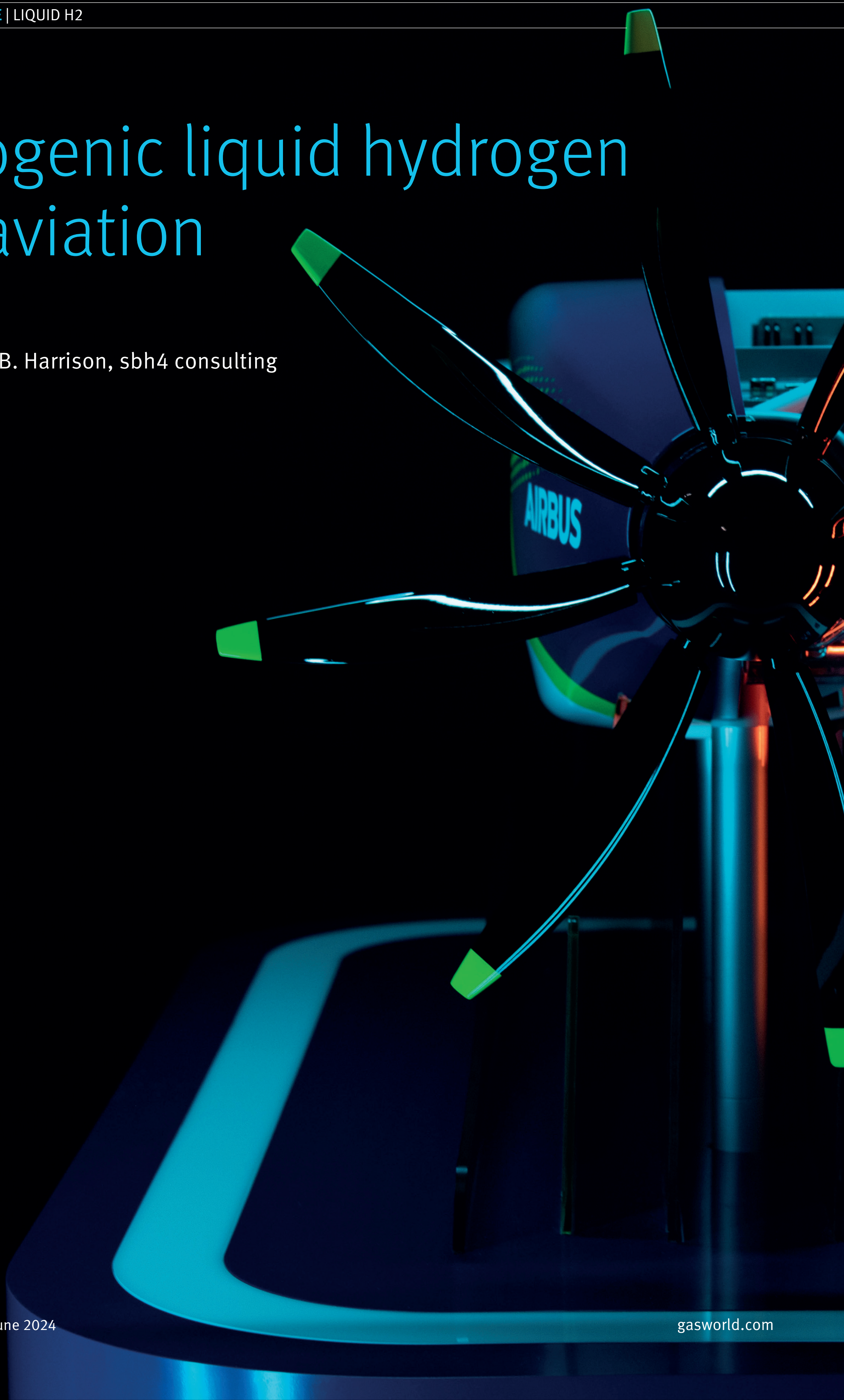
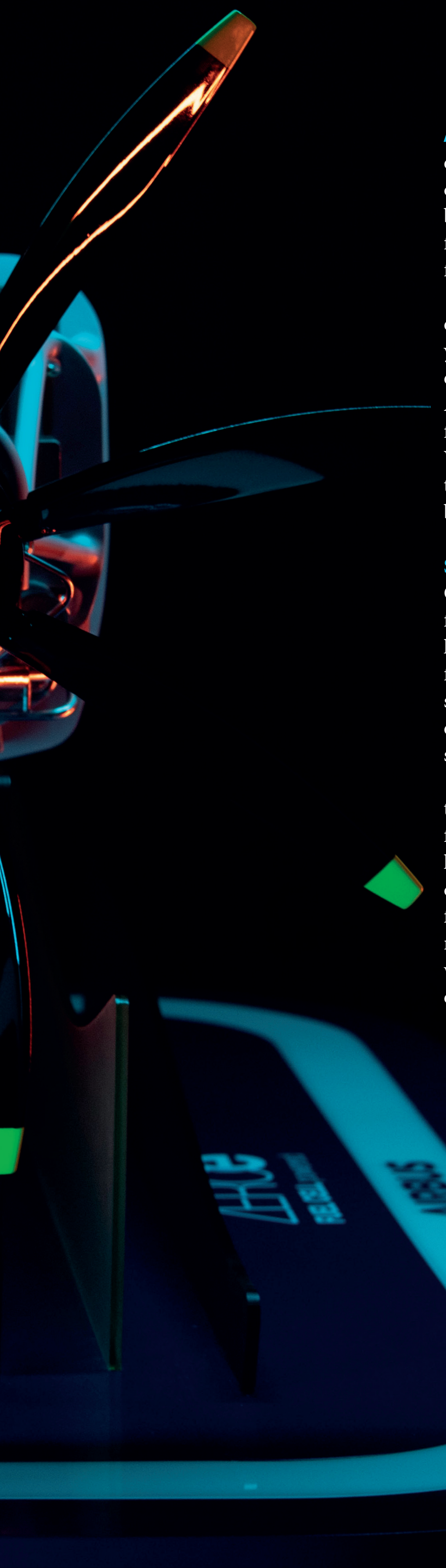
Cryogenic liquid hydrogen for aviation

By Stephen B. Harrison, sbh4 consulting



© Airbus | Airbus ZEROe Fuel Cell Engine



About 8 gigatonnes of carbon dioxide (CO_2) are emitted by the global transport sector each year. Almost half of that is from cars. Just over a quarter from trucks, buses, and lorries. About one eighth from shipping, and another eighth from aviation.

Taking another view, aviation CO_2 emissions are 1 billion tonnes per year: similar to the total annual CO_2 emissions from Germany or Canada. And aviation CO_2 emissions are rising faster than other transport sectors. With this context, the imperative to defossilised the aviation sector becomes clear.

Sustainable aviation is the future

Green hydrogen can be produced from renewable electrical power. Blue, low-carbon hydrogen is produced from fossil fuels with permanent storage of the CO_2 emissions. These energy vectors may unlock the key to sustainability in the aviation sector.

Long-mission duration drones were the first major application of hydrogen for aviation. Compressed gaseous hydrogen stored in a lightweight type 4 composite cylinder can flow through a fuel cell to achieve a significantly longer range than a battery-powered drone with a similar payload. The first wave of hydrogen -fuelled aircraft are also turboprop aircraft with powerful fuel cells to drive the propellors.

Storage challenges of gaseous and liquid hydrogen

In aviation, both the volumetric and gravimetric energy density are of critical importance. In a commercial aircraft, volumetric density plays a role since space must be left for fare-paying passengers.

The total mass of the fuel and its container, or gravimetric efficiency, is critical when benchmarking across alternative fuels. For liquid hydrogen in an aluminium alloy storage tank, the gravimetric efficiency of liquid hydrogen storage is currently limited at around 30%.

For vertical take-off in a space rocket, gravimetric energy density is key. On board rockets, ultra-lightweight composite tanks are used. The advantage of this construction is that a gravimetric efficiency between 75 and 85% can be achieved. On the other hand, these ultralight tanks can only be used once.

For commercial aviation, the idea of a single-use tank would not be realistic. However, multiple use composite tanks to store liquid hydrogen are under development. This technology may offer the prospect of achieving a gravimetric efficiency of more than 50% in a re-usable tank.

A helping hand from thermodynamics

As hydrogen is compressed, its density progressively increases. For example, at 350 bar a compressed gas cylinder with a volume of 1 litre contains 16 grams of hydrogen. At double the pressure, 700 bar, the same container holds 27 grams, almost twice as much.

When hydrogen is cooled to a cryogenic liquid, its density reaches 36 grams of hydrogen per litre of storage tank volume. Beyond the gaseous and liquid phases of matter, there is an additional phase known as a super-critical fluid. In this phase, when hydrogen is both cold and compressed, the density of hydrogen is greater than normal liquid hydrogen at atmospheric pressure. At 300 bar, a 1-litre storage tank would contain 40 grams of cryo-compressed hydrogen.

Zero Avia, based in the UK and the US startup VERNE announced their collaboration to explore the use VERNE's cryo-compressed hydrogen storage solution for aviation. The power input requirement to densify VERNE's cryo-compressed hydrogen is approximately half the electrical power required to liquefy hydrogen. As hydrogen aviation scales up, this energy saving will escalate to become many MWh of avoided power usage.

Helium to minimise hydrogen losses

The US company GenH_2 has developed a cryogenic liquid hydrogen concept that uses a little extra power to save a major loss of power. The GenH_2 technology cools helium in a Brayton refrigeration cycle to a temperature about 10 °C colder than -253 °C, the temperature of liquid hydrogen at atmospheric pressure.

The helium sub-cools liquid hydrogen to make sLH_2. There is a power penalty involved in operating the Brayton refrigeration cycle, however the boil-off losses of hydrogen in the supply chain are reduced.

When cryogenic liquid hydrogen sits in a storage container for more than a few hours, a tiny amount of ambient heat begins to 'leak' through the storage vessel and vaporise the hydrogen. The pressure in the tank builds up to the point where safety devices release the pressure.

When hydrogen is vented, the energy that was required to produce the hydrogen is wasted. So, avoiding boil off venting can justify some additional amount of power for sub-cooling liquid hydrogen.

Liquid hydrogen infrastructure expansion

90% of global hydrogen liquefaction capacity exists in North America. In western Canada, Air Products has operated a 30 tonne per day hydrogen liquefier for many years at Sarnia. Air Liquide at Bécancour, in eastern Canada operates a liquefier with a capacity of 10 tonnes per day.

Through the course of 2023 and 2024, Plug Power has started up 15 tonne per day hydrogen liquefiers in Georgia and Louisiana. Just north of Las Vegas in Nevada, Air Liquide inaugurated their 30 tonne per day liquefier in 2022. The site, which also produces and stores hydrogen represented an investment of $250 million for the company.

The compact nature of Europe's industrial base in the northwest of Germany, NL, Belgium, and northern France has favoured the economics of compressed gaseous hydrogen distribution. This, combined with two comprehensive hydrogen pipeline networks in this region have historically subdued the need for liquid hydrogen infrastructure. However, aviation and other applications are likely to drive Europe in a similar direction to North America.

In Europe, the 10 tonne per day liquefier operated by Air Liquide at Waziers in France is Europe's largest hydrogen liquefier. Air Products operates a 5 tonne per day liquefier in the Rozenburg part of the Port of Rotterdam, NL and Linde operates

© Daimler Truck | **GenH2 tank filling**

© Air Products and Chemicals | **Inc - Liquid hydrogen tank** two similar capacity units in Germany. In 2022, Air Products announced the construction of a new hydrogen liquefier at Botlek, which will double Europe's hydrogen liquefaction capacity when it opens in 2025.

Supply chain concepts

In addition to hydrogen liquefiers being scarce, the absence of liquid refuelling infrastructure at airports would be a bottleneck for cryogenic liquid hydrogen in aviation. To kick-start access to liquid hydrogen for aviation, the startup Universal Hydrogen has conceived a removable, refillable liquid hydrogen storage tank and supply chain concept. The company is based both at Toulouse, where Airbus has one of its main manufacturing locations and Hawthorne in California.

Universal Hydrogen proposes to use cryogenically insulated, metal containers with more than 1,000 litres capacity to store liquid hydrogen. The containers can be rolled on and off the aircraft in the same way that luggage waggons are currently used to load and unload passengers' suitcases. The containers are moved by truck to a central filling location and redistributed to the aircraft.

The universal hydrogen concept avoids liquid hydrogen tankers moving around the airport to refuel fixed tanks on the aircraft. It also eliminates the need for static storage and refuelling equipment in multiple locations on the airport apron.

Hydrogen derivatives

Given the challenges associated with storing gaseous hydrogen with a high energy density and the immaturity of the liquid hydrogen supply chain, alternatives to hydrogen are being considered for sustainable aviation.

Green ammonia is a zero-carbon fuel. Ammonia can be partially cracked using high temperature waste heat from an engine and then burned on a jet engine in a similar way to kerosene or hydrogen. Reaction Engines in the UK and Aviation H_2 in Australia have been involved in developing the specialist equipment that may one day see ammonia used as a fuel for jet aircraft.

Synthetic aviation fuel, or e-SAF can be produced when green hydrogen is combined with CO_2. It can be burned in conventional jet engines, avoiding the cost of new aircraft, and eliminating the need to develop new infrastructure for hydrogen storage and refuelling at the airport.

Use of e-SAF avoids the use of petroleum derived kerosene. This means it displaces fossil fuels and has a positive impact to support a reduction in CO_2 emissions from human activity.

Methanol can also be produced as a clean hydrogen derivative. Methanol can be reformed to syngas and then fed to a high temperature PEM fuel cell to provide motive power for turbo-prop aviation. Methanol is less toxic than ammonia and can be stored in the aircraft wing for extended range.

Sustainable aviation is in its infancy. The breadth of solutions is broad. The winning solutions may be known to us today or could yet emerge. However, the benefits of pursuing defossilisation in this sector will be felt in our lifetime and will leave a legacy that we can be proud of for generations to come. gw

Liquid hydrogen for aviation

Reaction Engines Test Site, copyright Reaction Engines Ltd