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Potential Deployment and Integration of Liquid Organic Hydrogen Carrier Technology within Different Industries

Liquid organic hydrogen carrier technology to support on demand hydrogen supply and energy storage

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The deployment of hydrogen as an infrastructure fuel and an energy vector across a range of industries is expected to aid with meeting decarbonisation goals and achieving net zero emissions. For the transition towards a low carbon hydrogen economy, not only the production of hydrogen needs to be addressed, but also its transportation and storage. Liquid organic hydrogen carriers (LOHCs) are an attractive solution for the storage and transportation of hydrogen to allow a reliable and on-demand hydrogen supply, enabling industrial decarbonisation. This work describes the potential deployment and integration of LOHCs within different industries. These include: the transportation sector; steel and cement industries; the use of stored hydrogen to produce fuels and chemicals from flue gases and a system integration of fuel cells and LOHCs for energy storage.

1. Introduction

Energy-intensive industries as well as the transportation sector contribute significantly to global greenhouse gas (GHG) emissions (1). To mitigate climate change and achieve the goals of the Paris Agreement (2), it is necessary that each sector develops pathways towards GHG emission reductions and accelerate the transition towards deep decarbonisation. The production and use of a low-carbon hydrogen is seen as a ground-breaking aspect of a low carbon future, especially for hard-to-decarbonise sectors (3–14). A significant amount of renewable electricity will be required to enable energy-intensive industries and the transportation sector to reduce their emissions and meet decarbonisation goals when deploying green hydrogen produced *via* water electrolysis using renewable energy sources (11). Given that capacities of renewables and electricity costs for the production of green hydrogen are extremely heterogeneous (15–18), it is expected that the production of green hydrogen in all required locations at adequate costs will be challenging in the future. Similar to fossil fuels, which are imported and exported across the world, geographical locations with high renewable potential and low costs of electricity are expected to be focal points for the production of green hydrogen. Robust hydrogen storage and transportation systems are among the key components in the successful transition from fossil fuel-based energy systems towards hydrogen-based alternatives (19–23).

Storage and transportation of hydrogen at scale are yet to be addressed. An innovative method for long-distance transport and long-term high density hydrogen storage is to use LOHCs. This process is a two-step cycle, which is based on loading of hydrogen *via* catalytic hydrogenation into LOHCs, such as unsaturated organic compounds, followed by unloading of hydrogen *via* catalytic dehydrogenation after transport and storage (24–27).

In our previous work we provided an overview and perspectives on the LOHC technology among different hydrogen storage and transportation technologies (27). This study describes the potential deployment and integration of LOHCs within different industries. These include: the transportation sector (automobiles, ships, trains); steel and cement industries; the use of stored hydrogen to produce fuels and chemicals from flue gases; a system integration of fuel cells and LOHCs for energy storage.

2. System Integration of Fuel Cells and Liquid Organic Hydrogen Carriers for Electrical Energy Storage

Renewable sources, typically wind or solar, provide the energy required for the electrolysis of water to produce hydrogen (26). For the electrolysis stage, polymer electrolyte membrane (PEM) electrolysis is the preferred method, due to the ability of the system to respond to the characteristic fluctuations in renewable energy power supplies (25). The hydrogen produced can then be stored in LOHCs (through the hydrogenation step, **Figure 1**).

Interestingly, it has been reported that when dibenzyltoluene is employed as the LOHC, the hydrogen produced *via* electrolysis does not need to be dried before the catalytic hydrogenation reaction (28). When a ruthenium-based catalyst was used in a pellet form rather than as a powder, the activity of the catalyst was found to be virtually unaffected by water, while only a small decrease in hydrogenation activity was recorded when employing platinum catalysts with wet hydrogen (28). Costs associated with energy-intensive hydrogen drying processes can therefore be avoided. To better understand this observation, the tolerance of the catalyst should be investigated with other LOHC candidates.

When required, the stored hydrogen can be released from the LOHC (through the dehydrogenation step) and converted back into electricity, again using fuel cells. In this step, either PEM fuel cells (PEMFCs) or solid oxide fuel cells (SOFCs) can be utilised. PEMFCs are better designed to produce variable quantities of energy and thus meet changes in energy demand (25). Thus, the SOFC technology is only advantageous when there is a constant electricity demand (25). Nonetheless, using the SOFC technology to convert green hydrogen back into electricity is widely believed to become a future conventional method for stationary, green electricity production (29).

Furthermore, the waste heat from SOFCs (operated at 600–1000°C) is of the correct level to allow its use in the dehydrogenation step of the LOHC process (25). The coupling of LOHC technology with SOFCs can therefore improve the overall efficiency of the LOHC technology. To emphasise this, scale-up calculations for a LOHC–SOFC integrated system predict that 1 kg h^{-1} of hydrogen is capable of producing around 18.04 kW of power, corresponding to a SOFC efficiency of 54.1% (29). Another study suggests that an overall electrical efficiency of 45% is achievable with a 10-year SOFC lifespan (30). Such a long lifespan can be maintained if LOHC vapour does not damage the SOFC (31).

In contrast, a combination of LOHC systems with PEMFCs would require heat from another source, such as burning a portion of the hydrogen produced, to facilitate the dehydrogenation reaction (25). This is because the waste heat of PEMFCs (below 180°C) is much lower than the heat required for the endothermic dehydrogenation process needed for hydrogen release. Hence an integrated

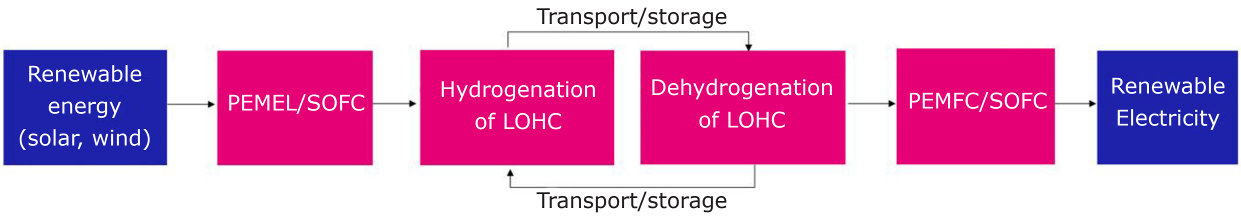

Fig. 1. Schematic representation of the integration of fuel cells into LOHC technology (25)

LOHC–PEMFC system would not be as efficient as a LOHC–SOFC equivalent (31).

Interestingly, the SOFC technology has also shown promise when combined with a mixed LOHC feedstock (29). In a temperature cascade dehydrogenation process, a eutectic mixture of *N*-ethylcarbazole (NEC), *N*-phenylcarbazole, ammonia and biphenyl-diphenylmethane increases the energy generated per unit mass of the LOHC (kilowatt hour per kilogram LOHC) by 1.3–2 times, compared to an individual LOHC (29). The system integration of the LOHC technology, fuel cell technologies and green hydrogen produced *via* electrolysis using electricity from intermittent renewable sources, can thus enable the local storage of excess energy or renewable electricity. Such a process is entirely sustainable as no harmful emissions are produced.

The concept of system integration can be used as a safety device for the storage of electricity on a large-scale, such as the National Grid, UK. There are currently several reports detailing the problem of electricity fluctuation in the National Grid, due to the lowered electricity demand during the COVID-19 pandemic (32). Despite a rise in the percentage of people working from home, resulting in an increased demand for domestic electricity, an overall decrease in electricity demand was observed (32). This can be attributed to the closure of non-essential offices, schools, hospitality and leisure venues. As a consequence, measures such as temporarily shutting down flexible windfarms are expected to be taken, in order to lower the excess of energy in the National Grid (32). Too much electricity in the National Grid is equally as concerning as too little electricity, as the rise in frequency increases the potential to damage infrastructure (33). As the proportion of renewable energy in the National Grid will predictably increase in the future, the fluctuations in electricity are also expected to increase. An energy storage technology, such as LOHC combined with fuel cells, could therefore be extremely beneficial. Similar would apply to ammonia and methanol, where such hydrogen carriers can be deployed in combination with fuel cells.

The above-mentioned energy storage ability of the LOHC technology has been reported to have implementation potential in residential and commercial buildings (localised energy storage) (**Figure 2**) (34, 35).

For such an application, heterocyclic aromatic compounds, such as NEC, have been considered. Although the fully dehydrogenated form is a solid at room temperature, which limits dehydrogenation to 90% and reduces the

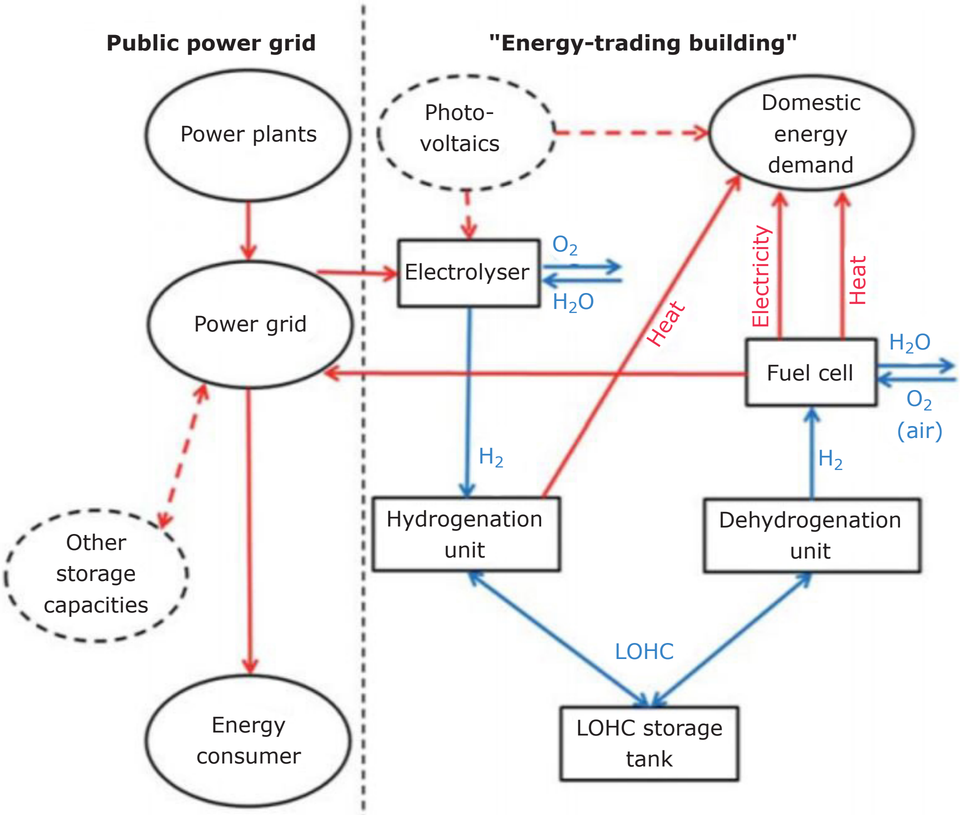

Fig. 2. Concept of integrating LOHC and fuel cell technologies to provide domestic energy. Republished with permission of The Royal Society of Chemistry, from (34); permission conveyed through Copyright Clearance Center, Inc

efficiency of the overall system, NEC is a safer feedstock than other possibilities (for example a toxic toluene/methylcyclohexane system). Thus, the requirements for domestic implementation are better accommodated (34).

In contrast to an application in which the loaded-LOHC is not stored in the vicinity of intended use, a 'decentralised energy storage' system is proposed. This technology also uses fuel cells to meet the local demands for electrical energy but has the added economic advantage that any unused energy can be sold back to the National Grid, for example. Furthermore, provided the building has such a resource as solar panels fitted onto the roof, the potential for a completely self-sufficient system exists, while any waste heat generated from the fuel cells, electrolyser and exothermic hydrogenation process may be used to heat the building (34). Yet, with the requirement of fuel cells, electrolysers, hydrogenation and dehydrogenation units, in addition to LOHC storage tanks, the physical space requirement and initial economic investment are high (34). It has, however, been suggested that houses already possessing a crude-oil storage tank may avoid the requirement for a subsequent tank (34).

3. Green Hydrogen for Production of Sustainable Fuels and Chemicals

The transformation of green hydrogen back into electricity is just one example which demonstrates how the LOHC technology can facilitate energy storage. Green hydrogen, stored and transported in LOHCs, can also be used as a 'green' feedstock for the synthesis of fuels and chemicals. Moreover, green hydrogen production and storage is a vital part of most carbon capture and utilisation (CCU) technologies which are focused on capturing CO_2 from either air or industrial flue gases and converting it into chemicals or fuels. For the moment, the hydrogen required for CCU technologies is considered to be generated from sustainable energy resources, however detailed integrated processes have often not yet been developed. The availability of green hydrogen for CCU processes is limited by competing demands such as hydrogen used in fuel cells for the transportation sector, and hydrogen used as domestic and industrial fuel supply.

Green hydrogen production is a key accelerator of CCU for production of chemicals and fuels at a commercial scale. Therefore, the production of hydrogen *via* electrolysis and its storage and transportation using LOHCs (or other hydrogen carriers such as ammonia or methanol) can be viewed as an integral part of sustainable chemicals and fuels manufacturing. One of such examples is methanol production, with a global production capacity of around 85 million metric tonnes in 2016, which is expected to rise in the coming years (36). Conventionally, methanol is synthesised using synthesis gas (syngas) produced from fossil fuels. However, a move towards the use of renewable hydrogen for sustainable methanol synthesis, using CO_2 captured either from the air or from industrial flue gases, would enable a reduction of global GHG emissions.

Thus, a scenario under which low-cost green hydrogen (i.e. produced at locations with an abundant energy supply and so cheaper electricity) is transported using LOHCs to the industrial sites (for example, cement, steel, refinery industries) with high CO_2 emissions to produce sustainable chemicals and fuels, might become viable in the future. Nevertheless, technoeconomic assessments and market penetration studies are required in order to understand under which circumstances this scenario can be realised.

4. Cement Industry

In the coming years, the proportion of electricity to be obtained from renewable sources is expected to increase. By 2024, it is predicted as much as 30% of the global electricity demand will be met with renewable energy sources: an increase of 4% in four years (37). The expected 15–30% decrease in the cost of solar power within the same time frame is also expected to accelerate the growth of renewable energy generation sites (37). However, the fluctuations in renewable electricity supply make it unreliable for direct industrial use. Integration of the LOHC technology within a cement plant has thus been studied as method of energy storage, which can be utilised to equalise the plant's energy output (**Figure 3**) (38).

The electricity for a cement plant can be supplied from renewable sources. During favourable conditions, the excess electricity is converted into hydrogen *via* electrolysis, followed by loading the hydrogen onto the LOHC and storing it. The dehydrogenation reaction is then performed at times of insufficient power supply from the renewable sources. The hydrogen released can be converted into electricity using fuel cell technology, a combustion engine or turbine (38). If an adequate power supply still cannot be achieved with the

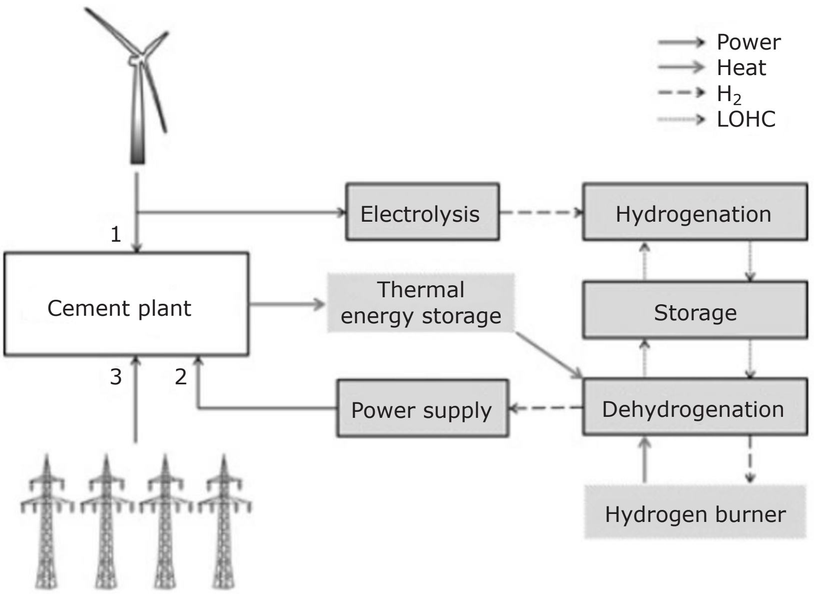

Fig. 3. Schematic representation of the coupling of a cement plant to a LOHC system. Reproduced from (38), Copyright © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

added electricity from the storage, the plant can be connected to the National Grid.

The higher temperatures required for the endothermic dehydrogenation reaction (i.e. hydrogen unloading) is a bottleneck of the LOHC technology, with the requirement of an external heating source resulting in a lowered system efficiency. In order to improve the efficiency of the LOHC system, the heat required for the dehydrogenation reaction can be coupled to the waste heat of a cement plant (**Figure 3**) (25). Arguably, this is a more suitable solution than the coupling of the dehydrogenation reaction to the waste heat from the exothermic hydrogenation reaction for heat recovery, as this is typically not of the same temperature level as is required for the dehydrogenation reaction. The waste heat from a cement plant, however, is more suitable (temperature level of up to 600°C) for the dehydrogenation process. Attractively, this avoids the need to reduce the efficiency of the process by burning a portion of the released hydrogen and there are no extra costs associated with employing an external heating source (25, 38).

Integrating a LOHC system with a cement plant allows an overall reduction in the working electricity cost of a cement plant. For a plant with an average power demand of 12.5 MW, it has been found that converting the hydrogen released in the dehydrogenation reaction to electricity and using this to power the plant would reduce electricity costs by around €1 million per annum (38). Although this saving has not been expressed as a percentage of the total electricity cost, it has been suggested that successful coupling of wind energy and the LOHC technology to a cement plant would achieve amortisation in fewer than 10 years. This is on the condition that investment costs are kept to a limit of €3.5 million. In addition, it should also be noted that the savings in electricity costs are calculated on the assumption that a thermal energy storage system is also installed, which ensures hydrogen can be released from the LOHC even in times of lower exhaust heat from the cement plant (38). In the absence of such a thermal storage system, fluctuations in the temperature of the waste heat must be provided for with the addition of a hydrogen burner (38).

5. Steel Industry

The iron and steel industry is responsible for an annual output of approximately 2.5–3.0 Gt_{CO2} $year^{-1}$, with up to 10% originating from within the European Union (EU). This represents 6% of total global CO_2 emissions, and 16% of total industrial CO_2 emissions. To reach the EU climate targets, the iron and steel industries must decrease their CO_2 emissions by up to 90% by 2050. Several processes are being explored to reduce CO_2 emissions from the steel industry. They can be broadly divided into two categories: carbon-based (coal- or natural gas-based) and hydrogen-based steel production (39). In carbon-based steel production, the residual gas emissions from the iron and steel industry can be transformed into valuable products, such as fuels or chemicals, or captured and stored or both. Hydrogen-based technologies, which use hydrogen as the reducing agent instead of carbon, avoid carbon emissions altogether, provided that hydrogen used in these processes is carbon-free hydrogen, produced by electrolysis of water using renewable electricity.

Numerous steel manufacturers have started to explore hydrogen-based technologies. As an example, voestalpine AG, Austria, has set up a goal of direct avoidance of CO_2 emissions in their steel manufacturing over the coming years by moving towards the use of green hydrogen for steel production (i.e. direct reduction of iron (DRI)). To this end, voestalpine together with their project partners have commenced the production of green hydrogen at the voestalpine premises in Linz, Austria within the framework of the EU-funded project called H2FUTURE (40, 41). In this project, the proton exchange membrane electrolysis technology is demonstrated on an industrial scale (6 MW), simulating rapid load changes in electricity generated from renewable energy sources and from electric arc furnace steelmaking (grid balancing). Thyssenkrupp Steel Europe AG, Germany's biggest steelmaker, is also looking into using hydrogen for steel manufacturing. RWE AG, a German multinational energy company, and Thyssenkrupp Steel Europe AG have agreed to collaborate towards a longer-term hydrogen partnership to supply green hydrogen for steel manufacturing (42, 43). RWE plans to build a 100 MW electrolyser which can produce 1.7 tonnes of hydrogen per hour for Thyssenkrupp Steel Europe AG. This could potentially cover 70% of the quantity required by the Thyssenkrupp steelmaker's blast furnace in Duisburg, Germany.

Another example is a joint venture between SSAB, LKAB and Vattenfall, all in Sweden, within the framework of the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project. The aim is again to reduce CO_2 emissions and decarbonise the steel industry by replacing coal with hydrogen in the steelmaking process to produce fossil-free steel at Sweden's pioneering fossil-free steel production plant (**Figure 4**) (44–46).

Interestingly, the HYBRIT project faces two major challenges: (a) to develop an effective process to use 100% hydrogen on an industrial scale; (b) to produce hydrogen in an energy efficient way that is economically justifiable and commercially viable (46). To this end, the HYBRIT project has recently invested SEK 200 million (£17.5 million) in a pilot plant for storage of green hydrogen in

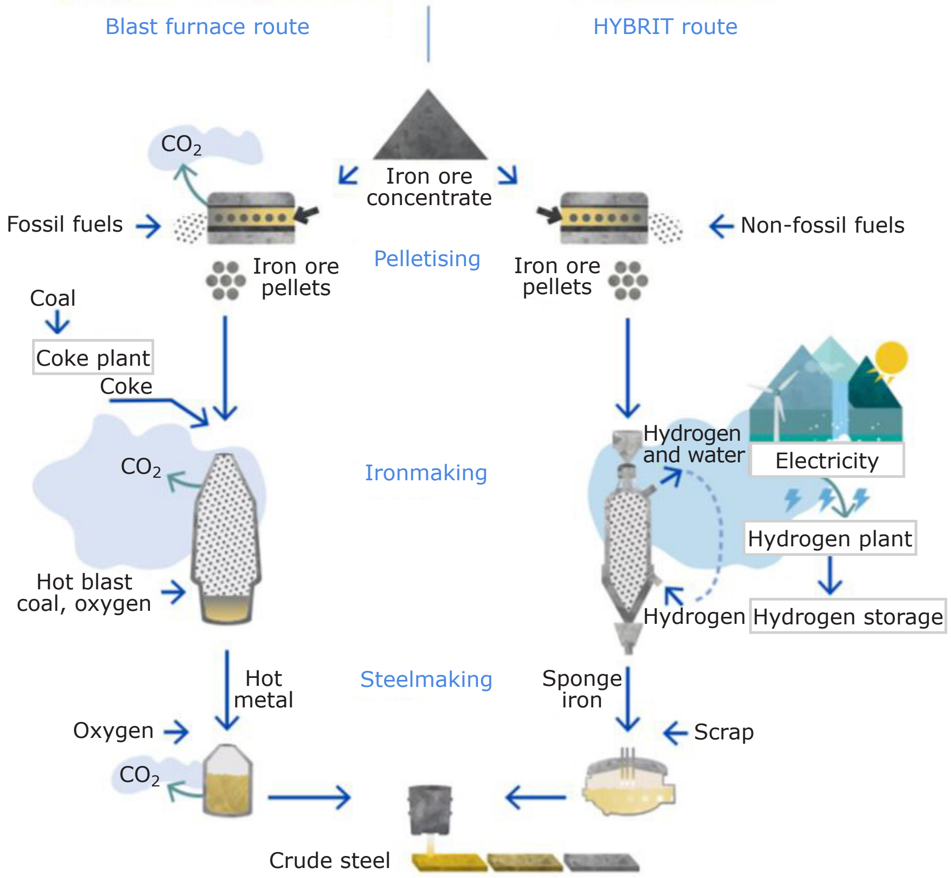

Fig. 4. Steel manufacturing in the HYBRIT route using green hydrogen *vs*. blast furnace route. Reprinted from (46) under Creative Commons Attribution 4.0 International (CC BY 4.0)

Lulea, Sweden near the SSAB steel manufacturing site (47). The implementation study for the HYBRIT initiative has recognised the need for large-scale storage of hydrogen. To ensure an even flow of green hydrogen produced from renewable energy for steel manufacturing at the SSAB site, a large-scale hydrogen gas storage facility is required to balance the electricity system with an increasing proportion of weather-dependent power generation. It is expected that the integration of large-scale storage of green hydrogen to a fossil-free value chain for steel manufacturing will allow the fossil-free steel to be price competitive.

In the HYBRIT project, the 100 m^3 subterranean (25–35 m underground) pilot hydrogen gas storage facility is built in a bedrock cavern with a steel lining as a sealing layer to store pressurised hydrogen (47). In contrast to SSAB, other steel manufacturing companies might not have the facilities for the underground storage of green hydrogen. Furthermore, geographically some of the steel manufacturing sites might not have access to low-cost surplus renewable electricity. In addition, if they are located in energy demanding industrial districts, numerous sectors will compete for green hydrogen or renewable electricity to reduce their CO_2 emissions in the near future. To ensure a competitive production cost for the fossil-free steel (i.e. DRI technology), an effective hydrogen storage and transportation technology, such as the LOHC technology, might thus be required to allow a reliable and on-demand supply of green hydrogen.

As large-scale storage of hydrogen is an important part for a fossil-free value chain for steel manufacturing, it should become an integral part of the DRI technology. For the deployment of the LOHC technology in the steel industry, two scenarios can be foreseen. One is an onsite hydrogen production and storage in LOHCs. Such a scenario can be realised when a steel manufacturing site has access to surplus renewable electricity from intermittent resources to produce hydrogen that should be stored to balance the electricity. Another one is using LOHCs to transport hydrogen, which is produced at geographical locations with high availability of renewable electricity, to a steel manufacturing site with low availability of renewable electricity but high demand for green hydrogen.

6. Mobility Application: Transport Industry

BMW AG, Germany, has been developing automobiles that employ hydrogen technology for around 40 years (48). The first model built using such a technology was named the BMW Hydrogen 7, and comprised the storage of liquid hydrogen in a cryogenic tank. However, during its early development serious technological challenges were realised (48). For instance, sufficient hydrogen storage space must be provided to enable longer-distance travel, but size and weight limitations for a practical motor vehicle must also be considered. In addition, the safety risks associated with burning hydrogen in the internal combustion engine must also be adequately minimised. As only 100 vehicles of the Hydrogen 7 model were ever released, it can be deduced that the disadvantages of the technology outweighed the advantages (48). More recently, BMW has announced a partnership with Toyota Motor Corporation, Japan, to develop a fuel cell-based system suitable for integration within its motor vehicles (49). It is predicted that the new model will be commercially available by 2022 (49).

As an alternative for onboard liquid hydrogen storage in mobility applications, the LOHC technology has been suggested (**Figure 5**) (50). Advantageously, onboard storage of hydrogen in the LOHC would resemble that of gasoline and diesel (liquid state of the LOHC at ambient pressures), which is widely understood, and the safety hazards of storing high-pressured hydrogen are removed (48). Moreover, a range of 500 km is reportedly achievable using 100 l of NEC loaded with hydrogen (equivalent to 5 kg of hydrogen) as the LOHC (48).

For motor vehicles, the loaded LOHC would be transported to the refuelling station, before a subsequent release of hydrogen from the carrier in a catalytic dehydrogenation reaction occurring onboard the vehicle (50). In contrast to diesel and gasoline fuels, the dehydrogenated LOHC would not be consumed, but stored within the vehicle until replaced with new hydrogen-loaded material at a designated station (48). The unloaded LOHC can then be transported back to a hydrogenation site and reloaded. Therefore, either two tanks, or a tank capable of separating the loaded and unloaded forms of the LOHC, is required. The hydrogen produced could then be used in an internal combustion engine or combined with fuel cell technologies. Despite the burning of a portion of hydrogen to meet the working temperature of a typical fuel cell, it has been predicted that the overall efficiency would still be higher than that of a combustion engine (48).

Highlighting the attractiveness of implementing the LOHC technology within the mobility sector,

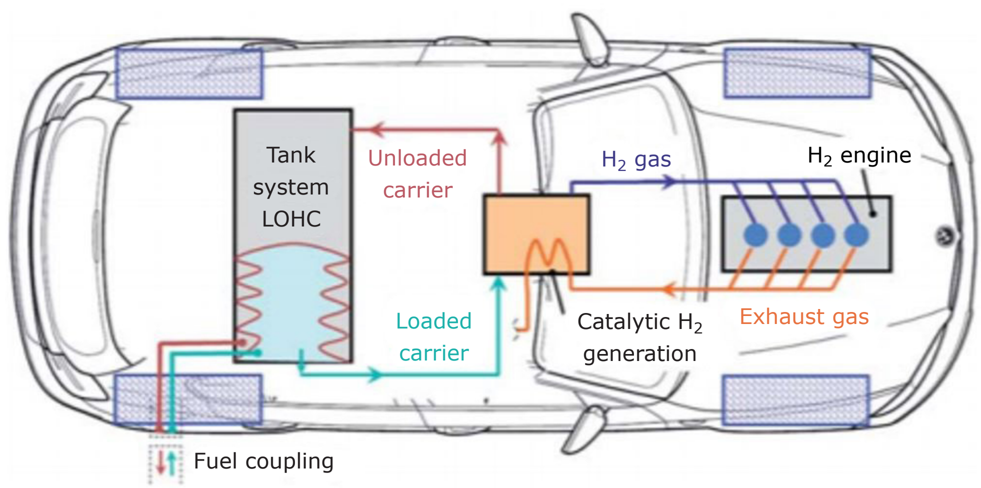

Fig. 5. Schematic representation of the LOHC technology within a motor vehicle. Republished with permission of The Royal Society of Chemistry, from (50); permission conveyed through Copyright Clearance Center, Inc

Hyundai Motor Company, South Korea, has recently announced plans to develop an onboard LOHC storage technology (51). This encompasses a partnership with Hydrogenious LOHC Technologies GmbH, Germany, who will supply dibenzyltoluene to be used as the LOHC. Initially, the technology will be introduced in South Korea, before being extended to the European market (51). It is expected that the development of LOHC compatible automobiles will raise the profile of the technology as an important tool in the transition to the hydrogen economy.

The use of hydrogen in maritime applications is also an active research area aimed at reducing the pollution from the maritime industry. One of the major challenges is the storage of hydrogen on board of ships (52). The LOHC technology is seen as one of the potential hydrogen storage solutions (52–54). For instance, the use of a double chamber tank system has been proposed, which is capable of separating the loaded and unloaded carriers during the fuelling process into different sections of the tank (53). Nevertheless, providing a suitable level of heat to facilitate the dehydrogenation reaction remains problematic.

Similarly, the use of LOHCs in trains has also been considered (55). Since a significant portion of trains are currently operated using diesel, or a combination of electricity and diesel, future environmental-focused objectives are likely to concentrate heavily on finding alternatives to these fuels (55). Although trains can be powered electrically with renewable electricity to meet zero-emission transportation goals, building the infrastructure of overhead wiring is relatively expensive. Currently, 42% of the UK railway routes are electrified and can become zero-carbon when using renewable electricity (56). The remaining 58% still rely on diesel (56). An alternative approach to electrification is the use of hydrogen fuel cells to generate electricity onboard to power trains (57). Hydrogen powered trains have a potential to revolutionise railway operations in Europe (56).

Using LOHCs for onboard hydrogen storage, coupled with hydrogen fuel cells for electricity production to power trains would avoid the production of hazardous emissions (i.e. CO_2, soot, nitrogen oxides), while still permitting long-distance travel, an essential criterion for trains. In a recent study, the LOHC technology (with dibenzyltoluene as the LOHC) was found to be a very promising option for hydrogen storage, transport and release and can be combined with electricity generation by hydrogen fuel cells to power trains (55). The choice of dibenzyltoluene as a LOHC was influenced by its favourable properties, such as low flammability, low toxicity and liquid-state within the range of hydrogenation and dehydrogenation temperatures, in addition to its commercial availability as a heat-transfer oil (55). Notably, this technology has been supposed to be favourable over alternatives, such as batteries, which are typically characterised by low energy densities (55). Furthermore, the hydrogen fuel cell technologies required for the integration with the LOHC technology for onboard hydrogen storage are expected to become a lower cost alternative to battery and diesel options in the second half of the decade.

Even though the studies into hydrogen-powered aviation are somewhat immature in comparison to trains and cars, it is anticipated that sustainable aviation will quickly become a central research focus in the coming years. Like other mobility sectors, hydrogen is again expected to be named

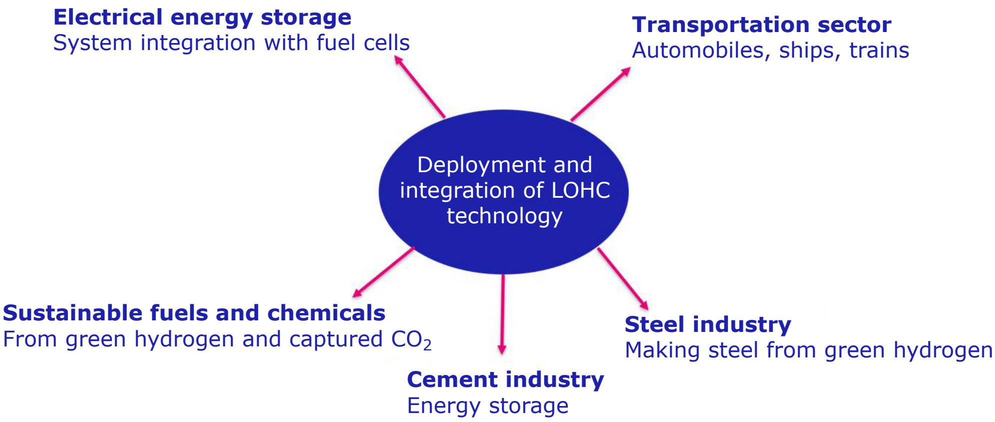

Fig. 6. Schematic representation of the potential deployment and integration of the LOHC technology within different industries

as a primary energy source for propulsion in the aviation industry. This can be realised either through powering aircrafts with electricity generated through hydrogen fuel cells, direct burning of hydrogen in gas turbines or using hydrogen as a building block for production of sustainable synthetic aviation fuels (58). Notably, Airbus has already revealed three hydrogen-powered planes to lower aircraft emissions, which comprise the use of hydrogen gas-turbine engines (59, 60). In addition, Airbus SE, The Netherlands, has postulated the combined use of hydrogen fuel cells with a gas-turbine engine to create a 'highly efficient hybrid-electric propulsion system' (61). The urgency of this sustainable transition has also been emphasised by the Swedish government. A mandatory reduction in GHG emissions, originating from aviation fuels, will be introduced for fuel to be sold in the country from 2021 (62). This will start at a 0.8% reduction in 2021 and reach 27% by 2030, in preparation for reaching their national fossil-free target in 2045 (62).

In summary, the LOHC technology is an attractive solution for the storage and transportation of hydrogen to allow a reliable and on-demand hydrogen supply, enabling industrial decarbonisation. The potential deployment and integration of the LOHC technology within different industries, such as the transportation sector, steel and cement industries, the use of stored hydrogen to produce sustainable fuels and chemicals from flue gases, and a system integration of fuel cells and LOHCs for energy storage, is depicted in **Figure 6**.

7. Summary and Perspectives

The possibility of deployment and integration of LOHC systems within different industries is reviewed in this study. These include: the transportation sector, steel and cement industries, the use of stored hydrogen to produce fuels and chemicals from flue gases and system integration of fuel cells and LOHCs for storing renewable electricity. An effective system integration of the LOHC technology with different industries might help with the cost reduction of the LOHC technology, when for example, waste heat is used for dehydrogenation of LOHCs. Importantly, the deployment of the LOHCs for storage and transportation of hydrogen to allow a reliable and on-demand hydrogen supply might enable energy-intensive industries to reduce their emissions and meet decarbonisation goals.

Numerous possibilities for the deployment and integration of LOHCs within different industries might necessitate the use of different LOHC carriers in each instance. While a carrier choice offers a large amount of flexibility in the LOHC technology, the myriad of possible carriers and catalysts combined with reactor technologies might be considered as one of the factors impeding the integration and commercial deployment of the LOHC technology across different industries. Customer-tailored solutions and offerings might need to be developed to accommodate specific requirements. A review of the most prominent LOHC systems, focusing on properties of LOHCs and catalytic materials used for hydrogenation and dehydrogenation of LOHCs, is presented in our following work dedicated to the analysis of LOHC systems (63).

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