Perspectives and Potential of Liquid Organic Hydrogen Carriers in the German Energy Scenario

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The energy transition is a global process and requires new import routes for energy demanding countries like Germany. Countries with great potential for renewable energy production may become key players in the global energy transition. In this contribution, we assess the potential of the liquid organic hydrogen carrier (LOHC) technology. LOHCs enable an energy-efficient storage and transportation using existing infrastructure for liquid hydrocarbons. Exemplary roles of LOHCs in the German energy landscape are illustrated. Lastly, LOHC demonstration projects in Germany are presented.

Keywords: Chemical hydrogen storage, Energy carrier, Energy import, Energy storage and conversion, Energy transition

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1 Introduction

Earth is beyond six of nine planetary boundaries [1], which describe a framework for limiting the impact of mankind on the Earth system as a whole. The atmospheric concentration of carbon dioxide is a control variable for the Earth system process climate change and has been set at 350 ppm, which is far outside the safe operating space since decades. In the recent years, many high impact agreements on fighting climate change were established. In 2015, 196 parties defined the need to limit global warming to a maximum of 2.0 °C and to strive for 1.5 °C when compared to average pre-industrialisation temperatures [2]. This agreement from the United Nations Climate Change Conference COP 21 in Paris has ever since been reemphasised by several countries and legally adopted by the European Union [3]. In 2019, the European Green Deal defined the goal towards "Net Zero" greenhouse gas emissions by 2050 demanding a complete replacement of fossil energy carriers by renewable alternatives [4].

Recently, the European energy supply security was seriously challenged by the rapid cut-off of fossil energy imports from the Russian Federation. In consequence, the call of the German Chancellor Scholz for a "Zeitenwende" [5] drastically accelerated the energy transition ambitions and actions of the Federal Republic of Germany. Currently, liquefied natural gas (LNG) terminals are erected within a short time to secure the natural gas demand of the German industry and households [6]. In parallel, multiple hydrogen strategies are developed and presented by organisations, states or regions, countries, and the European Union [7]. Especially within European strategies, the need of importing renewable energy is common sense as the geographical disparity of energy demand and potential in renewable energies is a major challenge. Noteworthy, many countries have always been importing energy, mostly via natural gas, crude oil, or derivatives thereof. Here, strong dependencies have been established over time, which is currently evidenced by the impact of the banned import of Russian natural gas and crude oil. Further, the absence of significant choices renders bilateral impacts challenging. In the German hydrogen strategy, which has been released in 2020, ambitious goals have been defined for the availability in green hydrogen (Fig. 1) [8]. The challenge is easily depicted when comparing the current total demand in hydrogen with the antici-

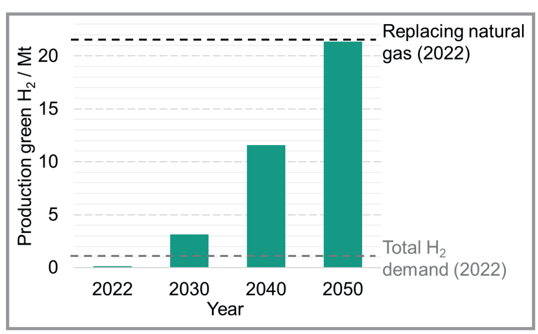

Figure 1. Targeted production of green hydrogen in Germany [9] with current production, total demand of hydrogen and the required equivalent to replace the energy content of the current natural gas demand [10].

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pated production capacity of green hydrogen in 2030, which is approx. twice as high [9]. Even though the further increase in the targeted national production capacity until 2050 is enormous, the final higher heating value (HHV) of the projected hydrogen will be comparable to the natural gas demand of Germany in 2022 [10].

2 Hydrogen as Chemical Energy Carrier and Chemical Hydrogen Storage

When discussing a future hydrogen economy, hydrogen use has to be considered beyond its role in the energy system. Hydrogen has ever been and will remain an elementary feedstock in chemical industry [11]. Hence, the use of green hydrogen as a chemical to replace vast amounts of fossil-based hydrogen in the chemical industry (Fig. 2) [12] needs to be prioritised over many upcoming large-scale use cases until abundant green hydrogen will become available. Nevertheless, green hydrogen must also play an essential role in the defossilisation of hard-to-abate sectors, such as the steel industry [13] and aviation [14]. Chemical industry must change from technology deciding approach to a feedstock-based decision-making. Hence, the sustainability and availability of the feedstock and products is important, while the most efficient ways towards this goal are required to become economically viable. More importantly, a rapid change must be realized to halt climate change demanding for sustainable technologies with short implementation time.

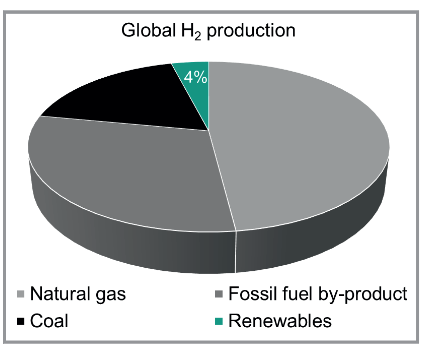

Figure 2. Contribution of different feedstock in the global production of hydrogen [12].

Molecular hydrogen has a high gravimetric energy density of 141.82 $MJ\,kg^{-1}$ based on the HHV, which by far exceeds other chemical energy carriers (Fig. 3) [15]. Compressed or liquefied hydrogen may reach a volumetric energy density of 8.28 $MJ\,L^{-1}$. While this is in the range of compressed methane and liquid ammonia, longer chained hydrocarbons and liquefied methane have a two to four times higher volumetric energy density. Further, such a comparison of energy carriers does not take into account the required storage infrastructure, which drastically lowers the practical gravimetric energy density in the case of liquefied and compressed gases [15]. Conversely, common liquid fuels of fossil origin enable simplified storage and transportation. Together with the high energy density, this represents the foundation for their success story during industrialisation making modern life strongly dependent on fossil-based energy carriers. In order to become resilient against this dependence, the transition from the past (and ongoing) molecule-to-energy approach by exploiting fossil fuels towards a future energy-to-molecule industry is inevitable. Here, Power-to-X (PtX) technologies are developed to drive this transition from fossil feedstock to renewable and circular energy sources. The production of hydrogen using renewable electricity is typically the first step, which is followed by on-site consumption of hydrogen or its transportation. With regards to aforementioned required import of renewable energy units to meet the local energy demand and to provide hydrogen as important feedstock for the chemical industry, the development of efficient technologies for transportation and storage of hydrogen is of utmost importance.

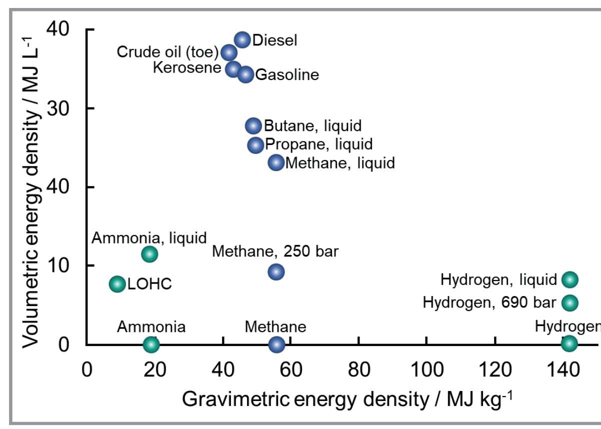

Figure 3. Energy densities of common fossil-based fuels and petrochemical products (blue symbols) together with upcoming alternatives for chemical hydrogen storage (green symbols).

Common ways for storage and transportation of hydrogen include high-pressure gas tanks or cryogenically cooled liquid hydrogen. A serious disadvantage of these methods is the considerable loss of energy during storage and the need for special containers and new infrastructure [16]. Intensive research is therefore being carried out into alternative storage options. The possibilities range from porous materials and liquid hydrogen carriers to complex and intermetallic hydrides [17]. One promising approach in the field of chemical hydrogen storage is the liquid organic hydrogen carrier (LOHC) concept [18].

Chemical hydrogen storage with LOHCs is based on the catalytic hydrogenation of unsaturated hydrocarbons. In the hydrogenation reaction, covalent bonds are formed between hydrogen and hydrogen-lean molecules. If required, the bound hydrogen can be released from the resulting hydrogen-rich molecules by means of catalytic dehydrogenation [15]. The LOHC molecules are not consumed in this reversible process while the use of liquids as hydrogen carrier molecules facilitates a closed storage and material cycle (Fig. 4) [19, 20]. Therefore, LOHC systems can be charged and discharged with considerable quantities of hydrogen in a cyclical process [20]. The reversibly bound hydrogen enables volumetric energy densities in the range of liquefied hydrogen (Fig. 3). The clear advantage of LOHCs is their compatibility with the existing fuel infrastructure for hydrocarbons and the ability to store hydrogen without losses, even in the long term or for overseas transportation under standard conditions [21]. For example, typical storage tanks in the existing oil infrastructures can be used for storage [22].

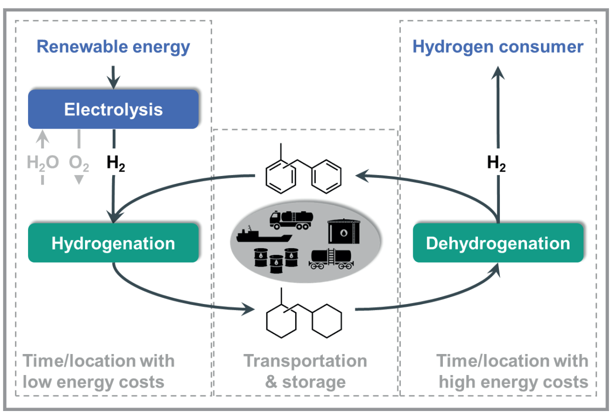

Figure 4. Facilitation of import of renewable energy in the form of chemically bound hydrogen in liquid organic hydrogen carriers without infrastructural limitations regarding transportation and storage.

An LOHC system must fulfil a number of requirements for practical application [21, 23–26]. In principle, a suitable system should enable selective hydrogenation and dehydrogenation to ensure circularity. The LOHC system should have an appropriately high storage capacity in the range of 5.0–7.3 wt % reversibly bound hydrogen and favourable hydrogen bond enthalpies. Low by-product formation and high thermal stability over the entire temperature range can increase the number of possible cycles before the LOHC needs to be replaced. A low melting point eliminates the necessity of adding solvents to broaden the liquid range, while a high boiling point facilitates hydrogen purification through LOHC condensation. In addition, a suitable LOHC system has the lowest possible production costs, good technical availability, and is toxicologically and ecotoxicologically less critical than common hydrocarbon-based fuels.

Based on these technical requirements, many different substances are discussed in the literature as potential LOHC compounds. These include cyclic alkanes, such as benzene/cyclohexane [27], toluene/methylcyclohexane (MCH) [28], or naphthalene/decalin [29], but also some heterocyclic aromatic hydrocarbons, such as N-ethylcarbazole (H0-NEC)/perhydro N-ethylcarbazole (H12-NEC) [30]. An alternative approach is the use of well-established and commercially available heat transfer oils. Isomeric mixtures of benzyltoluene and dibenzyltoluene, which are frequently used industrially as heat transfer oils, can be used as LOHC systems [31]. Compared to the H0-NEC/H12-NEC system, the benzyltoluene (H0-BT)/perhydro benzyltoluene (H12-BT) and dibenzyltoluene (H0-DBT)/perhydro dibenzyltoluene (H18-DBT) systems have several advantages. These include an increased hydrogen storage capacity (6.2 wt %; 6.8 MJ L^{-1}; 7.6 MJ kg^{-1}) and a significantly lower melting point. The latter prevents the uncharged hydrogen carrier from solidifying under ambient conditions and thus avoids the resulting technical challenges [32]. Further, the released hydrogen may not even require dedicated purification steps [33]. Lastly, both systems are characterized by an excellent technical availability alongside the availability of an (eco)-toxicological classification, and a high thermal stability [31]. In spite of their different properties and performance, LOHC storage molecules are all produced from fossil resources. Therefore, the use of economical and sustainable sources should be considered. Plastic waste could be one such potential resource [34].

Rüde et al. [26] propose H0-BT/H12-BT as the favoured LOHC system for future technical applications due to its enhanced stability and the ability to achieve higher reaction rates under the same conditions when compared to H0-DBT/H18-DBT. This is substantiated by the planned construction of large-scale hydrogen storage applications, capable of storing 1800 t of hydrogen per year, which will rely on H0-BT/H12-BT as LOHC system [35]. Therefore, in the following chapters, the term LOHC will refer to the H0-BT/H12-BT LOHC system being the currently most relevant LOHC system for industrial applications in Germany.

3 Exemplary Roles of LOHC in Germany

Potential applications of the LOHC technology are as diversified as hydrogen utilisation. Exemplary roles range from long-term storage applications to chemical utilisation and applications in the mobility sector. No matter what the purpose is, the strong endothermal character of the dehydrogenation of LOHCs always demands for coupling with heat generating processes or waste heat streams, which increases the efficiency of the hydrogen release and prevents the sacrifice of part of the hydrogen to provide the required energy. General bottlenecks are the overall availability of technical LOHC systems, which would require a ramp-up in the production alongside technical implementation. Further, hydrogenation and dehydrogenation process units must be built.

3.1 Large-Scale Import of Hydrogen

One of the major advantages of the LOHC technology are the energy efficient storage at ambient conditions and the compatibility with the widely available infrastructure for transportation and storage of liquid hydrocarbons [15, 36]. This makes the LOHC concept a competitive and economical viable alternative to physical hydrogen storage techniques, in particular for long distance transportation routes [37, 38]. The required amount of LOHC to cover the HHV of the current annual German natural gas demand is approx. 340 Mt for the depicted 21 Mt of hydrogen (Fig. 1). To put this number in relation, Germany had an annual import of crude oil of approx. 90 Mt in the recent years [39]. Regarding the available infrastructure, the Port of Wilhelmshaven is the most important entry point for liquid hydrocarbons with an annual handling of 21 Mt of liquid cargo and several pipelines to distribute imported crude oil. [40]. Import of renewable energy units via LOHCs only represents one option for a diversified future import strategy. For example, a nationwide hydrogen grid was recently announced as a basis for a European integrated network infrastructure, which facilitates hydrogen import via German ports with a direct feed into the grid [41].

The required increase in liquid cargo handling seems immense, but comparison with alternative import technologies for hydrogen elucidates the benefit of LOHC compatibility with existing infrastructure. A very large crude carrier (VLCC) can have a capacity of 250 000 t [42] and is compatible with common LOHC molecules (Fig. 5a). Hence, four carriers per day may cover the initially discussed 21 Mt of hydrogen per year. The world's first liquefied hydrogen carrier by Kawasaki Heavy Industries operating between Australia and Japan has a capacity of approx. 90 t of hydrogen [43], which would sum up to >650 carriers per day for the same supply of hydrogen. Noteworthy, a large liquefied hydrogen carrier has been announced with a storage capacity of approx. 10 000 t of hydrogen [44]. The average number of daily vessel calls in the Port of Hamburg, which is amongst the biggest ports worldwide, is 20, whereof four were classified as carrier for liquid cargo in 2020 [45]. Specialised infrastructure for the transportation of hydrogen can only be established step by step. Even though capacities can be expected to increase rapidly for liquid hydrogen carrier ships, the gap to existing VLCCs is huge (Fig. 5b). Hence, the LOHC technology represents a rapid import route for hydrogen, which may be implemented on a short time scale. The first realisation of such import in Germany has been announced in 2022. By 2026, an annual amount of 8000 t of hydrogen (129 000 t of LOHC) will be shipped from Sweden to the Netherlands and in part be further distributed to Germany [46]. Approx. 40 shiploads are projected per year via the Port of Rotterdam, which results in an average capacity of 200 t hydrogen, which is already exceeding state-of-the-art liquid hydrogen carrier ships. Large-scale hydrogen import facilities using the LOHC technology are also planned at the Port of Amsterdam [47].

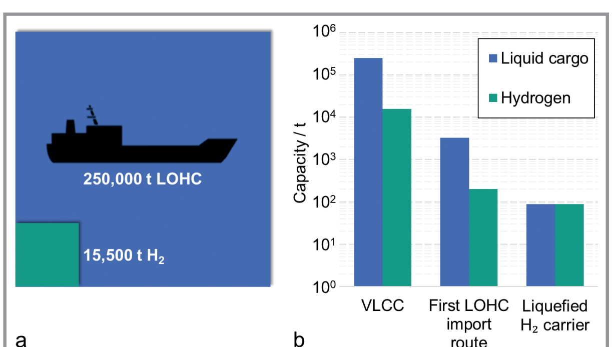

Figure 5. a) Hydrogen storage capacity of LOHCs depicted as the capacity for transportation of LOHCs in very large crude carriers (VLCCs) and b) comparison with the projected capacity of the first implementation of LOHC import routes in Germany [46] and a liquid hydrogen carrier ship [43].

3.2 Strategic Energy Reserves

As LOHCs enable facile storage with minimum energy losses in existing infrastructure for liquid hydrocarbons, the technology is also suitable for national strategic energy reserves. In Germany, the strategic petroleum reserves currently account to 15 Mt crude oil and 9.5 Mt refinery products (Fig. 6) [48]. By law, the reserves have to be equivalent to the domestic consumption of at least 90 days [49]. With more and more implemented processes for utilisation of and access to hydrogen and other sustainable feedstock, the refining industry will adapt to this feedstock of the future. Here, hydrogen, carbon dioxide, and biomass are crucial aside from recycling of waste streams. Strategic reserves for the chemical industry and for such refineries of the future in the form of LOHC may represent an efficient way to accumulate imported energy units. Due to the lower energy density of LOHCs, a total of 127 Mt would correspond to the current crude oil equivalents of the strategic energy reserves. This is in the range of the current yearly refining capacity of 104 Mt [50].

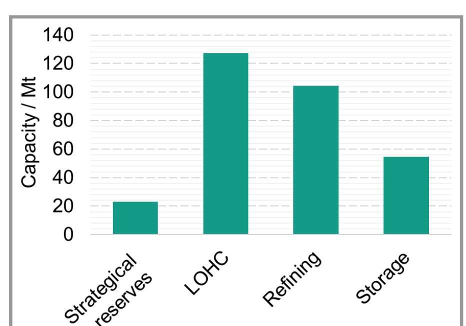

Figure 6. Comparison of the average strategic energy reserves of Germany from 2018–2022 [48] with the corresponding required storage capacity for LOHC, as well as the German capacity for crude oil refining and storage [50].

While a significant storage capacity is already available, full transition to LOHCs as sole strategic energy reserves would require additional infrastructure for storage (Fig. 6) but is also unlikely due to the aforementioned required diversification approach. The current national tank storage capacity amounts to 55 Mt [50]. In general, existing storage infrastructure, such as fixed roof tanks and floating roof tanks, are compatible with H12-BT [22]. As a large fraction is also stored in underground caverns [50], an assessment of the general suitability would be required. Recently, bulk-scale storage of LOHCs was assessed in a feasibility study with respect to energy storage in the United Kingdom [22]. In particular, the viability of re-purposing conventional storage facilities for crude oil to store hydrogen in the form of LOHC was evaluated. H0-BT/H12-BT was identified as a promising LOHC, while no limitations were identified for storing and handling this LOHC. In general, a high compatibility with the complete existing infrastructure for crude oil was demonstrated demanding no or, in some cases, minor modifications to accommodate H0-BT/H12-BT.

3.3 Seasonal Storage

Similar to the strategic energy reserves, LOHC is also suitable for seasonal storage of excess renewable electricity as such long storage cycles also demand for a high efficiency and long-term stability. The shorter the storage cycles, the better the suitability of other technologies as the loading and unloading efficiency become more important and energy input during storage can be accepted. In Germany, seasonal storage is currently mostly applied for underground natural gas storage, which has an overall capacity of approx. 30 GW [51]. The storage level is a result of the interplay between consumption, export, and import. During the warmer seasons, the storage level typically reaches 100 % due to a reduced demand and in preparation for the colder seasons. Since the absence of Russian natural gas imports, the storage level is kept higher to secure the energy demand [10]. Contrary to this rather strategical control over the storage level, future seasonal storage applications will be mostly affected by an increased production of renewable electricity from photovoltaics during summer terms in combination with an increased energy demand in winter. To replace the current natural gas storage capacity with LOHC, a total of 124 Mt would be required. A potential shift from importing fossil fuels to meet cold season energy needs to sustainable alternatives is a promising use of local excess power [52].

3.4 Autonomous and Individual Energy Transition

All previous examples of use cases for the LOHC technology are directly linked to a transition of the energy system towards imported renewable energy units while being rather independent from new infrastructure. As indicated, such transportation and storage in existing infrastructure enables short-term roll-out of implementation routes. This allows for logistics, while modular hydrogenation and dehydrogenation units may be rapidly erected at the corresponding sites of hydrogen production and demand, respectively. This is particularly true for the release of chemically bound hydrogen from the LOHC on the site of hydrogen application, which can be integrated into a dedicated larger logistical network at a later stage. This can be seen as preparation via isolated solution for utilisation of green hydrogen until a nationwide hydrogen grid may be established in 2032 and extended by local pipelines [41]. This enables rapid replacement of fossil-based hydrogen by sustainable hydrogen wherever and whenever the associated increased costs and investments can be accepted. Such role models for the energy transition are required and can be diverse. For example, large headquarters, refineries, or chemical industry can switch to such a sustainable solution using the LOHC technology within short time. The implementation of the energy-to-molecules strategy on large-scale will require time, which makes the alignment of a unified transformation challenging. Hence, such autonomous and individual approaches allowing for rather independent implementation are inevitable.

3.5 Back-up and Emergency Energy Storage

Electrification is an important asset in the energy transition and strengthens the dependence on a stable electricity grid. Hence, crucial electrified infrastructure must be protected from blackouts. Large facilities, such as hospitals, already have generators to secure vital power supply. Such generators, which are part of many back-up power strategies, may be replaced by hydrogen fuel cells in combination with a dehydrogenation unit and LOHC storage. Storage infrastructure exists in many cases as diesel generators are widely applied nowadays. In the future, more and more applications and facilities must be protected from blackouts of the electricity grid to ensure functionality and fast responses. For example, electrified fleets of ambulances, police cars, fire engines, disaster control, or even military equipment must have access to electricity for recharging even for longer periods of blackouts.

3.6 Chemical and Energetic Use of Hydrogen as Sustainable Feedstock

Many branches of industry demand sustainable hydrogen to cut emission of greenhouse gases from production processes. The chemical industry always had a huge demand of hydrogen [11], which is also part of the so-called synthesis gas (mixture of hydrogen and carbon monoxide), a starting point for many catalytic processes. Hence, rapid transformation of chemical processes to sustainable feedstock seems promising and is the targeted use case for the first LOHC import routes [46]. However, most catalytic syntheses are operated at elevated pressure levels, which requires compression of LOHC-derived hydrogen. Compression of hydrogen is an energy-intensive process (Fig. 7) that drastically increases the overall cost. For example, compression of ambient hydrogen to 36 bar requires 5 % of its HHV [53]. Hence, low pressure applications in industry are better suited, such as the steel industry [13]. Direct utilisation of the chemically bound hydrogen in LOHCs also represents a potential solution to circumvent compression and even handling of molecular hydrogen. This can be achieved in so-called transfer hydrogenations [54]. Lastly, green hydrogen can also be utilised in chemical processes at the site of production followed by import of crucial hydrogen derivatives, such as methanol and ammonia.

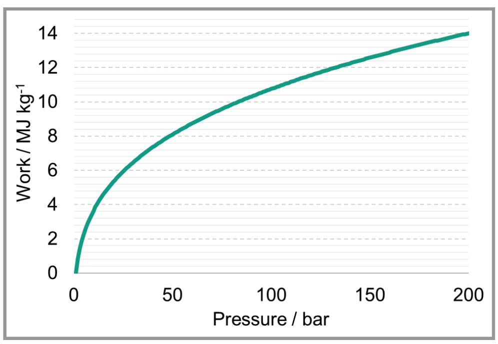

Figure 7. Specific adiabatic compression work required for hydrogen at 1 bar and ambient temperature [53].

3.7 Mobile Applications

As discussed, hydrogen release from LOHCs is most economic when combined with direct consumption of hydrogen at low pressures. Hence, direct utilisation of released hydrogen in fuel cells is appealing, which combines liquid energy carriers and electricity generation rendering this approach an ideal solution for mobile applications. However, space is often limited, in particular for small vehicles, while today's LOHC technology requires rather large equipment. The larger the mobile entity, the easier a potential implementation. Consequentially, recent developments in Germany focus on maritime applications [55], inland shipping [56], and non-electrified railways [57]. In a recent perspective by a team from the Massachusetts Institute of Technology (MIT), Biswas *et. al.* describe the potential of LOHC for mobility applications by suggesting long-haul trucks with on-board dehydrogenation [58].

4 Current LOHC Applications and Demonstration Projects in Germany

The LOHC technology has the potential to shape the future hydrogen economy and support the defossilisation of the energy sector. This is supported by a number of ongoing demonstration projects ranging from mobile applications, to small on-site energy storage, up to large demonstration plants. A number of these projects have already been realized in Germany, whereof a selection is herein presented.

With the Micro Smart Grid [59], the Fraunhofer Institute for Industrial Engineering (IAO) has created a 'living laboratory' in the multi-storey car park of the institutional headquarter in Stuttgart, where latest technologies are presented under scientific supervision and their everyday operation is demonstrated. The facility includes over 30 charging stations for electric vehicles, making it one of the largest charging infrastructure installations in a multi-storey car park. All traction power is generated by a photovoltaic system and a lithium-ion battery storage system helps coordinate production and consumption. In addition, the facility also features Europe's first LOHC hydrogen storage system with 30 kW output power. This hydrogen storage system is connected to the electricity supply via a fuel cell, making it a high energy, long-term storage system in the micro smart grid.

The Living Lab Energy Campus (LLEC) at the Forschungszentrum Jülich (FZJ) is testing a scientific and technological platform for the development of highly integrated energy supply systems [60]. The aim is to set up a real-world laboratory and to develop options for a sustainable energy supply for the research centre with its more than 7000 employees [61]. This is achieved through adaptive and predictive control strategies in the areas of heat, electricity, chemical energy storage, and mobility. Within the project network, various energy demonstrators will be installed on the campus [60]. Seasonal stationary hydrogen storage using the LOHC technology is investigated in one of those demonstrators. It represents a prototype with a performance level of 300 kW, which is unique worldwide to this date. The demonstrator is connected to electrolysis, a hydrogen pipeline, and the full heat supply centre [62]. As a reactor configuration, the demonstrator uses a 'one reactor' concept enabling bidirectional storage and release. This technology has previously been demonstrated on a pilot scale [63, 64] and lowers the investment costs for the construction of a seasonal and stationary hydrogen storage solution based on LOHC technology as the number of reaction apparatuses is reduced. Operating costs can also be reduced, as the 'one reactor' is ideally continuously operated to avoid long heating or cooling times. Both the hydrogenation of the hydrogen-lean LOHC components and the dehydrogenation of the hydrogen-rich LOHC components can take place in a single reaction apparatus, which is realized by adjusting the reaction pressure [65, 66].

Together with Linde, Hydrogenious LOHC Technologies, and Siemens Energy, H_2 MOBILITY Deutschland is operating an LOHC-based hydrogen filling station in Erlangen offering two pressure stages [67]. At the Hydrogenious headquarters, a solar power system is used to generate electricity to produce green hydrogen via a PEM electrolyser. Hydrogen is stored in LOHCs, transported to the hydrogen filling station via a tank truck, and stored in underground tanks with a capacity of 1.5 t of hydrogen, which exceeds the capacity of common pressurized hydrogen fuelling stations. Only conventional technology is used for transportation and storage demonstrating the excellent compatibility of LOHCs with existing infrastructure. Hydrogen is released, compressed to 45 bar, and buffered in an intermediate storage tank, where it is further compressed to either 350 bar for buses and trucks or 700 bar for cars and light commercial vehicles [68]. This marks a significant milestone in energy research as it presents the world's first hydrogen station with LOHC technology enabling large-scale on-site storage and release of hydrogen [67].

The world's largest plant for storage of green hydrogen in LOHCs is built at CHEMPARK Dormagen. LOHC Industrial Solutions NRW GmbH, a subsidiary of Hydrogenious LOHC Technologies, is managing and operating the plant in cooperation with Covestro Deutschland AG, which is providing future supply of green hydrogen. The plant capacity will enable the storage of approximately 1800 t of hydrogen per year making it one of the currently largest green hydrogen supply chains in the world. The project aims to scale up the LOHC technology and focuses on integration of the thermal energy released during the LOHC hydrogenation process into the steam network, thereby improving the overall efficiency of the process. This development represents a significant step towards the advancement of the LOHC technology and the establishment of a substantial green hydrogen supply chain [35].

TransHyDE is one of three hydrogen flagship projects in Germany to establish the National Hydrogen Strategy [69]. The project advances, evaluates, and demonstrates hydrogen transport technologies. Amongst physical storage techniques, ammonia and LOHCs are studied as chemical hydrogen carrier. The TransHyDE project Helgoland is testing the implementation of a hydrogen storage and transportation chain from the island Heligoland to the mainland. Green hydrogen, produced by the H2Mare hydrogen flagship project in an offshore wind park, is transported by pipeline to the island and stored using LOHCs. After transportation using the existing infrastructure, hydrogen is released in the Port of Hamburg in a dehydrogenation plant.

The Hermann-Josef Hospital in Erkelenz, North Rhine-Westphalia, is partnering with Robert Bosch GmbH and Hydrogenious LOHC Technologies for a demonstration project for climate-friendly energy supply. This initiative is coordinated by the Helmholtz Hydrogen Cluster HC-H2 in Jülich and couples several hydrogen technologies [70]. As part of the project, a natural gas-powered gas engine is replaced by a stationary 100 kW solid oxide fuel cell (SOFC). For the operation of the SOFC, hydrogen is supplied in the form of loaded LOHC components. The SOFCs and the LOHC dehydrogenation unit are thermally coupled to use the heat stream from the SOFC for the endothermal dehydrogenation [61]. The project aims to significantly reduce carbon emissions and provide a more efficient energy supply. In the first phase of the project, the SOFC system will be operated with natural gas. This already reduces the amount of released carbon dioxide about 40 %. By the end of 2026, the partners plan to demonstrate the innovative combination of the two new hydrogen technologies, SOFC and hydrogen supply through LOHC, in the second phase. The goal is to evaluate a more climate-friendly and, in the long term, more cost-effective solution. In particular, it will be investigated whether half of the hospital base load can be covered by the multi-SOFC project. The demonstration project is intended to be a globally visible role model for the future energy supply of large buildings [71] and represents a great example for aforementioned individual island solutions to drive the energy transition.

Researchers at the Helmholtz Institute Erlangen-Nürnberg for Renewable Energy (HI ERN) are pursuing a project towards a demonstrator for emission-free rail transportation using LOHC technology for non-electrified lines, which may replace diesel locomotives. Electrifying the entire non-electrified railway network is costly and time-consuming. The range of battery-electric locomotives are limiting deployment on many routes rendering hydrogen-powered trains an attractive alternative. However, refuelling trains with compressed or cryogenic hydrogen requires new infrastructure at the supply depots. The LOHC technology may circumvent this issue as it enables hydrogen storage and transportation at ambient conditions. This technology has the potential to make rail transportation more sustainable without significant additions to the infrastructure [57].

5 Summary and Conclusions

Future import routes for renewable energy units using the energy carrier hydrogen will be diverse due to the urgent need for defossilisation to halt climate change. All potential imports are equally associated with benefits and challenges. However, to accelerate the use of green hydrogen to implement a sustainable hydrogen economy, rapid implementation is an important factor. Here, the high compatibility of the LOHC technology with existing infrastructure for transportation and storage is a valuable asset enabling large-scale import of green hydrogen in the near future. The bottlenecks are the available quantity of LOHC molecules, which requires scale-up in the production despite technical availability, as well as hydrogenation and dehydrogenation units for hydrogen storage and release, respectively. However, the benefits of making use of the globally available infrastructure and efficient long-term storage provide many potential applications in the near future. LOHC may contribute to the future strategical energy reserves, support seasonal storage of renewable electricity, is an ideal storage technology for sustainable back-up power plants, and generally represents a versatile tool for individual approaches towards a local energy transition. A large variety of demonstration projects within Germany are proof for these areas of application and the great potential of the LOHC technology.

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Perspectives and Potential of Liquid Organic Hydrogen Carriers in the German Energy Scenario

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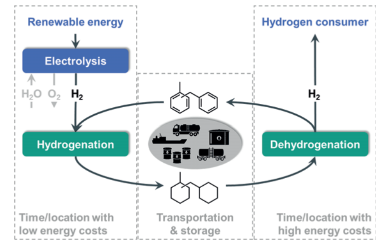

Essay: The global energy transition requires new import routes for clean energy. The liquid organic hydrogen carrier (LOHC) technology is compatible with existing liquid hydrocarbon infrastructure for storage and transportation, which enables a rapid implementation of import routes to energy demanding countries. This article assesses the potential of LOHC in the German energy landscape and highlights first demonstration projects. ....

