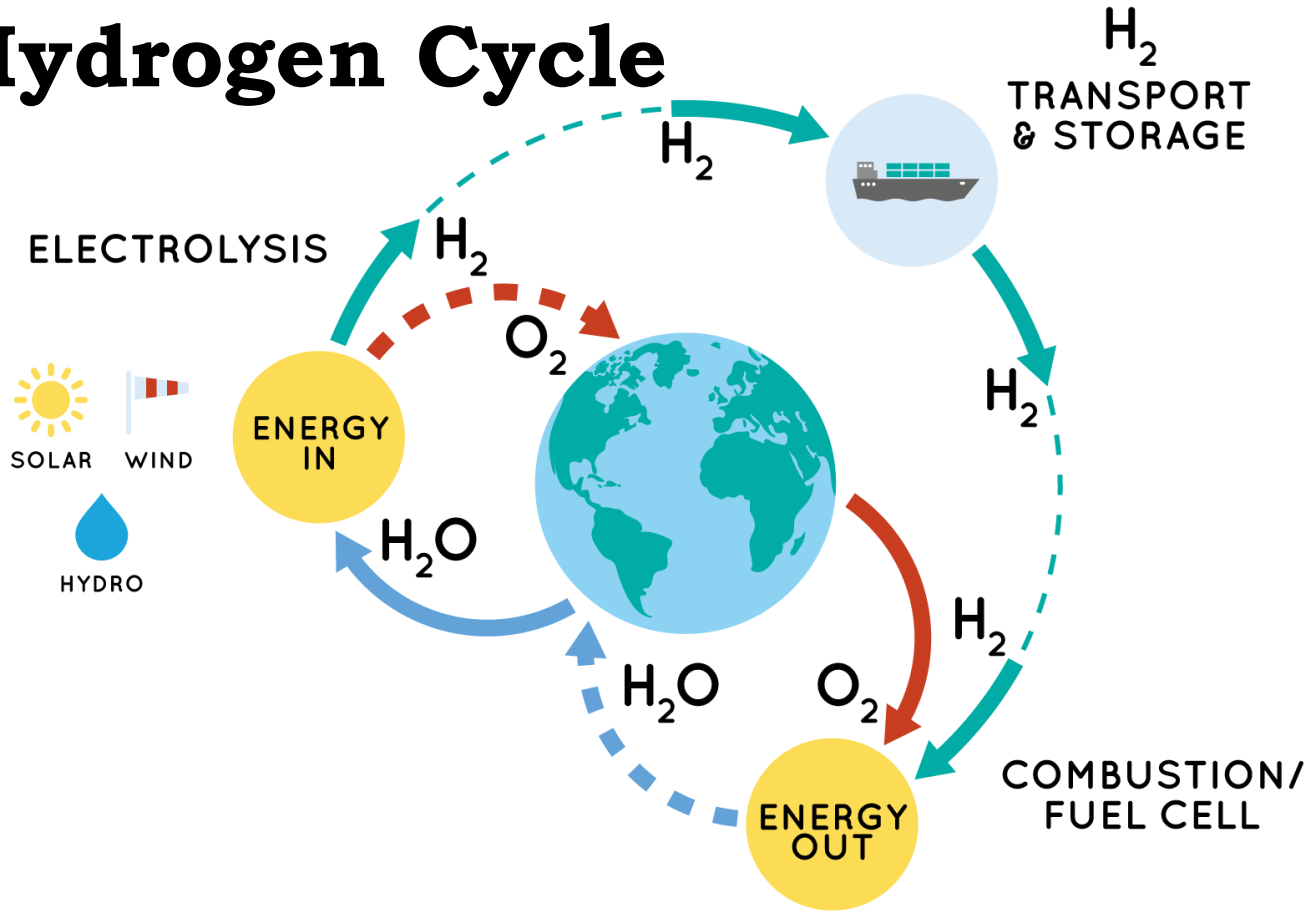
2025 - 2030

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.

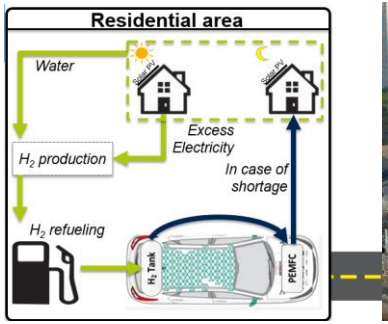
The Hydrogen Cycle



Hydrogen Markets

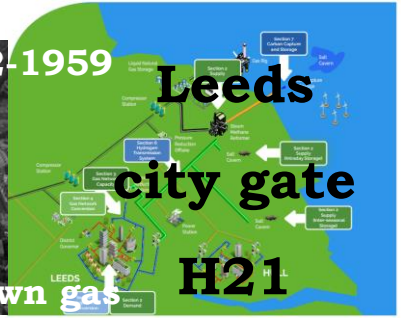
Industry

Electricity Balancing



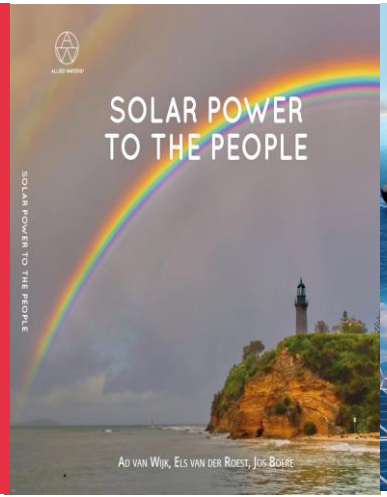
Transport

Heating

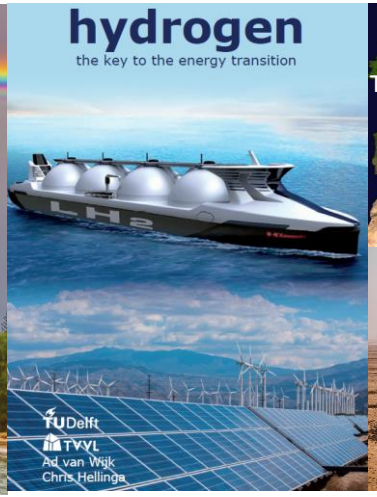


Further reading
www.profadvanwijk.com

April 2017



November 2017



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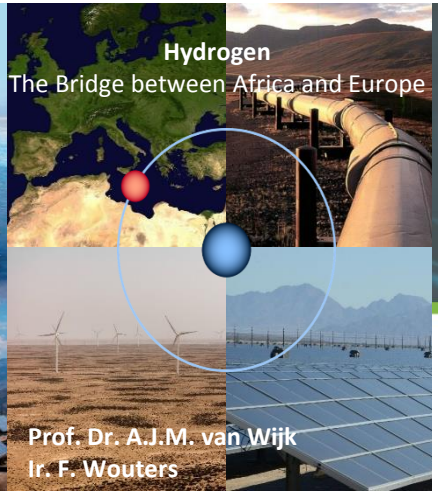

September 2019

April 2020