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Application and Analysis of Liquid Organic Hydrogen Carrier (LOHC) Technology in Practical Projects

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Abstract: In contemporary times, the utilization of liquid organic hydrogen carriers (LOHCs) has gained prominence due to their high volumetric storage density and material properties closely resembling conventional fuels. Numerous countries are incorporating LOHCs in hydrogen demonstration initiatives, encompassing applications such as hydrogen refueling stations, hydrogen-powered ships, and trains. This paper conducts a comprehensive review of seventeen LOHC projects, spanning Germany, Europe, and other nations, presenting detailed project specifications. This review includes information on project consortiums, funding sources, covered supply chains, transport modalities, and employed technologies. Through a global evaluation of LOHC projects, this review underscores the promising and competitive nature of LOHCs as a viable option for the large-scale and long-distance storage and transportation of hydrogen. The future development of this field is discussed at in the last section.

Keywords: liquid organic hydrogen carriers; LOHC projects; hydrogen storage and transportation

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1. Introduction

Hydrogen is a versatile element that appears as a clear low-density gas under normal environmental conditions. Due to its low volumetric energy density in this particular state, the storage and transportation of hydrogen are carried out in a physically or chemically converted state. The currently applied storage and transportation methods mainly include high-pressure hydrogen storage and liquid hydrogen [1]. High-pressure hydrogen storage technology is currently the most mature, with numerous practical applications in hydrogen refueling stations and fuel cell vehicles. While high-pressure hydrogen storage exhibits an advantage in mass hydrogen density, it falls short in terms of volumetric hydrogen density, typically achieving 40 g/L under the standard operating pressure of 70 MPa in most countries [2]. Under current low hydrogen consumption scenarios, hydrogen transport using long tube trailers is still feasible. However, as the hydrogen demand increases in the future, this method will become inadequate, and safety concerns will be exacerbated upon scaling up. Liquid hydrogen storage offers a volumetric hydrogen density of up to 71 g/L, while maintaining liquid hydrogen requires stringent insulation conditions, with the energy consumption during liquefaction being equivalent to approximately 30% of the stored energy content [3,4]. Similarly to natural gas infrastructure, pipeline transportation is also feasible and practically in use for hydrogen transportation. For lower mixing ratios of hydrogen (with volume fractions ranging from 5% to 10%), compatibility with most existing pipelines is feasible, but the feasibility of higher mixing ratios largely depends on the specific circumstances of each pipeline and the adaptability of its end-use equipment to changes in gas properties [5]. The assessment of the hydrogen suitability of pipelines at the component level is limited to assessing the suitability of the material and maintaining the function that this component fulfills in the gas network. It is essential to check whether a material is suitable for use in a hydrogen atmosphere and to ensure the continued integrity of the pipe or system [6]. Specific conditions of the existing infrastructure also have to be inspected and evaluated. Furthermore, the relevant rules and regulations would have to be consulted before whether the pipelines are suitable can be determined [7].

In recent years, one particularly promising avenue that has come under the spotlight is the use of liquid organic hydrogen carriers (LOHCs) for hydrogen storage and transportation [8,9]. LOHCs are organic, carbon-based liquids in which hydrogen is stored via a reversible chemical reaction (hydrogenation). If required, the stored hydrogen is released from the liquid via the reverse chemical reaction (dehydrogenation). Afterwards, the dehydrogenated carrier liquid can be reloaded with hydrogen again, forming a full storage cycle. Since many substances can undergo a reversible hydrogenation reaction, the definition of an LOHC depends on the existence of a liquid state under normal conditions [10]. Due to their physical resemblance to conventional liquid fuels, LOHCs hold the potential for easy use and transport within existing infrastructures [11–15]. Aromatic and heterocyclic compounds possess the advantages of high hydrogen storage density, reversible hydrogen absorption and release, the absence of CO_2 as a by-product during dehydrogenation, and compatibility with industrial equipment, making them the most extensively researched and closest to practical application among LOHCs [15,16]. Considering the energy requirements of the dehydrogenation process, scientific research also focuses on optimizing the process [17,18]. To facilitate the efficient separation of products and catalysts, non-homogeneous catalysts are commonly employed to catalyze dehydrogenation and hydrogenation reactions [19,20]. Furthermore, to fine-tune the thermodynamic properties, efforts such as the incorporation of heteroatoms (N or O atom) into the carbon rings [21,22] or the substitution of a more electron donating group outside the ring [23] have proven their effectiveness in precisely adjusting the energetics when governing dehydrogenation processes.

Researchers are also diligently endeavoring to transpose this technology onto a mobile platform, thereby extending its application to larger transport vessels such as ships, trains, or trucks. In the maritime/inland transport mode, conventional oil tankers as well as barges can be used for LOHC transport. The transport capacity of tankers varies from 10 t to 75 t [13,24]. This equals a maximum of 600 kg of stored hydrogen for inland, and about 4200 kg for maritime transport per transport unit, depending on the chosen LOHC compound. Also, coastal and inland transportation convoys of multiple barges with variable payloads are possible, which can increase the overall capacity of a single transport. Rail is by far the land transportation mode with the highest capacity. Existing infrastructure can be used for LOHC transport. The more cost-efficient transport mode by rail can be used to cover longer distances. Trucks are suitable for shorter distances of <100 km. No special trucks are needed for LOHC transport, since conventional tank trucks can be used for the delivery [25].

Despite the abundance of research delving into chemical reactions, carriers, catalysts, and transportation techniques, a comprehensive analysis of practical LOHC projects executed in recent years is notably scarce. To evaluate one technology regarding its potential for economically successful application, projects and tests in the operational environment are extremely important. Through pilot projects, the feasibility and stability of LOHCs in practical applications can be verified in terms of whether it can meet the intended design objectives and technical specifications. Simultaneously, during actual operations, we can identify and summarize the strengths and weaknesses of the LOHC technologies, providing a guiding direction for further technological improvements and refinements. Through the use of innovative or pioneering demonstration projects, light can be shed on their potential effects on society, the economy, and the environment, thereby offering a basis for reference in the development of relevant policies across different nations. In this paper, we delve into a comprehensive discussion of seventeen pioneering LOHC projects that have taken root not only in Germany, but also across Europe and beyond, spanning the globe.

2. LOHC Projects

Seventeen LOHC projects are identified overall. The locations of the identified projects across the three clusters of Germany, Europe, and International/Worldwide are visualized in the form of the following figures.

2.1. Projects in Germany

Eleven projects have been found in Germany and detailed information can be seen in the Table 1. From these projects, dibenzyltoluene/perhydro-dibenzyltoluene (in short, DBT) seem to be the most prominently used LOHC compounds in Germany. The chemical structures of both LOHC molecules, the dehydrogenated form dibenzyltoluene (H0-DBT) and the hydrogenated form perhydro-dibenzyltoluene (H18-DBT), are shown in Figure 1. DBT is a promising option, with the potential to reach an industrial scale application with high hydrogen storage densities, thus ensuring space-efficient energy storage without compromising safety or stability. Within the typical range of hydrogen content, DBT offers an acceptable level of 6.2 wt%. This is equal to a volumetric storage density of hydrogen around 57.2 kg H_2/m^3 [26] or ~6800 MJ/m^3, based on the lower heating value of hydrogen of 33.3 kWh/kg [27]. Furthermore, DBT has high boiling points and rather low melting points, which results in various advantages over the other carriers. Due to the high boiling points of over 370 °C, DBT faces low evaporation and can be handled without constrains, even at elevated temperatures [10]. Moreover, with the high boiling point, the dehydrogenation reaction could occur mostly in the liquid phase, which brings an additional benefit as there is no evaporation and condensation step required in the reactor. The melting points being lower than −34 °C mean that DBT is in a liquid phase in nearly all appearing environmental conditions [9,12]. This is an advantage as the already established and proven infrastructure for liquid hydrocarbons can be used without restrictions. On the other hand, it poses the risk of flocculation and high viscosity under cold ambient conditions in winter, thus making it difficult to pump the liquid. Mixtures of H0-DBT/H18-DBT and benzyltoluene could provide a solution to this problem [28]. Since the discovery of the DBT as an LOHC, the hydrogenation of H0-DBT to H18-DBT has been intensively studied. In first investigations at temperatures below 200 °C, ruthenium-based catalysts show the highest activity and selectivity, with a decreasing order of activity depending on the catalyst support as follows: $Ru/Al_2O_3 \geq Ru/C > Pd/C > Pd/Al_2O_3$ [29,30]. For the dehydrogenation of H18-DBT, Pt-based catalysts have been extensively studied in recent years and have proven to be the most suitable catalyst for this task [31].

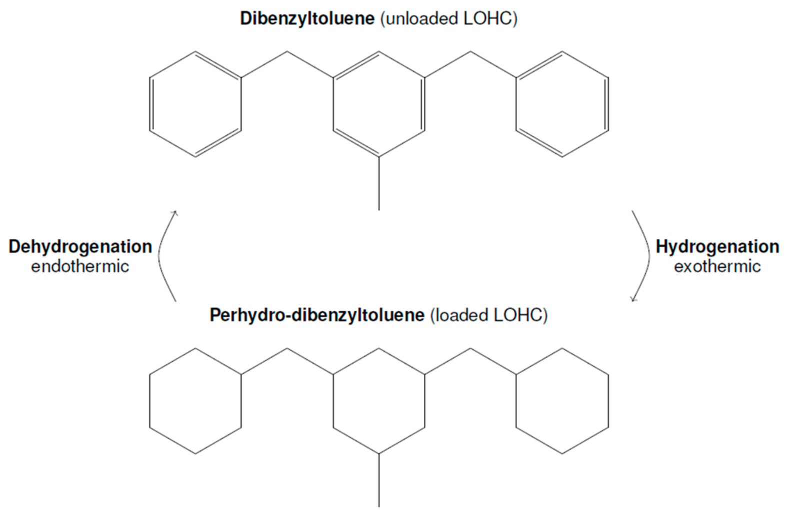

Figure 1. Chemical structures of the LOHC system perhydro-dibenzyltoluene/dibenzyltoluene.

Table 1. List of identified LOHC projects in German.

No.	Project Name	Project Specifications
1	AquaVentus [32] 2023–2035	Description: Use electricity from offshore wind farms to produce green hydrogen Location: Helgoland Target: 10 GW green hydrogen (offshore wind) until 2035, transport per pipeline with later storage as LOHCs (2024) Consortium: Agentur für Wirtschaftsförderung Cuxhaven, Aktiengesellschaft EMS, Brunsbüttel Ports GmbH, Buckstay Group GmbH, Deutsche AVIA Mineralöl-GmbH, CHATHAM PARTNERS, Cuxport GmbH, DNV, Deutsche Shell Holding GmbH, Fraunhofer IFAM, EnBW Energie Baden-Württemberg AG, EnTec Industrial Services GmbH & Co. KG, Entwicklungsgesellschaft Brunsbüttel mbH, E.ON SE, GASCADE Gastransport GmbH, Gemeinde Helgoland, German LNG Terminal GmbH, GÖRG Partnerschaft von Rechtsanwälten mbB, H_2-Industries SE, HHLA Hamburger Hafen und Logistik Aktiengesellschaft, HanseWerk AG, H. C. Hagemann GmbH & Co. KG, Hydrogenious LOHC Technologies GmbH, HynamicsDeutschland GmbH, ILF Beratende Ingenieure GmbH, Kongstein GmbH, Linde GmbH, Mabanaft GmbH, MHI Vestas Offshore Wind A/S, Northland PowerN.V.,Nederlandse Gasunie, Orsted Wind Power Germany GmbH, OWT Offshore Wind Technologie GmbH, Parkwind nv, Reuther STC, ROSEN Technology and Research Center GmbH, RWE Renewables GmbH, Siemens Gamesa Renewable Energy SA, Siemens Energy AG, Stiftung Offshore Windenergie, Tractebel Overdick GmbH, Vallourec Deutschland GmbH, Vattenfall Innovation GmbH, Versorgungsbetriebe Helgoland, VIRYA ENERGY NV, Weidmüller Interface GmbH, WindMW GmbH Financing: No information available Supply chain: Electrolysis, hydrogenisation, transport LOHC compound: No information available Electrolysis: Offshore wind energy and on-site electrolysis Hydrogenisation: Excess hydrogenation heat to cover residential demand of heating energy Transport: Primary mode of transport: water, tank ship
2	SmartQuart [33,34] 2020–2024	Description: Products and solutions for the planning, construction and operation of energy-optimized neighbourhoods in Germany Location: Bedburg, Essen and Kaisersesch Target: Development of a smart concept for a sustainable hydrogen infrastructure including the LOHC technology; different scenarios for industrial and residential applications Consortium: E.ON, gridX, Hydrogenious LOHC Technologies, RWTH Aachen, Viessmann, H_2 MOBILITY Germany, RWE Power Financing: Partly funded by BMWi (8.6 million EUR) Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: (Di-)Benzyltoluene Electrolysis: Use of excess renewable energy (wind, solar); usage of excess electrolyser heat to power a nearby wastewater treatment plant Hydrogenisation: No information available Transport: Planned usage of existing fossil fuel infrastructure Dehydrogenisation: No information available Usage: Heat, electricity, mobility, and industry
3	Get H_2 [35,36] 2024–2030	Description: Planning of realization of infrastructures for the production, purchase, transport, and storage of green hydrogen (H_2) in several projects Location: Lingen Target: Build up a countrywide hydrogen infrastructure Consortium: RWE Generation SE, Siemens, ENERTRAG, public utility Lingen, Hydrogenious LOHC Technologies, Nowega, Research center Jülich, IKEM, Salzgitter Flachstahl, Thyssengas, bp, Evonik, OGE Financing: Applied for IPCEI funding Supply chain: Electrolysis, hydrogenisation, transport, usage LOHC compound: Dibenzyltoluene Electrolysis: Power-to-gas plants, electricity from wind and sun, usage of excess electrolyser heat Hydrogenisation: No information available Transport: Road, tank trucks Usage: Focus on mobility and large-scale industrial consumers

Table 1. *Cont.*

No.	Project Name	Project Specifications
4	TransHyDE/H_2Mare [37] 2021–2025	Description: The H_2Mare-lead project develops ways to produce hydrogen and hydrogen downstream products using off-grid wind turbines directly at sea Location: Helgoland/Hamburg Target: Generate a LOHC supply chain from off-shore wind energy, dehydrogenation at the port of Hamburg Consortium: More than 200 partners, not further disclosed Financing: BMBF funded (total volume of 700 million EUR, fraction for TransHyDE/H_2Mare not declared) Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation LOHC compound: No information available Electrolysis: No information available Hydrogenisation: No information available Transport: Road, water; usage of existing fossil fuel tank ship infrastructure Dehydrogenisation: No information available
5	Kopernikus Power-to-X [38] 2016–2025	Description: Investigating Power-to-X (ptx) technologies Location: Not location-specific Target: Research on possible technologies to convert green electrical energy into chemical forms of energy (e.g., LOHCs) Consortium: AREVA H_2GEN GmbH, AUDI AG, AVL List GmbH, Beiersdorf AG, Bund für Umwelt und Naturschutz Deutschland e.V. (BUND), CAT Catalytic Centre, Clariant Produkte, Deutschland) GmbH, Climeworks Deutschland GmbH, Covestro Deutschland AG, DB Energie, DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., DECHEMA), Deutsches Institut für Wirtschaftsforschung (DIW Berlin), Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR), Evonik Creavis GmbH, Ford-Werke GmbH, Forschungszentrum Jülich GmbH (FZJ), Framatome GmbH, Fraunhofer-Institut für Solare Energiesysteme (ISE), Friedrich-Alexander-Universität Erlangen Nürnberg (FAU), Greenerity GmbH, Helmholtz-Institut Erlangen-Nürnberg, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Heraeus GmbH & Co. KG, H-TEC SYSTEMS GmbH, Hydrogenious LOHC Technologies GmbH, International Association for Sustainable Aviation e.V. (IASA), INERATEC GmbH, Institut für Energie- und Umweltforschung Heidelberg GmbH (ifeu), Institut für ZukunftsEnergie und Stoffstromsysteme gGmbH (IZES), Karlsruher Institut für Technologie (KIT), Leibniz-Institut für Interaktive Materialien e.V. (DWI), Linde AG, Ludwig-Maximilians-Universität München (LMU), Max-Planck-Institut für Chemische Energiekonversion (CEC), Öko-Institut e.V., Ostbayerische Technische Hochschule Regensburg (OTH), RWTH Aachen, SCHOTT AG, Siemens AG, sunfire GmbH, Technische Universität München (TUM), Volkswagen AG (VW), Wacker Chemie AG, Wissenschaftszentrum Berlin für Sozialforschung (WZB), WWF Deutschland, Zentrum für Angewandte Energieforschung Bayern e.V. (ZAE Bayern), International Association for Sustainable Aviation e.V. Financing: BMBF 29.7 million EUR Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: Dibenzyltoluene -> Benzyltoluene Electrolysis: Search for ways to reduce the amount of iridium used in electrolysis as much as possible, without making the process less efficient Hydrogenisation: No information available Transport: Road, tank trucks; usage of existing infrastructure (e.g., storage, tank vehicles) possible Dehydrogenisation: Investigation of alternative ways to provide dehydrogenation heat Usage: Mobility, Chemical industry, Industrial furnaces (glass manufacturers)
6	LOHC fuel station Erlangen [39] 2021 onwards	Description: Hydrogen fuel station Location: Erlangen Target: First German LOHC fuel station from green hydrogen (PV) Consortium: Hydrogenious LOHC Technologies, H_2 Mobility Financing: No information available Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: Dibenzyltoluene Electrolysis: Use of solar energy Hydrogenisation: No information available Transport: Road, tank trucks Dehydrogenisation: No information available Usage: Mobility (Fuel station)

Table 1. *Cont.*

No.	Project Name	Project Specifications
7	Hydrogen Lab Bremerhaven [40] –2022	Description: Investigating the potential of green hydrogen in four selected applications Location: Bremerhaven Target: Implementation of a test area for electrolysis; development of a complete hydrogen supply chain under the usage of the LOHC technology Consortium: Fraunhofer IWES, University Bremerhaven Financing: 20 million EUR from Bremen and EU Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: Dibenzyltoluene Electrolysis: Use of wind energy Hydrogenisation: No information available Transport: No information available Dehydrogenisation: No information available
8	LOHC train [41] 2019–2023	Description: Equip trains with LOHC technology Location: Jülich Target: Development of a LOHC-powered commuter train Consortium: Helmholtz Institute Erlangen/Nuremberg, Research Center Jülich, Hydrogenious LOHC Technologies, FAU Erlangen/Nuremberg, Fraunhofer HHI Financing: 28 million EUR from Bavarian State Ministry of Economic Affairs, Regional Development and Energy Supply chain: Dehydrogenisation, usage LOHC compound: No information available Dehydrogenisation: No information available Usage: Mobility (commuter train)
9	Hydrogenlogistics [42] 2017–2019	Description: The Hydrogenlogistics project has developed, built, and tested a modular dehydrogenation system for hydrogen carrier materials on an industrial scale, which will be used to supply hydrogen refuelling stations Location: Germany (non-specific) Target: Cost reduction of hydrogen transport by 80%, development of modular dehydrogenation system (ReleaseBOX/ReleaseUNIT) for hydrogen fuel stations Consortium: Hydrogenious LOHC Technologies, EU H2020 Financing: EU 2.3 million EUR (3.3 million EUR in total volume) Supply chain: Transport, dehydrogenisation, usage LOHC compound: Dibenzyltoluene Transport: Road, tank trucks Dehydrogenisation: No information available Usage: Mobility
10	Helmholtz Hydrogen Cluster [43] 2021 onwards	Description: The The Helmholtz Cluster for Sustainable and Infrastructurally Compatible Hydrogen Economy (HC H_2) will act as a nucleus for a hydrogen model region, research future innovative hydrogen technologies and accompany them into practical application Location: Jülich Target: Research possibilities for a LOHC-driven hydrogen infrastructure Consortium: Research Center Jülich, DLR, Campus Power-to-X, RWTH Aachen, FH Aachen, iNew, FAU Erlangen/Nuremberg Financing: No information available Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: No information available Electrolysis: Use of excess renewable energy Hydrogenisation: No information available Transport: Road, tank trucks; use of existing logistics Dehydrogenisation: No information available Usage: E.g. train with LOHC technology
11	HECTOR [44] Until 2023	Description: Pilot plant for storage of green hydrogen in LOHC Location: Dormagen Target: 2nd biggest plant worldwide for storage of green hydrogen with LOHC technology Consortium: LOHC Industrial Solutions NRW, Hydrogenious LOHC Technologies, Covestro, Research center Jülich, Royal Vopak Financing: 9 million EUR from progres.nrw fund (20 MEUR in total volume) Supply chain: Hydrogenisation LOHC compound: Dibenzyltoluene Hydrogenisation: Usage of excess hydrogenation heat for local energy supply

However, it has to be noted that the dehydrogenation process requires a large amount of heat energy to drive the endothermic reaction. In the best case, this heat requirement is fully covered by an external heat source, such as waste heat from industrial processes. On the contrary, when no heat source is available and the H18-DBT is at an ambient temperature, the total energy requirement for the endothermic dehydrogenation process must be covered by the use of the stored/generated hydrogen. For this case, DBT reaches an efficiency of only 64%, which corresponds to a volumetric energy density of ~4300 MJ/m^3 [26].

Therefore, many projects in Germany, shown in the Figure 2, demonstrate a commitment to energy conservation and cost optimization. These pioneering initiatives are ingeniously enhancing the overall efficiency of their LOHC concepts, thereby significantly boosting sustainability. This distinctive attribute sets these projects apart from their counterparts, leading us to consider them superior in their domain.

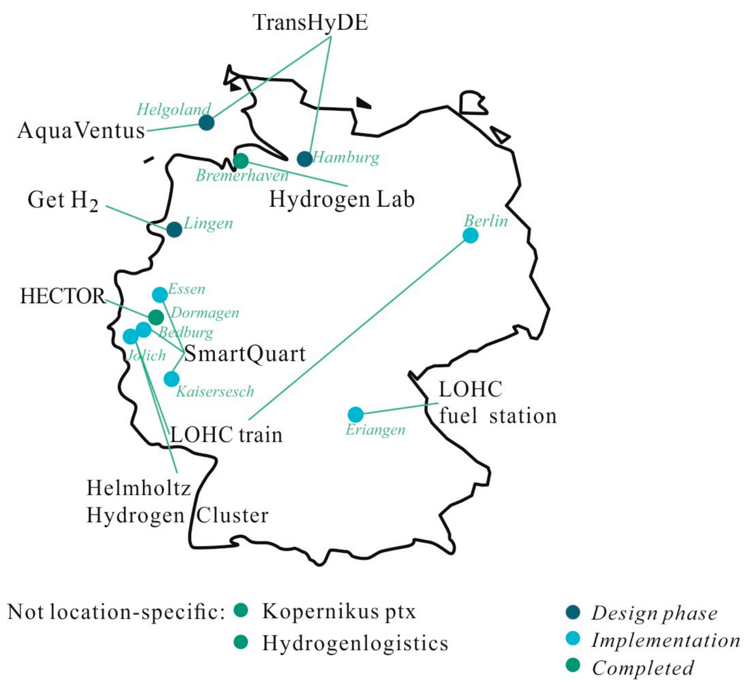

Figure 2. LOHC project locations in Germany.

For example, the AquaVentus project uses the excess hydrogenation heat to cover the residential heating energy demand of the residents of Helgoland. This directly influences the overall energy efficiency of the production system. Notably, this project stands out among all recognized LOHC initiatives with an ambitious target of generating 10 GW of hydrogen energy. Although the timeline to attain this milestone extends until 2035, it underscores the project's commitment to scaling up green energy production at an unprecedented level.

In addition, the SmartQuart project harnesses surplus heat from its electrolysis process to energize neighboring industrial facilities, such as a proximate wastewater treatment plant. Furthermore, it strategically banks on extensively utilizing the pre-existing fossil fuel infrastructure for the transportation and storage of LOHCs. SmartQuart stands out as an exceptionally innovative H_2 project, dedicated to exploring the groundbreaking H_2/LOHC concept with three exemplary 'real laboratories', which are mimicking real-life cases of H_2 and LOHCs.

GET H_2 plans also to use the excess heat of electrolyzers, while the TransHyDE/H_2Mare project also underscores the strategic utilization of pre-existing fossil fuel infrastructures, i.e., fossil fuel tank ships. By integrating such innovative approaches, both ventures not only minimize costs, but also maximize resource utilization, thereby presenting an attractive proposition from multiple perspectives, including financial and environmental sustainability.

One of the biggest current hydrogen projects, Kopernikus Power-to-X, announced the investigation of alternative ways of providing the needed dehydrogenation heat inside the project's LOHC sector, which could lead to a higher potential of LOHCs overall. This makes Kopernikus Power-to-X a very important project for the future LOHC research trajectory. Moreover, the usage of the existing transportation infrastructure further adds to the positive aspects of this prominent project.

Among the most prominent hydrogen initiatives today, Kopernikus Power-to-X has declared its intent to delve into alternative methods for supplying dehydrogenation heat within the project's LOHC sector. In an endeavor to enhance efficiency and push the boundaries of hydrogen energy storage, the Kopernikus Power-to-X project is actively seeking innovative pathways to generate the essential dehydrogenation heat within its LOHC domain. This pioneering research holds the promise of significantly boosting the overall performance and capacity of the LOHC system, thereby solidifying its role in the future of sustainable energy solutions.

Project HECTOR in Dormagen takes its place alongside other listed projects, distinguished by its commitment to transforming surplus hydrogenation heat into a valuable resource for the local energy needs. This pioneering initiative uniquely focuses on optimizing the underutilized thermal output from hydrogenation processes. In contrast, the data available for the rest of the enlisted projects do not disclose any strategies that may be employed to leverage the existing infrastructure or to devise methods for utilizing or generating the essential heat energy during the hydrogenation and dehydrogenisation cycles. Furthermore, a significant portion of the ongoing projects do not embody the entire LOHC supply chain in its totality. Instead, as research institutions dedicated to further investigating the possibilities of LOHC technology, they are primarily focused on honing the specific core components or functionality of LOHC technology.

2.2. Projects across Europe

The transport chain of LOHCs can be split into two categories as follows: uninterrupted transport and interrupted transport. Single-link transport chains (uninterrupted transport) are characterized by the fact that the delivery and reception points (source and destination) can be reached without changing the means of transport. Multi-link transport (interrupted transport) involves a change of the means of transport and thus of the transshipment processes. The interrupted transport can be split into pre-carriage (gathering of shipments), main-carriage (transport between transport nodes), and on-carriage (distribution to customer). For the project "Green Hydrogen @ Blue Danube", the typically interrupted transport of LOHCs is planned to be transported, for most of the route, by ship across the Danube, which can be seen in the Figure 3. The near-distance distribution then continues using trucks.

As a collaboration of Hydrogenious LOHC Technologies and VERBUND, the Green Hydroge @ Blue Danube project is one of the most prominent projects regarding LOHC technology. Besides the overall project reaching many parts of Europe along the river Danube, the project roll-out is supposed to take place in Bavaria and Austria, where the general setup will be tested on a small scale. Green Hydrogen @ Blue Danube plans to heavily use the existing fossil fuel infrastructure in the form of tank ships to transport the loaded LOHCs from Romania to Austria and Germany. Moreover, this pioneering project holistically integrates the entire LOHC supply chain, encompassing every stage from the inception through to electrolysis and the eventual utilization of LOHCs.

HySTOC in Finland forms a big step towards developing distribution and storage systems for hydrogen refueling stations, and is therefore a crucial project for the vision of using LOHCs in the transportation sector and in everyday life. Although the Green Crane project is based primarily in Spain, a main goal of the project is to implement a LOHC supply chain to Lingen/Germany, where other LOHC-themed projects are also based. In the future, this could enable synergies in terms of LOHC supplies and the overall technological research. One significant advantage lies in the comprehensive integration of the entire LOHC supply chain, and a portion of the hydrogen is harvested as a valuable by-product, which increases the system's energy efficiency.

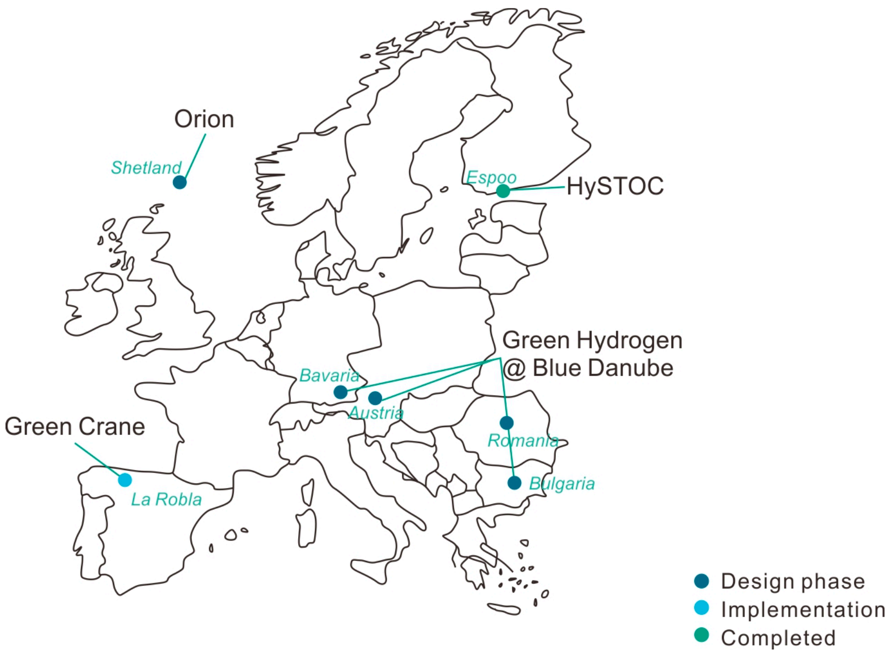

Figure 3. LOHC project locations in Europe.

Embarking on an ambitious journey that extends well into the future, the Orion Project boasts one of the most extensive project durations, spanning until 2050 and beyond. Orion is steadfastly aimed at achieving a monumental annual production capacity of 32 TWh of hydrogen, which is planned to be exported to other countries via the use of LOHC technology. This would drastically influence the LOHC supply in the future, but whether the project lives up to its ambitious expectations is somewhat questionable. For a comprehensive overview of European projects' details, kindly refer to the Table 2.

Table 2. List of identified LOHC projects across Europe.

No.	Project Name	Project Specifications
1	IPCEI Green Hydrogen @ Blue Danube [45] 2022–	Description: In the "Blue Danube" project, green hydrogen produced in Bulgaria and Romania will be stored in LOHCs and transported via the Danube to customers in Austria and Germany Location: Romania and Bulgaria to Germany and Austria Target: European supply chain for green hydrogen; project roll-out in Bavaria with 3000 tons of green hydrogen via LOHCs Consortium: VERBUND, Hydrogenious LOHC Technologies, Bosch, DB Schenker, Donau Tankschifffahrtsgesellschaft, Siemens Energy Financing: No information available Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: (Di-)Benzyltoluene Electrolysis: Solar, hydro, and wind energy, on-site electrolysis Hydrogenisation: No information available Transport: Water (Danube), road, tank ships, tank trucks; inland vessels from fossil fuel transport Dehydrogenisation: No information available Usage: Industry, mobility

Table 2. *Cont.*

No.	Project Name	Project Specifications
2	HySTOC [46] 2018–2022	Description: Complete hydrogen logistics up to use at the refuelling station is being researched Location: Finland (Espoo) Target: Research applicability of LOHC technology for the distribution and storage of hydrogen refuelling stations Consortium: Institute of Chemical Reaction Engineering, Oy VTT Technical Research Centre of Finland Ltd., Hydrogenious LOHC Technologies, HyGear B.V., Oy Woikoski Ab, FAU Erlangen/Nuremberg Financing: EU funded (2.5 million EUR) Supply chain: Hydrogenisation, transport, usage LOHC compound: Dibenzyltoluene Hydrogenisation: No information available Transport: Road, tank trucks, 1000 l electrically heated IBC containers Usage: Mobility (refuelling station)
3	Orion Project [47] 2026–2050+	Description: Production and transport of hydrogen Location: Shetland Target: Annual production of 32 TWh blue/green hydrogen with partial exports to GB and other countries Consortium: Shetland Islands Council, OGTC, Highlands and Islands Enterprise Financing: 11.5 million EUR Shetland Islands Council Supply chain: Electrolysis, hydrogenisation, transport LOHC compound: No information available Electrolysis: Use of on- and offshore wind Hydrogenisation: No information available Transport: Water, tank ship; export via existing facilities possible
4	Green Crane [48] 2019–2024	Description: Transport LOHCs from Spanish seaports to the Netherlands and establish large LOHC storage facilities around the ports Location: La Robla (Spain) Target: Hydrogen transport from Spain to central Europe Consortium: Enagás Renovable, Hydrogenious LOHC Technologies, Vopak, Térega, Petronor, Arcelor-Mittal I+D, Bosch, McPhy, Vestas, Falck Renewables, IGNIS Energia, H2V, Gransolar Financing: Partly EU funded Supply chain: Electrolysis, hydrogenisation, transport, dehydrogenisation, usage LOHC compound: No information available Electrolysis: Water electrolysis with PEM electrolyser; water electrolysis with ALK electrolyser; by-product Hydrogenisation: No information available Transport: Water, ship Dehydrogenisation: No information available Usage: Mobility, energy, industry

2.3. International Projects

Further projects located out of Europe are Dii Desert Energy and the Haru Oni project of which locations and details are shown in the Figure 4 and the Table 3, whereas the former has to be understood as a form of a research initiative regarding general hydrogen topics, along with a project section to build up a stable energy supply via LOHC technology. In neither of the projects is there a specified strategy to harness surplus hydrogenation heat for the addressing of energy efficiency concerns.

Haru Oni is based in Chile, and plans to create relevant amounts of e-fuel, i.e., e-methanol. In the early project stages, the Porsche AG plans to import those e-fuels and test their applicability for motor sports. Unfortunately, it is not specified whether further use in the transportation sector or in private transport is planned. It should be that the produced e-fuels are not to be understood as LOHCs, as there are plans to use methanol as a fuel, instead of unloading the hydrogen from the carrier fluid. This negatively influences the system's overall environmental impact because the multi-use character of LOHCs is not exploited in this project.

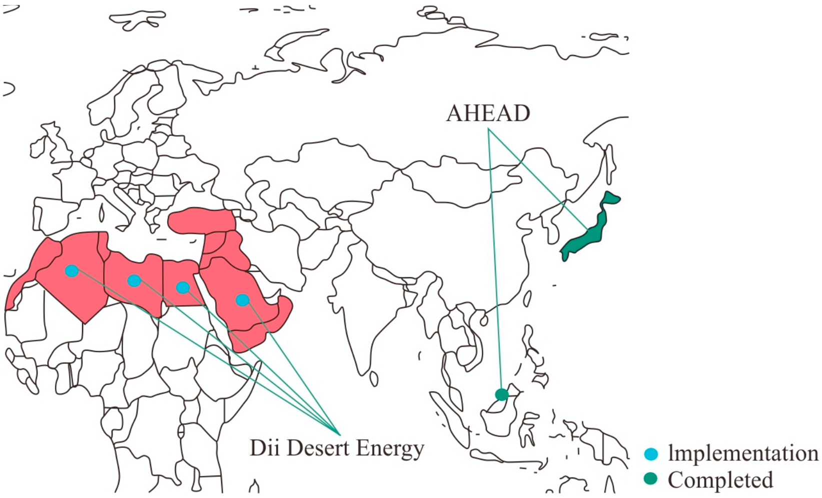

Figure 4. Locations of international LOHC projects.

A third project is the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD). Instead of DBT, the toluene system/methylcyclohexane, another promising option for liquid hydrogen storage, has been used as the hydrogen carrier in this project. The chemical structure of LOHC molecules, the dehydrogenated form toluene (TOL), and the hydrogenated form methylcyclohexane (MCH) are presented in Figure 5.

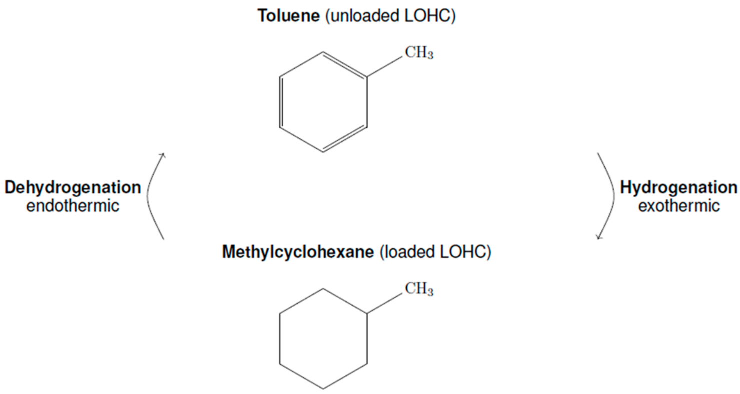

Figure 5. Storage cycle of the LOHC system toluene/methylcyclohexane. Methylcyclohexane is abbreviated as MCH.

TOL/MCH demonstrates same range at the same level as the DBT system, reaching around 6.2 wt% of hydrogen content. However, due to the lower liquid density of MCH as the hydrogenated component with 769 kg/m^3, the volumetric storage density of hydrogen in the TOL/MCH system is lower than for DBT [49]. Research in the field of TOL/MCH as an LOHC has been proceeding over a much longer time than for DBT, and the used aromatic compounds have been known for decades [12]. Historically, many different catalysts have been investigated for the hydrogenation of toluene, such as Ni, Pd, and Pt. In the most recent publications regarding this topic, the following sequence of catalyst activity on alumina supports was reported: Rh > Pt > Ir > Re. However, at elevated temperatures above 170 °C, the Rh activity decreased, and the Pt presented the catalyst with the highest activity [50]. The basic knowledge of the MCH dehydrogenation and preferred catalysts were established already in the 1980s. On this basis, the use of Pt-based sulfur-modified catalysts proves to be particularly advantageous. Many recent publications focus on the development of Pt-based bimetallic catalysts including the addition of a second metal, such as Sn, Mo, or Cu, to the catalysts. In most cases, it was found that the addition of the second metal has beneficial effects up to a certain mixture ratio. When the contents of the second metal are too high, the dilution effects of the Pt can usually be observed, which leads to a decrease in the activity of the catalyst [51–53]. Another direction of research in MCH dehydrogenation catalysts is the improvement of the support structure. Most common catalysts use Al_2O_3 supports, but many other types, such as Mg-Al-O, USY zeolite, TiO_2, TiO_2-Al_2O_3, or Silicalite (SiO_2), have also been investigated [31].

Based on this technology, the Japanese company Chiyoda Corporation already offers an LOHC system called SPERA [54]. The Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) project of Chiyoda is active in the experimental research and planning of the practical application of hydrogen supply chains that stably supply existing but unused energy transported in a stable manner from overseas to Japan using LOHC technology. There, the released hydrogen from MCH is utilized as fuel for gas turbines in a power plant.

The melting points of toluene and methylcyclohexane are low, thus do not present any risk of freezing when in practical use in cold ambient conditions. This characteristic also results in the rather low boiling points of both components. These low boiling points lead to a high evaporation rate at ambient conditions, which further increases at higher temperatures. Therefore, as for the AHEAD project, the adequate sealing and pressure tightness of all handling and storage equipment for the TOL/MCH system is more important than for other LOHC systems in order to avoid losses to the environment.

Table 3. List of identified international LOHC projects.

No.	Project Name	Project Specifications
1	Dii Desert Energy [55] 2009 onwards	Description: Production and export of green hydrogen Location: Middle East and North Africa Target: Build up emission-free and stable energy supply chains with the help of the LOHC technology Consortium: Dii network, H_2 Industries Financing: No information available Supply chain: Electrolysis, hydrogenisation, transport LOHC compound: No information available Electrolysis: Wind and solar energy Hydrogenisation: No information available Transport: Water, ship
2	AHEAD Demonstrator Project [56] 2017–2020	Description: Production of hydrogen via steam reforming and export from Brunei in the form of LOHCs to Japan Location: Japan/Brunei Target: Showing the possibilities of building up a hydrogen transport chain with LOHCs Consortium: Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD): Chiyoda Corporation, Mitsubishi Corporation, Mitsui & Co., Ltd., Nippon Yusen Kabushiki Kaisha Financing: National Research and Development Agency, New Energy and Industrial Technology Development Organization (NEDO) Supply chain: Hydrogenisation, transport, dehydrogenisation, usage LOHC compound: Toluene Hydrogenisation: No information available Transport: Water, ship Dehydrogenation: No information available Usage: Energy

3. Summary and Outlook

For all the 17 projects, the majority of those putting more effort into LOHC pilot projects, including hydrogen refueling stations and hydrogen ships and trains carrying LOHCs as a hydrogen source, are found in Germany. This way of loading LOHCs onto mobile devices rather than the use of hydrogen tanks greatly improves the safety of hydrogen storage and transportation.

Among these projects, considering the reasonably good performance of all properties, H0-DBT/H18-DBT and TOL/MCH seem to be the most prominently used LOHC compounds. They are currently tested in the identified projects under practical conditions to evaluate their economic viability and to improve the systems by collecting data from the field.

Since the hydrogenation of the LOHC storage cycle is typically performed at a location with excessive (e.g., renewable) energy, this source of heat might not have a dedicated use on site. In contrast, the endothermic dehydrogenation reaction is usually carried out at a location with higher energy scarcity, where hydrogen is required either as an energy carrier or as feedstock. Therefore, many projects are dedicated to increasing the total efficiency of their LOHC concepts, and are therefore implementing ways to save energy and costs, such as the project AquaVentus, SmartQuart, GET H_2, Kopernikus Power-to-X, and HECTOR, ect. They significantly increase the overall efficiency of the system by utilizing the unavoidable heat losses and waste heat throughout the hydrogen system, such as from the hydrogenation process, fuel cells, and electrolyzers. Moreover, the application of LOHC systems can also be combined with the external waste heat of the micro gas turbine or the natural gas-fired combined heat and power (CHP) system.

Governments and companies do not invest in the entire hydrogen supply chain, but only a part of it in order to test the feasibility and cost effectiveness of one section. Some of the identified LOHC projects are mainly concepts for successfully implementing the still-young LOHC technologies. Most of the projects do not cover the complete LOHC supply chain of electrolysis, hydrogenation, transport, dehydrogenization, and usage, but are researching and implementing parts of the said supply chain. This way, focusing on demonstrating select or several key segments with a forward-looking approach can reduce the implementation complexity and investment scale of projects. By having multiple projects individually showcase different segments within various hydrogen value chains, these efforts can collectively achieve a comprehensive, future-oriented demonstration across all technological stages of the entire hydrogen supply chain of LOHCs.

As the global demand for clean energy continues to rise, with hydrogen playing an evermore significant role as a zero-emission energy source, governments worldwide are introducing industrial development plans for hydrogen, and intensifying their backing for research and development across a range of hydrogen storage technologies, including LOHCs. With the breakthrough of key technologies and the validation of scalability in large-scale productions, it is expected that LOHC technology will accelerate its pace of commercial application in the coming years, particularly demonstrating significant potential in areas such as long-distance transportation and distributed energy systems.

Although LOHC technology has proven to be feasible in current pilot projects, the issue of cost must be considered for its large-scale commercialization. The assessment of LOHC costs poses a challenge, as data from large-scale commercial deployment are not yet available, and still need some time to be validated and analysed in the future.

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