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LUT ELECTRICAL ENGINEERING 2021

RESEARCH LABORATORIES

Applied Electronics
- Prof. Pertti Silventoinen

Control Engineering and Digital Systems
- Assoc. Prof. Tuomo Lindh
- Prof. Olli Pyrhönen
- Assoc. Prof. Pedro Nardelli

Electricity Markets and Power Systems
- Prof. Samuli Honkapuro
- Prof. Jamshid Aghaei
- Assoc. Prof. Jukka Lassila

Electrical Drives
- Assoc. Prof. Pasi Peltoniemi
- Prof. Juha Pyrhönen

Renewable Electricity Generation and Storage
- Prof. Jero Ahola
- Prof. Pertti Kauranen

Solar Economy
- Prof. Christian Breyer

FOCUS ON THE ELECTRIFICATION OF THE WHOLE ENERGY SYSTEM

- Energy system modelling
- Smart grids and electricity markets
- Wind and solar power generation
- Electrochemical energy conversion and storage methods (PtX)
- Electrified drivelines for different industrial and mobile applications
- Measurement, control, estimation, identification, optimization and communication methods
- Power electronics, control electronics and sensors for different energy applications

Research staff (~130): 11 (tenure) profs., 38 doctors, 52 post-graduate students + research assistants, turnover ~10 M€

RENEWABLE ELECTRICITY GENERATION AND STORAGE

Key research topics:
- Hydrogen production by water electrolysis and different power-to-x processes
- Use of solar and wind power in different applications
- Electrochemical energy conversion and storage methods
- Energy efficiency in pumping, compressing and fan systems

Research objectives:
- Optimization of the cost and energy efficiency of water electrolysis-based hydrogen production by different means, at system, stack and at cell level.
- Study and verification new power-to-x concepts having a remarkable potential in energy transition
- Improvement of profitability of solar PV based power generation in buildings by optimal system design, dimensioning and control
- Optimization of life-cycle cost of electrical motor-driven pump, fan, and compressor systems

Research methods:
- Wide range of different methods, e.g. modelling, simulation, optimization, estimation, identification, control, laboratory experiments, proof-of-concepts

Neo-Carbon Food Pilot site at LUT Campus in June 2019. Photo: Teemu Leinonen

4.11.2021

Power-to-hydrogen as an enabler

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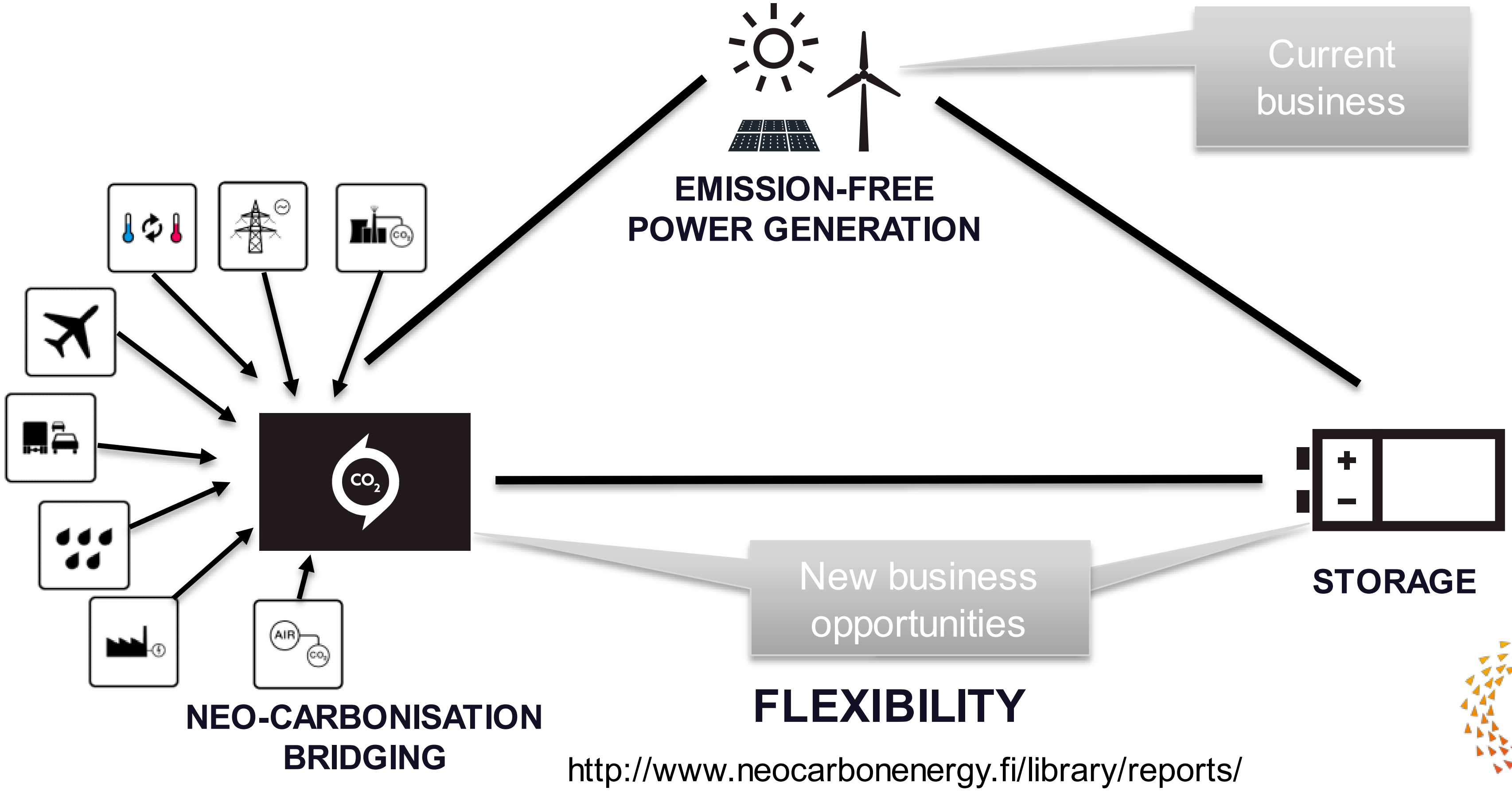
Electric power system will become the main energy system



http://www.neocarbonenergy.fi/library/reports/

NEO CARBON ENERGY

Opportunity: Green hydrogen will be a key element in the production of sustainable fuels, ammonia, and steel

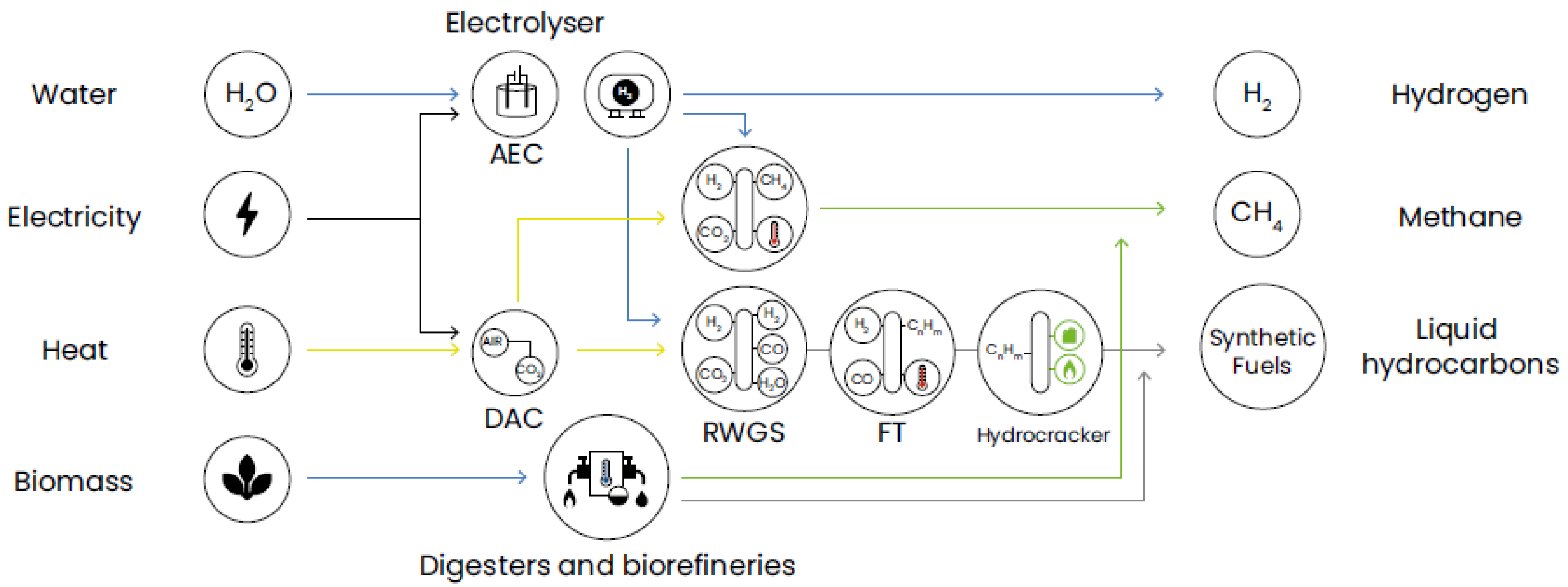
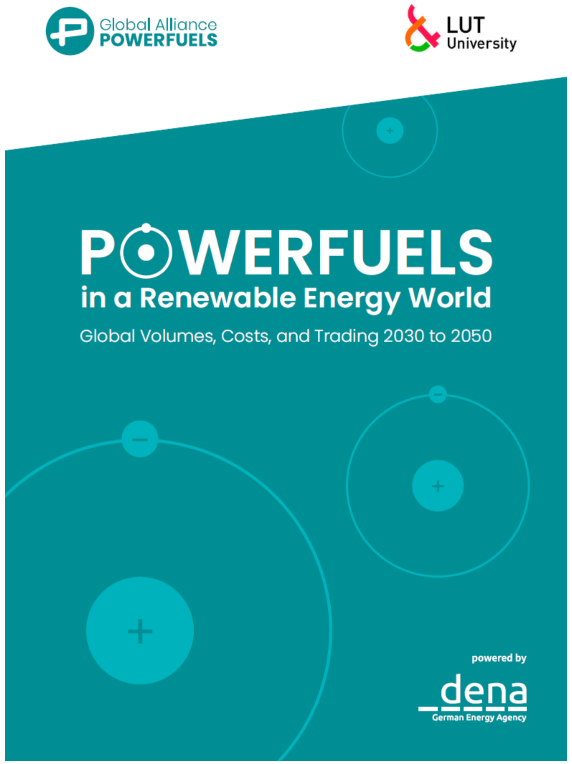
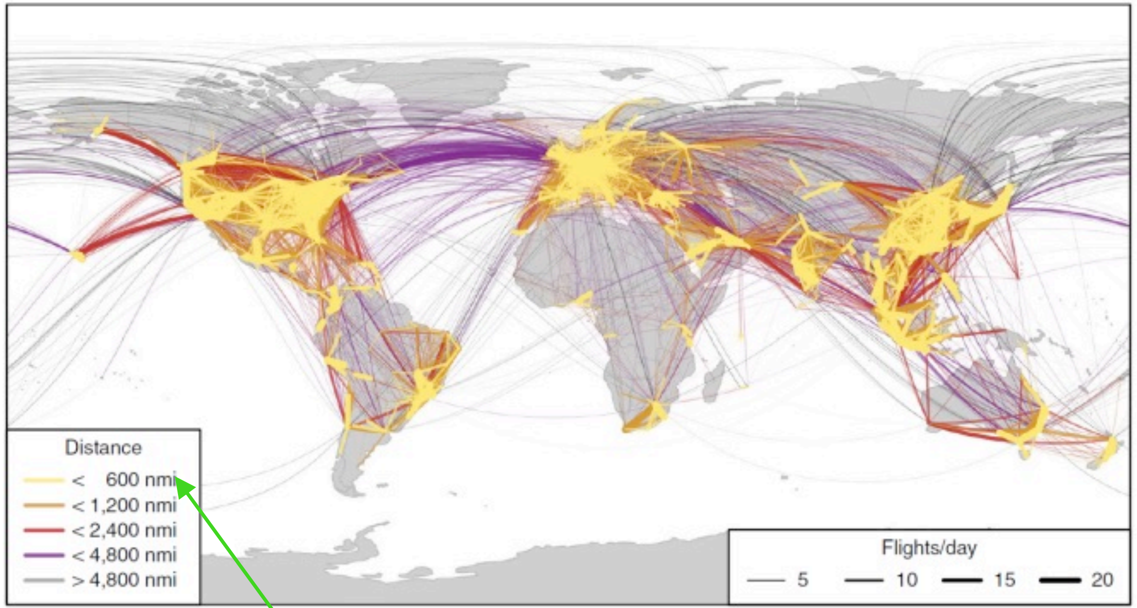


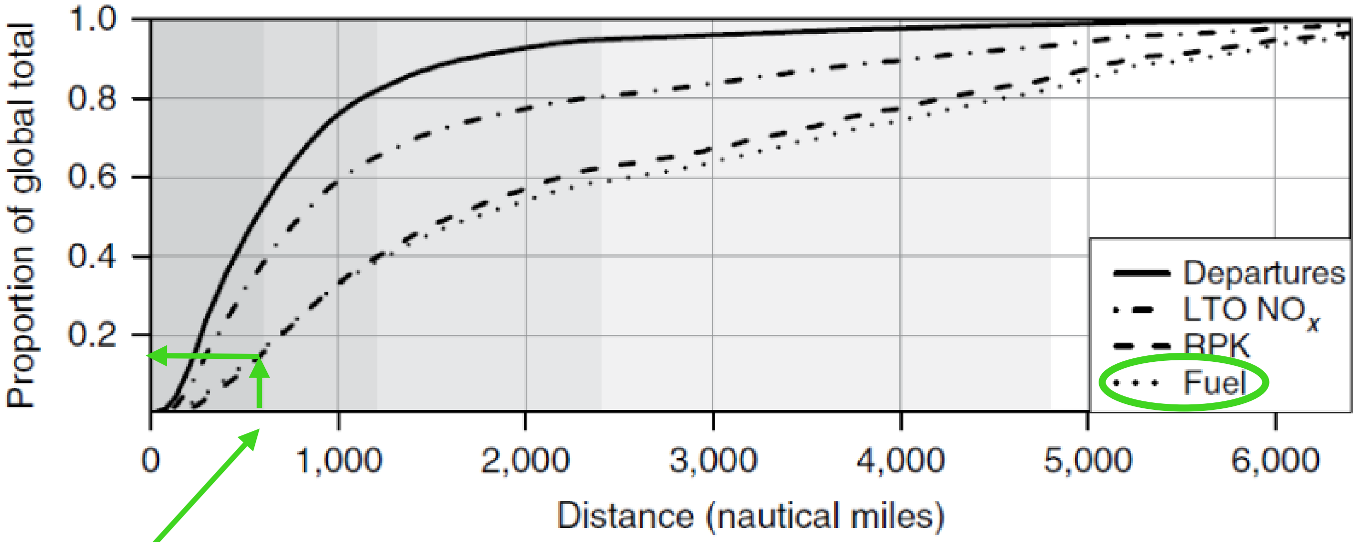
Figure 2: Schematic of the value chain elements in the production of sustainable fuels.



Source: The Dena Global Alliance Powerfuels Report, available at:
https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/Global_Alliance_Powerfuels_Study_Powerfuels_in_a_Renewable_Energy_World.pdf

Inter-continental flying will be based on liquid fuels also in foreseeable future

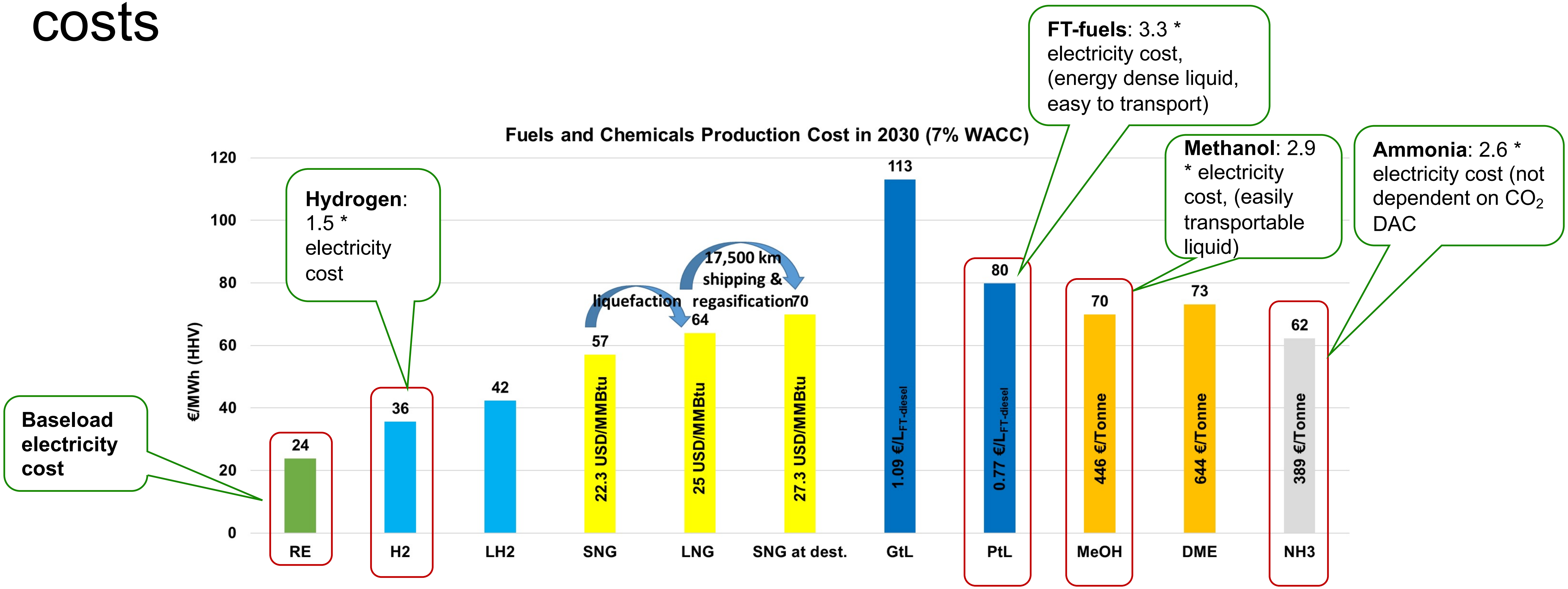




Electric flights at distances < 600 nmil (1100 km) ~15 % of total fuel consumption of battery energy density 800 Wh/kg will be reached

Source: Andreas W. Schäfer, et. Al., Technological, economic and environmental prospects of all electric aircraft, Nature Energy, Vol. 4, February 2019, pp. 160-166.

Opportunity: Electricity cost in hydrogen production is the most important factor in PtX fuels and chemicals production costs



Source: http://www.neocarbonenergy.fi/wp-content/uploads/2016/02/13_Fasihi.pdf

Opportunity: Global demand of PtX fuels net-zero emission energy system in 2050 will be enormous

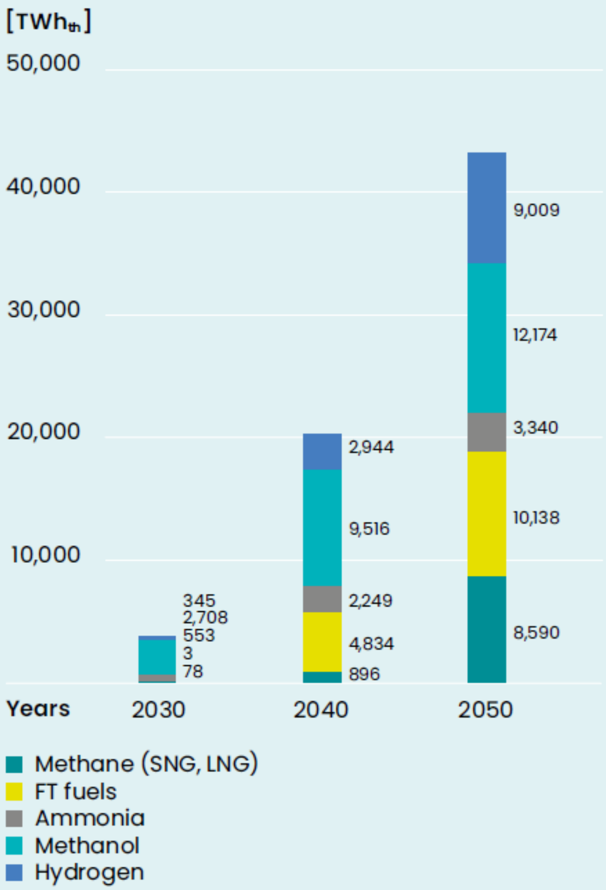


Figure ES1: Global powerfuels demand across the transition.

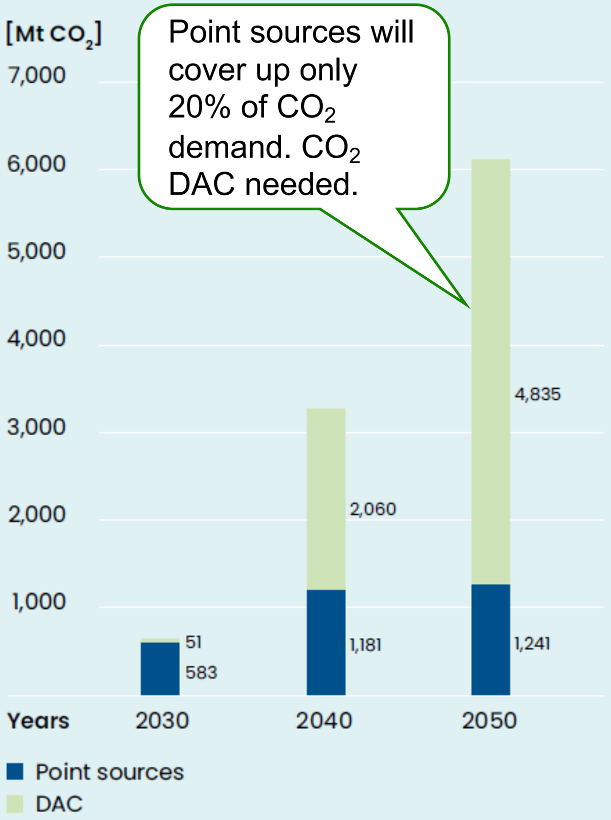


Figure ES2: Global CO_2 demand for powerfuels production across the transition.

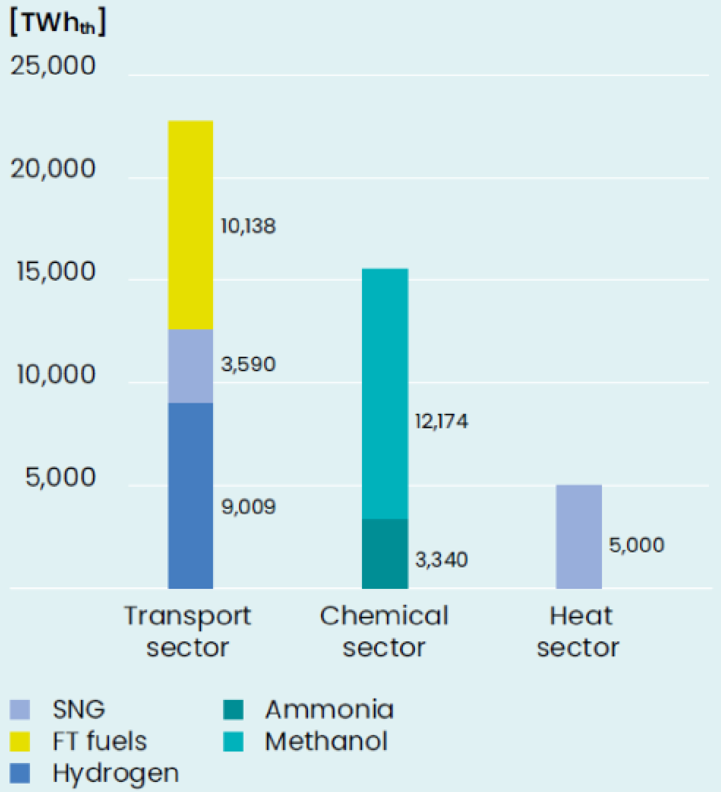
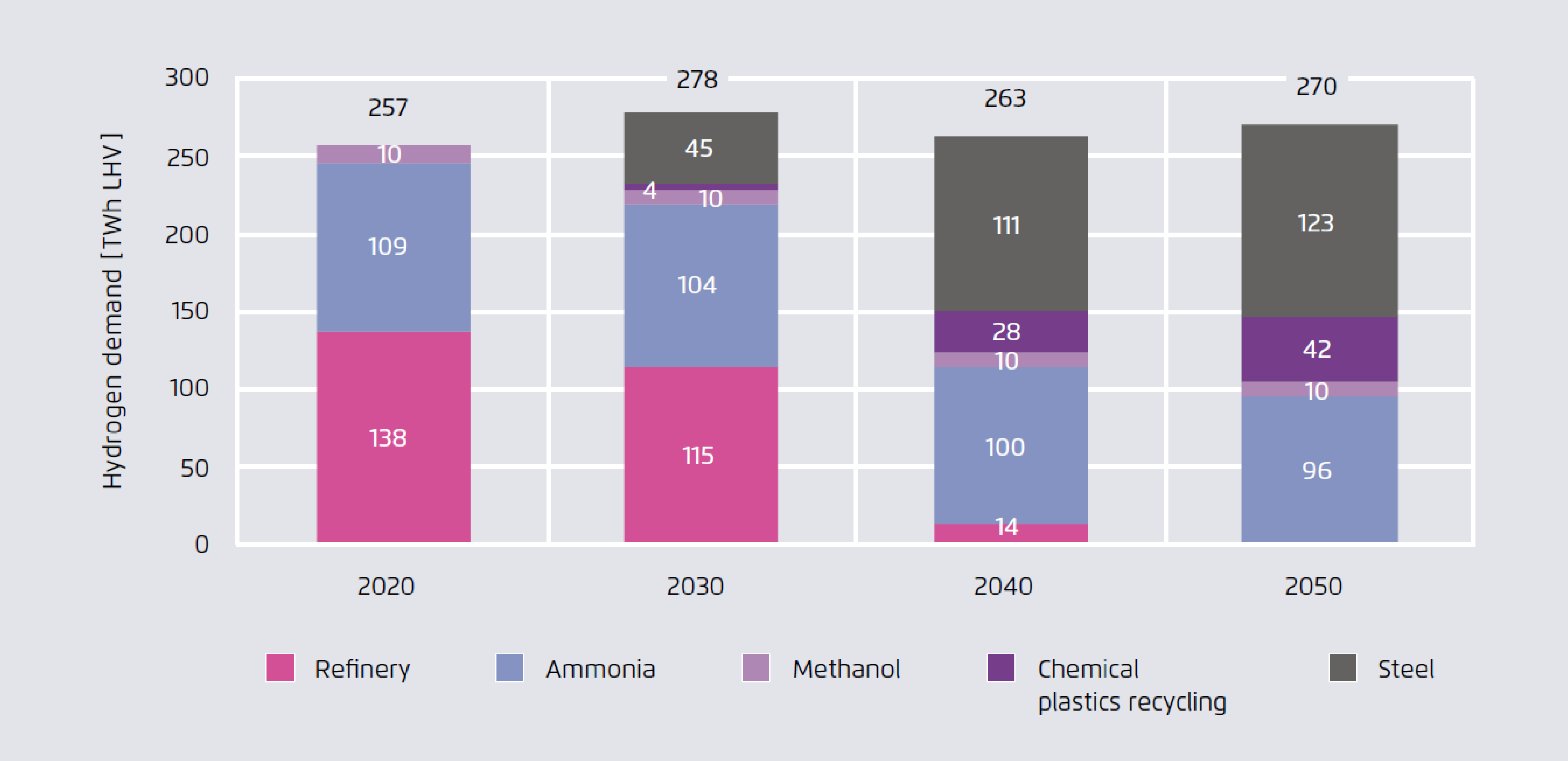


Figure ES3: Global powerfuels demand by sector in 2050.

*Primary energy consumption in Finland in 2020 was 378 TWh

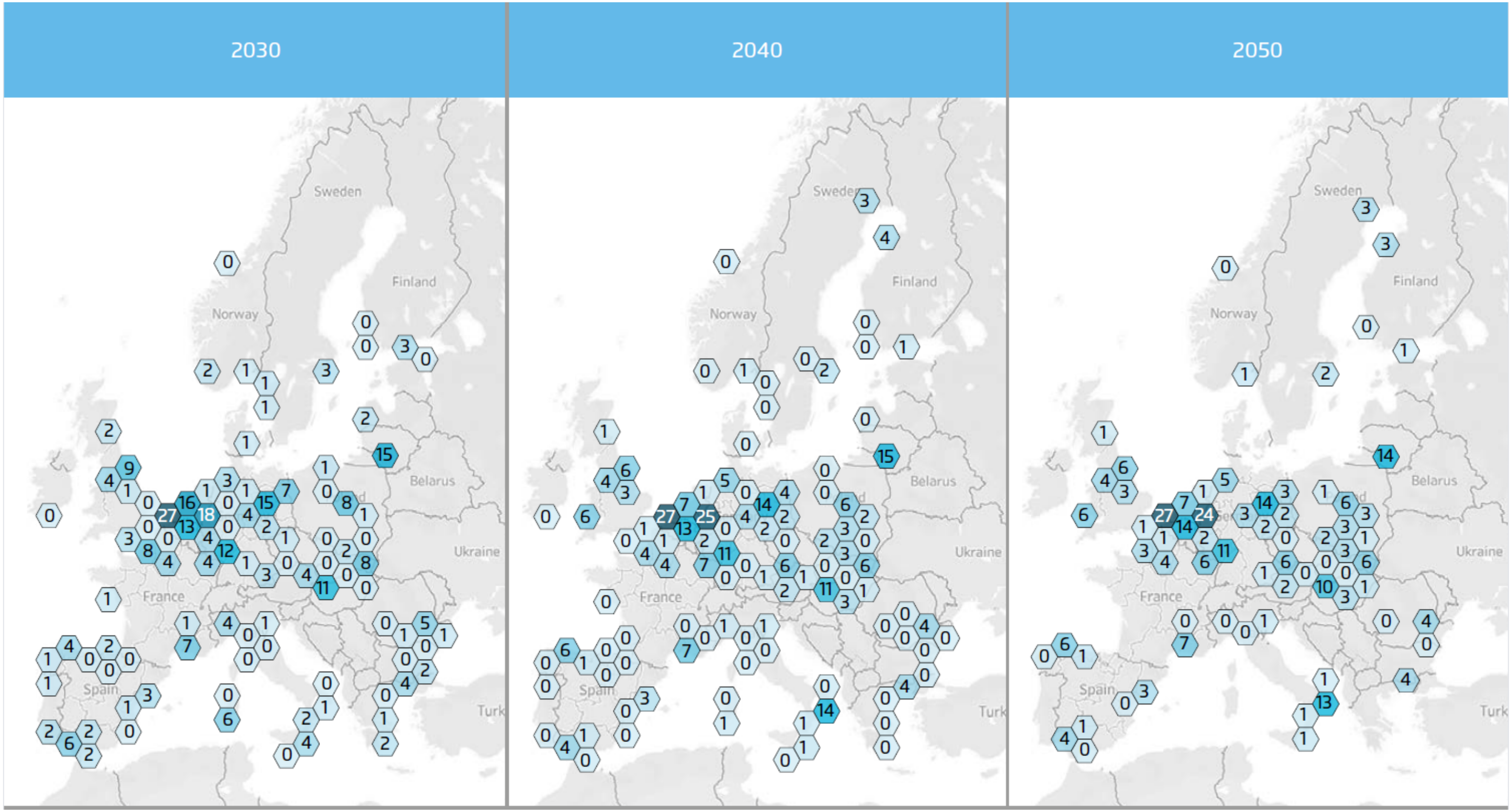
Source: The Dena Global Alliance Powerfuels Report, available at: https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/Global_Alliance_Powerfuels_Study_Powerfuels_in_a_Renewable_Energy_World.pdf

Opportunity: Estimate of industrial hydrogen demand in Europe from 2020 to 2050 [TWh/a]



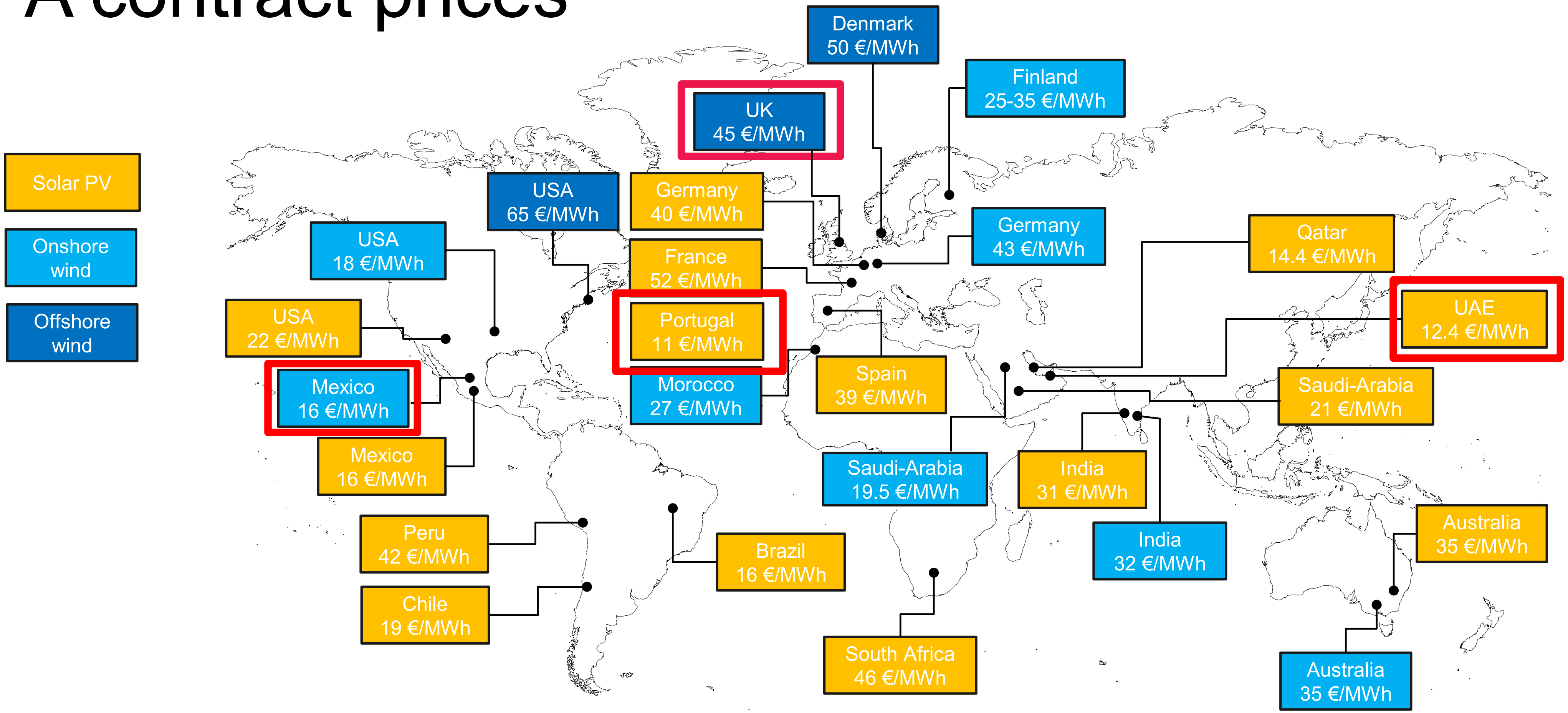
Source: Agora Energiewende, No-regret hydrogen, Charting early steps for H2 infrastructure in Europe, 2021

Projected hydrogen demand in Europe [TWh/a]



Source: Agora Energiewende, No-regret hydrogen, Charting early steps for H2 infrastructure in Europe, 2021

Competition: Global wind and solar power public PPA contract prices



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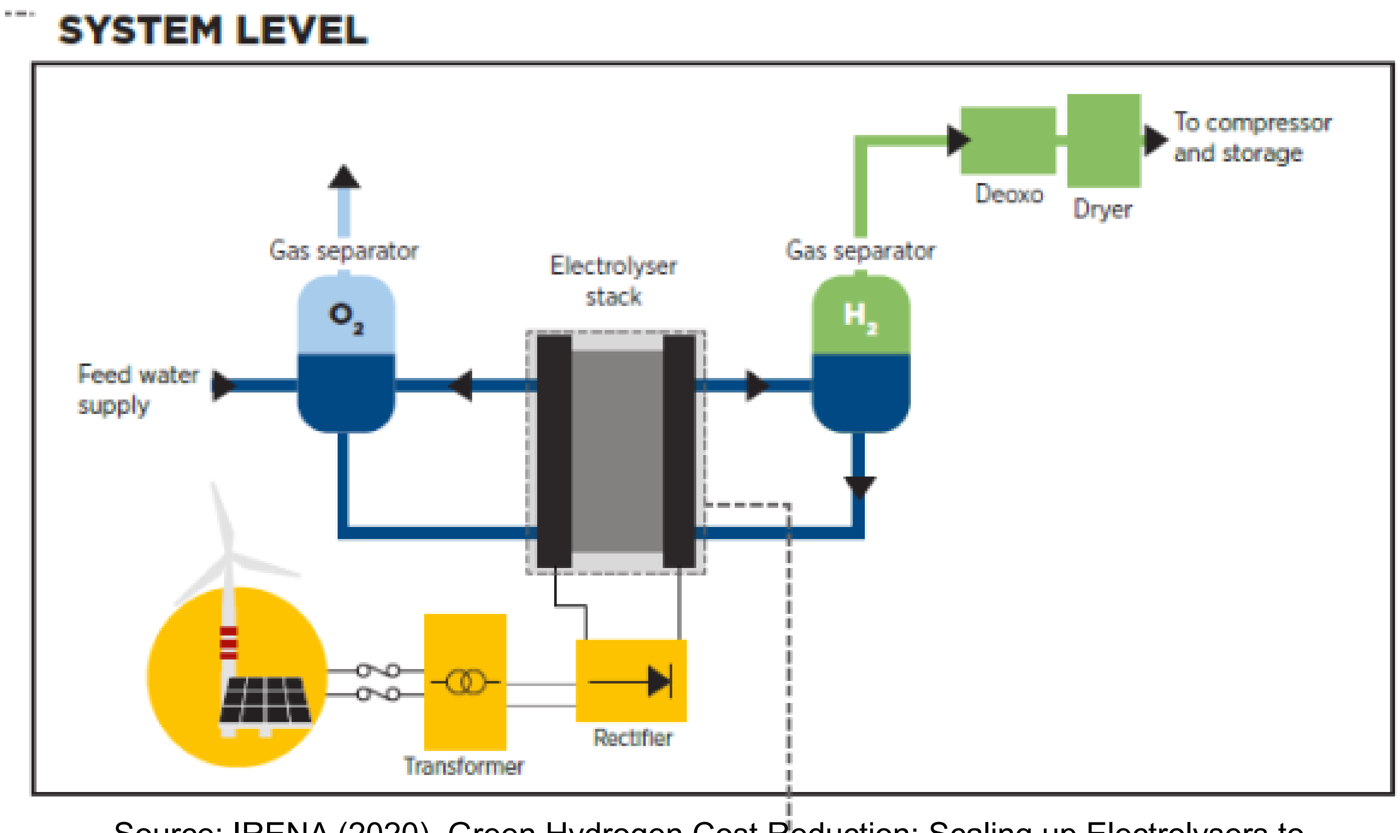
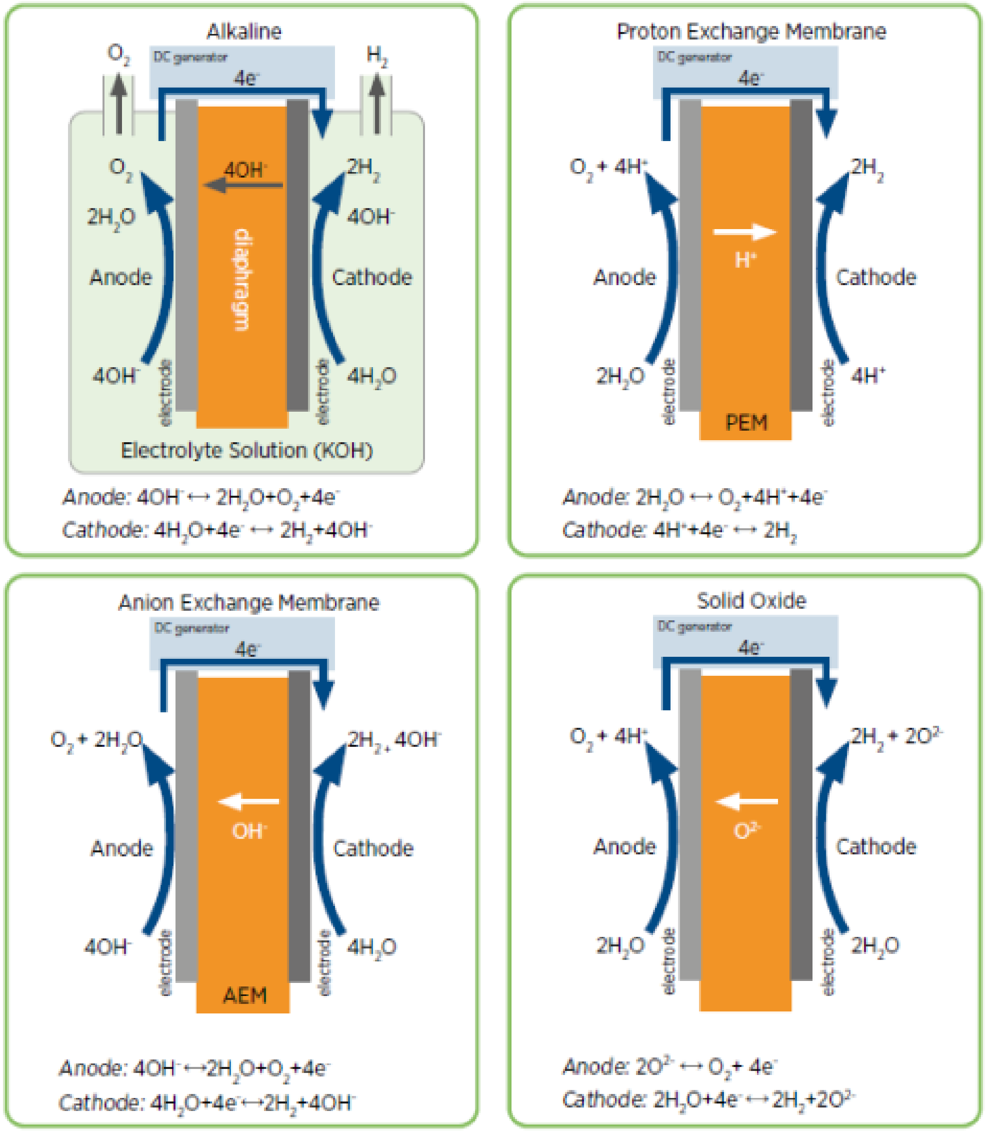
Green hydrogen production technologies

Water electrolyzer system level and most prominent electrolyzer cell technologies



Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal,
International Renewable Energy Agency, Abu Dhabi

Different types of commercially available electrolysis technologies.

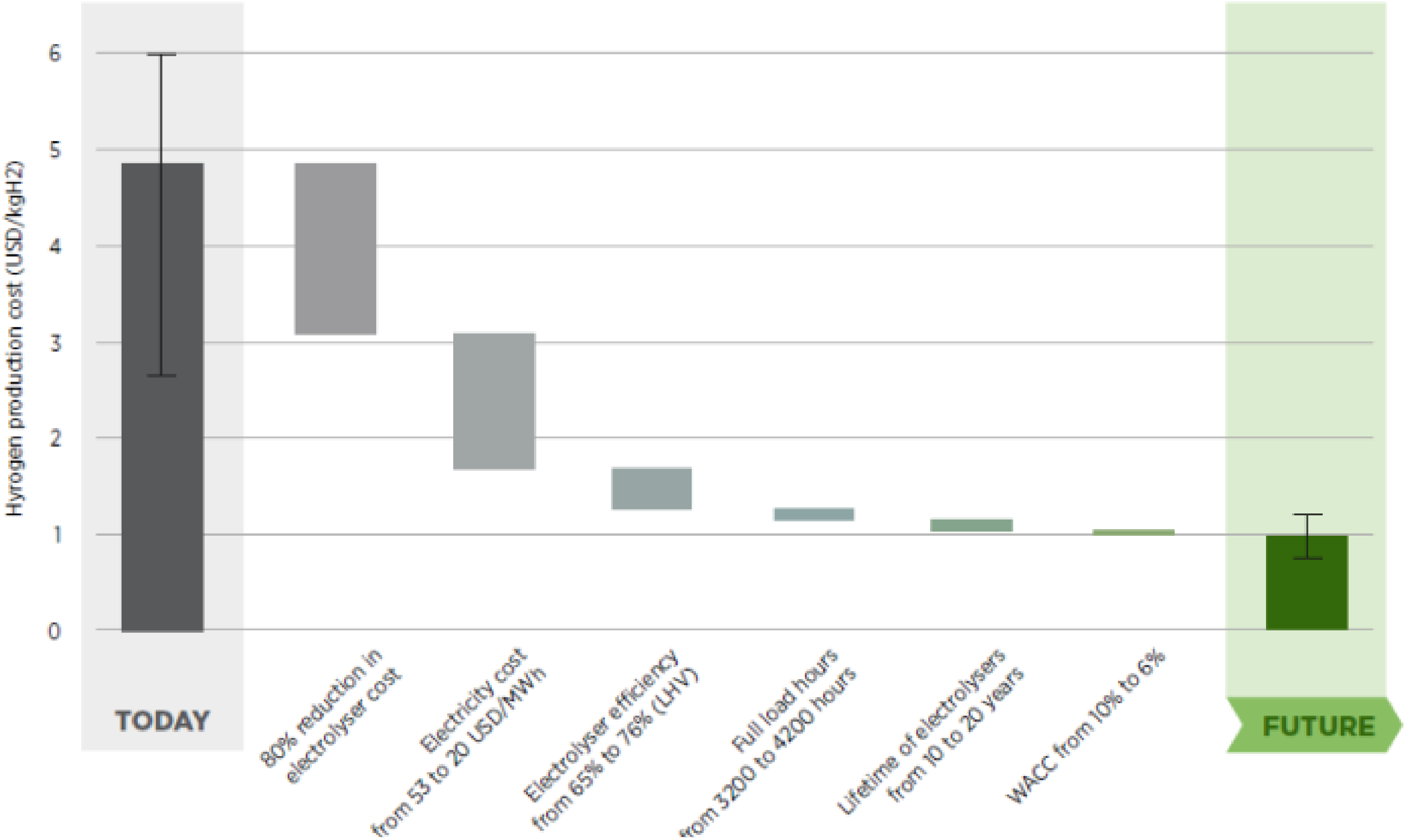


Production of green hydrogen by alkaline water electrolysis

Summary:

- Located in Kokkola, Finland
- Power-to-Hydrogen: 1800 Nm^3/h (H_2)
- 3x3 MW pressurized alkaline water electrolyzers, 3x600 Nm^3/h, 16 bar (H_2)
- The main use of H_2 plant is at nearby Cobalt plant, hydrogen delivery by a pipeline
- The rest of H_2 compressed to 200-300 bar and stored in bottles for delivery with trucks

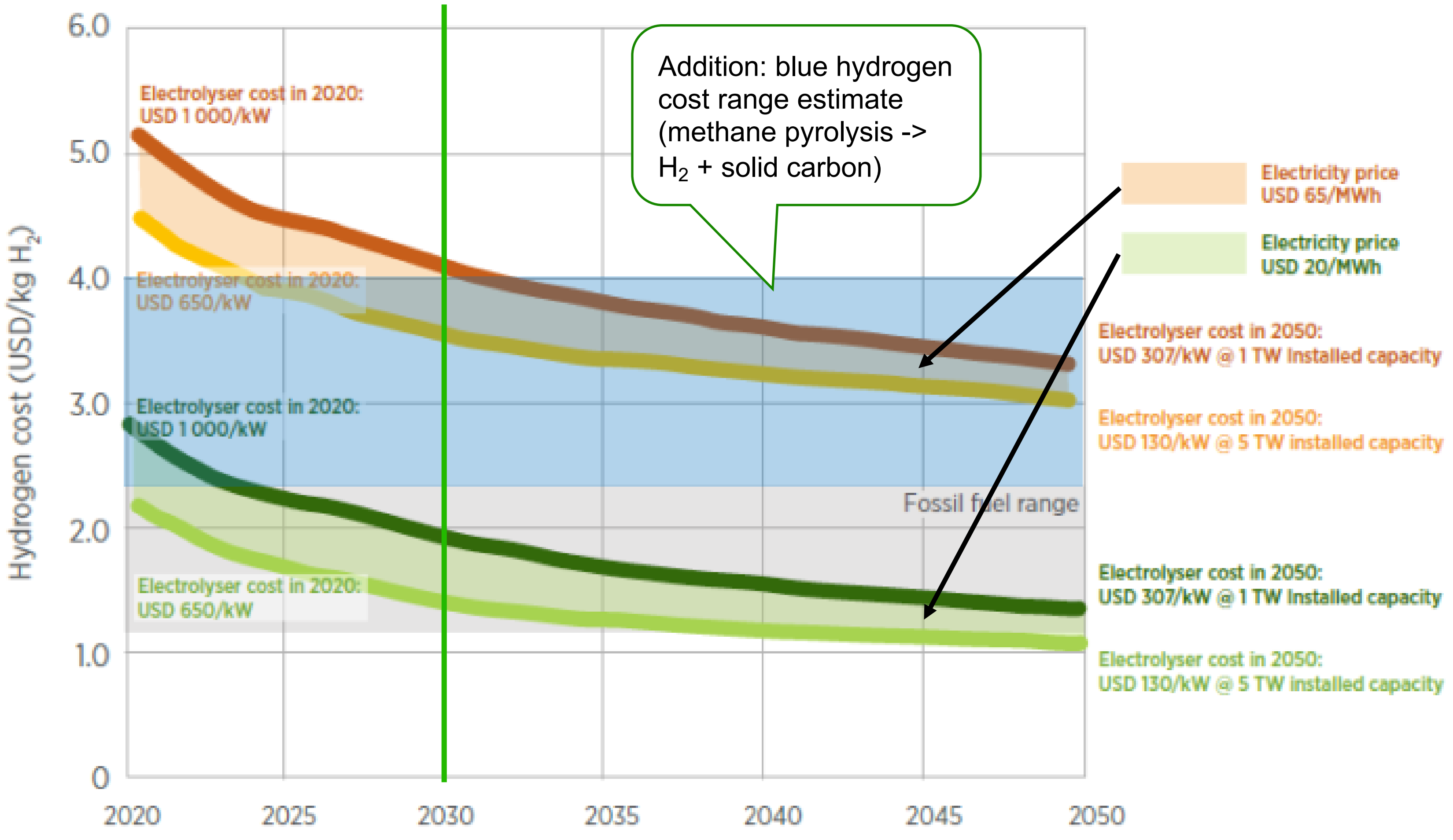
Path down to 1 USD/kgH2 production

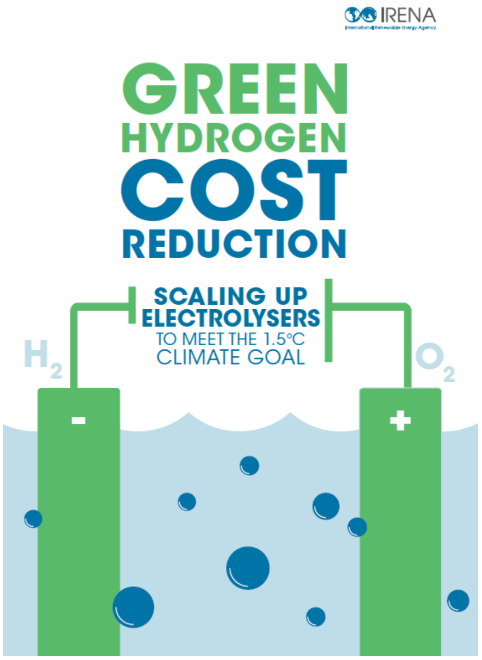


Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi

Green hydrogen production cost evolution

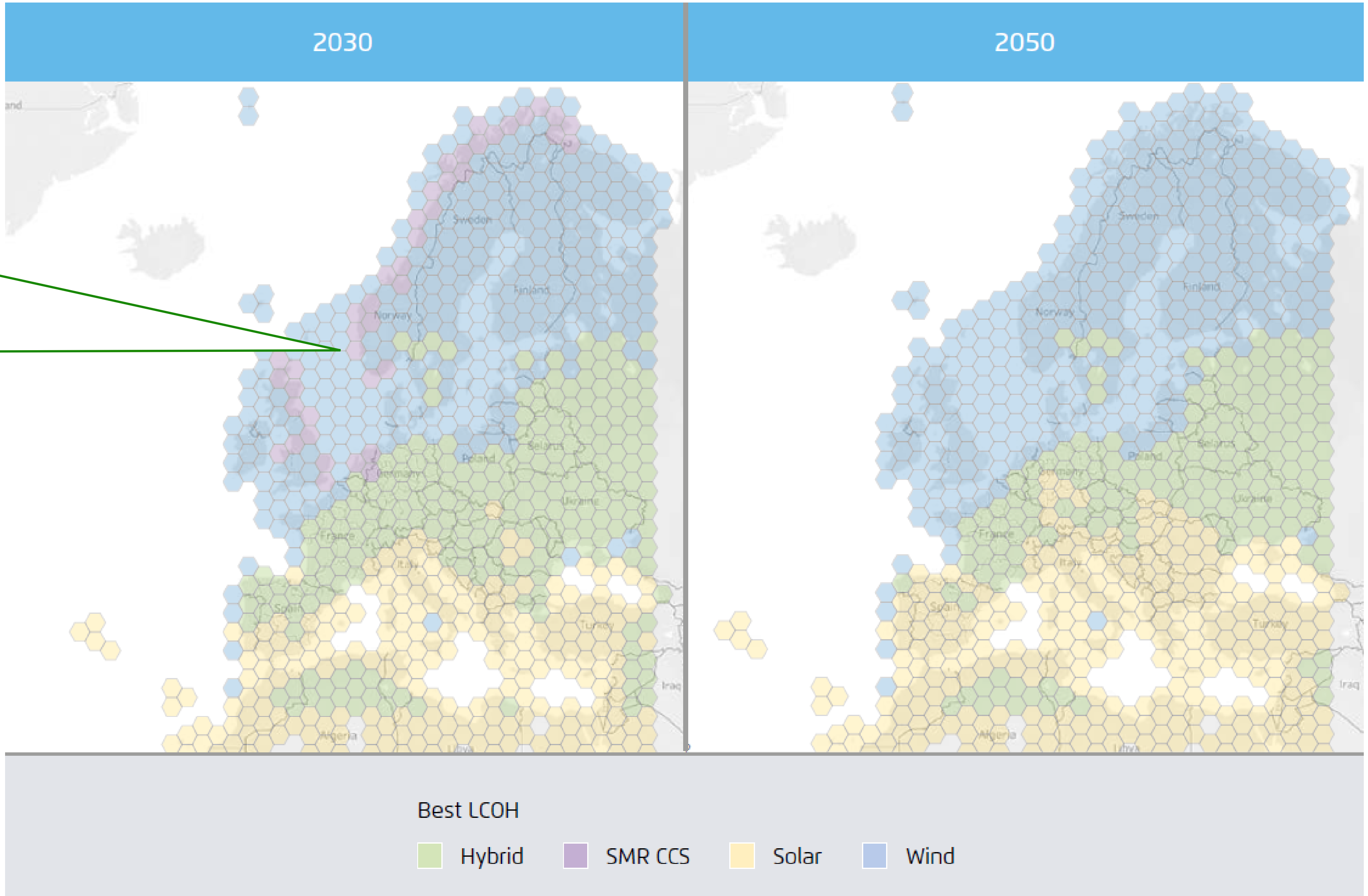




Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi

Note: Efficiency at nominal capacity is 65%, with a LHV of 51.2 kWh/kgH2 of hydrogen (kWh/kg H2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Competitivity of hydrogen production including SMR with CCS



Hydrogen production from natural gas by steam-methane reforming with CCS competitive only in very short-term.

Source: Agora Energiewende, No-regret hydrogen, Charting early steps for H2 infrastructure in Europe, 2021

Hydrogen transmission and storage

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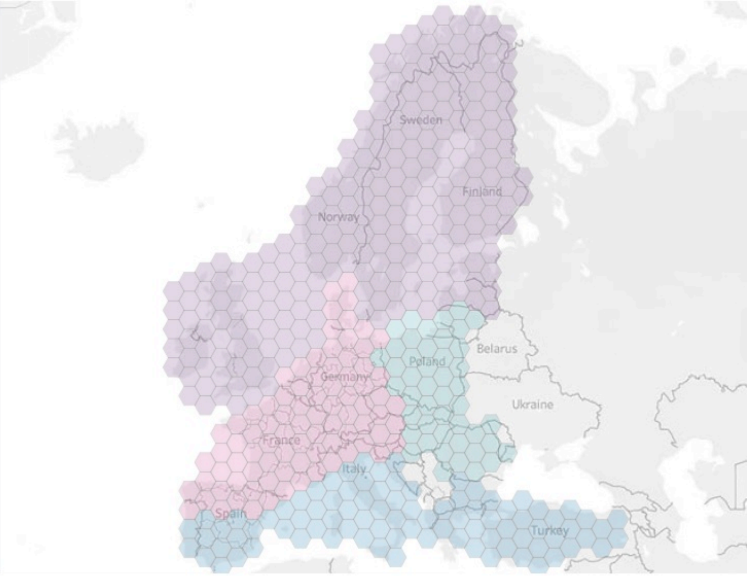
Hydrogen storage utilization in Europe

Regional split for hydrogen storage Figure 14

North Europe
Central/West Europe
South Europe
Central/East Europe

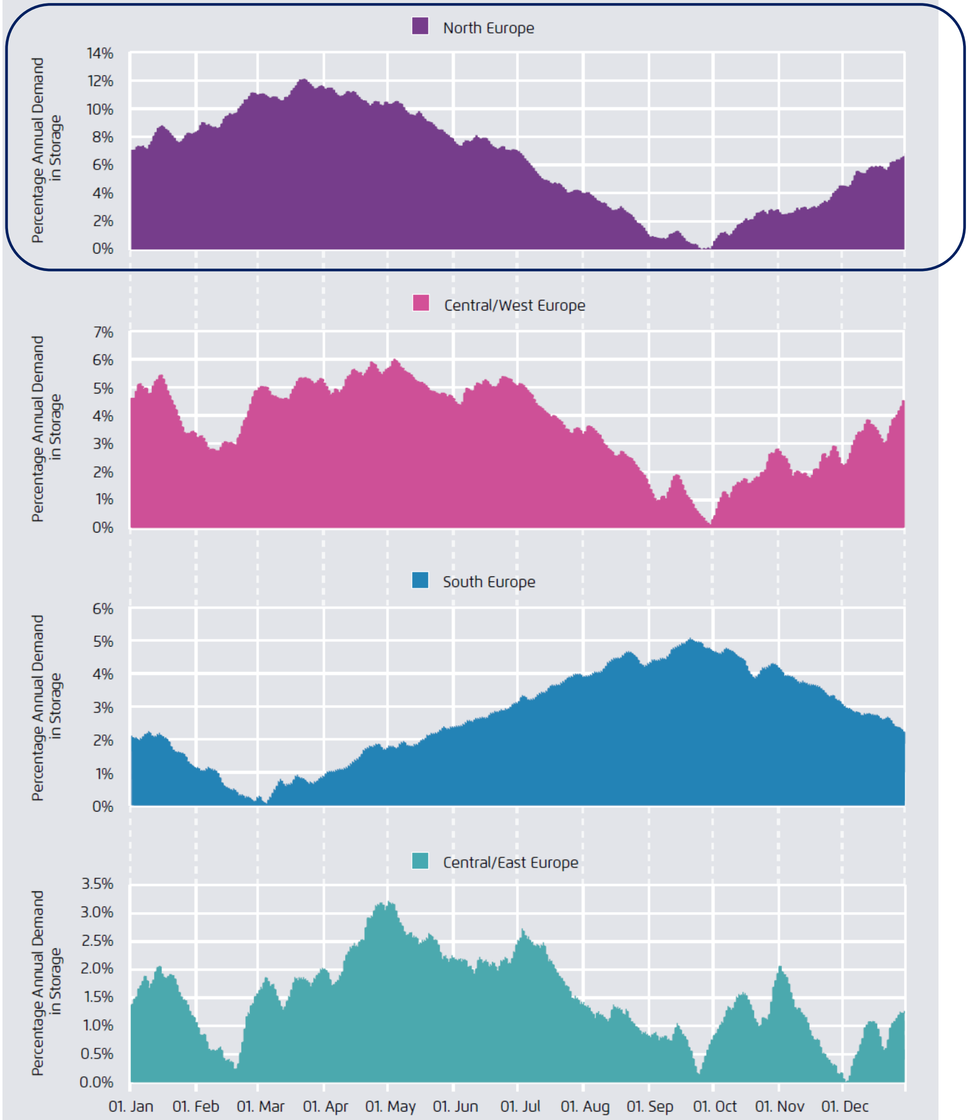


AFRY analysis. © 2020 Mapbox © Open...

The number of cycles and storage need lower South-Europe than in North Europe.

	North Europe	Central/West Europe	South Europe	Central/East Europe
Sum of injected volumes over the year (in % of annual demand) [A]	24.9%	25.2%	43.0%	20.6%
Total storage capacity requirement (i.e. maximum H_2 volume stored at any point within the year) (in % of annual demand) [B]	12.1%	6.0%	5.1%	3.2%
Number of full cycles per annum [B/A]	**2.06**	**4.22**	**8.45**	**6.38**

Cumulative storage requirements by region Figure 17



AFRY analysis. Units indicate the % of annual hydrogen demand. In all cases, the minimum storage fill is 0%. The maximum figure implies the total volumetric size of the required storage facilities.

Source: Agora Energiewende, No-regret hydrogen, Charting early steps for H2 infrastructure in Europe, 2021

European Hydrogen Backbone Report

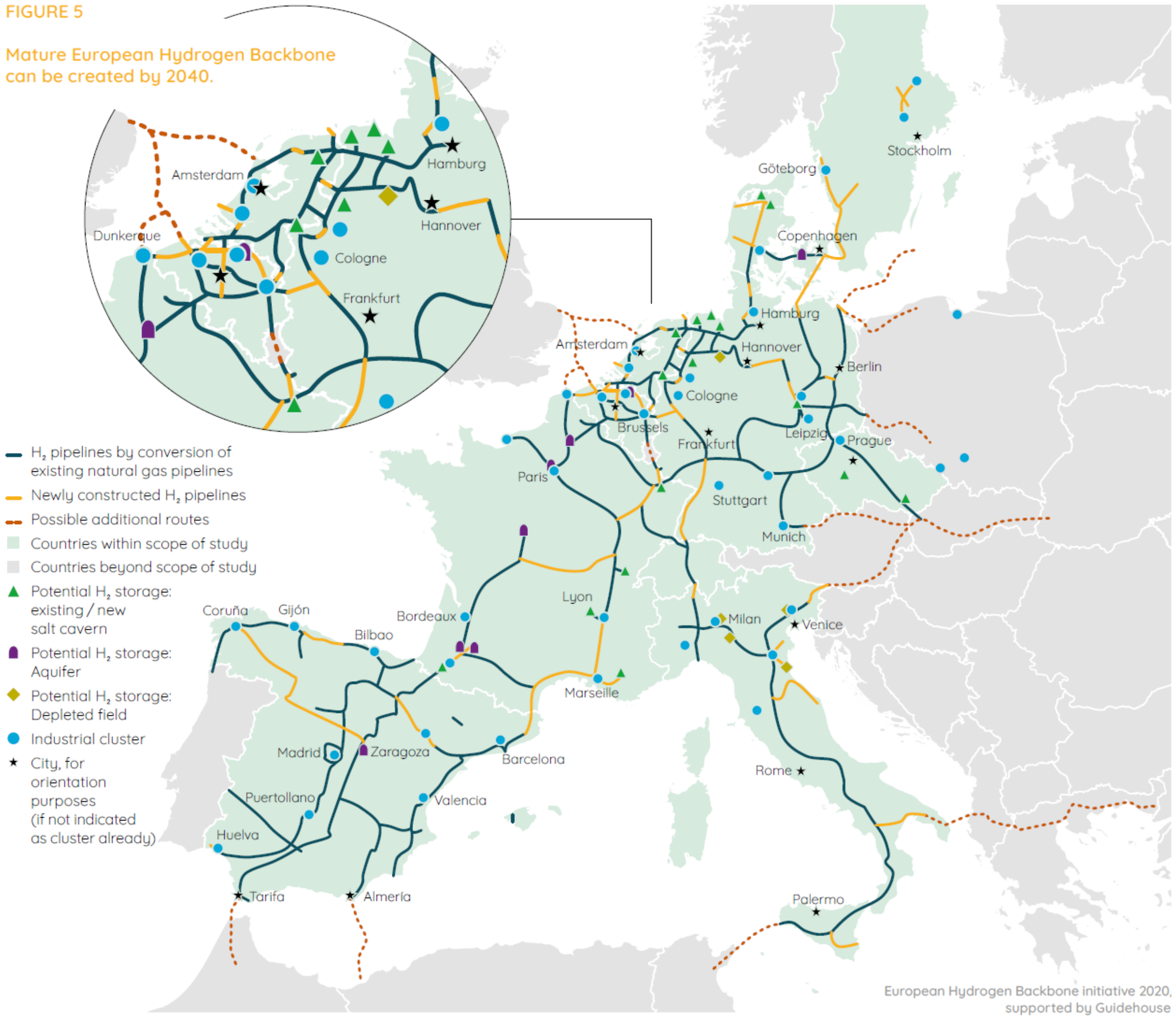


FIGURE 5

Mature European Hydrogen Backbone can be created by 2040.

Levelized cost of hydrogen transport through pipeline infrastructure 1000 km (1 kgH2 = 33 kWh)

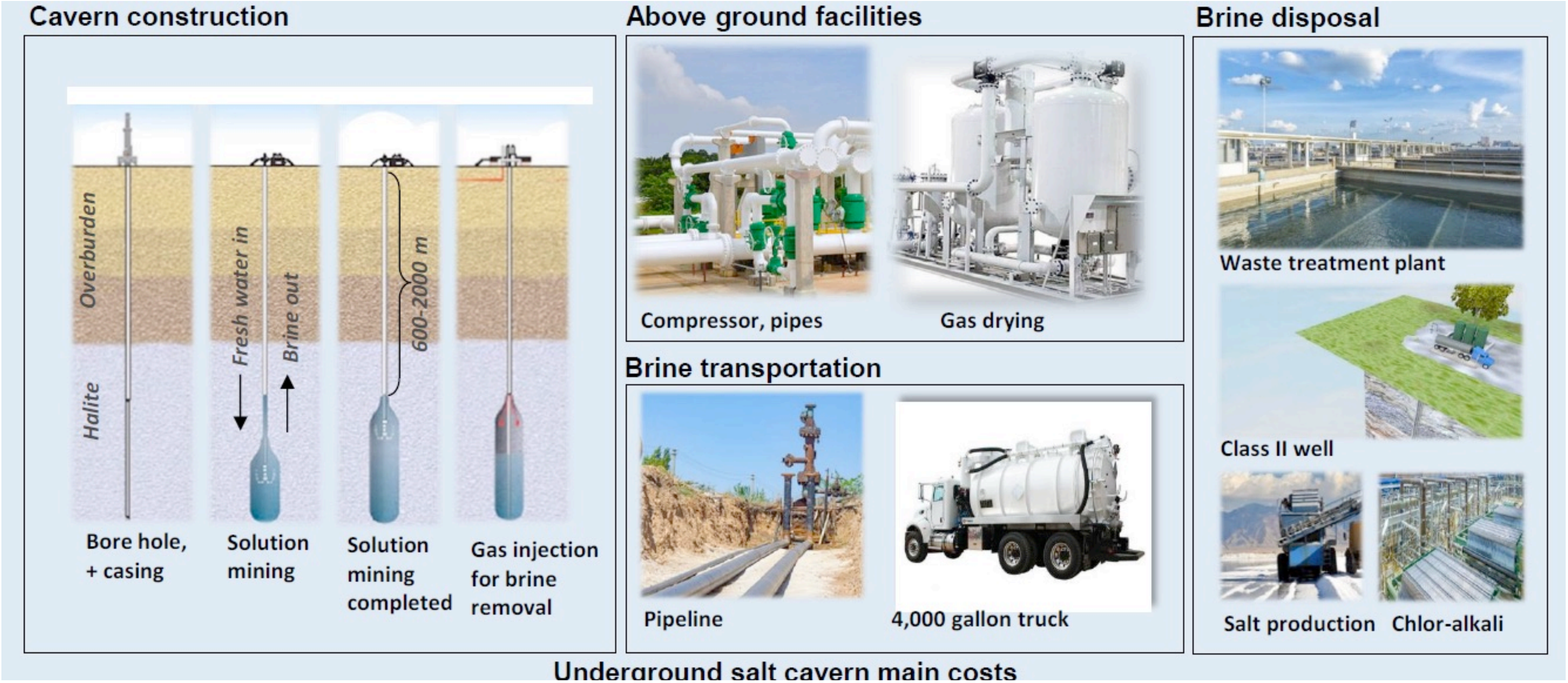
		Low	Medium	High
Levelised cost, 100% new infrastructure	€/kg/1000km	0.16	0.20	0.23
Levelised cost, 100% retrofitted infrastructure	€/kg/1000km	0.07	0.11	0.15
Levelised cost, European Hydrogen Backbone (75% retrofitted)	**€/kg/1000km**	**0.09**	**0.13**	**0.17**

In energy terms this equals to 4 €/MWh/1000km

Source: European Hydrogen Backbone Report, July 2020, available: https://gasforclimate2050.eu/news-item/gas-infrastructure-companies-present-a-european-hydrogen-backbone-plan/

Bulk hydrogen storage in underground salt cavern

- Cavern construction: Geological survey ; bore and installation of production tubing ; solution mining ; de-brine and mechanical integrity tests
- Base parameters: cavern roof depth 800 m ; pressure 120 bar ; 30 % cushion gas ; volume 80 000 m^3 ; 1 mile pipeline to facility
- Main costs: cavern construction, brine disposal, above ground facility

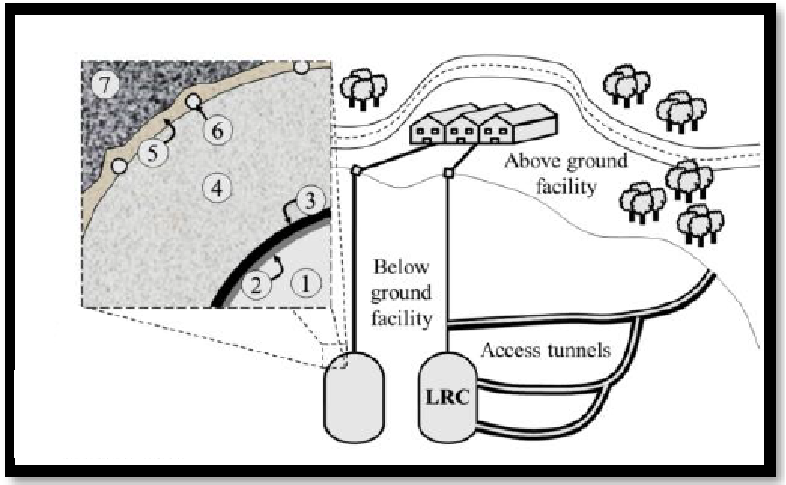


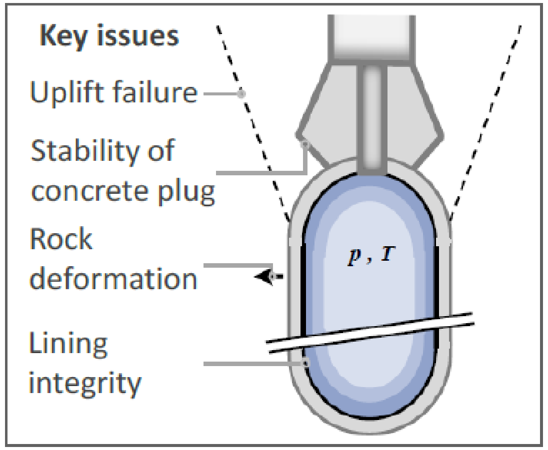
Source: R.K. Ahluwalia, et. Al., System Level Analysis of Hydrogen Storage Options, 2019 Annual Merit Review and Peer Evalauation Meeting, Washington, D.C., 2019

Bulk hydrogen storage in lined rock cavern

- Used for storing compressed natural gas in Skallen in Sweden since 2003
- Parameters: volume 40 000 m^3, vessel height 52 m, vessel diameter 36 m, distance from surface 115 m, access tunnel 1 km, storage pressure 150-200 bar
- Main cost elements: cavern excavation, access tunnel, concrete and steel lining
- Enables high-purity storage of H2. In salt caverns problems may arise.

1. Cavern
2. Steel Lining
3. Sliding Layer
4. Concrete
5. Shotcrete
6. Drainage
7. Rock Mass

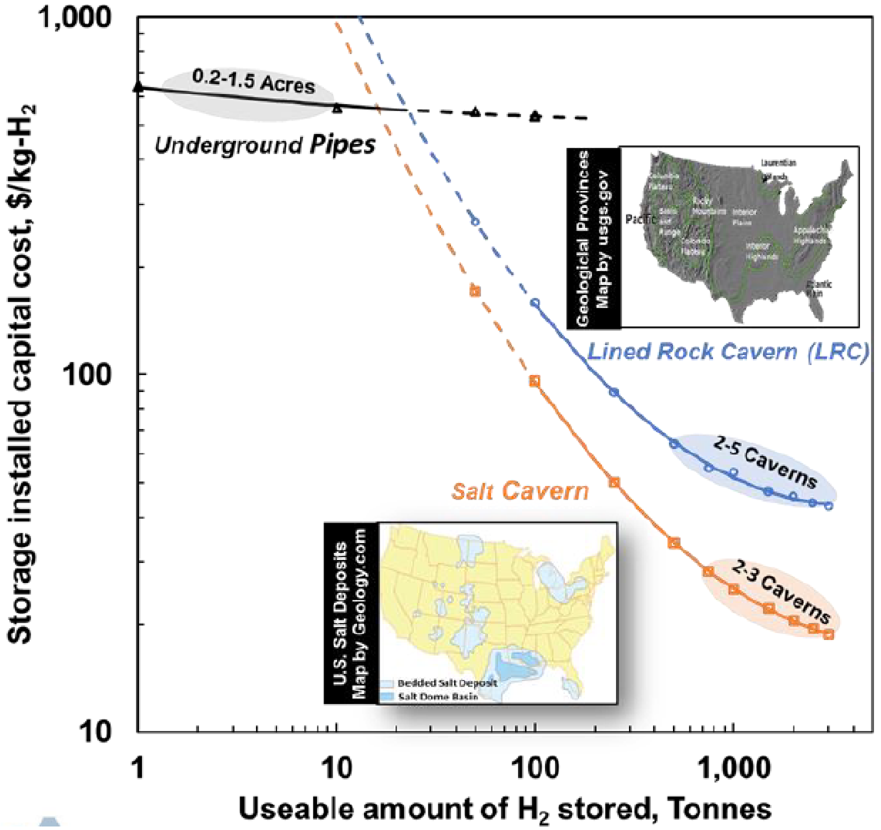




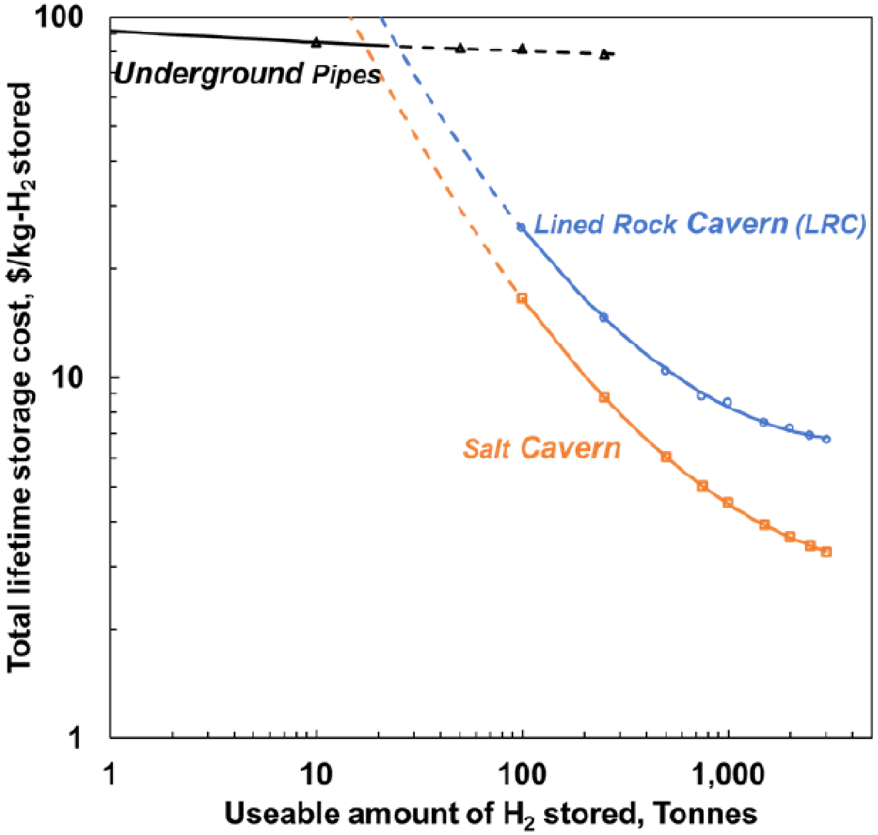
Sources: R. Glamheden, P. Curtis, Excavation of a cavern for high-pressure storage of natural gas, Tunneling and Underground Space Technology 21 (2006) 56-67.
R.K. Ahluwalia, et. Al., System Level Analysis of Hydrogen Storage Options, 2019 Annual Merit Review and Peer Evalauation Meeting, Washington, D.C., 2019

Bulk hydrogen storage – Salt caverns and lined rock caverns

Installed Capital Cost
- Underground pipes: 100 bar
- LRC and salt caverns: 150 bar



Yearly Storage Cost
- Inclusive of CAPEX and operating & maintenance cost



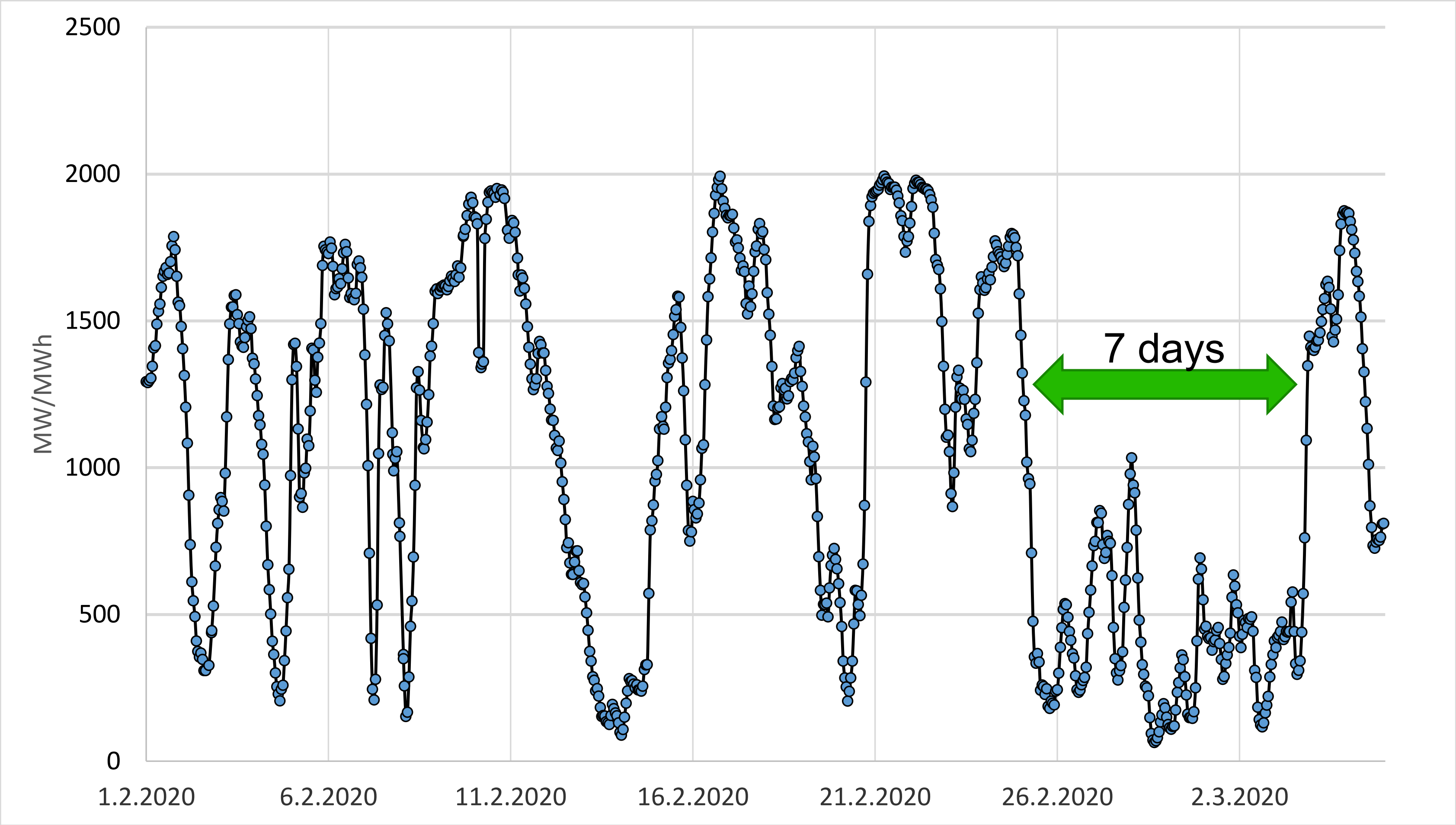
In scale of 1000 tH2 (33 GWh, LHV) CAPEX of lined rock cavern hydrogen storage: ~1.5 €/kWh
Capex of battery energy storage: 200-500 €/kWh

Source: R.K. Ahluwalia, et. Al., System Level Analysis of Hydrogen Storage Options, 2019 Annual Merit Review and Peer Evalauation Meeting, Washington, D.C., 2019

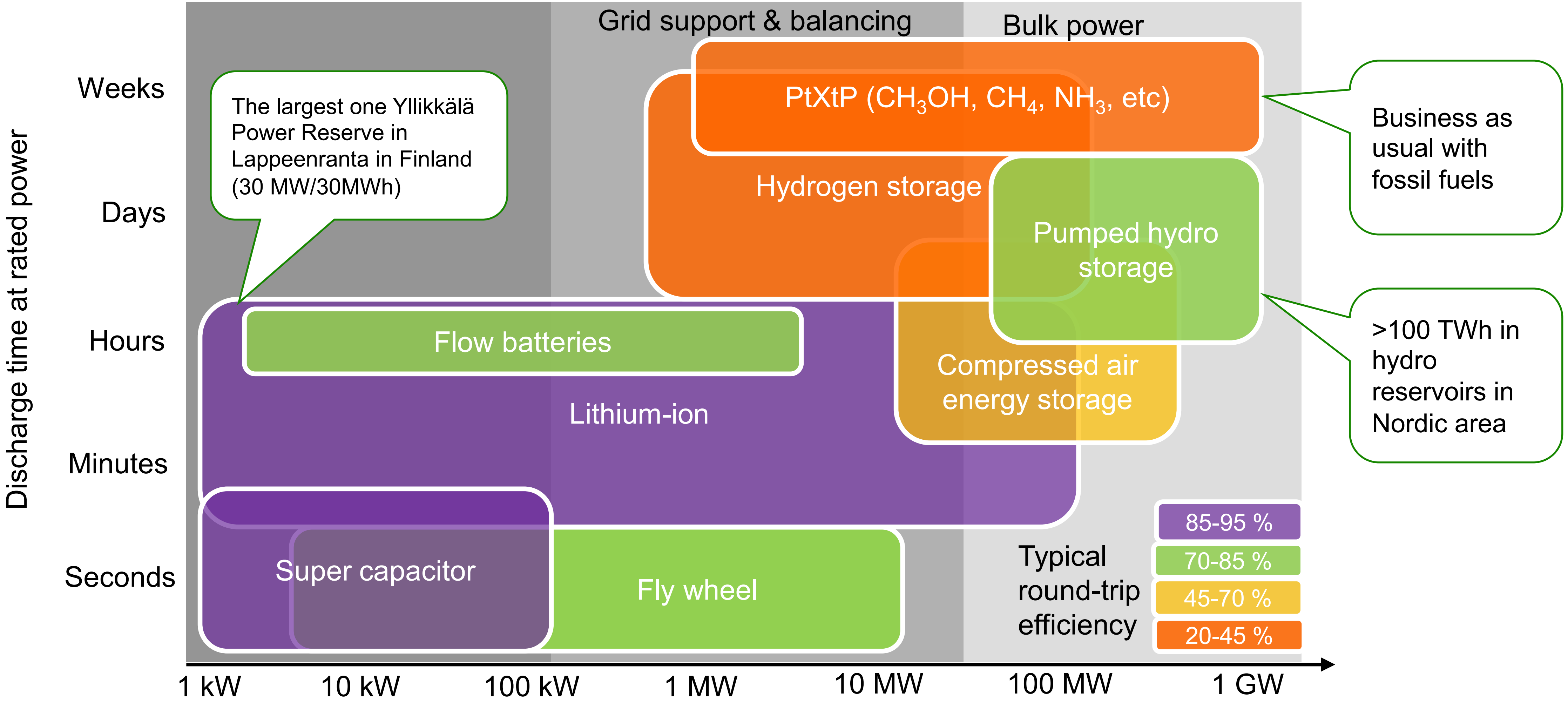
9.3.2021

Grid balancing with hydrogen

Example: Wind power generation variation in Finland 1.2.-5.3.2020

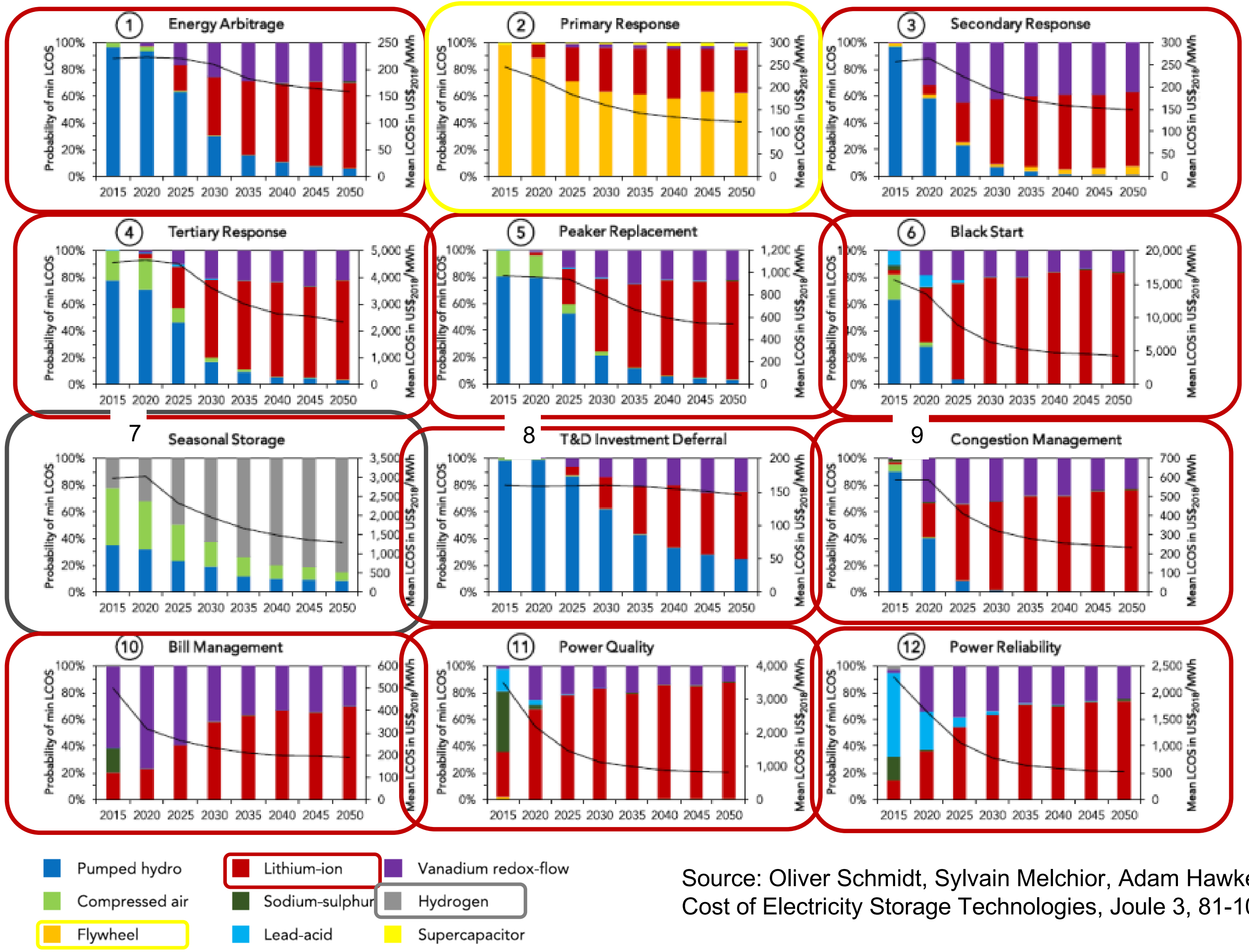


GRID BALANCING: There is no single solution for an energy storage



Global energy storage project database (by US DOE): https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/

GRID BALANCING: Li-Ion batteries and hydrogen are expected to become winners as energy storages providing grid services



Role	Application	Description
	1. Energy arbitrage	Purchase power in low-price and sell in high-price periods on wholesale or retail market
System Operation	2. Primary response	Correct continuous and sudden frequency and voltage changes across the network
	3. Secondary response	Correct anticipated and unexpected imbalances between load and generation
	4. Tertiary response	Replace primary and secondary response during prolonged system stress
	5. Peaker replacement	Ensure availability of sufficient generation capacity during peak demand periods
	6. Black start	Restore power plant operations after network outage without external power supply
	7. Seasonal storage	Compensate long-term supply disruption or seasonal variability in supply and demand
Network Operation	8. T&D investment deferral	Defer network infrastructure upgrades caused by peak power flow exceeding existing capacity
	9. Congestion management	Avoid re-dispatch and local price differences due to risk of overloading existing infrastructure
Consumption	10. Bill management	Optimise power purchase, minimize demand charges and maximise PV self-consumption
	11. Power quality	Protect on-site load against short-duration power loss or variations in voltage or frequency
	12. Power reliability	Cover temporal lack of variable supply and provide power during blackouts

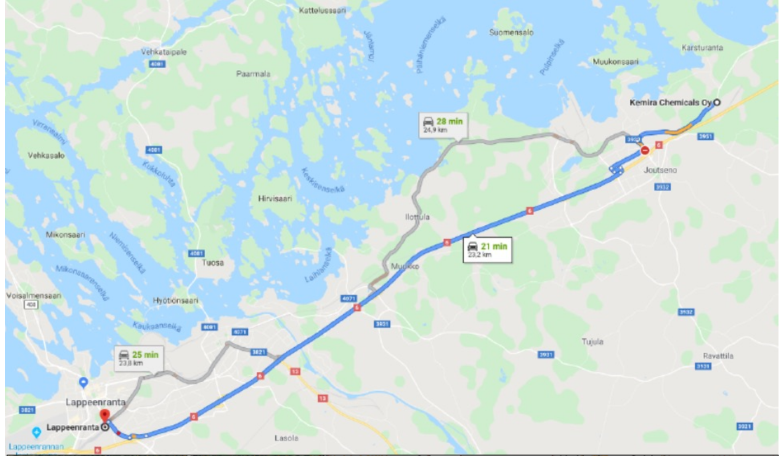
Source: Oliver Schmidt, Sylvain Melchior, Adam Hawkes, Lain Staffer, Projecting the Future Levelized Cost of Electricity Storage Technologies, Joule 3, 81-100, January 16, 2019.

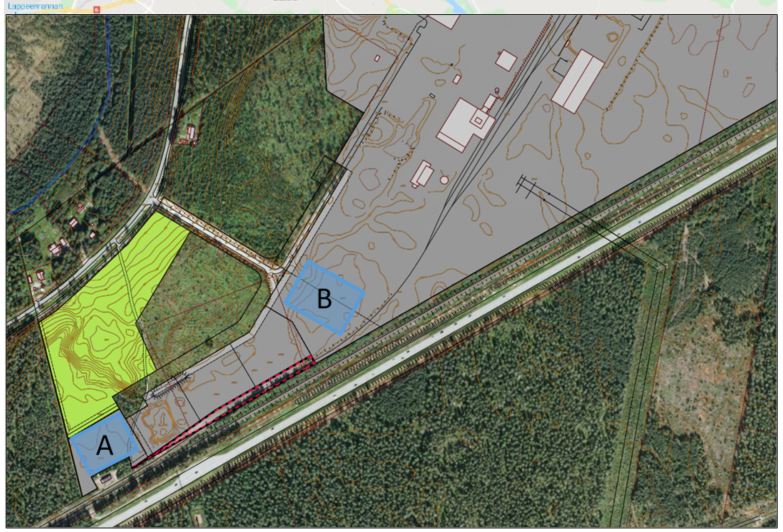
9.3.2021

Project P2X Joutseno

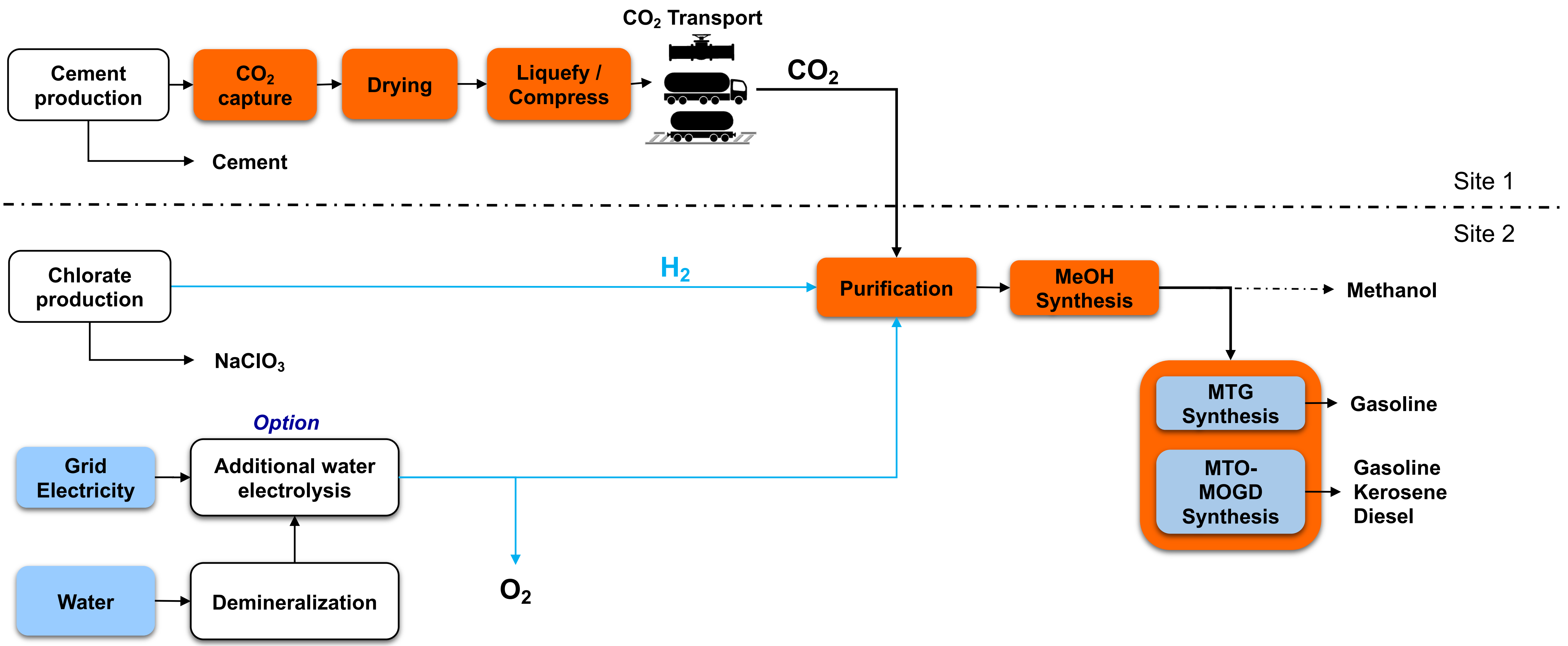
Project P2X Joutseno: Industrial-scale PtX pilot – Feasibility study and development

- The main objective was to study the feasibility and profitability
  - Costs and technologies based on budgetary offers
- Main feedstocks:
  - Hydrogen (H_2) 5 000 t/a, (Chlor-Alkali electrolysis, Kemira Chemicals
  - Carbon dioxide (CO_2) 36 667 t/a, Finnsementti
- End products:
  - Metanol 26 667 t/a (~1000 truck loads)
  - Refining of methanol into gasoline, diesel and kerosene through different routes (MeOH + MTG, MeOH + MTO-MOGD)
- LUT partners:
  - St1 Oy, Kemira Oy, Wärtsilä, Finnsementti Oy, Shell Long Term Research, Neste Oyj, Finnair Oyj.
  - City of Lappeenranta
  - Local machine workshops
- Funders Etelä-Karjalan Liitto, LUT and companies



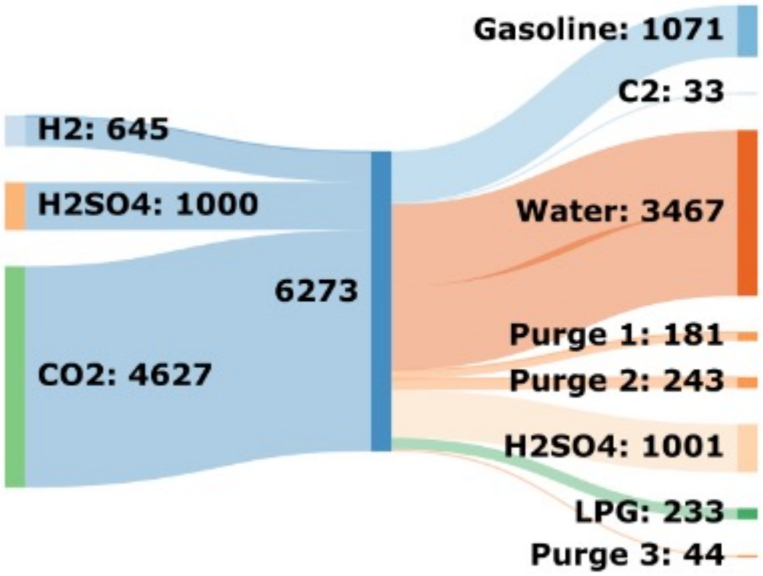


P2X Joutseno – Studied processes

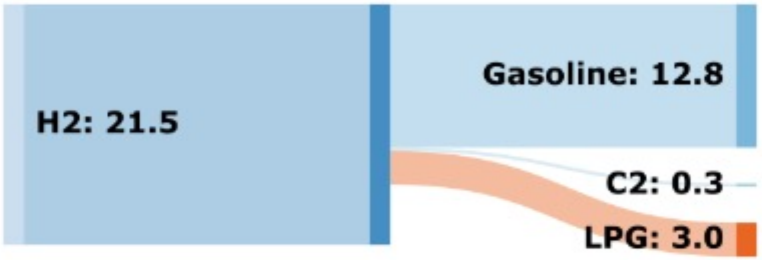


MeOH + MTG

Total mass flow rate (kg/hr)



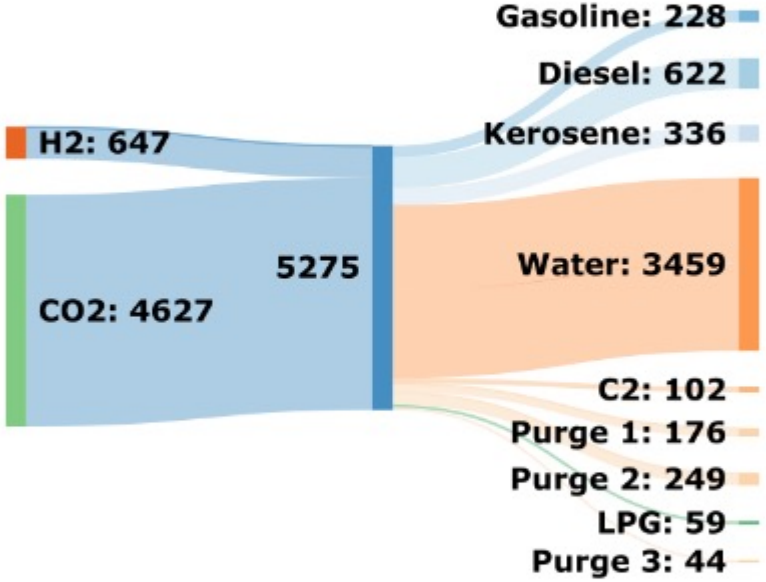
Thermal power (MW)



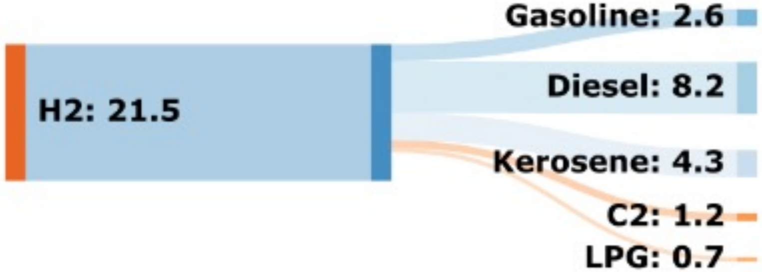
60% (Gasoline)
75 % (All)

MeOH + MTO-MOGD

Total mass flow rate (kg/hr)



Thermal power (MW)



20% (K)
70% (G,D,K)
79 % (All)

Techno-economics

No hydrogen from electrolysis

				Base case				
Electricity price €/MWh)		**20**	**30**	**40**	**50**			
IRR (investor)		14.4 %	13.3 %	12.1 %	11.0 %			
Hydrogen price (€/MWh)			**10**	**15**	**20**	**25**	**30**	
(€/kg)			**0.3**	**0.5**	**0.6**	**0.8**	**1.0**	
IRR (investor)			16.7 %	12.1 %	7.3 %	2.1 %	-3.9 %	
Total investment (reserve)	**-30 %**	**-15 %**	**0 %**	**15 %**	**30 %**			Note that base case includes a 15% reserve
IRR (investor)	43.9 %	27.4 %	18.2 %	12.1 %	7.8 %			
Gasoline (€/tn)	**1000**	**1200**	**1300**	**1400**	**1600**	**1800**		Fossil price + biofuel premium. German biofuel premium price has been above 400 €/tonCO2 between early November 2019 and late April 2020 (STX, 2020).
IRR (investor)	-9.1 %	3.0 %	7.7 %	12.1 %	20.5 %	28.4 %		
Debt rate			**1 %**	**2 %**	**3 %**	**4 %**	**5 %**	Debt ratio is assumed to be 70% of total investment after subsidies
IRR (investor)			13.3 %	12.1 %	11.0 %	10.0 %	9.0 %	
O&M				**2% & 3%**	**3% & 4%**	**4% & 5%**		Operation as % of actual revenue, maintenance as % of technical investment
IRR (investor)				12.1 %	7.8 %	3.3 %		
Operation time (h)		**6000**	**7000**	**8000**				
IRR (investor)		2.2 %	7.4 %	12.1 %				
Investment subsidy (TEM)			**30 %**	**40 %**	**50 %**			
IRR (investor)			9.1 %	12.1 %	15.9 %			

9.3.2021

Carbon neutral Finland report

Press release and report available at: https://www.lut.fi/web/en/news/-/asset_publisher/lGh4SAywhcPu/content/lut-wartsila-and-st1-power-to-x-solutions-should-be-raised-to-the-core-of-finland-s-energy-and-climate-solutions

Background and assumptions

- Strategic level study: the main emphasis is in electricity demand, production and transmission
- The main objective is to study the recycling of CO_2 from point sources into fuels with PtX: How it affects the electricity consumption. Only hydrogen production with water electrolysis is taken into account.
- Other assumptions: Reforming of H2 from natural gas ends (~600 MW)
- Heating is assumed to be electrified by heat pumps.

Implications to national economy

- Investments:
  - Fuel manufacturing plants 10-20 billion EUR (50-100 % bio-CO_2)
  - Wind power plants 25 – 50 billion EUR
  - Electricity and hydrogen transmission infrastructure
- Profits:
  - Emission reductions – carbon neutral Finland
  - No need for transportation fuel imports – 5 billion EUR/a
- Thousands of new jobs, especially in regressive areas
  - Land leases
  - Tax incomes

Electricity demand – All bio-CO_2 into fuels

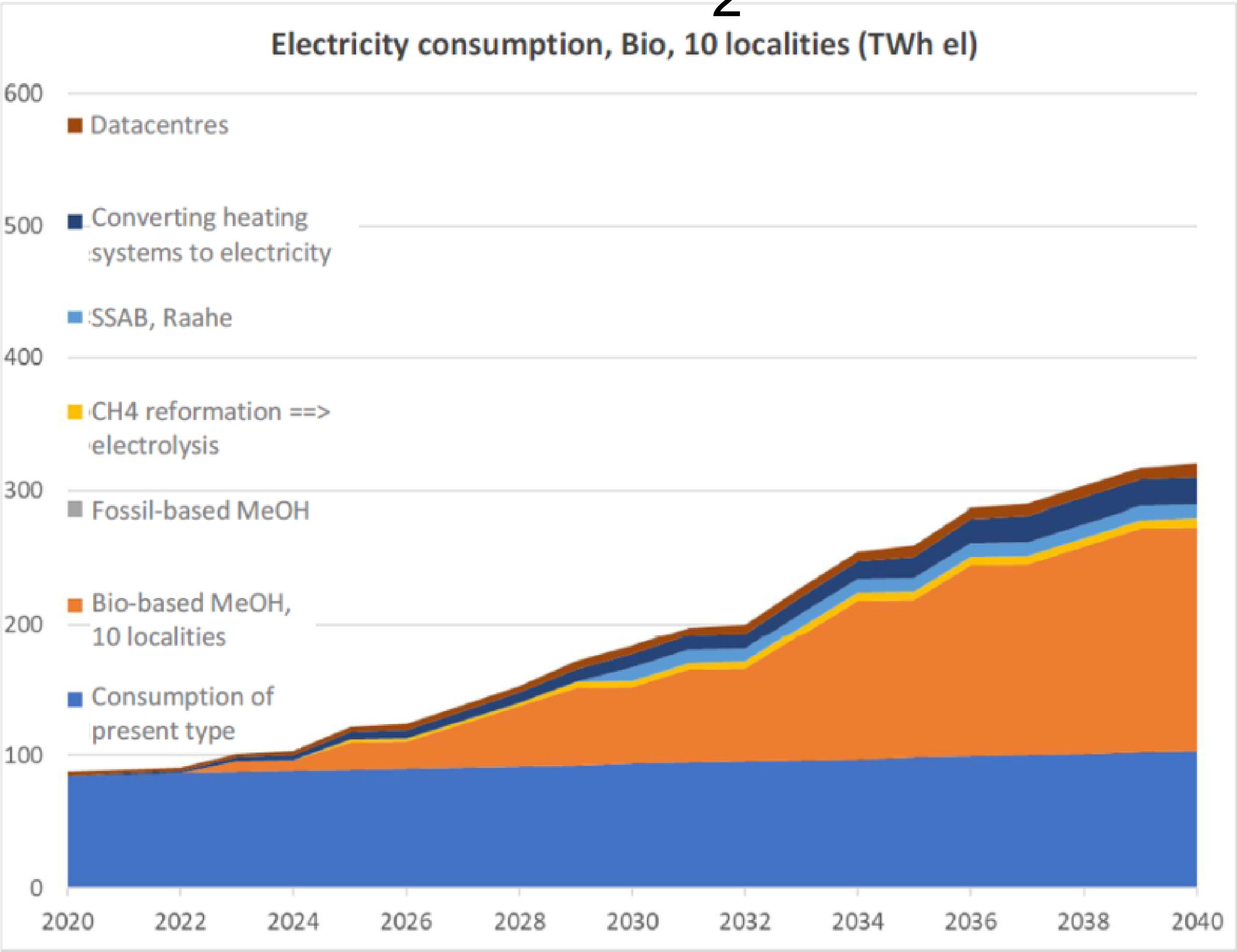
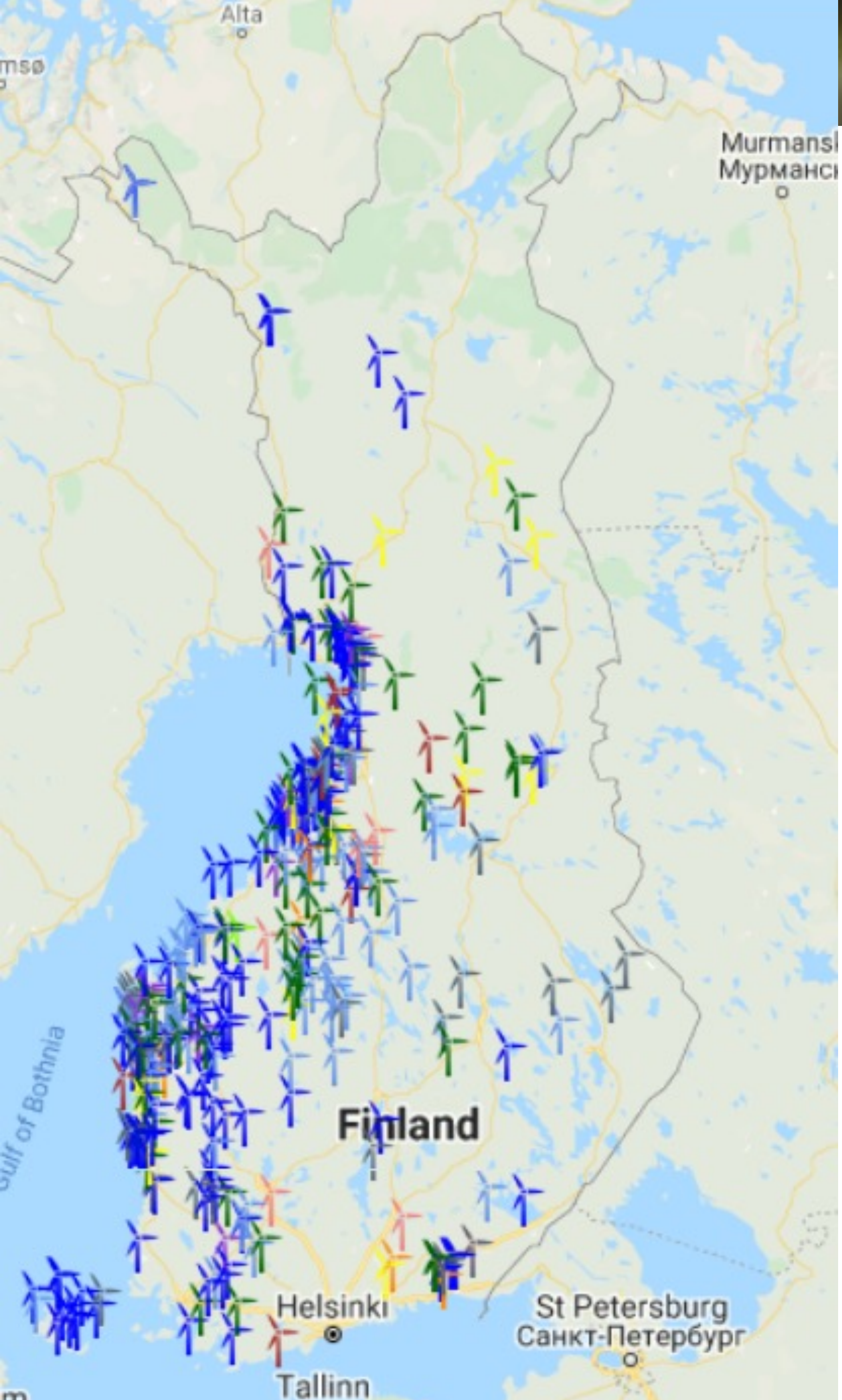


Figure 5. Increase in demand for electricity if the carbon dioxide emissions of chemical pulp plants (21 million tonnes CO2) are recycled to create fuels



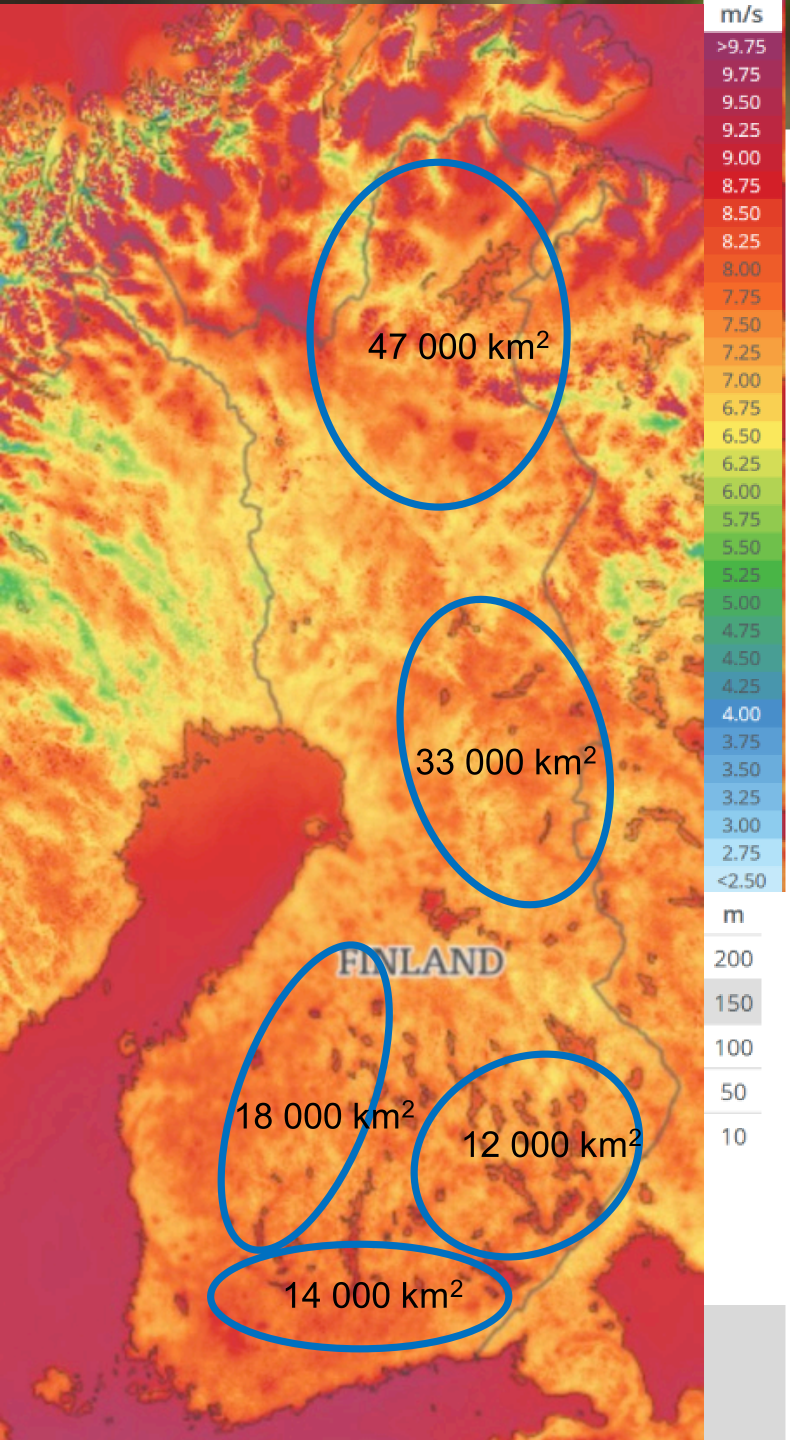
Current wind power projects

- Implementation: 4,2 GW ; 12 TWh/a (35%, 8670h, 4MW)
- Planned: 12,3 GW ; 37 TWh/a (35%, 8670h, 4MW)
- Totally: 50 TWh/a.

Onshore	Projects	MW	WTG
6 Under Construction	10	378	85
5 Fully Permitted	74	3849	945
4 Land Use Plan or STR Done	48	3177	754
3 STR Process Ongoing	1	18	4
3 Land Use Plan Proposal	15	1491	247
3 EIA Done	6	494	83
2 Land Use Plan Draft	4	222	44
2 EIA Process Ongoing	4	1120	212
1 Land Use Plan Process Started	9	1055	205
0 Identified Project / Pre-Screening	30	1153	306
In Total	**201**	**12957**	**2885**

Suomen Tuulivoimayhdistys

Offshore	Projects	MW	WTG
4 Land Use Plan or STR Done	3	820	166
3 EIA Done	4	1920	140
0 Identified Project / Pre-Screening	3	820	105
In Total	**10**	**3560**	**411**



On-shore wind power potential

Assumptions: 1 turbine/km2, filling ratio 10% in selected areas, the whole country level filling ratio 3,7 % + current construction. Danish objective 2030 is 4,1 % of land area for filling factor. Capacity factor 53%

Source: https://globalwindatlas.info/

	km2	Height 150 m/s		Height 200		No of units 10 %	Production 150 m GWh/unit		AEP/alue TWh/a		Production 200 m GWh/unit		TWh/a	
Pohjois-Lappi	47 000	8,0	9,0	8,7	10,0	4700	21,0	22,25	99	105	22,3	22,3	105	105
Kainuu & Etelä-Lappi	33 000	8,0	8,8	8,7	9,8	3300	21,0	22,25	69	73	22,3	22,3	73	73
Etelä-Karjala & Savo	12 000	8,0	8,7	8,7	9,5	1200	21,0	22,25	25	27	22,3	22,3	27	27
Etelä-Suomi ja Kymi	14 000	7,5	9,0	8,8	9,8	1400	19,2	22,25	27	31	22,3	22,3	31	31
Varsinais-Suomi ja Etelä-Pohjanmaa	18 000	7,9	8,5	8,6	9,6	1800	20,5	22,25	37	40	22,3	22,3	40	40
	124 000					12 400			257	276			276	276

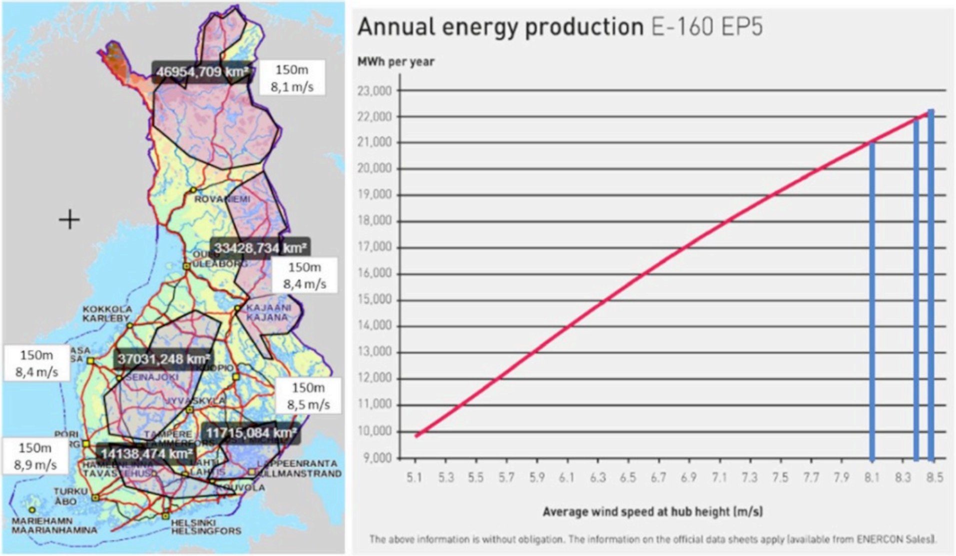


Figure 10. Wind power construction areas (shown in purple on the map) on the basis of wind speed. Source: https://globalwindatlas.info/ and the annual generation curve of an Enercon EP5-160 turbine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