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CO_2 circularity and green hydrogen for renewable e-fuels

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IFAT Hydrogen Stage

6th May 2026, 13:00 to 13:50

CO_2 circularity and hydrogen for renewable e-fuels

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1. Hydrocarbons are the building blocks of fuels we use in our daily lives
2. Sustainable hydrocarbons are made from circular CO2 and renewable hydrogen
3. Examples of the technologies and value chains that enable recycling of waste CO2

1) Why make e-fuels when hydrocarbons are so abundant in the world?

E-fuels are a type of ‘Renewable Fuel of non-Biological Origin’ or RFNBO. They reduce CO2 emissions by substituting fossil fuels with circular use of CO2. EU (RED III) is 70% GHG reduction vs fossil, UK requirement (RTFO) is 65% GHG emissions reduction.

CCUS

If captured fossil (or geogenic) CO2 is used to produce e-fuels, the CO2 emissions take place only once, not twice.

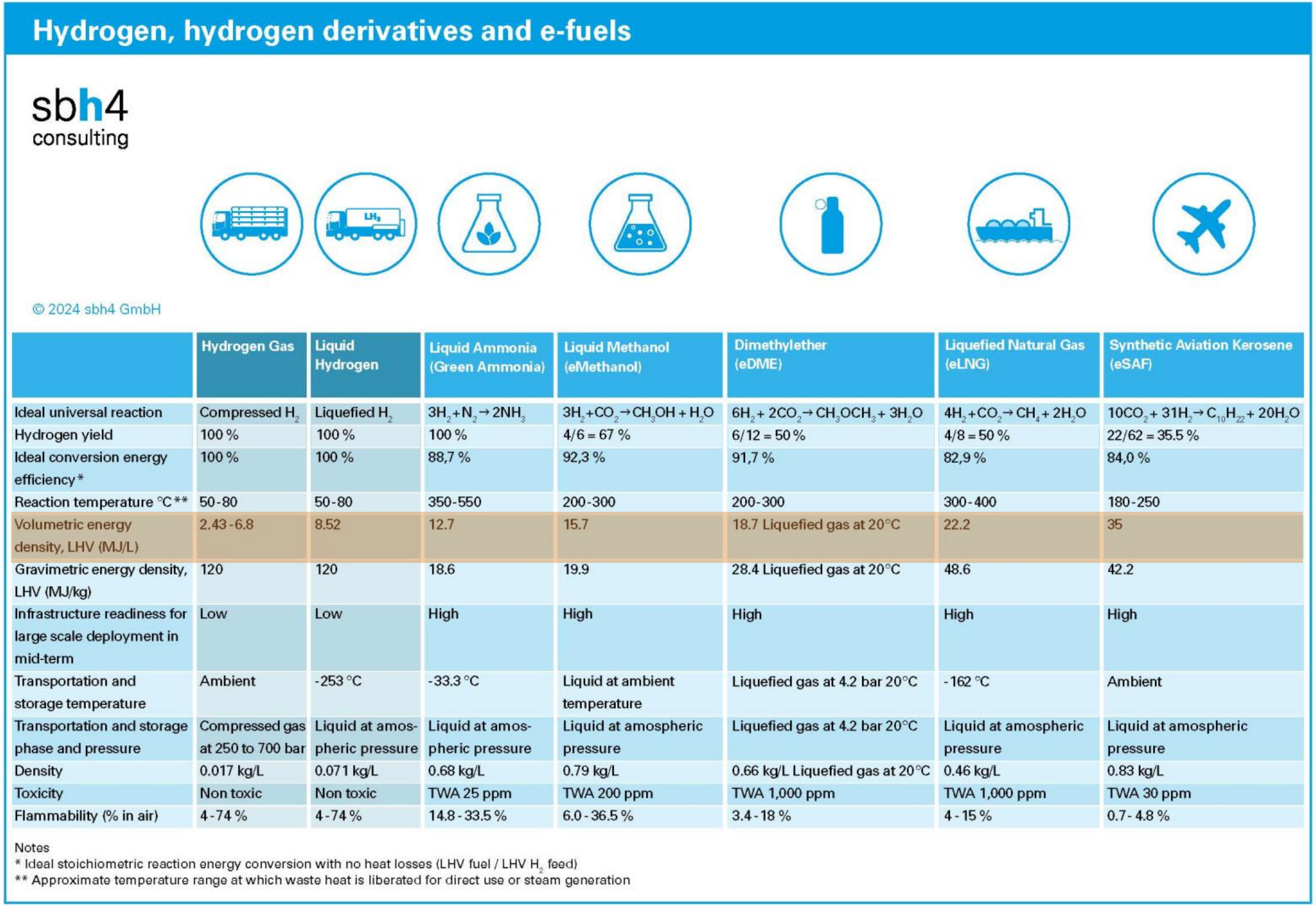
DAC

If CO2 from Direct Air Capture (DAC) is used to produce e-fuels, the CO2 use is circular.*

BECCUS

If captured biogenic CO2 is used to produce e-fuels, the CO2 use is circular.

* Assuming the DAC equipment is powered with renewable electricity and heat..



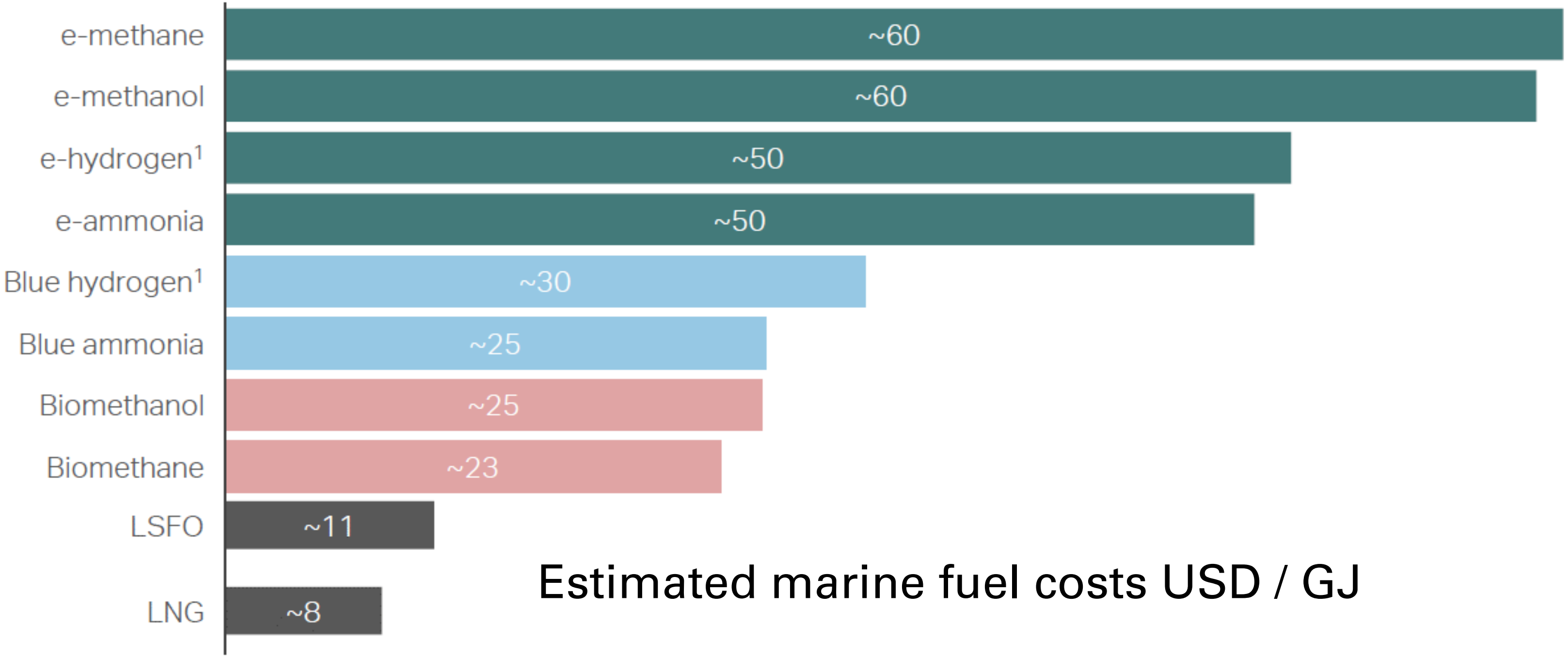
Hydrogen, hydrogen derivatives and e-fuels

	Hydrogen Gas	Liquid Hydrogen	Liquid Ammonia (Green Ammonia)	Liquid Methanol (eMethanol)	Dimethylether (eDME)	Liquefied Natural Gas (eLNG)	Synthetic Aviation Kerosene (eSAF)
Ideal universal reaction	Compressed H_2	Liquefied H_2	$3H_2+N_2 \rightarrow 2NH_3$	$3H_2+CO_2 \rightarrow CH_3OH + H_2O$	$6H_2 + 2CO_2 \rightarrow CH_3OCH_3 + 3H_2O$	$4H_2+CO_2 \rightarrow CH_4 + 2H_2O$	$10CO_2 + 31H_2 \rightarrow C_{10}H_{22} + 20H_2O$
Hydrogen yield	100 %	100 %	100 %	4/6 = 67 %	6/12 = 50 %	4/8 = 50 %	22/62 = 35.5 %
Ideal conversion energy efficiency *	100 %	100 %	88,7 %	92,3 %	91,7 %	82,9 %	84,0 %
Reaction temperature °C **	50-80	50-80	350-550	200-300	200-300	300-400	180-250
Volumetric energy density, LHV (MJ/L)	2.43-6.8	8.52	12.7	15.7	18.7 Liquefied gas at 20°C	22.2	35
Gravimetric energy density, LHV (MJ/kg)	120	120	18.6	19.9	28.4 Liquefied gas at 20°C	48.6	42.2
Infrastructure readiness for large scale deployment in mid-term	Low	Low	High	High	High	High	High
Transportation and storage temperature	Ambient	-253 °C	-33.3 °C	Liquid at ambient temperature	Liquefied gas at 4.2 bar 20°C	-162 °C	Ambient
Transportation and storage phase and pressure	Compressed gas at 250 to 700 bar	Liquid at amospheric pressure	Liquid at amospheric pressure	Liquid at amospheric pressure	Liquefied gas at 4.2 bar 20°C	Liquid at amospheric pressure	Liquid at amospheric pressure
Density	0.017 kg/L	0.071 kg/L	0.68 kg/L	0.79 kg/L	0.66 kg/L Liquefied gas at 20°C	0.46 kg/L	0.83 kg/L
Toxicity	Non toxic	Non toxic	TWA 25 ppm	TWA 200 ppm	TWA 1,000 ppm	TWA 1,000 ppm	TWA 30 ppm
Flammability (% in air)	4-74 %	4-74 %	14.8-33.5 %	6.0-36.5 %	3.4-18 %	4-15 %	0.7-4.8 %

Notes
* Ideal stoichiometric reaction energy conversion with no heat losses (LHV fuel / LHV H_2 feed)
** Approximate temperature range at which waste heat is liberated for direct use or steam generation

- Liquid e-fuels are significantly easier to transport and store than hydrogen due to a high volumetric energy density as a liquid
- Use of hydrogen to produce hydrocarbon e-fuels introduces CO2 circularity
- E-fuel production relies on low-cost renewable power
- Access to low-cost (biogenic) CO2 is also an important consideration to reduce the CO2 intensity of the e-fuel

E-fuels have a cost penalty versus other drop-in replacements to fossil fuels, such as biofuels and blue fuels (hydrogen from fossil fuel with CCS). However, e-fuels will be adopted due to regulations creating a market for them and limitations that exist scaling biofuels.



Estimated marine fuel costs USD / GJ

Industry Transition Strategy October 2021
MærskMc-Kinney Møller Center for Zero Carbon Shipping

It is expected that regulations will mandate that an increasing percentage of sustainable aviation fuel (SAF) will be RFNBOs, or e-fuels. ReFuelEU Aviation regulations are shown.

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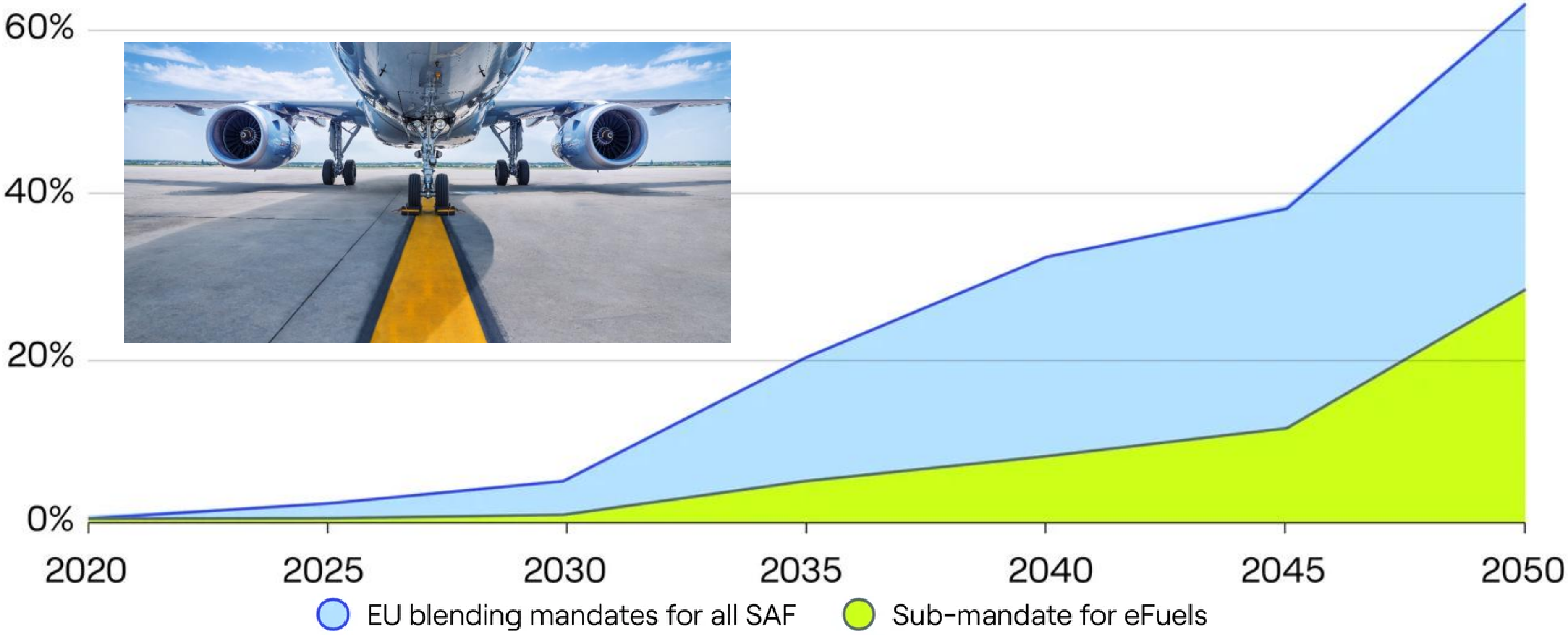


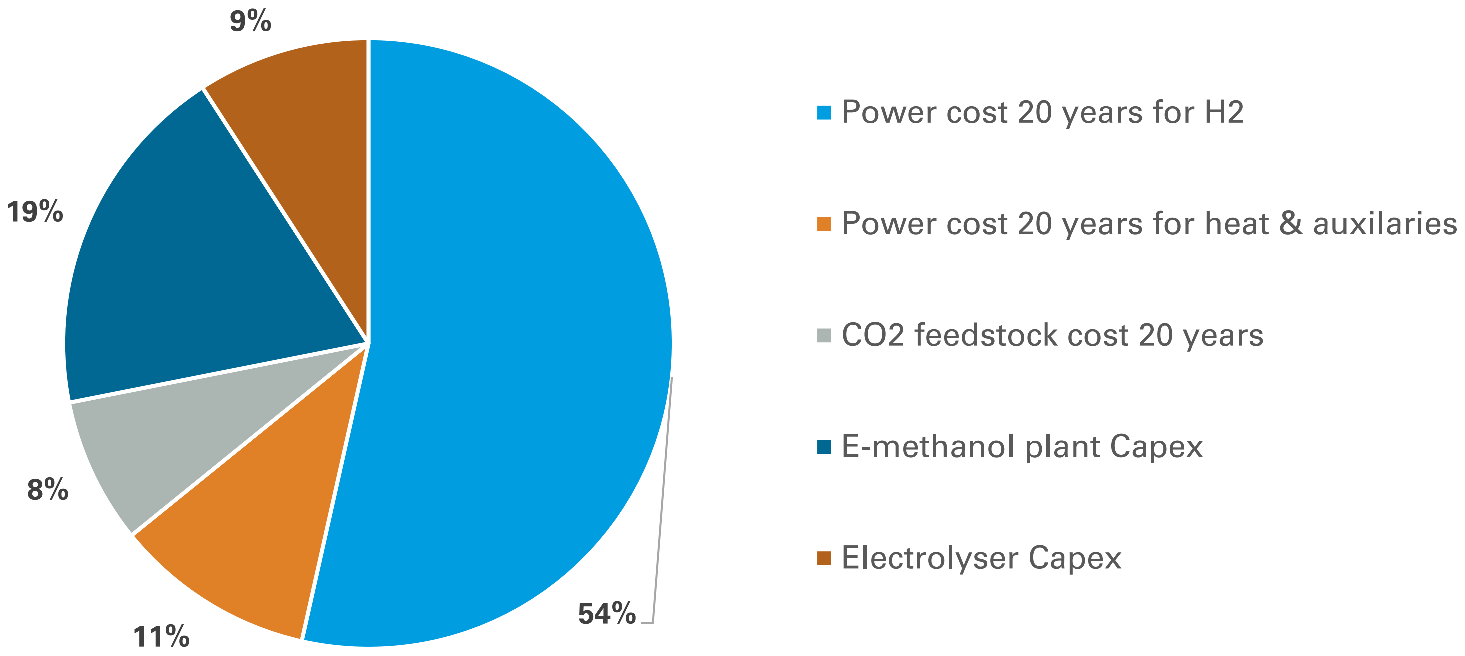
https://www.topsoe.com/sustainable-aviation-fuel/saf-outlook

European Energy Kassø: 32,000 tonnes per year e-methanol facility. Direct hydrogenation of biogenic CO2 pathway using green hydrogen from Siemens Energy Elyzer 300 PEM electrolysers and Clariant's MegaMax® CO2 hydrogenation catalyst. E-methanol off takers include AP Moller Maersk, Lego and Novo Nordisk. Mitsui now owns 49% of the project.

Images courtesy of European Energy

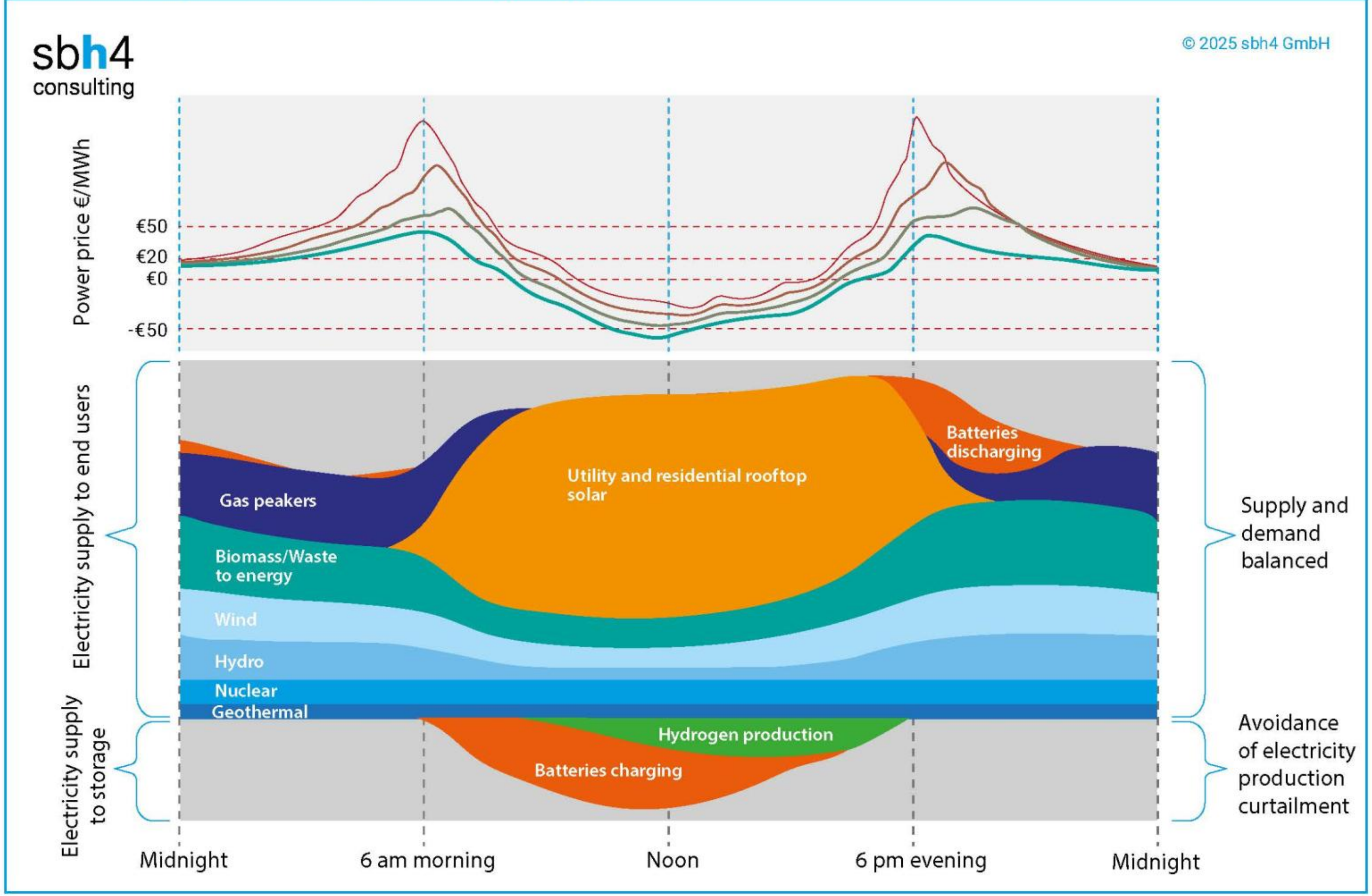
2) Electrolytic renewable/green hydrogen for sustainable e-fuels

Typical 20-year opex and capex costs for an e-methanol project. Renewable electricity for hydrogen production is the most significant cost element. The CO2 costs are generally less than 10%.



Source: author’s research of FTS projects with green hydrogen and electrically heated SMR

Curtailed power for low-cost hydrogen



“Intentionally intermittent” electrolyser operation can exploit periods of negative and zero-priced electricity to reduce the cost of e-fuels.

The amount and duration of wind and solar renewable power curtailment in California, Germany and many other locations is increasing annually.

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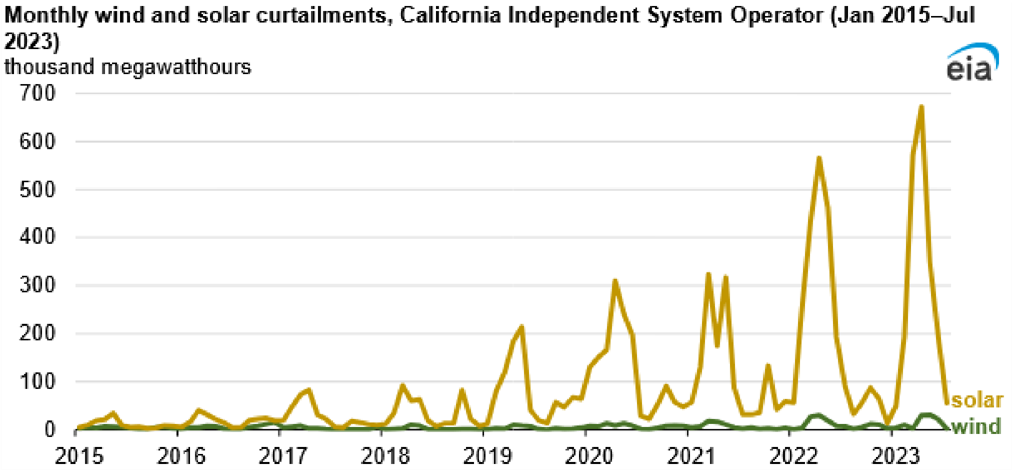
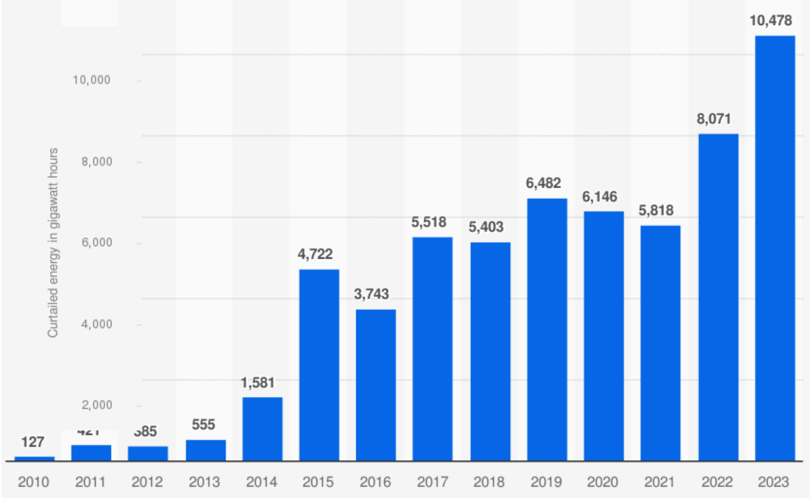

Monthly wind and solar curtailments, California Independent System Operator (Jan 2015–Jul 2023)
thousand megawatthours

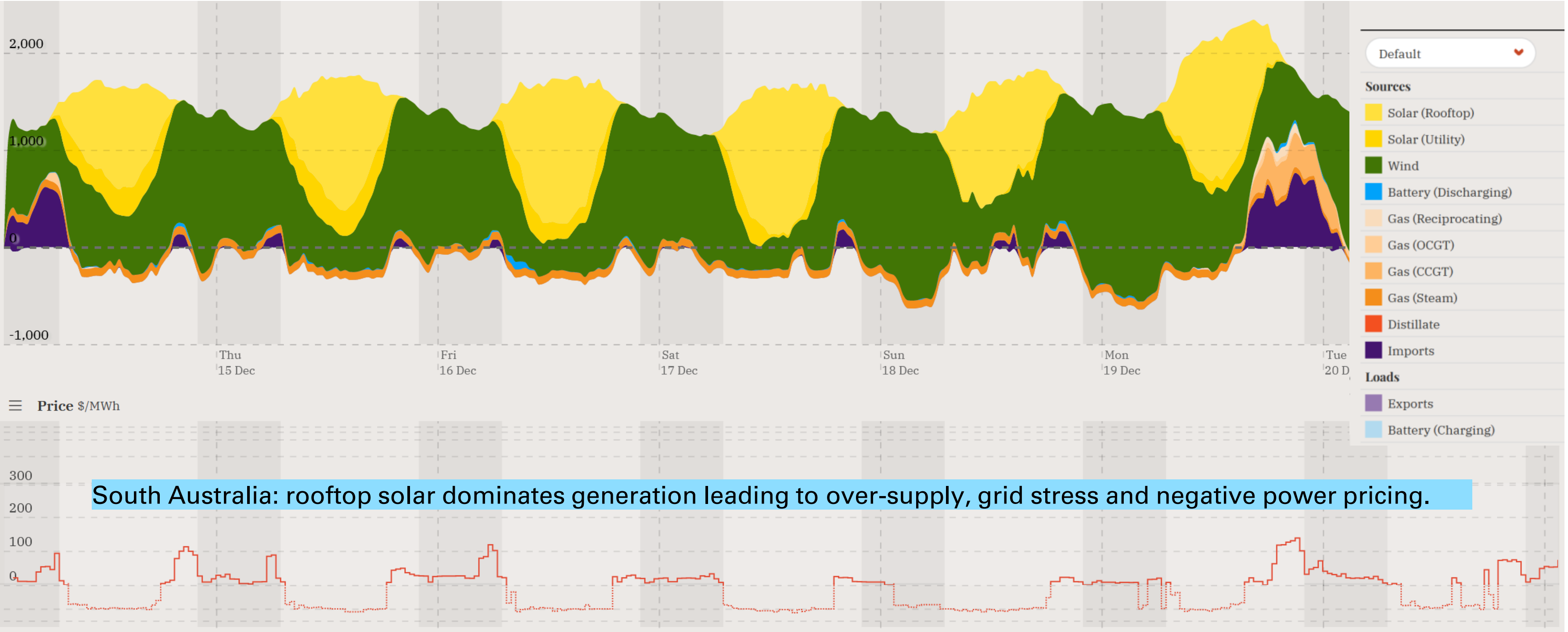
California



Germany

https://www.eia.gov/todayinenergy/detail.php?id=60822
https://www.statista.com/statistics/1332954/renewable-energy-power-curtailment-germany/

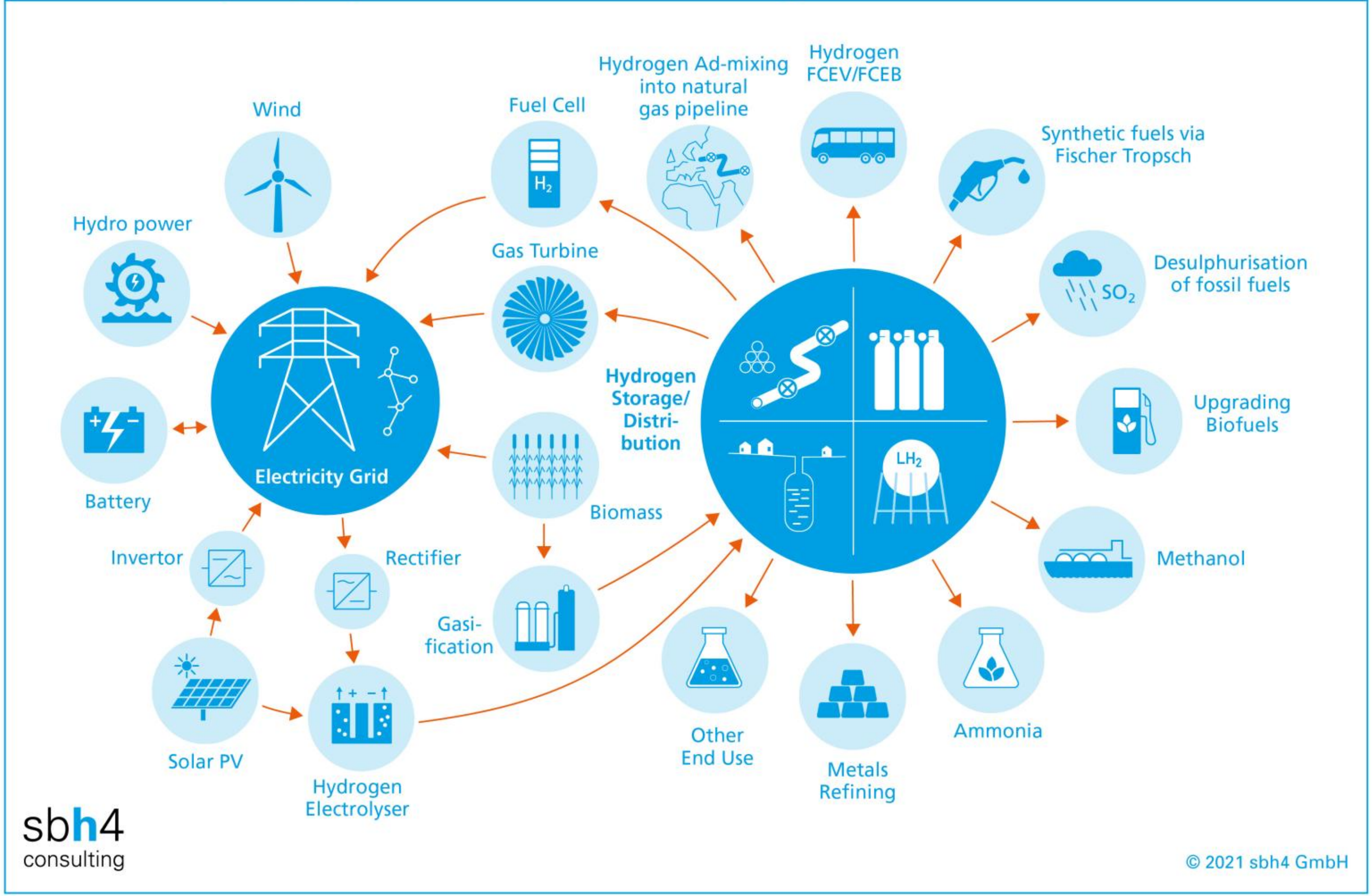
We can see the "renewables penetration end-game" when we examine data from South Australia, where negatively priced power exists for around 10 hours per day during periods of solar power curtailment.



South Australia: rooftop solar dominates generation leading to over-supply, grid stress and negative power pricing.

https://opennem.org.au/energy/sa1/?range=7d&interval=30m

Renewable hydrogen production, distribution, storage and utilisation value chains



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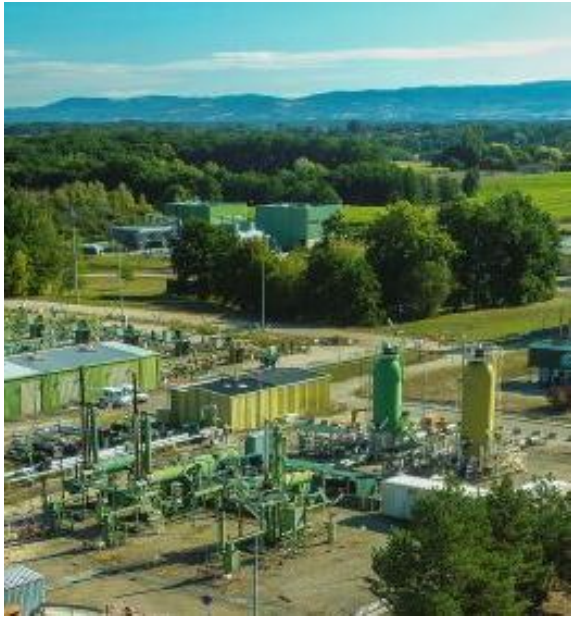
Intermittent hydrogen production requires hydrogen storage to allow the downstream e-fuels processing to operate continuously and ensure an efficient use of capital.

Underground hydrogen storage (UHS) in salt cavern demonstration projects are proceeding in Europe. They often re-purpose existing underground natural gas storage (UGS) infrastructure.

Harsefeld UGS, Hamburg, Germany will be expanded to include 5,000 tonnes UHS in new salt caverns in the SaltHy project.



HyPSTER, Ertrez France. 50 tonnes of hydrogen in EZ53 cavity will be followed by additional caverns to 6,700 tonnes.

UHS to be implemented at an existing SSE site in Aldbrough on the Yorkshire coast in the UK.

https://innovation.engie.com/en/news/interview/new-energies/hypster-an-engie-group-innovation-goes-to-industrial-scale/29098
https://www.engie-deutschland.de/en/magazine/natural-gas-storage-facilities-clever-technology-security-supply-germany
https://amp-theguardian-com.cdn.ampproject.org/c/s/amp.theguardian.com/environment/2022/dec/18/sse-begins-work-on-hydrogen-storage-cavern-on-yorkshire-coast

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3) Waste to Energy can help to close the CO2 circularity loop

CCU/S from Waste to Energy plants (eg Ørsted Avedøre & Stockholm Exergi) are proposed. Use of CO2 for e-fuels combined with carbon dioxide removal (CDR) can share the investment costs in CO2 capture.

https://www.esgtoday.com/microsoft-signs-1-million-tonne-bioenergy-based-carbon-removal-agreement-with-orsted/

https://www.svt.se/nyheter/lokalt/stockholm/vartaverkets-sista-kolpanna-stangs-tidigare-an-planerat

CO₂ capture technology selection – rules of thumb for initial screening of liquid solvent systems.

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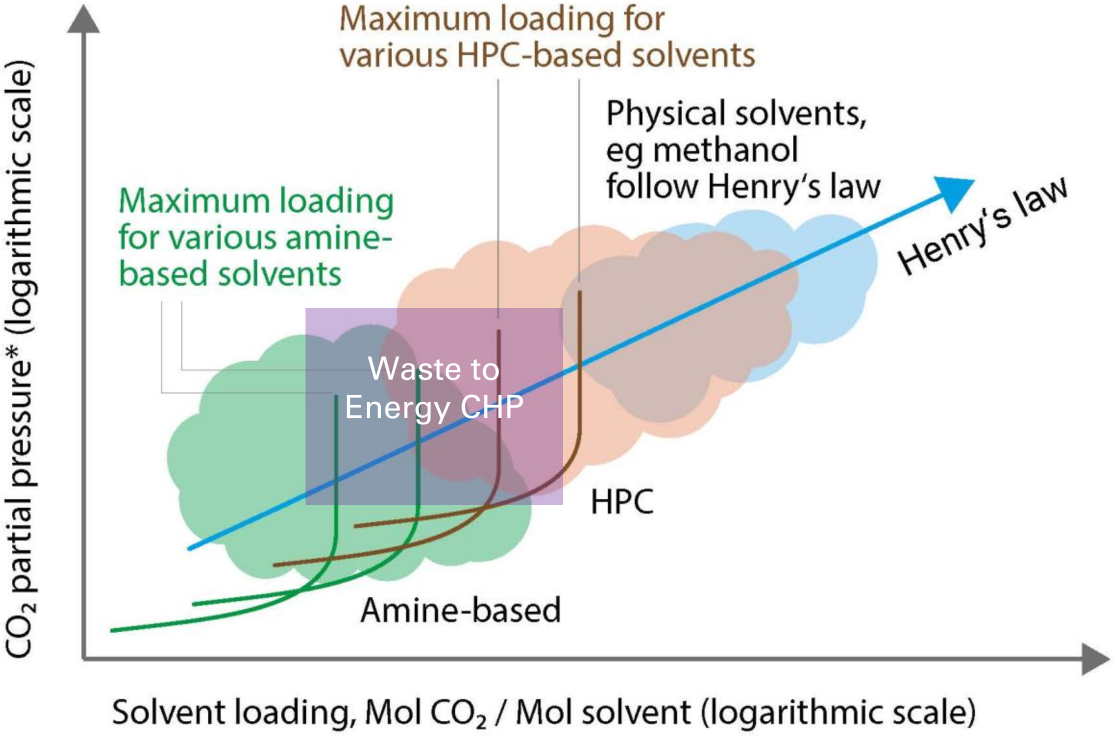
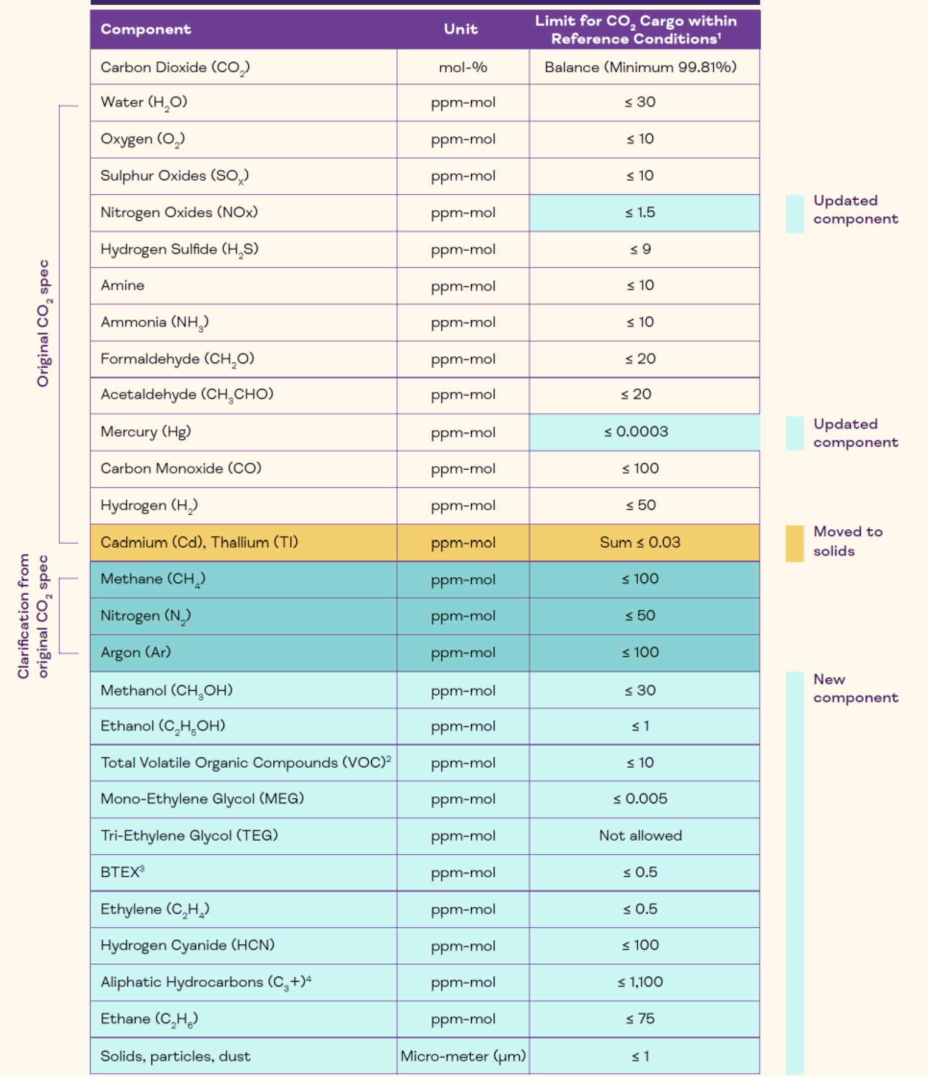


* CO_2 partial pressure = CO_2 molar concentration x stream pressure

- CO2 capture from Waste to Energy CHP sits at the overlap of amine and HPC systems.
- Chemical solvents (amine and HPC) react with the CO2 (chemisorption) and require high regeneration energies.
- Technology selection, process integration and heat management can reduce the costs of CO2 capture

Northern Lights liquid CO2 specification leans towards CO2 liquefaction and cryogenic distillation for CO2 purification.

https://norlights.com/wp-content/uploads/2024/06/NorthernLights-GS-co2-spec2024.pdf



Component	Unit	Limit for CO_2 Cargo within Reference Conditions[1]
Carbon Dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)
Water (H_2O)	ppm-mol	≤ 30
Oxygen (O_2)	ppm-mol	≤ 10
Sulphur Oxides (SO_X)	ppm-mol	≤ 10
Nitrogen Oxides (NOx)	ppm-mol	≤ 1.5
Hydrogen Sulfide (H_2S)	ppm-mol	≤ 9
Amine	ppm-mol	≤ 10
Ammonia (NH_3)	ppm-mol	≤ 10
Formaldehyde (CH_2O)	ppm-mol	≤ 20
Acetaldehyde (CH_3CHO)	ppm-mol	≤ 20
Mercury (Hg)	ppm-mol	≤ 0.0003
Carbon Monoxide (CO)	ppm-mol	≤ 100
Hydrogen (H_2)	ppm-mol	≤ 50
Cadmium (Cd), Thallium (Tl)	ppm-mol	Sum ≤ 0.03
Methane (CH_4)	ppm-mol	≤ 100
Nitrogen (N_2)	ppm-mol	≤ 50
Argon (Ar)	ppm-mol	≤ 100
Methanol (CH_3OH)	ppm-mol	≤ 30
Ethanol (C_2H_5OH)	ppm-mol	≤ 1
Total Volatile Organic Compounds (VOC)[2]	ppm-mol	≤ 10
Mono-Ethylene Glycol (MEG)	ppm-mol	≤ 0.005
Tri-Ethylene Glycol (TEG)	ppm-mol	Not allowed
BTEX[3]	ppm-mol	≤ 0.5
Ethylene (C_2H_4)	ppm-mol	≤ 0.5
Hydrogen Cyanide (HCN)	ppm-mol	≤ 100
Aliphatic Hydrocarbons (C_3+)[4]	ppm-mol	≤ 1,100
Ethane (C_2H_6)	ppm-mol	≤ 75
Solids, particles, dust	Micro-meter (µm)	≤ 1

Original CO_2 spec

Clarification from original CO_2 spec

Updated component

Updated component

Moved to solids

New component

4) The need for new CO2 supply chains

Liquid CO2 supply chains exist today with typical applications in the food and beverage sector. The volumes required, logistics routes and transport modalities for e-fuels production will require investment in new CO2 logistics infrastructure to support new transport modes, routes and increased volumes.

Overland, CO2 pipelines are the most efficient mode of CO2 transportation. For offshore routes, there is a crossover at longer distances favouring liquid CO2 shipping.

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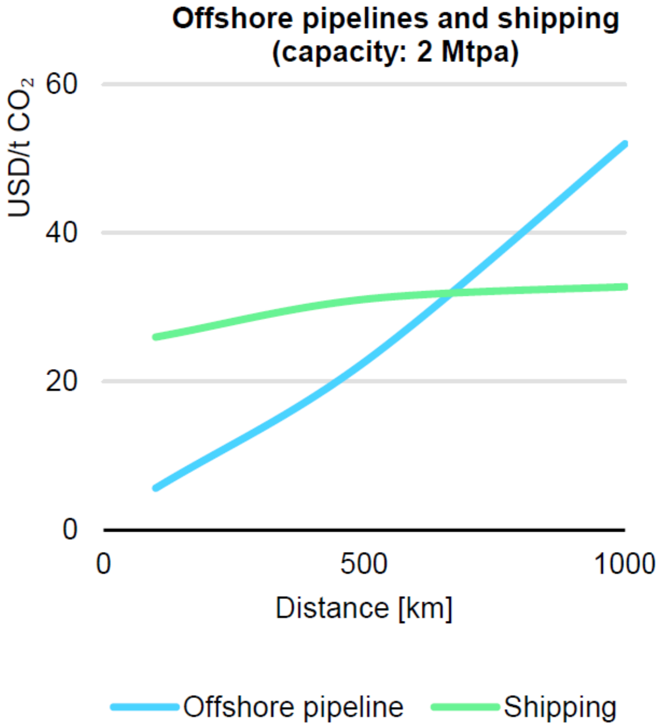

https://iea.blob.core.windows.net/assets/d0cb5c89-3bd4-4efd-8ef5-57dc327a02d6/CCUSPoliciesandBusinessModels.pdf

In the short and medium term, e-fuel projects that source CO2 will rely on rail, road, rivers or the sea for inbound liquid CO2 movements. If captured CO2 pipelines emerge in the future, they will be very cost-effective, but for many sites, they will not cover 'the last mile'. A combination of logistics modes will be needed.

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Images courtesy of and copyright ermewa

Summary

1) Moving liquid e-fuels is much cheaper than moving hydrogen or CO2. Production close to low-cost inputs is more important than production close to liquid e-fuels markets.
2) Green hydrogen production is overwhelmingly the most significant cost input for e-fuels. Low-cost green hydrogen is essential for low-cost e-fuels.
3) Low-cost hydrogen means low-cost renewable power. But moving power is expensive and may complicate "green" certification if the distances are too long. Site location selection close to low-cost power is essential.
4) Using curtailed renewable power for hydrogen production can reduce hydrogen production costs and can assist with "green" hydrogen certification.
5) The use of intermittent curtailed power influences electrolyser operation and technology selection. Storage of power (batteries) or hydrogen may be required to ensure effective e-fuels production.
6) To reduce CO2 intensity of e-fuels, use of biogenic CO2 will be favoured.
7) CO2 capture and circularity from Waste to Energy plants is likely to be a viable source of CO2 for e-fuels.
8) The liquid CO2 logistics infrastructure is not aligned to new routes and volumes required for large CO2 utilisation, eg e-fuels production – time and capex / opex allowances must be made in project planning.
9) Shipping, road and rail logistics modes offer more route planning and asset utilisation flexibility than pipelines.

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Introduction to Stephen B. Harrison and sbh4 consulting

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Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work at sbh4 over the past 8 years has focused on hydrogen, industrial decarbonisation, CCU/S, biofuels, e-fuels and clean fertilizers.

With a background in industrial gases, including 27 years at BOC Gases (AFROX), The BOC Group and Linde Gas, Stephen has intimate knowledge of hydrogen and many other gases from commercial, technical, operational and safety perspectives. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

Stephen supports the IFC to track down and evaluate the most attractive green hydrogen, biofuels and decarbonisation projects worldwide. He has also supported EIB and ADB on several hydrogen and CCS initiatives.

Stephen has extensive due diligence and investment advisory experience in the clean-tech sector. Private Equity firms, investment fund managers and green-tech start-ups are regular clients.

Industrial corporations often seek his guidance on their industrial decarbonisation plans and growth strategies to offer products and services to the emerging hydrogen economy and energy transition.

Startups are increasingly turning to Stephen to guide their technology development roadmaps from a solid techno-economic basis. He also advises and supports their tech-to-market strategies.