WHY BURNING HYDROGEN IN INTERNAL COMBUSTION ENGINES IS A SMART AND AFFORDABLE OPTION FOR REDUCING CO2 EMISSIONS

INTRODUCTION

Transporting people and goods accounts for nearly 20% of the world's CO2 emissions. Transportation sectors, such as automotive, shipping and aerospace, are under increasing pressure to decarbonise, not only to address society's expectations, but also to meet targets set by the European Union.

Electrification is clearly one route towards decarbonisation, and the likely winner for light road vehicles and private cars. But batteries have limits that make them less suited to heavier vehicles that needs lots of energy, or vehicles that do not have reliable access to a chargepoint or which need significant autonomy.

The internal combustion engine (ICE) holds many advantages. It burns fuel, which is easy to transport and distribute. It has 100 years of innovation behind it to optimize transfer of energy from fuel to propulsion. When that fuel is fossil fuel, the combustion engine is clearly no longer viable. But, if the fuel was green hydrogen, the combustion engine would be an interesting solution for decarbonising many vehicles.

This paper will discuss the opportunities from repurposing ICEs for hydrogen and the engineering challenges to be overcome.

Decarbonising transport: Electrification is not the only answer

The most common market reaction to decarbonizing transport has been a move toward electrification, replacing internal combustion engines (ICEs) with electric powertrains, making batteries as a sole energy source. These are highly efficient, generate no 'tailpipe emissions' and can be 100% clean if green energy is used. The automotive industry in particular has seen a significant shift toward electric vehicles (EVs), largely focused on personal vehicles and some buses.

This transformation is welcome. However batteries have their limits and are not a panacea.

They are currently not appropriate for many larger commercial vehicles such as trucks, construction machinery, and agricultural vehicles – as well as long distance shipping and naval vessels – due to battery-specific challenges such as poor gravimetric energy density (ie generating enough energy would need too battery much weight), and the length of time it takes to recharge. Some are exploring hybrid electrical architecture, using hydrogen to power fuel cells, which generate electrical power, known as a Fuel Cell Electrical Vehicle (FCEV).

Batteries also have limits in aviation. There is no reason they couldn't be used for short distance ferries, light aircraft flying short to medium distances, and Electrical Vertical Take-Off and Landing vehicles (EVTOLs) – in fact a number of early-stage electric vehicles exist in these areas. However, the poor gravimetric energy density (MJ/kg) of current battery technology compared to other energy sources means electrification is not an appropriate solution for use in larger commercial aircraft, or ships that must remain at sea for long periods of time.

It's also likely some smaller aircraft could be FCEVs. Again, though, the poor volumetric energy density of hydrogen, even at liquid stage, means the technology couldn't be used for anything larger.

It's also clear that new type of hybrid aircraft, smaller and slower than current models, which mixes electrical and thermal engines using SAF (Sustainable Aviation Fuel) offer a solution for short range flight[1].

THE POSSIBILITY OF HYDROGEN COMBUSTION ENGINES

Electrification is not the only game in town. Internal combustion engines could still remain relevant, if we use them to combust hydrogen rather than fossil fuels.

A high volumetric energy density, due to long carbon chains and reasonable gravimetric energy density, means fossil fuel has been best-in-class since the end of the nineteenth century. But the combustion of carbon chains generates CO2, which makes it worst-in-class for net zero goals.

Today, advances in technology mean it's possible to convert ICEs, enabling them to burn hydrogen instead of fossil fuels.

But this is not without its challenges.

Hydrogen fuel tanks

The first challenge is to address the issue of low volumetric energy density when storing hydrogen in a vehicle. Although hydrogen has good gravimetric energy, meaning you get lots of energy per kilogram burned, it has poor volumetric density, ie each kilogram takes up a lot more space than a kilogram of petrol or diesel. That would mean a vehicle would need a large, heavy tank to store enough hydrogen fuel to power the equivalent driving range of a fossil fuel engine. (Chart 1 shows the difference between CH2 (compressed hydrogen)/ LH2 (liquid hydrogen) when stored or not).

The key here is the formula P.V = K.T which shows that the product of volume V and pressure P is proportional to temperature T.

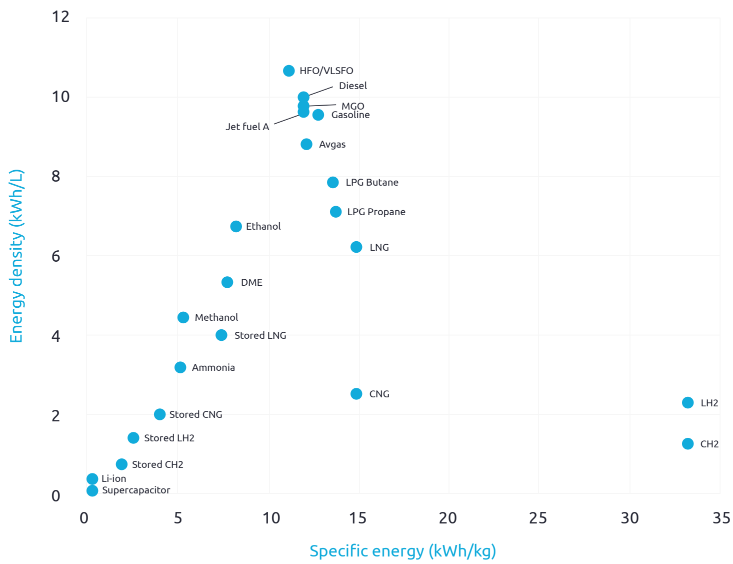
One answer, then, is gaseous hydrogen held under higher pressure to reduce volume. This is the current solution for road and rail vehicles, where 1KG of compressed hydrogen (CH2) at 700 bar provides ~100km of autonomy. Ships have slightly more flexibility on space, but safe and efficient storage is still needed to be developed which can hold large amounts of hydrogen for long periods of time – making the trade-off between low temperature or high pressure – both on ships, and bunkering at ports.

Aviation presents different challenges as there are physical upper limits to the space and weight it can carry before flight becomes impossible. At normal atmospheric pressure and ambient temperature, you would need approximately 3,000 litres of gaseous hydrogen to achieve the same amount of energy as one litre of kerosene fuel. The only viable solution for storing hydrogen – whether for fuel cells, or to power turbo-propulsion and turbo fans via combustion – is to use 10 bar pressure and reduce the temperature to -253ºC, where hydrogen turns from a gas to a liquid, increasing its energy density.

That would still be limited to regional aircraft due to added weight even under optimal conditions. Long range will need to use SAF.

CHART 1:

Volumetric versus gravimetric fuels challenges (sources: Mdpi, Research gate)



Notes: Avgas = aviation gasoline; CH2 = hydrogen compressed at 70MPa; CNG = natural gas compressed at 25 MPa; DME = dimethyl ether; HFO/VLSFO = heavy fuel oil/very low sulphur fuel oil; LH2 = liquefied hydrogen; Li-ion = lithium-ion battery; LNG = liquefied natural gas; LPG = liquefied petroleum gas; Stored CNG = Type IV tank at 250 bar; Stored CH2 = best available CH2 tanks at 70 MPa; Stored LH2 = current small-scale LH2 on-board tanks; Stored LNG = small-scale storage at cryogenic conditionsl MGO = maritime gasoil.

Numbers are expressed on a lower heating value (LHV) basis. Weight of the storage equipment is included.

Adapting ICEs for burning hydrogen

Given the maturity of thermal engine technology, burning hydrogen in an ICE is an interesting option, both from a technical and an economic standpoint, especially in vehicles that are hard to electrify.

Nevertheless, some technical challenges must be overcome. For instance:

- Developing and adapting current ICE technologies to hydrogen, while maintaining a reasonable cost for the motor

- Upgrading pollution control systems to manage the small amounts of NOx emissions from hydrogen

To explore this further, we should consider piston-driven ICEs for motor vehicles and turbine-driven ICEs for aircraft. Hydrogen combustion for ships is likely to follow a model of upgrading existing combustion engines, first for dual fuels and eventually hydrogen or ammonia. All face similar challenges which are discussed below.

ICEs can, in principle, run on hydrogen to produce mechanical energy, releasing only carbon water vapour and NOx. Converting an ICE to hydrogen doesn't change the principle – only a few modifications are necessary, although NOx emission control requires precise combustion process management.

These modifications are essential because:

» **Overcoming reduced specific power:** Compared to an atmospheric engine with premix and spark ignition, hydrogen significantly reduces (at least 20 to 25%) the specific power of the engine (occupies a relatively large volume, decreases the amount of air that can enter the cylinder at each cycle).

But since a high compression ratio (the ratio between the volume of the cylinder and combustion chamber) of 13 to 14 is possible - energy efficiency can reach 36%. This improves upon conventional fuel engines where lower compression ratios (up to 10 nowadays) mean energy efficiency does not exceed 30%.

The specific power limitation can be eliminated via appropriate injection devices (high pressure direct injection) and air boosting with oxygen (addition of a compressor or a turbocharger). Together this can produce very high efficiency motors (above 40%), which can exceed even the best diesel engines.

» **Removing risk of self-ignition:** Hydrogen is very sensitive to self-ignition and backfire phenomena (auto-ignition in the intake manifold). In addition, the engine must be clean, in particular free of carbon deposits which, in turn, could cause self-ignition. It is to remedy these drawbacks that the rotary engine was adopted by the Japanese firm Mazda during the development of its hydrogen-powered vehicles at internal combustion, in 1991.

» **NOx emission control requires precise combustion process management.** NOx is generated at very high temperature when hydrogen combustion happens in the presence of a lot of air. We want to avoid an optimized lean mixture, which creates, a high combustion flame and high proportion of air in the mixture, which create optimal condition for NOx generation. However, when run extremely lean (below R = 0.5), combustion temperature dramatically decreases because of strong thermal dilution. This significantly limits the amount of NOx generated.

Other solutions can also be used to reduce NOx emissions, including:

- Thermal dilution with Exhaust Gas Recirculation (EGR)
- Stratified combustion, which consists in precisely controlling the local mixture composition in the combustion chamber in order to make the combustion happens at optimal richness.
- NOx emission can be treated with the appropriate after-treatment device (NOx-trap, SCR), which are tailpipe devices, similar to catalytic converters.

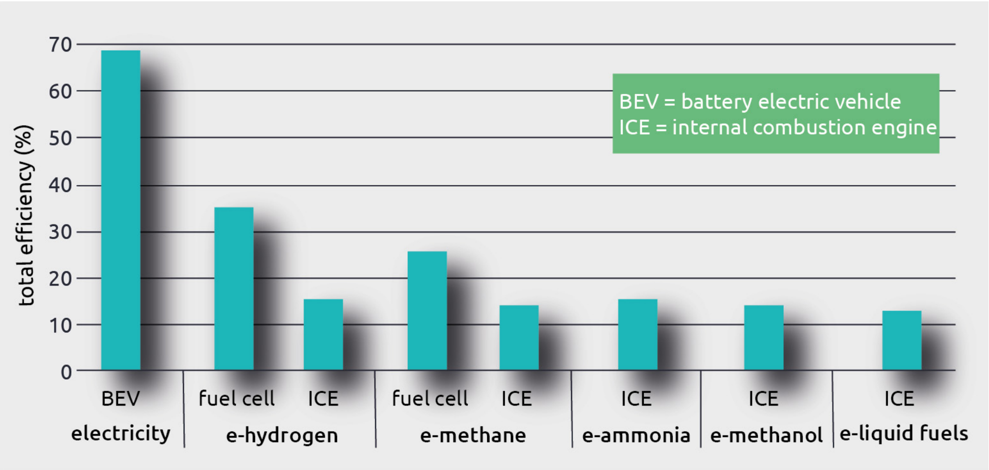


CHART 2:

e-Fuel WTW energy efficiency (source: Concawe Report on Role of e-fuels in the European transport system)

HYDROGEN COMBUSTION: WHAT IS INDUSTRY DOING?

In this section, we will look at real world innovations towards utilising hydrogen combustion.

Automotive

So how is the automotive industry adapting? A few notable companies have made significant investments in hydrogen combustion. For example:

- Toyota is looking to burn hydrogen in ICEs, while Honda will focus on EVs and FCEVs
- Renault to reveal a concept car equipped with a 'hydrogen engine'
- ORECA Magny-Cours to assess hydrogen technology, while developing its own hydrogen ICE

To explore this in more detail, we interviewed GCK Group, an innovative player in green mobility and a true believer on thermal engine retrofit – to get in-depth technical, economic and social interviews (see Interview 1).

Hybrid solutions

Pure hydrogen may not always be possible, but it can still help reduce emissions through a mix of diesel and hydrogen.

This is something that is already being used in the naval marine sector, (eg MAHLE Powertrain or MAN , …), another industry where batteries are so far impractical due to their weight. Can it also be a solution for terrestrial mobility? To understand how this is possible, we interviewed ARQUUS, Business area Defense of the Volvo Group, designing tailored solutions for military applications (see Interview 2).

Aerospace

Initiatives are underway – in the air and on the ground – to test hydrogen-fuelled ICEs and the direct use of hydrogen as a fuel in a gas turbine. Examples include:

- Airbus and CFM International have launched a joint project to ground- and flight-test a direct combustion engine fuelled by hydrogen in preparation for the entry into service of a zero-emission aircraft by 2035
- Rolls Royce believes that, while hydrogen can be used directly as a fuel in a gas turbine, it is likely to start in the shorter haul segments. Sustainable aviation fuel (SAF) gas turbines will remain the most likely solution for long-range flights, moving forward.

Shipping and naval

Shipping has been slower that aviation or automotive to respond to the green transition, but changes are now happening. The International Maritime Organization has set an ambitious goal to reduce greenhouse gas emissions in the maritime sector by 50% compared to 2008 by the year 2050. There are few notable maritime commitments to hydrogen combustion at present, though Maersk is scaling up the use of e-methanol, made from green hydrogen . However, there is a growing pool of innovation that could yet transform the industry. For example:

- A Global Maritime Forum analysis found over 85 zero-emission vessel pilots demonstrations initiated during 2021 and early 2022, of which 14 were pure hydrogen combustion.
- A number of companies and projects are working on hydrogen combustion, including MAN Energy Solutions, who are developing a hydrogen-fired four-stroke ship engine.

Companies are exploring innovative approaches to the storage problem. Startup Amogy has developed a system which converts ammonia to hydrogen, which can then be immediately used as fuel, as part of a single process, addressing the need for challenging storage conditions of hydrogen.

INTERVIEW 1: GREEN CORP KONNECTION (GCK), AN INNOVATIVE PLAYER IN GREEN MOBILITY

GCK, based in Auvergne-Rhône-Alpes and made up of 8 industrial companies, has built a 360 degree approach to the energy transition for mobility, combining multiple technological building blocks, their integration into vehicles, and green energy supply.

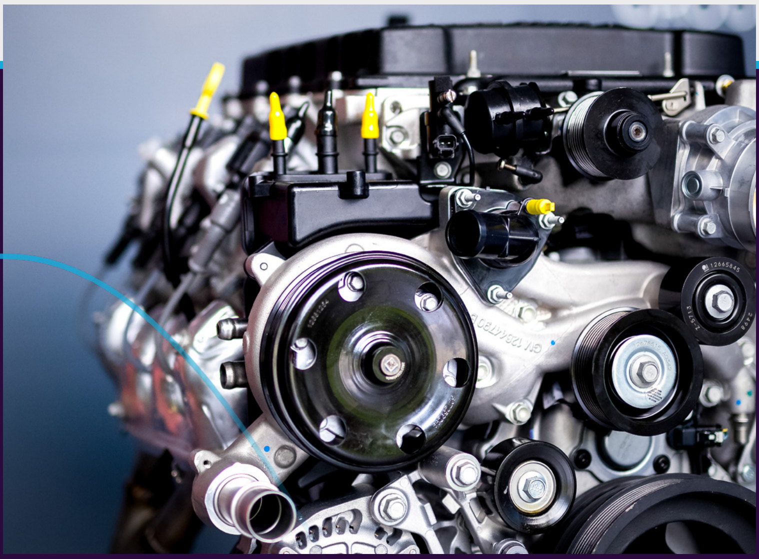
In order to respond with the best technology adapted to each use case, GCK has implemented numerous technological development projects over the last few months: a range of innovative battery packs, a range of high power density electric motors, a range of hydrogen combustion engines, and a high power fuel cell system.

GCK has become a key player in the field of vehicles and the integration of these technological building blocks through its heavy vehicle retrofit activity. The group works with numerous companies and local authorities to convert fleets of combustion engine vehicles (LCVs, coaches, boats, refuse collection vehicles, snow groomers, etc.) into electric, battery and hydrogen vehicles. To develop its vehicles, the group relies on its motorsport laboratory and its test centre at the Charade circuit, where GCK has a technology park project dedicated to training and R&D on all carbon-free mobility technologies.

Finally, with its Energy Division, GCK provides mobile green energy supply and refueling solutions for electric and hydrogen vehicles.

Faced with the challenges of decarbonization of mobility, Europe has chosen to move away from a monopoly of the internal combustion engine, and towards a monopoly of electric mobility for light vehicles from 2035. Whether based on fuel cell or battery technologies, this monopoly will create an upheaval (technologically, socially, economically and geopolitically) of the entire automotive and vehicle construction sector. The GCK group believes that this trend will be difficult to transpose to all heavy mobility or intensive professional use, due to the reduced versatility of battery or fuel cell electric vehicles. This is why GCK has chosen a technology-agnostic approach to low-carbon mobility by developing batteries, electric motors, hydrogen combustion engines and fuel cells

More generally, with this strategy defined by Europe, the vehicle construction and after-sales industries (maintenance) will be strongly impacted by significant loss of jobs and skills around the combustion engine. It will also be faced with supply issues for components, minerals or materials, controlled by geopolitical powers outside Europe, and in competition with other application sectors (energy, industry, construction, etc.).



While the PAC and battery technologies are undeniably clean and virtuous for a large number of uses, they are not the only ones capable of addressing the challenges of the carbon footprint of transport and mobility, particularly heavy transport.

The hydrogen combustion engine solution, represents a solution that is as virtuous (if not better in certain cases) over a complete life cycle as fuel cell solutions, while benefitting from the transition of know-how, employment and industrial tools in the sector.

Indeed, a hydrogen combustion engine (HICE) maintains the same industrial model as the diesel or petrol engine and, with a few adaptations, most of the components of these engines will be kept.

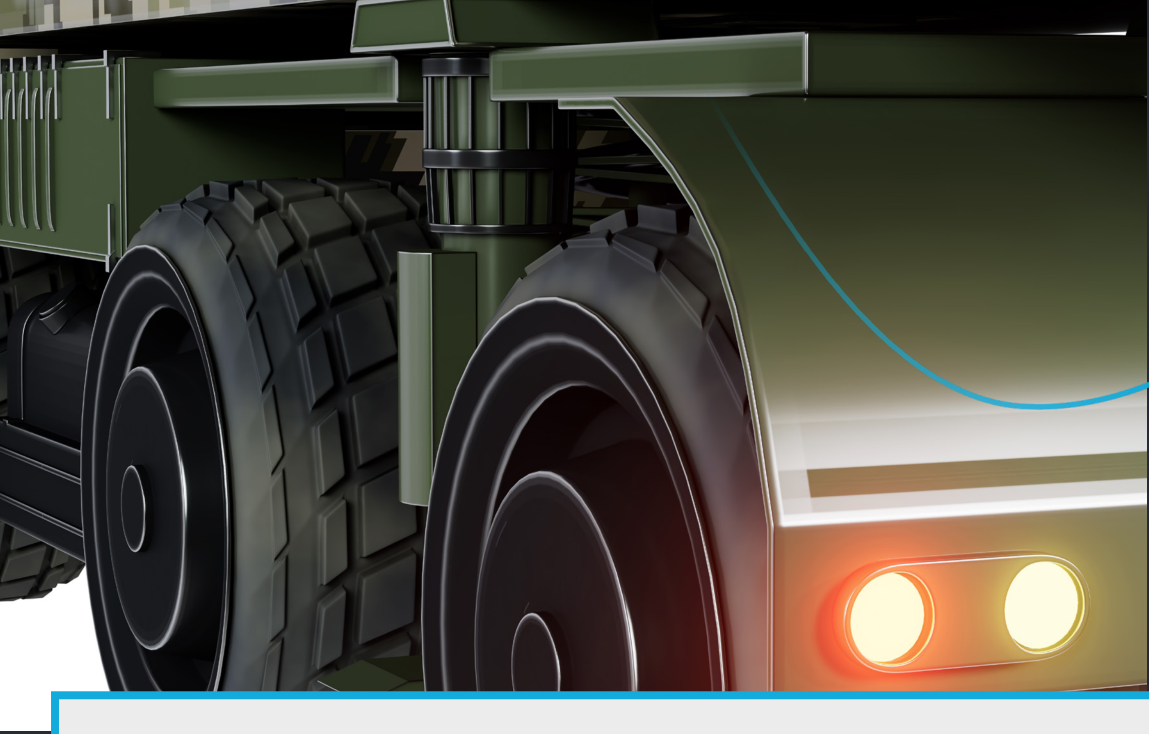
This HICE technology also has a triple interest for the ecological transition:

- Its low CO2 impact during manufacture
- In use, it is low CO2 (depending on how the hydrogen is produced) and the almost total absence of emissions of NOx and particulate pollutants
- It's total cost of ownership (TCO), mainly due to its low production cost, is lower than battery or fuel cell electric vehicles.

With rapid deployment, HICE would support the energy transition of the automotive, while preparing for the arrival of fuel cell solutions, whose industrial maturity, while showing strong momentum, is not yet equivalent to that of combustion engines or, to a lesser extent, that of the battery sector for light vehicles.

Beyond these industrial or ecological considerations, the HICE solution will also make it possible to respond to uses that neither the fuel cell nor the battery can technically or economically address (construction and mining equipment, aeronautics, etc.). It will provide real environmental benefit without increasing the pressure on a key resources (e.g. copper), which should be reserved for more important uses.

In June 2023, GCK introduced one of the world's first GT racing cars powered by a hydrogen combustion engine at the 24 Hours of Le Mans.



INTERVIEW 2: ARQUUS COMPANY, LEADER IN DEFENCE GROUND MOBILITY SOLUTIONS

The French army's defence energy strategy is based on three parts: Consume safely, consume less, consume better. In order to respond to this in the context of external operations, possible areas of progress involve:

- Increasing energy resilience of bases and systems
- Increasing agility of maneuvering forces through reducing the logistical footprint of bases and systems
- Controlling fuel logistics
- Reducing dependence on fossil fuels
- Reducing the emissions of vehicles on their return to the mainland
- Controlling operating costs

Land equipment

For deployed equipment in the theatre of operations, the priorities concern the reduction of fuel logistics as well as the autonomy of the vehicles.

If for the same mass, excluding the container, hydrogen is more efficient than hydrocarbons (factor #3), its volume and mass are multiplied by 5 when integrating the container (gaseous at 700 bar) or the storage technology (LOHC). While maintaining the same autonomy, its use for internal combustion engines is not feasible for military use because of its impact on the architecture of the vehicles and on the fuel supply logistics chain. Moreover, an internal combustion engine capable of running on either 100% diesel or 100% hydrogen does not exist.

In order to meet the needs of mobility of the vehicles, the compactness of the engines and the potential use of poor quality fuels, these vehicles will not be able to comply with the regulations governing pollutant emissions. Even if exemptions to the regulations exist for military equipment, these machines will have to be more virtuous with regard to pollutant emissions when they return to metropolitan France.

Dual fuel solutions, i.e. simultaneous injection of diesel and hydrogen, can significantly reduce CO2 emissions (by up to 70%) while still being able to operate on 100% single fuel when returning to theatres of operation.

The use of LOHC (Liquid Organic Hydrogen Carrier) to safely transport this hydrogen becomes a relevant vector to transport this liquid in tanks capable of carrying either conventional fuel or LOHC.

The extraction of hydrogen from the LOHC is done through an energy efficient loop based on a catalyst that recovers the exhaust gases from the internal combustion engine to trigger the process.

From conventional internal combustion engines, the transformation of these into dual fuel engines can be envisaged via kits during retrofit operations.

On Forward Operating Bases (FOBs), massive energy storage via hydrogen is a more efficient solution than batteries to overcome traditional fuel shortages.

Forward Operating Bases

The energy resilience of these bases in the event of a breakdown in the fuel supply chain is one of the major areas of progress in the system for producing and storing energy for forces in the theatre of operations.

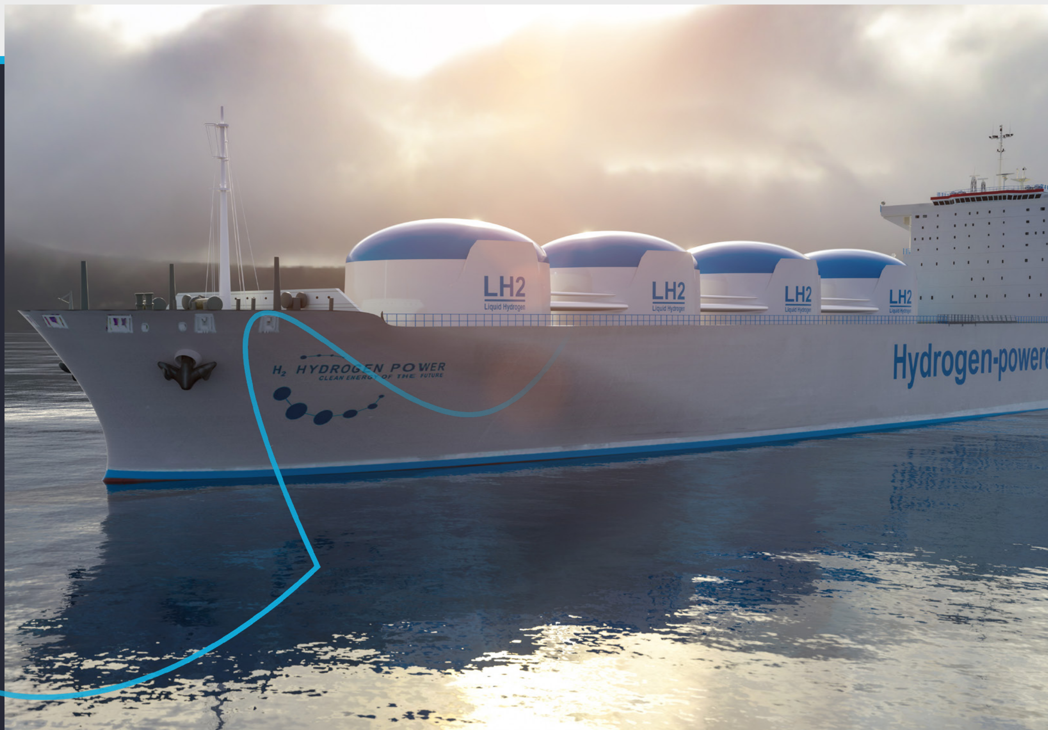
The first way is energy storage at a battery park. Although the energy yield of this type of storage is high, the energy density of these batteries is low and three 20-foot containers are needed to store 18% of the energy needs of a base of 1,000 men for one day, which represents a mass of the complete system of 65 tonnes (50 tonnes of batteries).

The second option is to use hydrogen as an energy carrier to store this energy and then transform it into electrical energy via dual fuel generators.

The hydrogen is then stored in LOHC and the hydrogen enrichment of this LOHC can be done in situ (need for a high temperature electrolyser, a catalyst and an energy source which can be a civil network when accessible) or at the main rear base and then transported by standard refueling vehicles.

The hydrogen production station is packaged in a 20ft 25t container (catalyst) and connected to a 12m3 flexible tank.

The hydrogen is then extracted from the LOHC via catalysts that harness the waste energy of the internal combustion engines and then mixed with the single fuel in the intake cycle of these engines.



CONCLUSION

For many in the transportation sector, reducing carbon emissions will mean initially adopting EVs or FCEVs. But this doesn't mean combustion of fuels will immediately be consigned to the engineering history books. We just need different fuels.

Burning hydrogen in a piston- or turbine-driven thermal engine generates no CO2, just water and some NOx. The maturity of ICE technology means systems can be adapted to hydrogen and other e-fuels – synthetic fuels derived from the use of an electrochemical process – at a much lower cost than developing FCEVs. And dual-fuel technologies illustrate how hybrid solutions are often paving pragmatic journeys towards very challenging objectives!. Adapting ICEs to hydrogen will also protect a huge number of jobs at risk of disappearing following the advent of EV technology.

In aviation, the appropriate solution for decarbonization will depend on usage. For example, electric batteries and fuel cells are a promising solution for short- and medium-haul aircraft with a limited number of seats. For short-haul commuter flights, replacing original turboprops with a fuel cell and electric powertrain is a potential solution, with the possibility to use hydrogen as a fuel. For long-haul aircrafts, though, the only viable option is to combust fuel, which could be SAFs or hydrogen. For shipping, adapting combustion engines is achievable, but storage solutions must still be found for long journeys.

In summary, although EVs and FCEVs are seen by many as the most sustainable answer to the transportation industry's environmental challenges, the use of ICEs powered by hydrogen and e-fuels also represents a cost-effective, pragmatic, and sustainable solution in many cases.

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