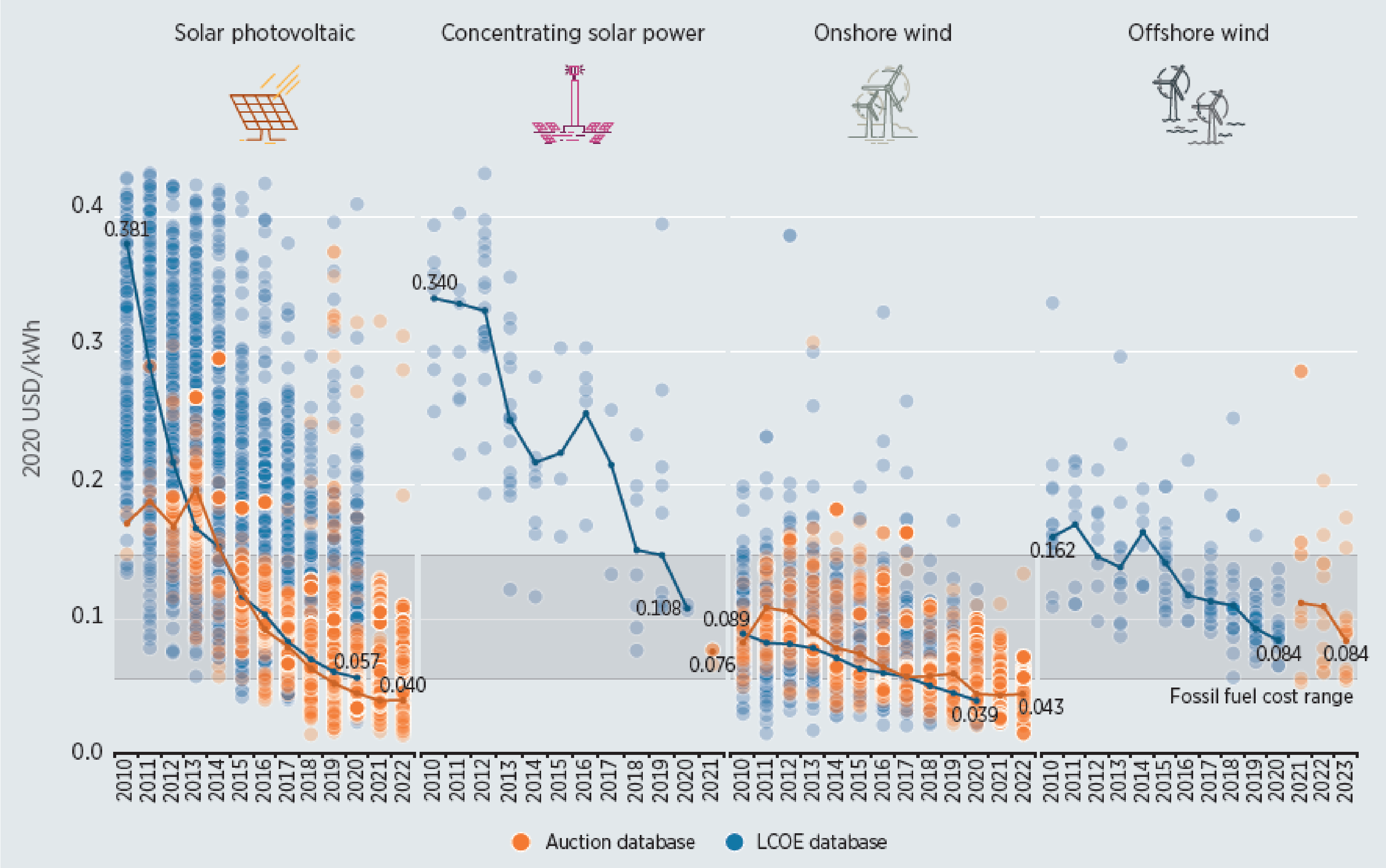
Norway trip synthesis of hydrogen research and development

24-6-2022

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

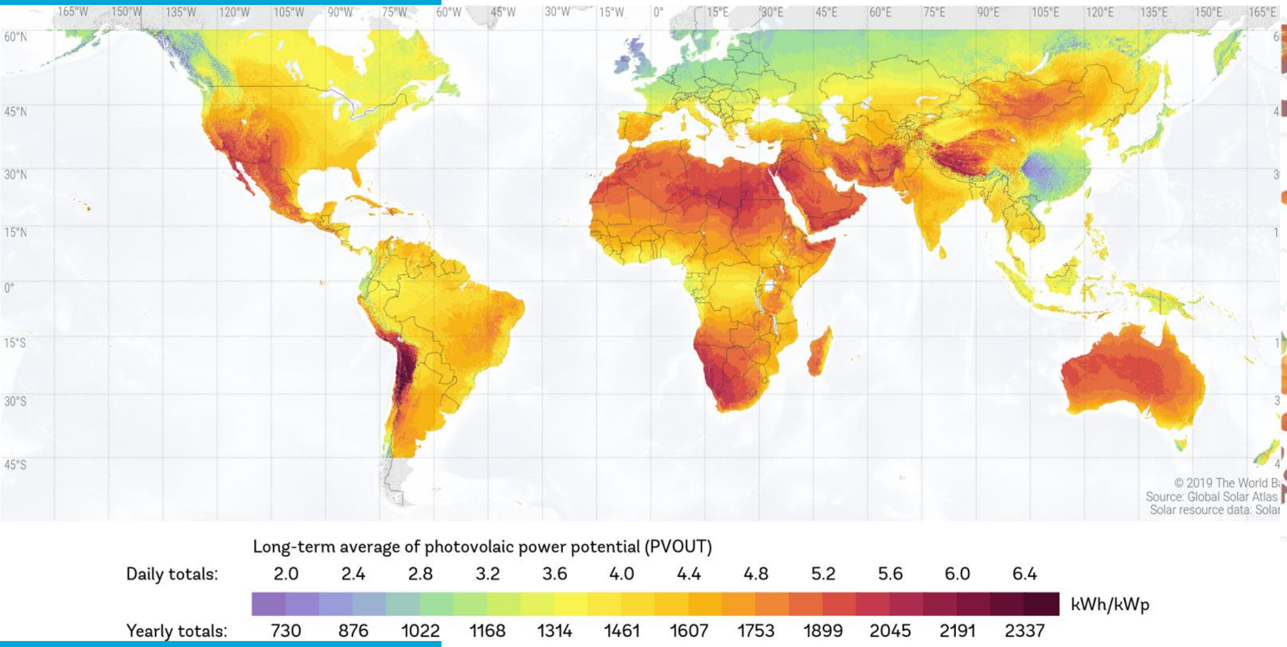


Source: IRENA Renewable Cost and Auction and PPA Databases

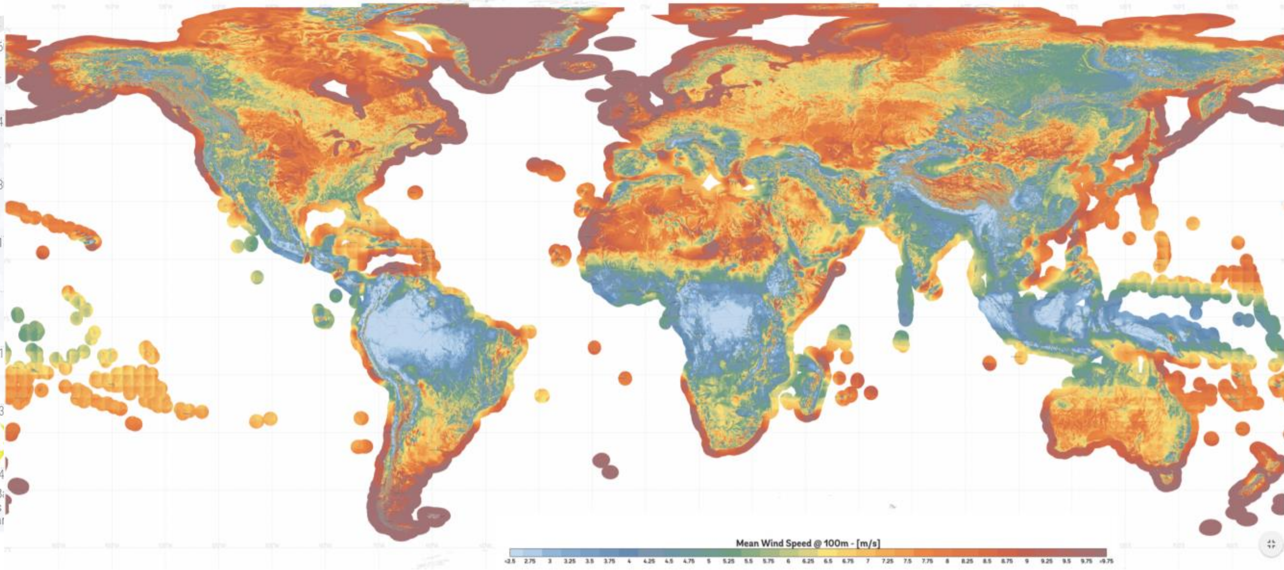
IRENA, "Renewable power generation costs in 2020,“ https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

However, low cost solar and wind electricity only at places with high irradiation and/or high wind speeds and with lots of available space

These locations are often far from energy demand



Solar Resources Map



Wind Speed at 100 meter height Map

Mohammed Bin Rashid Al Maktoum Solar Farm Dubai; 3.000 MW ready growing to 5.000 MW

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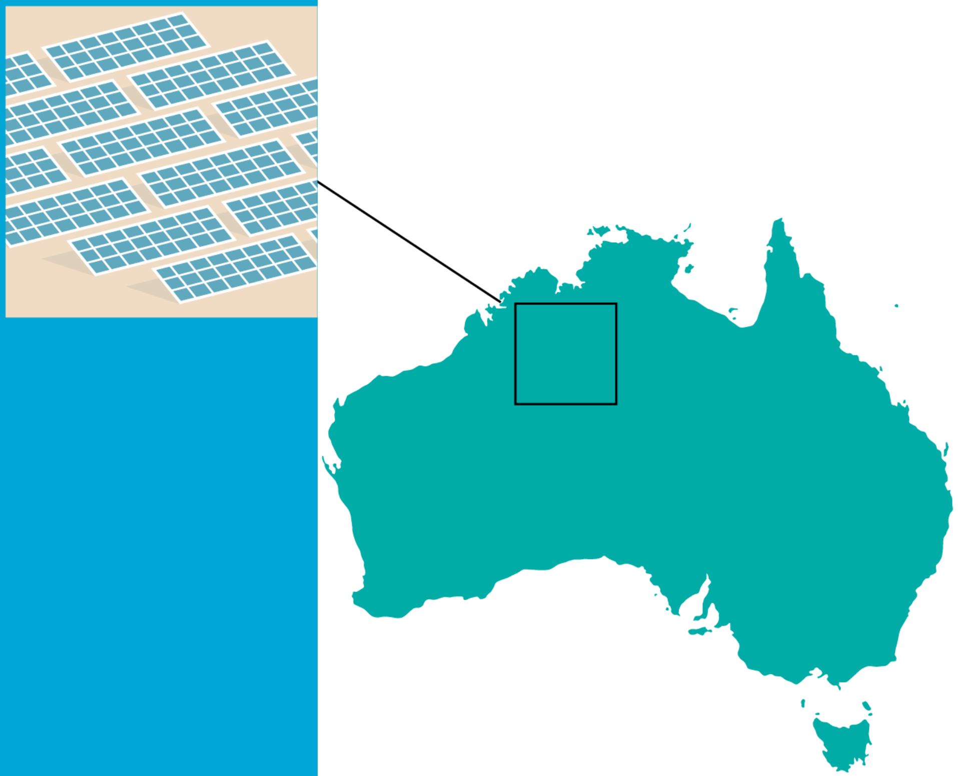
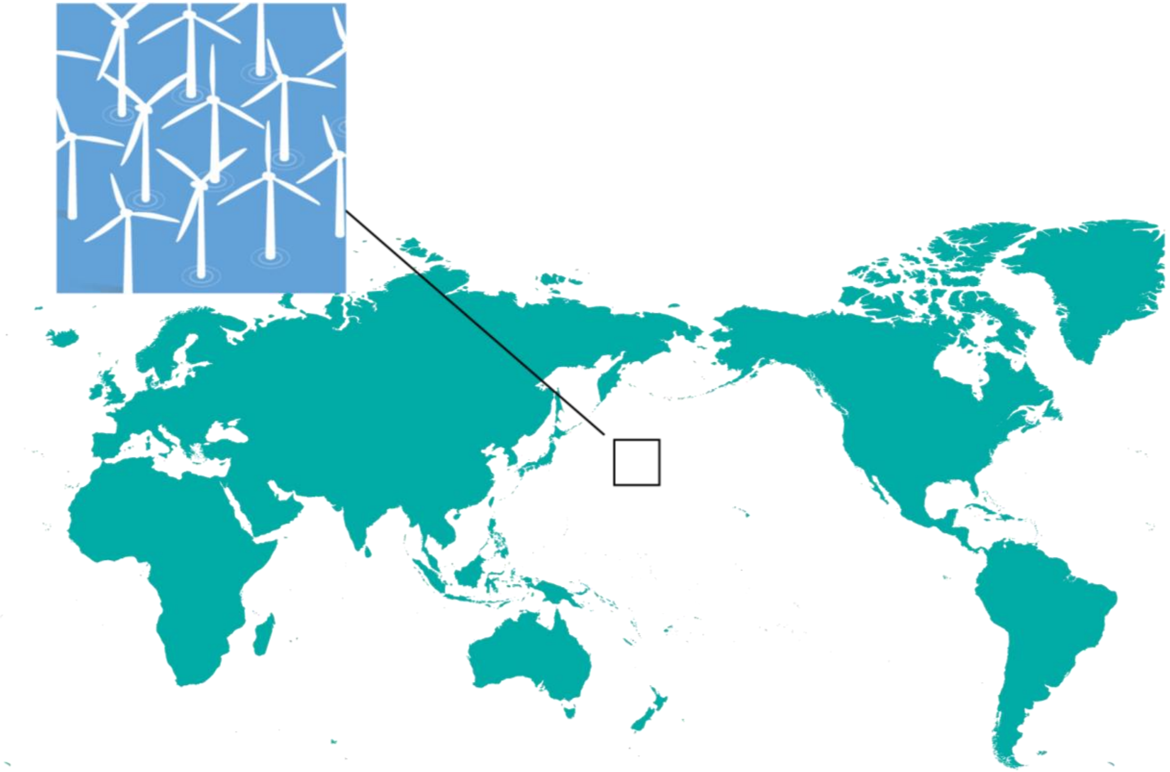
Surface needed to produce all the world's energy
556 EJ = 155.000 TWh



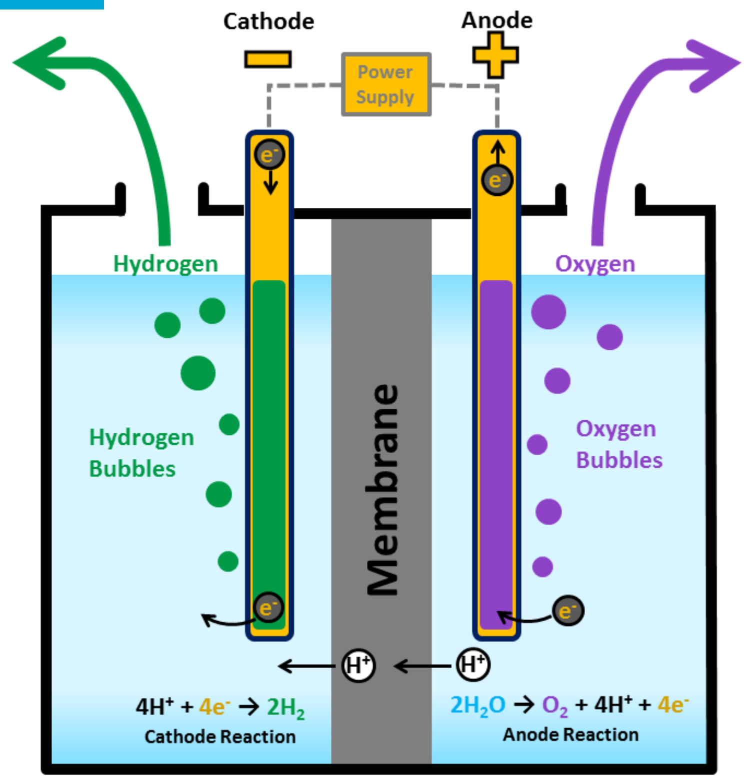
10% SOLAR AUSTRALIA

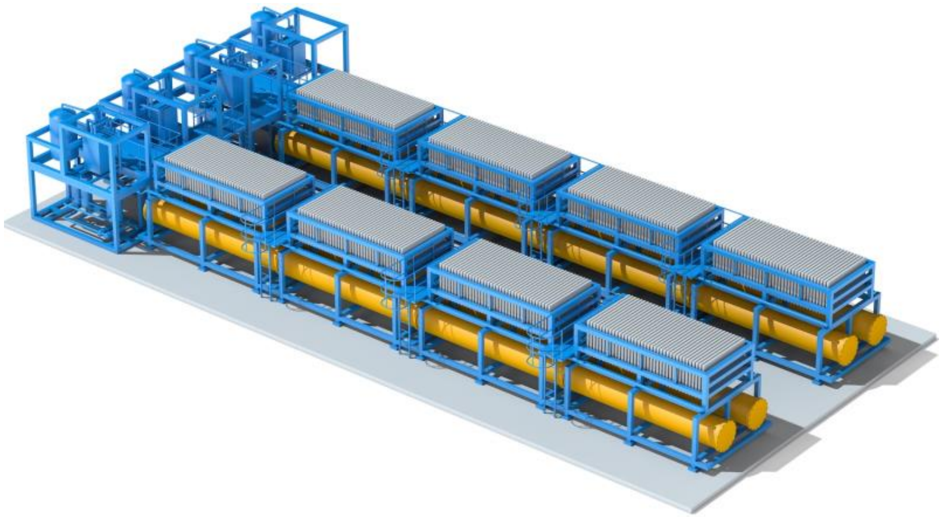


1.5% WIND PACIFIC OCEAN

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

Water Electrolysis



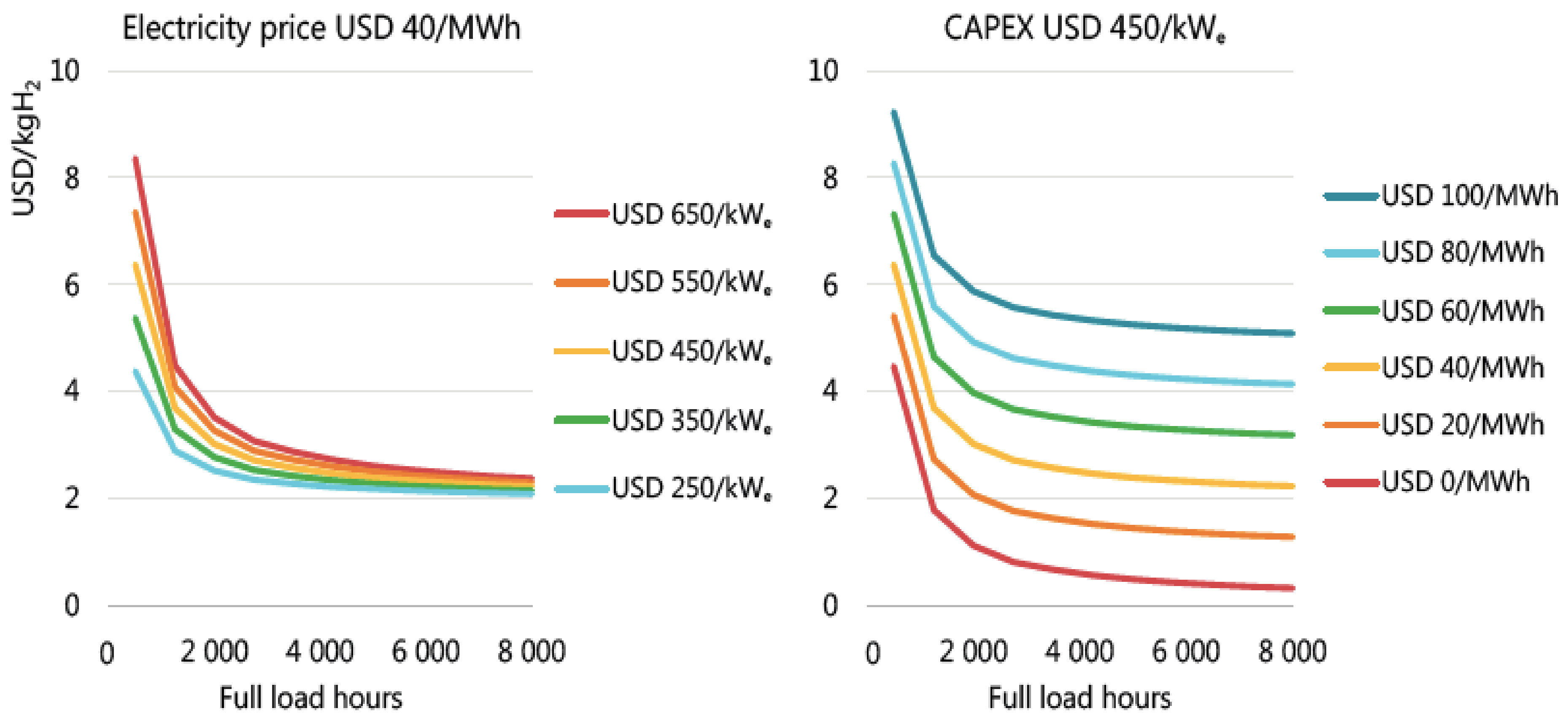


20 MW alkaline electrolyser ThyssenKrupp

	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.

Hydrogen production cost; LCoH

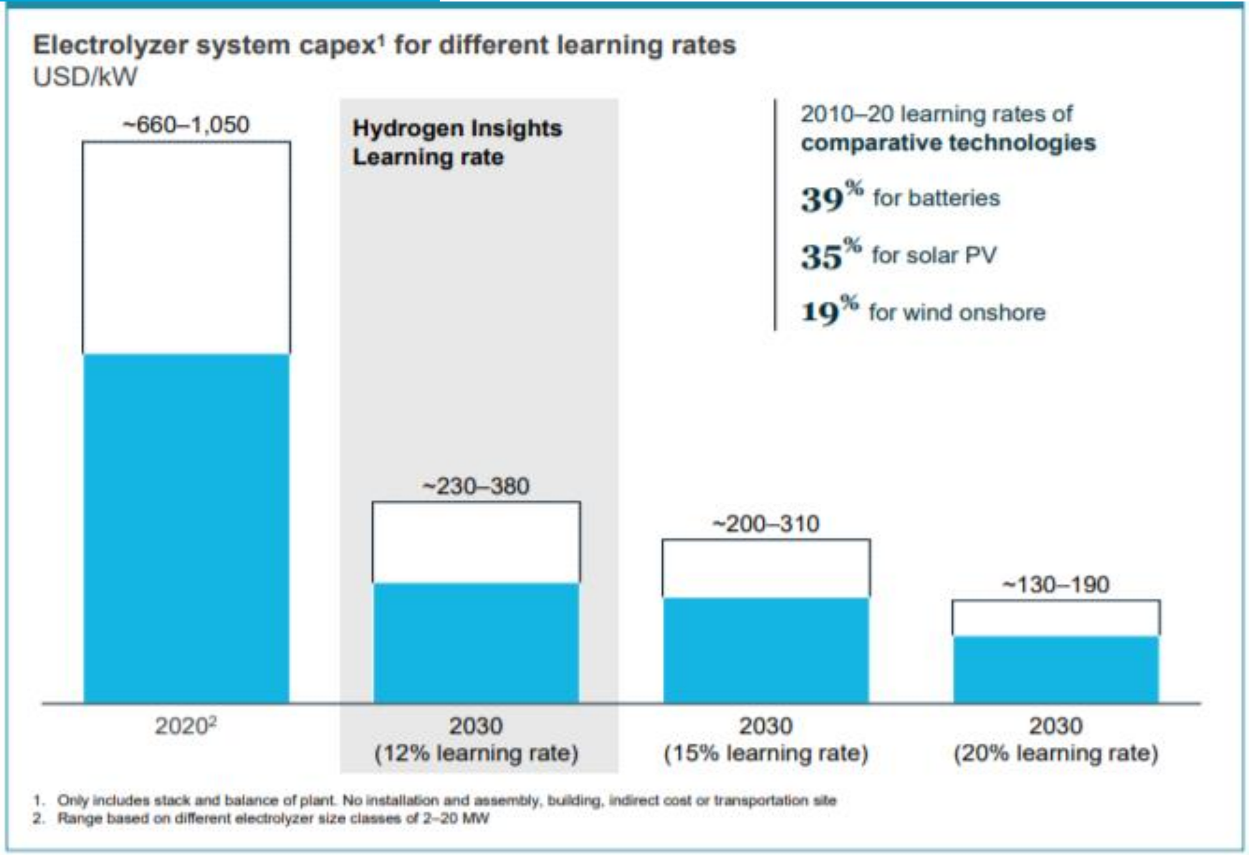


Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

Source: IEA 2019.

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%)

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

Floating wind turbine development


Equinor design floating wind, oct 2021

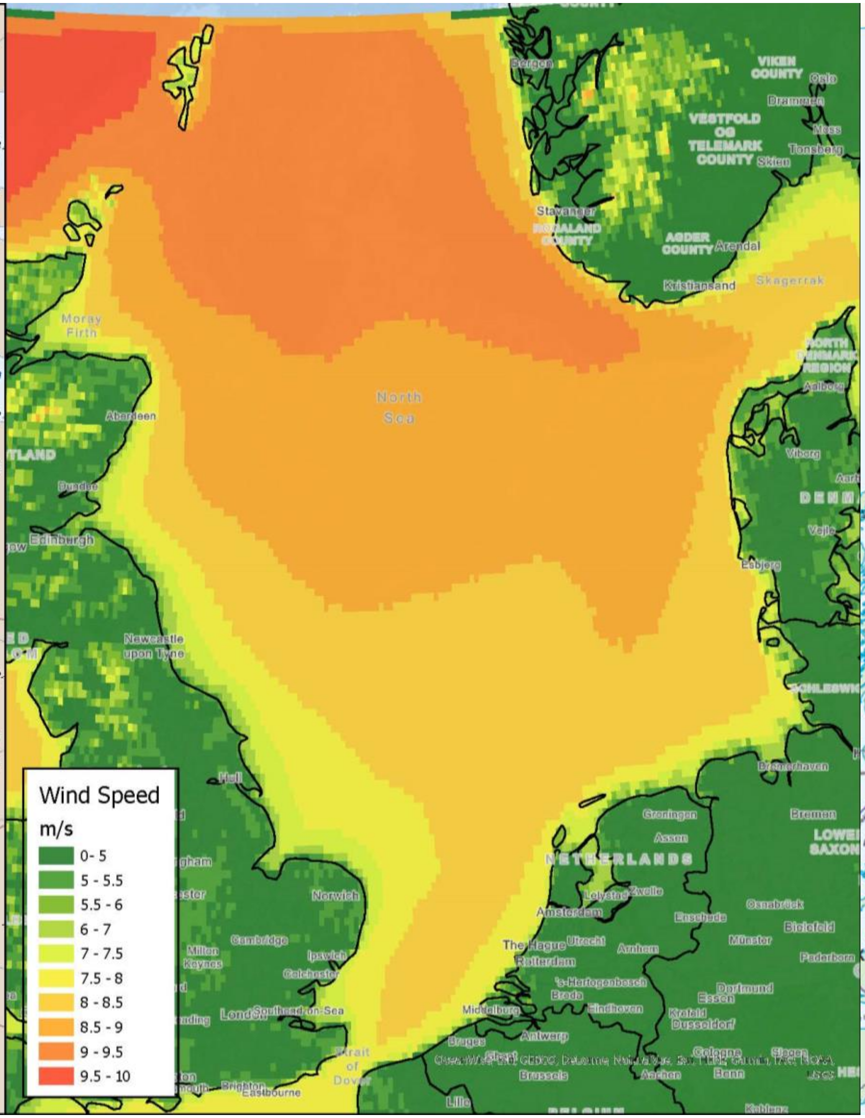

Vestas 9.5 MW floating wind, dec 2020

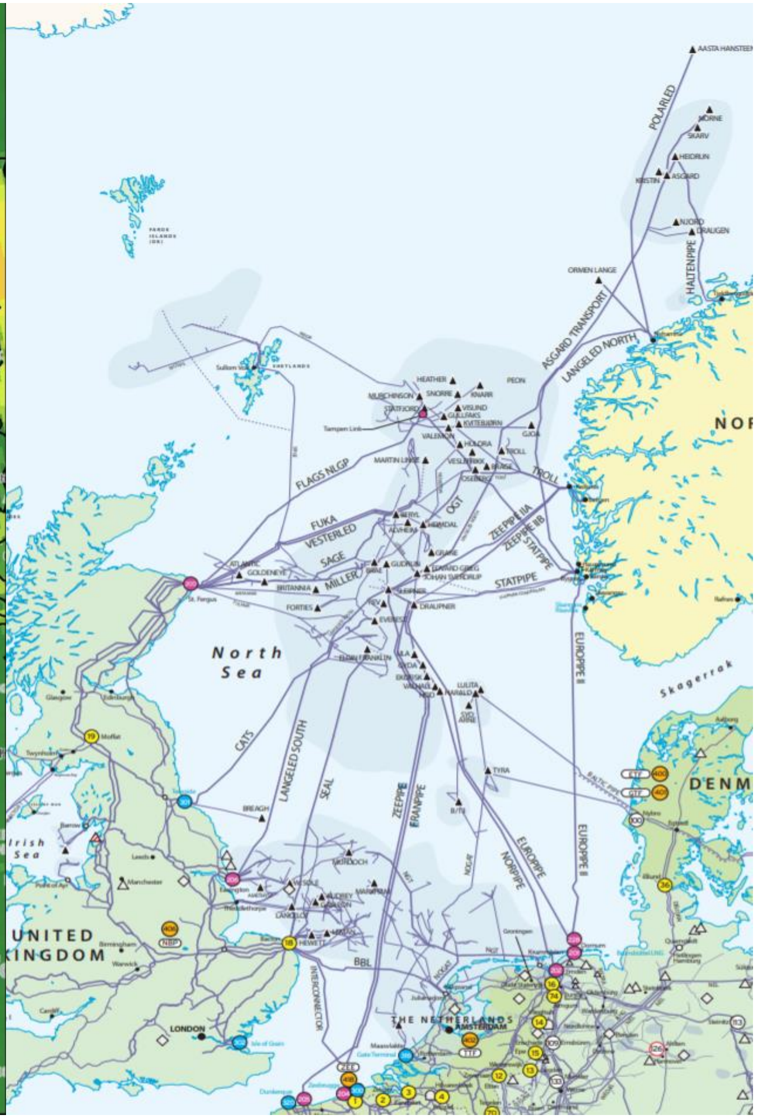
"ScotWind" seabed tender, March 2022 : Auction 8,600 km² of sea space which could host almost 25 GW of offshore wind. 17 projects won. With 15 GW floating offshore wind.

Dolphyn floating offshore wind-hydrogen

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

Water Depth, Wind speed, Gas pipelines North Sea





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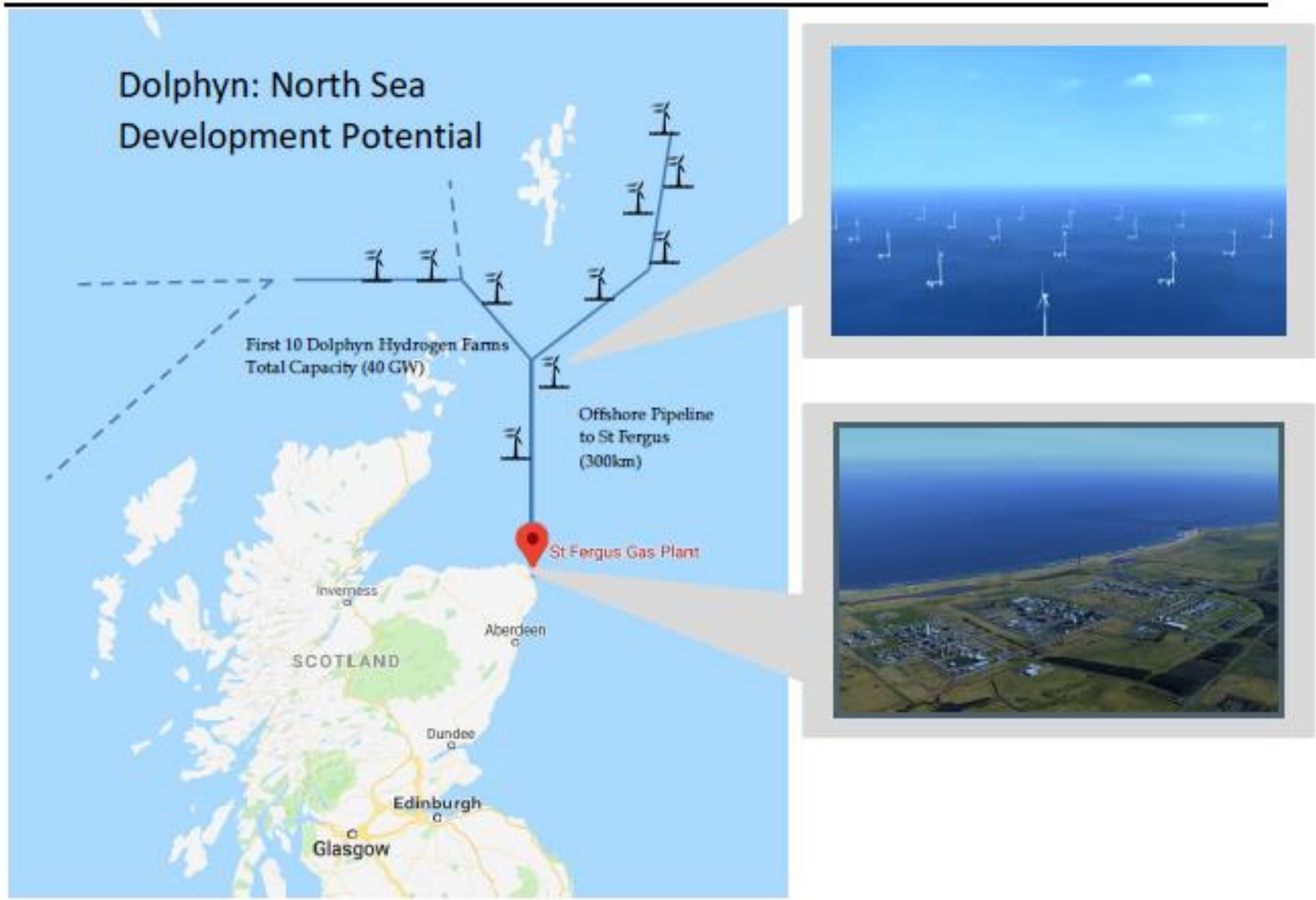
Dolphyn North Sea Offshore wind Hydrogen 10x4GW



GE Haliade X 12-14 MW

Haliade-X	12 MW	13 MW	14 MW
Output (MW)	12	13	14
Rotor diameter (m)	220	220	220
Total height (m)	260	260	260
Frequency (Hz)	50 & 60	50 & 60	50 & 60
Gross AEP (GWh)	~68	~71	~74
Capacity Factor (%)	63	60-64%	60-64%
IEC Wind Class	IB	IC	IC

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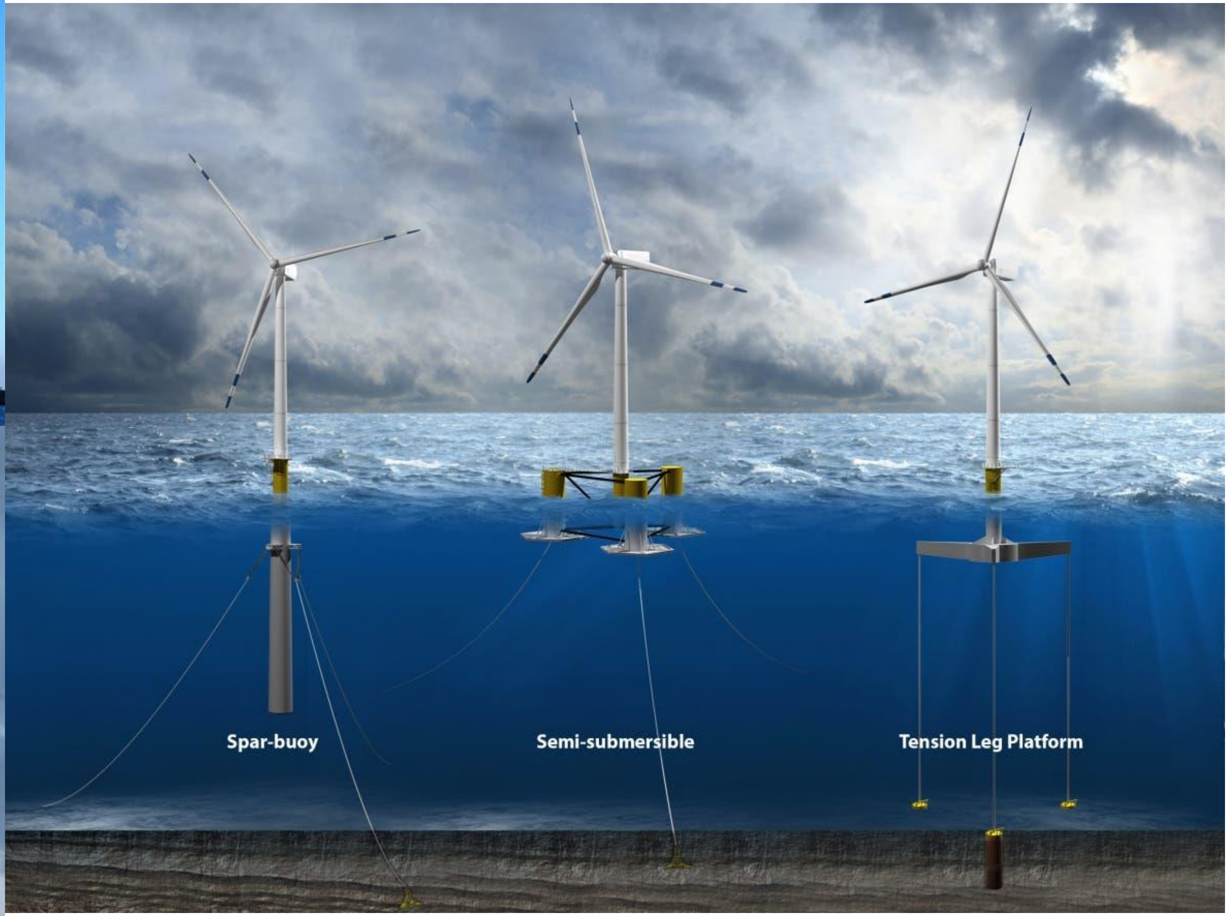
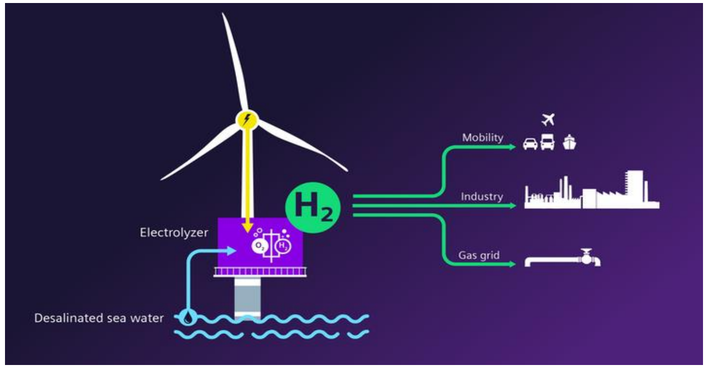
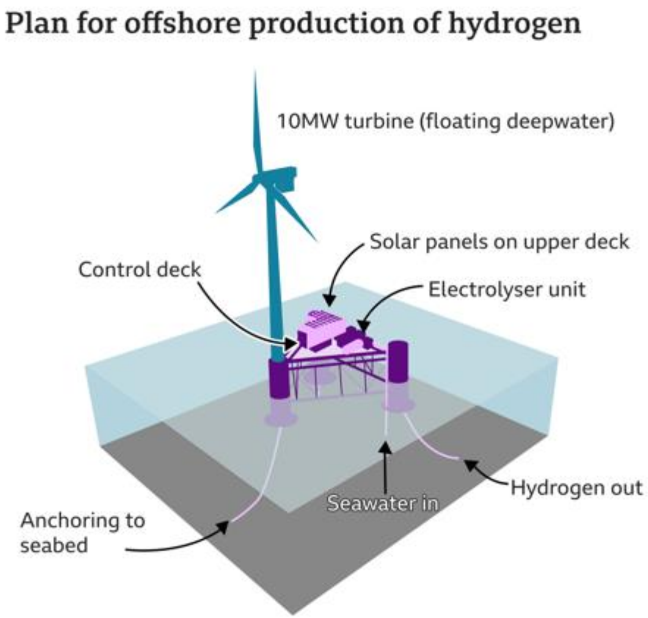
Offshore (Floating) integrated Wind-Hydrogen Turbines





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

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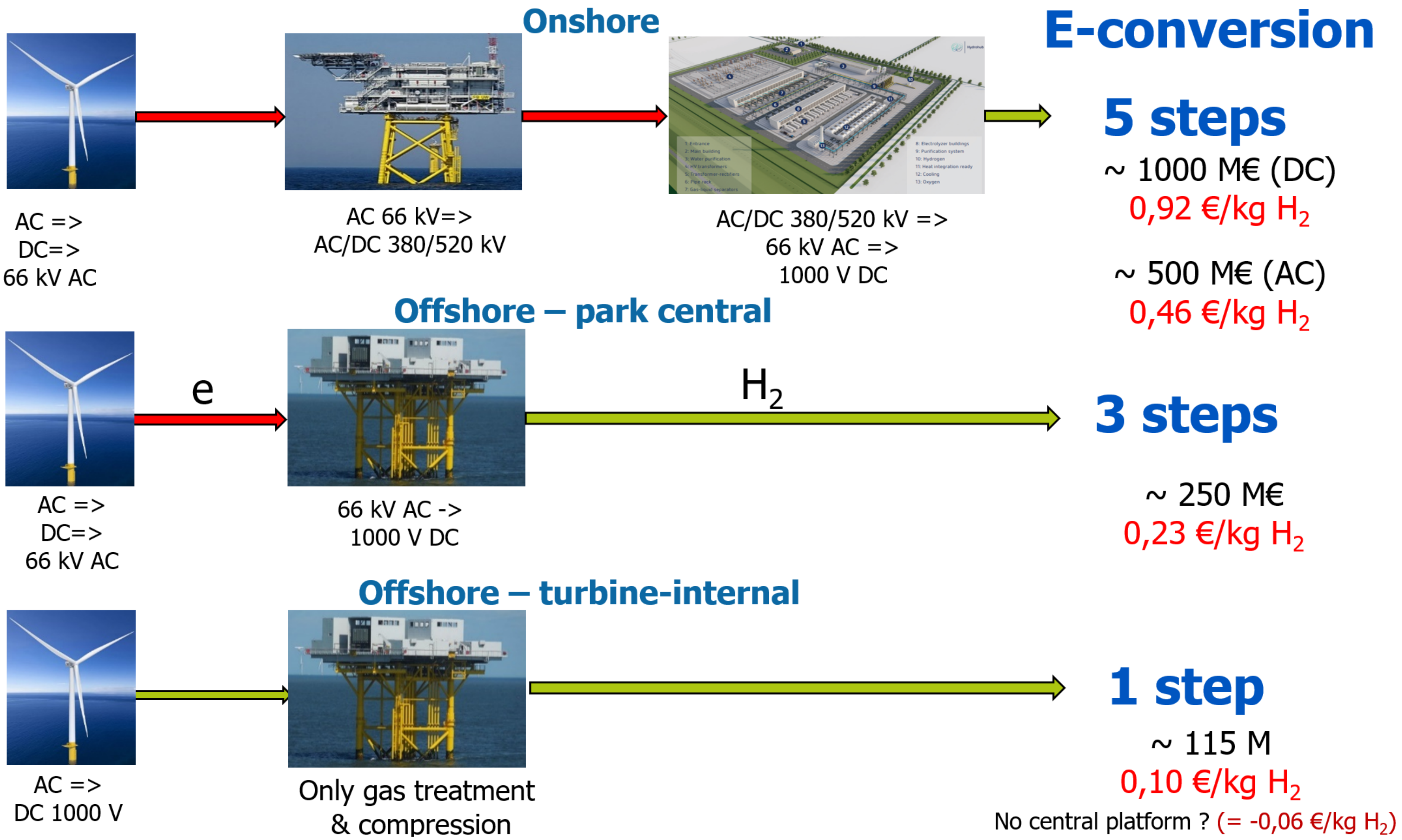
Integrating electrolyser in wind turbine reduces hydrogen production cost, due to savings on electricity conversions



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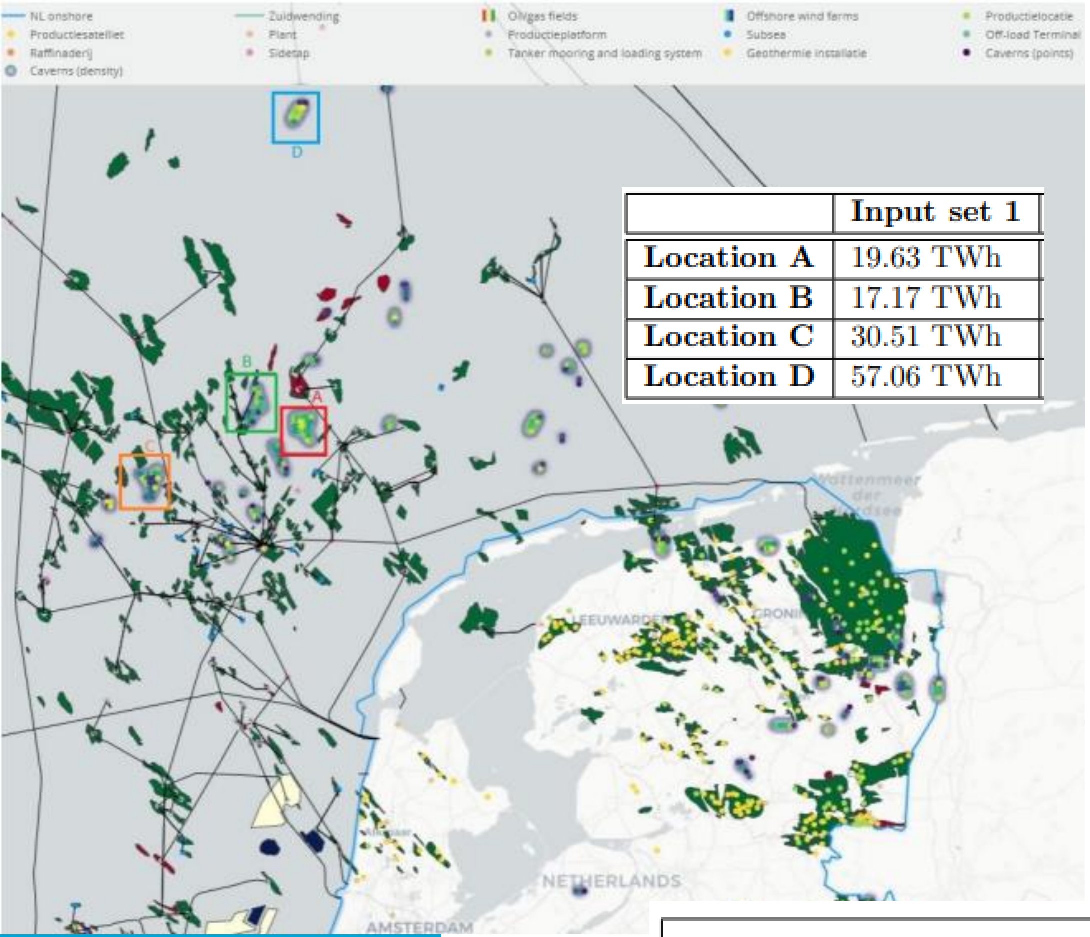
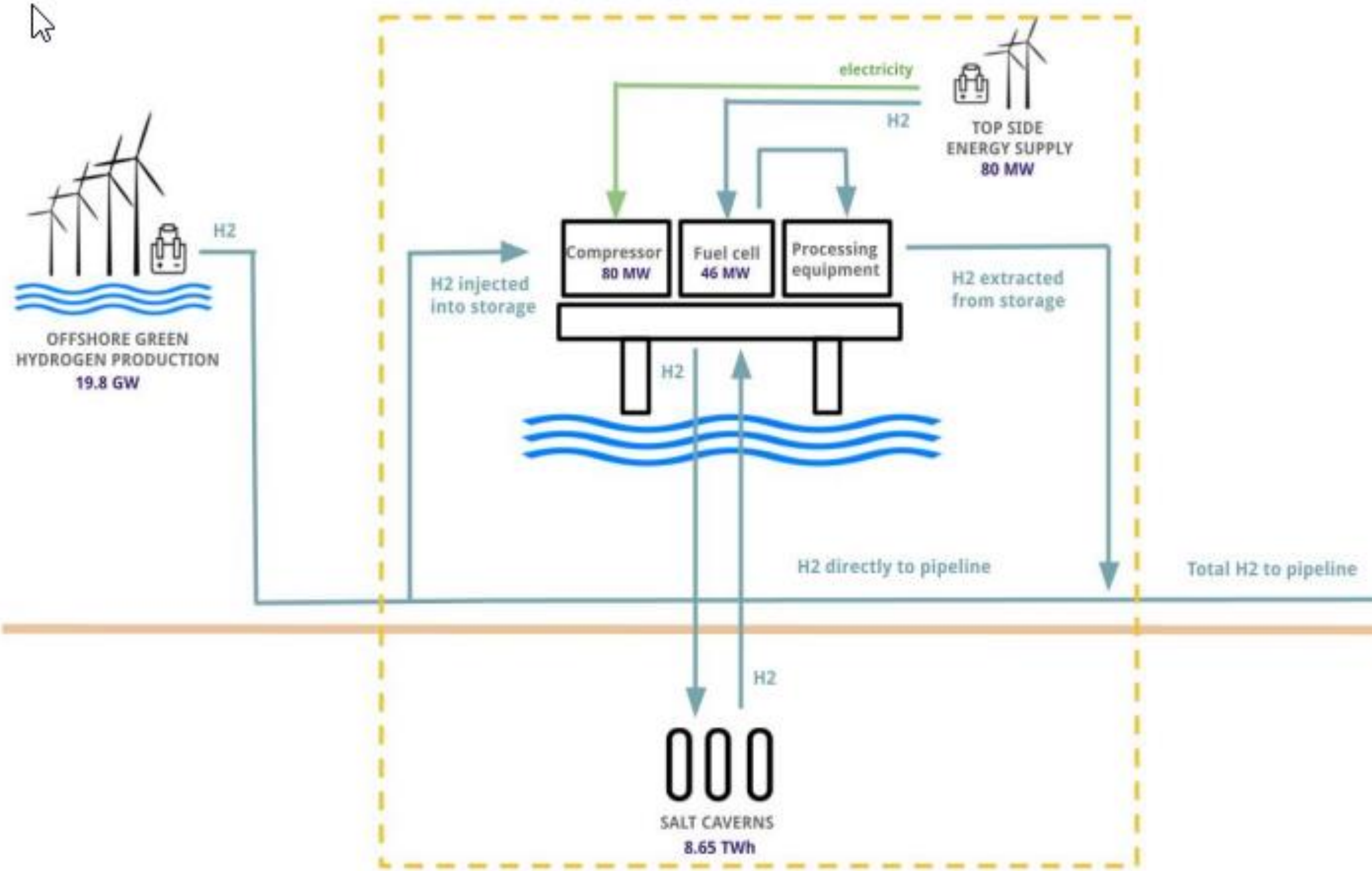
Base-load offshore wind hydrogen supply



	Input set 1
Location A	19.63 TWh
Location B	17.17 TWh
Location C	30.51 TWh
Location D	57.06 TWh



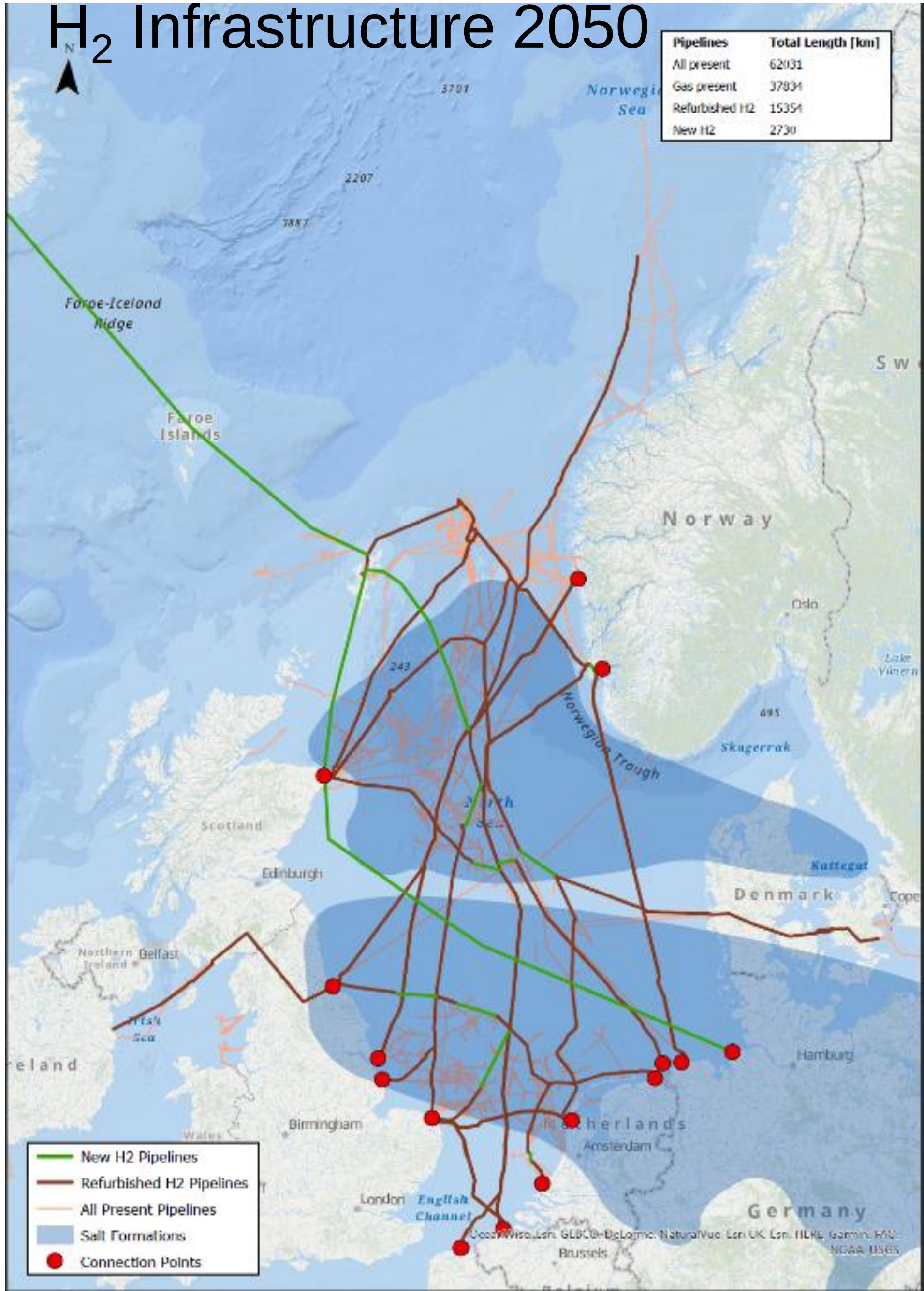
	Year 1 quantity [GWh]	Year 1 quantity [Mton]
H2 production by electrolysis	85800	2.18
H2 inserted in storage	23300	0.59
H2 directly to pipeline	62500	1.59
H2 extracted from storage	23000	0.58
H2 transported to shore	85500	2.17

D.S. Eradus, the techno-economic feasibility of green hydrogen storage in salt caverns in the dutch north sea, MsC thesis TU Delft, January 2022

North Sea Hydrogen infrastructure

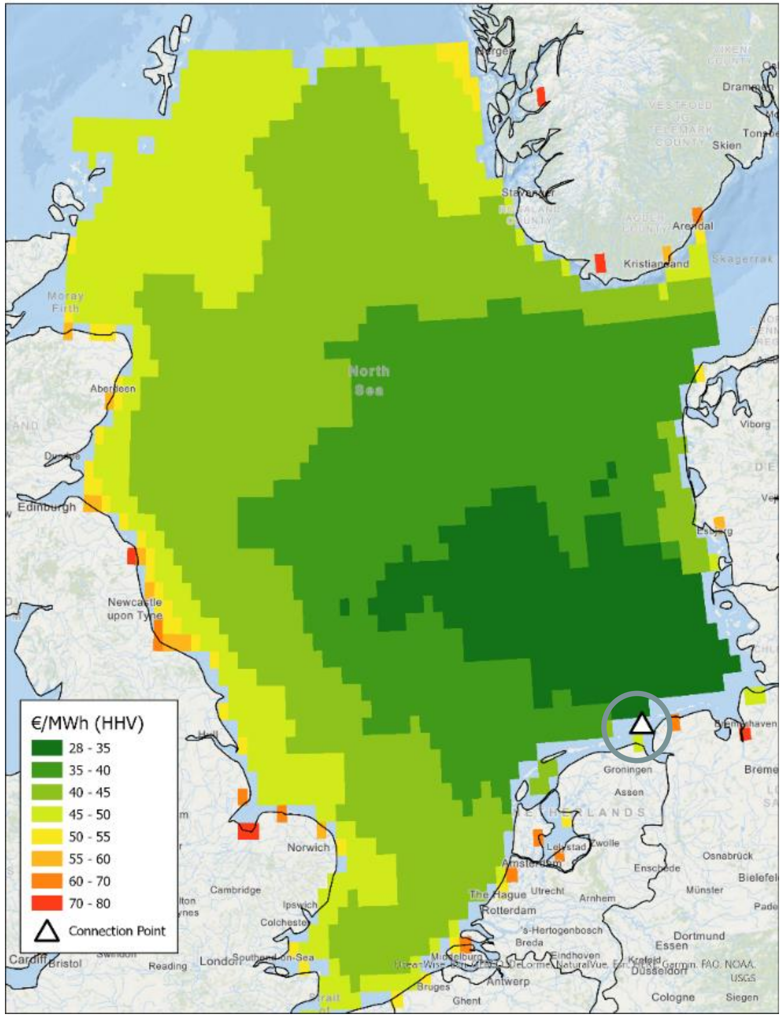
H_2 Infrastructure Dutch part North Sea

H_2 Infrastructure 2050

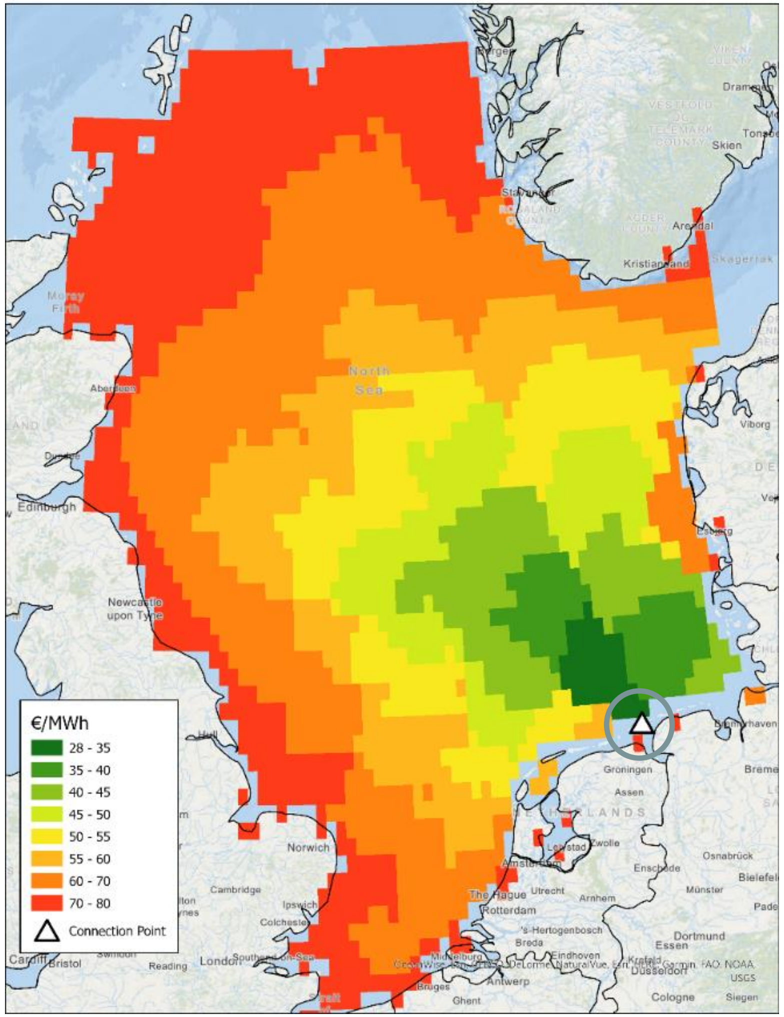


North Sea offshore wind energy shore landing cost in Eemshaven Netherlands for hydrogen and electricity

LCOH €/MWh



LCOE €/MWh



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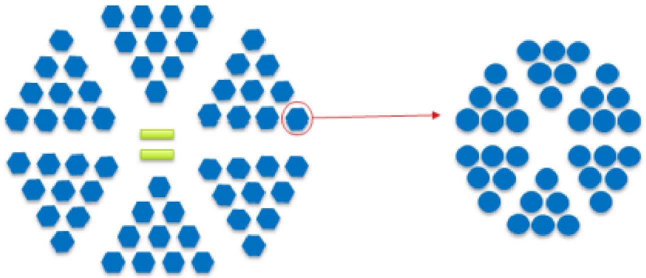
Offshore wind hydrogen projects starting off

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

Offshore solar hydrogen production



C. Zervas, Offshore Solar to Hydrogen A techno-economic analysis, MsC Thesis TU Delft, sept. 2021

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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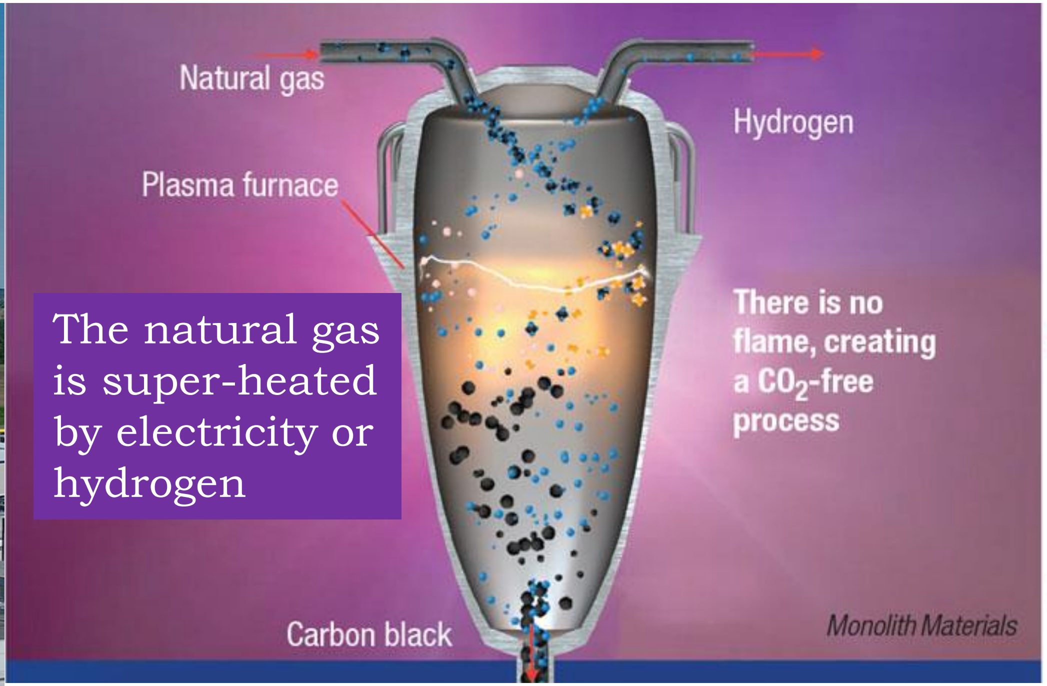
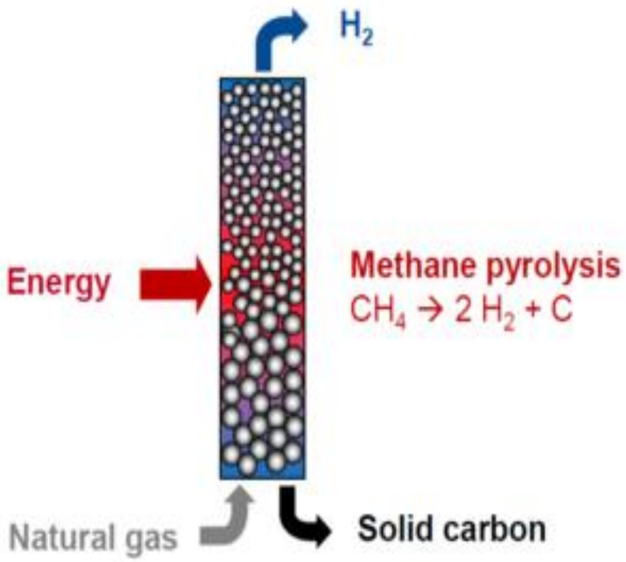
Methane Pyrolysis

Olive Creek, Nebraska, US



Monolith: Plasma Methane Pyrolysis



Monolith clean H_2 production has been granted 1 billion dollar loan by US DOE to expand hydrogen production, dec 2021

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Olive Creek, carbon black/hydrogen production

Olive Creek I (OC1) Facility	
Capacity	Hydrogen Production: ~5 ktpa Carbon Sequestration: ~15 ktpa
Completion	2021
Location	Nebraska, United States
Technology Level	Full commercial scale (TRL 9)

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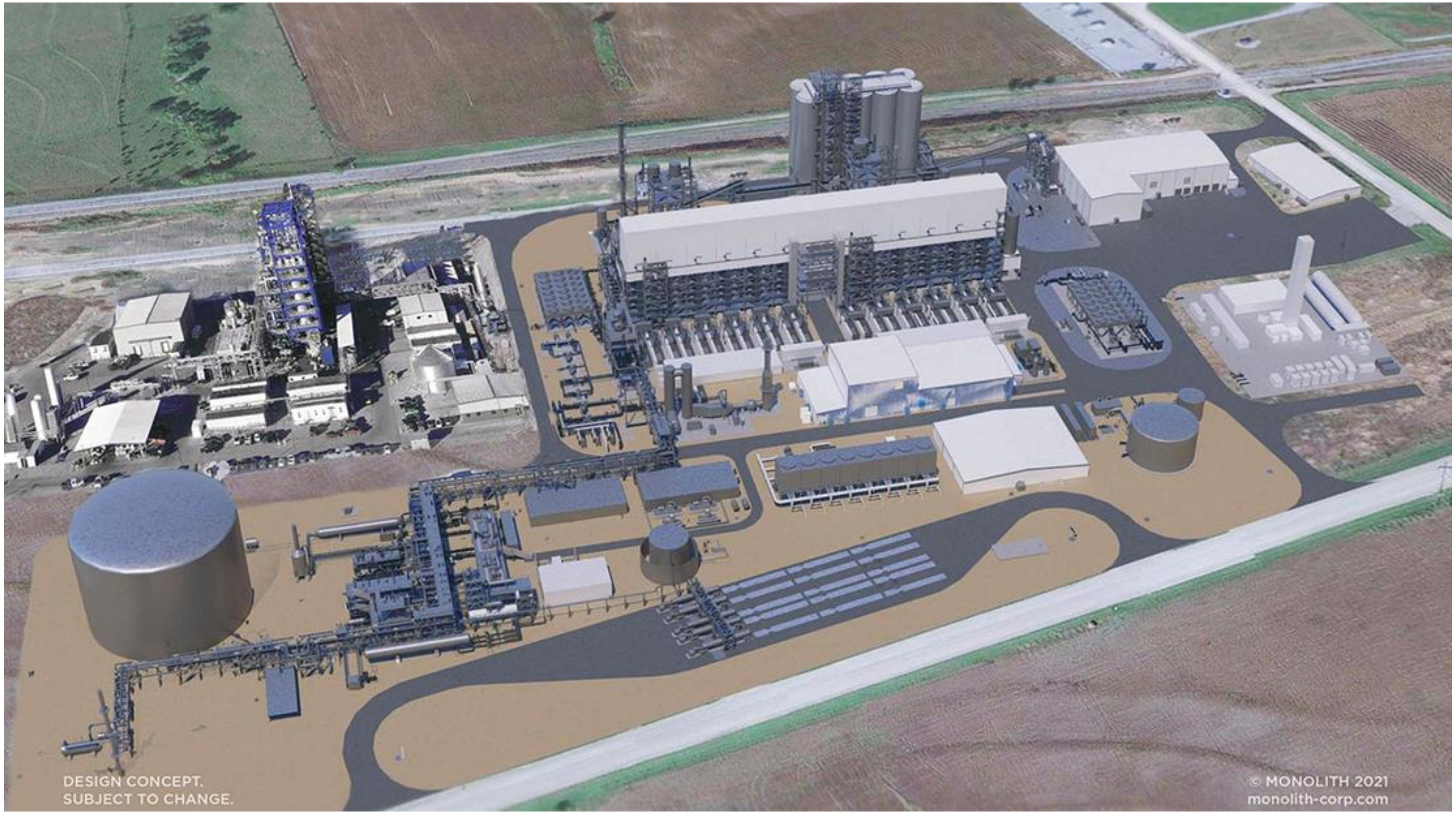
Monolith clean H_2 production
Granted 1 billion dollar loan by US DOE to expand production, dec 2021



Biomass digester + small scale SMR (Steam Methane Reformer) produces biogas with conversion to green H_2 and green CO_2 Results in negative CO_2 emissions

1. Ventilation fan
2. Desulphurisation vessel
3. PSA-vessels
4. Off-gas storage
5. Hydrogen storage
6. Water separator for vacuum pump
7. Vacuum pump
8. Coolant heater
9. Reformate cooler
10. Electronics cabinet
11. Steam generator
12. Reformer unit
13. Low temperature shift
14. Coolant expansion vessel
15. Burner air blower
16. Water purification system

Waste Water Treatment
Integrated, sustainable, circular energy and water system

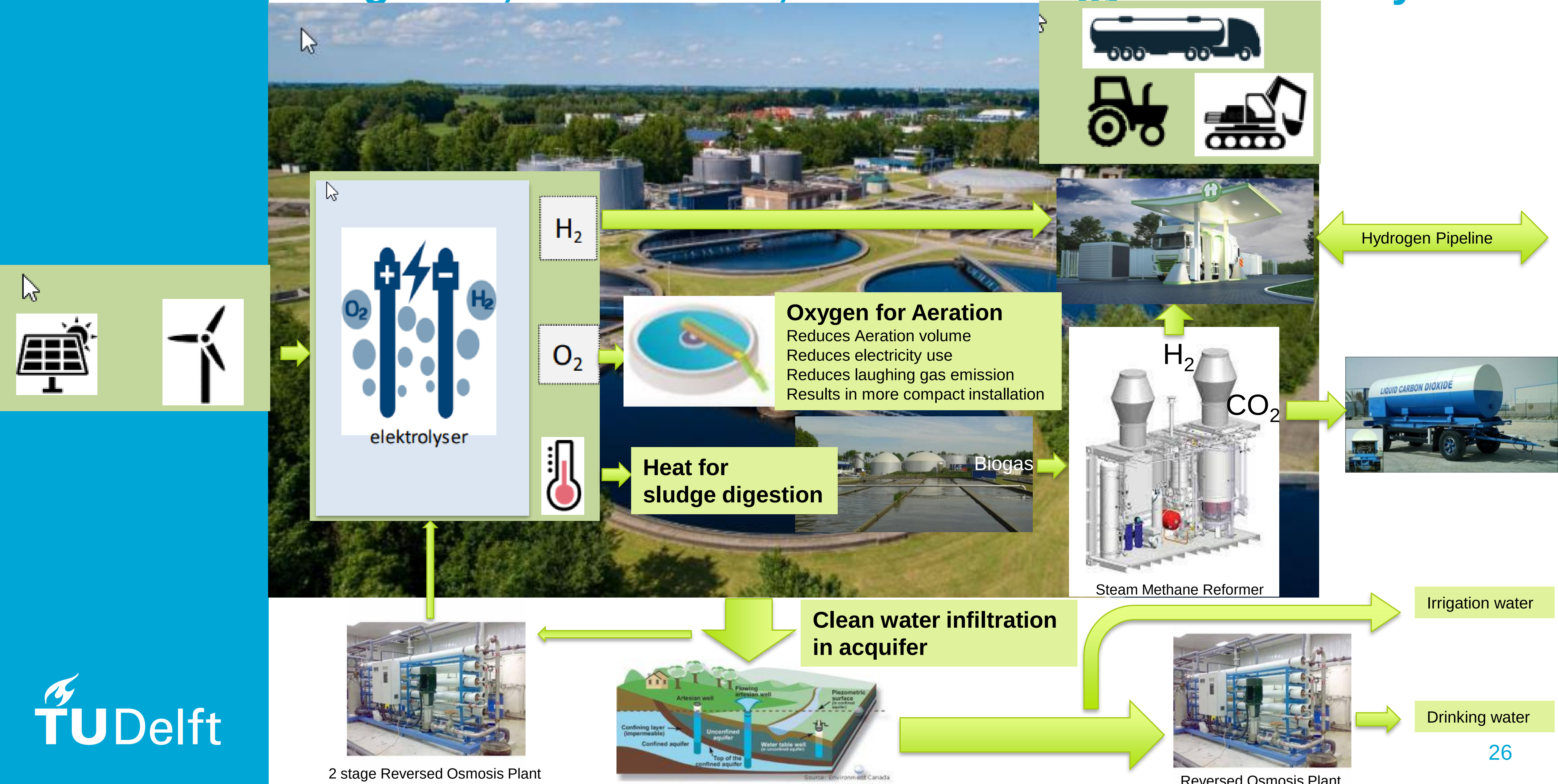


Photo-electrochemical conversion

First prototype solar hydrogen panel Solhyd (KULeuven)

'Very disruptive' direct solar-to-hydrogen commercially viable by 2030, says oil group Repsol

Recharge, Bernd Radowitz, 30-8-2021

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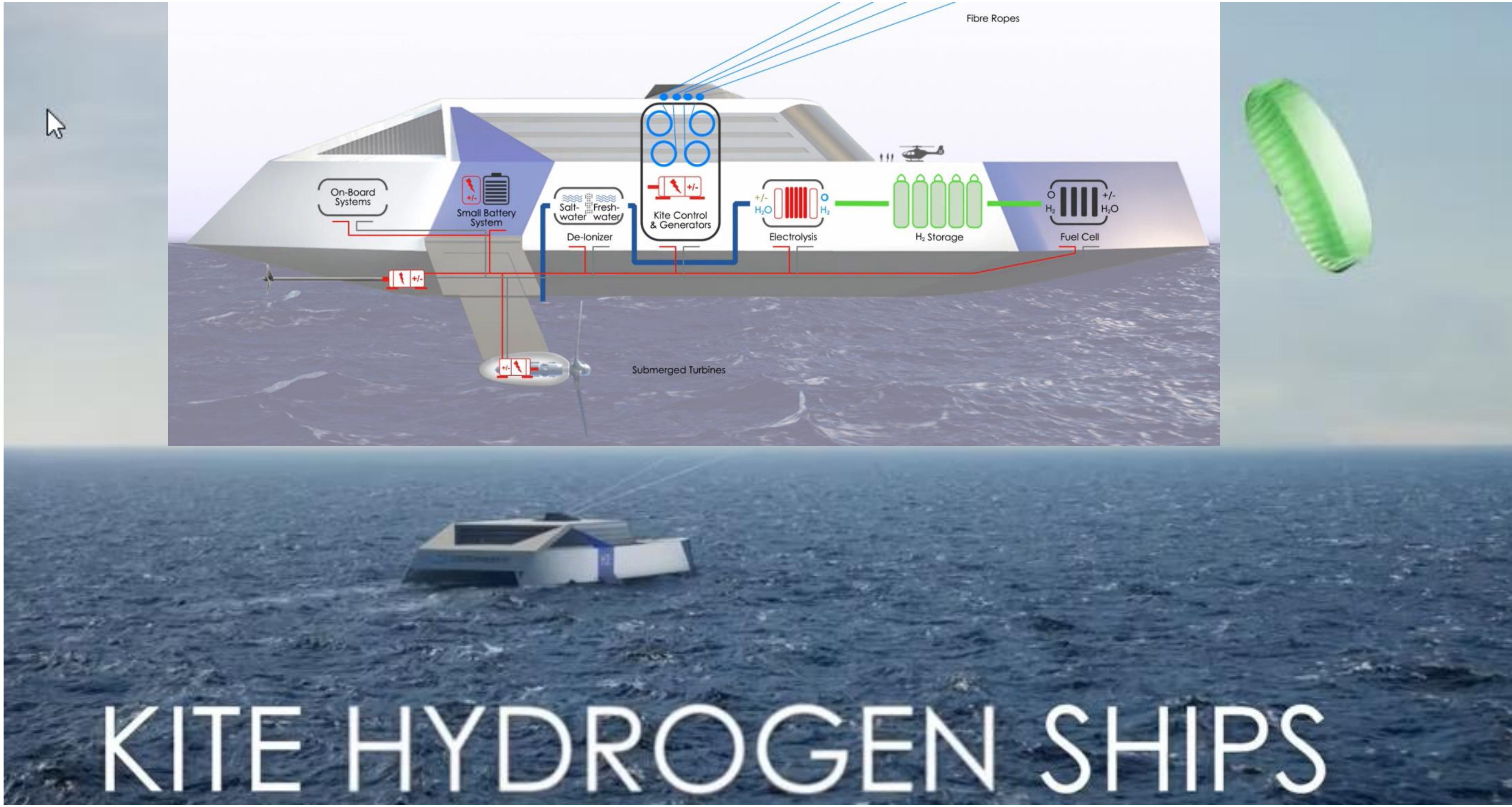
Offshore wind kite hydrogen production

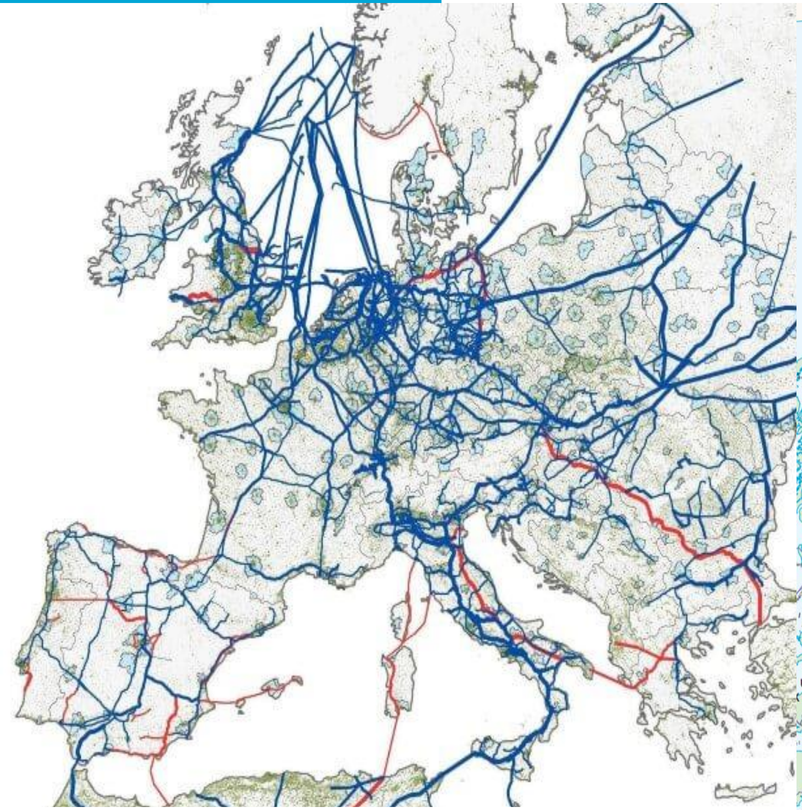


https://vimeo.com/575387429

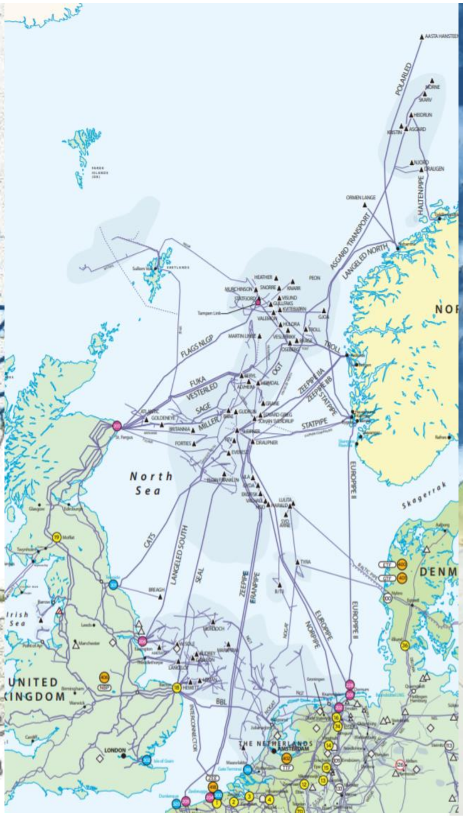
Gas Infrastructure in Europe can be reused for hydrogen

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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Cost for energy transport

(Relatively) Low-Capacity drives electrical transmission costs up.

Liquids have high energy densities and low pumping costs

	Electrical	Liquid Pipeline			Gas Pipeline	
Energy Carrier	HVDC	Crude Oil	Methanol	Ethanol	Nat Gas	Hydrogen
Flow (amps,kg/s)	6,000	1,969	1,863	1,859	368.9	69.54
Rated Capacity (MW)	2,656	91,941	37,435	50,116	17,391	8,360
Capital Cost ($M/mile)	$3.9M	$1.47M	$1.92M	$1.92M	$1.69M	$1.38M
Operating Power: Rated Capacity	12.9%	0.78%	2.02%	1.51%	2.67%	1.94%
Capital Cost ($/(mile-MW))	$1,467	$16	$51	$38	$97	$166
Transmission Cost ($/MWh/1000mi)	$41.50	$0.77	$2.2	$1.7	$3.7	$5.0

= 0.1€/kg H_2/1,000km

Electrical transmission faces high cost for sending electricity

- Costs for transmission methods are usually broken down to $/mile
  - It is more useful to consider the cost per distance per *capacity*

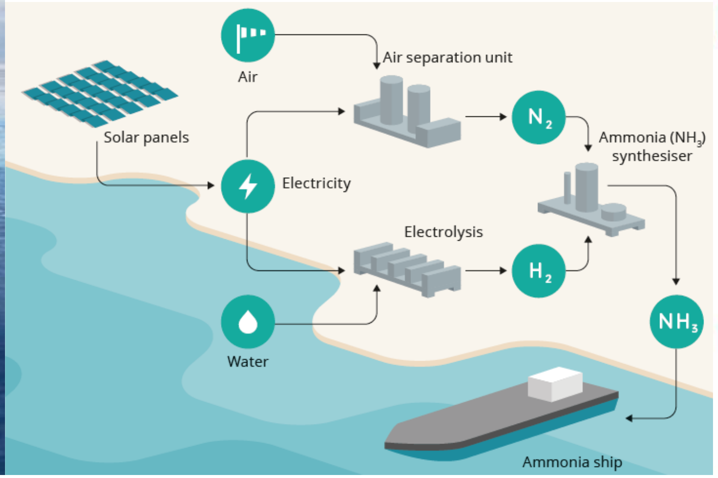
Strategic Alliance, June 2018 https://www.hydrogen.energy.gov/pdfs/review18/pd102_james_2018_p.pdf

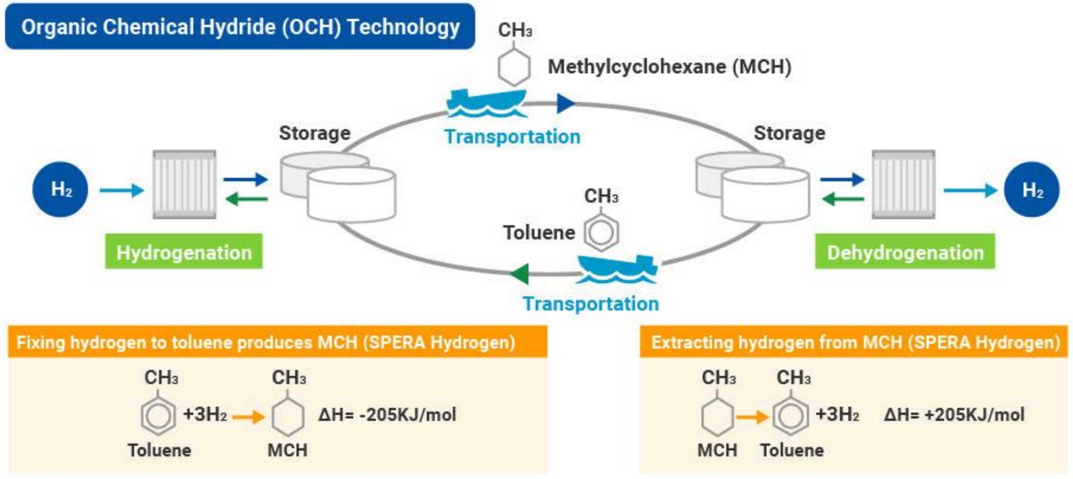
Hydrogen transport by ship

Liquid Hydrogen

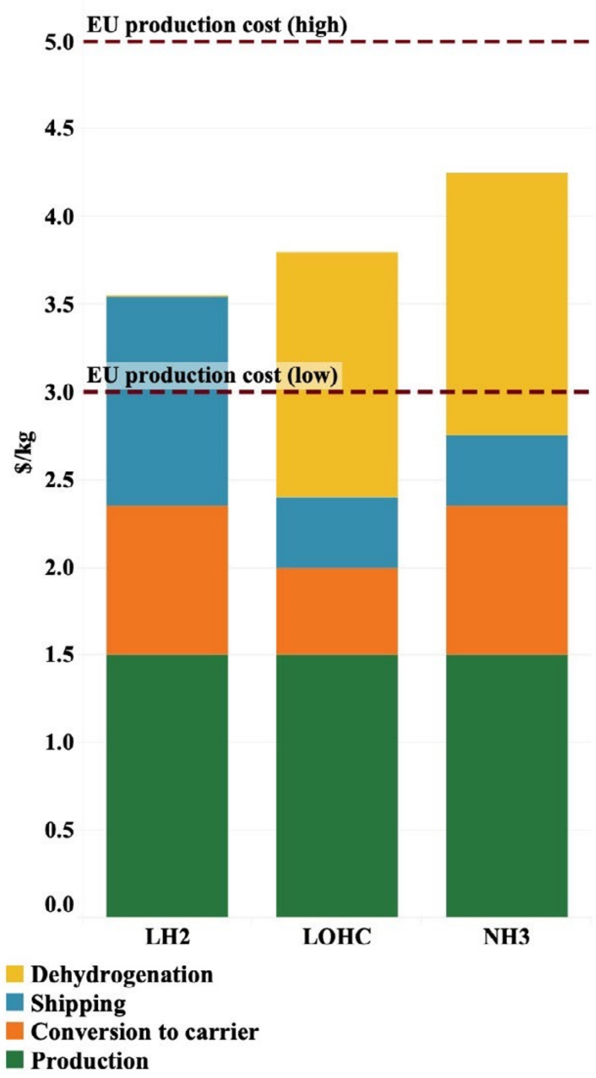
Ammonia

LOHC Liquid Organic Hydrogen Carrier





Estimated delivered cost of green hydrogen from the western region of Saudi Arabia to Rotterdam



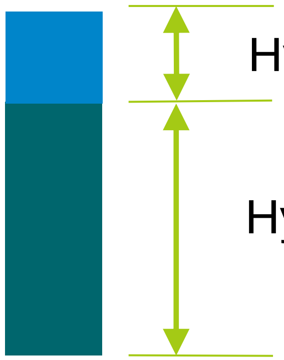
Source: Kapsarc, ILF

From Presentation: KSA EU Hydrogen Relationship

Frank Wouters

Director EU GCC Clean Energy Technology Network

March 2022



Hydrogen transport (5000km): $0.5/kg

Hydrogen production: $1.5/kg

48” Pipeline

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REPowerEU; Joint European Action for more affordable and sustainable energy, EC 8-3-2022

REPOWER EU TRACK	FOCUS	FF55 AMBITION BY 2030	REPOWEREU MEASURE	REPLACED BY THE END OF 2022 (BCM equivalent) estimate	ADDITIONAL TO FF55 BY 2030 (BCM equivalent) estimate
GAS DIVERSIFICATION	NON-RU NATURAL GAS	-	LNG diversification	50*	50
		-	Pipeline import diversification	10	10
	MORE RENEWABLE GAS	17 bcm of biomethane production, saving 17 bcm	Boost biomethane production to 35bcm by 2030	3.5	18
	HYDROGEN ACCELERATOR	**5.6 million tonnes of renewable hydrogen, saving 9-18.5 bcm**	**Boost hydrogen production and imports to 20mt by 2030**	**-**	**25-50**
ELECTRIFY EUROPE	HOMES	Energy efficiency measures, saving 38 bcm	EU-wide energy saving, e.g. by turning down the thermostat for buildings' heating by 1°C, saving 10bcm	14	10
		Counted under overall RES figures below	Solar rooftops front loading – up to 15 TWh within a year	2.5	frontloaded
		30 million newly installed heat pumps installed in 2030, saving 35 bcm in 2030	Heat pump roll out front loading by doubling deployment resulting in a cumulative 10 million units over the next 5 years	1.5	frontloaded
	POWER SECTOR	Deploy 480 GW of wind capacities and 420 GW of solar capacities, saving 170bcm (and producing 5.6 Mt of Green Hydrogen)	Wind and solar front loading, increasing average deployment rate by 20%, saving 3bcm of gas, and additional capacities of 80GW by 2030 to accommodate for higher production of renewable hydrogen.	20	Gas savings from higher ambition counted under green hydrogen, the rest is frontloaded
TRANSFORM INDUSTRY	ENERGY-INTENSIVE INDUSTRIES	Front load electrification and renewable hydrogen uptake	Front load Innovation Fund and extend the scope to carbon contracts for difference	Gas savings counted under the renewable hydrogen and renewables targets	

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A108%3AFIN

Hydrogen Accelerator requires 300-400 GW installed electrolyser capacity in 2030

2*10 million ton green hydrogen	Renewable Resource			Electrolyser		Hydrogen Production	
2030	Capacity	Full load hours	Electricity Production	Capacity	Full-load hours		
	GW	hr/yr	TWh	GW	hr/yr	Million ton	TWhHHV
EU production							
Offshore	30	5.000	150	30	5.000	3	118
Onshore wind	35	3.000	105	30	3.400	2	79
Solar PV	150	1.500	225	125	1.750	4	158
Grid connected electrolysers	Renewable/Nuclear electricity from grid			7	7.000	1	39
Import							
Onshore wind	30	3.500	105	25	4.100	2	79
Solar PV	150	2.100	315	115	2.650	6	237
Offshore wind	10	5.000	50	10	5.000	1	39
Hydropower/Nuclear	8	6.000	51	8	6.000	1	39
Total				**350**		**20**	**788**

https://hydrogeneurope.eu/reports/

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Hydrogen Accelerator; hydrogen pipeline infrastructure

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

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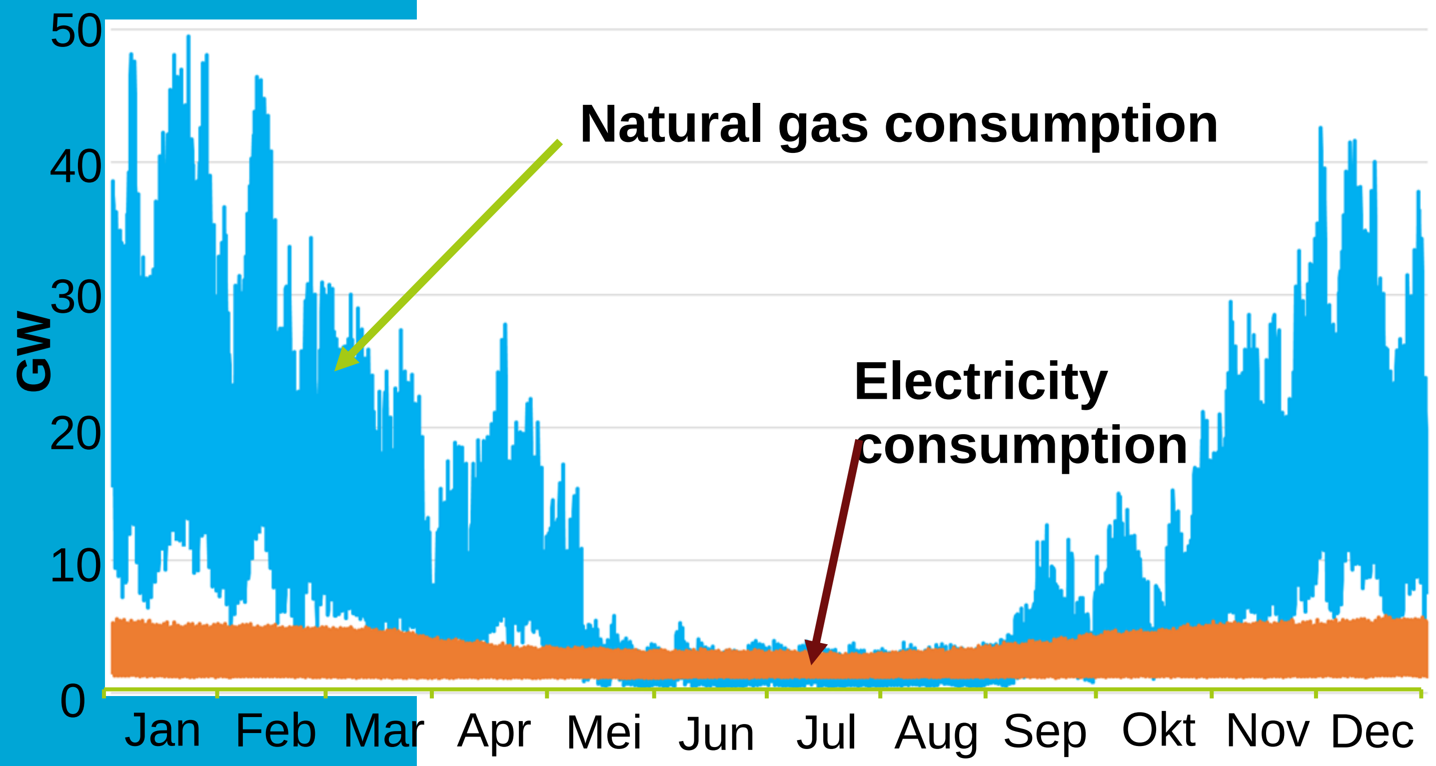
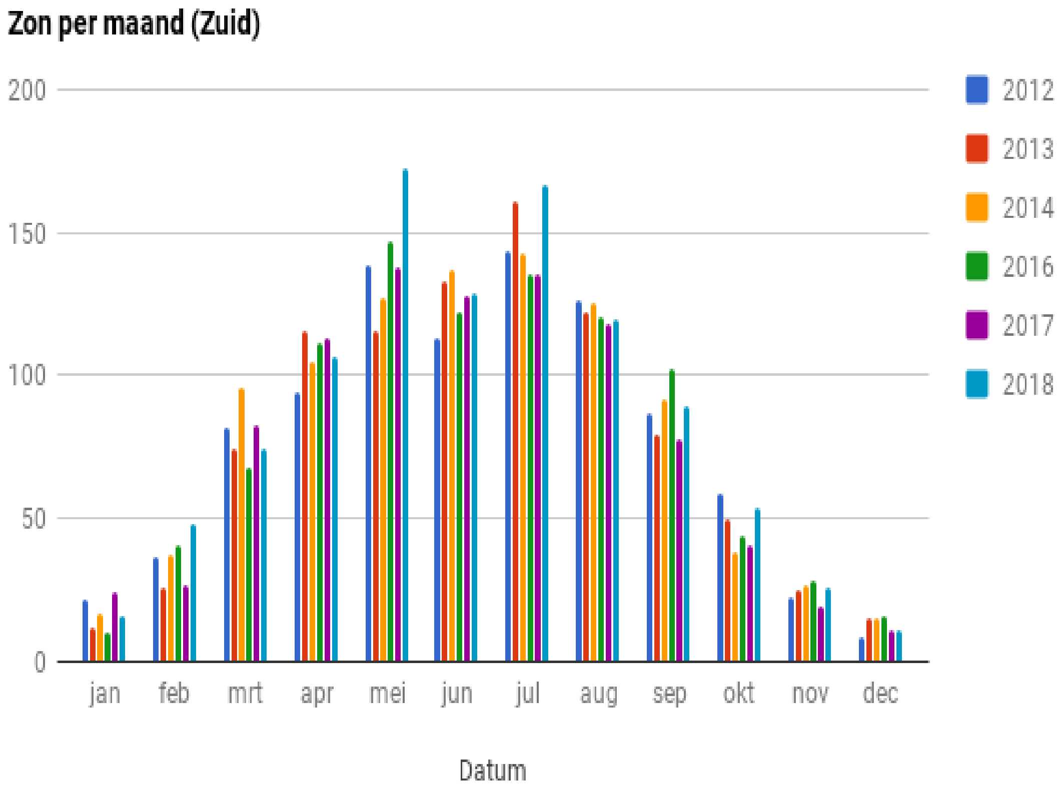
Storage will become an even larger challenge then today
Today large scale seasonal storage is already present
Example the Netherlands



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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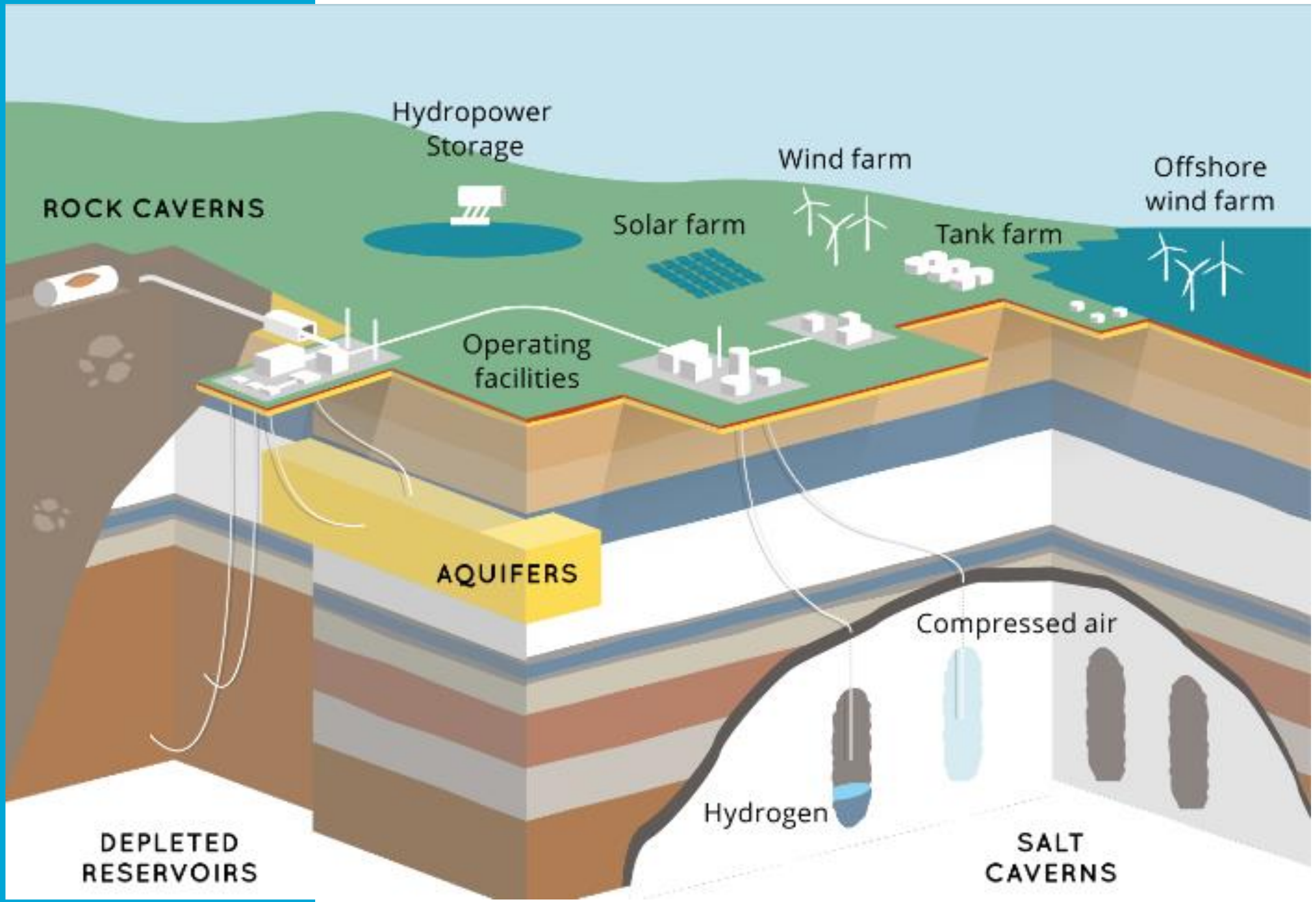
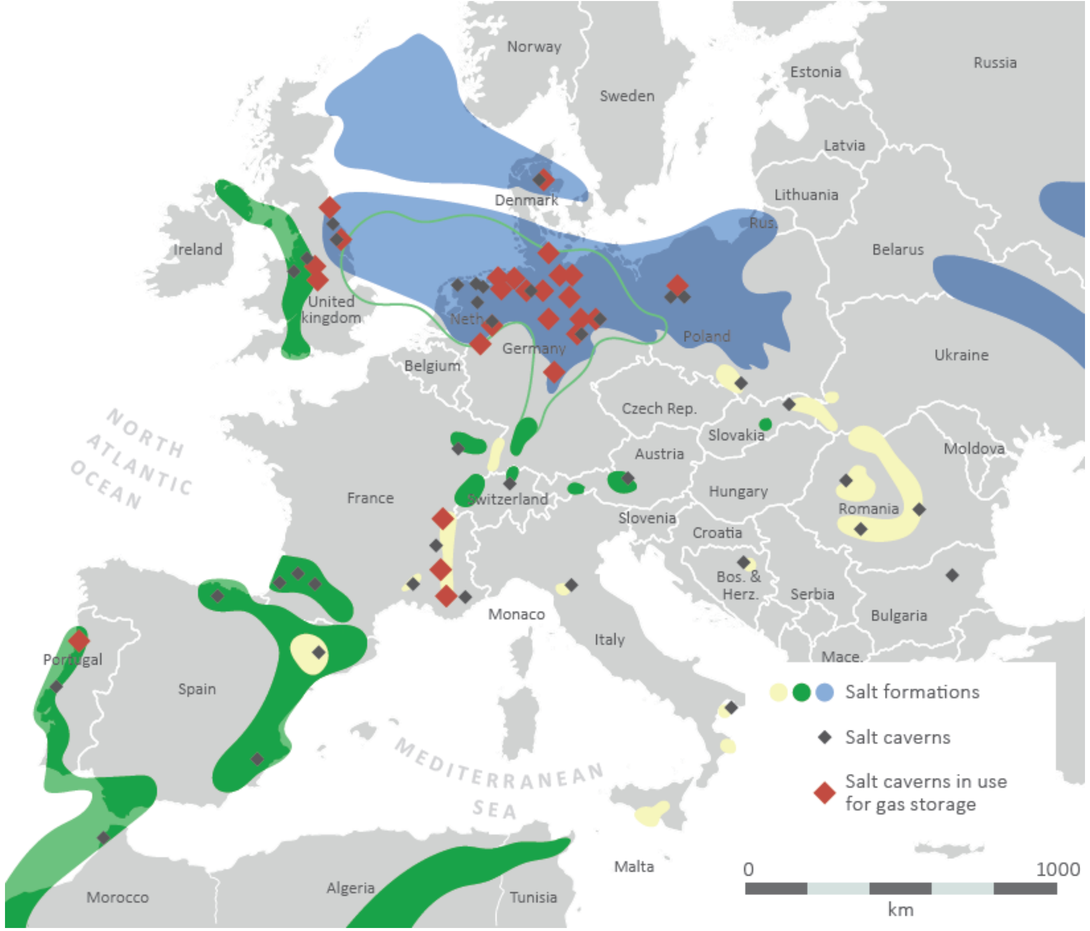
Hydrogen storage in salt caverns



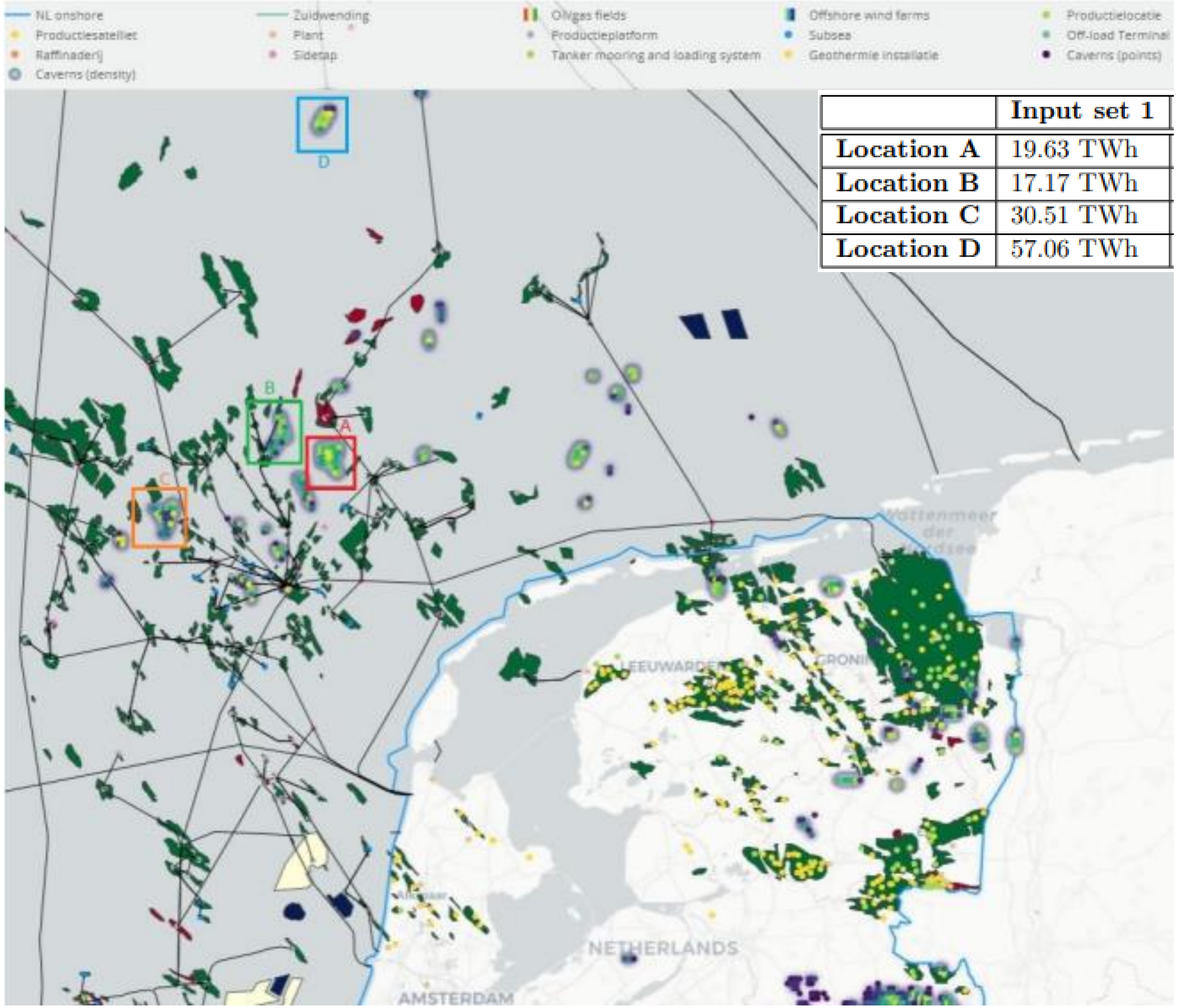
Salt formations and caverns in Europa



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

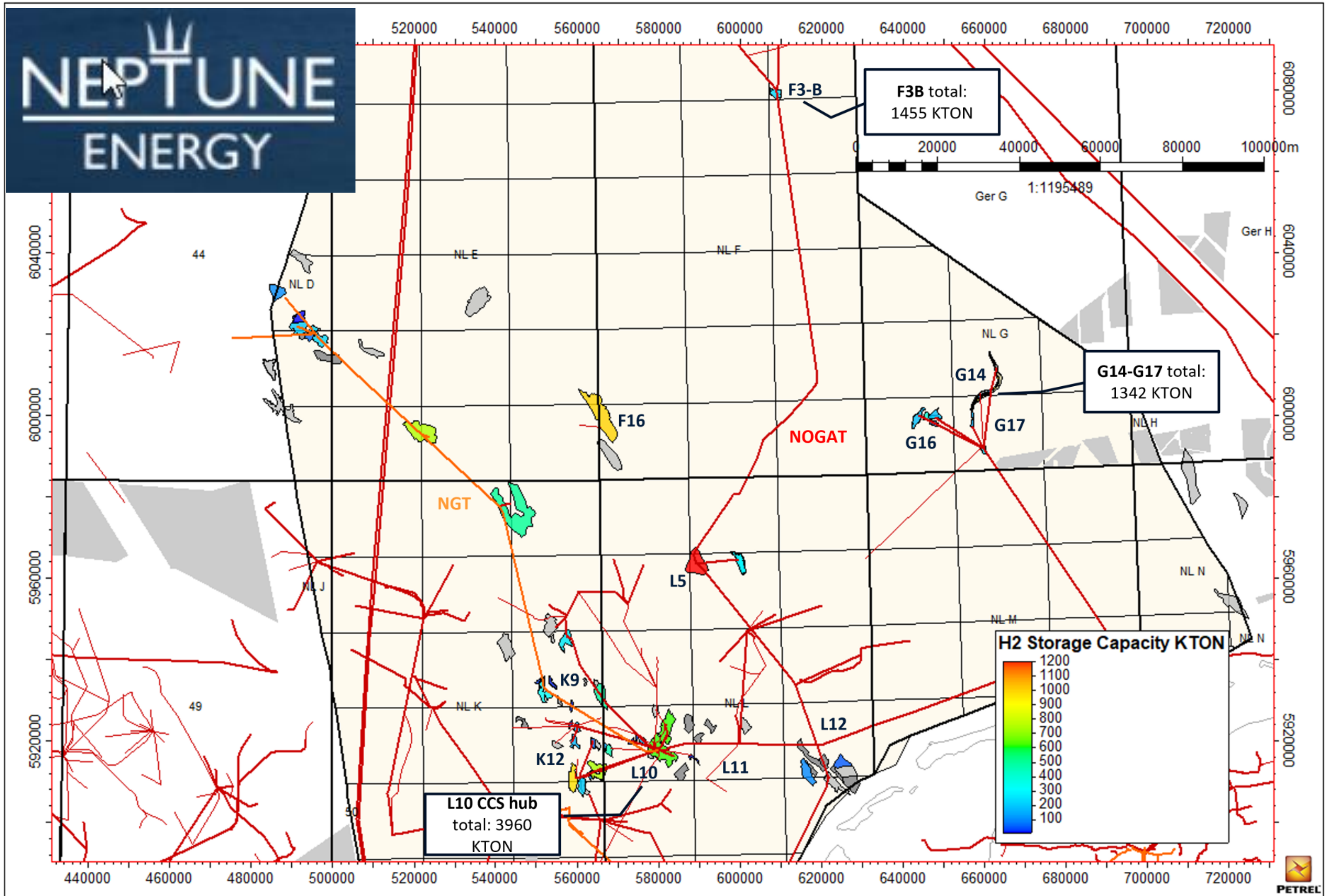
Suitable Salt Cavern storage clusters at Dutch part of the North Sea



	Input set 1
Location A	19.63 TWh
Location B	17.17 TWh
Location C	30.51 TWh
Location D	57.06 TWh

Potential hydrogen storage capacity in NEPTUNE empty gas fields at Dutch part NorthSea

not all of these fields are suitable



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 $H2$ 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

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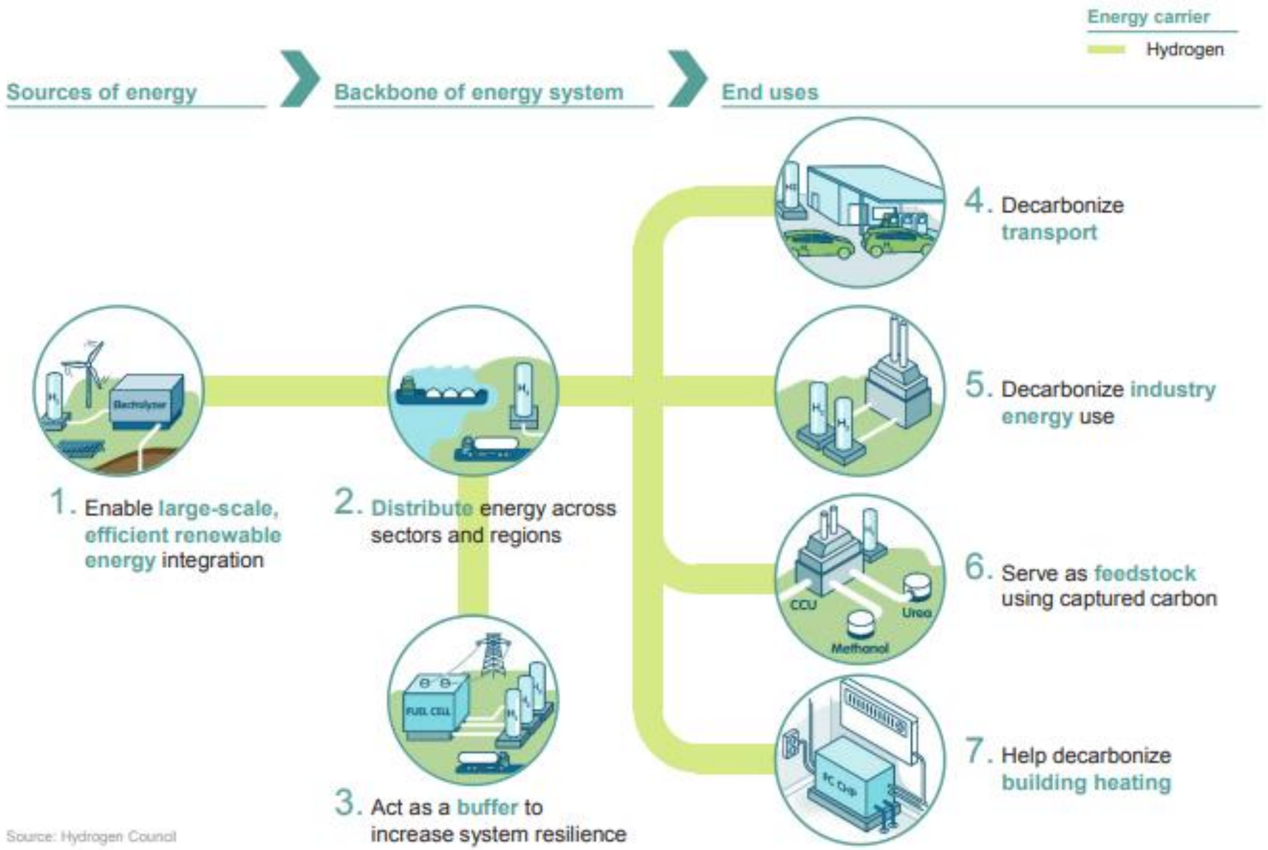
Hydrogen in a carbon-free energy system

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

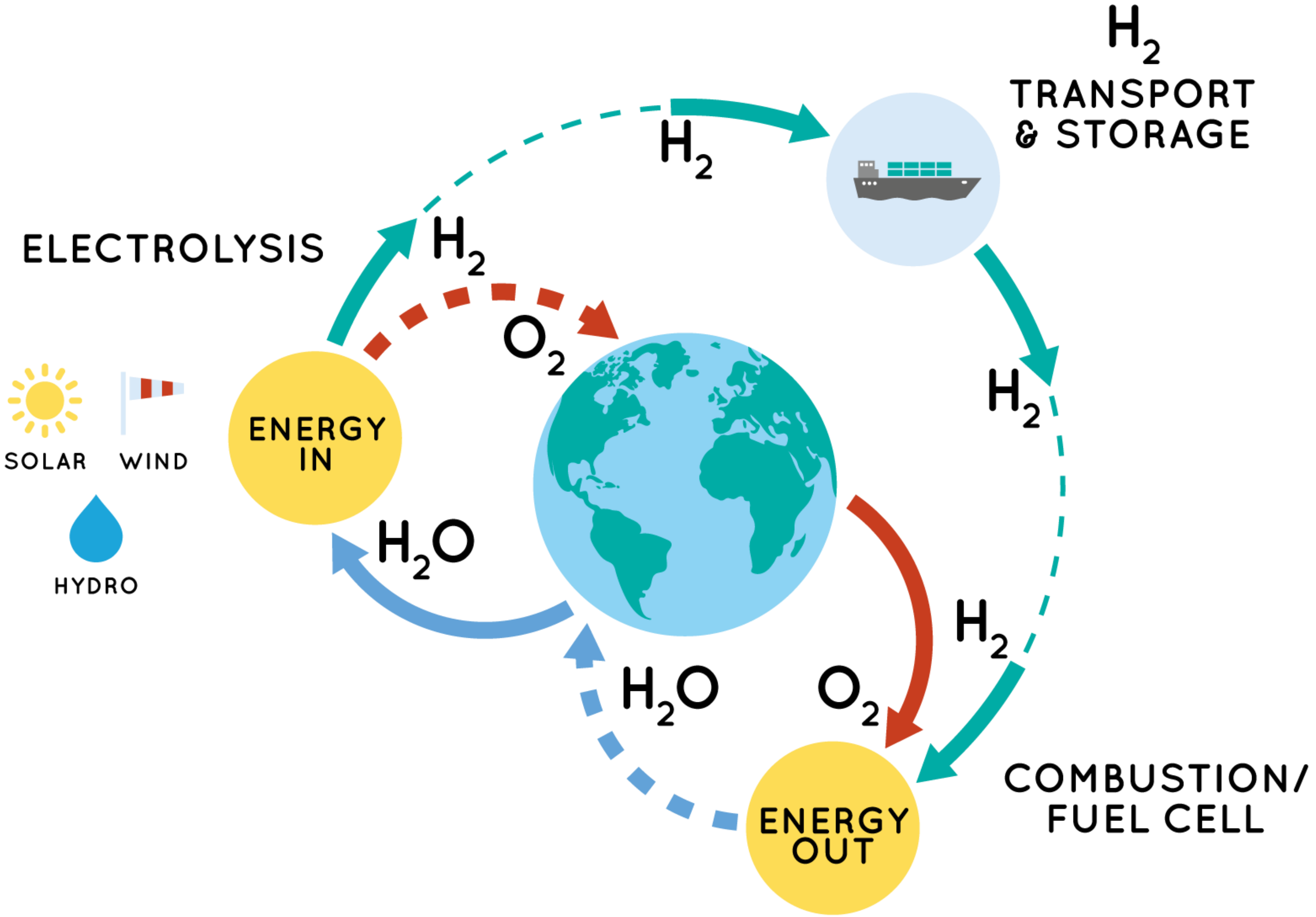
2. To decarbonize hard to abate energy use (industry, feedstock, mobility, heating and balancing electricity system)

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

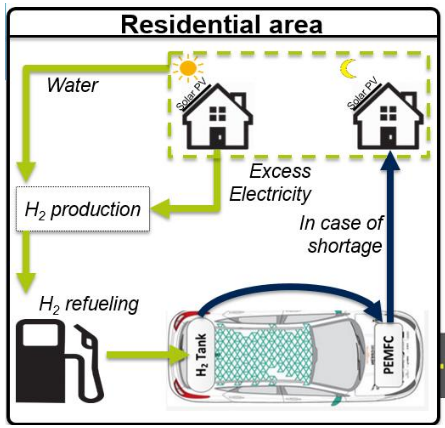
The Hydrogen Cycle



Hydrogen Markets

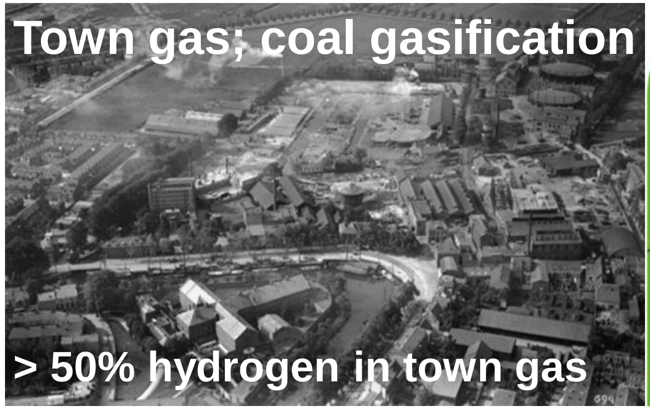
Industry Feedstock/HT Heat

Electricity Balancing

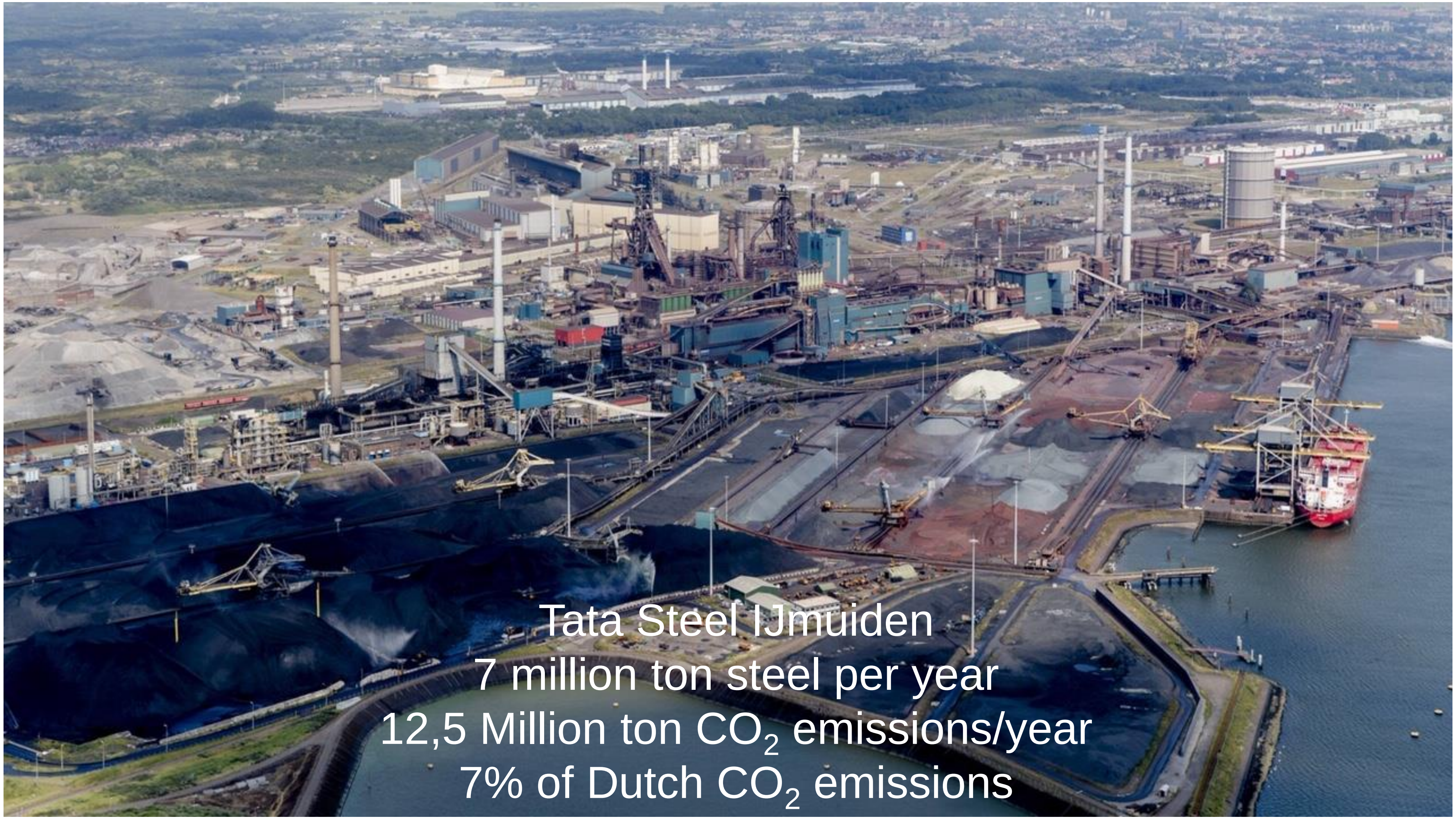


Transport

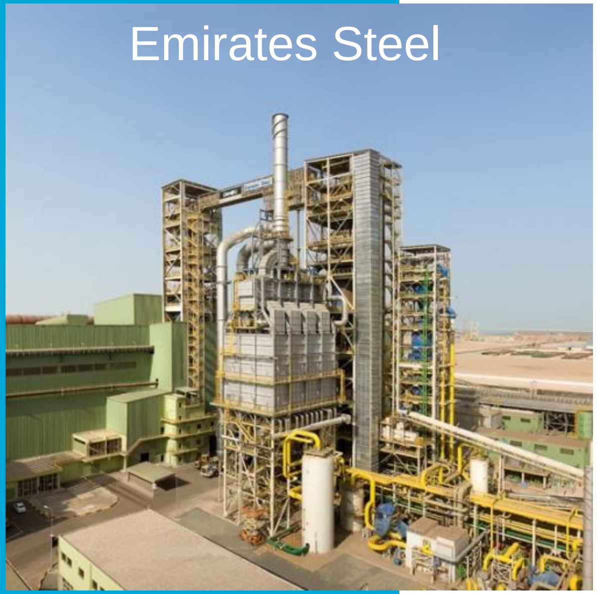
Heating



The Future for Steel Plant and site IJmuiden



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

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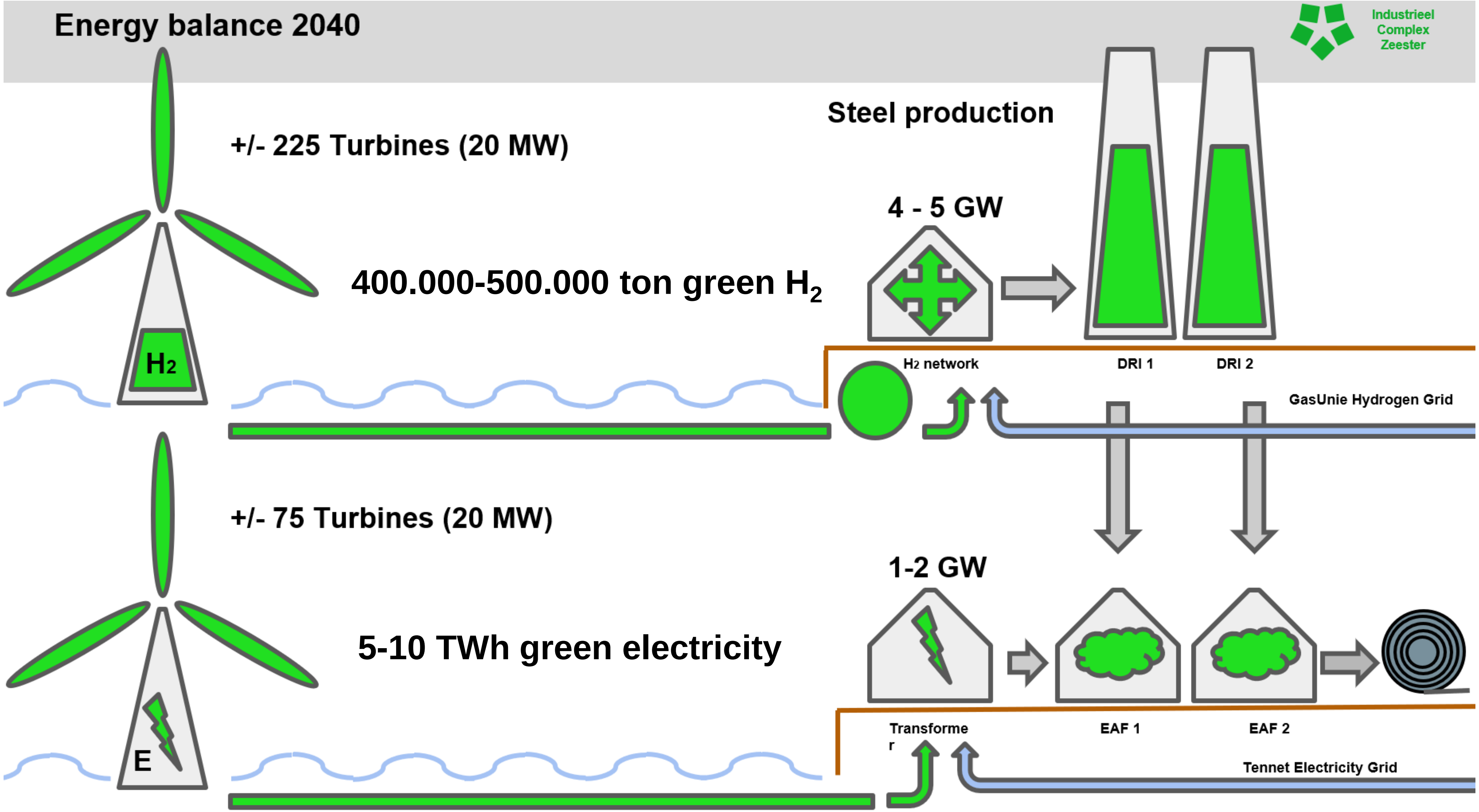
Tata Steel on ‘base load’ green hydrogen and electricity



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

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

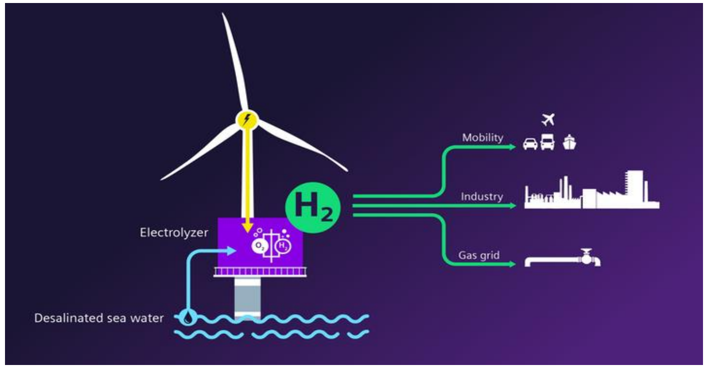
Offshore wind turbine about 100 ton steel per MW

Foundations, Mast, Nacelle

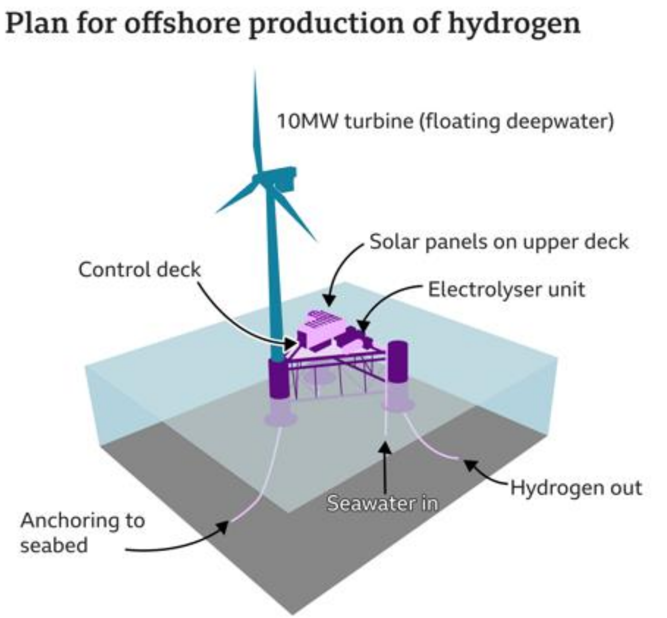
Offshore (Floating) integrated Wind-Hydrogen Turbines

GE Haliade X 12-14 MW

SG 14-222 DD 14-15 MW



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

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Domestic heating with hydrogen boilers

Remeha

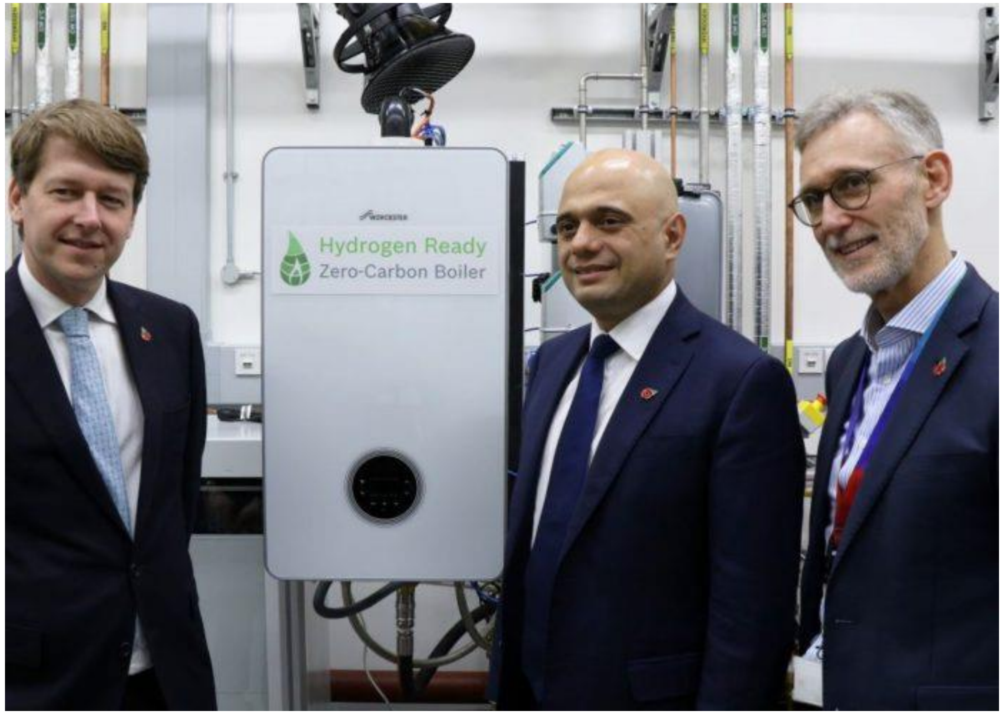
Remeha HYDRA

	Hydrogen	Natural gas	
CO_2	0	9	%
	0	190	g/kWh
	0	2500	kg/jaar*
CO	0	48	ppm
NOx	20	30	mg/kWh Hs
Efficiency**	115	108	% LCV
	97	97	% HCV
Output Heating	24	24	kW
Output DHW	28	28	kW

* At average gas consumption
** Tretour = 30°C, 30% load

Hydrogen boiler
(launched March 2019)

Worcester Bosch



Hydrogen ready boiler
(launched November 2019)

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Smart hybrid solutions, cost efficient and less nuisance:

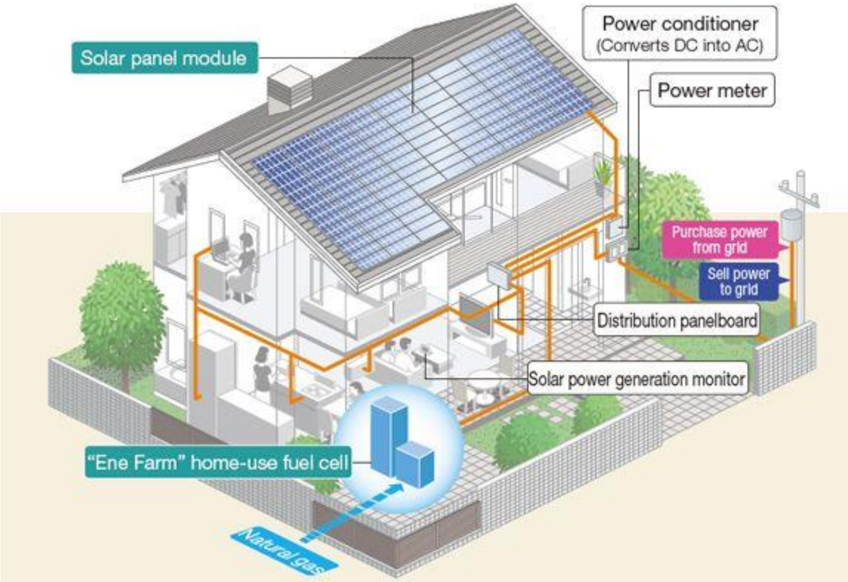
- Insolate what is easy to do and cost effective
- Heat pump for baseload heat; COP 5,2 in stead of COP 3,4
- Hydrogen boiler for peakload heat in winter
- No electricity grid expansion necessary

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

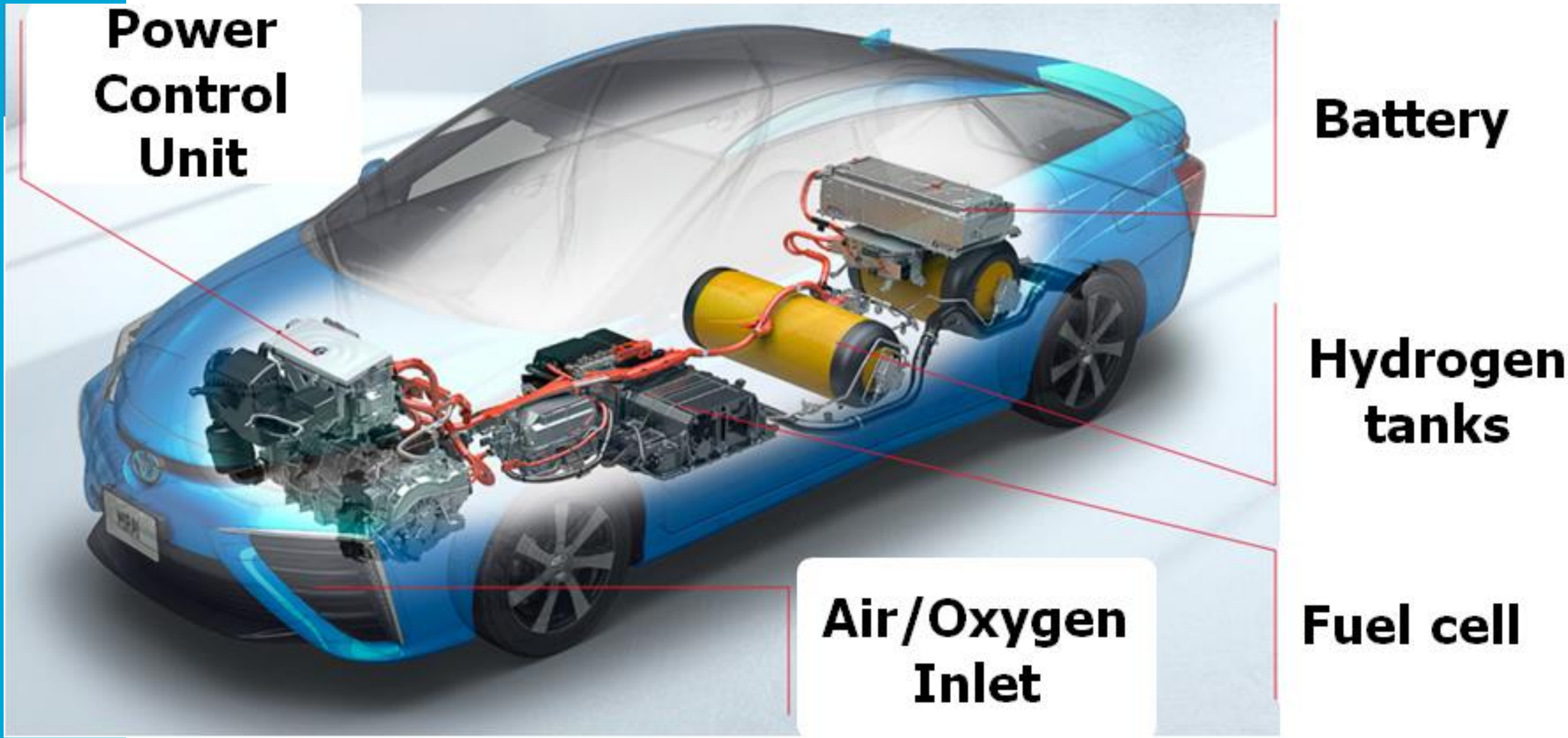


The future for mobility is electric!

Tesla Model S

Toyota Mirai

Toyota Mirai; Fuel cell car



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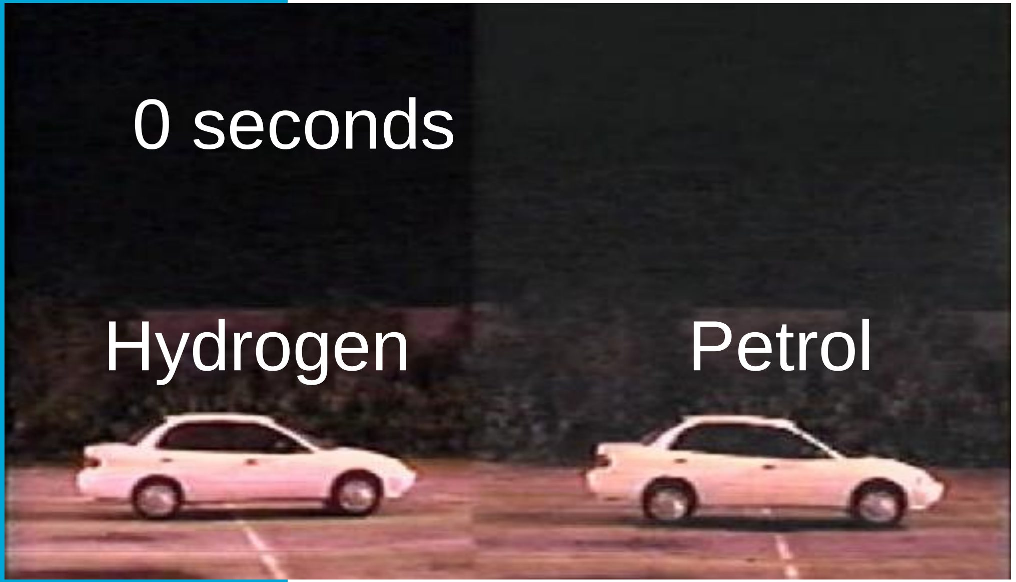
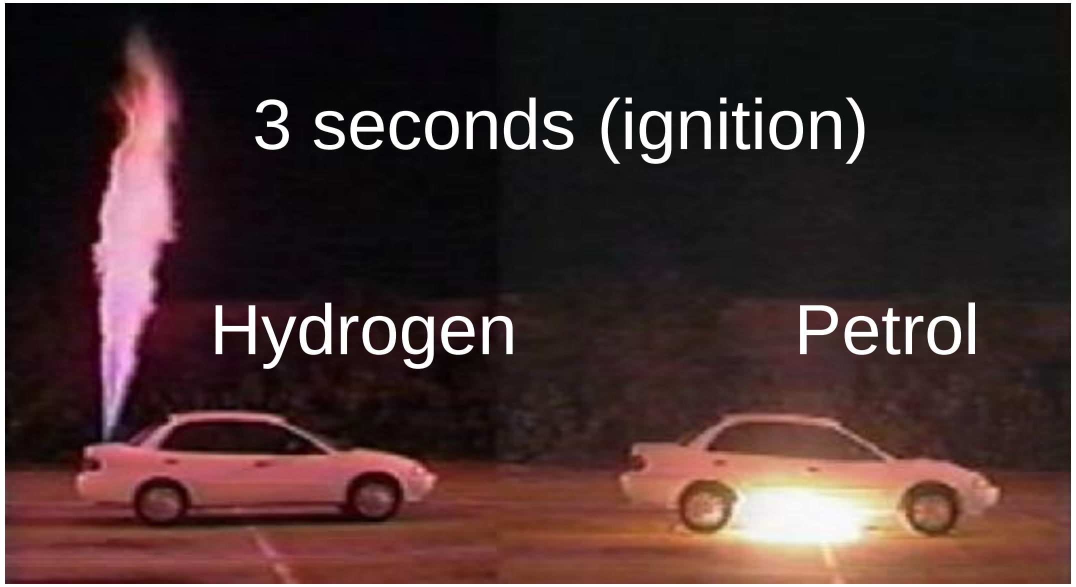
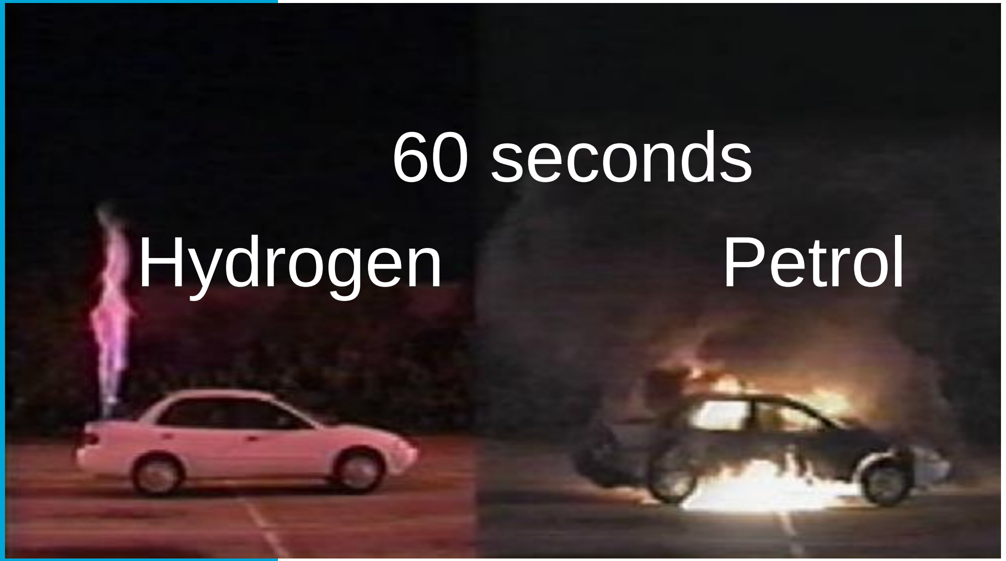
Veiligheid: Waterstof versus benzine







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Hydrogen in transport

JosScholman/New-Holland:
Tractor, dual fuel (diesel+H_2)

Doosan:
Hydrogen fuel cell drones

Stellantis/Opel:
Hydrogen fuel cell Van

Toyota: Hydrogen fuel cell Fork Lift

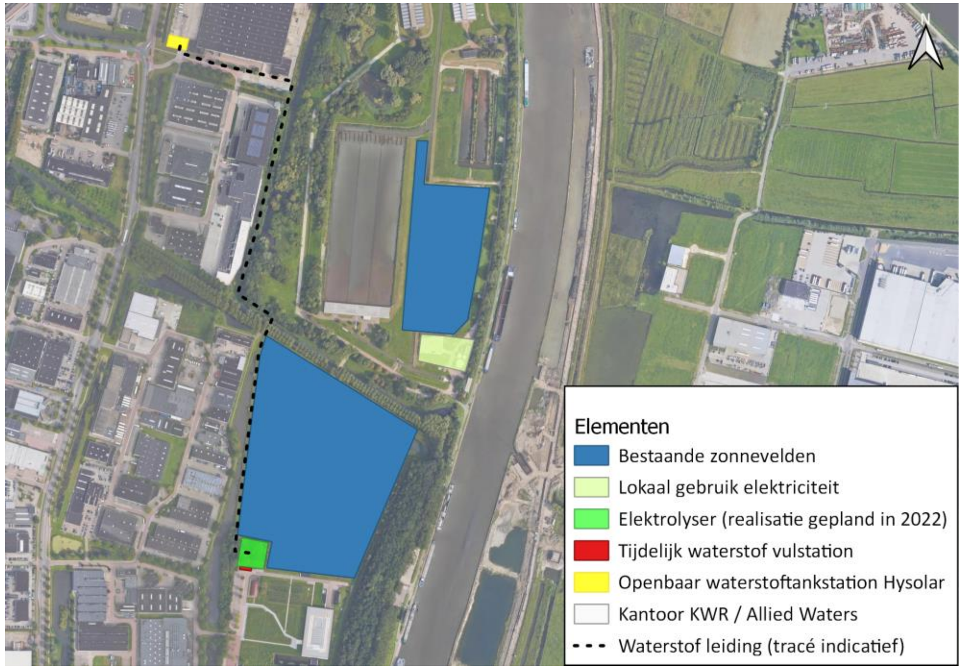
Caetano: Hydrogen bus with
Toyota fuel cell

Hyzon-Holthausen: Production
Hydrogen fuel cell trucks

Tractor dual fuel, hydrogen-diesel
11 kilo hydrogen in tanks on the roof

Power to X project Nieuwegein

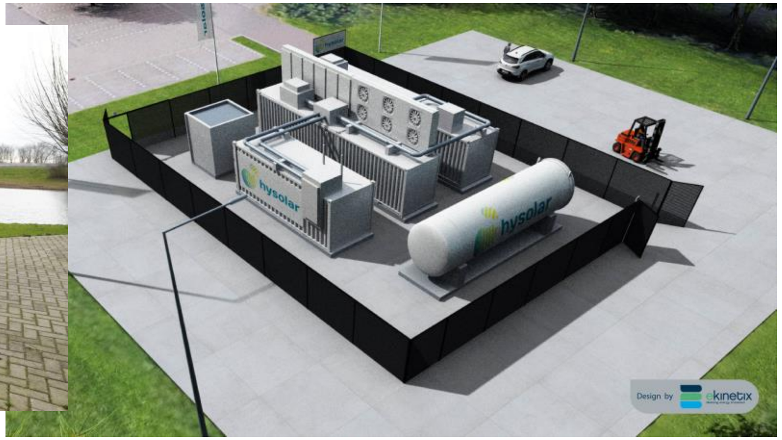
Zonnepark op WRK terrein + op dak KWR gebouw



Waterstof tankstation bij JosScholman
Nieuwegein/Utrecht
Officieel geopend 8 Oktober 2021

Waterstof vulstation bij KWR

Dual Fuel Tractor en Holder;
60-80% waterstof bijmengen mogelijk

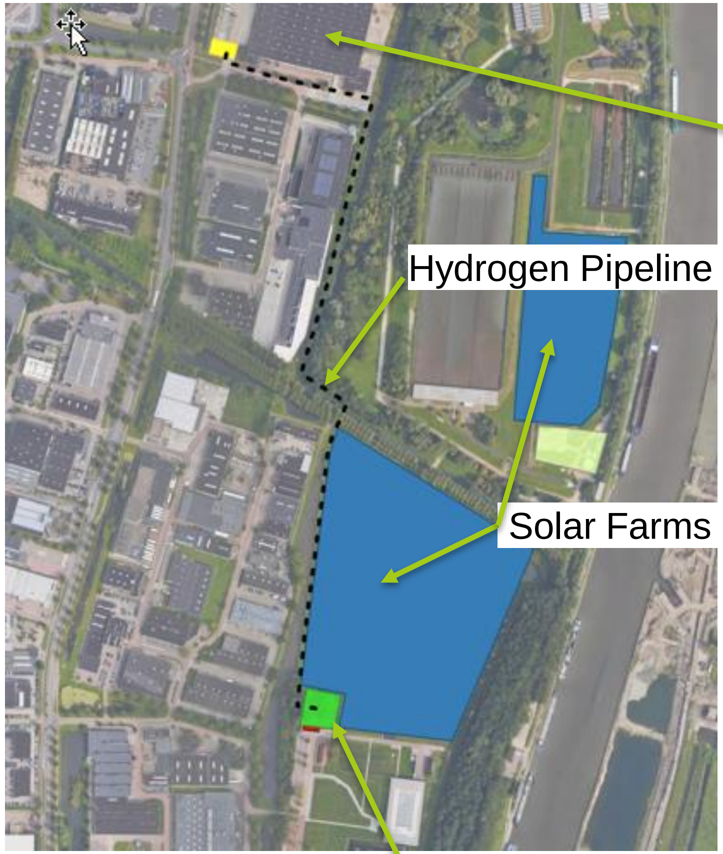


Electrolyser realisatie in 2022

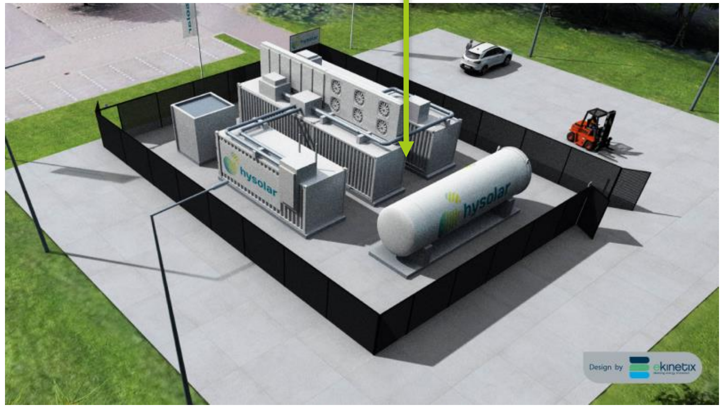
Additionality principle discriminates hydrogen versus electricity

Dual Fuel Tractor and Holder;
60-80% hydrogen in diesel engine

Crane drive train converted to
Hydrogen Fuel Cell Electric



Electrolyser Realisation early 2023



Converting machines to battery electric and buying green electricity is GREEN (but not possible)

Converting machines to hydrogen fuel cell electric and buying green electricity to produce green hydrogen is NOT GREEN?

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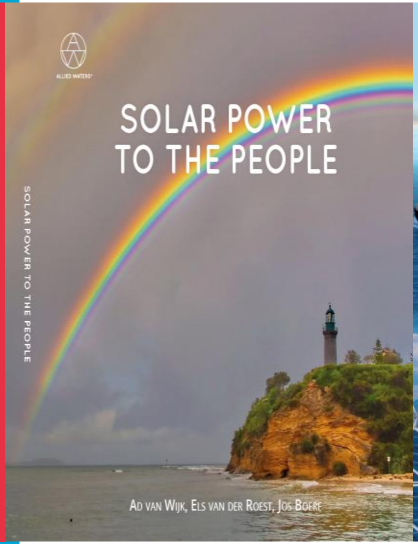
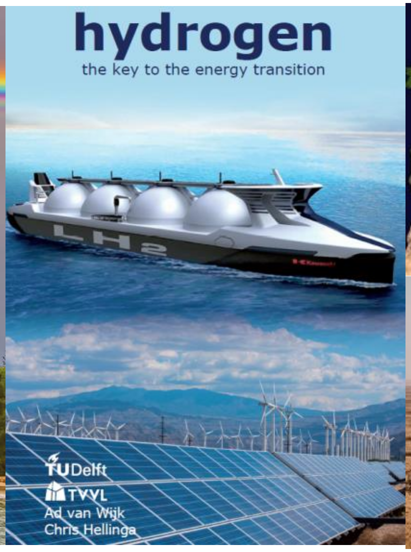
24 Hours LeMans in 2024 on hydrogen

Further Reading
www.profadvanwijk.com

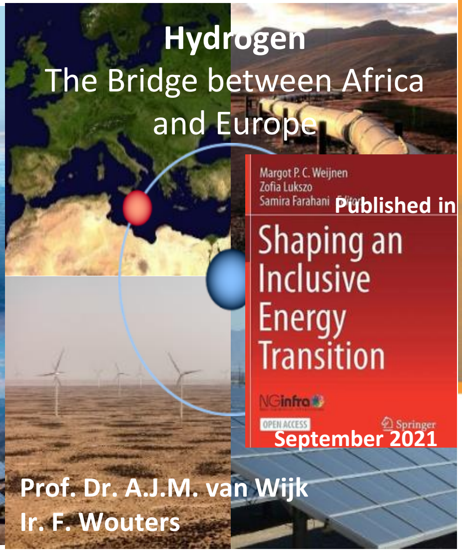
April 2017



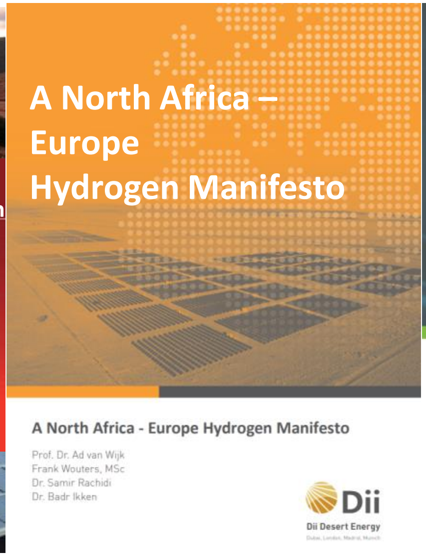
November 2017



May 2018



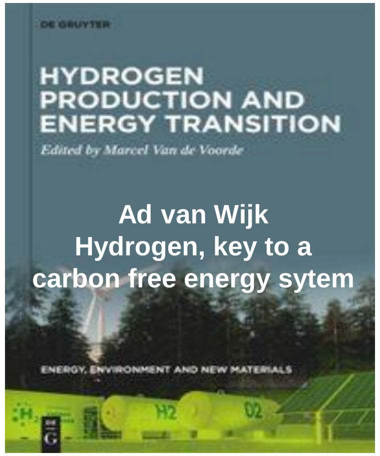
September 2019



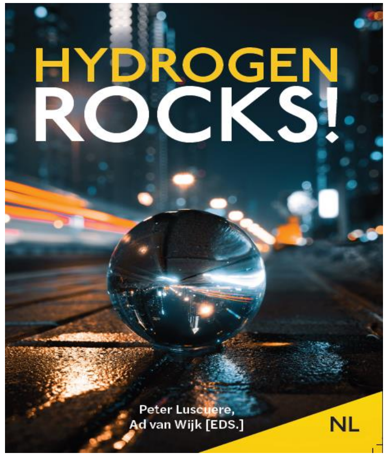
November 2019

April 2020

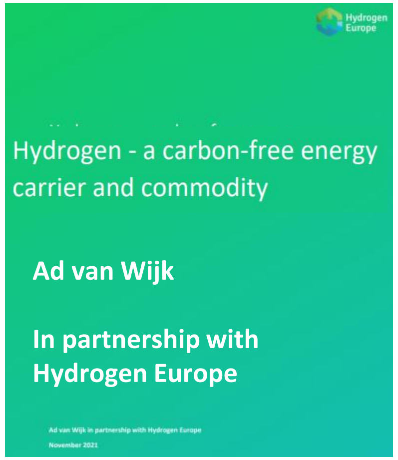
April 2021



September 2021



October 2021



November 2021

May 2022