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Technology roadmap for hydrogen-fuelled transportation in the UK

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HIGHLIGHTS

- Hydrogen-fuelled transportation is reviewed.
- Characteristics, advantages and drawbacks of using hydrogen in different transportation modes are investigated.
- Common and specific research areas from short to long term for the different transportation modes are suggested.

ARTICLE INFO

Article history:
Received 27 October 2022
Received in revised form
5 April 2023
Accepted 11 April 2023
Available online 30 April 2023

Keywords:
Hydrogen technology
Roadmap
Road
Aviation
Marine
Rail

ABSTRACT

Transportation is the sector responsible for the largest greenhouse gas emission in the UK. To mitigate its impact on the environment and move towards net-zero emissions by 2050, hydrogen-fuelled transportation has been explored through research and development as well as trials. This article presents an overview of relevant technologies and issues that challenge the supply, use and marketability of hydrogen for transportation application in the UK, covering on-road, aviation, maritime and rail transportation modes. The current development statutes of the different transportation modes were reviewed and compared, highlighting similarities and differences in fuel cells, internal combustion engines, storage technologies, supply chains and refuelling characteristics. In addition, common and specific future research needs in the short to long term for the different transportation modes were suggested. The findings showed the potential of using hydrogen in all transportation modes, although each sector faces different challenges and requires future improvements in performance and cost, development of innovative designs, refuelling stations, standards and codes, regulations and policies to support the advancement of the use of hydrogen.

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https://doi.org/10.1016/j.ijhydene.2023.04.131

Nomenclature

APU	Auxiliary power unit
CO	Carbon monoxide
CO_2	Carbon dioxide
CCUS	Carbon capture, usage and storage
CH_2	Compressed hydrogen
CcH_2	Cryo-compressed hydrogen
DI	Direct injection
DWT	Deadweight tonnage
EPU	Emergency power unit
ESS	Energy storage system
FC	Fuel cell
GVW	Gross vehicle weight
HGV	Heavy good vehicles
HC	Hydrocarbon
H_2	Hydrogen
H_2ICE	Hydrogen-fuelled internal combustion engine
HRS	Hydrogen refuelling station
ICE	Internal combustion engine
LCOH	Levelised cost of hydrogen
LNG	Liquefied natural gas
LH_2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
Li-ion	Lithium-ion battery
H_2	Hydrogen
MGO	Marine gasoil
MH	Metal hydride
MOF	Metal organic framework
MC	Molten carbonate
NOx	Nitrogen oxides
NH_3	Ammonia
O_2	Oxygen
PV-T	Photovoltaic thermal
PFI	Port fuel injection
PEM	Proton exchange membrane
sLH_2	Supercooled liquid hydrogen

Introduction

The transportation sector was responsible for the emission of 97 million tonnes of carbon dioxide equivalent in the UK in 2020 (about 24% of the total greenhouse emissions), making the sector the largest greenhouse gas emitter in the UK [1]. Hydrogen is emerging as a low- and zero-carbon fuel alternative towards the decarbonisation of the transportation sector. Since 1975, the landscape of hydrogen has changed remarkably, as evidenced by the quadruple growth of the global demand for hydrogen (i.e., 73.9 million tonnes in 2018 compared to 18.2 million tonnes in 1975) where, at present, the produced hydrogen is largely used for ammonia (NH_3) production and fossil fuel refining [2]. Whilst the current installed hydrogen capacity is relatively small as compared to the market size of other fuels (e.g. natural gas and diesel) and applications (e.g. domestic heating, electricity supply and transportation), there is potential to unlock larger UK markets for hydrogen fuel and applications to meet zero-carbon emissions as the demand for hydrogen continues to grow with technology maturity.

Creating a hydrogen future has been envisaged as a vision and the pathway towards zero-carbon power sector, buildings, transportation and industry by many countries, including the UK, whilst literature on hydrogen technology from production to application has been extensively published. For the transportation sector, the UK Hydrogen Strategy, which was published in 2021, estimated the potential demand for hydrogen to be between 0 and 6 TW h for 2030, a value that is estimated to reach 20–35 TW h by 2035 [3]. However, before extensively rolling out hydrogen on a large scale, there are still challenges to address, priorities to identify, areas of research to explore and advance, knowledge gaps to bridge and technology readiness to improve. From a research and development perspective, this article investigates the characteristics of the hydrogen-fuelled transportation modes in the UK context, identifying the main characteristics (propulsion, storage and supply chain), advantages and challenges of each transportation mode and presents research areas of priority with the potential to transform the vision for hydrogen-fuelled transportation into reality in the short, medium and long term.

The current literature lacks comparative studies on the potential of using hydrogen in the different transportation modes, which could be helpful to identify on what priorities industry, academia and government should focus on for the development of hydrogen-fuelled transportation in the UK. As such, this article aims to prioritise areas of research that need to be investigated to enable hydrogen technologies and hydrogen-fuelled transportation in the short, medium and long term in the different transportation modes. Technologies that convert hydrogen fuel into power for transportation application presents technologies that convert hydrogen fuel into power for transportation application proposes. In the present context of the UK and based on the literature review, Hydrogen-fuelled transportation for different modes describes the use of hydrogen for transportation for road, aviation, maritime and rail applications, covering aspects from the current status of development, characteristics and supply chain (hydrogen production, purification, storage, distribution and refuelling infrastructure). Critical analysis and future research areas of hydrogen-fuelled transportation modes presents a critical review of the use of hydrogen in the different transportation modes, highlighting and comparing the main characteristics, advantages and challenges to recognise the specific and common research areas that are required to stimulate the widespread adoption of hydrogen in the short, medium, and long term. The study is closed in Conclusion with conclusions.

Technologies that convert hydrogen fuel into power for transportation application

Fuel cells (FCs) convert hydrogen into electrical energy. As such, hydrogen FC vehicles have an electric drivetrain, similar to battery electric vehicles, but their energy input is provided by hydrogen stored onboard the vehicles. They present similar range and refuelling characteristics to conventional vehicles [4]. Energy is released from hydrogen using an onboard FC stack without tailpipe greenhouse gas emissions. This is because the only by-product of the FC reaction is water, which is generally released into the atmosphere. To maintain an efficient reaction, operational parameters of FCs, such as temperature, current density, humidity, reactant ratio and pressure, must be controlled [5]. Additional power for cooling FC stacks is required. On shutdown, FC stacks have to remove water from the stack to prevent freezing [6].

FC technologies include (but are not limited to) alkaline, proton exchange membrane (PEM), solid oxide, phosphoric acid, molten carbonate (MC), and direct methanol FCs. Their fuel, efficiency, cost, and lifetime are summarised in Table 1. Among all, PEM FCs are the most suitable for transportation applications due to their high reactivity, ability to cold start, high energy density and low weight. However, they are prone to hydrogen impurities due to low operating temperatures and require complex water management, which increases their maintenance cost and reduces their lifetime [7].

Hydrogen can also be combusted by internal combustion engines (ICEs) to produce drive power for transportation. Similar to conventional natural gas-fuelled ICEs (also referred to as gas engines or single gas fuel engines), hydrogen-fuelled internal combustion engines (H_2ICEs) operate based on the Otto cycle principle [8]. H_2ICEs share the common operational challenges faced by conventional gas engines which are related to air-to-fuel ratio, intake temperature, engine knocking and NOx formation as well as additional issues, such as (i) high flame speed and low ignition energy, leading to a steep rise in cylinder pressure and possible pre-ignition of fuel, and therefore potential explosion inside the engines, (ii) higher combustion temperature in hydrogen engines, leading to higher NOx formation rates, which can be addressed by exhaust gas recirculation and catalytic reduction filters (well established technologies for conventional engines), and (iii) smaller engine output power and torque due to the less space available in the cylinders and combustion chamber for air intake, as a result of the lower volumetric energy density of hydrogen [9]. As such, to burn hydrogen as the only fuel input, modifications on conventional gas engines are required [10]. To date, two adaptation strategies have been suggested to solve the problem that hydrogen could self-ignite due to its low self-igniting temperature and result in premature ignition, leading to knocking effects. They include (i) direct injection (DI), which works by injecting liquid hydrogen (LH_2) at high pressure during the combustion cycle (because low temperature avoids self-ignition) and (ii) injection with gas valves, which works by injecting hydrogen at high pressures when the intake cycle begins. In addition, the injection of liquid or pressurised hydrogen is also introduced to solve the problem of less space being available for air intake, although this results in a smaller power output.

Alternatively, hydrogen can be combusted by conventional dual-fuel ICEs, which are compression engines that require no modification on the fuel injection system but a hydrocarbon pilot fuel to ignite the fuel [10]. The engines operate by burning either 100% liquid fuel (e.g. diesel, liquefied natural gas (LNG) and methane) or a mixture of gas hydrogen and liquid fuel at

Table 1 – FC technologies, data taken from Refs. [16–22].

FC type	Fuel	Electrolyte	Temperature (°C)	Efficiency (%)	Cost (£/Kw)	Lifetime[a] (hours)	Advantages	Disadvantages
Alkaline	H_2	Potassium hydroxide	150–200	~50	110–400	5000–8000	Low cost; high potential for mass production; better reaction kinetics than PEM	High degradation of electrodes; require pure oxygen
PEM	H_2	Polymer	60–140	Up to 60	~285	<5000	Low operating temperature; high power density; ease of scale-up	Low durability, high cost
Solid oxide	Syngas (CO/H_2), methane, or NH_3	Barium cerate	200–700	50–70	1700–2280	Up to 90,000	Less sensitive to the purity of H_2	Long start-up time; high operating temperatures
Phosphoric acid	H_2	Phosphoric acid	150–200	30–40	2275–2850	30,000–60000	Ideal for stationary applications	Less efficient; low power density
MC	Natural gas, coal or biogas	Lithium/potassium/sodium carbonate	600–700	>60	2275–3420	20,000–30000	Low capital costs; ideal for stationary applications	Low power density; high operating temperatures
Direct methanol	Methanol	Polymer	30–80	30	~1140	20,000	Light weight; compact; used for portable applications	Low power density

[a] A lifetime of 5000 h corresponds to a mileage of 150,000–200,000 km [17].

various portions. During the gas mode, the lean-burn Otto cycle applies where the air-hydrogen mixture is compressed and ignited by a pilot fuel, i.e., a small quantity of liquid fuel (approximately 1–15% of the total fuel input) which is injected into the combustion chamber. During the liquid fuel mode, the Diesel cycle applies where liquid fuel is injected into the combustion chamber at high pressure for combustion [11].

Gas and steam turbines are alternative technologies that can convert hydrogen into drive power. Gas turbines consist of built-in compressors, combustors, compressor turbines and power turbines and operate based on the Brayton cycle principle [12]. Compared to diesel-fuelled gas turbines, hydrogen-fuelled gas turbines show lower efficiency, lower fuel flow rates and consequently increased mass flow rates of air and exhaust due to the differences in fuel properties [9]. This necessitates modifications on the compressor and turbines to accommodate different flow rates for optimal performance [13]. On the other hand, steam turbines work in proximity to boilers, condensers and pumps, and make use of boil-off gas (i.e., the outcome of the natural evaporation of hydrogen where LH_2 storage tanks are not perfectly insulated [14]) or hydrogen. Combustion turbines are prone to issues such as metal deterioration and steam/stress corrosion cracking when they burn pure hydrogen at high temperatures [15], making the choice of materials an important aspect to consider during turbine design.

Hydrogen-fuelled transportation for different modes

Road

Fig. 1 summarises the technical considerations and the thermodynamic and combustion properties of hydrogen when compared to methane and gasoline (exemplifying conventional fuels).

FC and H_2ICE vehicles have been developed for road transportation. The main advantages of FC vehicles are the higher fuel conversion efficiency and the low noise, although a higher hydrogen purity is required for the operation of the FC. A 99.97% purity for both gas hydrogen (Grade D) and LH_2 (Grade B) is required for FC vehicles, while a 98% purity for gas hydrogen (Grade A) is required for H_2ICEs [26]. H_2ICEs have a lower peak fuel conversion efficiency than FCs. Their average fuel conversion efficiency is more than 35% whereas their peak fuel conversion efficiency could be more than 50% if they are coupled to a hybrid powertrain [65]. On the other hand, H_2ICE vehicles take the advantage of traditional gas engines and present the potential for dual-fuel operation, although these vehicles are characterised by high fuel consumption, potential emissions of harmful NO_X, wide flammability limits, low minimum ignition energy of hydrogen and are noisier than FC vehicles [27].

Technical considerations in using hydrogen for on-road transportation:

- Emissions: compared to conventional fuels, hydrogen does not emit hydrocarbons (HCs), carbon dioxide (CO_2) and carbon monoxide (CO)
- High energy density by mass: compared to conventional fuels, hydrogen shows higher energy density by mass (about two to three times)
- Low density: hydrogen has a low volumetric energy density (9.9 MJ/m^3), creating a problem for its storage
- Flammability limit: compared to conventional fuels, hydrogen has a wide range of flammability limit (4–75%) resulting in higher safety concerns but also ability to favour lean combustion (i.e. higher fuel economy, lower emission of NOx)
- High diffusion coefficient in air: compared to conventional fuels, hydrogen can disperse more easily in the air, i.e. forming uniform mixture of fuel and air and dispersing rapidly if is leaked
- Low minimum ignition energy: hydrogen has a lower minimum ignition energy, enabling lean combustion with prompt ignition. However, there is a risk of hot spot ignition too.
- High auto-ignition temperature: hydrogen can increase the thermal efficiency of the system due to the higher compression ratio
- Small quenching distance: hydrogen has a higher tendency to lose combustion heat and backfiring

	Hydrogen	Methane	Gasoline
Use in ICE	Yes	Yes	Yes
Use in PEM fuel cell	Yes	No	No
Use in solid oxide fuel cell	Yes	Yes	Yes
Molecular weight (g/mol)	2.016	16.4	107
Density (kg/m^3)	0.0824	0.643	730
Energy density by mass (MJ/kg)	120	50	44.8
Energy density by volume (MJ/m^3)	9.9	32.6	32,704
Heat of combustion (MJ/kg of air)	3.48	2.9	3.05
Diffusion coefficient in air (cm^2/s)	0.61	0.16	0.005
Flammability limit (% vol.)	4–75	4.3–15	1.4–7.6
Minimum ignition energy (mJ)	0.02	0.29	0.24
Auto-ignition T (^oC)	585	540	228–470
Flame velocity (m/s)	2.65–3.25	0.37–0.45	0.37–0.43
Quenching distance (mm)	0.64	2.1	2

Fig. 1 – Technical consideration for using hydrogen for road transportation [23–25].

Cars

Light-duty vehicles, such as cars, taxis and vans, were responsible for 68.7% of the total domestic emissions of the transportation sector in the UK in 2020 [1]. Currently, hydrogen-fuelled commercial vehicles are available on the UK market with limited demand [28]. The schematics of the powertrain of current hydrogen-fuelled cars (i.e., FC and H_2ICEs cars) together with a brief description of their main components, characteristics, advantages and drawbacks are illustrated in Fig. 2.

Fig. 3(a) illustrates the state-of-the-art hydrogen production, storage, distribution, refuelling and use for automotive application. Hydrogen can either be produced off-site (centralised production) or on-site. Centralised production involves bulk quantities of hydrogen, taking advantage of economies of scale and removing the need for costly compressors if hydrogen is delivered at required pressures. However, it has higher transmission and distribution costs and relies on infrastructure readiness, e.g. road transport, pipelines, refuelling stations, etc. On the other hand, on-site production minimises transmission and distribution costs, although requires more energy and potentially larger space for on-site production and compression and its levelised cost of hydrogen (LCOH) tends to be higher than centralised production [11]. To provide low-cost hydrogen, hydrogen production technologies integrated with carbon capture, usage and storage (CCUS) using fossil fuels as feedstocks are suitable in the short term whilst moving towards deeper market penetration of zero-carbon emission technologies, such as water electrolysis utilising renewable energy sources and cheaper materials for PEM electrolysers.

When hydrogen is produced at a central facility, it can be transported to the hydrogen refuelling station (HRS) via (i) carbon steel pipelines for hydrogen-natural gas blends, (ii)

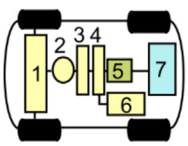
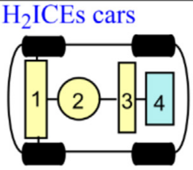
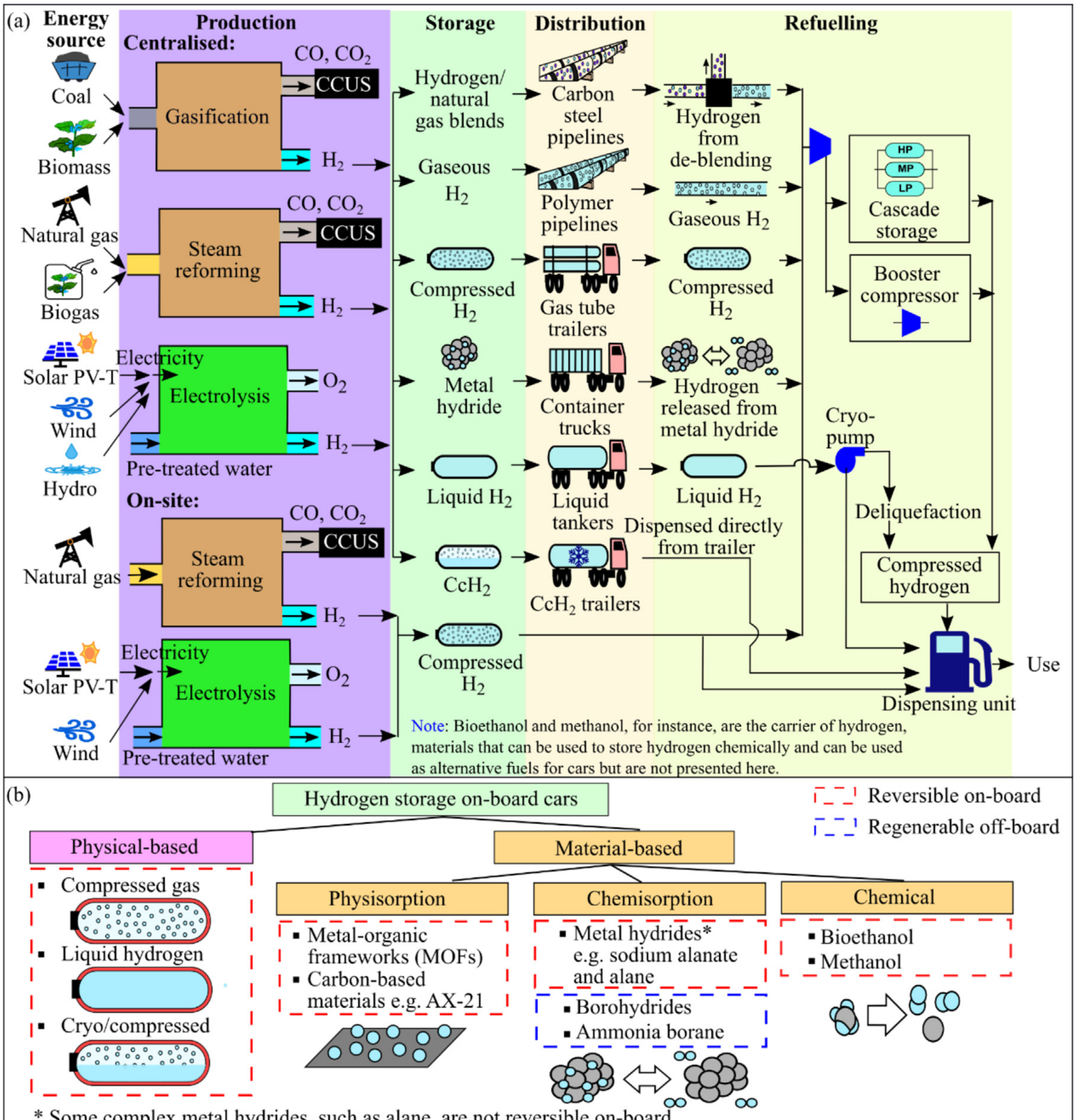
Fuel cell cars  1 Transmission 2 Traction motor 3 Motor inverter 4 DC/DC converter 5 Fuel cells 6 Electrical energy storage 7 Hydrogen storage	Propulsion system: PEM FCs (higher than 60 kW) convert the chemical energy of hydrogen to electrical energy to power the car. They are used because of their (i) high efficiency, (iii) high power density, (iii) cold-start capability, and (iv) low operating temperature (80–100 °C). However, they are expensive (need for large manufacturing volumes and alternative catalyst materials to substitute platinum for lower costs). Use of battery to assist power. Hydrogen storage: Compressed gas (700 bar) stored onboard (5.46–5.63 kg H_2) using high-pressure composite pressure vessels (Type IV) to achieve high pressure at a low container weight. Storage tanks are typically located in the rear of a car (mounted transversely in front or above the rear axle) which requires large storage volumes and limits space availability. Materials used for storage should be compatible with issues, such as leakage, abrasion, wear and corrosion. Strength, hardness and machinability should be considered during material selection. Commercialised or demonstration models: Hyundai ix35, Hyundai Nexo, Toyota Mirai, Honda Clarity, Mercedes-Benz GLC, Riversimple Rasa, Symbioo kangoo van Advantages: Higher efficiency of FCs (about 60%) compared to ICEs; long driving range (more than 300 km); refuelling experience similar to conventional vehicles with short refueling time (about 5 minutes); no harmful emissions (only water vapour); no requirement for large scale production of Li-ion batteries (energy intensive process); quieter and with less vibration driving experience Drawbacks: High capital and refuelling cost; impurities in the hydrogen affects the lifespan of the FC (additional purification cost); use of rare earth materials as catalyst; development of refuelling infrastructure
H_2ICEs cars  1 Transmission 2 Internal combustion engine 3 Pressure regulator 4 Hydrogen storage	Propulsion system: Hydrogen used in ICE. Use port fuel injection (PFI) or direct injection (DI) spark ignition. PFI shows high part load efficiency with very low emissions and low power output. DI shows very high efficiency with controllable emissions but its durability is low. Technical problems in line with the use of hydrogen by ICEs: (i) controlling abnormal combustion, which may result in pre-ignition, backfire and spark-knock and (ii) the current technology cannot offer the required power output at high efficiency with high durability and low emissions. Hydrogen storage: Liquid or compressed hydrogen storage requiring large storage volume, and high injection pressure where liquid hydrogen is stored in cryogenic tanks with pressure generated onboard. In the form of compressed hydrogen, the full tank capacity cannot be utilised, and therefore efficiency is low. Demonstration models: BMW Hydrogen 7 (dual-fuel hydrogen/gasoline), Mazda RX-8 Renesis RE Hydrogen (dual-fuel hydrogen/gasoline), Mazda Premacy RE Hydrogen, Ford Superchief F250 (tri-fuel), Toyota Corolla Advantages: ICE is well-established (less work required for transition to H_2ICEs); cheaper than fuel cell cars; hydrogen combustion less affected by the presence of impurities, i.e. lower fuel cost (no purification required); refuelling experience similar to ICEs with short refuelling time (about 5 minutes); longer driving range compared to battery electric cars (more than 300 km); no modifications in powertrain, with similar weight to ICEs; no use of rare earths; no requirement for large scale production of Li-ion batteries (energy intensive process) Drawbacks: Low efficiency of ICE (about 20–25%) i.e. lower driving range; potential NOx emissions; high refuelling cost; development of refuelling infrastructure

Fig. 2 – Schematics and comparison of current hydrogen-fuelled (i.e., FC and H_2ICEs) cars with a description of the technologies based on [23–25,29–33].



	P (bar)	T (K)	ΔH (kJ/mol H_2)	Refueling station
Physical-based				
Compressed gas	350–700	300	-	Tube banks, compressors
Liquid gas	6–8	20	-	Liquid hydrogen storage
Cryo/compressed	50–300	20–50	-	Liquid hydrogen storage, liquid hydrogen pump
Material-based				
Physisorption				
AX-21	50–300	77–120	3–6	Liquid hydrogen storage, liquid hydrogen pump
MOF-177	50–250	77–120	2–5	Liquid hydrogen storage, liquid hydrogen pump
Chemisorption				
Sodium alanate	100	423–453	37–47	Fresh and spent storage
Alane	10–50	423–453	7	Tube banks, compressor, chillers
Sodium borohydride	10–50	423–453	51	Fresh and spent storage
N-ethyl carbazole	10–50	423–453	20–33	Fresh and spent storage
Ammonia borane	10–50	423–453	53–63	Fresh and spent storage
Chemical				
Ammonia	8–10	300	30.6	Liquid fuel refueling station
Methanol	1	300	16.3	Liquid fuel refueling station
Ethanol	1	300	28.7	Liquid fuel refueling station

Fig. 3 – (a) State-of-the-art supply chain of hydrogen for automotive application and (b) state-of-the-art of hydrogen storage onboard cars, based on [23,31,52,53].

fibre reinforced polymer pipelines for gaseous hydrogen, (iii) gas tube trailers for compressed hydrogen (CH_2) gas, (iv) container trucks for chemical or metal hydrides (MHs), (v) cryo-compressed trailers for cold- or cryo-compressed hydrogen (CcH_2) and (vi) liquid tankers for LH_2. When CH_2 is distributed to and dispensed at a HRS in the same form, there are four refuelling strategies that may be applied, namely cascade storage, constant pressure, booster compressor and direct dispensing [34,35]. A recently developed strategy called vessel consolidation shows the potential to meet compression demand at a 60% reduced cost using a smaller compressor [36]. The choice of refuelling strategies is also made in line with how hydrogen is produced and distributed and the pressures required. With excess renewable energy sources, on-site hydrogen production may be favourable due to reduced costs that will be otherwise spent on hydrogen distribution. When CH_2 is produced on-site at the required pressures, it can be supplied directly to a dispensing unit. When LH_2 is distributed to and/or stored on-site at a refuelling station, it can be converted by a cryo-pump into high pressure compressed gas for dispensing, if required [35].

Table 2 illustrates the current operating and planned HRSs in the UK, which predominantly have a capacity of lower than 100 kg H_2/day with limited geographical availability. As such, to stimulate the future roll-out of hydrogen-fuelled transportation in the UK, the development of larger capacity HRS (more than 1000 kg H_2/day) will be required [37]. The capacity of hydrogen refuelling stations affects the choice of hydrogen distribution strategy and vice versa. For instance, pipelines and liquid tankers are ideal for HRSs which can dispense more than 500 kg H_2/day, gas tube trailers are suitable for small capacities (between 50 and 100 kg H_2/day), while on-site hydrogen production through steam reforming and electrolysis can be carried out for both [38]. FC and H_2ICE vehicles could share the same hydrogen production, transportation and distribution supply chain and, as such, the development of one would support the development of the other [39]. The maximisation of the use of the HRS, the reduction of the capital and operating cost and public and policy support are required to increase the economic performance of HRSs.

Fig. 3(b) illustrates the technologies that are applicable for hydrogen storage onboard cars. Technical issues that limit hydrogen storage onboard cars include low energy density, high operating pressure of CH_2, poor efficiency, expensive catalysts, low response rates, stability and risk of violent reactions [31]. Whilst CH_2 at 700 bar in Type IV is the common choice for hydrogen storage onboard vehicles and has been adopted by FC car manufacturers for Hyundai ix35 (PEM FC stack power of 100 kW and storage of 5.63 kg of CH_2 at 700 bar for a driving range of 594 km [33]), Toyota Mirai (PEM FC stack power of 128 kW and storage of 5 kg of CH_2 at 700 bar for a driving range of 647 km [33]) and Honda Clarity (PEM FC stack power of 100 kW and storage of 5.46 kg of CH_2 at 700 bar for a driving range of 480 km [33]), storing LH_2 onboard cars has also been trialled in a few prototypes, such as the Necar 4 model by Daimler (storage capacity of 70 L to drive a 70 kW FC) [42], the Bora HyMotion model by Volkswagen (storage capacity of 50 L to drive a 75 kW FC) [43] and the HydroGen 3 (storage capacity of 68 L) [44]. Prototypes of other storage options for FC car applications have also been showcased, such as cryo-compressed storage, which was used in the i8 FC model developed by BMW (storage capacity of 7.2 kg at −220 °C and up to 350 bar to power a 90 kW FC for a 500 km driving range) [45], MHs storage, which was used in the Miata and Demio models by Mazda [46], and borohydride storage, i.e. sodium borohydride ($NaBH_4$) in water, which was tested in the Daimler Chrysler Natrium model and the Ford Mercury Sable reconverted by Team New Jersey [47]. Batteries are used in the current layout of FC cars to assist power [33], as in the case of the Toyota Mirai, which employs a lithium-ion (Li-ion) high-voltage battery that is located behind the rear seats in the vehicle. Li-ion batteries have replaced nickel-metal hydride (NiMH) batteries that were used in the previous version of the

Table 2 – List of HRSs in the UK [37,40,41].

Status	Location	Operator	Capacity (kg H_2/day)
Operating	Orkney	ITM Power	80
	Tullos, Aberdeen	Aberdeen City Council	80
	AMP, Sheffield	ITM Power	80
	Swindon, J Matthey	ITM Power	80
	Hatton Cross, London	Air Products	80
	NPL, Teddington	ITM Power	100
	CEME, Rainham	ITM Power	100 (planned to reach 270)
	Teddington	ITM Power	100
	Swindon, Highworth Road	BOC	200
	Kittybrewster, Aberdeen	BOC	360
	Birmingham	ITM Power	1,200[a]
	Metroline, Perivale	Ryze	1500
	Wallyford	H_2Tec	n/a
Planned	Belfast	Energia	60
	Llanwern	Air Products	1500
	Liverpool	BOC	n/a
	Glasgow	n/a	n/a
	Tees Valley	n/a	n/a

[a] For bus and car refuelling.

Toyota Mirai due to their higher energy density and power output and superior environmental performance [48].

For H_2ICE vehicles (either only hydrogen or dual fuel), no commercial models are currently available on the market [49]. BMW developed between 2003 and 2007 a dual-fuel vehicle equipped with a 6 L twelve-cylinder high-pressure DI engine fuelled with LH_2 (storage capacity of 8 kg) [50]. Following that, Mazda developed the dual-fuel RX-8 Hydrogen RE (2003) and Premacy Hydrogen RE Hybrid (2005–2007) cars that used a twin-rotor Wankel rotary engine (which is beneficial to limit the problem of backfiring with hydrogen combustion) supplied by gasoline or CH_2 stored at 350 bar [49]. More recently, Toyota started the testing of a Corolla Cross H_2ICE car equipped with a 1.6 L three-cylinder high-pressure DI turbo engine. The first tests of the vehicle showed performance similar to that of ICEs due to the increased hydrogen combustion power and torque that was achieved, together with a long driving range and reduced refuelling time (as low as 90 s) [51].

Trucks

Heavy goods vehicles (HGVs), i.e. all commercial trucks with a gross vehicle weight (GVW) of over 3500 kg or 3.5 tonnes, were responsible for 19.2% of the total domestic emissions of the transportation sector in the UK in 2020 [1]. Hydrogen-fuelled trucks are an appealing low-carbon alternative to conventional medium- and heavy-duty trucks running on petroleum fuel diesel, which are responsible for large CO_2 emissions due to their low fuel efficiency, long driving range and high idling time [54]. Compared to cars, hydrogen-fuelled trucks require (i) constant power during the entire period of transportation, (ii) a smaller number of HRSs due to the return-to-base operation, (iii) low manufacturing volume, which results in a lower difference in capital cost between conventional and hydrogen-fuelled trucks compared to cars, (iv) high energy density to increase the driving range of trucks and (v) high vehicle longevity (25,000–30,000 h for trucks as opposed to 8000 h for cars) [32,55]. The schematics of the powertrain of hydrogen-fuelled trucks together with their main characteristics, advantages and drawbacks are presented in Fig. 4.

The state-of-the-art hydrogen supply chain for hydrogen-fuelled trucks is illustrated in Fig. 5. Hydrogen for truck applications can be produced at a centralised facility or locally at a HRS. Centralised production at a local facility may be more cost-efficient than on-site production for a market with low demand, as production equipment can be operated for a high number of hours with a high system utilisation rate [58]. On-site production is likely to be only feasible for small to medium stations (up to 400 kg/day) due to the power and space

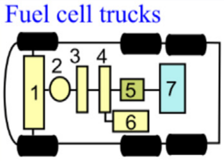
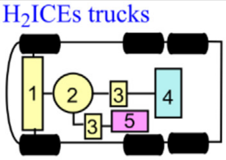
Fuel cell trucks  1 Transmission 2 Traction motor 3 Motor inverter 4 DC/DC converter 5 Fuel cells 6 Electrical energy storage 7 Hydrogen storage	Propulsion system: PEM FC characterised by (i) larger power output to increase trucks' driving range and (ii) high durability (vehicle lifespan 25,000–30,000 hours). Hybrid architecture: FC coupled with battery for peak acceleration. The chassis purely designed for FC trucks are required to allow a more flexible placement of the components in the powertrain Hydrogen storage: CH_2 at 350 or 700 bar or subcooled LH_2 (potential future use of CcH_2). Compared to cars, the problem of storage location availability is less critical. Potential locations (according to the vehicle type and application) are (i) side-rail tank (valid for different vehicle weights), (ii) back-of-cab (class 4 and above), (iii) under the chassis Commercialised or demonstration models: Symbio FC range extended truck, Toyota Kentworth, Hyundai Xcient, Hyzon Motors HyMax450, Nikola Tre, Daimler GenH2 Truck Advantages: Higher efficiency of FC (about 60%) compared to ICE; long driving range (400–1000 km); short refueling time (about 10–15 minutes); no harmful emissions (only water vapour); higher longevity; lower weight than battery electric trucks; quieter and with less vibration driving experience; constant power during the entire shift Drawbacks: High capital and refuelling cost; additional purification cost as impurities in the hydrogen affect the lifespan of the fuel cells; significant use of rare earth materials as catalyst; development of refuelling infrastructure
H_2ICEs trucks  1 Transmission 2 Internal combustion engine 3 Pressure regulator 4 Hydrogen storage 5 Diesel storage	Propulsion system: Hydrogen used in H_2ICE (single and intermittent use or dual-fuel). Dual fuel systems using H_2 and alternative fuel is a cost-effective option for low-carbon heavy-duty vehicles in the short- and medium-term. By adding H_2 to the conventional engines, it is possible to improve the performance and efficiency of the combustion process while reducing carbon emissions and pollutants at the exhaust. The conversion to H_2 requires little or no changes to the engine and powertrain Hydrogen storage: Compressed H_2 (350 or 700 bar). Compared to the conventional powertrain, minor modifications are required for (i) the hydrogen storage tank and (ii) high injection pressure, which could be obtained by using liquid hydrogen stored in cryogenic tanks with pressure generated on-board or compressed hydrogen (the full tank capacity cannot be utilised, i.e. lower efficiency) Demonstration models: Ford Superchief F250, Volvo FH16 (ULEMCo reconversion) Advantages: Dual fuel hydrogen-diesel long haul heavy-duty trucks are (i) cheaper than FC trucks and (ii) flexible: can work with H_2 as the only fuel or in combination with other fuels (by blending or by switching between fuels in dual-fuel configuration); no use of rare earths; hydrogen combustion less affected by the presence of impurities; lower fuel cost (no purification); longer driving range than battery electric trucks; no modifications in powertrain; weight similar to ICE trucks Drawbacks: Low efficiency of ICE (about 20–25%) i.e. lower driving range; potential NOx emissions; high refuelling cost; development of refuelling infrastructure

Fig. 4 – Schematics and comparison of hydrogen-fuelled (i.e., FC and H_2ICEs) trucks [32,33,54,56,57].

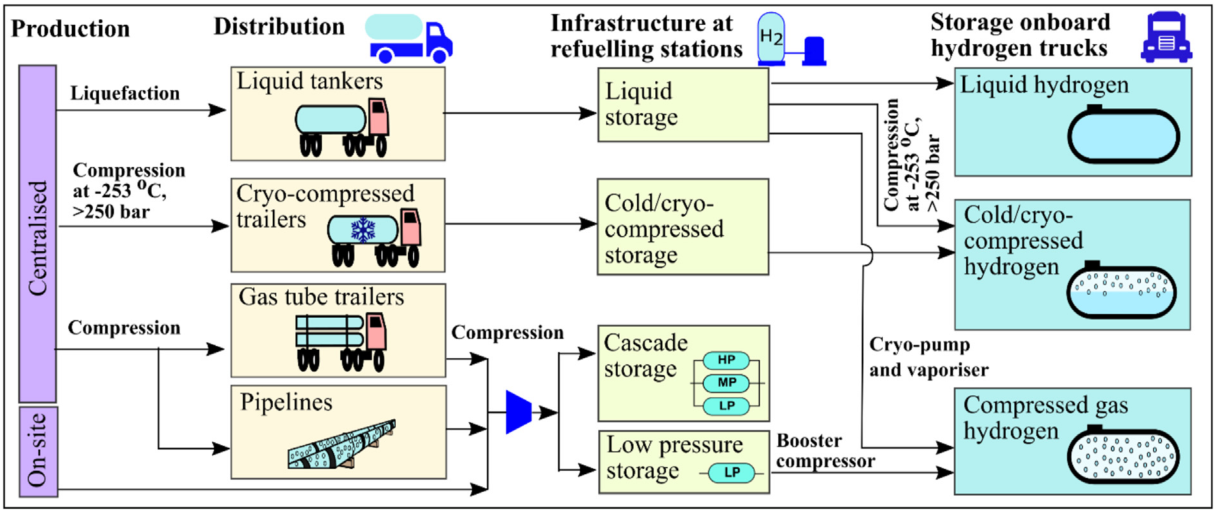


Fig. 5 – State-of-the-art hydrogen supply chain for truck application [31,74,75].

requirements for large on-site production facilities [59]. Compressed gas tube trailers are limited by their maximum transport capacity. To avoid delivering hydrogen more than 1–2 times a day, a method other than gaseous trucking is required for heavy-duty vehicles, such as trucks [60,61]. In the short term, the distribution of hydrogen will be achieved by expanding tube trailer distribution [62]. As the hydrogen market grows and improvements to liquid storage and pipeline distribution are made, liquid tankers or pipeline infrastructure will have to be used [63].

Compared to vehicles, a larger quantity of hydrogen is required for the refuelling of hydrogen-fuelled trucks, which ranges from 32 kg of CH_2 at 350 bar for the Hyundai Xcient (for a driving range up to 400 km) up to 70 kg of CH_2 at 700 bar for the truck Nikola Tre (for a driving range up to 800 km, which manufacturing is under development by Nikola Motors in collaboration with Iveco [64]. As such, higher capacity HRSs are mandatory for the refuelling of hydrogen-fuelled trucks and the development of the transportation mode. Assuming a refilling capacity of 60 kg, a HRS would require 2400 kg of hydrogen per day to refill 40 trucks [65]. The hydrogen refuelling process for onboard CH_2 storage is standardised (SAE J2601-2) for trucks and buses with over 10 kg onboard hydrogen storage. Communication between the dispenser and tanks sets the refuelling rate, which depends on the initial temperature, tank pressure and pre-cooling strategy. For fast refuelling at 700 bar, a pre-cooling unit is required to cool the hydrogen to 233 K (–40 °C). On the other hand, refuelling at 350 bar does not require a pre-cooling unit, reducing station complexity and energy requirements [35,58]. Current research is investigating technologies to increase the average and peak refuelling rate of CH_2 up to 10 kg/min and 20 kg/min, respectively, which could be beneficial not only for truck application but also for the aviation and maritime industry [66].

Daimler Truck and Linde AG are currently developing an advanced LH_2 storage system, called subcooled liquid hydrogen (sLH_2), in their H_2Gen truck [65] with production expected from 2027. The increased maximum working pressure of sLH_2 (from 4 bar to 20 bar) would allow to achieve a larger energy density and reduced hydrogen evaporation for a longer time [67]. In addition, the technology is expected to have large hydrogen storage capacity (more than 80 kg), high flow rate (400–500 kg of hydrogen per hour for each pump) and low energy demand for refuelling (0.05 kW h per kg of hydrogen as opposed to 1.5 kW h for CH_2 at 700 bar) and lower HRS footprint [65,68]. CcH_2 storage could also be a suitable alternative for truck applications [69]. Initially developed by BMW for hydrogen-fuelled cars, cryo-compressed technology represents a hybrid solution between LH_2 and CH_2 that uses cold temperatures (between 20 and 50 K) and relatively high pressure (up to 300 bar) for hydrogen storage. By doing that, CcH_2 storage can eliminate the boil-off losses (which are present with LH_2) and have high energy storage density [70]. Additional advantages include the reduction in cost for carbon fibre cost compared to CH_2 stored in Type IV storage tanks (which cost can be significant for the large storage volumes required in trucks) [70] and the more robust refuelling process with reduced losses compared to sLH_2 refuelling [65]. The company Cryomotive is currently working on the implementation of the storage technology for truck application [65]. MHs are less favourable for onboard storage in trucks due to their heavy weight, which may hamper performance and limit the payload.

H_2ICE trucks have been tested and trialled both as dual fuel and as only hydrogen-fuelled, although commercial models are still not available on the market. As a short term solution for the decarbonisation of the transportation sector, dual-fuel hydrogen trucks are based on the reconversion of diesel trucks by retrofitting the fuel injection system and the onboard hydrogen storage [71]. In recent years, the UK company ULEMCo has worked on the retrofitting of heavy-duty trucks for dual-fuel use with hydrogen in combination with diesel or hydrate vegetable oil (HVO), which was used in a waste collection truck [72]. Cummins Inc. has recently developed and tested H_2ICE truck for medium- and heavy-duty application using a 6.7 L and 15 L ICE, respectively, fuelled by CH_2 stored in twin fuel tanks at 700 bar (40 kg). The full production of the truck is expected to be in 2027 [73].

Buses

Buses were responsible for 2% of the total domestic emissions of the transportation sector in the UK in 2020 [1]. Currently, only 2% of the UK bus fleets operation are zero-carbon emission [76], showing the potential for the decarbonisation of the sector. Low-carbon buses can be powered by hydrogen-fuelled FCs and have been demonstrated over the last twenty years, with the first hydrogen bus using a FC realised by Ballard in 1993 [77], and several buses have been trialled in the UK. PEM FCs are considered the most suitable for bus applications. In comparison, alkaline FCs are less efficient and require pure oxygen, phosphoric acid FCs are heavy due to low power density and MC and solid oxide FCs involve high and very high operating temperatures, respectively.

Early bus trials used FCs as the only energy source and found a few operational issues, i.e., failure to meet the power requirements of buses due to poor dynamic response, shorter lifespan, and damage to FCs due to acceleration and deceleration. As such, hybrid FC buses, as illustrated in Fig. 6, were developed, which can reduce FC size, fuel consumption and overall costs (from 18.4 to 29.1 kg H_2/100 km to less than 10 kg H_2/100 km) [78]. In this type of bus, an auxiliary energy storage system (ESS), such as a battery and/or a supercapacitor, is kept charged using electricity from the hydrogen FC. The FC provides continuous energy and, under low loads, is used to power the motor. During peak power demand, the ESS is discharged, reducing transient loads of the FC [79]. The power control unit can charge the battery/supercapacitor, power the motor or do both [80]. The auxiliary ESS allows brake energy to be recovered and the FC to operate near peak efficiency, extending its lifetime and increasing fuel economy [81]. As optimal sizing for cost minimisation varies with drive cycle, average speed and start and stop [82], buses designed for a specific route can reduce lifetime costs. Drive cycles with higher average speeds and fewer stops have a larger optimal FC stack power size (80 kW) than those with lower average speeds (40 kW).

Four naturally aspirated and ten turbocharged H_2ICE buses were trialled in a project called HyFLEET [85], which showed a fuel consumption of 21.6 kg/100 km, a net weight of 12–12.9 tonnes, a driving range longer than 200 km, an engine output of 150–200 kW at 2 rpm and a hydrogen storage capacity of 50 kg. It was found that (i) fuel injectors for turbocharged would cause considerable downtime and (ii) unlike climate conditions which have a marginal impact, both traffic conditions and passenger load would affect the fuel consumption of buses by ±20% [85]. Neither has a new trial in place nor further improvement made on H_2ICEs buses, leading to the current unfavourableness of H_2ICEs buses when compared to FC buses.

Similar to the supply chain for truck application, hydrogen can be supplied by a centralised production facility or converted from LH_2 on-site at refuelling stations for bus refuelling. Hydrogen distribution by compressed gas tube trailers and on-site hydrogen production are currently on trial for buses [60,61]. Hydrogen bus fleets provide predictable demand with back-to-back operation and high utilisation rates for HRSs, enabling the development of refuelling infrastructure. Whilst infrastructure requirements at bus depots vary with the options of hydrogen storage, distribution and onboard bus application, most refuelling stations in Europe receive CH_2 from tube trailers and require compressors on site to meet the required 350 bar refuelling pressure [74]. Stationary and/or mobile hydrogen storage including storage for transportation, storage at bus depots and storage onboard buses are required for buses refuelling. For stationary storage at bus depots, CH_2 is most applied. HRS for bus applications are currently being developed [86] and refuelling time for buses in trials have found to be as low as 5–7 min [87].

CH_2 at 350 bar is currently used for onboard storage in buses [33]. In the UK, single-decker (Kite Hydroliner) and

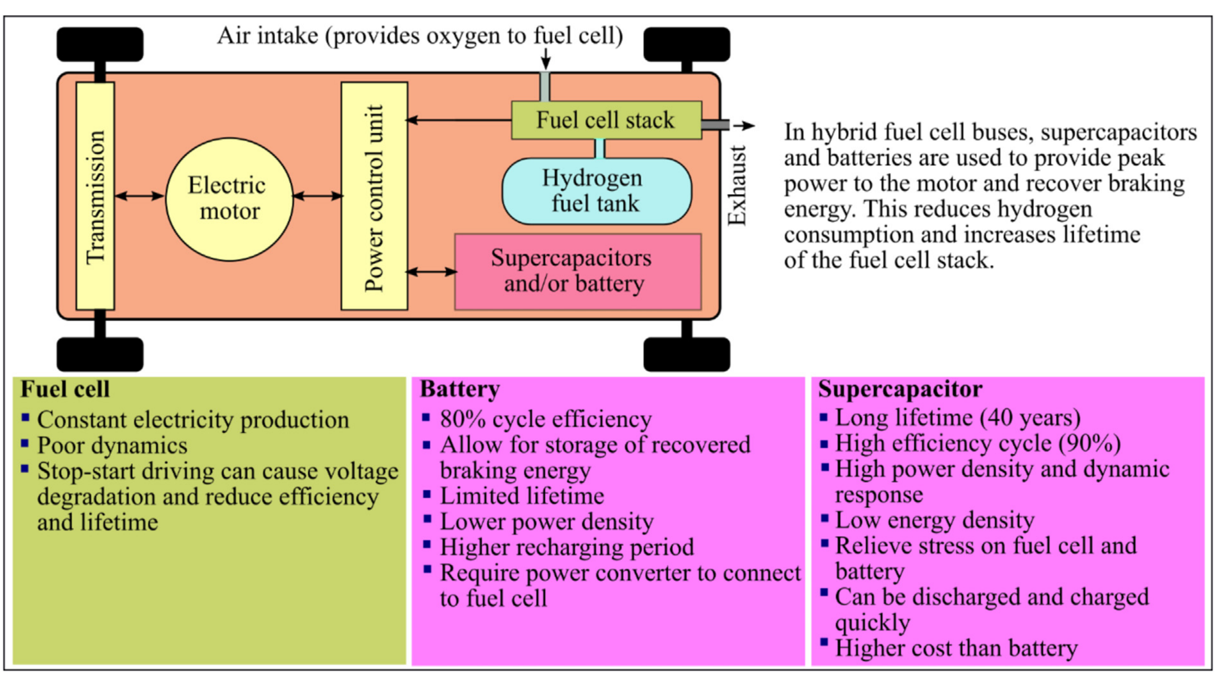


Fig. 6 – Schematics and characteristics of hybrid FC buses [16,79,83,84].

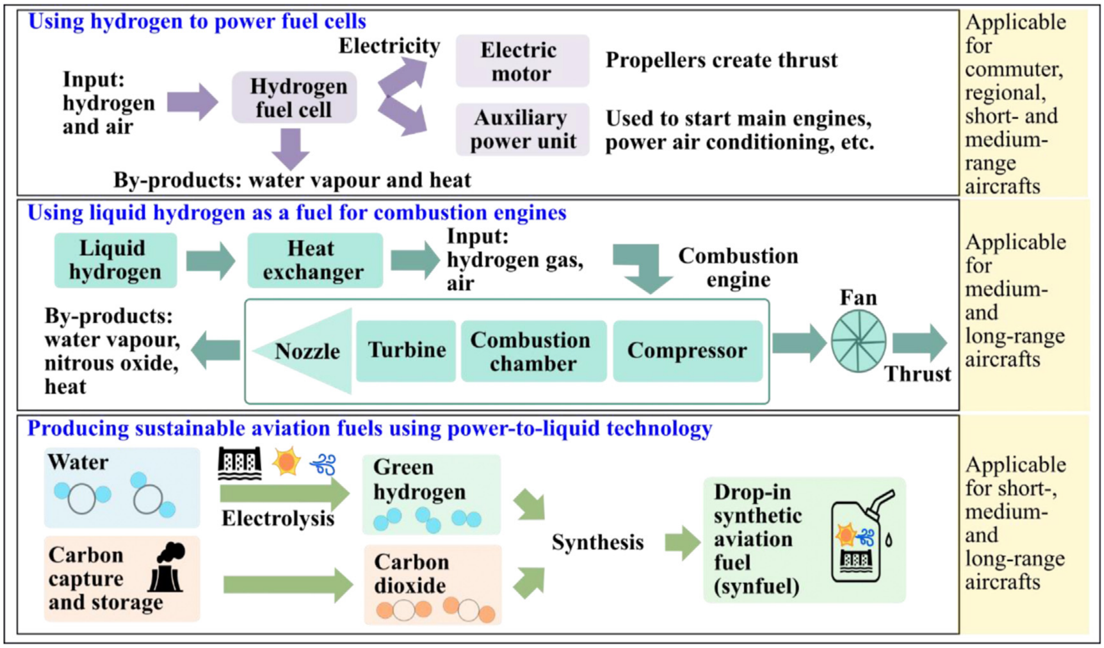


Fig. 7 – Three pathways to use hydrogen for aviation, adapted from Ref. [92].

double-decker (Streetdeck Hydroliner) hydrogen-fuelled buses manufactured by Wrightbus entered service in 2021. These buses were developed using a FC system made by Ballard with a Siemens drivetrain [88]. The Kite Hydroliner uses CH_2 at 350 bar (32–50 kg) to fuel a PEM FC with stack power of 70 kW and is integrated with a battery that can store up to 48 kW h [89], while the Streetdeck Hydroliner uses CH_2 at 350 bar (27 kg) to fuel a PEM FC with stack power of 85 kW in combination with a battery that can store up to 27.4 kW h [90]. CcH_2 storage could also be a suitable alternative for bus applications. Ahluwalia et al. [74] investigated the feasibility of using CcH_2 storage for bus application by evaluating its behaviour in terms of performance, stress and loss-free dormancy. Compared to the storage of CH_2 at 350 bar in buses, it was identified the potential to increase gravimetric (+91%) and volumetric (+175%) capacity and reduce cost material cost (−21%). For CcH2 onboard storage, LH_2 storage at the refuelling station is preferable as it can be almost directly used to refuel a cryo-compressed storage tank onboard a bus [65] and as a long storage period of CcH_2 is not ideal for practical application, converting LH_2 on-site at bus depots into CcH_2 is preferable to the alternative of transporting CcH_2 from a centralised production facility to bus depots. The use of liquid organic hydrogen carriers (LOHCs), such as formic acid (CH_2O_2), for bus application was also investigated [91]. After formic acid dehydrogenation, the hydrogen was used to power a 25 kW FC. The main identified issues were the use of highly stable and active dehydrogenation catalysts and the availability, purity and price of formic acid.

Aviation

Domestic aviation was responsible for 0.5% of the total domestic emissions of the transportation sector in the UK in 2020, while international aviation accounted for 11.8% of the total emissions of the transportation sector in the UK in 2020 [1]. As shown in Fig. 7, there are three pathways to use hydrogen for aviation purposes [92]: (i) using hydrogen to power FCs (for propulsive, auxiliary and/or emergency power use), (ii) using LH_2 as a fuel for combustion engines and (iii) producing sustainable aviation fuels from hydrogen, e.g. synthetic hydrocarbon fuels such as synthetic kerosene-like fuel (synfuel) using power-to-liquid methods and CCUS.

The electrical energy supplied by hydrogen FCs onboard an aircraft can be used to drive (i) electric motors for propulsion, (ii) auxiliary power units (APUs) for auxiliary applications, such as starting the main engines and supporting ground operations e.g. taxiing, lighting, de-icing, cabin air conditioning or heating, pressurising and providing passenger entertainment modules and (iii) emergency power units (EPUs), as a contingency plan. APUs and EPUs produce approximately 20% of airport ground emissions, making them key components to decarbonise. FCs show a good prospect of replacing traditional kerosene-fuelled, gas-turbine powered APUs or EPUs [93–95] in the short term (within the next 10 years). This is because (i) the efficiency of gas-turbine powered APUs, i.e. 30–40% during flight and 20% for ground operations, is lower than that of FCs and (ii) research and development on FCs show the potential to offer lower weights whilst achieving higher system efficiencies [93]. In addition, NOx emissions can be reduced by 100%, although the hydrogen FC pathway will release approximately 2.5 times more water vapour than the traditional kerosene-fuelled option [96]. Hydrogen FCs should be integrated with batteries onboard the aircraft, which will provide energy storage to enable fast loading and power peak shaving at the optimal size of the FC system [96]. This is possible in the short term provided that immediate infrastructural change is made to enable fast charging in airports. Among all FC technologies, alkaline, PEM, solid oxide, and direct methanol FCs have been identified as suitable for propulsion and the first three have been trialled. Currently, PEM FCs are the most preferable technology for aviation applications due to their relatively higher system gravimetric power densities, quiet and low temperature operation, although the high volumetric requirements for onboard hydrogen storage and high cost represent a limiting issue.

LH_2 has long been considered as a jet fuel since the 1970s [97] and investigated for airbuses in the 2000s [98]. The basic concept of a hydrogen combustion engine is much the same as current kerosene engines [99]: prior to entering the combustion chamber, LH_2 is heated by a heat exchanger using heat recovered from hot-spots in the jet engines e.g. exhaust, compressors, combustion chambers and turbines. This vaporises the hydrogen which is then combusted with oxygen in the engines to power turbines and fans, resulting in thrust to drive the aeroplane forwards as shown in Fig. 8. To accommodate differing properties of hydrogen combustion and operate at lower temperatures onboard aircraft, new engines must be designed or conventional engines must be modified. When compared to conventional kerosene engines, LH_2 powered engines can have ~64% lower specific fuel consumption and are expected to improve efficiency by 1–5% in creating thrust [100]. However, their efficiency is lower compared to the use of hydrogen to power FCs for propulsion, i.e., 40% as opposed to 45–50% [92]. NOx formation, which depends on residence time in the combustion chamber and temperature at which combustion takes place, is a key issue associated with combustion engines. If combustion engines burn hydrogen instead of kerosene, NOx emissions could be reduced by 50–80% (and release 2.5 times more water vapour, which is similar to the hydrogen FC pathway) [96]. With effective engine redesign which incorporates technologies such as micromix combustion, LH_2 powered engines operating at lower temperatures would only emit 0.005–0.0139% of NOx emissions of conventional aircraft [100,101]. Micromix combustion uses cross-flows to mix air and gaseous hydrogen to create "multiple miniaturized diffusion-type flames" and eliminate the risk of flashback [102]. Lean direct injection, which applies a similar principle as micromix combustion, has been explored but found to produce the same amount of NOx as conventional aircraft [101].

Liquid or cryogenic hydrogen storage onboard aircraft requires four times the volume for the same energy content provided by kerosene. This causes a design challenge as conventional aircraft store fuel in the wings, which is no longer possible for LH_2 due to the higher volume requirements. Novel aircraft designs as shown in Fig. 8(a) are necessary to meet these requirements. Changes to the aircraft structure are necessary to accommodate cryogenic fuel tanks and fuel lines onboard the aircraft. Blended wing body can increase fuel storage capacity in the wings, improve energy efficiency (31.5% and 40% using state-of-art technologies and future engine technologies, respectively) and reduce noise [103]. The company Airbus has recently announced the launch of their demonstration aircraft ZEROe, which uses the platform of the large wide-body airliner A380 to accommodate four hydrogen storage tanks that supply LH_2 to the ICE that is located along the rear fuselage. The aircraft could become available for commercial operation by 2035 [104]. The real benefits of LH_2 combustion in aviation come for long-range flights, in which the lower mass of LH_2 (compared to kerosene) can reduce 25% of the total weight of the aircraft (inclusive of the mass of the cryogenic storage system), leading to up to 11% improvement in efficiency [105,106]. Additionally, the lower specific fuel capacity of cryogenic engines could reduce fuel costs if cost parity between hydrogen and kerosene is achieved [100].

To accommodate the volume of liquid or cryogenic hydrogen required at airports, infrastructure needs to be developed. One option for hydrogen supply is from a centralised production facility where hydrogen is distributed via a national hydrogen grid. In this case, hydrogen would be piped either in gaseous or liquid form to the airport. If hydrogen is in gaseous form, airports must have the capacity to liquefy it. The large volume of hydrogen fuel required indicates that pipelines are the more logistically suitable option for gateway international airports because, if the whole quantity of fuel required is delivered by gas tube trailers or liquid tankers, there would be congestion that would make the process of delivery unfeasible. However, if gas tube trailers or liquid tankers are chosen for gaseous or LH_2 delivery to local, regional and gateway international airports, decoupling airport demand from the national grid may be a way to mitigate congestion issues with supply and demand at peak times. This requires on-site production of hydrogen at airports or specific production facilities located close to airports, whereas airports could store large quantities of hydrogen on-site at times of low demand to be used at times of high demand. In all cases, liquid tankers with cryogenic storage containers could deliver LH_2 to the aircraft as they do with kerosene currently. Alternatively, dedicated underground piping systems could deliver hydrogen directly to aircraft in refuelling bays. Airbus and Ariane group are currently working on the realisation of the first of a kind HRS refuelling LH_2 for aviation application, which is expected to be operational in 2025 and will be used to refuel the demonstrator ZEROe aircraft [107].

Moving to hydrogen fuel for aircraft propulsion is a long term goal. In the short term, airports could power ground support equipment, such as forklift trucks and baggage tugs, from stationary hydrogen FC technologies. Ground support equipment was responsible for the emission of ~6 Mt of CO_2 emissions in 2020 [20]. Examples of moving towards hydrogen technology to power fork-lift trucks or baggage tugs have been showcased by Amazon, Walmart and Plug Power [20], proving their cost competitiveness when compared to conventional battery or combustion engines powered by diesel, kerosene, natural gas etc. Whilst replacing or retrofitting ground support equipment to be powered by hydrogen FCs is viable, the low availability and relatively high cost of green hydrogen present the main challenges. Fig. 8(b) summarises changes required for the use of hydrogen technologies to supply propulsion and auxiliary power required by regional, short-, medium- and long-range aircraft, covering onboard power supply and hydrogen storage, aircraft design and hydrogen distribution and infrastructure.

Maritime

Domestic shipping was responsible for 5% of the total domestic emissions of the transportation sector in the UK for the

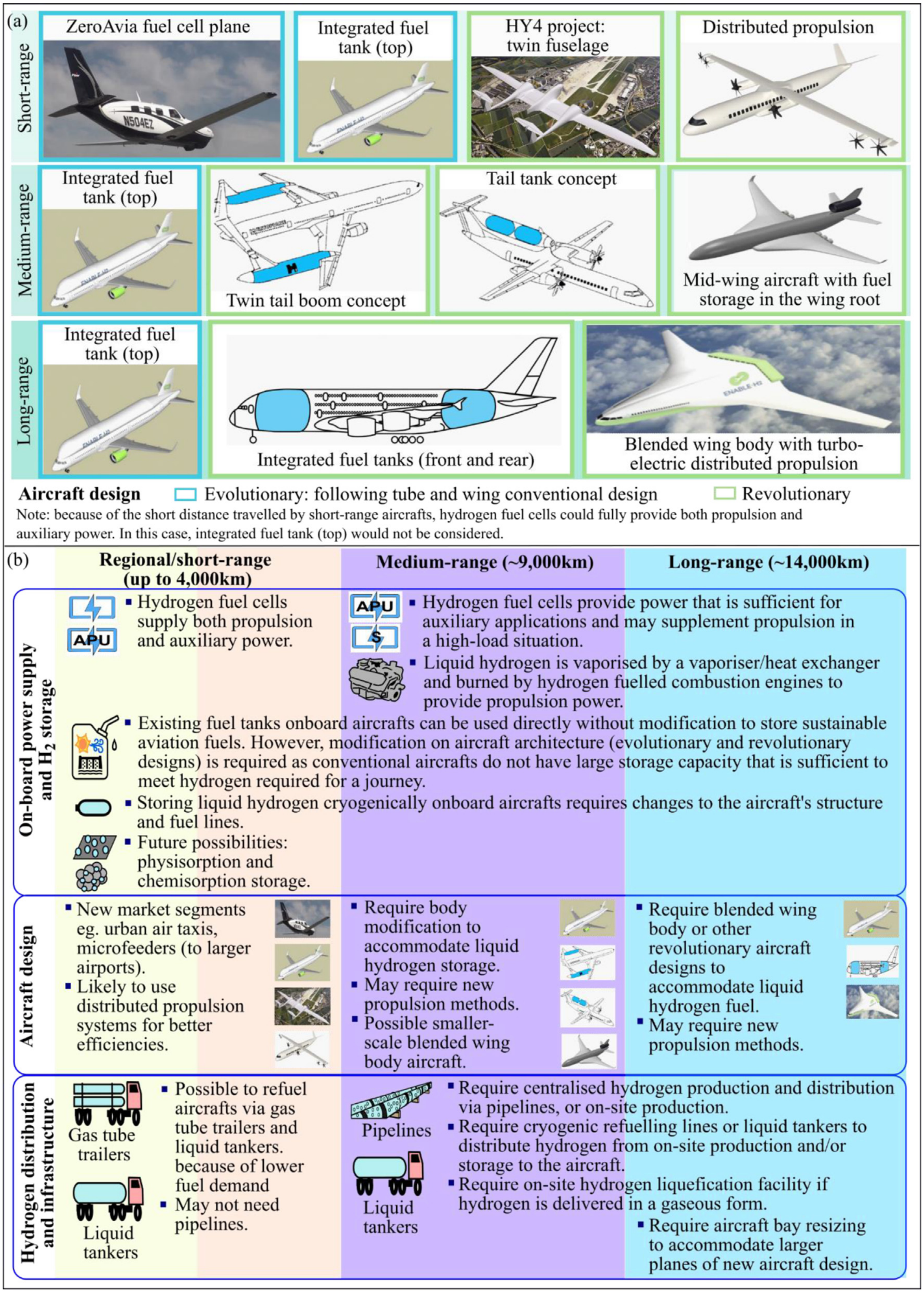


Fig. 8 – (a) Possible future evolutionary and revolutionary designs for aircraft bodies and (b) changes required for the use of hydrogen by regional, short-, medium- and long-range aircrafts. Images sourced from Refs. [99,105,108–110].

year 2020, while international shipping accounts for 5% of the total emissions of the transportation sector in the UK in 2020 [1]. Currently, hydrogen is not adopted for maritime commercial applications [111]. However, H_2ICEs, hydrogen-fuelled gas/steam turbines, and FCs are possible prime movers (which supply propulsion and/or auxiliary power) for seagoing vessels. As such, there are five possible hydrogen pathways for marine applications, as shown in Fig. 9.

Similar to the conventional diesel mechanical power plant, the H_2ICEs incorporated into a hydrogen-fuelled power system would be of different sizes where larger H_2ICEs operate to meet full power demand when the vessels transit at sea and smaller H_2ICEs are run to meet part loads when the vessels manoeuvre and wait in the harbours [113]. The excess waste heat from H_2ICEs could be recovered to vaporise LH_2 and allow using a smaller evaporator. H_2ICEs are the more viable option for international shipping until FC technology becomes more cost-competitive and has the capacity to enable long-distance transits [111]. As reported in Technologies that convert hydrogen fuel into power for transportation application, conventional gas turbines must be modified to accommodate the properties of hydrogen. This is necessary to retain the efficiency of gas turbines, the mass flow rates of air and exhaust as well as the flow rate of hydrogen for optimal

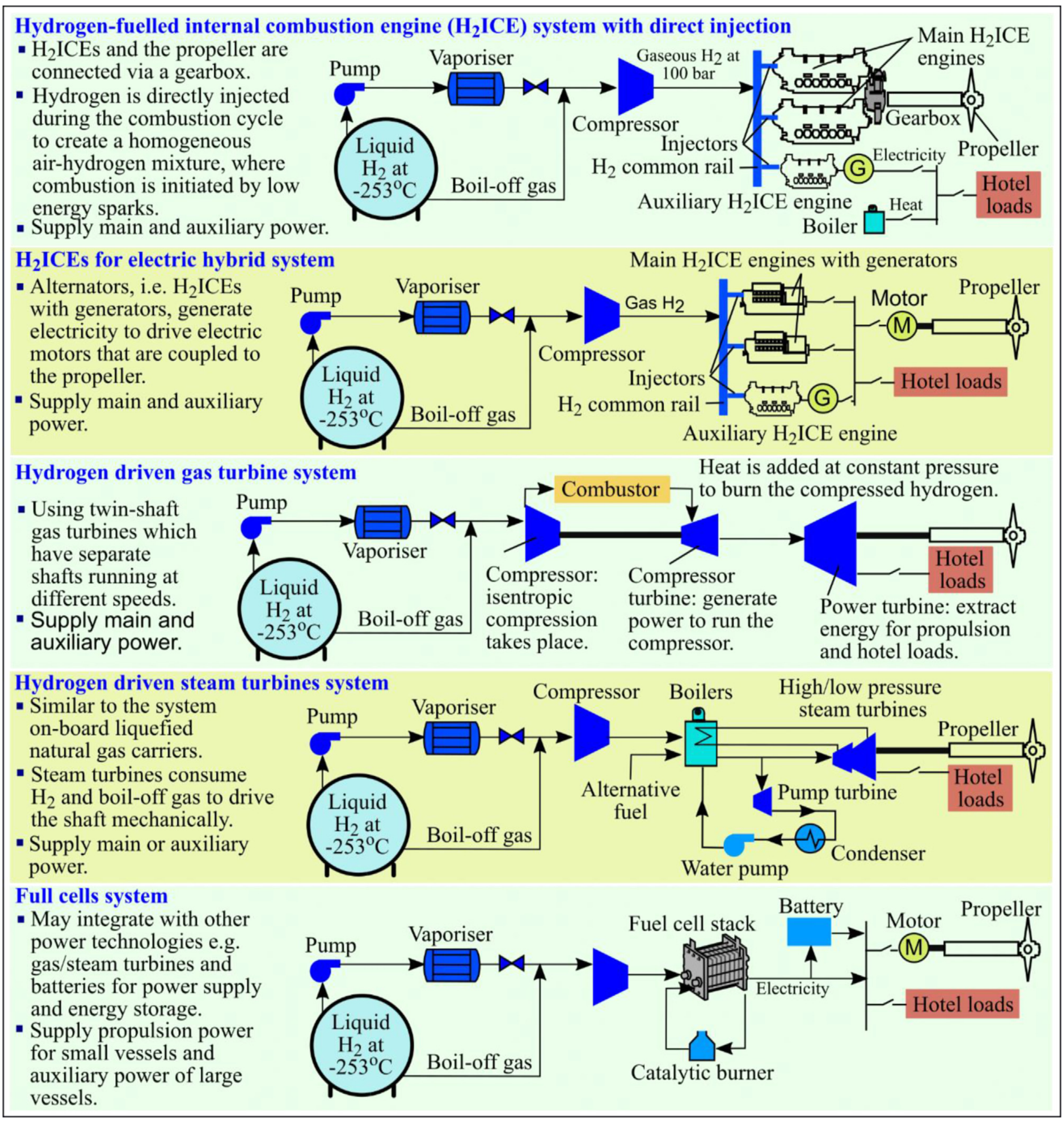


Fig. 9 – Five possible pathways to use hydrogen for maritime, based on [9,14,112].

performance when hydrogen is used as the fuel for gas turbines in the long term [13]. As evidenced by steam turbine power plants deployed by existing LNG carriers [114] which burn marine gasoil (MGO) and boil-off gas, steam turbines can be run using different fuels interchangeably [115]. As such, LH_2 and its boil-off gas could be adopted as marine fuel for future marine steam turbine systems, as showcased by the conceptual system configuration reported by Ahn et al. [14], which burned MGO, LH_2 and boil-off gas. Such a system could be adopted as a temporary solution to reduce CO_2 emissions [116], although new marine steam turbine power system designs capable to meet full power demand with zero carbon emissions are required towards decarbonisation of the maritime sector.

Compared to H_2ICEs, deploying large-scale FCs onboard seagoing vessels is more complex. This is because FC power plants involve the conversion of electrical energy into mechanical energy and are physically larger i.e., requiring almost double the space used by the H_2ICE alternative, which poses an issue for smaller vessels under 2 MW [117,118]. Currently, FC technology suits small vessels that commute along short routes with frequent visits to the same ports. Of all FC technologies, PEM and solid oxide FCs are mostly suitable for maritime use [119]. For PEM FCs used for maritime application, one of the challenges is that the exposition of the cathode to sea air could produce the degradation of the polymer membrane, which would require the pre-treatment of the air to remove sodium chloride (NaCl) vapours [120]. Alternatively, FCs can be used as APUs for maritime application, as in the case of the Viking Lady ship, which used a MC FC fuelled by LNG [120].

Currently, commercial application of hydrogen for maritime application is very rare and limited to small boats, for instance the Hydrogenesis Passenger Ferry (with a capacity of 2 crews and 12 passengers) which operates commercially in Bristol, UK [121]. Whilst there is no current commercial hydrogen application available for seagoing vessels [14], the general consensus is that hydrogen would have niche use for specific applications, such as roll-on roll-off passenger ferries and cruise vessels in the short to medium term, as evidenced by the two demonstration projects in the UK: (i) Hydrogen Diesel Injection in a Marine Environment (HyDIME) which demonstrated the production of hydrogen from wind and tidal power via electrolysis to run diesel and H_2ICE onboard a commercial ferry that operated in the Orkney Islands [122] and (ii) HySeas I–III which designed and demonstrated the operation of a hydrogen-electric hybrid system integrating PEM FCs and batteries for a passenger vessel that commuted between Kirkwall and Shapinsay in the Orkney Islands [123].

Existing commercial vessels would continue to operate for decades as the lifespan of seagoing vessels is 30 years on average. To reduce or eliminate their carbon footprint, a switch to hydrogen fuel can be achieved by retrofitting existing marine power plants. Such retrofit is expensive and requires the redesign of marine power systems onboard the vessels. Factors, such as hydrogen storage capacity onboard vessels, hydrogen infrastructure available for bunkering, the number of voyages and port calls and economic implications, should be considered during retrofit design, as suggested by Mao et al. [124]. An example of retrofitting is the Tranship II project, which aims to retrofit the Prince Madog ship with a hydrogen hybrid propulsion system that works in combination with a diesel-fuelled main engine [125]. For both retrofit and new-build system designs, onboard hydrogen storage requires remarkable space and presents a key challenge. The storage tanks can be spherical or cylindrical and made of aluminium alloy, steel or carbon fibres with thermal insulation (to minimise heat loss) where the storage pressure may range between 200 and 700 bar [10]. CH_2 stored in cylindrical tanks at high pressures is less advantageous for marine applications due to its smaller storage capacity (which requires refuelling of the storage tanks more frequently) and complexity in handling high pressures. On the other hand, when hydrogen is produced onboard and/or consumed at high flow rates with less frequency of refuelling over a longer storage period, storing LH_2 in spherical tanks at temperatures between −253 and −239 °C (i.e., the boiling and critical points of hydrogen) and atmospheric pressure is more beneficial, as this offers the possibility to store the maximum quantity of hydrogen at the minimum volume [112]. Due to the significant difference between ambient and hydrogen storage temperatures, the formation of hydrogen boil-off gas is unavoidable but can be minimised by thermal insulation of the storage tanks, which results in more weight (double to quadruple the weight of diesel tanks) [13]. The increased weight will be trivial for large ships with a deadweight tonnage (DWT) greater than 100,000 tonnes whose fuel tank weight is 1–2% of the DWT [126].

Fig. 10 illustrates technologies envisaged for hydrogen production, distribution, bunkering, onboard storage and power conversion for seagoing marine vessels in the short term. Hydrogen production facilities can be located either at an off-site location, on-site at the ports or onboard marine vessels. If hydrogen is produced off-site, it should locate as closer as possible to ports that provide bunkering services for a lower hydrogen transportation cost. When the distance between hydrogen production facilities and the ports is less than 300 km, gas tube trailers are more likely to be used unless the cost of hydrogen transportation via liquid tankers can offset that of hydrogen liquefaction [127]. At ports, hydrogen is stored in the form of a liquid or a gas, whereas LH_2 could make use of existing LNG infrastructure. Bunkering is a key issue for marine vessels that do not have the facility to produce hydrogen onboard [126]. When hydrogen is transferred to marine vessels during bunkering, the options are [128]: (i) delivering and storing hydrogen in a gaseous form, where the pressure of gaseous hydrogen is adjusted through compression or pressure balancing for higher or lower pressure respectively; (ii) delivering gaseous hydrogen and storing in a liquid form, which requires hydrogen liquefaction prior to storage and (iii) delivering and storing hydrogen it in a liquid form, which requires a cryogenic pump. When dealing with CH_2, it is critical to control the flow rate of hydrogen, as the heat that is released during adiabatic compression may soften the pressure vessels and lead to catastrophic failure [129]. At early stages of use of hydrogen for maritime application, the bunkering with both CH_2 and LH_2 will presumably be shore-to-ship, while ship-to-ship bunkering with LH_2 will be required in the future to accommodate the refuelling of large amounts of hydrogen needed by sea vessels in a reasonable time [130]. Sea

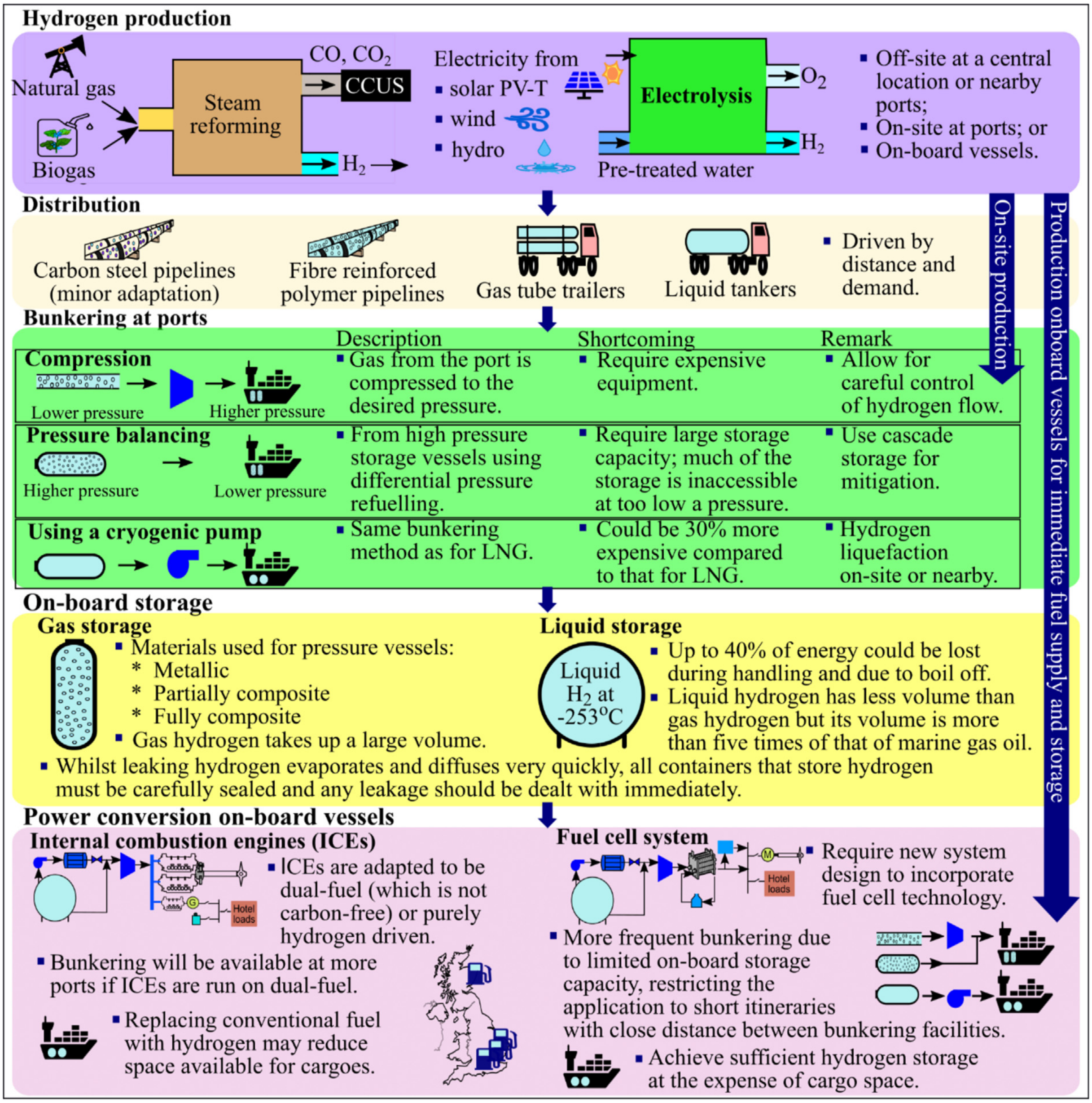


Fig. 10 – Hydrogen supply chain for marine application in the short and medium term.

vessels transiting very long distances and serving a multitude of ports will require bunkering services in multiple locations whereas those covering relatively short distances and returning to the same port on a daily basis can operate effectively utilising the bunkering service at one single port. Similar to the aviation case, hydrogen could also be used at ports for powered equipment, such as cranes, cargo trolleys, reach stakers, forklifts, terminal tractors and harbour tugs, as investigated in the project H2Ports [131].

Rail

The rail sector was responsible for 1.4% of the total domestic emissions of the transportation sector in the UK in 2020 [1]. Currently, 29% of the total railway fleets in the UK are run by diesel on both electrified and non-electrified lines [132], although rail represents the greenest form of transportation in the UK [76]. Trains powered by renewable electricity (on electrified lines) and hydrogen (on both electrified and non-electrified lines) are possible solutions to decarbonise railways in the UK with the aim of reducing rail emissions by 2040 [132], phasing out diesel trains from the rail network [133] and achieving net-zero-emission transport by 2050 [134].

Among rail applications, the decarbonisation of shunters and mainline locomotives has less potential due to the economic competitiveness offered by alternative transport strategies, such as delivery by truck [135]. For long distances, the application of hydrogen technology for locomotives that are used in the freight sector is constrained by the low volumetric energy density of hydrogen, which reduces the availability of space for payloads [136], although studies are currently conducted on investigating the potential use of LH_2 for locomotive

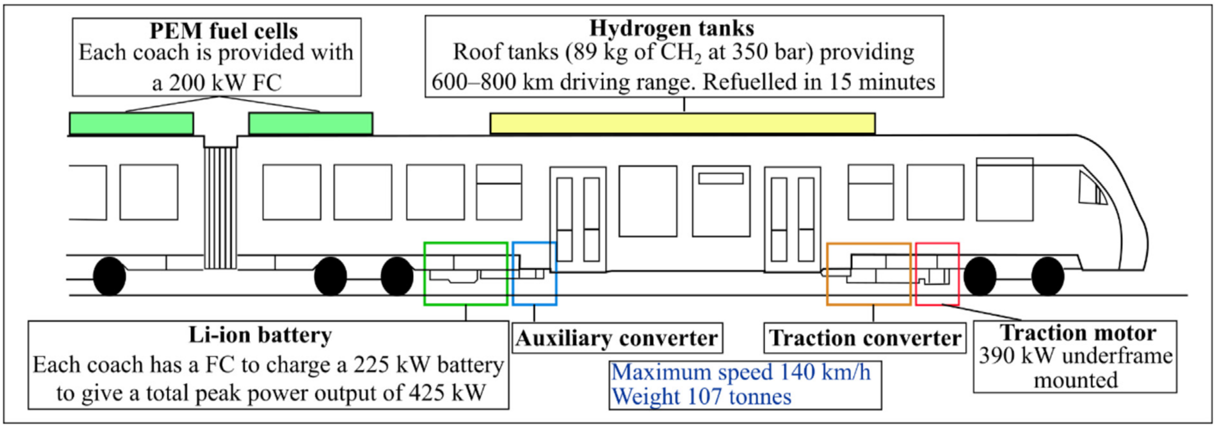


Fig. 11 – Schematics of a hydrogen FC hybrid train model (as designed for the Coradia iLint prototype by Alstom [136]).

application [137]. On the other hand, multiple-unit trains (or simply referred to as multiple units) powered by hydrogen FCs are considered to have the highest market penetration potential because their performance and costs are comparable with that of diesel trains, representing a more economical alternative to the electrification of the rail lines with limited frequency and demand [135]. As such, hybrid hydrogen FCs and batteries as substitutes for diesel to power traction motors and auxiliaries in multiple-unit trains were investigated [138] and are seen as one of the most promising medium- and long-term strategies to further advance the decarbonisation of the UK rail system, in particular when electrification is too disruptive or expensive [139]. Fig. 11 shows the schematics of the prototype of the hydrogen FC hybrid train Coradia iLint by Alstom [136].

Using the current state-of-the-art technology, the power generated onboard hydrogen-fuelled trains will not be sufficient to enable (i) freight services and (ii) long-range services at high speed with high acceleration. The power management in a FC hybrid train is a primary factor for optimal operation, which varies with the amplitude and duration of power demand at different operational phases such as acceleration and coasting [140]. During acceleration, the power output of FCs is primarily used to operate the traction inverter and the auxiliary converter, which supply the power demand onboard the train. Lithium nickel manganese cobalt oxide (Li-NMC) batteries can be used for acceleration boost. During short acceleration with limited power demand, Li-ion batteries are used to power the train. During coasting, FCs recharge Li-ion batteries and power the auxiliary converter. Once batteries are charged, the power output of FCs is reduced to power the auxiliary converter only.

The first hydrogen-fuelled train prototype used hydrogen stored with metal hydrides to power a 17 kW FC integrated with a battery in a mining locomotive. MHs were chosen because of their low operating pressure, compact sizing and high efficiency [141]. Their heavy weight was considered a less important issue for railroad applications [142]. However, heat exchange during hydrogen absorption and desorption is a key engineering issue for rail application as MHs are poor in heat transfer and require (i) heat to release hydrogen and (ii) a heat exchange agent to store the heat released during hydrogen absorption. Currently, CH_2 stored at 350 bars in Type III or IV pressure vessels on the rooftop of the train is the principal storage design for railroad applications [138]. However, the loading gauge of UK trains is smaller due to the low height of the Victorian tunnels [136], resulting in a safety issue for the design for the UK market. To overcome this challenge, hydrogen could be stored in the motor coach (reducing the space available in the coach by 10–15% [136]) or underneath the train (as demonstrated by the HydroFLEX FC train [143]). A few studies were conducted in the UK on hydrogen-fuelled trains, such as the HydroFLEX FC train, which was developed as a joint venture between Birmingham University, Porterbrook and other manufacturing companies, such as Ballard Fuel Cell, by retrofitting a diesel Class 319 multiple-unit train with hydrogen FC system and batteries [144]. Operational trials on the mainline railway were conducted in 2020. In the next phase, it is planned to demonstrate the realisation of a "bi-mode" train configuration, which will operate in both electrified and non-electrified routes using overhead electrical wires and hydrogen FCs, respectively [135]. By 2023, the technology will also be ready to convert currently operating trains to hydrogen-fuelled ones [76]. In addition, Arcola Energy developed in collaboration with the Consortium of Rail Industry Leaders a hydrogen train for the Scottish market by integrating the FC technology into the ScotRail Class 314 passenger train [145]. The train was demonstrated and tested at COP26 in November 2021. Recently, LH_2 fuelled trains were also investigated for locomotive application [137]. The investigated locomotive would be able to have a maximum speed of 150 km/h for a driving range of 1000 km and a reduction of 20% in refuelling times compared to CH_2 at 700 bar [146], although multiple research areas to address for the development of LH_2 fuelled locomotives were identified (optimal design of vessels and baffles for the reduction of boil-off gases, optimal location and method of refilling, materials and arrangement of the storage vessel, etc.) [137].

Rail transport presents a high and approximately constant energy demand, which would be beneficial for the realisation of cost-effective HRS [67]. In the study from Funez Guerra et al. [138], it was reported that a HRS would require a daily capacity of 4000 kg of hydrogen to refuel 20 Coradia iLint trains (i.e., to carry 200 kg hydrogen onboard each train at 350 bar). Mobile and temporary HRSs (i.e., trucks and containerised stations with storage and compression equipment) have been developed and applied to refuel hydrogen trains with CH_2 at 350 bar, whereas the first large scale HRS for multiple-unit trains from Linde group was inaugurated in Germany in 2022 and supply 1600 kg of hydrogen per day, refuelling 14 regional multiple-unit trains [147]. The identification of the optimal configuration of the hydrogen train for different rail applications (for example CH_2 for multiple unit trains and LH_2 for locomotives), will also impact the hydrogen supply chain for train refuelling and the configuration of the HRSs. As previously described, the storage of CH_2 within the motor coach presents a drawback due to the large volume required, which reduces space available for passengers in multiple-unit trains and payloads in locomotives, respectively [136]. The configurations of the storage system and the components will be optimised according to the driving range and the operation of a train to optimise the storage and use of hydrogen [148].

Critical analysis and future research areas of hydrogen-fuelled transportation modes

Based on the analysis of the literature review of the hydrogen-fuelled transportation modes, Table 3 was elaborated to compare the current state of development and the characteristics in terms of propulsion, storage and supply chain and highlight the main differences. In addition, Table 4 illustrates the main achievement, missing gaps/priorities and benefits of the different types of hydrogen-fuelled transportation modes. Based on the critical review of hydrogen-fuelled transportation modes, Tables 5 and 6 were produced to illustrate future specific and common research areas for the different transportation modes, respectively.

Currently, commercial hydrogen models are available on the market but the limited demand. Research is required to increase performance, reduce capital and operating costs for the vehicles and the refilling together with the roll-out of the refuelling infrastructure. In particular, the development of large HRSs is considered key for the rollout of hydrogen vehicles due to the strong relationship identified between the availability of HRSs and the use of hydrogen fuel vehicles [16]. The intervention of the UK government is required to set deployment targets for HRSs, develop Standards and ensure a sufficient match between demand and supply and avoid under-utilisation of HRSs [149]. To increase the power density and the power response of FCs (compared to batteries and conventional ICEs), future hydrogen-fuelled requires a higher level of integration with ESSs [25]. Supercapacitors have the potential to improve the power of the FC vehicle due to their higher power density, efficiency and longevity compared to batteries. However, research is required to develop an advanced control system for the optimisation of power management [25]. For H_2ICE vehicles, future research will investigate the fuel injection equipment and operating strategies [150]. The use of PFI injection systems in combination with batteries is considered the best option for H_2ICE vehicles in the short-term, provided that research is conducted to modify existing engines, increase the power density and efficiency of the vehicle, detect and mitigate pre-ignition and knock and develop a better understanding of the kinetics of hydrogen mixed with another fuel (for dual fuel application) [150]. Future research in the medium-term will investigate the advancement of DI (spark ignition or high-pressure), which compared to PFI will present the benefits of higher power density, efficiency and transient response, no risk of back-fire and reduced modifications required to the engine, and on strategies to achieve optimised design, high performance and low NOx emissions (which could be achieved by injecting water in the combustion chamber) [150].

Future research on hydrogen-fuelled trucks will focus on improvement in performance, durability, fuel efficiency and lifetime of hydrogen FCs. Improvements in hydrogen storage capacity are required to increase the driving range and the payload of the truck. As such, the use of strategies alternative for storage, such as sLH_2 and CcH_2, will be realised in the medium-term. The definition of the optimal storage strategy and chassis design to allow more flexibility in the placement of the components onboard trucks is required. For H_2ICEs, most of the current research is on light-duty vehicles. For the application of the technology in trucks, new design, control and calibration of H_2ICEs are required to ensure more durability and high performance over conventional duty cycles for trucks [50]. If dual-fuel engines are adopted by hydrogen-fuelled trucks in the interim, improvement in fuel injection timing, engine speed and emission control would make them more advantageous. HRSs for truck application would have to be designed to (i) ensure high flow, refuelling capacity and reliability and (ii) match hydrogen refuelling characteristics with truck application e.g. shorter hydrogen refuelling time and adjustment of the hydrogen refuelling to the driving range. In addition, the development of truck-specific refuelling Standards is required to account for (i) CH_2 700 bar compression, (ii) refuelling with LH_2 (for sLH_2 and CcH_2 onboard storage) and (iii) a further increase in temperature during compression because of the higher flow of hydrogen required by trucks. Hydrogen-fuelled buses present similar challenges to trucks. As such, an improvement in terms of durability, fuel efficiency and durability is required to increase the performance in the short to medium term and further ease the roll-out of hydrogen-fuelled buses. As opposed to trucks, buses have a start-stop driving duty cycle. As such, the realisation of the optimal integration of FC with the EES (battery or supercapacitor) should be identified and defined based on the bus application and driving range [151]. The development of the optimal design for different types of hydrogen-fuelled buses, such as coaches and minibuses, is required for further roll-out of hydrogen-fuelled buses.

To develop the use of hydrogen in the aviation sector, power technologies (i.e., FCs, combustion engines and hybrid power systems) must be modified and advanced together with new aircraft designs, fuel storage and supply systems onboard. Integration of the necessary systems and tubing has not been implemented yet and must be realised in the medium term [152]. The use of hydrogen instead of kerosene for aviation will result in an increase in water vapour emissions. Research should investigate the effect of the increase in water vapour emissions due to the use of hydrogen-fuelled aircrafts on the formation of contrail and identify strategies for

Table 3 – Current development status, characteristics and remarks about supply chain of hydrogen-fuelled transportation modes.

	Technology	Development status	Characteristics (propulsion and storage)	Remarks about supply chain
Cars	FC	Several pilots, commercialised with limited market	• PEM FC stack power 64–128 kW, Li-ion battery to assist power, storage of 5.6 kg of CH_2 in 1 tank at 700 bar (for Toyota Mirai) [33]	• Depending on the production strategy (centralised vs. on-site). CH_2 at 700 bar usually stored with on-site supply tanks [65]
	H_2ICE	Demonstration	• Dual-fuel or only hydrogen demonstration models developed (BMW, Mazda, Toyota Corolla), storage of CH_2 or LH_2	• H_2ICE vehicles could benefit of the same supply chain used for FC vehicles • Lower refuelling cost due to purity required
Truck	FC	Demonstration (serial production announced)	• PEM FC: stack power 80–226 kW [33] • Storage: CH_2 at 350–700 bar (32–80 kg) [33] or sLH_2 (Daimler). Potential future use of CcH_2 storage • Battery used to assist power (capacity 12–250 kW h) [33]	• Depending on the production strategy (centralised vs. on-site). Use of sLH_2 or CcH_2 would require LH_2 supply chain • Refuelling of large amount of CH_2 at 700 bar requires pre-cooling
	H_2ICE	Demonstration (serial production announced)	• Dual-fuel mode: reconversion of engines to accommodate use of hydrogen and alternative fuels • CH_2 stored in twin fuel tanks at 700 bar (40 kg) to power H_2ICE (6.7 or 15 L) (Cummins from 2027) [73]	• H_2ICE truck could benefit of the same supply chain used for FC trucks • Lower refuelling cost due to purity required
Buses	Hybrid (FC and battery)	Commercialised	• PEM FC stack power 75–150 kW, storage of CH_2 in 4–9 tanks at 350 bar, battery power output: 100–250 kW (Hydroliner single- or double-decker) [88,90] • Potential future use of CcH_2 storage	• Depending on the production strategy (centralised vs. on-site). CcH_2 would require LH_2 supply chain • HRS could be located at the bus depot
Aviation	Hybrid (FC and battery), H_2ICE, APU/EPU	Demonstration	• Small range: (i) small airplane: FC used for propulsion • Long range: H_2ICE located along the rear fuselage, 4 storage tanks of LH_2 [104] • APU/EPU: the use of solid oxide FCs was investigated and considered as promising	• Hydrogen distributed via pipelines because the large quantity required could create traffic congestion via trailer • Specific production facility located close to the airport would be needed
Shipping	Hybrid (FC and battery), H_2ICE, APU/EPU	Demonstration	• Smaller vessels: FC stack power 200 kW • Larger vessels: (i) Hydroville: dual fuel (12 hydrogen tanks at 200 bar pressure and 2 diesel fuel tanks) [170], (ii) HySeas III: PEM FC stack power 600 kW, storage of CH_2 at 350 bar (600 kg), and Li-ion battery (768 kW h) [123] • The use MC FC as APU was investigated	• Specific production facility located close to the port would be needed • Long times required for bunkering (ship-to-ship bunkering with LH_2 preferred over shore-to-shore bunkering with CH_2 or LH_2)
Rail	Hybrid (FC and battery)	Demonstration	• Hydroflex: bi-mode train, PEM FC stack power 400 kW storage of CH_2 at 350 bar (4 tanks with capacity of 20 kg) located underneath the train, Li-ion battery (400 kW) [146] • More investigation required for use of LH_2 in locomotives	• Depending on the production strategy (centralised vs. on-site). • HRS could be located at the train depot

mitigation [153]. Alternative fuels, such as synthetic kerosene-like fuels, could also be used for aircrafts in the short- and medium-term. Using power-to-liquid technology, green hydrogen and CO or CO_2 captured are used to produce synthetic jet fuels that are similar to kerosene. The produced synthetic jet fuels are to be blended with traditional kerosene (up to 50%) and will be compatible with current infrastructure, aircraft and combustion engines without requiring any modification [154]. In comparison to hydrogen FCs and H_2ICEs, this pathway offers lower climate impact i.e., 30–60% reduction (although there is no significant difference in NOx and water vapour emissions) [96]. The main barriers to sustainable aviation fuels from hydrogen are the current high cost and low scale production (which require slight modifications). Future production of sustainable aviation fuels from hydrogen could achieve 14.5–30.9 Mt per year, corresponding to 4–8% of global aviation use by 2035 [154]. Most countries are likely to start with short-haul flights, e.g. commuters, regional and short-range aircraft, whereas the aviation industry in some countries may take a longer timeframe to switch from kerosene to hydrogen. To achieve this, future research should look at developing airport infrastructure for the use of hydrogen and developing a technology for the refilling of aircrafts on runways [152]. The operation of hydrogen-fuelled aircrafts relies on facilities and ground support equipment in the airport, which necessitates infrastructure refurbishment. Significant steps towards the decarbonisation of the aviation industry can be obtained by using hydrogen for ground support equipment at airports, such as engine start units, cargo loaders, pushback trucks, baggage tractors, trolleys, etc. [155]. The use of direct methanol FCs in forklifts has shown promising results [156], provided that the increase in FC performance and reduction in cost are achieved in the future. Forklifts could also be powered by hydrogen stored in MHs,

Table 4 – Commercial status, missing gaps or priorities, and potential benefits of hydrogen-fuelled transportation modes.

	Technology	Commercial status	Missing gaps/priorities	Benefits
Cars	FC	Commercial vehicles available on the market	• High requirements for hydrogen purity • Cost decrease: reduction of hydrogen price and refuelling cost, use of subsidies • Development of refuelling infrastructure and HRS	• Higher fuel conversion efficiency • Short refuelling time
	H_2ICE	Demonstration models	• Investigation of optimal combustion for PFI and DI • Adaptation to wide flammability limits and low minimum ignition energy of hydrogen • Reduction of NOx emissions	• Take advantage of traditional gas engines • Potential for dual-fuel operation
Trucks	FC	Commercial vehicles available on the market storing CH_2 at 350 bar; plans for future development of trucks using CH_2 at 700 bar, sLH_2 and CcH_2	• Design of optimised chassis, increased FC performance and higher hydrogen storage capacity • Definition of optimal strategy for H_2 storage in trucks • CH_2: large cost of Type IV cylinders for storage at 700 bar • Realisation of HRSs supplying large volumes of hydrogen with high flow rate • Development of truck refuelling Standards for CH_2 at 700 bar to accommodate large volumes of hydrogen required	• High potential for decarbonisation of heavy-duty sector • Lower difference in capital cost between conventional and hydrogen-fuelled trucks • Short refuelling time • Return-to-base operation eases the development of HRS for truck refuelling
	H_2ICE	Retrofitted dual-fuel ICE trucks, only hydrogen truck from 2027	• Improvement of performance of DI spark ignition and development of high-pressure DI • Reduction of NOx emissions	• Lower risk due to existing technology and mature supply chain • Lower capital cost in the short- and medium-term with little modification to the vehicle
Buses	Hybrid (FC and battery)	Commercial vehicles available on the market (one- or two-deck) storing CH_2 at 350 bar	• Optimal design of hydrogen hybrid buses (integration with batteries or supercapacitors) • Realisation of HRSs supplying large volumes of hydrogen with high flow rate	• The use of ESS allows operating near peak efficiency and increasing fuel efficiency • Back-to-back operation and high utilisation rates predictable demand and high utilisation rates for HRSs
Aviation	Hybrid (FC and battery), H_2ICE, APU/EPU	Short-range demonstration models	• New aircraft design • Diversification of airplane design (use of hydrogen FCs for short range and H_2ICE for long range) could limit infrastructure development • Handling and safety regulations of LH_2 • Development of refuelling infrastructure and Standards. Potential airport congestion due to distribution of large volumes of hydrogen	• LH_2 investigated for aerospace application • Low weight is advantage for long haul flights, no limitations in range • Lower noise • Use of hydrogen for power ground support equipment (forklifts, baggage tugs, etc.)
Maritime	Hybrid (FC and battery), H_2ICE, APU/EPU	Short-range demonstration models	• New steam turbine power system design • PEM FC: degradation of polymer membrane due to the exposition of the cathode to sea air • Definition of optimal strategy for bunkering • Development of refuelling infrastructure and Standards	• High potential for use of hydrogen in ICEs (in combination with other fuels or as only fuel) • Use of hydrogen for power ground support equipment (forklifts, baggage tugs, etc.)

Table 4 – (*continued*)

	Technology	Commercial status	Missing gaps/priorities	Benefits
Rail	Hybrid (FC and battery)	Demonstration	• Onboard storage system: the fuel tanks need to be designed for UK market • FCs would require replacement before the end of the lifespan of hydrogen-fuelled trains • Low maximum speed (160–170 km/h) • Locomotives require high power that could only be provide by more efficient storage • Development of Standards	• Flexible use in both electrified and non-electrified lines and resilient to network-wide disruption • Flexible levels of hybridisation to increase the performance and driving range • Refuelling in less than 20 min for more than 18 h of operation (i.e. less downtime) • No operational constraints

where the large weight of the storage material is a benefit in forklifts because it counterbalances the vehicle and increases its stability. The feasibility of using MHs in FC forklifts and the development of HRS with integrated MH compression were recently investigated in a prototype [157].

For seagoing vessels, future research in the short and medium term should focus on the advancement in power system design, energy management and naval architecture. It is necessary to develop hydrogen-fuelled prime movers (i.e., ICEs, gas turbines, steam turbines and/or FCs) in combination with energy storage (batteries) and technologies that can harness renewable energy, such as Flettner rotors, which use as propulsion system in LH_2 tankers was theoretically investigated by Alkhaledi et al. [158]. In addition, waste heat recovery and emission control strategies with optimal space utilisation onboard vessels are required. In short to medium terms, onboard storage capacity should be extended to offer larger storage volumes over longer periods safely with minimal technical issues (e.g., sloshing effects [126], heat or hydrogen losses and impurities). Such research and development may include designing better storage tanks or reactors for onboard dehydrogenation using cheaper and novel materials with improved insulation and enhanced heat management. This is crucial to supply fuel required by international shipping, which usually transits long distances over days before arriving at the next port of call for unloading, loading and bunkering. The use of alternative fuels, such as NH_3 and LOHC, is seen as potentially feasible in the maritime industry in the medium- and long-term. Compared to fuels used for maritime applications, NH_3 has huge potential because of (i) its relatively high energy density, (ii) being sulphur-free (i.e. no need for aftertreatment), (iii) its potential of being used both as fuel and cargo and (iv) protocols are already in place for safety and handling of NH_3 as cargo [159]. However, significant advancements to increase the performance of ICEs running on NH_3 and limit NOx are required to stimulate its use as maritime fuel. The use of LOHCs in sea vessels has also been recently investigated and showed promising results for maritime application [160], provided that future research will (i) identify more efficient heat management during hydrogenation, (ii) realise integration between the waste heat of high-temperature FCs and hydrogen dehydrogenation process and (iii) develop new catalysts. Future research should also look at planning and developing port infrastructure to accommodate the use of hydrogen and facilitate ship bunkering services, considering space reallocation and realisation of new facilities required for handling, storing and releasing LH_2 and CH_2 in large quantities at ports. For bunkering, the use of cassette-type fuel systems, which store hydrogen in a container that is then loaded on the ship, could be realised in the future because it would allow reducing the refuelling time, although this strategy would be more suitable for small ships [126]. As for aviation, the use of hydrogen-powered equipment, such as cranes, forklifts, cargo trolleys and harbour tugs, should be applied in the future to decarbonise the maritime sector.

Future research for hydrogen-fuelled trains should focus on the optimal design, analysis and optimisation of the rail powertrain, including the definition of the optimal design for the UK market. FC technology for rail application should focus on the increase of the power output of FCs and their durability (otherwise FCs would require replacement before the end of the lifespan of hydrogen-fuelled trains) by using alternative materials. Current hydrogen-fuelled trains are not high-speed and cannot ensure a long driving range with a large payload if used for freight train application. Alternative strategies to increase the power density of stored hydrogen, such as LH_2 and CcH_2, are, as such required to further advance the use of hydrogen in the rail environment, in particular for the development of hydrogen-fuelled locomotives or shunter units [137]. In addition, the development of bi-mode trains (running either using electrified lines or hydrogen) should be developed to increase the flexibility of operation [148].

Regarding common areas of research to stimulate the development of hydrogen-fuelled transportation, an improvement in all aspects of the supply chain (hydrogen production, purification, storage and distribution) is required.

The current cost of hydrogen is one of the main challenges that limit the deployment of hydrogen-fuelled vehicles. To accommodate the large demand that will be required for the development of hydrogen-fuelled transportation, it is required to increase renewable hydrogen production via electrolysis. Centralised and on-site zero-carbon hydrogen production would start to flourish in the short term together with the growth in renewable energy production, where the most viable choices are solar and wind. For large-scale renewable production, improvement in energy efficiency and size is targeted for electrolysers by 2030. PEM electrolysers are expected to dominate commercial markets in the short term because of (i) their flexible start/stop procedure making them the most suitable option when powered by intermittent renewable sources [161] and (ii) their capacity to produce hydrogen at higher pressures, which reduces the extra

Table 5 – Future specific research areas of hydrogen-fuelled transportation modes.

	Research area	Specific research	S[a]
Cars	Advancement and optimal design of FCs	• Improve efficiency, volume power density and performance and reduce stack dimensions	I/A
		• Increase durability (by investigating the effect of design and operation of membrane electrode assembly, bipolar plates and sealing materials and managing thermal heat from FCs)	I/A
		• Improve operation in sub-freezing conditions (as low as −40 °C) to avoid cell degradation and performance decay	I/A
		• Optimisation of the integration of EES (batteries/supercapacitors) and realisation of advanced control system	I/A
		• Use of metal supported solid oxide FCs to allow the use of alternative fuels, such as ethanol and methanol	I/A
	Advancement in H_2ICEs	• Advance fuel injection equipment, injection strategy and combustion performance	I/A
		• Identify optimal operation and limit NOx emissions	I/A
Trucks	Advancement and optimal design of hydrogen FCs	• Develop innovative materials and strategies to improve FC durability, efficiency and lifetime by using high activity catalysts/stable ionomers/membranes under dry conditions and reducing fuel starvation and cell reversal	I/A
		• Identify optimal position for storage tanks	I
		• Improve cold start performance and FC cooling	I/A
		• Improve electrification of the power system through optimal use of batteries to idle FC stack during periods of low power demand	I
		• Development of alternative strategies for hydrogen storage onboard trucks, i.e. sLH_2 or CcH_2	I/A
	Advancement in H_2ICEs	• Advance dual-fuel diesel-hydrogen trucks through operating strategies (engine speed & fuel injection timing)	I/A
		• Combustion and emission control, control and engine calibration	I/A
		• Limit NOx emissions	I/A
		• Develop H_2ICE trucks with new designs and advance DI H2ICEs (spark ignition DI vs. high-pressure DI)	I/A
Buses	Advancement and optimal design of hybrid FC buses	• Develop innovative materials and strategies to improve FC durability, efficiency and lifetime targets	I/A
		• Identify optimal position for storage tanks onboard buses	I
		• Development of alternative strategies for hydrogen storage onboard trucks, i.e. CcH_2	I/A
		• Develop optimal design for hybrid buses, hydrogen-fuelled coaches and minibuses	I
Aviation	FCs for aviation application	• Advance FC technology to boost efficiency with increased power density, enlarged capacity to provide propulsion and power all non-propulsion systems onboard	I/A
		• Extended lifetime at lower cost under extreme conditions e.g. low temperature, low pressure and low gravity	I/A
		• Mitigate water vapour emission	I/A
	Combustion engines (e.g. modified gas turbines)	• Required modifications: combustion chambers, turbine blades, compressor air pre-cooling, compressor cooling, hydrogen cooling, reheating and vaporisation (using heat exchangers for fuel preparation) and strategies to mitigate water vapour emission	I/A
		• New designs: novel combustors with heat exchangers to reduce NOx emissions, new power cycles and new airframe to ignite the hydrogen-air mixture more effectively	I/A
		• Hybrid power systems for aviation application: integrate new/modified combustion engines and/or FCs with batteries	I/A
	Design of hydrogen-fuelled aircrafts	• New or modified designs: (i) develop new structure and aerodynamic design, (ii) modify current configuration e.g. increase fuselage diameter and (iii) retrofit existing systems cost-effectively for hydrogen use	I/A
	Hydrogen storage and supply onboard aircraft	• Enable large-scale storage: (i) design well-insulated storage tank, (ii) develop advanced materials e.g. lightweight composite and polymer with improved durability and easy to access for maintenance and (iii) locate fuel tanks strategically	I/A
		• Design hydrogen fuel supply and control systems that withstand a wide range of temperatures: (i) new fuel lines design, fitting and system, (ii) efficient operation of fuel pumps and heat exchangers, (iii) fuel warming before use and (iv) reliable, highly sensitive leak detection sensors	I/A
	Airport infrastructure development	• Design and operate pipelines, trucks and storage tanks with excellent insulation to enable large-scale hydrogen supply and refuel the aircraft as well as ground support equipment (e.g. air conditioning unit, trolleys, baggage tractors, cargo loaders and stairs for passengers)	G/I/A

Table 5 – (continued)

	Research area	Specific research	S[a]
Maritime	Advance power systems for propulsion and auxiliary demand	• Design and energy management of power systems: (i) identification of best configuration: driven by H_2ICEs, gas or steam turbines, FCs or hybrid or integrated with batteries and renewable sources, (ii) emission analysis and control, (iii) strategies to achieve zero emissions (including NOx) and (iv) utilise boil-off gases for propulsion (if the power system is driven by cryogenic hydrogen)	I/A
		• New architecture: for optimal space allocation to accommodate propulsion systems, hydrogen storage, cargoes and hotel rooms	I/A
	Hydrogen storage onboard sea-going ships	• Identification of best strategy for storage: (i) LH_2: better storage tank design with super insulation materials to avoid sloshing effects and lower energy losses and boil-off, (ii) CH_2: cheaper pressure vessels; high pressure handling, (iii) NH_3: onboard purification system of hydrogen gas to remove impurities and (iv) LOHCs: research to conduct on more efficient heat management during hydrogenation; new catalysts and lower energy requirements for hydrogen release and integration with high-temperature FCs where waste heat is recovered to release hydrogen from LOHCs	I/A
		• Reactor designs for onboard dehydrogenation: (i) novel membrane material and better design of membrane reactors to offer lower cost, improve stability and retrieve hydrogen efficiently without being affected by ship movement and (ii) exploration of vortex and centrifugal reactors for potential onboard dehydrogenation	I/A
	Infrastructure development and bunkering approach	• Port infrastructure to meet ship demands with sufficient fuel supply: nationwide bunkering grid and services for compressed gas, liquid or cryogenic hydrogen, NH_3 and methanol with and without on-site hydrogen production	G/I/A
		• Bunkering approach for small and large sea-going ships that are powered by (i) compressed gas hydrogen: supply chains development; lower energy requirements and losses during hydrogen compression, shorten bunkering time, availability and effectiveness of bunkering ship and cassette-type fuel systems or (ii) liquid or cryogenic hydrogen: supply chains development, storage tank design to avoid sloshing effects, super insulation to minimise the loss of hydrogen for improved overall energy efficiency	I/A
Rail	Powertrain design, analysis, optimisation	• Develop an optimised layout for rail application: (i) integration of FC and storage tank for different train designs, (ii) safety analysis of roof-mounted storage tanks combined with overhead power lines and (iii) analysis of the impact of the change of weight characteristics	I/A
	FC technology advancement	• Increase the efficiency, mass/volume power density and durability	I/A
		• Analyse the reliability of electronic components in the rail environment	I/A
	Hydrogen storage onboard train	• Safely integrate the hydrogen storage tanks for different train designs	I/A
		• Increase the safety to store onboard large volumes of hydrogen: (i) additional safety standardised systems, such as ventilation of enclosed fuel tanks, (ii) separation of fuel tanks from electric engines and (iii) use of multiple tanks	I/A
		• Develop alternative technologies for storage: use of MHs, research on hydrate promotors and high pressure requirements	I/A
	Energy storage onboard trains	• Identify the optimal battery type and size for use in combination with hydrogen by optimising the charging characteristics, cycle life and weight/volume of the battery	I/A
		• Balance the useful life of FCs and batteries by optimising the traction design parameters and train control operation	I/A
	Retrofitting	• Reconfigure diesel engines into diesel-hydrogen engines (e.g. by adding hydrogen port injectors to the engines and hydrogen supply system)	I
	Development of refuelling infrastructure for trains	• Develop railway vehicle refuelling facility and equipment to supply high quality bulk hydrogen	I/A
		• Concept design and optimisation for different hydrogen storage options	I/A
		• Reduction of refuelling time and development of defueling systems for service and maintenance needs	I/A
		• Development of multipurpose hydrogen refuelling stations	G/I/A

[a] Stakeholders: (G) government, (I) industry, (A) academic.

compression required at a later stage in the hydrogen refuelling supply chain. Solid oxide electrolysers, which do not require any precious metals, are still in development but their commercial applications are expected to grow, in which new electrolytes and electrodes would be developed in the short term to extend their lifespan and improve their thermal and operational stability. With a relatively simple configuration that can produce hydrogen at a purity level of 99%, membraneless electrolysers are worth exploring as an innovative means to reduce equipment cost. Other electrolyser cell concepts are currently in development, including elevated temperature (up to 623 K) proton-conducting polymer cells,

Table 6 – Future common research areas of hydrogen-fuelled transportation modes.

Topic	Research area	S[a]
Hydrogen production	• Improve electrolysers with increased efficiency, longer lifetime, more flexible operation, optimisation and cheaper costs	I
	• New production plants at large scale with simpler plant design, renewable energy supply and efficient energy consumption	I
	• Small-scale electrolysers for on-site production: more compact design with larger hydrogen production capacity	I
	• PEM electrolyser: (i) reduce consumption of platinum, (ii) develop new catalyst to replace platinum and (iii) improve degradation resistance	I/A
	• Solid oxide electrolyser: new electrolytes and electrodes for simpler start/stop procedure, longer lifetime and improved thermal and operational stability	I/A
Hydrogen distribution	• Modification of existing pipelines, feasibility study and investigation of hydrogen embrittlement characteristics	G/I/A
	• Advanced tools for measuring hydrogen quality and data sharing; impact of hydrogen blends on seals, components etc.	I/A
	• Deblending with different membrane designs (e.g. polymer, carbon, metal, glass or ceramic) or combined with other technology (e.g. membrane-PSA) at lower cost	I/A
	• Modelling of the development and expansion of hydrogen distribution networks	I/A
Hydrogen purification	• Pressure swing adsorption: new design for improved hydrogen recovery and smaller size	I/A
	• Membrane separation: (i) better membrane materials (ideally, strong, stable with water and CO_2, operate at low temperatures without issues related to brittleness and oxidation) and compact design and (ii) micro- and bio-membrane reactors: compact design for increased capacity at reduced weight	I/A
	• Development of membraneless electrolysers: innovative design to achieve lower electricity requirement and hydrogen purity of 99.999%	I/A
Hydrogen storage	• Storage tanks: more compact, stronger, lighter, cheaper design and materials	I/A
	• Advance compressor technology: e.g. by using electrochemical hydrogen pumps	I/A
	• Improve conversion between LH_2 and CH_2: (i) innovative liquefaction process design incorporating efficient compressors and reducing energy consumption during cooling, (ii) simpler and more efficient design of cryo-pumps with better thermal insulation and lower energy consumption and (iii) optimal compression	I/A
	• LH_2: reduction of operating cost of the liquefaction unit, reduction of boil-off losses, development of large-scale storage	I/A
	• Research and development on alternative hydrogen storage technologies, such as CcH_2, and hydrogen carriers, such as LOHC and NH_3	I/A
HRS	• Refuelling facility and equipment: (i) compact compressors using cheaper materials with simpler design, higher output purity and improved efficiency during compression, (ii) smarter pressure control and cheaper cascade storage, (iii) compact and efficient hydraulic units, (iv) new booster compressor design with lower maintenance requirement, longer lifespan using cheaper materials and (vi) advanced electrochemical compressors	I/A
	• Development of multipurpose refuelling facility: (i) concept design and optimisation for different storage options, (ii) reduced refuelling time and (iii) defueling for service and maintenance	G/I/A
Cost reduction	• Hydrogen storage: (i) reduction carbon fibre cost for CH_2 storage and (ii) development of cost-efficient tank system manufacturing processes	I/A
	• FC: (i) modularity approach for manufacturing cost reduction, (ii) reduction of materials cost and usage through a) enhanced rated working current, b) thinner metal bipolar plate, c) sheet metal stamping and d) surface modification and (iii) adoption of new technologies	I/A
Regulations	• Develop international/national Standards, codes and regulations for use of hydrogen for all the transportation modes: development of Standards for refuelling of hydrogen (universal requirements for equipment, process, operation, quality/purity and safety during distribution, refuelling and driving)	G/I
	• New policies: regulations related to emissions, renewable energy and low/zero carbon transportation; subsides for fuel tax and new/retrofit plants	G
Additional topics	• Flexible co-, tri- or poly-generation: co-produce hydrogen, electricity, heating, and/or cooling as well as recover waste heat if available (from system development to commercial application)	I/A
	• Development of models for the whole transportation system: simulate scenarios for hydrogen production, storage, distribution, and end-use application for transportation taking account of relevant factors, such as energy supply and emissions and covering multimodal transport, logistics and autonomy	I/A
	• Circular economy and sustainability of hydrogen: investigate the development of hydrogen economy covering supply and consumption of resources and management of waste taking account of temporal and spatial heterogeneity	G/I/A
	• Develop hydrogen demand, market acceptance and global hydrogen economy	G/I/A

[a] Stakeholders: (G) government, (I) industry, (A) academic.

alkaline polymer water electrolysis cells and proton-conducting ceramic cells [161]. Future research on electrolysers will focus on (i) the operation of the cell at higher pressure, (ii) the identification of the optimal electrocatalyst material (for PEM electrolysers) capable of providing high efficiency and being robust (most of the research has been conducted on noble metals, although more recently the use of non-noble metals, alloys and ceramics as catalyst material has been investigated), (iii) the identification of the optimal structure and efficiency for separators (diaphragms and membranes) and (iv) the stackability of the electrolysers [162].

The development of a LH_2 supply chain capable of providing large volumes of hydrogen with reduced losses would also be required for the roll-out of large capacity HRSs. One of the biggest challenges is the realisation of large-scale LH_2 storages (between 20,000 and 100,000 m^3) as previous research investigated systems with capacities up to 6000 m^3 and the largest system currently operating has a capacity of 3200 m^3 [163]. Future research should focus on developing more efficient insulation systems that reduce boil-off losses and further investigating insulation strategies (i.e. vacuumed, fully or partially non-vacuumed) and materials [163]. Extensive laboratory research and pilot testing would be required before large-scale LH_2 could be achievable. To further increase the economic benefits of using hydrogen for transportation, FC cost must be reduced. This could be achieved, among others, by reducing stack dimensions and associated costs through i) enhanced rated working current, ii) thinner metal bipolar plate, iii) sheet metal stamping and iv) surface modification [164] and by the economics of scale [165]. The use of platinum group metals as catalysts is one of the major reasons for the current high cost of PEM FC. The reduction of platinum use and the development of platinum-free catalysts are considered fundamental research areas for PEM FCs [166]. Costs for storage should also be decreased by reducing the cost of storage tanks for CH_2 and energy consumption and the losses due to boil-off for LH_2 Furthermore, improvements in other FC technologies, such as solid oxide, direct methanol, etc., are required to further extend the decarbonisation of the transportation sector.

In terms of HRSs, synergies between transportation modes are required. To maximise them, progress should also be made in developing multipurpose hydrogen refuelling facilities and equipment that could enable efficient hydrogen supply and storage in bulk. The development of multimodal HRSs capable of supplying hydrogen to different transportation modes is fundamental for the roll-out of hydrogen-fuelled transportation to increase demand, reduce dispensing cost, increase the economics of the HRS [28] and de-risk investments [149]. A demonstration multimodal hydrogen transportation hub will be realised in Tees Valley to evaluate the feasibility of this type of project and investigate the effect of transportation mode use, daily demand, electrolyser capacity, etc. [167].

Safety should be considered with due care for each transportation mode and along the supply chain, s. The main safety concerns on hydrogen transportation are combustion, high-pressure, electrical, crash and fire hazards [23,168], which require precautions at all stages from technology design and development to application. The development of regulations, such as national and international Standards, codes and policies, along the hydrogen supply chain and onboard the vehicle is also required to stimulate the commercialisation of hydrogen-fuelled transportation. Regarding the use along the supply chain, Standards should be developed about hydrogen characteristics (properties, safety, fuel specification, contaminant test and terminology), hydrogen production (safety/general design, performance and installation), hydrogen storage and transport (safety/general design, storage tanks, embrittlement tests, piping and pipelines, venting, labelling, HRS design and operation, dispensing equipment and installation) and hydrogen detectors. Regarding the use onboard the vehicle, Standards are required for the system design and testing, safety, performance (efficiency, emissions and durability), terminology, hydrogen sensors, fuel system, recyclability, fuel tanks, refuelling dispensing connections and fuel specifications [169]. Other aspects, such as hydrogen demand, market acceptance and global hydrogen economy are prerequisites for transitioning towards hydrogen-fuelled transportation in the UK.

Conclusion

The transportation sector is responsible for slightly less than one-third of the total greenhouse emissions in the UK, making the sector the most significant greenhouse gas emitter in the country. All the transportation modes (on-road, aviation, maritime and rail) require significant changes to move towards a zero-carbon sector. Hydrogen-fuelled transportation could be one of the solutions.

This study reviews the use of hydrogen in all the transportation modes in the UK context, identifying the current status of propulsion, storage and supply chain and examples of the application of the technology in commercialised models, prototypes and demonstrators, highlighting the advantages and drawbacks of each transportation mode and offering a holistic approach. The findings show the potential for the use of hydrogen in transportation in the UK to be rolled out in the short to long term. Some of the main identified challenges include the current performance, design and cost of fuel cells and hydrogen-fuelled internal combustion engines, the capacity and performance of hydrogen storage, the integration with energy storage systems, the development of a large capacity supply chain and the realisation of innovative infrastructure for refuelling.

To inform the stakeholders involved in the transition to hydrogen-fuelled transportation, this study also investigates the future research needs commonly applied to all and specific for different modes, such as the improvement of the performance and efficiency of the vehicles and of the hydrogen supply chain and the development of innovative design, refuelling infrastructure, standards and codes and policies to support the roll-out of the technology, in addition to a reduction in cost obtained through the use of more efficient manufacturing processes and cheaper materials and less expensive refilling. Adequate research on these topics would be valuable in further enhancing the marketability of hydrogen and enabling its wider uptake for transportation in the UK.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The work presented in this article was delivered for a project entitled "A network for hydrogen-fuelled transportation (Network-H2)" which was funded by the UK Engineering and Physical Sciences Research Council (EPSRC; Reference: EP/S032134/1).

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