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Hydrogen and Derivatives for Aviation Propulsion

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Hydrogen Technology Expo Europe

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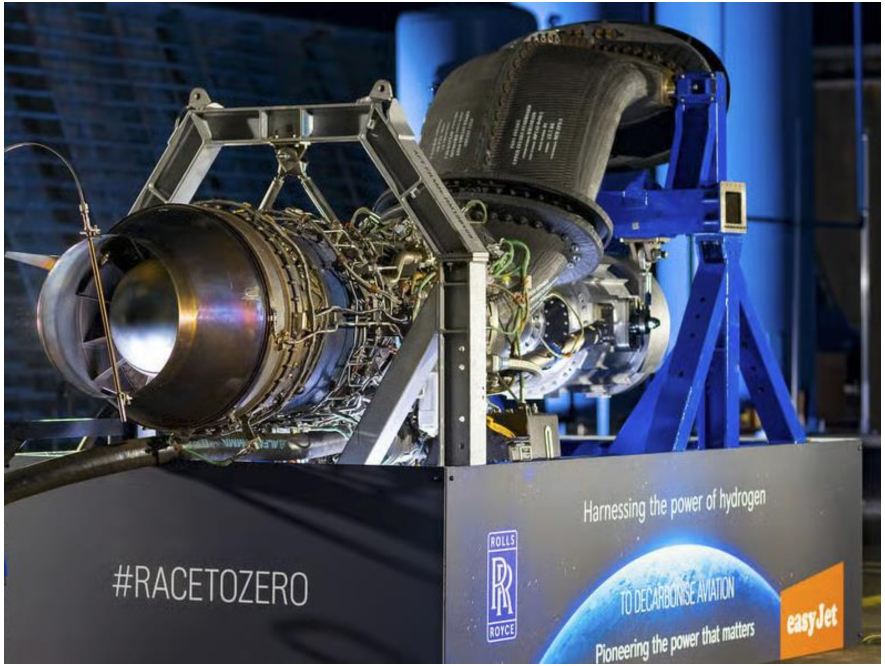
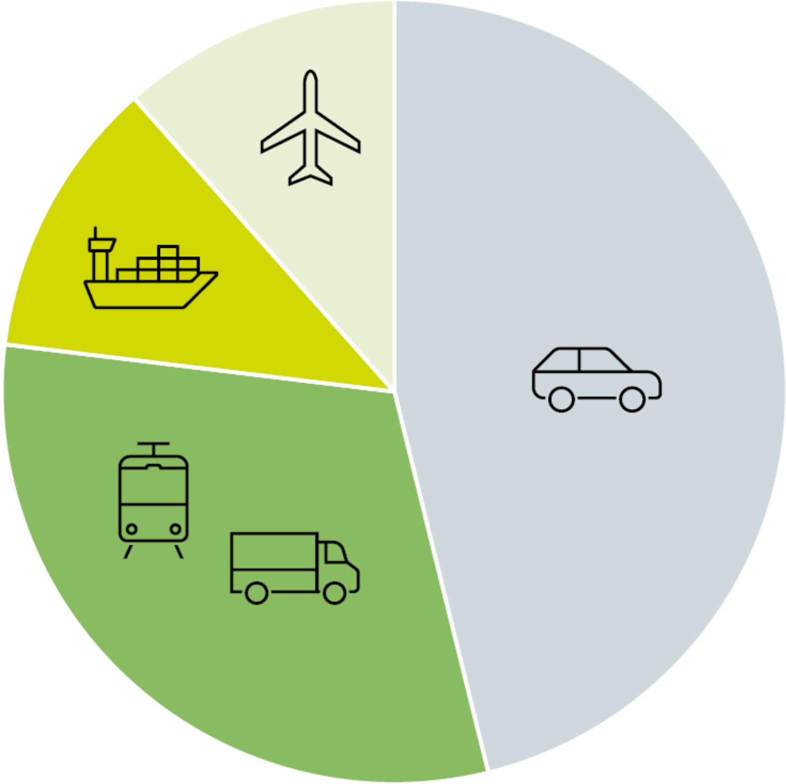
Decarbonisation of mobility cannot ignore the hard-to-abate aviation sector.



Easyjet and Rolls Royce test hydrogen fired AE 2100-A regional jet engine



7.8 Giga tons CO_2 emissions in transportation (2018)
https://www.iea.org/topics/transport

Source: ADVANCED FUEL CELLS TECHNOLOGY COLLABORATION PROGRAMME, 2020 REPORT ON MOBILE FUEL CELL APPLICATION: TRACKING MARKET TRENDS ADVANCED FUEL CELLS TECHNOLOGY COLLABORATION PROGRAMME
https://www.h2-view.com/story/rolls-royce-and-easyjet-complete-worlds-first-jet-engine-test-run-on-hydrogen/?utm_source=dlvr.it&utm_medium=linkedin&utm_campaign=rss

Hydrogen and derivatives are compelling solutions for aviation. Operational profile, fuelling time, power, fuel density and range are important decision factors.

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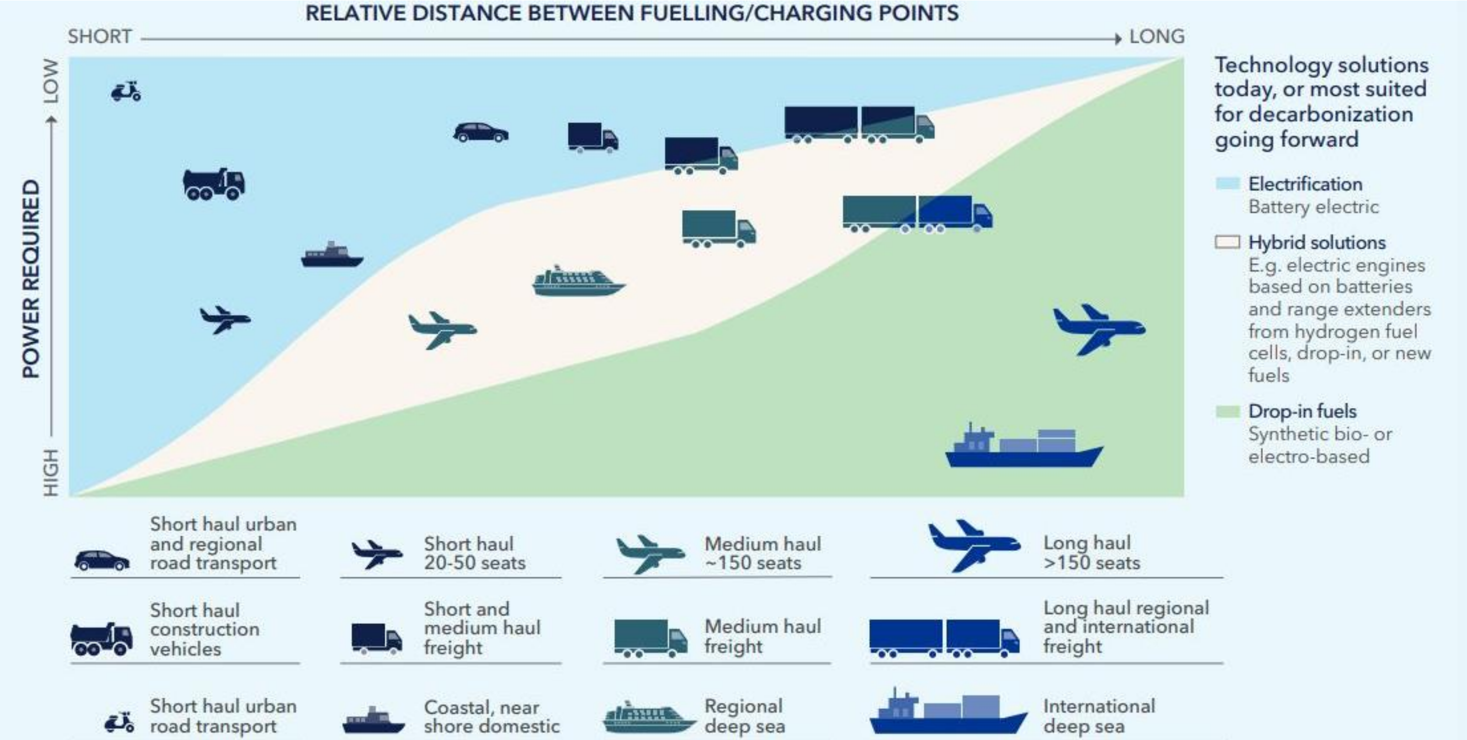

https://www.dnv.com/Publications/transport-in-transition-242808?utm_source=googleCPC&utm_medium=search&utm_campaign=Transport_in_Transition_PDF_EU&gad=1&gclid=Cj0KCQjwslejBhDOARIsANYqkD0xLAv_ScyD-gIbLBLswROkgbssgJLmZ3Ina5vun0zk8LzbbEnwNMMaAr5qEALw_wcB

Energy density of CNG compared to various forms of hydrogen

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	CNG at 250 bar, compressed natural gas	Compressed hydrogen gas at 350 bar	Compressed hydrogen gas at 700 bar	CryoCompressed hydrogen at 300 bar	Liquid Hydrogen
Temperature	25 °C	25 °C	25 °C	–235 °C	–253 °C
Pressure	250 bar	350 bar	700 bar	300 bar	Close to atmospheric pressure
Density	0.185 kg/L	0.029 kg/L	0.057 kg/L	0.080 kg/L	0.071 kg/L
Toxicity	TWA 1,000 ppm	non toxic	non toxic	non toxic	non toxic
Flammability (% in air)	5 -15 %	4 - 74 %	4 - 74 %	4 - 74 %	4 - 74 %
Volumetric Lower Heating Value (LHV)(MJ/L)	9.2	3.4	6.8	9.6	8.5
Gravimetric LHV (MJ/kg)	48.6	120	120	120	120
Infrastructure readiness for large scale deploy-ment in mid-term H/M/L	H	M	M	L	L
Commercialisation status and pilot projects	Many commercial CNG cars and fuelling sations worldwide	Many commercial FCEV Buses and HRS systems eg Van Hool A330 FC and Maximator	Commercial FCEV cars and HRS systems, eg Toyota Mirai and Maximator	TOTAL multi-energy filling station in Detmoldstraße, Munich	Australia to Japan LH2 shipping

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- The volumetric energy density of hydrogen at 700 bar is lower than CNG at 250 bar
- The implication is that high pressure compression is essential for distribution and storage of gaseous hydrogen, despite the high energy and capex costs of compression
- Liquefaction of hydrogen can improve the energy density but requires additional power for liquefaction and a high-cost investment in new distribution and storage infrastructure
- The technological challenge of working with hydrogen is more complex than working with CNG

The need for high gravimetric energy density in aviation favours liquid hydrogen. Volumetric energy density is also a consideration to maximise passenger space.

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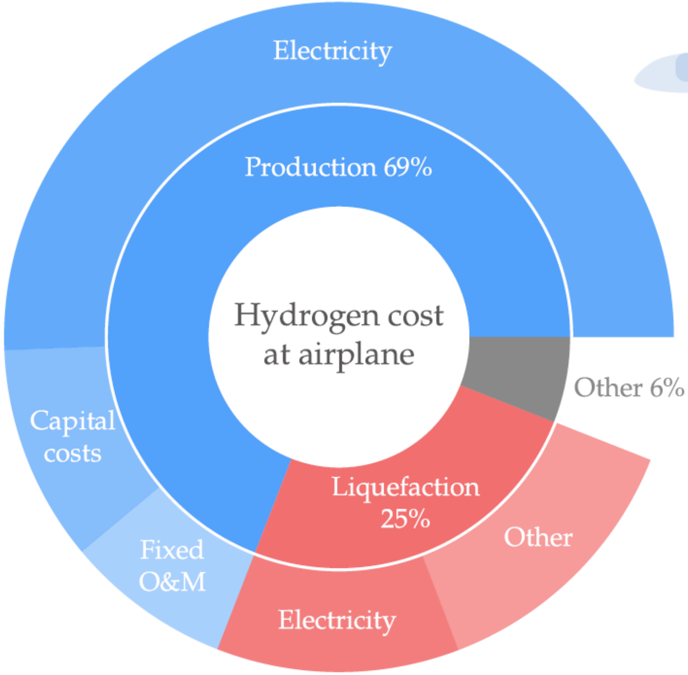

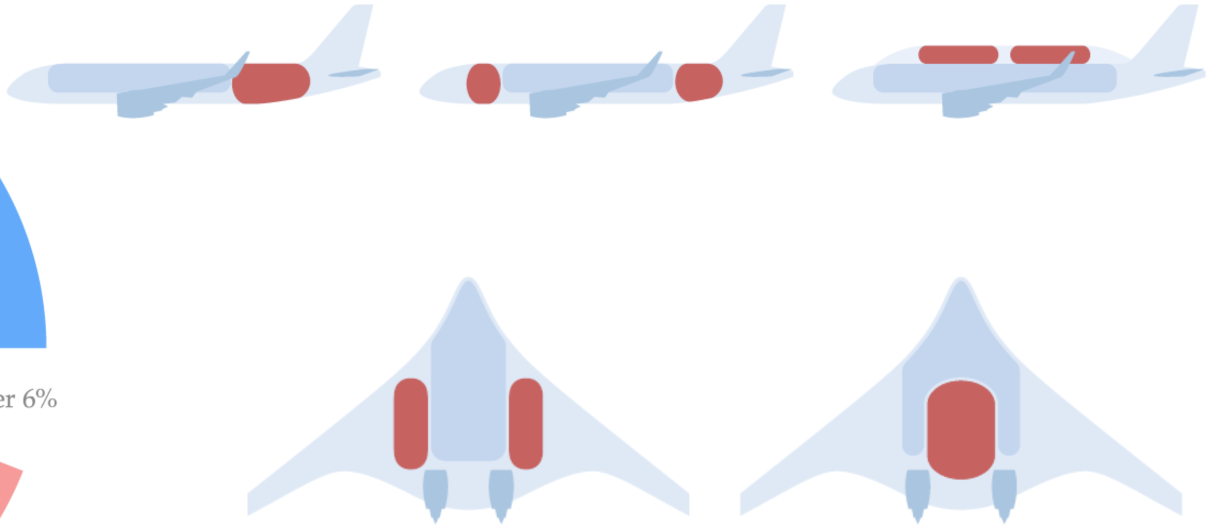

https://www.researchgate.net/profile/Joaquim-Martins-4/publication/366157885_Hydrogen-Powered_Aircraft_Fundamental_Concepts_Key_Technologies_and_Environmental_Impacts/links/63963b05484e65005b012a37/Hydrogen-Powered-Aircraft-Fundamental-Concepts-Key-Technologies-and-Environmental-Impacts.pdf?origin=publication_detail

Range matters, for operational missions in aviation. Fuel / storage energy density and fuel efficiency are key.

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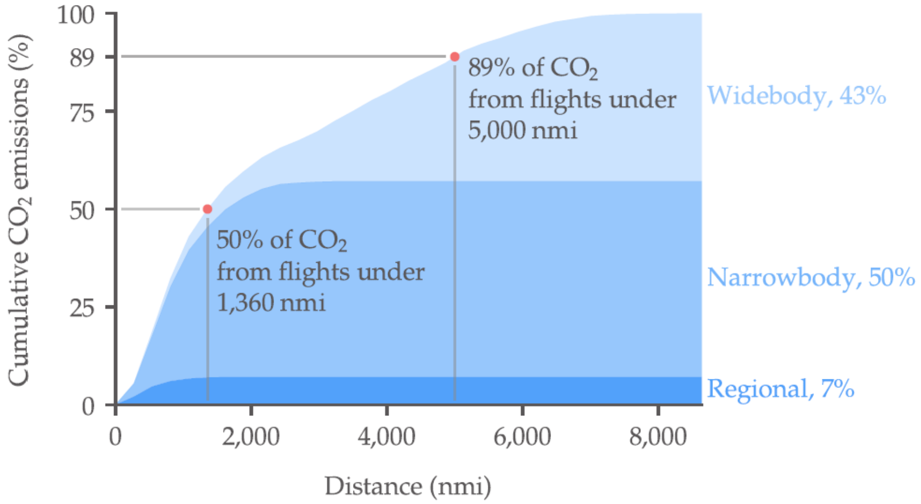
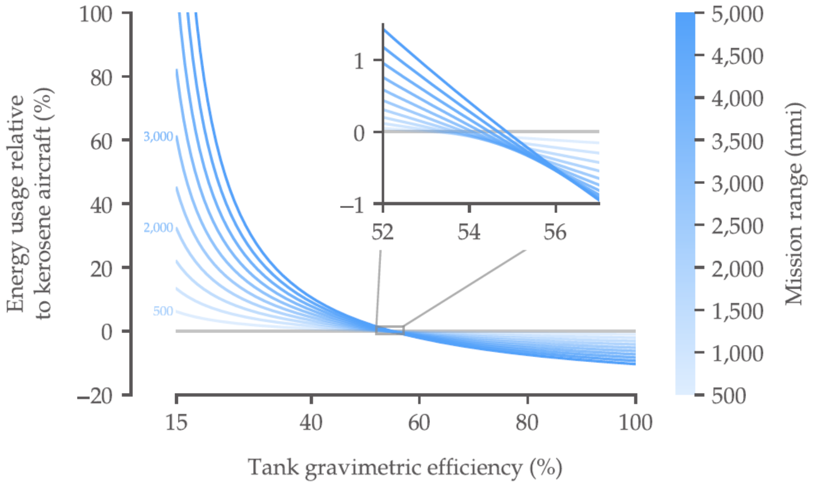
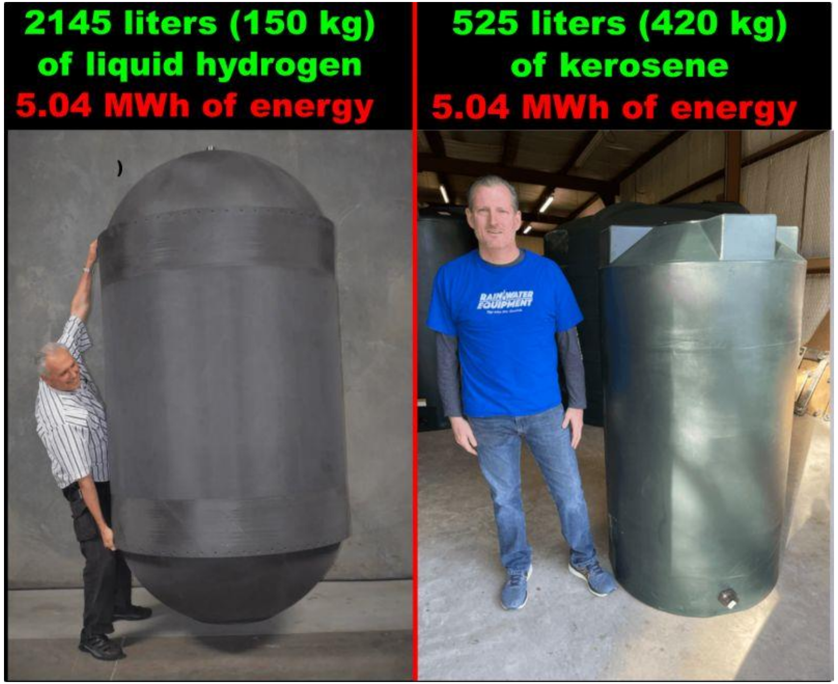


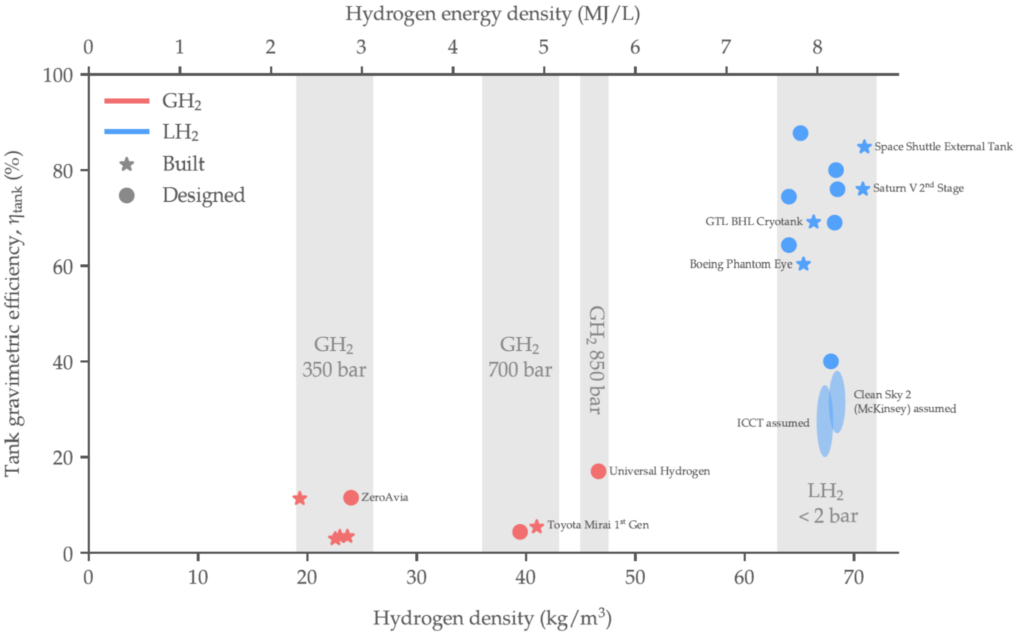


Tank type	Construction	Gravimetric efficiency
I	All metal	1–2%
II	Mostly metal with some fiber composite overwrap	2%
III	Composite tank with metal liner	4%
IV	Composite tank with polymer liner	5%
V	Liner-less composite tank	6%

https://www.researchgate.net/profile/Joaquim-Martins-4/publication/366157885_Hydrogen-Powered_Aircraft_Fundamental_Concepts_Key_Technologies_and_Environmental_Impacts/links/63963b05484e65005b012a37/Hydrogen-Powered-Aircraft-Fundamental-Concepts-Key-Technologies-and-Environmental-Impacts.pdf?origin=publication_detail

Composite cryogenic liquid hydrogen tanks – essential for extreme weight sensitivity in rocket fuel applications





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https://www.linkedin.com/posts/michael-sura-9a47511bb_hopium-hydrogeneconomy-hydrogenenergy-activity-7013862866801840128-xg_h/?utm_source=share&utm_medium=member_ios

Universal hydrogen – refillable liquid hydrogen modules for fuel-cell regional turbo prop flight

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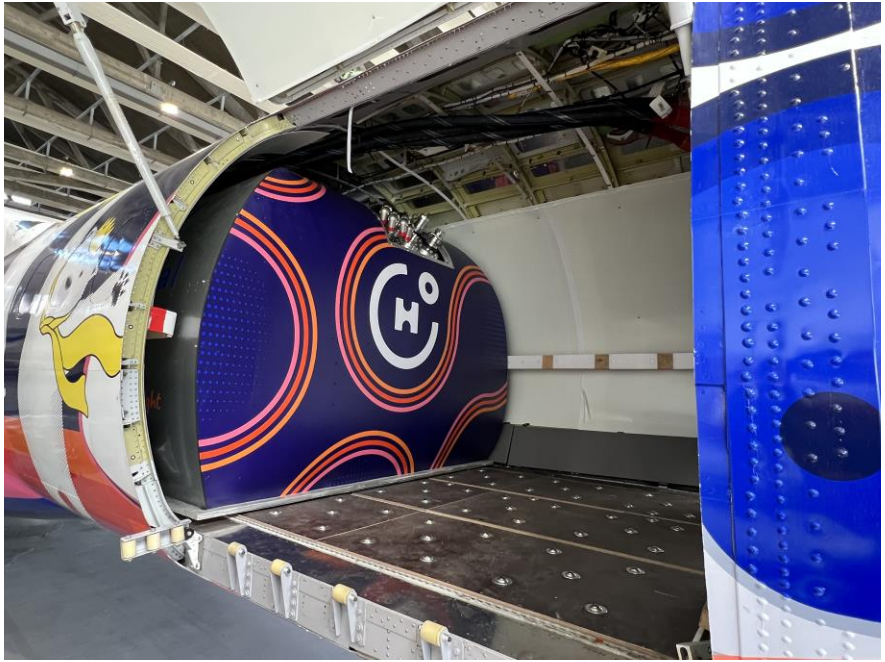

For land-based mobility volumetric energy density (accounting for typical container properties and system efficiencies) is generally key, for aviation gravimetric leads

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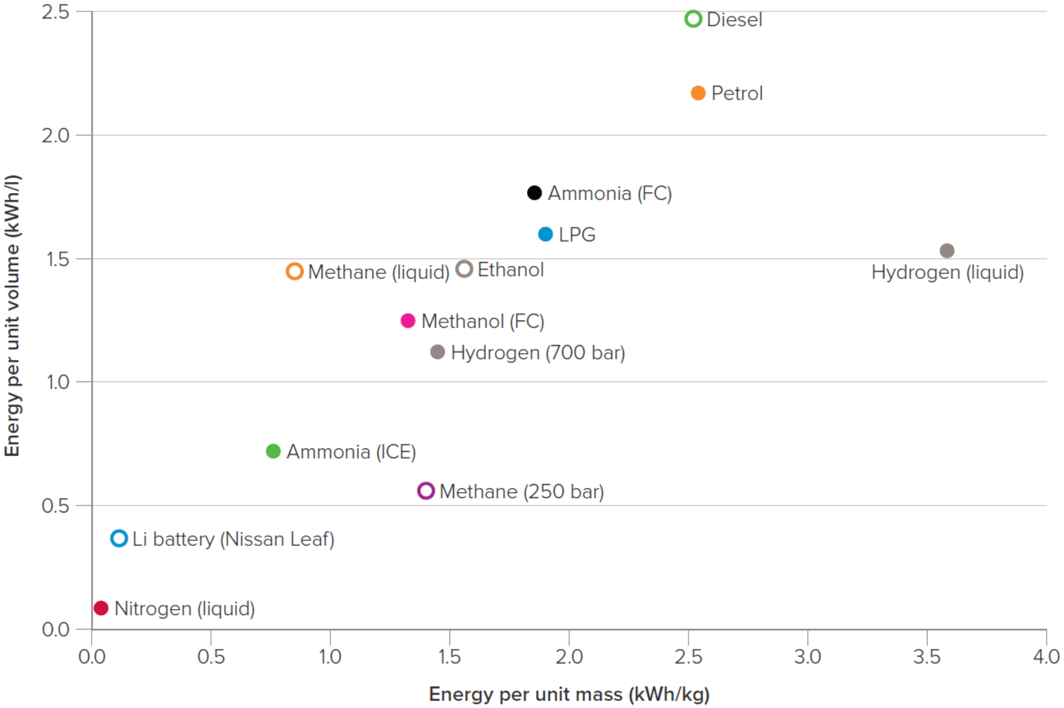
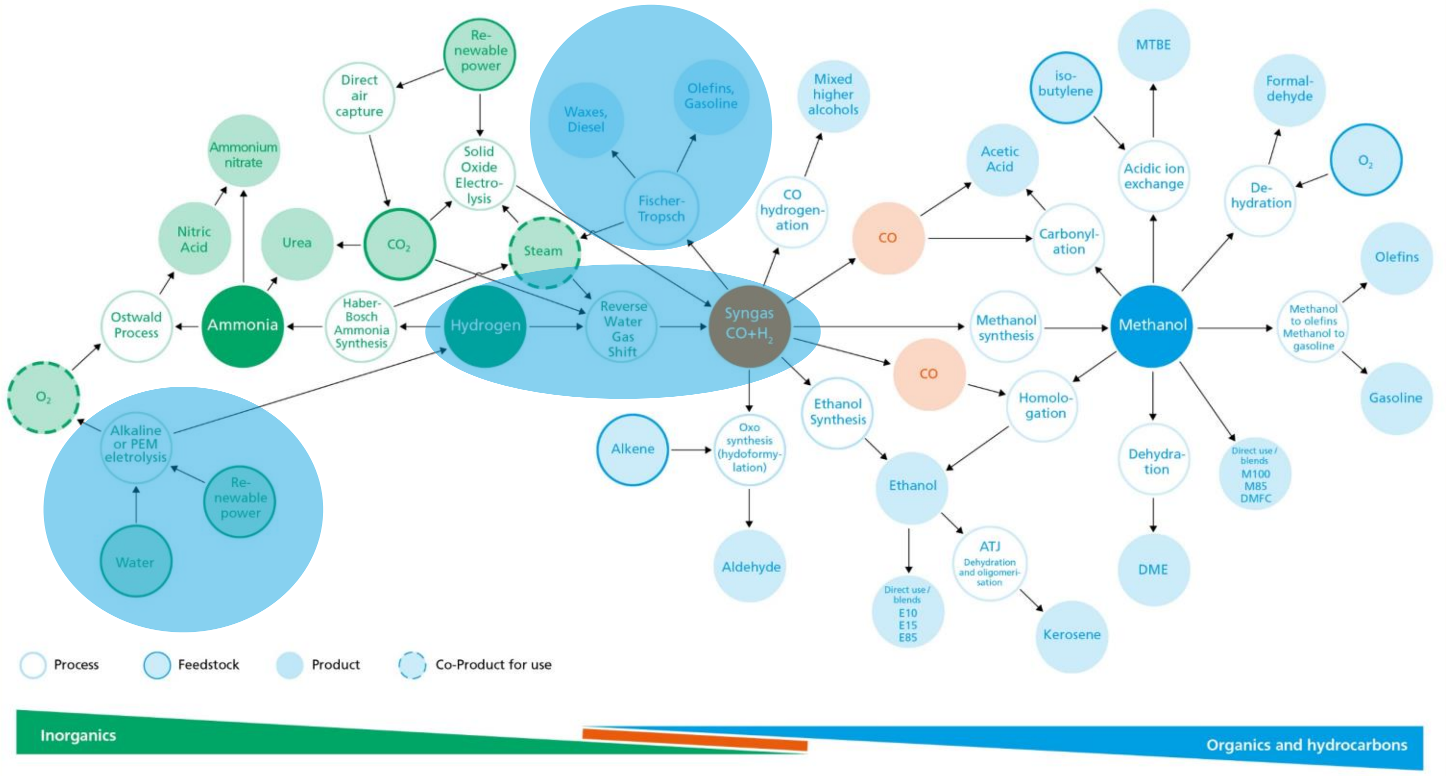


- The hydrogen molecule has a very high gravimetric energy density due to its low molecular mass
- However, the mass of the storage container must also be considered in the overall energy system
- When combining the mass of the fuel and its relevant storage container, compressed hydrogen gas becomes less competitive than ammonia, LPG, petrol and deisel, even at 700 bar
- However liquid hydrogen is still an exceptionally good energy vector by mass
- Most ground based applications benefit from a high volumetric energy density – aviation is more sensitve to gravimetric energy denstity

https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

E-fuels, e-fertilizers and e-chemicals production



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Hydrogen and hydrocarbon e-fuels for aviation and rocket propulsion

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Hydrogen is on the way in…

- Hydrogen-powered drones are in regular service for monitoring and surveilance, for example fertiliser dosing, chemical plant maintenance and pipeline surveilance. See Doosan Mobility as an example drone provider.
- Hydrogen powered drones may scale up and penetrate a wider range of applications, for exampel packet deliveries and urban taxis. See PlugPower & HevenDrones recent partnership announcement.
- The high gravimetric energy density of hydrogen makes it suitable as an aviation fuel, where weight is more sensitive than volume. However, the weight of the hydrogen storage vessel must be considered in addition to the hydrogen. Type 4 carbon fibre composite cylinders at 700 bar will be favoured.
- Hydrogen fuelled, fuel-cell powered turbo-prop aircraft have been tested in the UK, USA, Germany and China by companies such as Ruixiang, H2FLY, HES Energy Systems, ZeroAvia and Pipistrel. Gaseous or liquid hydrogen may be used as a fuel for these lighter aircraft.
- Airbus are developing ZEROe hydrogen fuelled jets. Liquid hydrogen will be required as a fuel for these larger jet aircraft that will serve longer routes at higher speeds.

But hydrocarbons are not yet on the way out…

- Rocket propulsion is a good candidate for liquid or solid hydrogen, but cost concerns favour fossil fuels.
- NASA specified hydrogen fuel for many operations to reduce the environmental impact and the world's largest hydrogen storage sphere is at Cape Canaveral
- The SpaceX programme (with the most planned satellite launches) uses methane, and will potentially use e-methane.
- E-fuels, or synthetic fuels can be produced to replicate the properties of aviation kerosene. They can be produced with low carbon intensity and can use recycled CO2, but they release CO2 when burned during flight, just like conventional fossil fuels. They may be an interim solution, with a peak between 2040 and 2050.
- In the EU, legislation in several countries has stipulated that a minimum percentage of all aviation fuels must be e-fuels by 2030.
- Boeing is focusing on e-fuels, for example through their partnership with SkyNRG.
- The US Air Force has tested AIRMADE™ SAF from Air Company

https://www.electrive.net/2020/09/30/h2-flugzeug-von-zeroavia-gelingt-erstflug/

https://www.h2-view.com/story/doosan-mobility-hydrogen-drones-enter-the-european-market/

https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html

Liquid hydrogen storage at Cape Canaveral

Production of synthetic aviation fuel (SAF) is dominating the first wave of e-fuels PtL projects.

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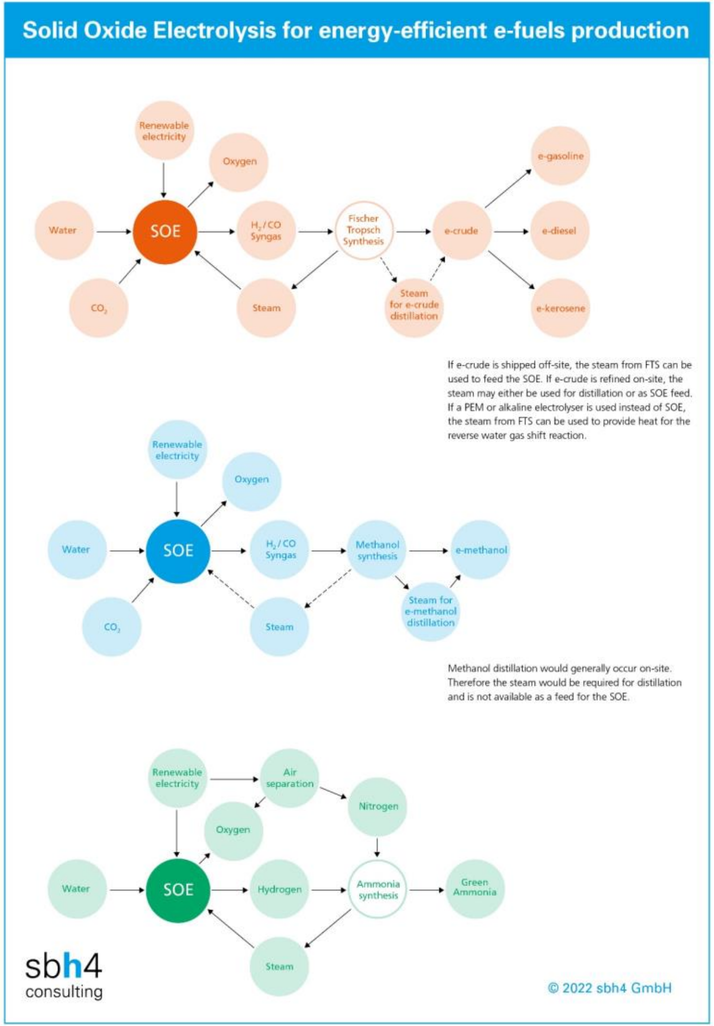
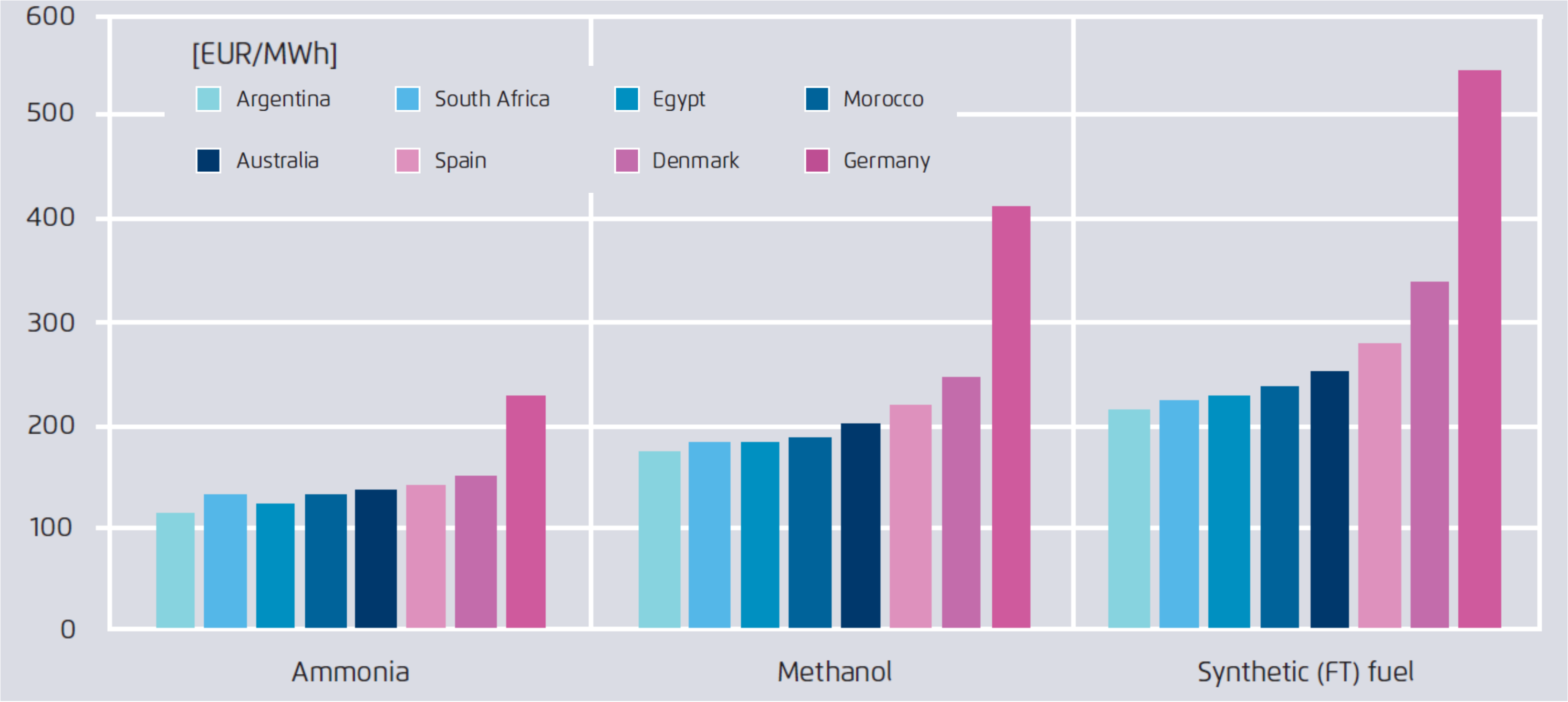
Images, BP Lingen refinery, Industriepark Höchst (INERATEC GmbH), Heide Refinery
e-Fuels are mandated to be 2% of the aviation fuels mix in Germany by 2030

Steam-fed Solid Oxide Electrolysis can use excess heat for high efficiency. Co-electrolysis generates syngas for PtL.



Synthetic e-fuels are more expensive than methanol, but their ability to leverage established supply chains and end-user equipment supports the higher prices for these "drop-in replacements" for fossil fuels.



Agora Energiewende – 12 insights on Hydrogen, Impulse, 245/17-I-2021/EN Nov 2021

Aviation H2, Australia – plans to use a mixture of hydrogen and cracked ammonia

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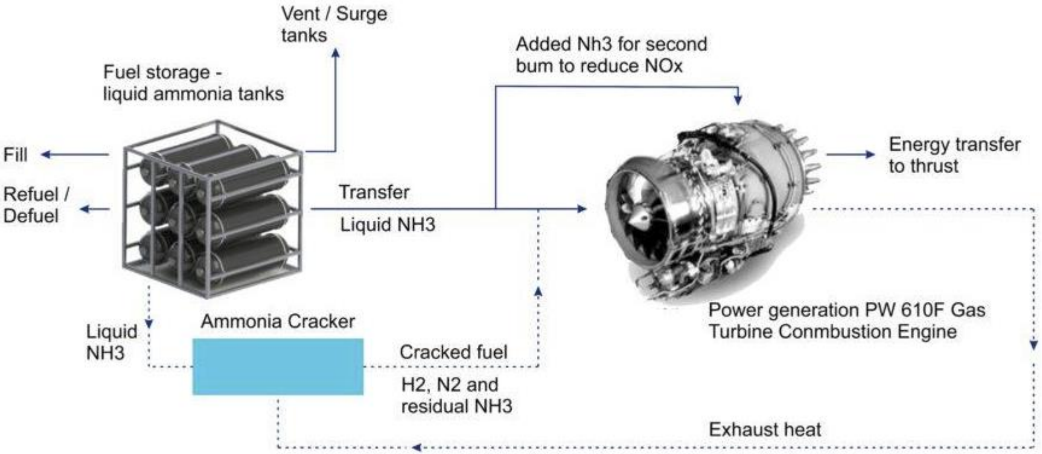

https://aviationh2.com.au/the-initial-research-and-testing-phase/

Reaction Engines, UK - ammonia cracker technology for use to prepare fuel for jet engines

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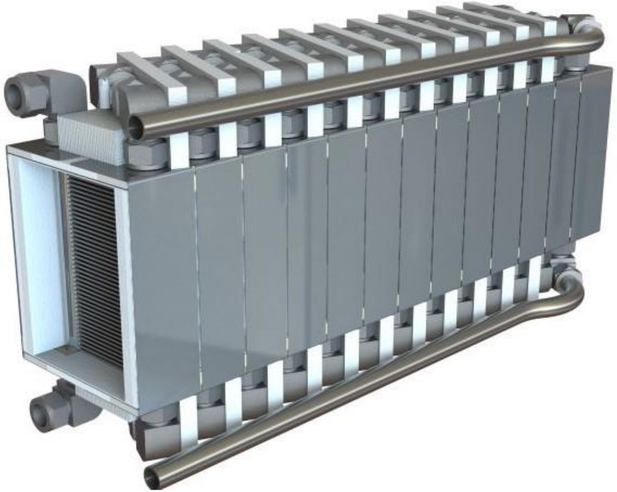

https://www.aerospacetestinginternational.com/news/engine-testing/reaction-engines-spin-out-will-develop-device-to-enable-ammonias-use-as-jet-fuel.html

https://www.flightglobal.com/engines/reaction-engines-unveils-low-carbon-spin-off-for-sabre-technology/146269.article sbh4

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Introduction to Stephen B. Harrison

Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and greenhouse gas emissions reduction. Hydrogen and CCTUS are fundamental pillars of his consulting practice, and he supports many industrial clients with their decarbonisation programmes.

Operating companies, gas analyser OEMs, private equity firms, investment fund managers and start-ups are also regular clients. Stephen has accumulated extensive M&A and investment due diligence experience in the clean-tech sector.

Stephen served as the international hydrogen and CCTUS expert for multiple World Bank, IFC and ADB projects in Namibia, Pakistan, Palau and Viet Nam. His background is in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for these leading international publications.

Stephen has served as a member of the scientific committee for CEM 2023. He also served on the Technical Committee for the Green Hydrogen Summit in Oman in December 2022 and the Advisory Board of the International Power Summit in Munich in September 2022.