Department for Business, Energy & Industrial Strategy

# Bulk Scale Storage and Transportation of Hydrogen using LOHC

## Phase 1 Feasibility Report (Public Report)

BEIS Low Carbon Hydrogen Supply 2 Competition Stream 1

24 October 2022

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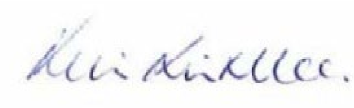
24 October 2022

# Bulk Scale Storage and Transportation of Hydrogen using LOHC

Phase 1 Feasibility Report (Public Report)



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## Acronyms and Abbreviations

| | |
|---|---|
| BT | Benzyltoluene |
| CDM | The Construction (Design and Management) Regulations |
| CLP | Classification, Labelling and Packaging Regulations |
| CFRT | Covered Floating Roof Tank |
| COMAH | Control of Major Accident Hazards Regulations |
| DGHAR | Dangerous Goods in Harbour Areas Regulations |
| EFRT | External Floating Roof Tank |
| EHS | Environment, Health and Safety |
| EU | European Union |
| FRT | Fixed Roof Tank |
| HFO | Heavy Fuel Oil |
| IFRT | Internal Floating Roof Tank |
| LOHC | Liquid Organic Hydrogen Carrier |
| MCH | Methylcyclohexane |
| NAMOS | The Dangerous Substances (Notification and Marking of Sites) Regulations 1990 |
| PBT | Perhydro-benzyltoluene |
| PD | Positive Displacement |
| PVRV | Pressure Vacuum Relief Valve |
| REACH | UK Registration, Evaluation, Authorisation and Restriction of Chemicals Regulation |
| TOL | Toluene |
| TRL | Technology Readiness Level |
| UK HSE | United Kingdom Health & Safety Executive |
| VOC | Volatile Organic Compound |
| VRU | Vapour Recovery Unit |

## Executive Summary

The aim of the BEIS Low Hydrogen Supply 2 (Hydrogen Supply 2 or HYS2) Competition is to identify, support and develop credible innovative hydrogen supply or enabling technologies to bring about a step change in their development. Stream 1 is intended for market entry solutions at Technology Readiness Levels (TRLs) 4-6. ERM has been funded by BEIS under this competition, specifically under “Category 3: Hydrogen Storage and Transport” to develop an innovative solution for the bulk scale storage and transportation of hydrogen using Liquid Organic Hydrogen Carriers (LOHC). This report covers Phase 1 of the project, presenting findings of a feasibility assessment of the proposed solution and a recommendation for the next stage of the project (Phase 2).

The potential for hydrogen in decarbonising energy systems has been recognised for many decades. However, there are challenges associated with transportation of hydrogen at bulk scale in its pure form, such as safety concerns (due to high flammability of hydrogen) and the potential high energy demand required to enable bulk transport of hydrogen (due to e.g. its low molecular weight and very low boiling point).

Liquid Organic Hydrogen Carriers (LOHCs) are liquids under ambient conditions and provide a means for storing and handling large volumes of hydrogen. They can contain around 70% of the hydrogen as liquid hydrogen, per unit volume, making them a potentially advantageous means of storing and transporting hydrogen at scale. They behave in a manner similar to conventional, petroleum derived, liquid fuels opening the opportunity for existing oil facilities to be repurposed for hydrogen.

In this study, the viability of re-purposing conventional oil storage facilities for the future storage of hydrogen in the form of LOHC has been evaluated. A successful evaluation paves the way for a real world demonstration in Phase 2, offering the UK the opportunity to gradually transition existing oil assets to store hydrogen at scale at multiple key locations. This will then also enable hydrogen to be transported around the UK by road, rail, ship or via the pipeline network that already connects many of our major oil terminals and ports.

Two LOHC pairs with high technology readiness level (TRL), namely Toluene (TOL) and Benzyltoluene (BT) - forming Methylcyclohexane (MCH) and Perhydro-benzyltoluene (PBT) when loaded with hydrogen respectively - have been assessed in terms of their physical and chemical characteristics. Their characteristics have been compared against different oil products commonly processed and handled in conventional oil storage and handling facilities.

The characteristics of TOL-MCH pair were found to be similar to light oil products such as gasoline or kerosene; whereas the BT-PBT pair were found to have similar characteristics to heavy oil products such as crude and heavy fuel oil. Hence, it is anticipated that existing infrastructure which handle light oil products can be suitably re-purposed to handle toluene/ MCH with no/ minor modification. Similarly, no/ minor modification is anticipated for re-purposing existing infrastructure which handle heavy oil products for handling the BT-PBT pair.

A high level assessment was carried out on the suitability of typical conventional oil storage facilities for handling LOHC. There are no known limitations on the storage and handling facilities (e.g. storage tank and loading/unloading systems) which could be utilised for storing and handling LOHC. Although there are preferential types of storage tank and pumping system for the relevant LOHC pair (e.g. floating roof tank and centrifugal pump are considered most suitable for TOL-MCH pair), others could be utilised after further checks and/ or suitable modifications. A safety review study was carried out to identify and assess the hazards associated with the operation of an existing oil storage facility for storing LOHCs. A number of hazards were identified; however, none are considered limiting in terms of the ability to store and transport LOHC safely.

A ‘real world’ LOHC trial programme has been developed, covering a full scale test programme, including the boundaries and scale of the trial system. The trials, which are to be held at a UK oil terminal, have been designed to resolve some of the remaining uncertainties identified from Phase 1, particularly regarding fluid flow characteristics, potential contaminant take up and a suitable regulatory pathway. Finalisation of the trial programme will be completed with the selected UK Oil terminal, prior to application for Phase 2 funding.

# 1. INTRODUCTION

## 1.1 Project Overview

Liquid Organic Hydrogen Carriers (LOHCs) have the potential to carry almost as much hydrogen ($H_2$) per unit volume as liquid hydrogen ($LH_2$) and can do so safely and cleanly at atmospheric temperature and ambient pressure. LOHCs are highly stable under normal conditions and, unlike $LH_2$, do not have issues relating to boil off. They behave in a manner similar to conventional, petroleum derived, liquid fuels opening the opportunity for existing oil facilities to be repurposed for hydrogen.

ERM is undertaking this feasibility study to evaluate the potential of re-purposing conventional oil storage facilities for the future storage of hydrogen in the form of LOHC. The aim of the study is to develop a plan for carrying out a 'real world' trial in order to demonstrate the performance of LOHC at an existing UK oil storage facility. A successful trial would pave the way for commercialisation of the use of LOHC as an effective storage and transport medium for hydrogen in the UK.

## 1.2 Background

ERM has been funded by BEIS ("the client") to develop an innovative low-carbon hydrogen solution under the "Low Carbon Hydrogen Supply 2 Competition", specifically under "Stream 1, Category 3: Hydrogen Storage and Transport". 'Stream 1' funds projects at Technology Readiness Levels (TRLs) of 4-6. Phase 1 funding is provided to complete a feasibility study of the proposed solution, whilst Phase 2 funding is also available for development of a demonstration trial.

## 1.3 Scope and Objectives

The objective of the project is to evaluate the potential of re-purposing conventional oil storage facilities in the UK for the future storage of hydrogen in the form of a LOHC. To do this, the project has been split into two phases; Phase 1 covers a feasibility study and Phase 2 covers the trial development and execution.

The Phase 1 work comprised:

- an evaluation of physical and chemical characteristics of two LOHC pairs with high TRL;
- a high level assessment on the suitability of typical conventional oil storage facilities for handling LOHC;
- development of a test programme for a series of 'real world' tests to determine LOHC performance using existing facilities that can be carried forward to demonstration trials in Phase 2;
- financial analysis; and
- development of a high level regulatory compliance roadmap to enable use of existing oil storage facilities to store and handle hydrogen in the form of LOHC.

# 2. SUMMARY OF PHASE 1 RESULTS

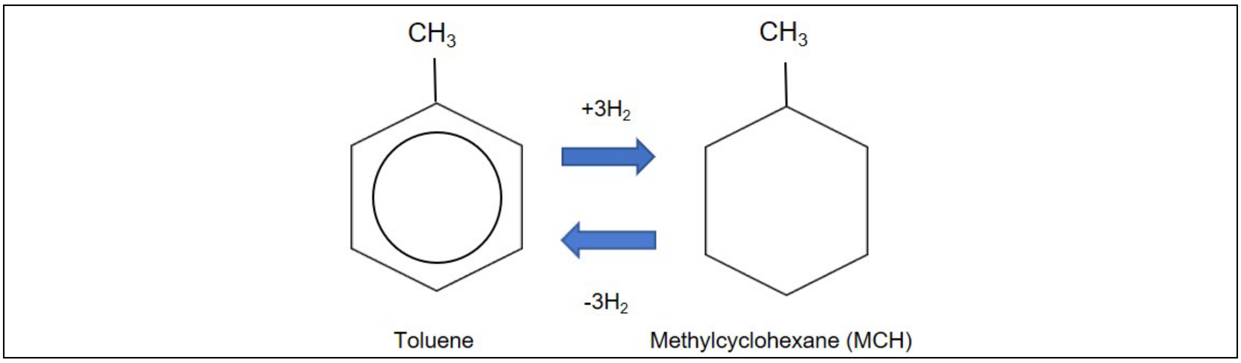
## 2.1 Review of LOHC Characteristics

Two LOHC pairs with high technology readiness level (TRL), namely Toluene (TOL) and Benzyltoluene (BT) - forming Methylcyclohexane (MCH) and Perhydro-benzyltoluene (PBT) when loaded with hydrogen respectively - have been assessed in terms of their physical and chemical characteristics.

More than 1,000,000 tonnes per annum of TOL is manufactured in and/ or imported into the European Economic Area [39]. It is currently used in a variety of products such as: lubricants and greases, polishes and waxes, non-metal-surface treatment products, inks and toners, biocides (e.g. disinfectants, pest control products), textile treatment products and dyes, anti-freeze products, leather treatment products, fuels and adhesives and sealants [39]. MCH is currently used in a variety of products such as: coating products, anti-freeze products, biocides (e.g. disinfectants, pest control products), lubricants and greases, air care products, washing & cleaning products and welding & soldering products. Currently only 1000 - 10,000 tonnes per annum of MCH is manufactured in and/ or imported into the European Economic Area [42].

Toluene incorporates 6 hydrogen atoms (i.e. 3 $H_2$ molecules) into its molecular structure to produce the fully hydrogenated (loaded) form of the LOHC, namely methylcyclohexane (MCH), as shown in Figure 2.1.

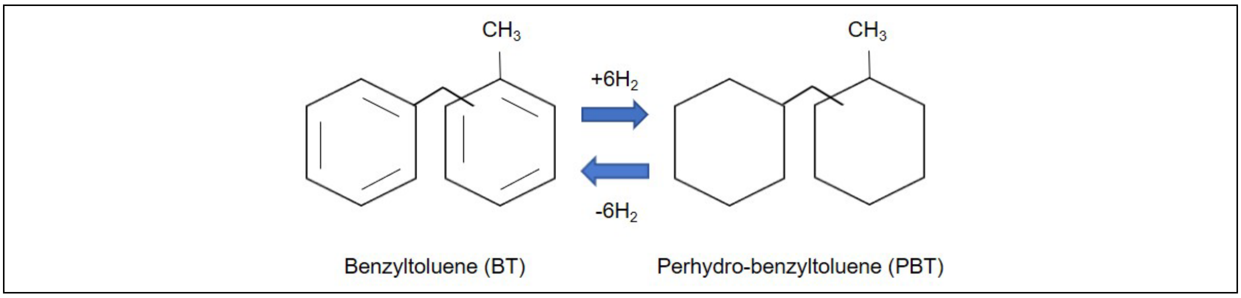
**Figure 2.1 TOL to MCH LOHC Pairing**




BT is currently used in heat transfer fluids and washing and cleaning products; currently only 1000 - 10,000 tonnes per annum of BT is manufactured in and/ or imported into the European Economic Area [40].

When fully loaded, benzyltoluene (BT) incorporates 12 hydrogen atoms to become perhydro-benzyltoluene (PBT), as shown in Figure 2.2.

**Figure 2.2 BT to PBT LOHC Pairing**




Toluene is already produced and in use on a large scale at present and therefore present few novel issues or uncertainties with regards to its storage, safety, environmental or regulatory issues. MCH and BT has only been produced and in use on a small scale at present. These LOHCs are typically stored in tanks which are specifically designed to store these substances.

As the purpose of this study is to evaluate whether existing oil infrastructure can be repurposed for the storage of LOHCs, comparing LOHC properties with those of a range of petroleum products will enable comparisons to be made with the properties of liquids more familiar to operators of oil infrastructure. Table 2.1 lists the substance identifiers, physical descriptions and molecular masses for the three LOHC pairings of interest, together with those for gasoline, diesel, crude oil and heavy fuel oil.

### Table 2.1: Substance Identifiers and Molecular Masses [references given in brackets]

| Substance | CAS No. | EC No. | Physical Description (@ 20 °C) | Relative Molecular Mass |
|---|---|---|---|---|
| Toluene | 108-88-3 [1] | 203-625-9 [1] | Colourless liquid [2] | 92.14 [2] |
| Methylcyclohexane (MCH) | 108-87-2 [3] | 203-624-3 [3] | Colourless liquid [4] | 98.19 [4] |
| Benzyltoluene (BT) | 27776-01-8 [5] | 248-654-8 [6] | Colourless liquid [6] | 182.3 [6] |
| Perhydro-benzyltoluene (PBT) | N/A | N/A | Colourless liquid [7] | 194.4 |
| Gasoline (C4 to C12) [8] | 86290-81-5 [9] | 289-220-8 [9] | Yellow liquid with petroleum hydrocarbon odour [10] | 60 to 150[a] [8] |
| Diesel (C12 to C20) [8] | 68476-34-6 [11] | 270-676-1 [11] | Brown slightly viscous liquid with characteristic odour [11] | 150 to 250[a] [8] |
| Medium Crude Oil | 8002-05-9 [12] | 232-298-5 [13] | Thick, light yellow to dark black coloured liquid. Petroleum odour [14]. | ~60 to >600[a] derived from [15] & [8] |
| Heavy Fuel Oil (C20 to >C50) [15] | 68476-33-5 [16] | 270-675-6 [16] | Heavy, viscous brown/black liquid with heavy petroleum odour [17] | ~250 to >600[a] [15] |

*Note a – the relative molecular masses for gasoline, diesel, medium crude oil and heavy fuel oil have a range dependant on the specific material.*

## *Physical Properties*

The main physical properties which are considered to have implications for this feasibility study are density, viscosity, vapour pressure, boiling point and melting point.

Table 2.2 shows the physical properties of the two LOHC pairings and the petroleum derived product range. The density and viscosity data are for atmospheric pressure. The table also shows the melting and boiling points as well as specific heat capacities data. Values are also presented for vapour pressure, flash point and autoignition temperature at atmospheric pressure, indicating how the thermal stability of the LOHCs compares with those of conventional fuels.

### Table 2.2: Density and Viscosity of LOHCs vs Liquid Petroleum Products [references]

| Substance | Density @ 20 °C ($kg/m^3$) | Dynamic Viscosity (mPa.s) | Kinematic Viscosity ($mm^2/s$) | Melting Point (°C) | Boiling Point (°C) | Specific Heat Capacity (J/g.K) | Vapour Pressure (Pa) | Flashpoint (°C) | Autoignition Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|
| Toluene | 862 [2] | 0.560 @ 25 °C [2] | ~0.65 @ 25 °C | -94.9 [2] | 110.6 [2] | 1.7 @ 25 °C [24] | 3786 @ 25°C [2] | 4 [2] | 480 [2] |
| Methylcyclohexane (MCH) | 769 [4] | 0.679 @ 20 °C [18] | ~0.88 @ 20 °C | -126.6 [4] | 100.9 [4] | 1.88 @ 25 °C [25] | 6133 @ 25 °C [4] | -4 [4] | 250 [4] |
| Benzyltoluene (BT) | 992 [6] | 3.98 @ 25 °C [19] | ~4 @ 25 °C | -80 [5] | 278 [6] | 1.52 @ 25 °C [19] | 1.01 @ 25°C [5] | 132 [6] | 473 [6] |
| Perhydro-benzyltoluene (PBT) | 876 [19] | 5.62 @ 25 °C [19] | 6.4 @ 25 °C | -80 (BT/PBT blend)[a] [7] | 278 to 282 °C (BT/PBT blend)[a] [7] | 1.73 @ 25 °C [19] | <1 @ 20 °C [7] | 130 (BT/PBT blend[b]) [7] | 510 (BT/PBT blend[b]) [7] |
| Gasoline | 620 to 880 @ 15 °C [9] | ~0.5 @ 15 °C | 0.46 to 0.88 @ 15 °C [20] | -60 [9] | 20 to 200 [26] | ~2 average between 0 to 100 °C [27] | 240,000 @ 37.8 °C [9] | <-21 [26] | ~250 [26] |
| Diesel #2 | 870 to 950 [11] | ~2.3 @ 15 °C [21] | ~3 @ 15 °C | -30 to -18 [11] | 282 to 338 [11] | | <133 (or <1 mm Hg) @ 15 °C [29] | 52 [11] | 254 to 285 [11] |
| Medium Crude Oil | 820 to 970 [12] | 7.5 @ 20 °C (based on 855 $kg/m^3$ density) [22] | ~9 @ 20 °C | - 30 to 30 [12] | -1 to > 720 [12] | | 6000 to 40,000 @ 37.8 °C [12] | Range[c] | Range[c] |
| Heavy Fuel Oil | 950 to 1010 [16] | ~300 @ 50 °C | 224 to 421 @ 50 °C [23] | 30 [16] | 202 - 511 [16] | | 20 to 861 @ 120 - 150 °C [16] | 64 - 310 [16] | 250 - 537 [16] |

*Note:*

Where references are absent for viscosities, it is because the viscosity values have been derived using the equation: kinematic viscosity ($m^2/s$) = dynamic viscosity (Pa.s) / density ($kg/m^3$).

*a: Due to the absence of CAS and EC numbers this information for PBT is limited to that provided for a BT/PBT blend, issued by the vendor.*

*b: Due to the absence of CAS and EC numbers this information for PBT is limited to that provided for a BT/PBT blend, issued by the vendor.*

*c: As crude oil compositions vary considerably [12], it has not been possible to establish the full range of flashpoints and autoignition temperatures*

LOHC characteristics have been compared against different oil products commonly processed and handled in conventional oil storage and handling facilities. Gasoline, diesel, medium crude oil and heavy fuel oil were selected as representative oil products for comparison with LOHC.

In terms of physical properties, notable findings are summarised as follows:

| Characteristics | Findings |
|---|---|
| Density and viscosity | • The densities of the loaded LOHCs are approximately 10% lower than those of the unloaded LOHCs. Therefore, the volumes required to contain the LOHCs after loading will be approximately 10% greater.<br>• BT has density approximating that of water. Thus, although they are immiscible in water, they are not easy to separate from water (e.g. via bottom withdrawal from a tank) in the event of contamination. This is in contrast with gasoline, diesel, crude oil and the toluene/MCH pairing.<br>• Each of the LOHCs has a density approximating one of the three conventional fuels. The toluene/MCH densities resemble those of gasoline, and the BT/PBT pairing resembles the density range of crude oil.<br>• As with the densities, the same loaded LOHCs also have viscosities approximating those of the same conventional fuels.<br>• The viscosity of the BT/PBT pairing should enable its use in existing crude oil and heavy fuel oil infrastructure. However, some modification to diesel and gasoline lines may be required as the viscosity of gasoline and diesel is approximately one tenth to one half that of BT/PBT, respectively, despite the BT/PBT values being reported at 10 °C higher.<br>• The toluene/MCH pairing has viscosities equivalent to or below that of all the petroleum products, so viscosity does not limit its use in conventional oil infrastructure. |
| Melting points, boiling points and heat capacities | • All the LOHC pairings have melting points below those of all the petroleum products.<br>• The toluene/MCH pairing has a boiling point similar to that of water, by far the lowest boiling point of the LOHCs, but not low enough to present handling issues.<br>• The toluene/MCH pairing has the highest reported specific heat capacity of the LOHCs.<br>• In summary, the melting and boiling points of the LOHCs do not represent any notable challenges. |
| Thermal stability (vapour pressure, flashpoint and auto-ignition temperature) | • The vapour pressure of the toluene/MCH pairing is comparatively high, higher than that of diesel.<br>• The vapour pressure of the BT/PBT pairing is comparatively low, far below that of diesel.<br>• The flash point of the toluene/MCH pairing is below that of average ambient temperature in the UK and lower than that of diesel.<br>• The autoignition temperature of MCH is similar to that of the petroleum products and much lower than that for toluene or the other LOHC pairings.<br>• In summary, the relatively high vapour pressure and low flash point of the toluene/MCH pairing presents handling risks not experienced with the BT/PBT pairing and in excess of the risks when handling diesel. It is noted, however, the toluene/ MCH pairing have relatively low vapour pressure and higher flash point compared to gasoline, indicating the suitability of existing gasoline infrastructure to handle toluene/ MCH in terms of their thermal stability. |

## *Chemical Properties*

Chemical properties are reported with regards to physical risk, health hazards and environmental hazard, in Table 2.3.

The classifications for the ‘H’ codes used in the Globally Harmonised System (GHS) for defining risks and hazards, are presented in Appendix A. The European Chemicals Agency (ECHA) Online Database has been used to inform the risks and hazards for the petroleum products, with Table 2.3 reporting those results common to at least 10% of those reporting to the database. The level of risk is categorised on a scale of 1 (most severe) to 4 (least severe) as shown in Figure 2.3. The cells in

Table 2.3 are coloured to indicate the category of risk for the H code with the highest risk in that cell. Where more than one H code representing the same type of risk has been reported by over 10% of contributors to the ECHA (e.g. how flammable the substance is), the H code for the higher category of risk is included in Table 2.3.

### Figure 2.3 Colour Coding of Risk Category as used in Table 2.5

| Category 1 | Category 2 | Category 3 | Category 4 |
|---|---|---|---|
| Most Severe | | | Least Severe |

### Table 2.3: Physical Risk and Health and Environmental Hazards when using the Globally Harmonised System [references]

| Substance | Physical Risk | Health Hazard | Environmental Hazard |
|---|---|---|---|
| Toluene | H225 [30] | H304, H315, H319, H332, H335, H336, H340, H350, H361, H370, H372 [30] | H412 [30] |
| Methylcyclohexane (MCH) | H225 [31] | H304, H315, H319, H335, H336, H361 [31] | H411 [31] |
| Benzyltoluene (BT) | None reported | H304, H315, H360FD [32], [7] | H411 [32], [7] |
| Perhydro-benzyltoluene[a] (PBT) | None reported | H304, H315, H360FD [7] | H411 [7] |
| Gasoline | H224 [9] | H304, H315, H336, H340, H350, H361FD [9] | H411 [9] |
| Diesel #2 | H226 [33] | H304, H315, H332, H351, H373 [33] | H411 [33] |
| Crude oil | H224 [13] | H304, H319, H336, H350, H373 [13] | H411 [13] |
| Heavy fuel oil | H226 [16] | H304, H332, H350, H361d, H373 [16] | H400, H410 [16] |

*Note a: Due to the absence of CAS and EC numbers this information for PBT is limited to that provided for a BT/PBT blend, issued by the vendor.*

The results of the colour coding of the risks and hazards in Table 2.3 are discussed below:

- The physical (i.e. flammability) risk of the toluene/MCH pairing is lower than that of gasoline and crude oil, but exceeds those of the other LOHCs and petroleum products. The other LOHCs have no reported flammability risk.
- The BT/PBT and toluene/MCH pairings present the same category of environmental hazard as each other and equivalent to that of the petroleum products, other than heavy fuel oil (which presents a greater risk).

In summary, the toluene/MCH has a flammability risk that the other LOHCs do not, but the toluene/MCH risk is still lower than that for gasoline or crude oil. Health hazards across all LOHCs constitute elements of category 1 severity, as do all the petroleum products. The environmental hazards of toluene/MCH and BT/PBT are approximately equivalent to or less than those of the petroleum products.

### *Materials Compatibility*

The two proposed LOHCs are compatible with steel materials commonly used in existing oil infrastructure. The suitability of the variety of materials used in existing infrastructure, such as other metals and seals, will be established later, in consultation with the specific vendor and the experimental site.

### *Contamination Considerations*

More detailed work, assessing the levels and types of contamination of LOHC which could occur when repurposing existing oil infrastructure, will be performed as part of Phase 2 programme. However, some initial queries have been undertaken in consideration of the fact that LOHCs, like petroleum products, do not require pressurised storage, and it is thus likely that without deliberate steps being taken, the LOHCs will come into contact with both air and moisture during handling and storage.

Responses from the two potential LOHC providers (Chiyoda and Hydrogenious), regarding the likely effects of air and moisture on their products, and the potential consequences to the effective loading and unloading of the LOHC molecules, can be summarised as follows:

- Toluene/MCH (Chiyoda) – While the LOHC can be considered stable when in contact with air or moisture, it is preferable to store the liquid with an inert gas. Chiyoda do have some processes to remove air/water impurities from MCH. Recent studies by Chiyoda found that an unspecified amount of rainwater does not affect their processing of MCH.
- BT/PBT (Hydrogenious) - To obtain a high process quality, particularly for the dehydrogenation, the contact with air and moisture should be minimised. According to current assumptions regarding the use of this LOHC, a nitrogen overlay is considered necessary during storage.

In summary, the toluene/MCH LOHC appears less vulnerable to air/moisture contamination.

A summary of LOHC characteristics compared to different oil products is presented in Table 2.4 and Table 2.5.

In conclusion, the characteristics of TOL-MCH pair were found to be similar to light oil products such as gasoline or kerosene; whereas the BT-PBT pair were found to have similar characteristics to heavy oil products such as crude and heavy fuel oil. Hence, it is anticipated that existing infrastructure which handle light oil products can be suitably re-purposed to handle toluene/ MCH with no/ minor modification. Similarly, no/ minor modification is anticipated for re-purposing existing infrastructure which handle heavy oil products for handling the BT-PBT pair.

## Table 2.4: Toluene/ MCH Characteristics Summary

| Properties/ Parameters | Comparison with Oil Products and Implications on Re-purpose of Existing Infrastructure | | | |
|---|---|---|---|---|
| | Gasoline | Diesel | Medium Crude Oil | Heavy Fuel Oil |
| Density and viscosity | Lower or similar viscosities compared to all oil products suggesting the suitability when utilising existing infrastructure to handle toluene/MCH pair. | | | |
| Melting points, boiling points and heat capacities | Toluene/MCH pairing has a boiling point similar to that of water and the highest reported specific heat capacity of the LOHCs. However, they do not represent any notable challenges | | | |
| Thermal stability | With lower vapour pressure and higher flash point compared to gasoline, indicating the suitability of existing gasoline infrastructure to handle toluene/ MCH | With higher vapour pressure and lower flash point compared to diesel, crude and heavy fuel oil, indicating detailed checks are required (e.g. on floating-roof tank design vapour pressure) to utilise existing diesel, crude and heavy fuel oil infrastructure to handle toluene/ MCH | | |
| Physical (flammability) risk | With lower physical (flammability) risk compared to gasoline, indicating the suitability of existing gasoline infrastructure to handle toluene/ MCH | With higher physical (flammability) risk compared to diesel, medium crude and heavy fuel oil, indicating the need for existing diesel, crude and heavy fuel oil to provide additional safety measures to handle toluene/ MCH. | | |
| Health hazard | With similar health hazard compared to all oil products, indicating no major modifications are required on existing infrastructure. Changes on operating procedures for personal handling of toluene/ MCH may be required. | | | |
| Environmental hazard | With environmental hazard either similar or lower to all oil products, indicating no major modifications (if any) are required on existing infrastructure to handle toluene/MCH in the event of e.g. spillage. | | | |
| Materials compatibility | Compatible with steel materials commonly used in existing oil infrastructure | | | |
| Contamination | If contaminated with water, toluene/MCH is likely to be easily separated from moisture due to it having a much lower density than water. | | | |

## Table 2.5: BT/ PBT Characteristics Summary

| Properties/ Parameters | Comparison with Oil Products and Implications on Re-purpose of Existing Infrastructure | | | |
|---|---|---|---|---|
| | Gasoline | Diesel | Medium Crude Oil | Heavy Fuel Oil |
| Density and viscosity | Higher viscosities compared to gasoline and diesel suggesting modifications are required on existing gasoline and diesel infrastructure to handle BT/ PBT pair. | | Lower viscosities compared to crude and heavy fuel oil suggesting the suitability when utilising existing crude and heavy fuel oil infrastructure to handle BT/ PBT pair. | |
| Melting points, boiling points and heat capacities | The melting and boiling points of the LOHCs do not represent any notable challenges | | | |
| Thermal stability | With lower vapour pressure and higher flash point (or in the similar range) compared to all oil products, indicating the suitability of re-purposing existing infrastructure to handle BT/PBT | | | |
| Physical (flammability) risk | With lower physical (flammability) risk compared to all oil products, indicating the suitability of re-purposing existing infrastructure to handle BT/ PBT | | | |
| Health hazard | With similar health hazard compared to all oil products, indicating no major modifications are required on existing infrastructure. Changes on operating procedures for personal handling of BT/ PBT may be required. | | | |
| Environmental hazard | With environmental hazard either similar or lower to all oil products, indicating no major modifications (if any) are required on existing infrastructure to handle BT/PBT in the event of e.g. spillage. | | | |
| Materials compatibility | Compatible with steel materials commonly used in existing oil infrastructure | | | |
| Contamination | BT/ PBT appears to be vulnerable to contamination from air and moisture in particular during dehydrogenation process. However, the likely level of exposure to air and moisture is unknown at this stage and may be manageable (e.g. with inert overlays). | | | |

## 2.2 Review of UK Oil Terminals

A high level assessment was also carried out on the suitability of typical conventional oil storage facilities for handling LOHC.

### *Typical Storage Tanks*

There are two types of storage tanks typically used in the existing oil infrastructures, namely: fixed roof tanks and floating roof tanks.

**Fixed Roof Tanks**

For storing a product that is not very vaporous, atmospheric fixed roof tanks (FRT) are a common choice as they are less expensive than floating roof counterparts. A typical FRT consists of a cylindrical steel shell with either a cone or geodesic dome shaped roof fixed onto the shell. As the tank is a sealed space (i.e. liquid and vapour tight), and generally is not rated for high/vacuum pressures, pressure vacuum relief valves (PVRV) or 'breather valves' are commonly installed to allow for changes in internal pressure such as during loading/unloading operations or changes in ambient conditions.

While FRTs are more commonly used for storing materials that are not very volatile, if storing a volatile product blanketing systems or vapour recovery systems can be used to limit vapour loss and minimise the possibility of flammable atmospheres forming. Blanketing systems inject an inert gas into the tank vapour space, producing a small positive pressure, limiting vapour escaping the liquid product. Blanketing systems also prevent air, moisture or other potential contaminants from entering the vapour space in the tank preventing product degradation

**Floating Roof Tanks**

Floating roofs are also very common for the storage of materials. Instead of being permanently fixed to the top of the shell, floating roofs float with the liquid and have a seal between itself and the shell to prevent water and other materials from entering the tank. As the roof is floating, it is evenly supported by the liquid and therefore quite stable. There is also minimal vapour space between the roof and the product which reduces vapour loss. The benefit of this is threefold:

- Limited financial loss from loss of product;
- Reduced emissions associated with volatile organic compounds (VOCs) allowing for compliance to environmental regulatory;
- Minimises the formation of a flammable atmosphere.

External floating roof tanks (EFRT) are the most common form of floating roof tank, which as implied the roof is the only barrier between the stored product and the atmosphere. EFRTs are designed with a roof drain that allows for rainwater hitting the top of the tank to be removed. Even with the drain, water (as well as air) ingress can occur at the seals with the shell. Wind can also be an issue with extreme winds causing the floating roof to buckle.

To prevent wind and rain from effecting a floating roof, tanks can also have another external roof. Covered floating roof tanks (CFRT) are similar to EFRTs in that they have heavier decks, but they also have a geodesic domed roof attached. These domed roofs are freely vented and do not act as a vapour barrier. EFRTs can be retrofitted to become CFRTs.

Internal floating roof tanks (IFRT) also exist. Such tanks consist of a FRT with an internal floating cover that floats on the liquid product. Unlike CFRTs, IFRTs tend to eliminate natural ventilation and are equipped with a PVRV. The gap between the internal cover and external roof can also be blanketed.

### *Typical Pumping System*

At a storage terminal, pumps are required to move products between the vessel and the storage tank, as well as between the storage tank and road tanker. With products being stored at low pressure /

atmospheric conditions, relatively low pumping pressures are required at the storage terminal. When unloading the vessels, cargo pumps on the vessel are typically used to move the product. For loading operations between the storage tank and vessel, and loading/unloading operations between the storage tank and road tanker, a pump on site is used.

Centrifugal pumps are the most common pump type on site due to their ability to handle a greater range of flowrates and cost. Centrifugal pumps work by allowing the flow of liquid to enter the centre of a spinning enclosed impeller, where the centrifugal force of the impeller pushes the liquid out of its side thereby enhancing the liquids velocity and pressure. Due the design of pump, liquid can only move one way through. Accordingly, for vessel loading operations the cargo pump on the vessel cannot be used as it is usually a centrifugal type pump and hence cannot pump in the correct direction of flow.

For more viscous liquids, it is common to use positive displacement (PD) pumps. PD pumps operate by drawing the liquid in the suction pipe into a cavity and then forcing the liquid into the discharge pipe. Due to the internal clearances high viscosities can be handled easily. Unlike centrifugal pumps, the efficiency of PD pumps actually increases with viscosity up to a certain point.

### *Suitability of Typical Facilities for Handling LOHC*

There are no known limitations on the storage and handling facilities (e.g. storage tank and loading/unloading systems) which could be utilised for storing and handling LOHC. Although there are preferential types of storage tank and pumping system for the relevant LOHC pair (e.g. floating roof tank and centrifugal pump are considered most suitable for TOL-MCH pair, as shown in Table 2.6), others could be utilised after further checks and/ or suitable modifications.

**Table 2.6: Suitability of Storage and Pumping System**

| LOHC | Storage Tanks | Pumping System |
|---|---|---|
| TOL/ MCH | Based on its flashpoint, storage condition and potential contamination, either fixed roof tank or internal floating roof tanks (with blanketing system) is the preferred storage tank choice.<br>However, recent studies by Chiyoda found that an unspecified amount of rainwater does not affect their processing of MCH, supporting the idea that external floating roof tanks or covered floating roof tanks could be used to store the LOHC. | Centrifugal pump is the preferred pump type |
| BT/ PBT | Based on its flashpoint, storage condition and potential contamination, fixed roof tanks (with blanketing system) are the preferred storage tank choice. However, there is also potential to store this product in external floating roof tanks or covered floating roof tanks. | Either centrifugal or positive displacement pumps are suitable |

A ‘real world’ trial programme has now been developed, covering a full scale test programme, including the boundaries and scale of the trial system. The trials have been designed to resolve some of the remaining uncertainties identified from Phase 1 particularly regarding fluid flow characteristics and potential contaminant take up. Finalisation of the trial programme will be completed at the start of Phase 2 work.

### *Hazard Identification (HAZID) Study*

As part of the project, a Hazard Identification (HAZID) study was conducted in order to identify and assess the hazards associated with the operation of an existing oil storage facility for storing LOHCs, identify uncertainties/ gaps and recommend actions where additional mitigation measures or controls are required. The study identified a range of hazards and potential mitigation measures. However, none of the hazards are considered limiting in terms of the ability to store hydrogen in the form of LOHC safely at the type of sites identified in this report. The overall risks are not thought to be any greater, and most likely will be lower, than the range of oil and petroleum products currently stored.

The HAZID identified actions which would need addressing throughout the LOHC project. These actions are equivalent to current project gaps and uncertainties, where elements of the project are unknown (e.g. LOHC properties or specific site information). The main categories of actions from the HAZID include:

- Water ingress and the potential for boilover in the event of a fully engulfing tank fire;
- Confirming equipment suitability (including tanks and seals);
- Contamination from air, water and previously stored products;
- Nitrogen blanketing requirements.

A number of uncertainties can be investigated further during the trial programme. It is envisaged that these to include the followings.

- **Contamination potential**

  The trial could include a series of tests to expose the loaded LOHC substances to different contaminants, which may include: air, water, oil products and unloaded LOHC substances. These would identify any potential issues associated with the contamination, e.g. whether it will cause product quality issues only, or any potential of hazardous consequences, as well as the limit of contaminants that may be acceptable.

- **Formation of VOCs during loading of TOL/ MCH**

  It is recognised that a connection to vapour recovery unit would be recommended to reduce the amount of VOC emissions that could be lost to atmosphere during loading operations of TOL/ MCH. The trial could include a series of tests to check the potential generation of VOCs during loading operations.

- **Exposure to heat/ high temperature**

  It is recognised that an existing storage tank may be equipped with a heating coil, which may lead to potential product evaporation/ hydrogen off-gassing if this system is not isolated during storage of loaded LOHC. The trial could include a series of tests to check the potential product evaporation/ hydrogen off-gassing if the loaded LOHC is exposed to different heat/ high ambient temperatures.

## *Review of Existing UK Oil Handling and Storage Facilities*

Across the UK there are more than a hundred liquid storage terminals storing a varying range of products such as crude oil, chemicals, vegetable oils and petroleum products. It is estimated that there is ~19,800,000 m3 of storage capacity across 117 terminals around the UK [1]. Of this 84 terminals handle crude, kerosene, gasoline, diesel, fuel oil or other petroleum products totalling ~17,100,000 $m^3$ of capacity.

During the desktop review of oil terminal facilities in the UK, it emerged that data on specific product capacity and tank allocation was confidential to each site and therefore was not available for use in analysis. However, it was found that overarching data for sites, such as total capacity, product types and number of tanks was publicly available [1] and was used in part as the basis for the analysis. As data on total capacities for specific products was not available, data on total petroleum product stocks for 2020[1] as reported by the Department for Business, Energy and Industrial Strategy (BEIS) [35] was also utilised as a basis for analysis. It was assumed that 2020 product stocks are proportional to total storage capacities in the UK at present. The year 2020 was chosen in part because at the time of reporting, data for 2021 was not confirmed and also because 2020 was the last year where the UK was obligated to hold greater product stocks as a member of the European Union (EU). This obligation from the EU's Oil Stocks Directive (2009/119/EC) required the UK to hold emergency stocks of crude oil and/or petroleum products equal to at least 61 days of consumption or 90 days of

[1] Capacity for crude oil included materials stored at both refineries and terminals.

net imports, whichever was higher. The assumed total petroleum product stock is presented in Table 2.7. Along with other assumptions detailed in this section, calculations on product capacities and potential hydrogen storage were made.

**Figure 2.4 UK Oil Terminals Map**

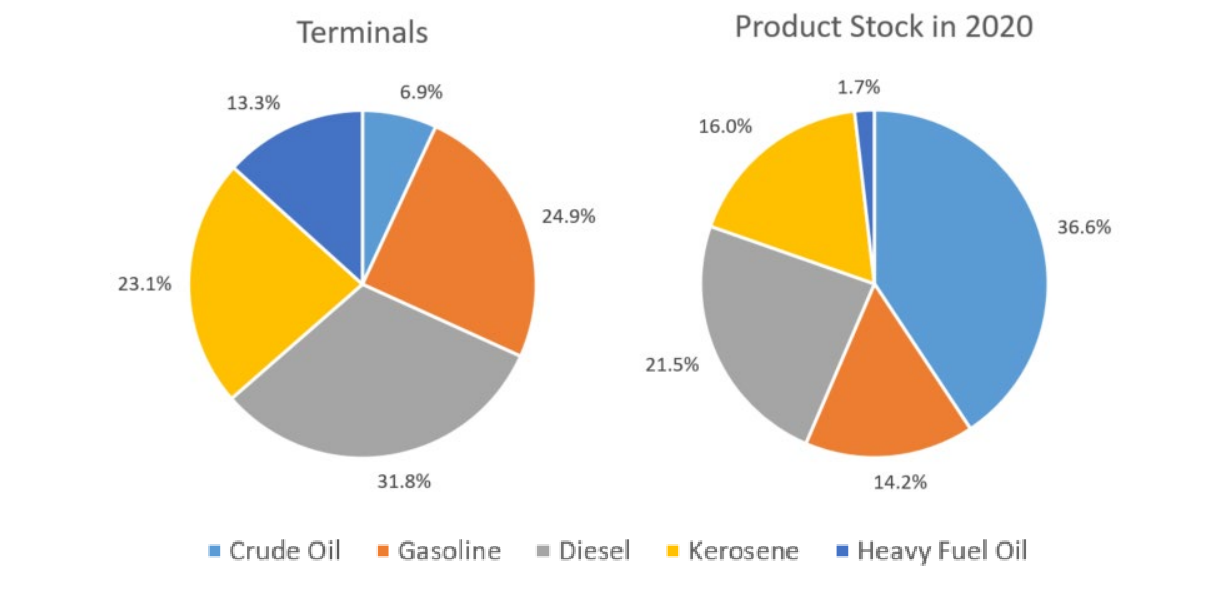

### Table 2.7: Assumed Total Storage Capacity for Petroleum Products

| Parameter | Gasoline | Diesel | Crude Oil | HFO | Other Products |
|---|---|---|---|---|---|
| Storage Capacity ($m^3$) | 2,450,000 | 3,690,000 | 6,280,000 | 284,000 | 4,450,000 |

The majority of oil terminals carry a range of different products. Figure 2.5 presents a comparison of the number of UK terminals carrying a specific product vs product stocks in the year 2020. Several conclusions and assumptions can be made from this comparison. For one, it can be seen that while only 6.9% of terminals store crude oil, capacity for crude totals 36.6% of all storage. This suggests that when crude is stored at a terminal, it is the main product. It has been assumed for analysis that at terminals handling crude, it is the sole product.

Conversely, whilst heavy fuel oils (HFOs) are stored at 13.3% of terminals, only 1.7% of capacity is designated for them suggesting limited storage at sites. Given the more limited uses of HFO this was to be expected.

### Figure 2.5 Proportion of UK Terminals storing Product vs Stock Stored in 2020




It was also found that there is more diesel storage capacity across the UK than gasoline. Given that no terminals across the UK store gasoline without also storing diesel (whilst the inverse is not the case) the greater storage capacity of diesel is expected. It was assumed that on average, for a site storing both gasoline and diesel, the capacities for each product are roughly the same.

Based on the review of LOHC characteristics, gasoline infrastructure and crude oil / HFO infrastructure could be repurposed for TOL/ MCH and BT/ PBT usage respectively with minimal modifications. Taking this finding forward, and assuming that TOL/ MCH can also utilise diesel and kerosene infrastructure, the anticipated LOHC and subsequent hydrogen storage volumes, if these terminals are repurposed with minimal modifications, are shown in Table 2.8. An energy efficiency of 100% was taken and lower heating value of hydrogen was used to calculate the energy stored. It was also assumed that storage volumes would be split as required between respective dehydrogenated LOHC ($H_0$LOHC) / $H_n$LOHC.

### Table 2.8: UK Repurposed LOHC Storage Capacity Potential

| | MCH | TOL | PBT | BT |
|---|---|---|---|---|
| Compatible infrastructure | Gasoline, Diesel, Kerosene | | Crude Oil, HFO | |
| LOHC Storage Capacity ($m^3$) | 4,830,000 | 4,040,000 | 3,590,000 | 2,970,000 |
| Hydrogen Storage Capacity (ktonne) | 229 | - | 196 | - |
| Energy (TWh) | 7.62 | - | 6.52 | - |

It was found that 229 ktonne and 196 ktonne of hydrogen could be stored in TOL/ MCH and BT/ PBT respectively if existing infrastructure was repurposed with minimal modifications. This equates to ~14.1 TWh and compares to the current UK gas storage reserves of around 9TWh. Based on data provided by BEIS report on the UK household energy consumption [36], such amount of energy would be sufficient to replace natural gas usage in all of the UK's 22 million gas connected homes for a period of 21 days. With both LOHC pairs having somewhat similar densities and very similar hydrogen storage capacities (6.16% and 6.22% for TOL/ MCH and BT/ PBT, respectively) the main factor in the different hydrogen storage capacities presented in Figure 2.5 is the storage volumes available for each oil product. It is worth noting though, that there is a degree of uncertainty in these calculated figures.

Nevertheless, there is significant potential storage capacity in the UK for storing hydrogen if the existing infrastructure is to be repurposed to store LOHC.

## 2.3 Review of UK Regulatory Compliance

A review of UK relevant safety regulations (including health and safety) has been carried out in order to develop a high level compliance roadmap envisaged if the existing infrastructure is to be re-purposed to store hydrogen in the form of LOHC.

For safe operation of any business or site handling dangerous substances, a range of UK regulations must be complied with. Due to the nature of the trial utilising existing infrastructure, measures to comply with the majority of regulations will be already in place. A high level compliance roadmap, presenting relevant notifications and documents to be complied with, has been developed and presented in Table 2.9.

Full Environment, Health and Safety (EHS) regulatory requirements, including environmental aspects, as well as construction permits will be reviewed and developed further at the start of Phase 2. Consultation with the Health and Safety Executive (HSE) will occur during Phase 2 once details regarding the trial such as site and LOHC source are confirmed.

## Table 2.9: Compliance Map

| Document/ Report | Competent Authority | Submit to Competent Authority? | Conformant Regulation | Timeline | Applicable Scenario |
|---|---|---|---|---|---|
| COMAH Notification | HSE/ EA/ SEPA/ NRW | Yes | Control of Major Accident Hazards (COMAH) Regulations 2015 | 4 months before operation | All |
| COMAH Report | HSE/ EA/ SEPA/ NRW | Yes | Control of Major Accident Hazards (COMAH) Regulations 2015 | 6 months before operation | All |
| Emergency Plans | HSE/ EA/ SEPA/ NRW | No | Control of Major Accident Hazards (COMAH) Regulations 2015 | Prior to operation | All |
| Health and Safety File | HSE | No | The Construction (Design and Management) Regulations 2015 (CDM) | Prior to construction | 2 |
| Construction Phase Plans | HSE | No | The Construction (Design and Management) Regulations 2015 (CDM) | Prior to construction | 2 |
| Health and Safety Management Report | HSE | No | Management of Health and Safety at Work Regulations 1999/ COSHH/ DSEAR | Prior to operation | All |
| Dangerous Substances Notification | Local Fire Authority/ HSE | Yes | The Dangerous Substances (Notification and Marking of Sites) Regulations 1990 (NAMOS) | Prior to operation | All, to be confirmed based on site selection |
| Press release | HCA | No | The Planning (Hazardous Substances) Regulations 2015 / Town and Country Planning (Hazardous Substances) Regulations 2015 | 21 days prior to Hazardous Substance Consent submission | All |
| Hazardous Substances Consent | HCA | Yes | The Planning (Hazardous Substances) Regulations 2015 / Town and Country Planning (Hazardous Substances) Regulations 2015 | 8 weeks prior to modification | All |

| Document/ Report | Competent Authority | Submit to Competent Authority? | Conformant Regulation | Timeline | Applicable Scenario |
|---|---|---|---|---|---|
| PPE Review | HSE | No | Personal Protective Equipment Regulations 1992 as amended | Prior to operation | All |
| Inquiry Dossier | HSE | Yes | UK Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation | Prior to operation | 2 |
| Registration Dossier | HSE | Yes | UK Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation | Prior to operation | 2 |
| Harbour Notification | Harbour Authority | Yes | Dangerous Goods in Harbour Areas Regulations 2016 (DGHAR) | 14 days prior to berthing | 1 |

# 3. PHASE 2 PROGRAMME

The Phase 1 study has determined that it is feasible to re-purpose conventional oil infrastructure for handling LOHC. A high level plan for carrying out a 'real world' trial to demonstrate the performance of LOHC at an existing UK facility has been developed. This trial would provide significant opportunities for the transitioning of existing conventional oil infrastructure to store hydrogen at scale.

The Phase 2 programme will cover the development and execution of the industrial trial programme identified in Phase 1. The following sections provide details of Phase 2 programme.

## 3.1 Industrial Trial Programme

The trial aims to evaluate the feasibility of storing LOHC in conventional oil storage tanks, transporting it via oil pipework/ pipelines, transporting it at bulk scale via road tanker, rail tanker or ship. It would involve a controlled series of tests to demonstrate how LOHC performs in terms of fluid behaviour, hydrogen retention, EHS performance and level of contamination from residual contaminants.

Specifically, the proposed trial seeks to confirm the following factors, as a minimum:

- ease of operability – e.g. demonstration that any operational changes that are required will be minor and that existing storage facilities are suitable to store and handle the LOHC;
- extent of Volatile Organic Compound (VOC) formation (if any) during loading/ offloading operations;
- EHS performance – e.g. demonstration that any identified hazards can be safely managed and that the overall risk of storing and handling LOHC is not significantly greater than that posed by the range of petroleum products currently stored in bulk;
- potential for hydrogen off-gassing;
- compatibility with existing facilities; and
- level of contamination in the LOHC from previously handled products

This will be achieved through the storage of LOHC in a tank at a UK Oil Terminal that was previously used to store another petroleum product. Prior to delivery of LOHC the tank and lines will be cleaned through standard industrial cleaning procedures. The LOHC will be held in a storage tank, monitored, and transported across site, multiple times across the trial period with samples taken to measure the level of contamination acquired. The LOHC will be loaded and unloaded via a rail or road tanker to fully demonstrate the ability to transfer the product successfully. However, when the site is selected, an additional transfer operation may be included in the trial, such as transfer via a jetty to a chemical tanker storage tank.

It is anticipated that the trial will include the following operations:

- delivery of approximately 200 te MCH to site;
- take delivery sample;
- load into 1,000 m3 pre-cleaned storage tank;
- store for 30 days, taking samples every 10 days;
- unload to rail wagon/ road tanker, store for 30 days and sample every 10 days;
- return to storage tank and store for 90 days, sampling every 30 days;
- unload to rail wagon/ road tanker and sample;
- removal of MCH from site.

### *Selection of LOHC Substance*

The project has assessed two LOHC pairs with high TRLs, namely MCH-TOL and PBT-BT. The global annual production and availability of the two LOHC's assessed is very different. More than 1,000,000 tonnes per annum of TOL is manufactured in and/ or imported into the European Economic Area [39] whereas currently only 1000 - 10,000 tonnes per annum of BT is traded [40]. Given this, and the fact the work to date has not identified any significant risks for one LOHC over the other and both are thought to be compatible with existing infrastructure, it is proposed to use TOL/MCH for the trial. The MCH-TOL pair was also found to be less expensive to procure compared to PBT-BT pair. The cost of MCH is estimated at 0.97 USD/ kg (approx.£0.87/kg) [43] whilst BT is estimated to cost at 4€/kg (approx. £3.5/kg) [44]. In terms of physical properties, MCH-TOL pair were found to have higher vapour pressure and lower flash point compared to PBT-BT pair, which present handling risks not experienced with the PBT-BT pair and in excess of the risks when handling diesel, crude oil or heavy fuel oil. Hence, by selecting the MCH-TOL pair the Phase 2 programme will cover the handling risks which would have not been present if using PBT-BT pair.

### *Selection of Project Boundaries*

At present there are several related LOHC projects underway in the UK allowing for different options for acquisition of LOHC for the trial. There are two specific project focus areas that present options for pairing with this LOHC storage and handling trial; hydrogen production and LOHC production projects. Therefore, three different project boundaries have been considered for the industrial trial project, as follows. They were assessed further in order to select the most suitable scenario for Phase 2 programme.

- **Scenario 1**
  Importing and storing loaded LOHC (MCH) at a conventional oil storage facility in the UK utilising existing infrastructure. In this scenario, MCH is transported to the site for use in the trial programme.
- **Scenario 2**
  Scenario 1 but paired with a hydrogen production project, meaning hydrogen will be available and stored on site to the run a hydrogenation plant to produce MCH from TOL. The hydrogenation pilot plant and compressed bulk hydrogen storage is included within the scope of this trial project. In this scenario, TOL is transported to the site for use in the trial programme. Existing infrastructure will be utilised to store TOL and MCH.
- **Scenario 3**
  Scenario 1 but paired with a LOHC production project rather than purchasing MCH from off site and transporting it to the trial site. MCH will be available and stored on site for use in this trial.

In scenarios 1 and 3, it is anticipated that MCH will be transported to site via ISO tank containers. In scenario 1 MCH will be imported from outside Great Britain either directly to site or a nearby port, depending on the selected sites facilities. The MCH will then be transported to the site via road.

In scenario 2, the MCH will be made on site through the hydrogenation of toluene. As with the MCH in scenarios 1 and 3, toluene will be transported to the trial site via ISO tank containers whilst hydrogen will be available onsite.

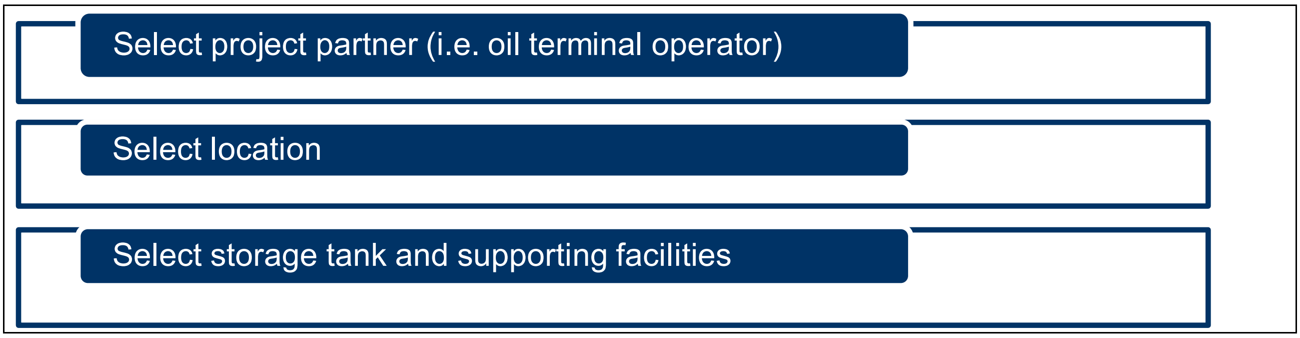
When considering the options for pairing the trial programme with other trial projects (Scenario 2 and 3), it was found that the timeline of most hydrogen trial projects do not suit the timeline envisaged for the Phase 2 programme. The hydrogen trial projects that were considered to be paired with the trial programme will only be in operational stage after 2024; hence their timelines do not suit the Phase 2 timeline which needs completion in early 2025.

When considering the costs and availability of existing assets for the trial, Scenario 1 appears to be the most suitable option. This will therefore be the assumed design option taken forward for the project. Initial engagement with several UK oil terminals has confirmed the suitability of existing facilities and enthusiasm for participating in the trial on this basis.

## 3.2 Selection Process of Key Elements for Phase 2 Programme

The proposed trial would involve the storage and transfer (including loading) of MCH into a storage tank that was previously used to store another petroleum product. This will be carried out at an existing oil storage facility in the UK utilising existing infrastructure. The key elements required for the Phase 2 trial are shown below and discussed individually below.

**Figure 3.1 Selection Process of Key Elements for Phase 2 Programme**




### *Select Project Partner*

This work involves a selection of project partner(s), namely the oil terminal operator(s). During this selection process, the project would need to confirm the level of support that can be provided by the partner(s). The site can provide support in the following activities, as examples:

- Engineering activities (including design and construction/ installation activities) which are required for any modification work needed for the existing storage tank and its transfer system;
- Procurement activities needed for the trial programme (e.g. provision of road tanker or rail wagon);
- Taking samples of LOHC at different stages of the project;
- Operating the trial programme;
- Decommissioning activities.

The preference is to work together with one partner only, to streamline the project. However, it is realised that some oil terminal infrastructure in the UK is operated and owned by different companies. Hence, it may be possible that the project will work together with 1-2 project partners.

At this stage, discussions have been held with two potential partners that are interested to participate in the Phase 2 programme. The site and partners will now work with us to fully develop the trial programme and submit our application for Phase 2 funding.

### *Select Location*

The MCH will need to be imported from outside Great Britain (most likely from France) directly to an import terminal and then delivered to site. The selected terminal will have the necessary approvals to import MCH and will comply with all necessary regulatory requirements. It will have existing importing facilities (e.g. jetty and loading arms) suitable for transferring MCH.

The proposed trial programme will involve the storage and transfer of around 200 tonnes of MCH. The Control of Major Accident Hazards Regulations (COMAH) 2015 set out two separate tiers of establishment, an upper and lower tier, that are determined through quantity of hazardous material expected to be present at site as per the CLP regulations. There are more stringent requirements associated with an upper tier COMAH site. The MCH is judged to be categorised as P5b flammable liquids within the regulation, due to it being categorised as Category 2 flammable liquids under CLP, with the lower and upper tier thresholds of 50 te and 200 te, respectively, under the COMAH regulations. In selecting a site for the trial we have therefore identified a facility which is already an upper tier COMAH establishment.

At this stage, the project has identified two potential sites in the UK where the trial may be executed; one in the Humber region and another in south-west region. The available facilities at each of these sites are currently being evaluated and a final selection will be made prior to the Phase 2 funding submission.

### *Select Storage Tank and Supporting Facilities*

It is envisaged that the trial will involve an existing tank with a storage capacity of around 1,000 $m^3$. The selection of tank size is important. A small size tank may have different arrangement (e.g. safety arrangements, etc.) compared to larger sized tanks. Hence, if a small size tank is selected, the results of the trial programme may not be fully representative of larger scale tanks. However, if a very large tank is selected, there is cost implications that would need to be considered by the project. On balance a 1,000m$^3$ tank storing 200 tonnes of MHC is assessed as large enough to provide all of the data needed to give confidence in the behaviour of MCH storage across all typical tank sizes.

The storage tank can be of a floating roof tank or fixed roof tank with blanketing system. The tank will be connected to  a pumping system to enable a transfer operation to either a road tanker or rail wagon or both. Any modification required to the tank or its pumping system will need to be confirmed at the start of Phase 2 programme. However, it is unlikely any significant modifications will be needed.

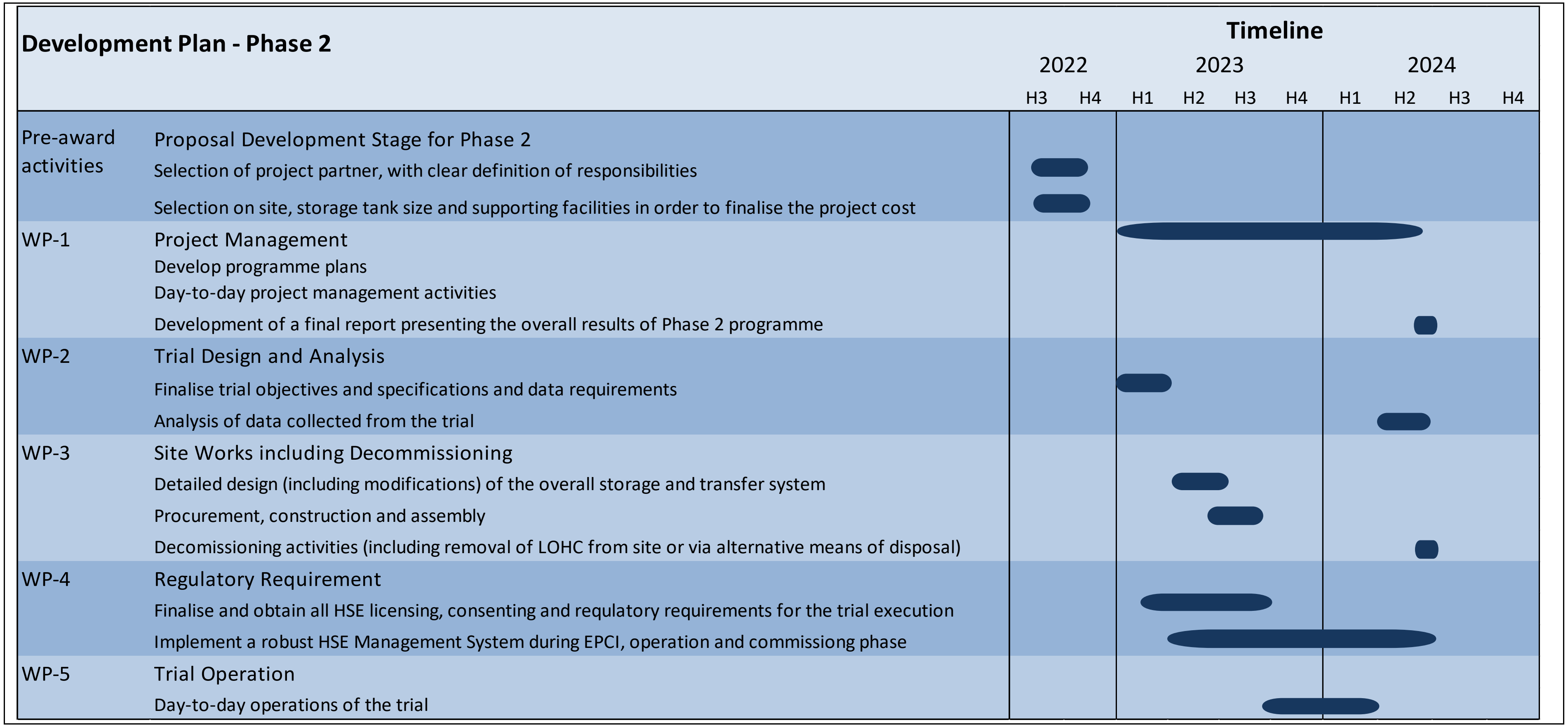
It is intended that the loading/ offloading operation into the tank is included within the trial scope. A connection to a Vapour Recovery Unit (VRU) is envisaged during the loading/ offloading operation in keeping with environmental legislation to prevent the emission of fugitive vapours (VOCs) into the atmosphere during the operation.

The selected site and tank will have a loading facility for road/rail tanker. It may also have connection and loading/ offloading facility to a marine vessel (jetty and loading arm) depending on the site and tank that is selected.

## 3.3 Project Timeline

It is envisaged that the Phase 2 programme would start in early 2023 and last for a period of 18 months (i.e. completing by mid 2024). The overall project timeline is shown below in Figure 3.2.

**Figure 3.2 Phase 2 Timeline**



## 3.4 Estimated Costs for Phase 2

It is envisaged that the work required for Phase 2 will require the involvement of two organisations, including an oil terminal operator. At the moment it is envisaged that the Phase 2 programme will cost between £2-3 million. The final price and scope of the trial programme will be confirmed in the event we decide to make a Phase 2 funding application. An estimate of the percentage breakdown for different work packages is provided below.

- WP-1 Project Management : 15%
- WP-2 Trial Design and Analysis : 20%
- WP-3 Site Works including Decommissioning : 45%
- WP-4 Regulatory Requirement : 10%
- WP-5 Trial Operation : 10%

# 4. BENEFITS AND BARRIERS

As outlined above, there are no significant technical barriers that could prevent re-purposing conventional oil storage facilities in the UK for the future storage of hydrogen in the form of LOHC. The work to-date has identified that the characteristics of TOL-MCH pair were found to be similar to light oil products such as gasoline or kerosene; whereas the BT-PBT pair were found to have similar characteristics to heavy oil products such as crude and heavy fuel oil. Hence, it is anticipated that existing infrastructure which handle light oil products can be suitably re-purposed to handle toluene/ MCH with no/ minor modification. Similarly, no/ minor modification is anticipated for re-purposing existing infrastructure which handle heavy oil products for handling the BT-PBT pair.

A high level assessment was carried out on the suitability of typical conventional oil storage facilities for handling LOHC. There are no known limitations on the storage and handling facilities (e.g. storage tank and loading/unloading systems) which could be utilised for storing and handling LOHC. Although there are preferential types of storage tank and pumping system for the relevant LOHC pair (e.g. floating roof tank and centrifugal pump are considered most suitable for TOL-MCH pair), others could be utilised after further checks and/ or suitable modifications. A number uncertainties were identified from Phase 1 work and hence the Phase 2 trials have been designed to resolve some of these uncertainties particularly regarding fluid flow characteristics and potential contaminant take up.

It should be highlighted that this work is limited to re-purposing of oil terminals only for storing hydrogen in the form of LOHC. It will also address loading and unloading facilities, specific to the oil terminal selected for the trial, and will consider the full range of export/ import facility options at a more generic level. These will include:

- Re-purpose of existing pipelines/ network
  It is suggested that work is carried out to check whether the existing pipelines/ network carrying oil or petroleum products can be re-purposed to transfer LOHC from one location to another within the UK. It is expected that the Phase 2 work for oil terminal feasibility would give some indications on the suitability of using existing materials for pipework and any issue associated with fluid flow characteristics - which may also be relevant to re-purposing existing oil pipelines/ network.

- Re-purpose of existing transport system
  This covers the existing transport (including e.g. oil marine tankers, rail and road tankers) to be re-purposed to transfer hydrogen in the form of LOHC. It is noted there is ongoing work being carried out to review the bulk marine transfer of hydrogen using LOHC by the Scottish government, Ref [38]. The first stage of the study (referred to as Phase 1) has been

completed, covering an evaluation of the environmental, health and safety performance for a number of LOHC options as well as a high level financial analysis to determine the levelised lifecycle delivery cost. A follow-up demonstration project will be carried out to evaluate the production, loading, transport and unloading of LOHC suitable for hydrogen delivery between ports within the UK and Northern Europe. Similar work will need to be carried out to review options of delivering LOHC in road tankers in efficient and cost-effective manner.

The overall work and demonstration in Phase 2 would provide significant evidence for the transitioning of existing conventional oil infrastructure to store hydrogen at scale and to move it around the country. It would also open up the opportunity for hydrogen to be exported from the UK to the EU.

There are a number of risks associated with re-purposing existing oil infrastructure to store and handle LOHC, as well as other implications associated with the wider export/ import and transportation of hydrogen in the form of LOHC. These are presented in Table 4.1.

## Table 4.1: Top Risks

| No. | Issue | Description | Mitigation |
|---|---|---|---|
| 1 | Material compatibility | It is understood that the two leading LOHCs are compatible with steel materials commonly used in existing oil infrastructure. However, the suitability of the variety of materials used in existing infrastructure, such as other metals and seals, are unknown at this stage. | Consultation with specific LOHC vendors will be needed to check the suitability of other metals and seals materials etc. as the vendors may already have such information. Consultation with UK HSE may also be needed for qualifying different materials to be repurposed to handle LOHC. |
| 2 | End market readiness | As with other alternative hydrogen carriers (such as ammonia, methanol, etc.), export of hydrogen in the form of LOHC requires end users with appropriate dehydrogenation technology. This is an emerging market which is not widely traded, and the cost of technology is still expensive. | It is expected that there is some additional support from the government to enable early projects to be realised via e.g. government funding for Capex, policy, etc. |
| 3 | Regulatory and consenting compliance | Specific LOHC substances, such as MCH, BT-PBT pair are not commonly stored, transported and handled in the UK.<br>It is currently judged that these substances would fall under existing categories within the existing regulation. For example, MCH is judged to be categorised under P5b flammable liquids within COMAH and land-use planning regulations due to it being Category 2 flammable liquids under CLP and the potential for major accident hazard. | Consultation with regulatory bodies is needed to confirm if there is any additional constrains associated with regulatory and consenting prior to export/ import and transportation of LOHC. |
| 4 | Supply chain | Currently the global annual production and availability of the unloaded LOHC substances (e.g. toluene and dibenzyl toluene) may be lower compared to existing supply chain for other alternative hydrogen carriers (i.e. ammonia and methanol). These substances are not currently produced in the UK; hence there will be reliance on supply from other countries to meet the demand on these substances if hydrogen is to be transported in the form of LOHC. | If hydrogen is to be transported in the UK in the form of LOHC, there is a need to build manufacturing facilities in the UK to supply unloaded LOHC substances to prevent reliance on supply from other countries. |
| 5 | Competition with other alternative hydrogen carriers (e.g. ammonia, | The cost to supply hydrogen in the form of LOHC may be more expensive compared to converting hydrogen to other alternative hydrogen carriers (e.g. ammonia, methanol, etc.) for specific applications.<br>Currently ammonia and methanol has already been produced at scale whilst the production of LOHC | Government policy would play an important role on this aspect. The cost of hydrogen at its end-user will also depend on the cost of storage and transport of the relevant hydrogen carrier, not only its conversion process. |

| No. | Issue | Description | Mitigation |
|---|---|---|---|
| | methanol, etc.) | from hydrogen (hydrogenation technology) is still a developing technology.<br>It is noted, however, that the cracking of ammonia/ methanol into hydrogen is still an emerging technology, as the case for dehydrogenation (conversion of LOHC into hydrogen). | As there is potential of re-purposing conventional oil storage facilities to store and transfer hydrogen in the form of LOHC, this removes the requirement to install and construct the storage and transport facilities. |
| 6 | Hydrogen demand | Uncertain hydrogen demand | Investigations on anticipated hydrogen demand for specific locations/ regions in the UK over specific duration would help in identifying the capacity of storage and transfer facilities needed to handle LOHC. This can be used as a basis to develop a programme of gradual conversion of existing oil terminals to serve specific locations/ regions to handle LOHC over specific timeline. |

As indicated in Section 2.2, there are 84 terminals in the UK which handle petroleum products totalling ~17,100,000 $m^3$ of capacity. If these terminals are re-purposed to store and handle LOHC, the UK can benefit from storage capacity of approximately 14.1 TWh of hydrogen in the form of LOHC, without installing/ constructing new storage facilities for hydrogen.

Consultation with existing oil terminals have indicated their interests to invest in synthetic fuels, such as green diesel, etc., in addition to hydrogen, as alternative low carbon fuels. Hence, if the government policy and market are supporting the use of synthetic fuels (instead of hydrogen), it is likely that the existing oil terminals will be used to store and handle synthetic fuels, instead of LOHC. Hence, this presents some challenges of using the existing terminals to store LOHC.

At this stage it is difficult to estimate the levelised cost of hydrogen that can be achieved. The project is limited to re-purposing of oil terminals to store LOHC. The level of modification that needs to be implemented into an existing terminal is currently unknown, pending for results of Phase 2 trial programme. In addition, each existing oil terminal has different storage and transfer facilities; indicating that different level of modifications are anticipated on specific terminals.

The project would also have some impacts on greenhouse gasses mitigated and potential carbon savings. By re-purposing existing oil terminals to store and handle LOHC (instead of petroleum products), it will result in emissions reduction of the entire oil storage and transfer facilities. It will have considerable effect in the way in which energy is generally produced or consumed. This would support production and consumption of low carbon hydrogen. However, at this stage it is difficult to estimate the specific value of greenhouse gasses mitigated and potential carbon savings as it is dependent on specific oil terminals (e.g. their facilities, capacities, etc.).

If oil terminals in the UK are to be re-purposed to handle hydrogen in the form of LOHC, it is likely that the re-purposing programme would occur as a gradual transition in line with market demand. Hence, it is expected that the existing resources/ workforce associated with storage and transport of hydrocarbon fuel at the existing oil terminals will also be transitioning to support hydrogen storage and transport operations. Depending on where LOHC should be converted back to hydrogen for transport to end-users, there are possibilities that some terminals will need to install/ construct dehydrogenation facilities onsite. The operations of dehydrogenation facilities may require an increase in the local workforce. Hence, there is potential job creation at the relevant oil terminals although at this stage it is difficult to quantify as it would be varied from one terminal to another depending on the capacities and arrangement of the dehydrogenation facilities that are needed.

# 5. DEVELOPMENT PLAN

A development plan for the demonstration trial has been developed as outlined in Section 0 of this document, identifying the key elements of the trial and a high level estimate of costs.

A business plan for how the process will continue to be developed after the funding for the pilot ends shall be developed as part of Phase 2 of the project. A successful Phase 2 trial would pave the way of the use of LOHC as an effective storage mechanism for hydrogen. We anticipate further public support would be required for the commercialisation stage, given likely public perceptions of hydrogen. However, sufficient UK regulatory and other policy frameworks on the use of LOHC as hydrogen storage (compared to other alternative liquid hydrogen carriers) would be critical to support the commercialisation stage.

# 6. ROLLOUT POTENTIAL

The Phase 2 trial would involve tests on different systems/ facilities available on existing oil infrastructure, including: storage tank, pumping system, loading/ unloading facility as well as export/ import facilities (e.g. jetty and loading arm), at an existing oil terminal. It will also address all of the regulatory hurdles and consent pathway required to achieve the repurposing of existing facilities for LOHC storage and handling. Upon successful completion of Phase 2, and assuming there is no major issues identified, the ability for oil terminals across the UK to store hydrogen at scale will be proven.

# 7. ROUTE TO MARKET

The key steps to commercialisation are outlined below:

- The Phase 2 trial described in Section 3 will demonstrate the performance of using existing oil terminal facility to store and transport LOHC. The trials have been designed to resolve some of the remaining uncertainties identified from Phase 1 particularly regarding fluid flow characteristics and potential contaminant take up and the regulatory consent pathway.
- Upon successful completion of the system demonstration this will provide the evidence for re-purposing of existing oil terminals to store and handle hydrogen in a commercial environment.

# 8. DISEMMINATION

Due to the short duration of this Phase 1 project, there has been little opportunity to disseminate the study findings to date. However, ERM regularly presents at Low Carbon Energy Conferences in the UK and overseas and will look to present a conference paper on the study (with BEIS approval) if the project progresses to Phase 2.

In addition, ERM has presented about LOHC technologies at a number of industry events within the last year, including:

- “Hydrogen storage, transport and use in a marine context - learnings from UK trials”, Gastech, September 2022, All-Energy May 2022
- “The commercial opportunity for LOHC as an enabler of industrial decarbonisation”, All-Energy May 2022
- “Hydrogen storage and transport using LOHC”, World Hydrogen Summit, Rotterdam, May 2022

A full programme of dissemination events would be proposed for the project as part of Phase 2.

# 9. CONCLUSION

The work undertaken in Phase 1 indicates there are no significant technical barriers that could prevent re-purposing conventional oil storage facilities in the UK for the future storage of hydrogen in the form of LOHC. A number of uncertainties were identified from Phase 1 work and hence the Phase 2 trials have been designed to resolve these, particularly regarding fluid flow characteristics and potential contaminant take up.

There is significant potential storage capacity in the UK for storing hydrogen if the existing infrastructure can be repurposed to store LOHC. In being able to use existing facilities, UK oil terminals will be able to store hydrogen as LOHC alongside current oil products and gradually transition as the hydrogen economy increases and fossil fuels decline.

It should be highlighted that this work is limited to re-purposing of oil terminals only for storing hydrogen in the form of LOHC. Phase 2 work will investigate whether the full infrastructure and export/ import facilities for petroleum products can be re-purposed, such as existing oil pipelines/ network as well as existing transport system (e.g. oil marine tankers, rail and road tankers). The overall work and demonstration project would provide significant opportunities for the transitioning of existing conventional oil infrastructure to store hydrogen at scale and to move it around the country via coastal tankers, rail tankers, road tankers and existing oil pipelines. It would also open up the potential for hydrogen to be exported from the UK to the EU.

A high level plan for carrying out a ‘real world’ trial to demonstrate the performance of LOHC at an existing UK facility has been developed (Phase 2). This demonstration would provide the technical evidence and regulatory pathway for the transitioning of existing conventional UK oil infrastructure to store and handle hydrogen at scale.

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## APPENDIX A – GHS RISKS AND HAZARDS CLASSIFICATIONS

| H Code | Classification of risk or hazard | Risk category |
|---|---|---|
| H224 | Extremely flammable liquid and vapour | 1 |
| H225 | Highly flammable liquid and vapour | 2 |
| H226 | Flammable liquid and vapour | 3 |
| H304 | May be fatal if swallowed and enters airways | 1 |
| H315 | Causes mild skin irritation | 2 |
| H319 | Causes serious eye irritation | 2 |
| H332 | Harmful if inhaled | 4 |
| H335 | May cause respiratory irritation | 3 |
| H336 | May cause drowsiness or dizziness | 3 |
| H340 | May cause genetic defects | 1 |
| H350 | May cause cancer | 1 |
| H351 | Suspected of causing cancer | 2 |
| H360FD | May damage fertility. May damage the unborn child | 1 |
| H361 | Suspected of damaging fertility or the unborn child | 2 |
| H361d | Suspected of damaging the unborn child | 2 |
| H361FD | Suspected of damaging fertility. Suspected of damaging the unborn child. | 2 |
| H370 | Causes damage to organs | 1 |
| H372 | Causes damage to organs through prolonged or repeated exposure | 1 |
| H373 | May cause damage to organs through prolonged or repeated exposure | 2 |
| H400 | Very toxic to aquatic life | 1 |
| H410 | Very toxic to aquatic life with long lasting effects | 1 |
| H411 | Toxic to aquatic life with long lasting effects | 2 |
| H412 | Harmful to aquatic life with long lasting effects | 3 |

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