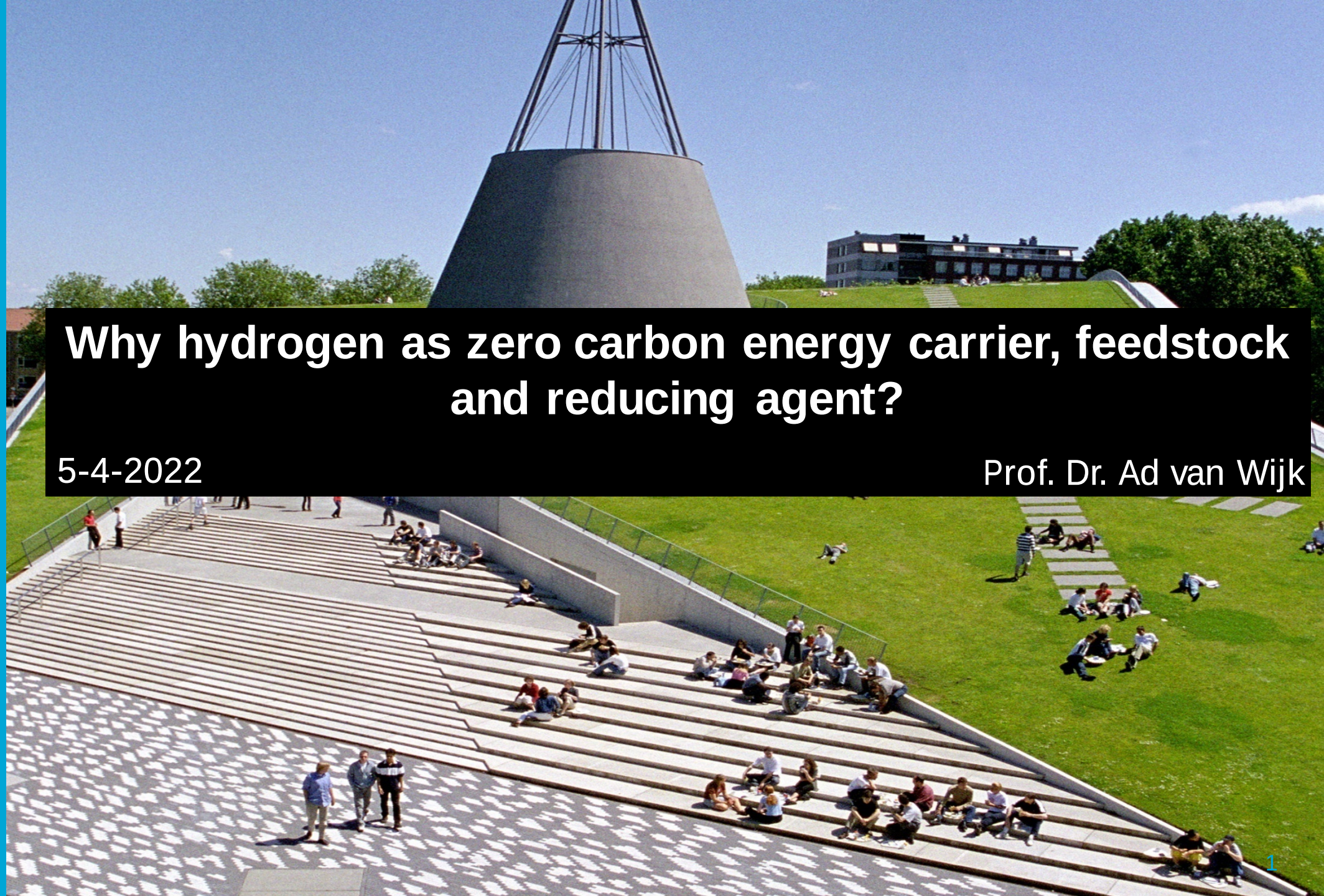


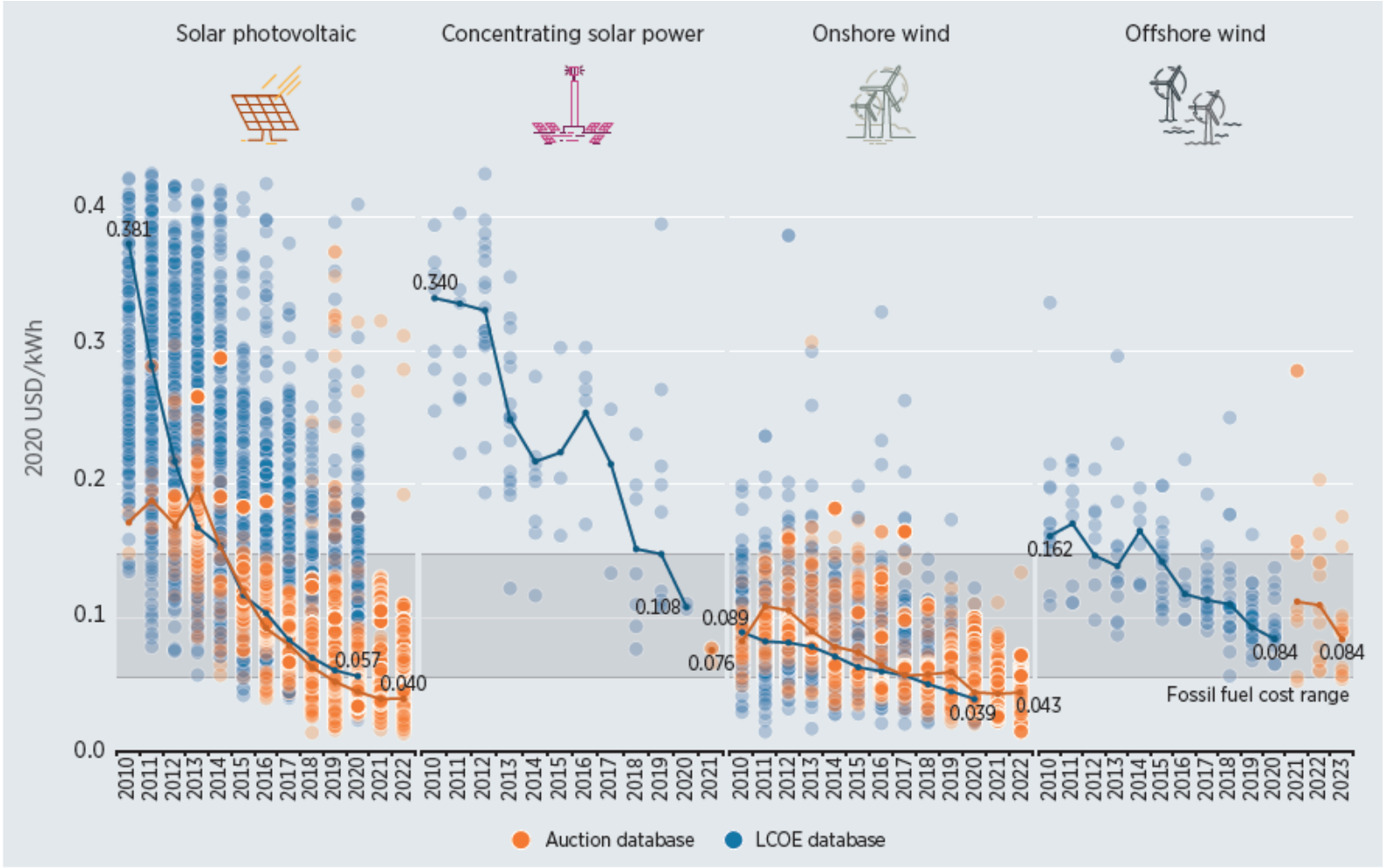
Why hydrogen as zero carbon energy carrier, feedstock and reducing agent?

5-4-2022

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

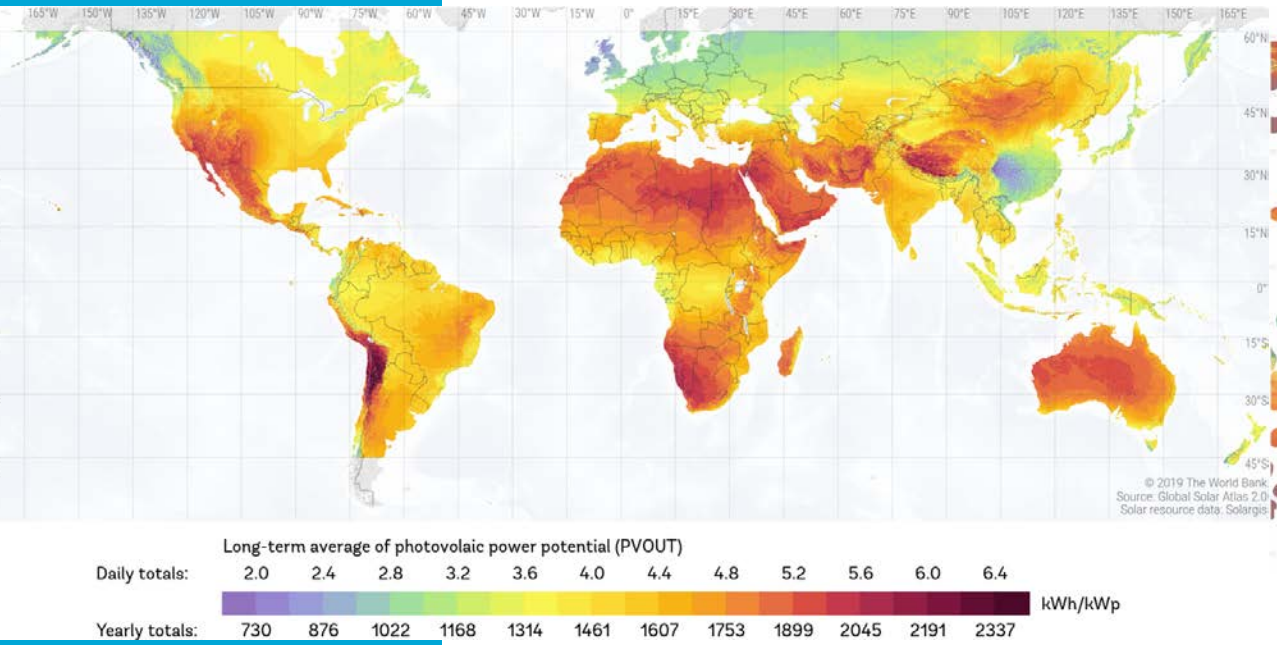


Source: IRENA Renewable Cost and Auction and PPA Databases

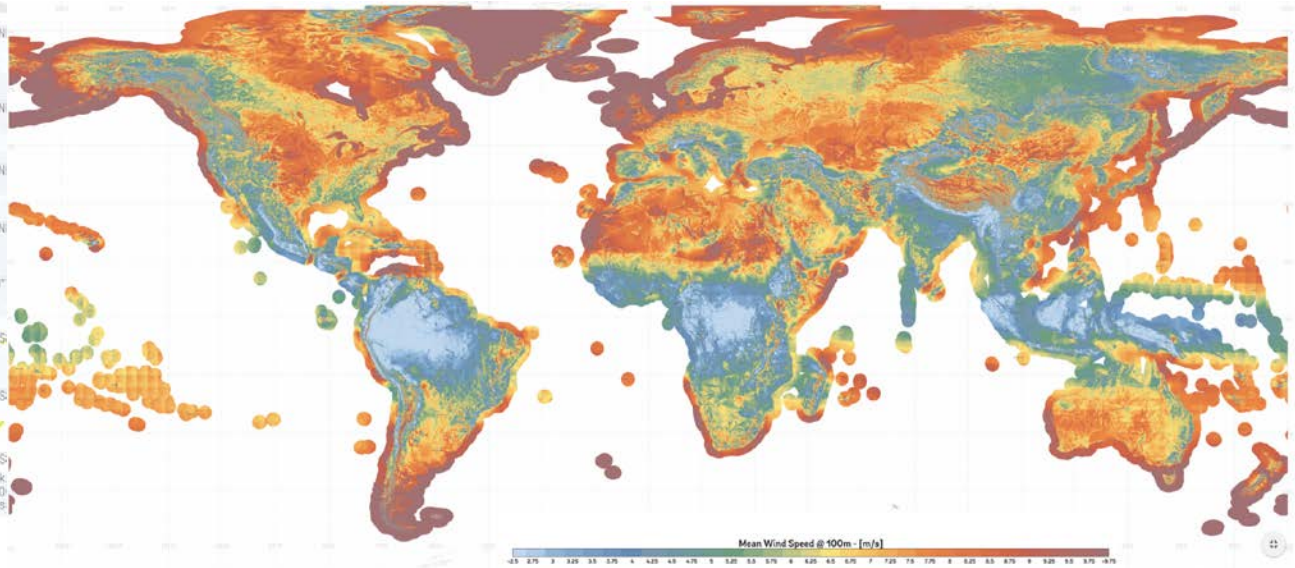
IRENA, "Renewable power generation costs in 2020,“ https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

Mohammed Bin Rashid Al Maktoum Solar Farm in Dubai; 3.000 MW ready, expansion to 5.000 MW

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

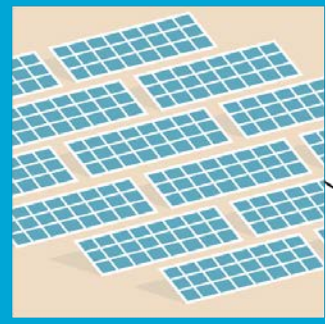


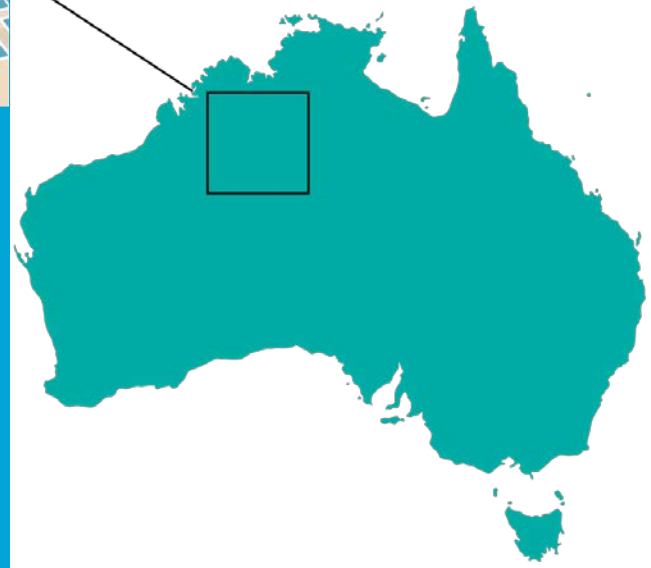
Solar Resources Map



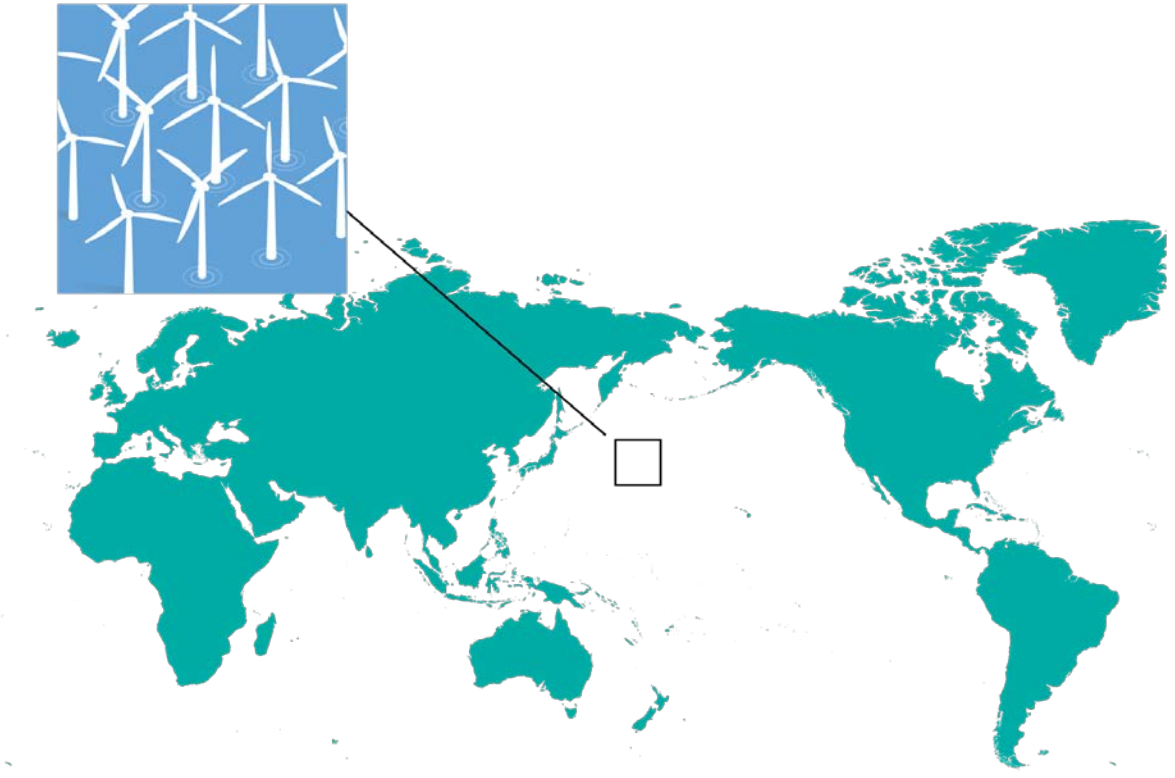
Wind Speed at 100 meter height Map

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





10% SOLAR AUSTRALIA

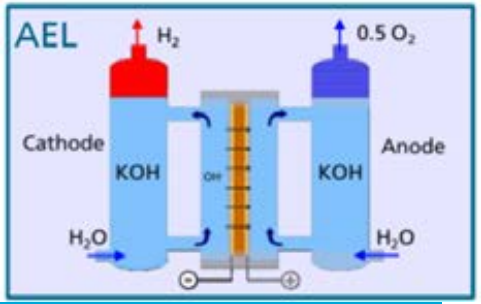


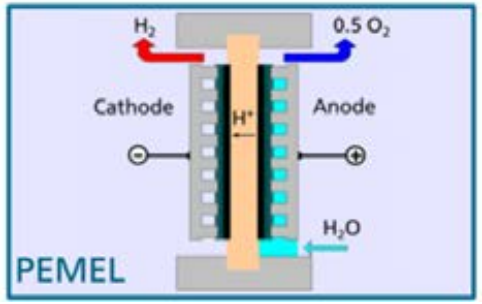
1.5% WIND PACIFIC OCEAN

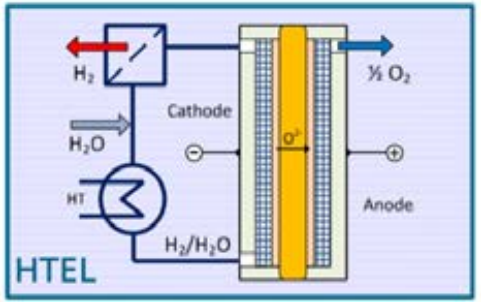
A. van Wijk, E. van der Roest and J. Boere, Solar Power to the People, Nieuwegein-Utrecht: Allied Waters, 2017

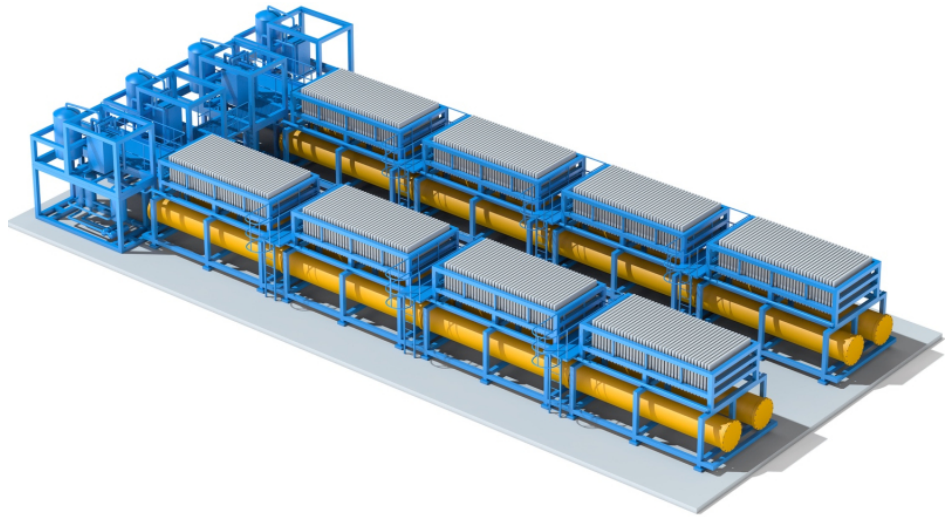
Water Electrolysis

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







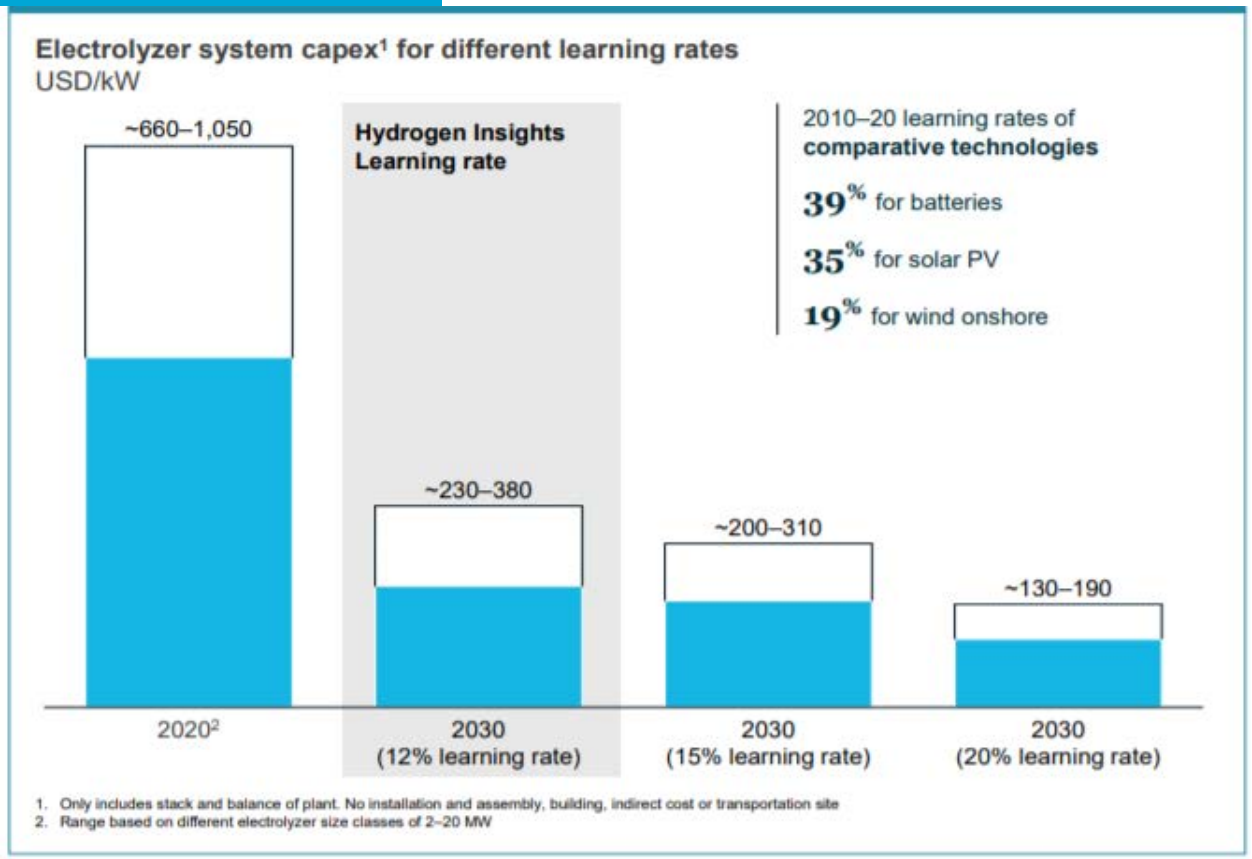


20 MW alkaline electrolyser ThyssenKrupp

	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.

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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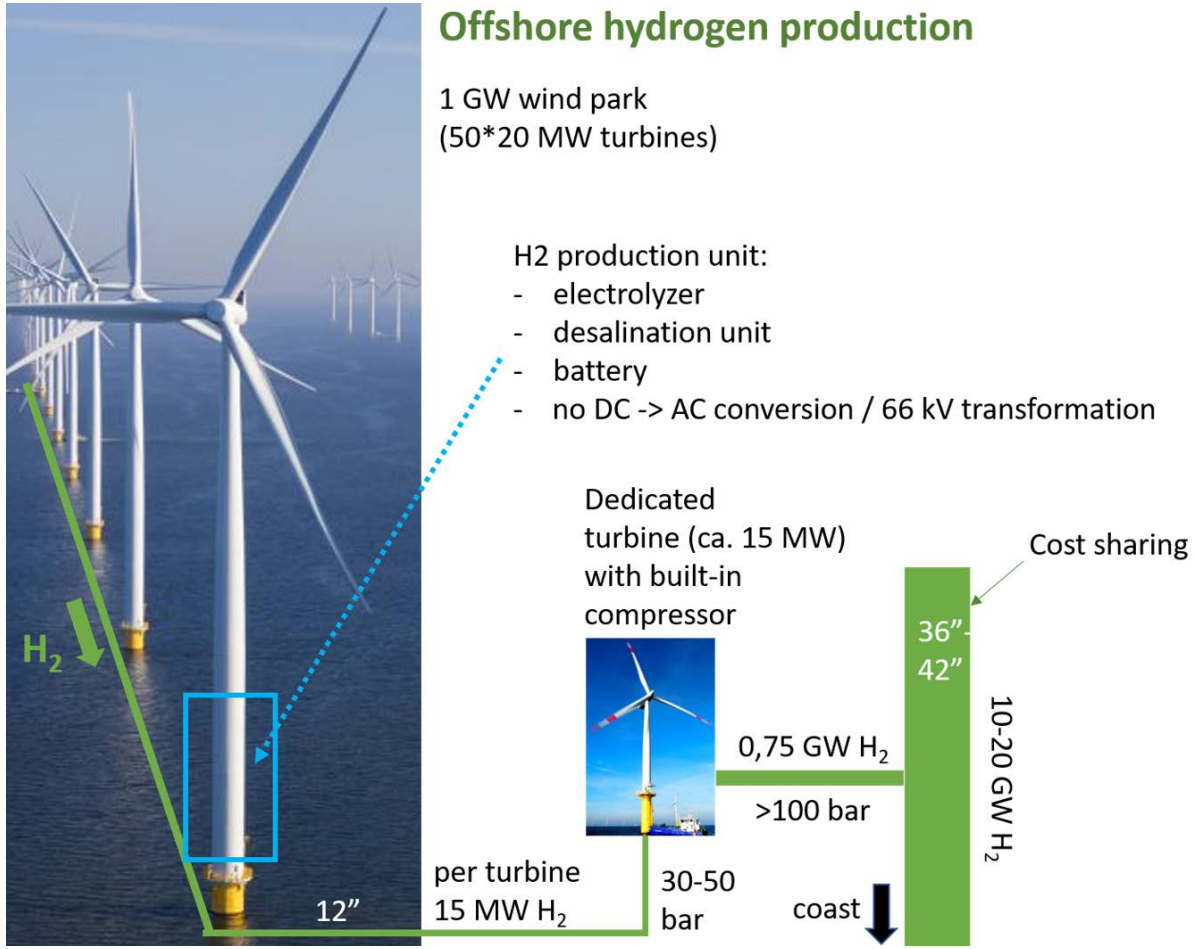
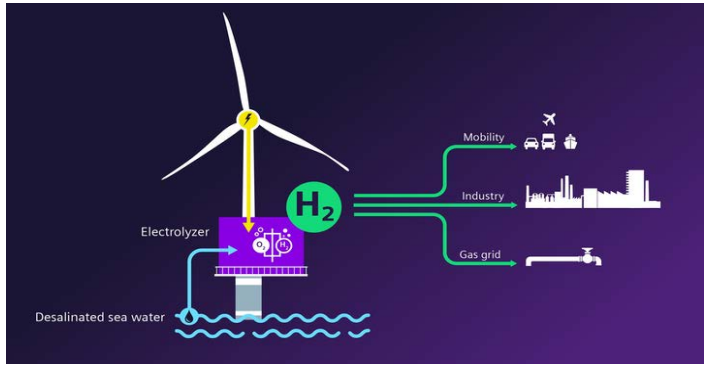
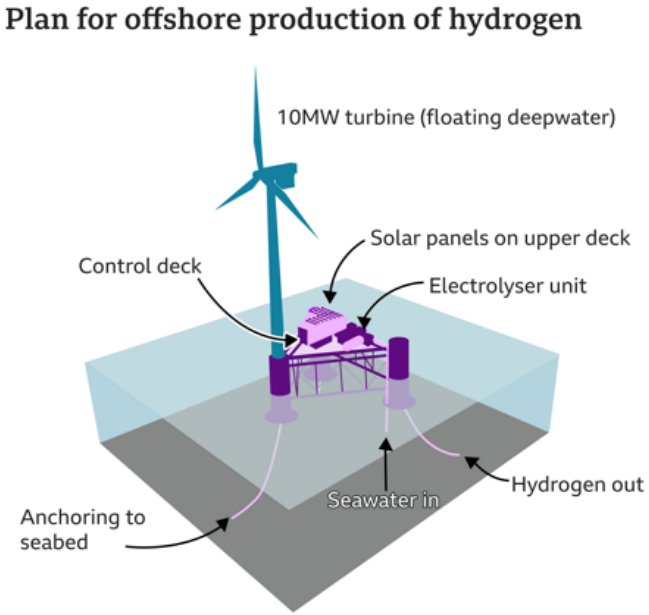
Offshore integrated Wind-Hydrogen Turbines





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



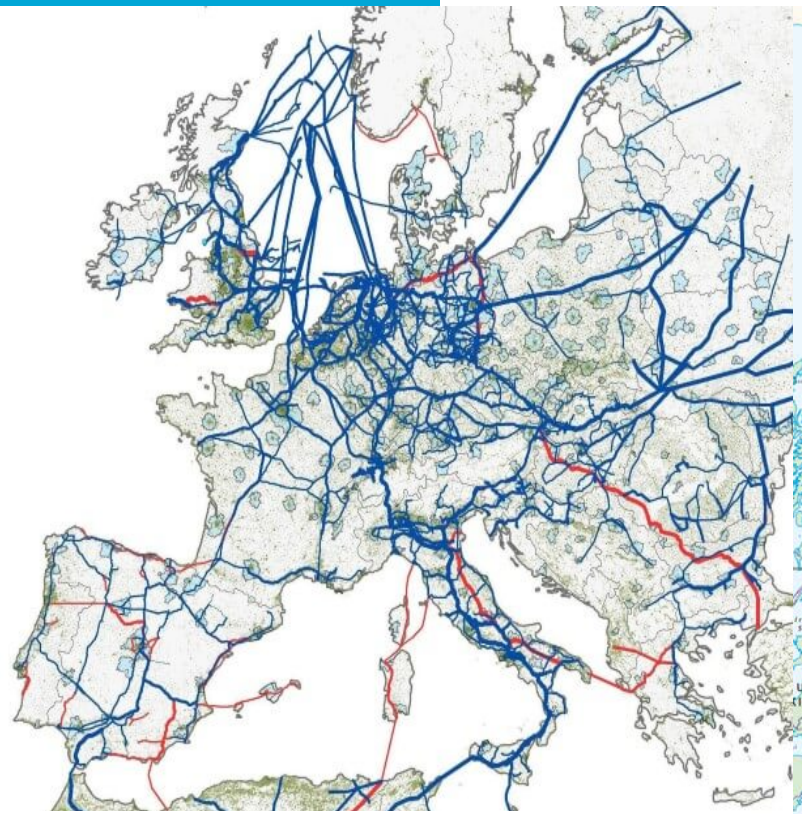
ERM UK, 10 MW floating offshore wind turbine with electrolyser at turbine platform

Integrating electrolyser in offshore wind-hydrogen turbine will reduce Total (Wind turbine + Electrolyser) CAPEX

Gas Infrastructure in Europe 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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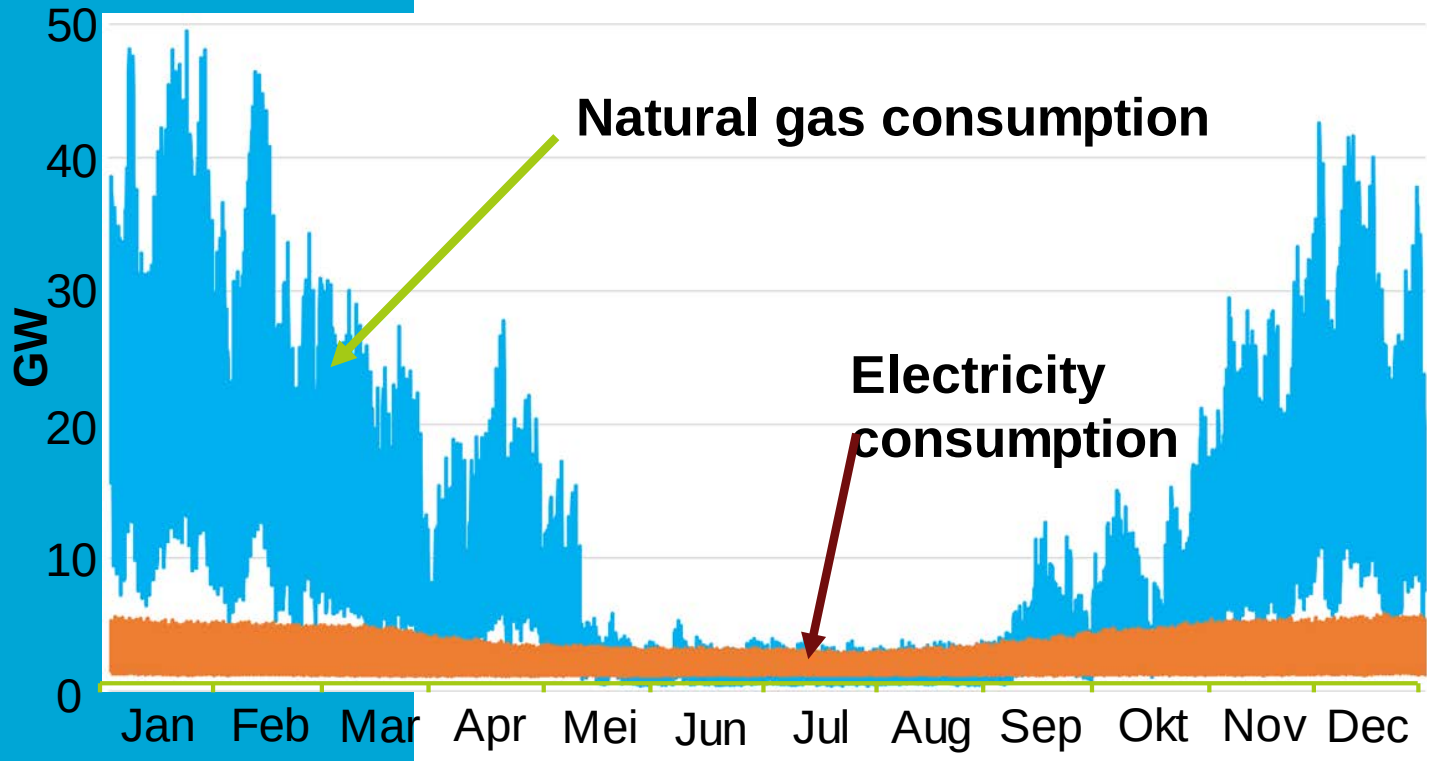
Hydrogen, connecting MENA region to Europe

Middle-East to Europe
Eastmed Hydrogen Pipeline

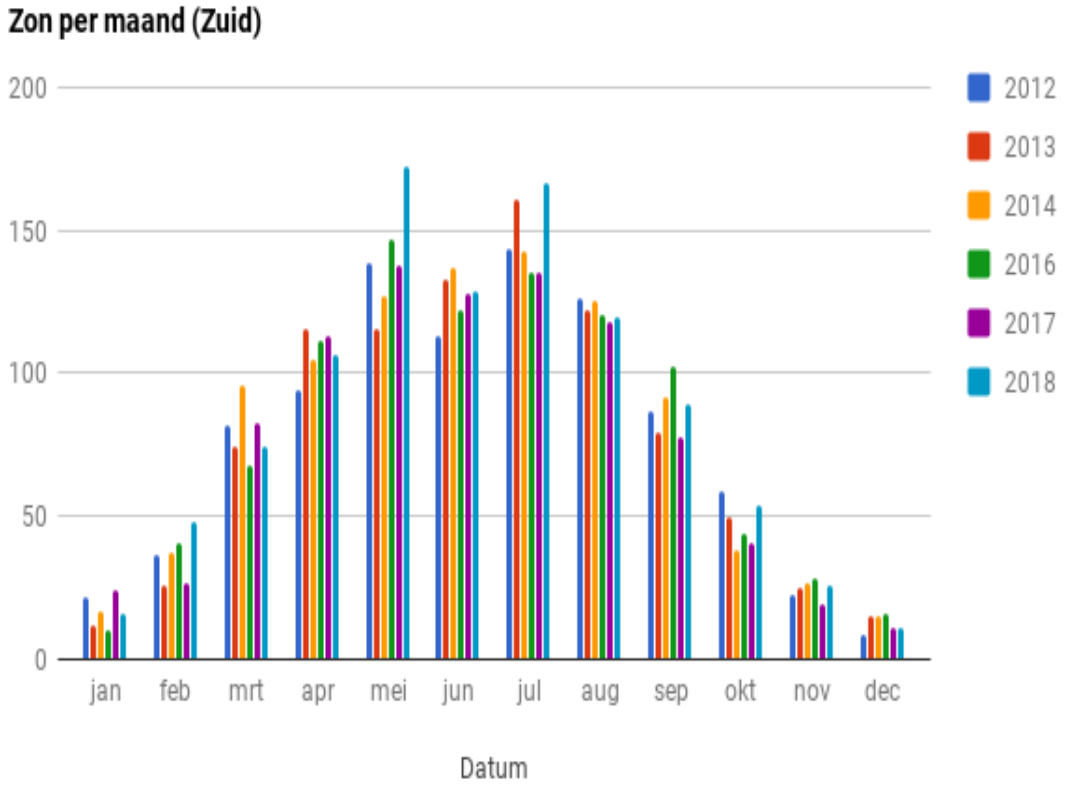
North-Africa to Europe
Repurposing and new pipelines

Storage will become an even larger challenge then today
Today large scale seasonal storage is already present
Example the Netherlands



7,8 million Dutch houses (2017)

Source: Kellner, 2018



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

In the Netherlands about 100 TWh seasonal gas storage available
= storage capacity of 1 billion battery electric vehicles with 100 kWh battery.

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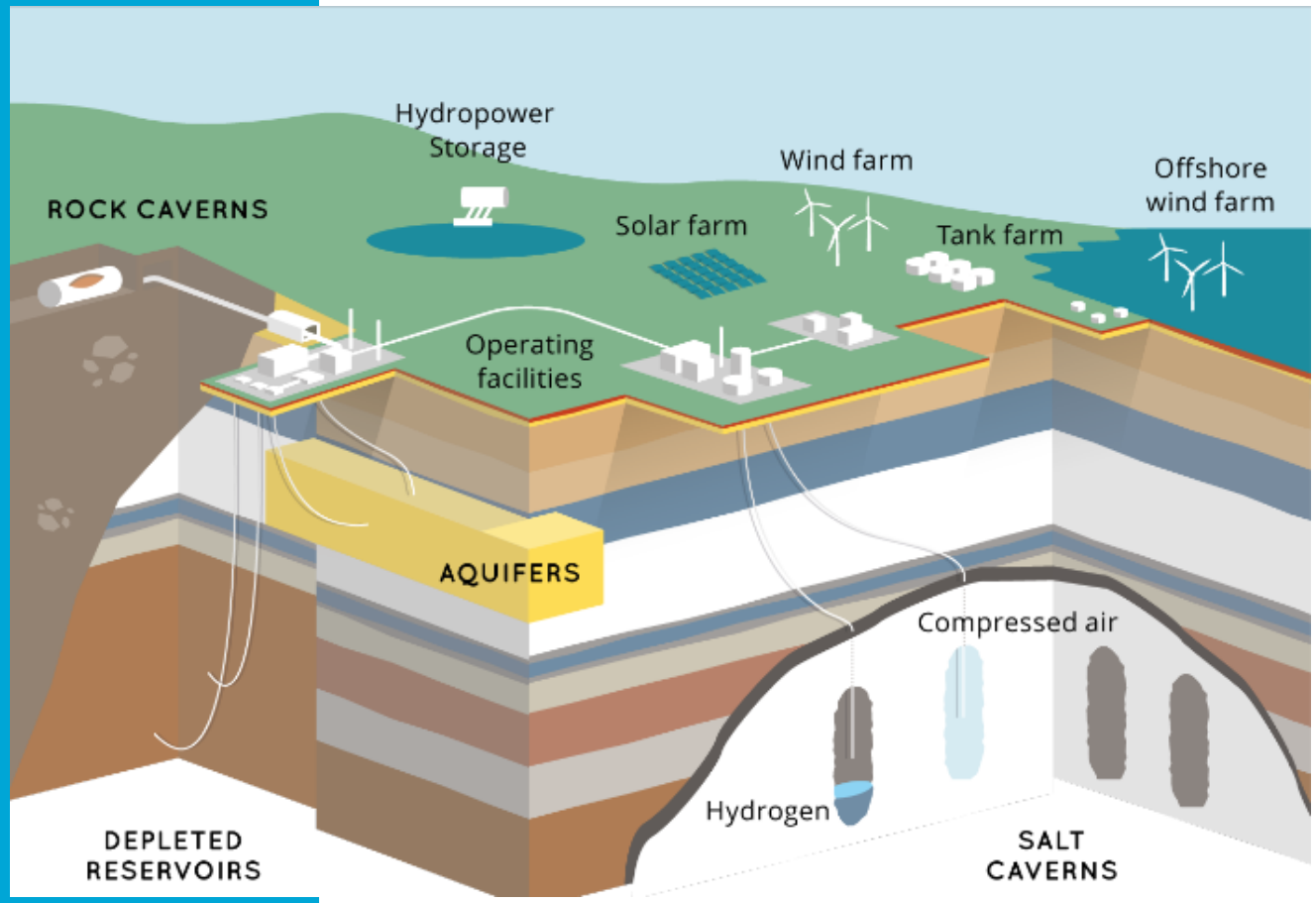
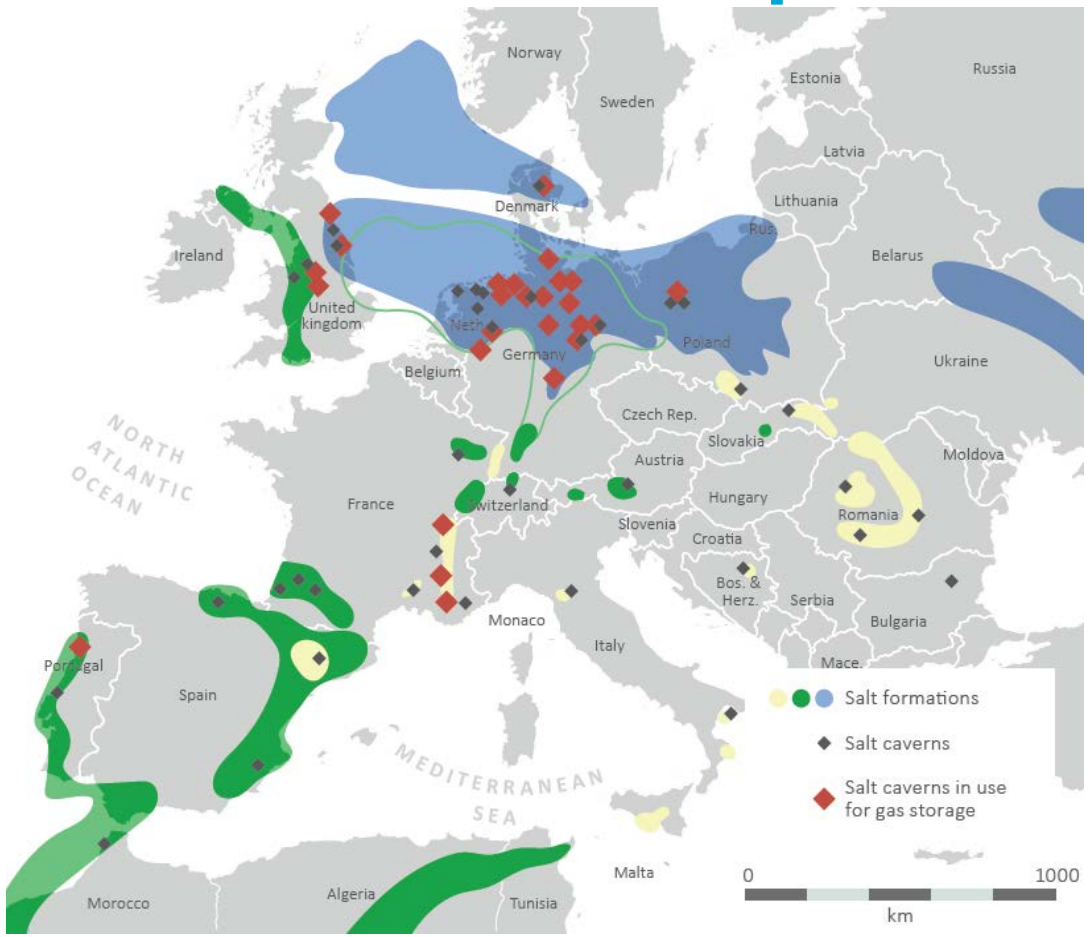
Hydrogen storage in salt caverns



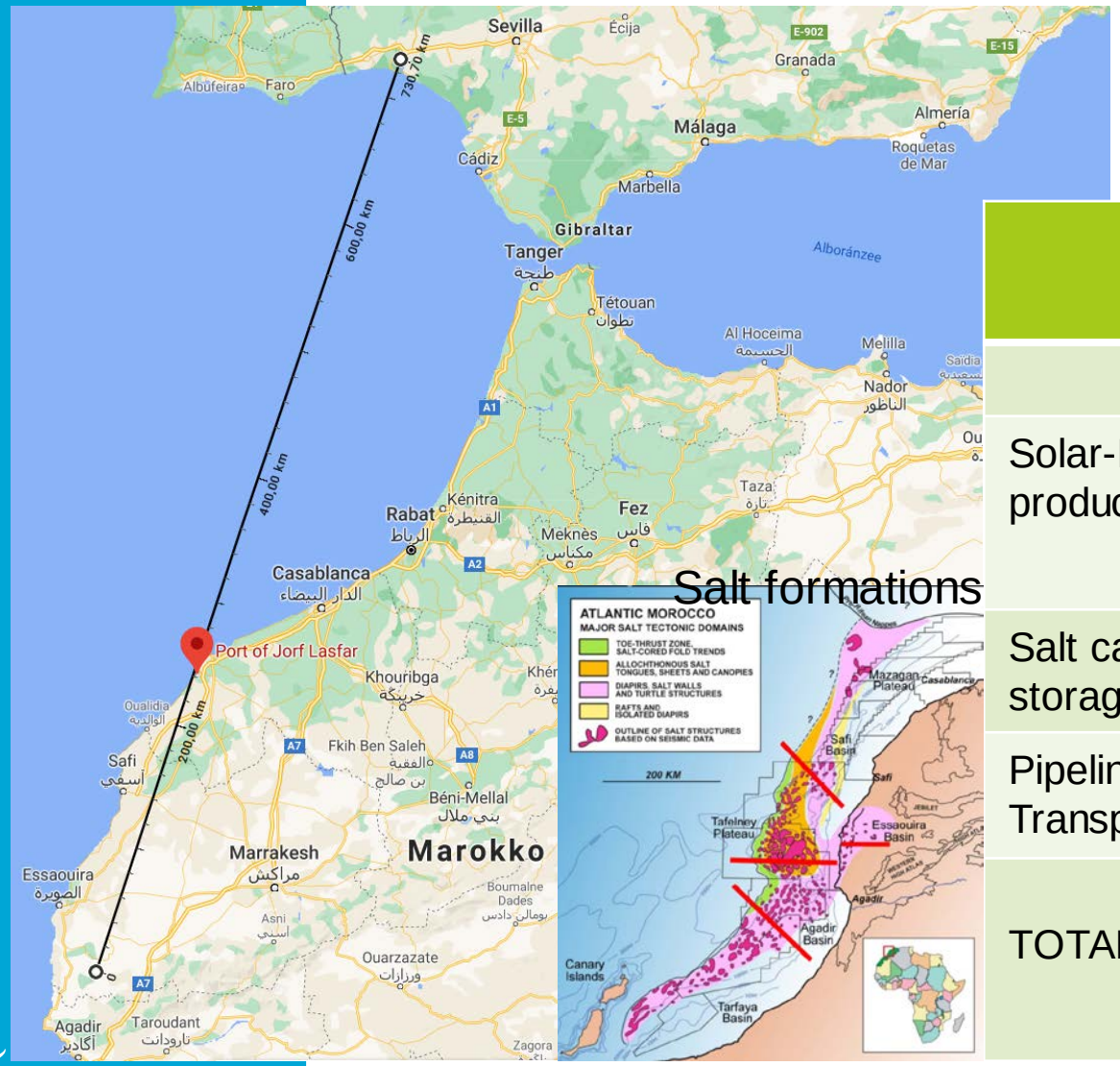
Salt formations and caverns in Europa



1 salt cavern can contain up to 6,000 ton (= 236.4 GWh HHV) hydrogen,
Salt Cavern CAPEX = 0.5 Euro per kWh, Total Salt cavern CAPEX is 100 million Euro

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

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		**1.4-2.0 €/kg H_2** =0.035-0.050 €/kWh$H_{2(HHV)}$

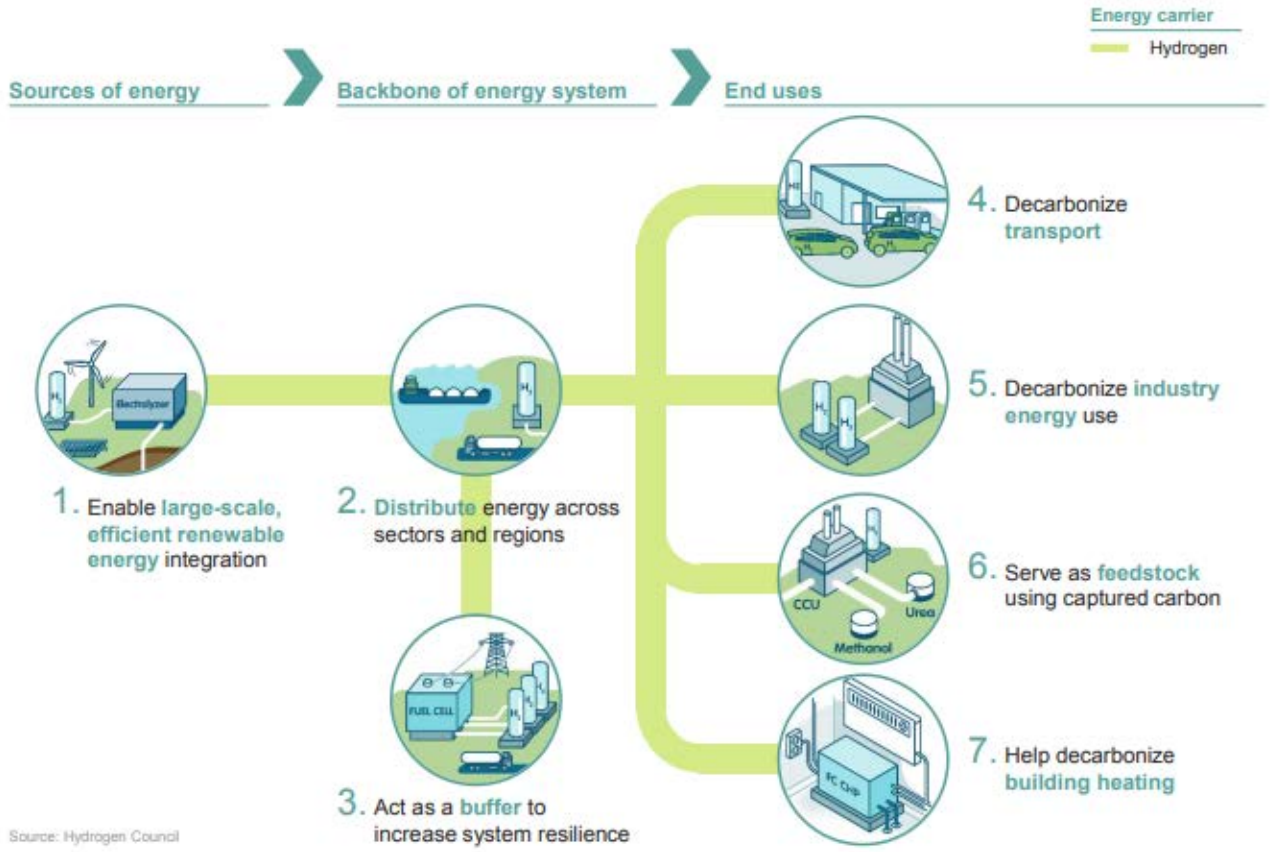
*Pedro Quintela de Saldanha; Sines *H*2 Hub; a cost perspective of the transmission & storage infrastructure of the Sines green hydrogen hub, TU Delft, MsC thesis, April 2021
**Gas for Climate/Guide house; "Extending the European Hydrogen Backbone; A European Hydrogen Infrastructure vision covering 21 countries." April 2021

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

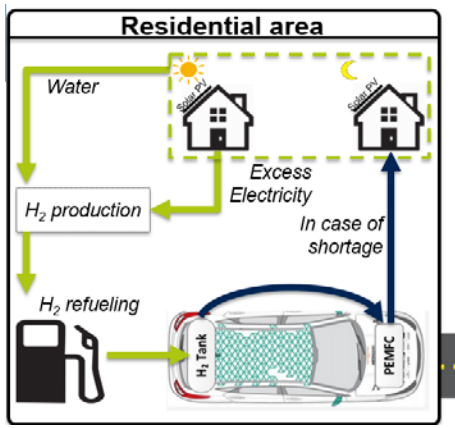


https://hydrogencouncil.com/wp-content/uploads/2017/06/Hydrogen-Council-Vision-Document.pdf

Hydrogen Markets

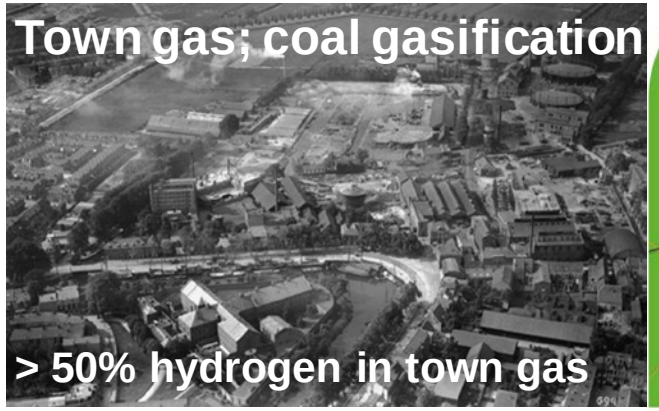
Industry Feedstock/HT Heat

Electricity Balancing



Transport

Heating



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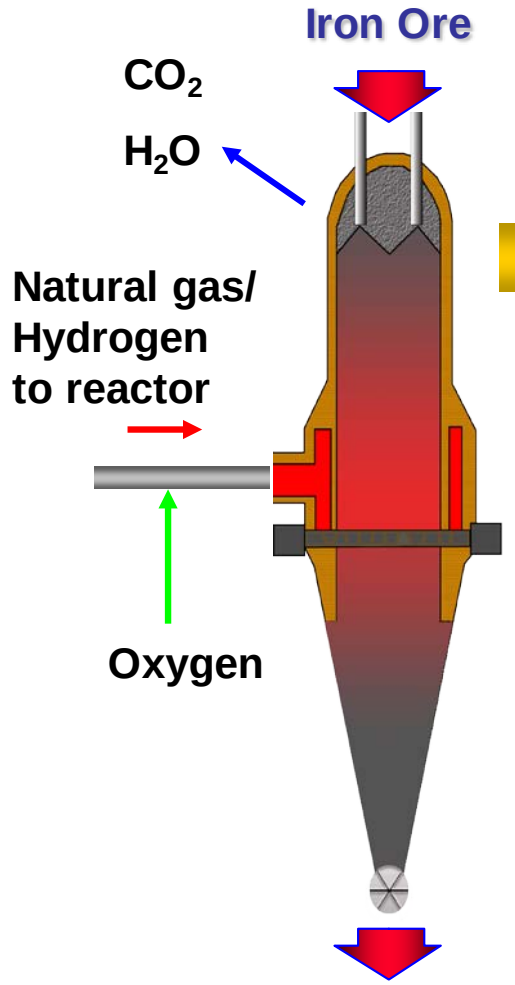
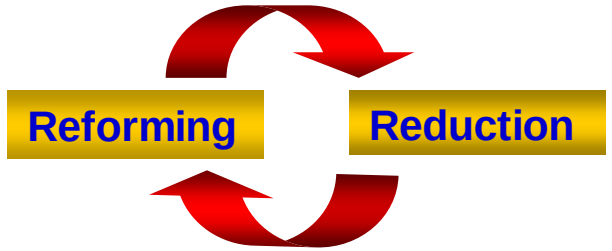
The Future for Steel Plant and site IJmuiden

DRI (Directed Reduced Iron) Proces on Natural Gas





In-situ Reforming

$CH_4 + H_2O \rightarrow CO + 3H_2$

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$

Reduction

$Fe_2O_3 + 3CO \rightarrow 2Fe° + 3CO_2$

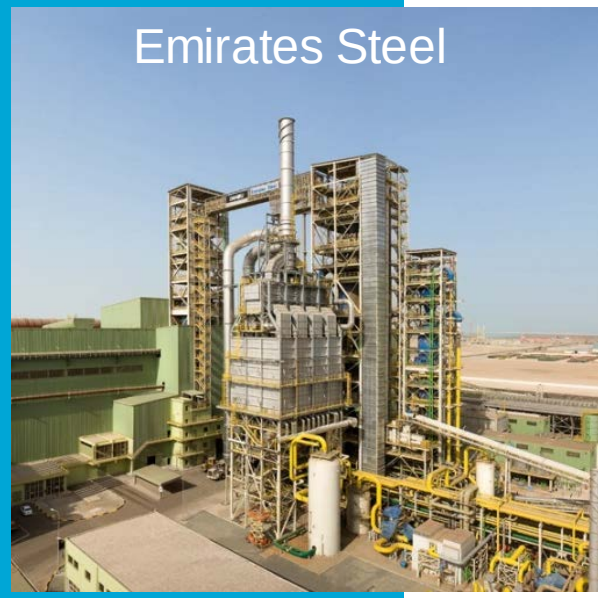
$Fe_2O_3 + 3H_2 \rightarrow 2Fe° + 3H_2O$

Carburization

$3Fe° + CH_4 \rightarrow Fe_3C + 2H_2$

Courtesy of Danieli

DRI (Directed Reduced Iron) Plants on Natural Gas mature technology



Two Modules:

2.0 Mtpy each
Carbon 1.5-2.5%
Met. 94%-96%
Hot DRI feed to EAF

Startup 2009/2011

One Module:

2.0 Mtpy
Carbon 3.0-4.0%
Met. 94%-96%
Hot DRI feed to EAF

Startup 2013

One Module:

2.5 Mtpy
Carbon 3.0-4.5%
Met. 94%-96.5%
Cold DRI

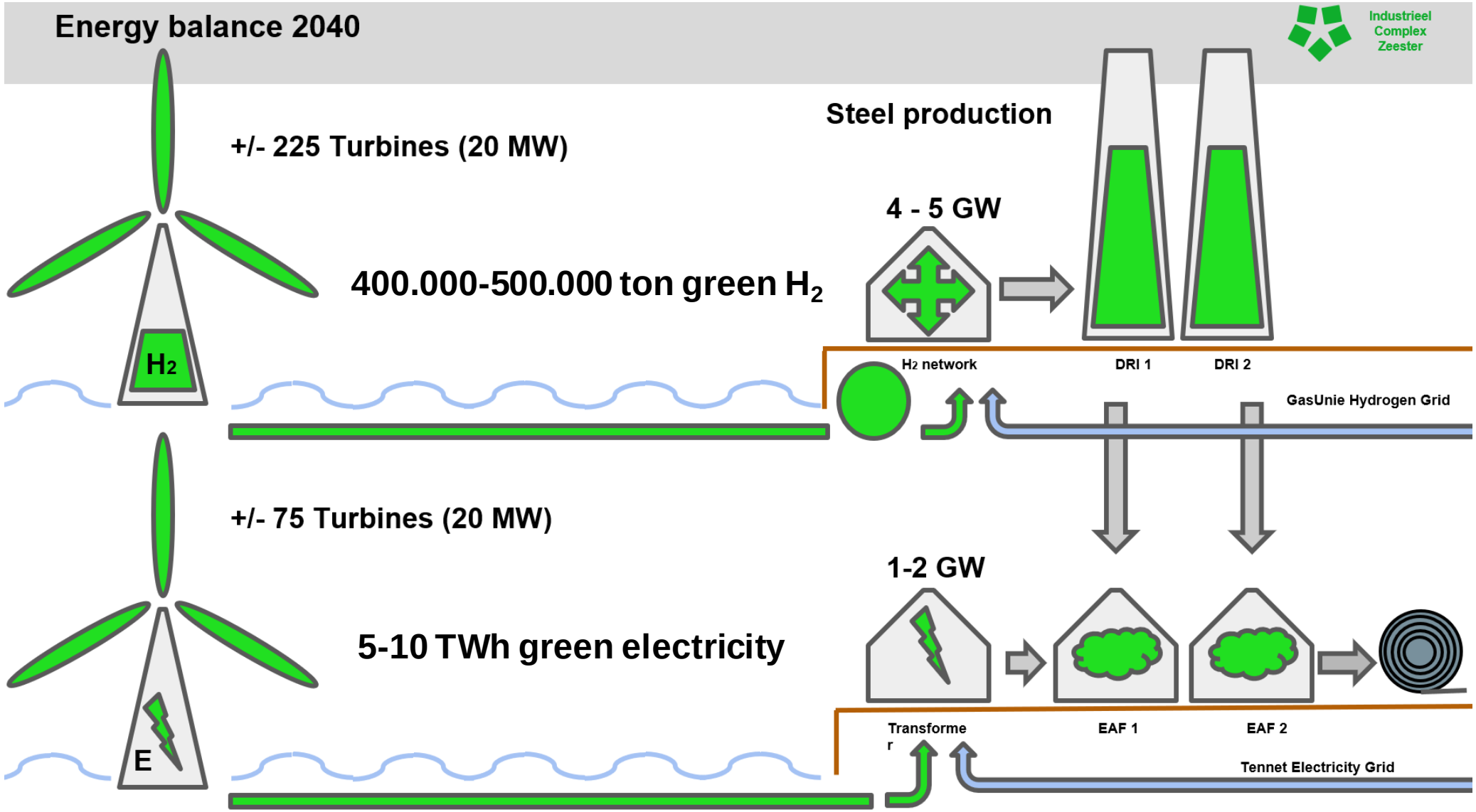
Startup 2013

One Module:

1.95 Mtpy
Carbon 1.5-2.5%
Met. 94%-96%
Cold DRI

Startup 2015

Tata Steel on green hydrogen, biomethane and electricity



Tata Steel the Netherlands chooses for hydrogen 15-9-2021

Manufacturing Offshore Wind Turbine components only possible at the coast, because of Size and Weight

Offshore wind turbine
about 100 ton steel per MW

For Foundations, Mast, Nacelle

Green steel production
for regular markets, offshore wind industry and 3D printing.

Industrieel Complex Zeester

Steel Production

3

Granulate

2

Turbine Steel

Rollers,
thick plate steel, 10 cm

1

Current Production

Rollers

Parts Production

3D printing
- Parts and Spare parts wind turbines
- New innovative products

Wind Turbine Parts
- Mast
- Foundation
- Nacelle,..

Regular manufacturing
- Automotive Industry
- Packaging

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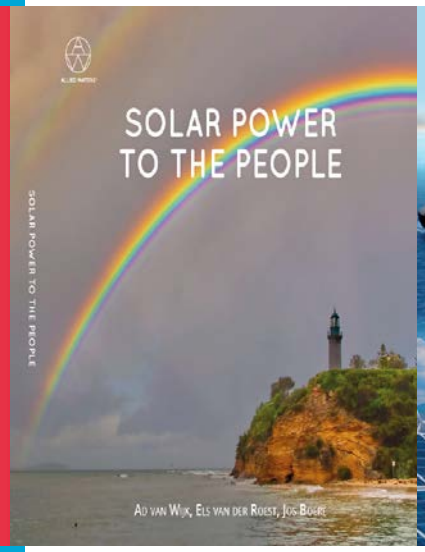
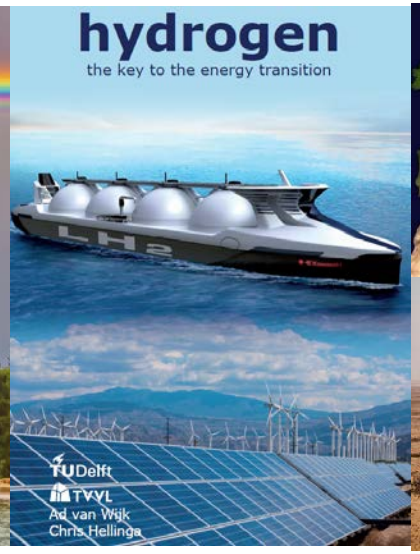
Further Reading
www.profadvanwijk.com

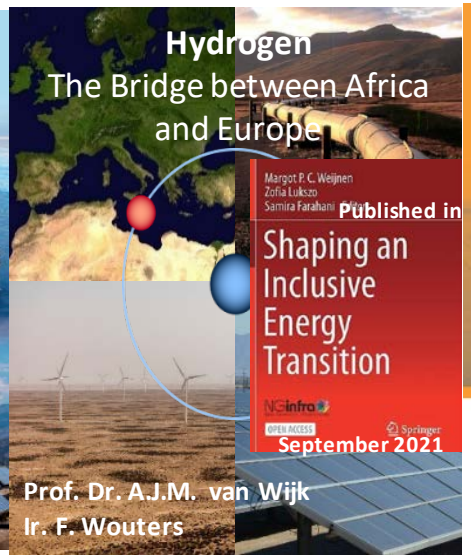
April 2017



November 2017

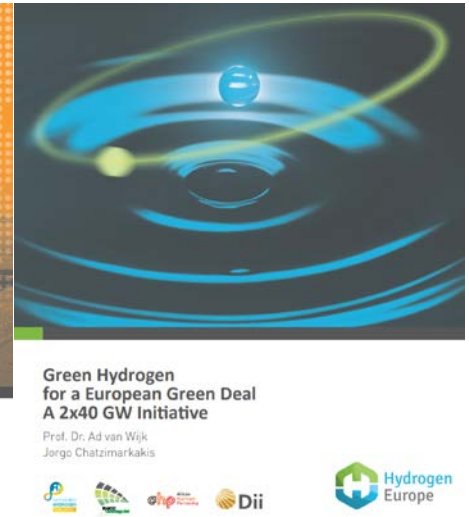


May 2018



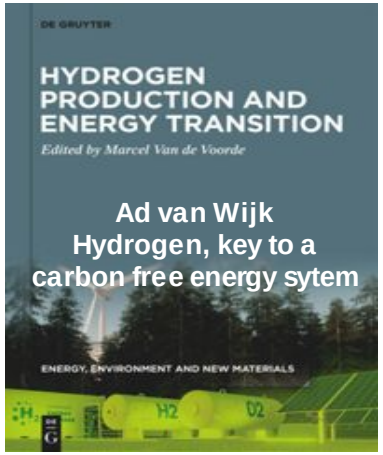
September 2019

November 2019

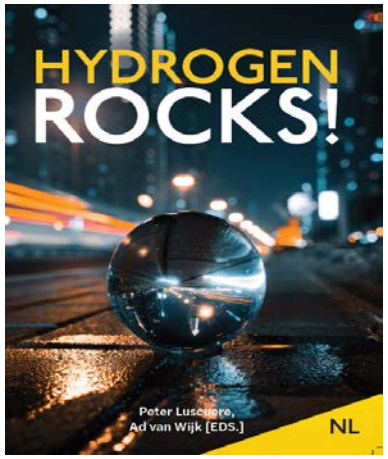


April 2020

April 2021



September 2021



October 2021

November 2021