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Phase 1 Report

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13th April 2021

BEIS Green Distilleries Competition

Phase 1 Report

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Glossary

Name	Description
BEIS	Department for Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
COMAH	Control of Major Accident Hazards
DBT	Dibenzyltoluene
DEC	Decalin
EHS	Environment, Health and Safety
ERM	Environmental Resource Management
FA	Formic Acid
FEED	Front End Engineering Design
H_0LOHC	Dehydrogenated Liquid Organic Hydrogen Carrier
H_nLOHC	Hydrogenated Liquid Organic Hydrogen Carrier
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
MCH	Methyl cyclohexane
NAP	Naphthalene
NDA	Non-Disclosure Agreement
NEC	N-Ethylcarbazole
OPEX	Operating Expenditure
PDBT	Perhydrodibenzyltoluene
PHPZ	Perhydro-phenazine
PHZ	Phenazine
PNEC	Perhydro-n-ethylcarbazole
TOL	Toluene
TRL	Technical Readiness Level. On a scale of 1-9, this method for estimating the maturity of technologies

Executive Summary

The aim of the Green Distilleries Competition has been to identify, support and then develop credible innovative fuel switching technologies/enabling technologies to bring about a step change in their development. This report represents Phase 1 of the Liquid Organic Hydrogen Carrier (LOHC) evaluation for distilleries. It presents the findings of the feasibility assessment and a recommendation for the next stage of the project (Phase 2).

In this study, the viability of using hydrogen to decarbonise heat in the UK distillery industry using a LOHC to transport and store the fuel has been evaluated.

The first stage was to evaluate the Environmental, Health and Safety performance for a number of LOHC options against other forms of hydrogen transport including liquid hydrogen, methanol and ammonia. This was used to determine which options should be taken forward for more detailed technical scrutiny and to compare the lifecycle costs. The results of this screening exercise revealed two options that should be taken forward for further examination:

- Methylcyclohexane – Toluene (MCH-TOL)
- Perhydrodibenzyltoluene – Dibenzyltoluene (PDBT-DBT)

An energy model for these two options as well as Ammonia, Methanol and Liquid Hydrogen were developed whereby the technical readiness/constraints, energy demands and likely equipment needs were identified. Consideration was also given to the potential to re-use waste heat and to re-purpose equipment.

The energy model and subsequent equipment scheme were then subject to a cost analysis. The key cost drivers and benchmark cost ranges were identified followed by a detailed bottom-up cost evaluation with key sensitivities explored in order to understand the drivers of commercial viability.

The outcome of the cost modelling suggested from an economic perspective, that DBT appeared to be the most favourable of the options considered, with levelised lifecycle delivery costs below £1.50 per kilogram of hydrogen.

The DBT option was then examined in more detail in order to develop the requirements for a demonstration project. The aim of the demonstration is to evaluate the production, loading, transport, unloading and storage of LOHC suitable for hydrogen delivery to a distillery for the production of heat through combustion in a steam raising boiler. Accordingly, a plan has been developed in four stages to design, trial and deliver a working LOHC project at industrial scale. This is summarised below.

Stage 1	Stage 2	Stage 3	Stage 4
Demonstrating the LOHC transport, storage, continual release process for conditions relevant to a typical whisky distillery	Design the trial (Concept and FEED) to build a 5te/day LOHC hydrogenation plant supplied by green hydrogen and a 1.5te/day release unit and storage facility	Build the 5te/day LOHC hydrogenation plant and the 1.5te/day release unit and storage facility to fire a single distillery steam boiler (2MW)	Increased release and storage capacity would be provided to enable the complete supply of a single distillery (A typical oil fired distillery has boilers of around 6MW in total)
2021	2022/23	2024	2025/26

1. INTRODUCTION

ERM has been engaged to assist BEIS ("the Client") for the provision of hydrogen feasibility study services related to the Green Distilleries project (GD152 - TRN 2564/08/2020).

1.1 Objectives

The objective of the study is to determine the viability of Liquid Organic Hydrogen Carrier (LOHC) to deliver hydrogen to UK distilleries for the production of heat required in the distilling process. It is also to outline a Phase 2 pilot trial plan to demonstrate the technical, economic and EHS performance of the most suitable carrier identified. This will demonstrate its ability to deliver hydrogen safely, reliably and efficiently to distilleries under real world conditions.

1.2 Project Overview

LOHC has the potential to carry as much hydrogen per unit volume as liquid hydrogen and can do so safely and cleanly at atmospheric temperature and pressure. It can be transported from point of origin, using coastal tankers, to deliver to local ports. From there it can be transported using conventional fuel road tankers to remote distillery locations and stored in conventional fuel storage tanks. Waste heat from the distillery can be used to disassociate (dehydrogenate) the hydrogen from the LOHC and the released hydrogen used to fuel the distillery. Depleted (dehydrogenated) LOHC can be collected by the visiting road tanker and returned to port providing an efficient cyclic delivery/return process.

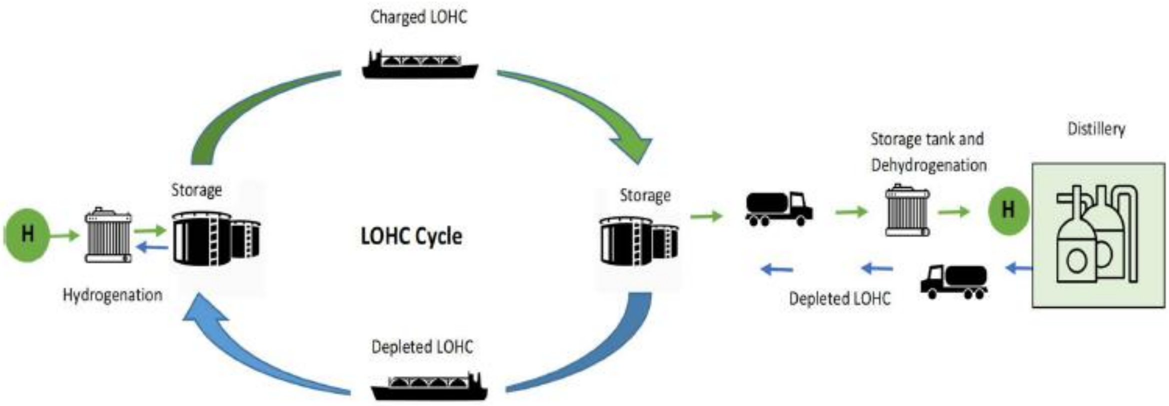
This feasibility study examines the techno-economic and environmental, health and safety (EHS) case for LOHC to decarbonise the UK distillery industry, by providing hydrogen to replace fossil fuels to fire the stills that drive the distillation process. It examines the technical readiness and projected cost for producing LOHC at scale, its transport by road tanker, its storage at location and the efficiency of the dehydrogenation process. It reviews the benefits and barriers of LOHC against other forms of hydrogen transport including liquid hydrogen, methanol and ammonia.

2. MODELLING RESULTS

The potential for hydrogen to decarbonise distilleries is currently being investigated but how the hydrogen would be delivered to and stored at distillery locations, many of which are remote, is a challenge. LOHC is a potential solution. It is a liquid, which has the potential to carry almost as much hydrogen per unit volume as liquid hydrogen and can do so safely and cleanly at atmospheric temperature and pressure. It can be transported from source of origin, using coastal tankers, to deliver to local ports. From there it can be transported using conventional fuel road tankers to remote distillery locations and stored in conventional fuel storage tanks.

Waste heat from the distillery can be used to disassociate (dehydrogenate) the hydrogen from the LOHC and the released hydrogen used to fuel the distillery. Depleted (dehydrogenated) LOHC can be collected by the visiting road tanker and returned to point of origin providing an efficient cyclic delivery/return process (see *Figure 2.1*).

Figure 2.1 LOHC Production, Transport and Usage



An examination of the techno-economic and EHS case for a range of LOHC options has been carried out by reviewing:

- the technical readiness for producing LOHC at scale
- the projected cost for producing LOHC at scale
- the transport of LOHC by ship to local ports
- the transport of LOHC by road tanker directly to distilleries
- the storage of LOHC at location
- the efficiency of the dehydrogenation process.

The LOHC options have been reviewed against other forms of hydrogen transport including liquid hydrogen, methanol and ammonia.

The LOHC production and transport process has already been proven from trials carried out in Germany[1] and Japan[2], but its suitability for use to deliver hydrogen to distilleries using conventional equipment has not. The study has therefore examined the suitability of transporting LOHC by road tanker and the potential for utilising existing fuel oil storage facilities as well as the potential to use waste heat to reduce energy requirements in the dehydrogenation process.

1 https://www.fch.europa.eu/project/hydrogen-supply-and-transportation-using-liquid-organic-hydrogen-carriers

2 https://fuelcellsworks.com/news/worlds-first-international-transport-of-hydrogen-from-brunei-to-japan/

2.1 EHS Review of LOHC Options

The EHS (Environmental, Health and Safety) performance has been compared for a number of LOHC options against other forms of hydrogen transport including liquid hydrogen, methanol and ammonia.

LOHC is formed by hydrogenating an organic solvent, which is subsequently dehydrogenated to release the hydrogen at the point of use. The base solvent can then be recycled for re-hydrogenation. Therefore, a number LOHC "pairs" involving the base solvent (H_0LOHC) and the hydrogenated solvent (H_nLOHC) were evaluated for the impact in relation to:

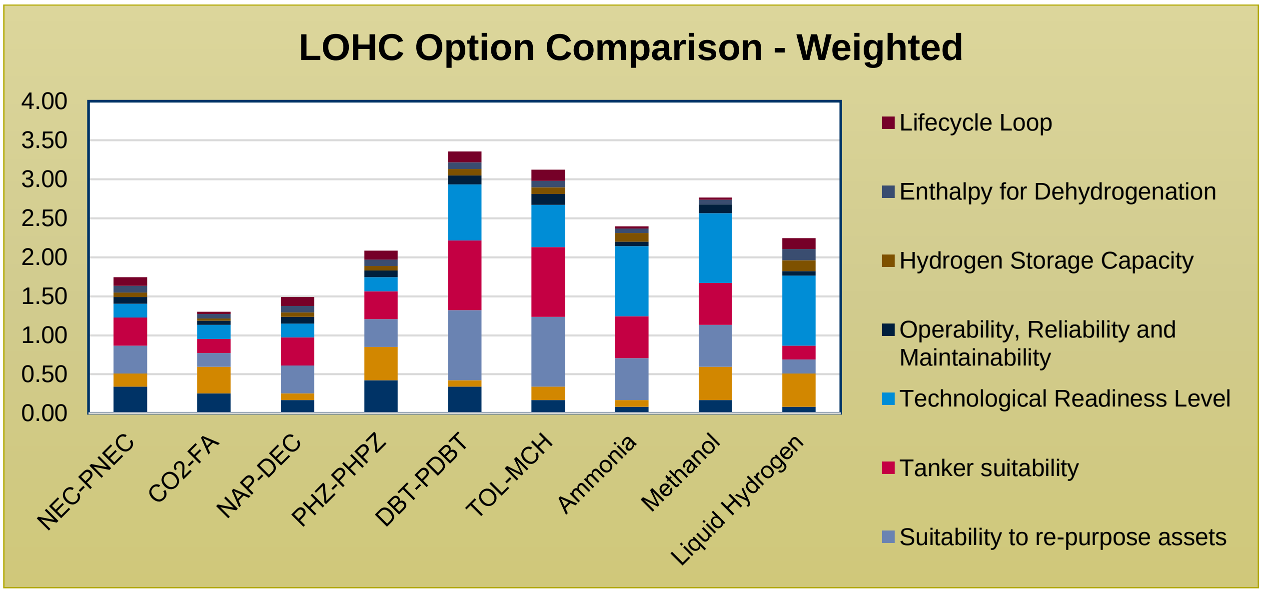
- Chemical and physical properties
- Energetic properties
- Technical readiness and availability
- Costs

Each pair was rated against one another to determine the relative ranking. The results of the screening exercise revealed two options that should be taken forward for further examination:

- Methylcyclohexane – Toluene (MCH-TOL)
- Perhydrodibenzyltoluene – Dibenzyltoluene (PDBT-DBT)

The results of the screening process are illustrated in *Figure 2.2* with the higher scores having the better overall HSE performance.

Figure 2.2 LOHC Screening Results



These options were developed along with a comparison against other forms of hydrogen transport including liquid hydrogen, methanol and ammonia.

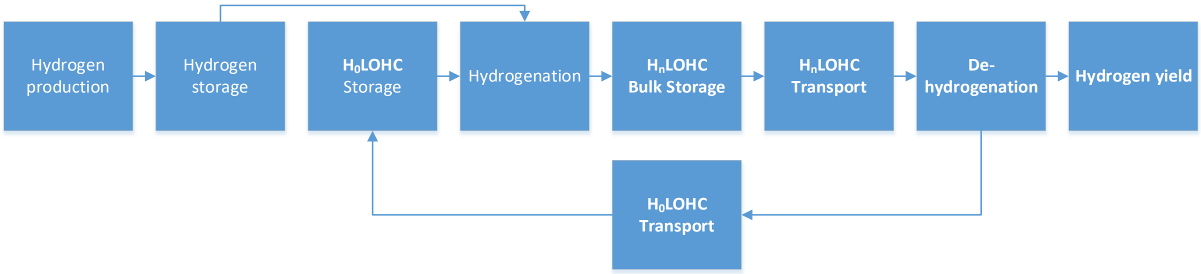
2.2 Development of the Energy Model for LOHC

The hydrogenation process typically operates in the range of 10-50 bar pressure and temperature around 130-200°C in a reactor that uses a noble metal catalyst. The reaction is exothermic and therefore the heat released can be used somewhere else. The base organic solvent feed is vaporised in a vaporiser and mixed with hydrogen and recycle gas.

The feed is super-heated to the reaction temperature and enters the top of the reactor charged with hydrogenation catalyst. The base solvent reacts with hydrogen to produce H_nLOHC. The effluent gas from the reactor is cooled and condensed. The liquid product is sent to bulk storage tanks prior transport.

Dehydrogenation of the H_nLOHC recovers hydrogen at a temperature of 250 to 300°C in the presence of a catalyst. This endothermic reaction requires heat, which is provided within the reaction process and can utilise waste heat from distillery processes. Upon release, the hydrogen is purified for use, and the base solvent is returned to storage.

The energy model is therefore based on a number of process steps illustrated below:



2.2.1 Methyl cyclohexane – Toluene (MCH-TOL)

MCH is the hydrogenated LOHC and TOL being the dehydrogenated LOHC (or base solvent). With a technical readiness level (TRL) of 8-9, this system is a well-studied cycloalkane system which is already being utilised on an industrial scale. Toluene is mass produced and available at low prices (~£0.5/kg) and MCH has a hydrogen storage capacity of 6.1% by mass.

An example of a trademark process offered in the current market is SPERA® hydrogen, developed by Chiyoda Chemical Group in Japan. SPERA® hydrogen is already being demonstrated at large scale (hydrogenation capacity of 300 Nm^3 H_2/h), with 4.7 tonnes of hydrogen being transported from Brunei to Japan each week.

2.2.2 Perhydro-dibenzyl toluene – Dibenzyl toluene (PDBT-DBT)

PDBT, the hydrogenated form of DBT, is already being utilised as an LOHC with a TRL of 9. DBT is a commercial heat-transfer oil that has been produced at scale since the1960s. DBT is slightly more expensive than toluene (~£4/kg) however, it has advantages over other LOHCs in regards to transport, safety and environmental considerations. PDBT has a slightly higher hydrogen storage capacity than MCH (6.2% by mass).

An example of technology is StoragePLANT (hydrogenation unit)/ ReleasePLANT (dehydrogenation unit), offered by Hydrogenious LOHC Technologies in Germany. A demonstration project is ongoing in Germany, with hydrogenation capacity of < 400 Nm^3/hr of hydrogen.

2.2.3 Ammonia

Ammonia has the ability to be utilised as a hydrogen carrier following synthesis via the Haber-Bosch process, which combines hydrogen with nitrogen obtained by air separation. Ammonia has been produced in very large quantities and used as a fertiliser for over 75 years, so therefore has a well-established supply chain, including infrastructure, safety regulations and handling practices. Ammonia has the highest hydrogen storage capacity of the hydrogen carriers being considered at 17.7% by mass.

Hydrogen is obtained by "cracking" ammonia, which requires further energy (heat at above 900°C) and significantly less efficient than the dehydrogenation of other LOHCs (63% hydrogen recovery, compared to ⩾95% for PDBT or MCH). Ammonia requires a storage temperature of -33°C.

2.2.4 Methanol

Methanol has the ability to be used a hydrogen carrier and is synthesised by steam reforming of hydrogen and carbon dioxide. Based on high temperature steam reforming, this option has a TRL of 9. Low temperature steam reforming processes are currently being developed – which would reduce the energy demand – but have a TRL of 3. High temperature steam reforming is an exothermic process, however, so some heat can be recovered to improve efficiency. Hydrogen is obtained from methanol via mixing with water and superheating.

Storage, transport and handling of methanol is well established due to its widespread use as a solvent. It has a high hydrogen storage density (12.1% by mass).

CO_2 is released during dehydrogenation and would need to be captured and recycled back to the methanol synthesis plant or reused elsewhere.

2.2.5 Liquid Hydrogen

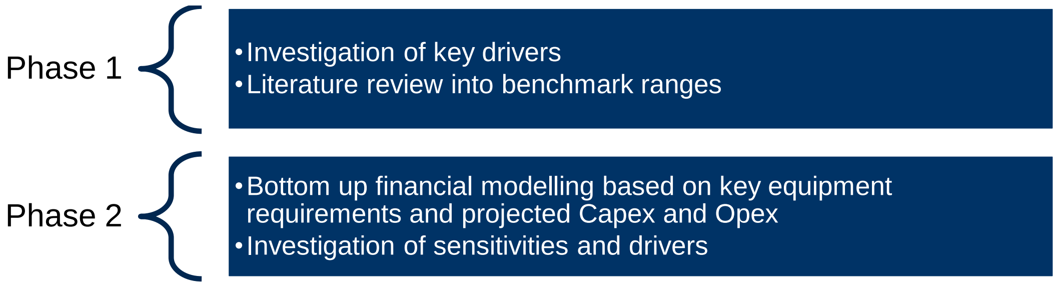
Hydrogen (H_2) can be transported in its liquid form, which removes the need for additional feedstock and hydrogenation/dehydrogenation processes and avoids any potential impurities being added to the hydrogen. Transportation of liquid hydrogen is a mature technology and is done so by both road tankers and pipelines.

Although the hydrogen storage density is 100% by mass, the density of liquid hydrogen is much lower than other LOHCs (71 kg/m^3, compared to PDBT at 910 kg/m^3). Liquid hydrogen needs to be stored at cryogenic conditions (-253°C), which requires specialised vessels.

2.3 Key Equipment Included in Cost Model

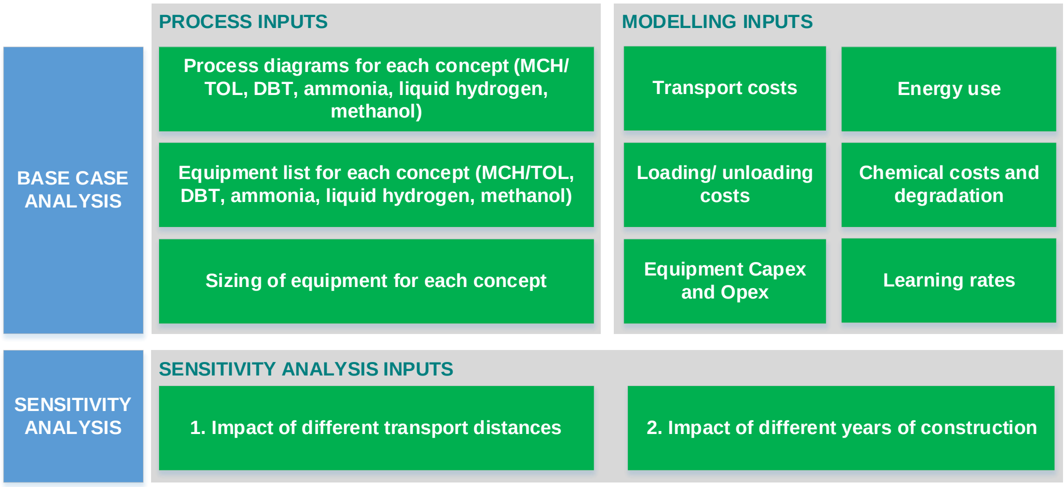
The development of the cost model was undertaken in two stages, summarised in *Figure 2.3* below. Firstly, key cost drivers and benchmark cost ranges were identified. Secondly, detailed bottom up cost modelling was undertaken, and key sensitivities explored in order to understand the drivers of commercial viability.

Figure 2.3 Phased Cost Model Construction



The key inputs and sensitivities included in the model are summarised in *Figure 2.4* below.

Figure 2.4 Key Inputs and Sensitivities included in the Model



For each hydrogen carrier option, the following key equipment items were included in the cost model (note that not all equipment items listed are applicable to every option):

- **Storage Vessels**: required for storage of; raw hydrogen and carrier chemical prior to dehydrogenation, hydrogenated carrier chemical awaiting transport to distillery, dehydrogenated carrier chemical awaiting transport back to the hydrogenation plant.
- **Carrier Chemical Production Facility**: applicable where it was favourable to produce rather than purchase the carrier chemical in bulk (i.e. nitrogen required for ammonia and carbon dioxide required for methanol).
- **Hydrogenation Plant**: self-contained plant unit
- **Dehydrogenation Plant**: self-contained unit local to the distillery
- **Road Tankers**: used for transportation of the hydrogenated hydrogen carriers to the distillery and the dehydrogenated hydrogen carrier back to the hydrogenation plant.
- **Compressors**: where required to compress components to suitable storage conditions or to the conditions required for hydrogenation.

2.3.1 Boiler Conversion

Many distilleries are off-gas grid sites and have tended to rely on fossil fuel oils for boiler fuel. The recent trend has been a switch towards gas boilers. Hydrogen boilers are expected to be relatively cheap, with costs comparable to gas boilers, requiring retro-fitting of a hydrogen-specific burner. Projections suggest that hydrogen will be more cost-effective at producing process heat or steam than the low carbon alternatives in many industrial sectors.

2.4 Key Cost Drivers for Each Carrier

Each of the potential carriers has economic advantages and disadvantages, arising from the key cost drivers, summarised below. Each cost driver has been evaluated by contribution to total cost in £/kgH_2 – green denotes a cost driver <10%, orange denotes a cost driver <30% and red denotes a cost driver >30% of total cost, respectively.

Table 2.1 Key Cost Drivers for Each Carrier

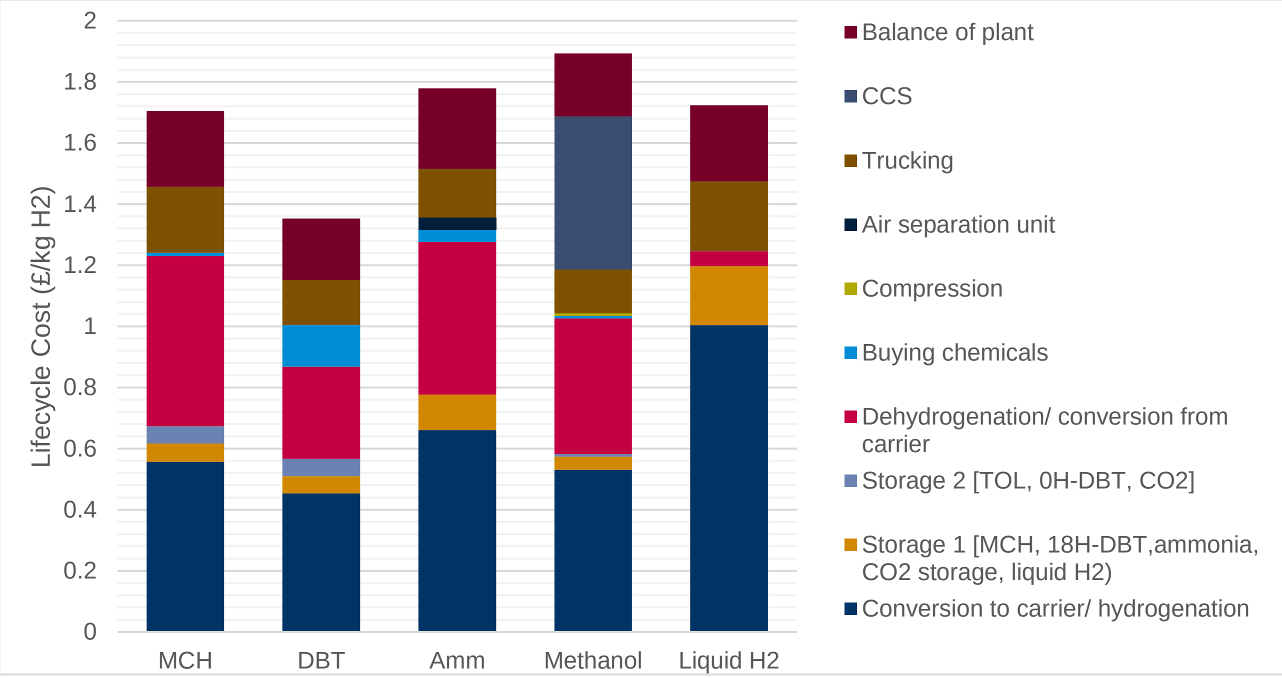
	MCH	DBT	Ammonia	Methanol	LH_2
Chemical costs	Less expensive than DBT but higher degradation rate	More expensive than MCH but lower degradation rate	N/A	N/A	N/A
Conversion/ hydrogenation	Reactors constitute highest cost for this medium	Reactors constitute highest cost for this medium	Synthesis constitutes highest cost for this medium	Methanation constitutes highest cost for this medium	High cost of conversion
Storage	Can be stored at ambient temperature in existing oil infrastructure	Can be stored at ambient temperature in existing oil infrastructure	Mature storage technology and high volumetric density	Moderate capex offset by high storage density makes this a low cost driver	High storage cost due to low temperature requirements
Trucking	Can be transported in existing oil tankers but moderate cost driver	Can be transported in existing oil tankers but moderate cost driver	High trailer capex offset by useful life and storage capacity	Relatively low trucking costs compared to other mediums but still a moderate cost driver	High capex but highest hydrogen storage density
Reconversion/ dehydrogenation	Reactors constitute highest cost for this medium	Reactors constitute highest cost for this medium	Reconversion can be avoided if off taker uses ammonia, high costs for cracking	Reforming constitutes highest cost for this medium	Competitive cost when electricity is expensive at point of delivery or cheap at point of liquefaction
Medium specific costs	N/A	N/A	Air separation and purification units required	Sustainable carbon source required and CCS	N/A
Uncertainty level	Emerging technology demonstrated at small scale projects such as Brunei AHEAD[3] project	Emerging technology demonstrated at small scale – conversion costs more uncertain.	Synthesis, storage and transport are mature technologies but cracking is emerging technology.	Commercially mature supply chains but producing carbon & CCS costs are very uncertain	High uncertainty due to low TRL – i.e. only one liquid hydrogen demonstration ship

2.5 Cost Comparison of Each Carrier

A comparison of total levelised cost of hydrogen on delivery for each concept is shown in *Figure 2.5* below.

[3] https://www.ahead.or.jp/en/

Figure 2.5 Cost Comparison of Each Carrier (2030 Costs, 100km Transport)



As can be seen from *Figure 2.5*, DBT appears the most attractive option from a purely economic perspective. EHS considerations are also likely to favour LOHC options over ammonia (which is toxic) and liquid hydrogen (which is highly flammable).

Ammonia, methanol and liquid hydrogen may prove more attractive for particular use-cases suited to those mediums. For example, if ammonia or methanol could be used directly by the off-taker, rather than requiring conversion back to hydrogen, then that would reduce the cost by ~£0.5/kg. Similarly, if liquid hydrogen was considered for a use-case where electricity prices were very cheap at the point of compression then this cost – which represents the major driver of the costs – would reduce. However, neither of these use-cases are considered particularly relevant for the specific situation of hydrogen use in a distillery that is under consideration in this study. As a result, the potential to optimise those options from an economic perspective is considered limited for this study, and DBT is recommended as the optimal solution given the data available at this time.

It should be noted that if a methanol option was pursued then this would rely on the availability of a sustainable source of carbon at the point of methanol production, and a storage option for carbon dioxide at the point of conversion to hydrogen. The costs associated with both of these items are extremely uncertain and likely to introduce prohibitive technical and commercial barriers, and so from an economic perspective, the DBT concept is considered preferable.

2.6 Potential to Repurpose Industrial Heat

Generating process heat for distillation is the primary source of emissions within the whisky industry. Process heat for distillation accounts for 91% of all heat-related fuel consumption and 83% of total fuel consumption, with electricity accounting for the other 17%[4]. Falling electricity emissions will only further increase the weight of process heat in the scope 1 and 2 emissions inventory – currently 530,000 tonnes CO_2/year.

The use of waste process heat has been researched as a potentially important driver behind improving the economics of LOHC dehydrogenation at distilleries. Assuming an

[4] scotch-whisky-net-zero-report.pdf (scotch-whisky.org.uk)

average thermal energy consumption rate of 6.6 kWh/lpa, the total potential waste heat from the sector is approximately 320,000 MWh/year, at an average temperature of 70-90°C[5]. This compares with the high temperatures required for dehydrogenation of the H_nLOHC, which recovers hydrogen within a temperature range of 250-300°C in the presence of a catalyst. The temperatures sufficient for dehydrogenation could potentially be upgraded using additional equipment such as waste heat boilers (for example a heat exchanger that uses exhaust gas heat to generate steam). During the next phase of the project, engagement with a distillery partner to gain a detailed understanding of waste heat availability will be undertaken in order to understand if there are economically viable options for upgrading waste process heat.

2.7 Modelling Conclusions and Recommendations

- Key challenges for LOHC include the economics of scale of production, demonstrating that it can be deployed using existing equipment and the efficiency of the dehydrogenation process, particularly the role that waste heat from distilleries can play in that.
- From a purely economic perspective, there is not a clear winner, however DBT appears favourable, with levelised lifecycle delivery costs below £1.50 per kilogram of hydrogen.
- The economic case for LOHC is improved through the ability to use conventional fuel storage facilities. An evaluation of existing assets that could be repurposed for a demonstration project is recommended to refine this element of the economic case.
- The high reconversion costs of LOHC are driven by high energy consumption, and the potential to repurpose waste industrial heat to reduce reconversion costs may improve the relative economics. Given ERM's current understanding of the temperature and availability of waste heat at a typical distillery, it is considered unlikely that this is sufficiently high temperature to be repurposed for the dehydrogenation process, however this will be investigated further in the second phase of the project.
- When comparing LOHC with other mediums:
  - Ammonia is the most established technology with the lowest costs. As with LOHC, the cost of reconversion is a major economic driver, and as the re-conversion process requires a high temperature, there is limited scope to repurpose low grade industrial heat to reduce energy requirements.
  - Methanol is promising as it has high storage density, low conversion and reconversion costs, however Carbon Capture and Storage (CCS) represents a key area of uncertainty. For projects where a suitable user or storage option for the CO_2 arising from the reconversion process could be found, methanol could represent an interesting option, however for most relatively remote distilleries this is not expected to be an attractive option.
  - Liquid hydrogen is a less promising technology. The costs are at present the highest, although further innovations are expected to reduce costs in future.

[5] Potential sources of waste heat for heat networks in Scotland (ed.ac.uk)

3. DEMONSTRATION PROJECT

3.1 Phase 2 Description

The potential for hydrogen to decarbonise distilleries has been investigated as part of the HySpirits project sponsored by BEIS. However, how the hydrogen can be delivered, stored and used at distilleries, many of which are remote, is a challenge for which LOHC provides a potential solution. This project has demonstrated that such a solution is viable both technically, economically and with regard to safety and environmental performance. The way in which hydrogen can be transported to a local port using LOHC and delivered to a distillery by a standard road oil tanker is illustrated in *Figure 2.1.*

The objective of Phase 2 of the study will be to identify and design a pilot trial to demonstrate the technical performance, EHS performance and full lifecycle cost of using LOHC for an operating distillery. This will demonstrate the ability to deliver hydrogen safely, reliably and efficiently to distilleries under real world conditions.

The LOHC production and transport process has already been proven from trials carried out in Germany and Japan,, but its suitability for use to deliver hydrogen to distilleries using conventional equipment has not. To provide hydrogen as a fuel for heat, there needs to be a continuous release process for LOHC and so its use in terms of transportation, storage, release and continuous hydrogen supply and combustion (through a hydrogen burner) needs to be verified. The proposed development plan for delivering an LOHC solution for hydrogen at distilleries considers four (4) increasing stages of demonstration over a 5-year period, each building on the last. These are as follows:

Stage 1	Demonstrating the LOHC transport, storage, continual release process for conditions relevant to a typical whisky distillery	At a test site	second half of 2021
Stage 2	Design the trial (Concept and FEED) to build a 5te/day LOHC hydrogenation plant supplied by green hydrogen and a 1.5te/day release unit and storage facility	Designed for a distillery in Scotland	2022/23
Stage 3	Build the 5te/day LOHC hydrogenation plant and the 1.5te/day release unit and storage facility to fire a single distillery steam boiler (2MW)	At a whisky distillery in Scotland	2024
Stage 4	Increased release and storage capacity would be provided to enable the complete supply of a single distillery (A typical oil fired distillery has boilers of around 6MW in total)	At a whisky distillery in Scotland	2025/26

The demonstrated commercial use of LOHC for the distillery industry would also be highly relevant to other industries (e.g. steel, glass, water treatment) where a significant storage of hydrogen is required to ensure uninterrupted supply. Therefore, the trials proposed for the distillery sector have a wider relevance to other UK industries.

The use of LOHC is also highly relevant to renewable hydrogen production where it would allow large volumes of hydrogen to be stored as LOHC in conventional oil storage facilities (e.g. existing oil terminals) and transported from there to local ports via coastal tankers. LOHC could therefore have a key part to play in enabling the UK hydrogen economy, enabling bulk transport of hydrogen at scale in a safe and efficient manner. The proposed trial would be the first LOHC trial to be conducted in the UK and follows the successful demonstration of LOHC as a hydrogen carrier in both Germany and Japan over the last 3 years.

3.1.1 Stage 1 - LOHC Delivery and Storage Trial

The Stage 1 trial will demonstrate the production, loading, transport, unloading and storage of LOHC suitable for hydrogen delivery to a distillery for the production of heat through combustion in a steam raising boiler. The initial thoughts were to perform a trial in the UK, but an option now exists to participate in a trial being conducted in Germany over the next 12 months that will demonstrate the key parts of the process required. This offers a cost-effective approach and would enable the project to progress more quickly to the design of a trial involving the use of LOHC at a distillery (Stage 2). The recommendation for Stage 1 is therefore as follows.

The Stage 1 trial, to be held in Germany, will involve the use of dibenzyltoluene (DBT) as the LOHC and will be conducted by Hydrogenious who have developed DBT LOHC technology over the last 5 years including a large scale production (hydrogenation) and storage unit and a corresponding release (dehydrogenation) unit.

The trial will consist of renewable hydrogen used to produce LOHC (1m^3 of LOHC carries the same mass of hydrogen as 0.76m^3 of Liquid Hydrogen) and will include:

- Production of renewable hydrogen using electrolysis
- Production of hydrogenated LOHC from the renewable hydrogen
- Loading of ‘live’ LOHC from storage vessel into a 30m^3 road tanker
- Transportation of the LOHC to its point of use
- Unloading the LOHC from the road tanker into an underground storage tank (30m^3)
- Pumping the LOHC from the storage tank to a pre-heater, utilising waste heat from the distillery if available, and then to a release (dehydrogenation) unit to release the hydrogen
- Compressing the hydrogen and delivering it via a short hydrogen pipeline to the end users
- Recovering ‘H_0LOHC from a second underground storage tank (30m^3) and returning to base via road tanker to be recharged

Hence, the trial will cover precisely the steps and processes to demonstrate for production, delivery and storage of LOHC at a distillery. It will also demonstrate the use of underground storage tanks for LOHC, which would provide significant visual improvements, if adopted for a distillery site. As such, it provides a unique opportunity to obtain the level of demonstration required quickly (trial is due to start in July 2021) in real-world conditions, extremely cost-effectively.

ERM has held several meetings with Hydrogenious over the last month to discuss the trial and technology to be deployed, and they would welcome ERM’s participation. ERM has a signed Non-Disclosure Agreement (NDA) and Hydrogenious will provide ERM with access to all project information, data and findings and will be able to witness the trials in Germany when they take place in summer 2021. (The trial is due to take place between July and October.) Participating in the trial, at nominal cost, will enable ERM to produce a report, presenting the findings to demonstrate the full production, loading, delivery, storage and dehydrogenation process. The report will focus on the delivery cycle required for a distillery and the suitability of all aspects of the system, including technology scaling, to decarbonise a large whisky distillery fully. The key parameters for the trial are as follows:

- Production of hydrogenated LOHC: 350kg/day
- Storage quantity: 30te
- Transported quantity by road: 30te
- Hydrogen released via dehydrogenation unit: 20kg/day
- Hydrogen release pressure: 45 bar
- Hydrogen release delivery pipeline: 50-100m
- Hydrogen pipeline pressure: 45 bar

The trial is already fully funded. Therefore, the only costs would be for ERM's attendance to witness the trial, interpreting the results and the cost of preparing a study report. The report would present the study findings and examine how they relate to the use of LOHC to deliver and store hydrogen at distilleries. This would then form the basis for the design of a real-world trial, involving the production, delivery, storage, hydrogen release and fuelling a fired boiler in Stage 2.

3.1.2 Stage 2 – Design of Industrial Scale Trial using LOHC/Hydrogen to Partially Fuel a Distillery

The Stage 1 trial will provide all of the evidence needed to demonstrate that LOHC can be economically and safely used to transport and deliver hydrogen to an industrial user (in this case a distillery). This, combined with the hydrogen burner studies conducted as part of other Green Distillery Competition projects, should provide all of evidence needed to design an industrial scale trial to use LOHC/hydrogen to fuel an operational distillery. This would ideally involve a multi-boiler oil fired facility, such that one of the boilers could be converted to hydrogen fuel without unduly impacting the overall level of production. The facility would also ideally have waste heat available that can be used to pre-heat the LOHC thereby saving energy during the release process.

ERM would identify a suitable distillery to sign-up for the trial during the first 6 months of the Stage 2 design, following satisfactory completion of the Stage 1 trial. A detailed project design (Concept and FEED study) would then be conducted working with the distillery to develop the trial, which would include:

- Selection of LOHC hydrogenation and storage unit (co-located at green hydrogen production site)
- Selection of suitable road tanker for LOHC transport to and from distillery
- Design of LOHC storage tanks (one for H_nLOHC, one for H_0LOHC) at distillery
- Selection of appropriately sized hydrogen release unit
- Design of pre-heating system for LOHC to utilize waste heat from distillery process
- Selection of hydrogen burner and re-design of boiler fuel system to supply hydrogen rather than oil
- Design of trial conditions, procedures and measurement of data
- Assessment of health, safety and environmental impacts including risk assessment
- Development of regulatory/consent requirements to enable trial to proceed

ERM would develop the Stage 2 FEED design utilising engineering sub-contractors to develop the necessary engineering drawings and fuel supply solution (building on the work of other Green Distillery projects such as HySpirits).

The aim of Stage 2 will be to design an overall system to deliver and supply sufficient hydrogen from LOHC to fire a 2MW distillery boiler continually. This will require around 1.2te of hydrogen per day compared to 3.7te of kerosene for an equivalent oil fired boiler.

A system to deliver the hydrogen will be developed as part of the design for the trial during FEED. Initial calculations carried out as part of the Phase 1 project indicate that a suitable system may comprise:

- 5te H_2/day Capacity LOHC hydrogenation and storage unit (co-located at green hydrogen production site)
- 30te capacity road tanker for LOHC transport to and from distillery
- 2 x 50te LOHC storage tanks (one for H_nLOHC, one for H_0LOHC) at distillery
- 1.5te H_2/day hydrogen release unit
- Heat exchanger for pre-heating LOHC prior to release unit utilising waste heat (100 - 200°C) from distillery process where available.
- 2MW (50kg H_2/hr) hydrogen burner and new fuel system pipework and controls to supply hydrogen rather than oil

Of these components, the three largest items are the production unit, the release unit and the storage tanks. The size of units required for the trial have already been designed and will soon be deployed on industrial scale projects in Germany (e.g. Project Puffin[6]; Implementation of first LOHC network with industrial sized LOHC production and release units).

The LOHC production and storage unit has a footprint of 13m x 13m, a total of 169m^2. It has an overall maximum height of 10m.

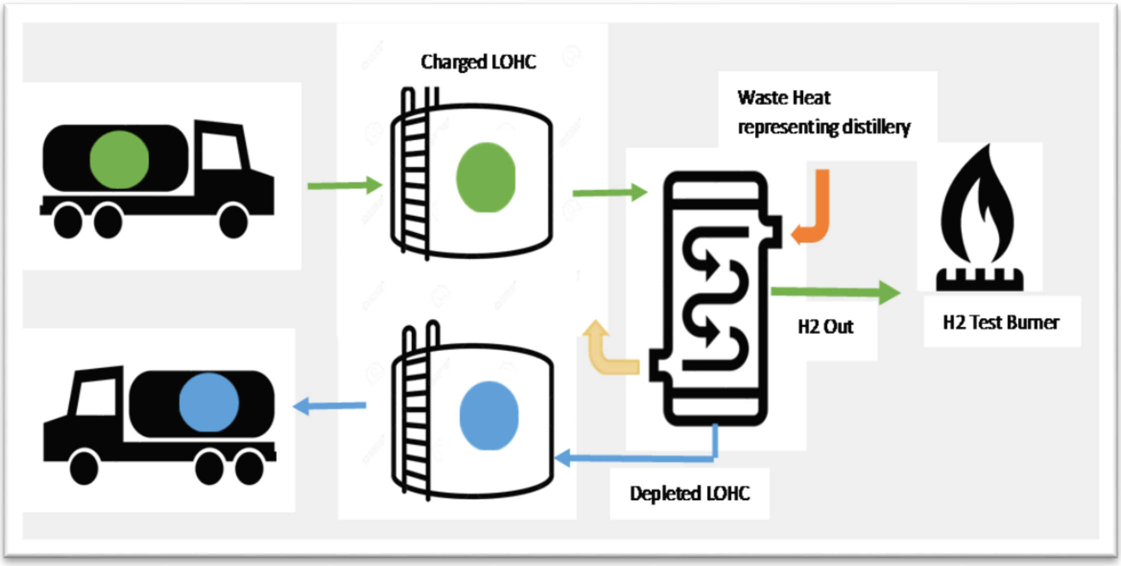
The LOHC Hydrogen Release unit has a footprint of 16m x 16m, a total of 256m^2. It also has a maximum height of 10m. Current design developments that are proposed are expected to reduce the footprint of both units by around 50% by 2030.

Underground storage tanks, currently being considered in the design, will be installed and tested in the proposed Stage 1 trial (in 2021). Two tanks will be deployed, one for H_nLOHC, and one for H_0LOHC. Both tanks will be sized at 30m^3 and their location underground will significantly reduce any visual impact.

Under the Stage 1 trial, LOHC will be pumped from the 'live' tank to the release unit to release the hydrogen. The used liquid is then returned to the second tank from where it is pumped back into a road tanker and taken to be 'recharged'. A diagrammatic representation of the trial design for Stage 2 is shown in *Figure 3.1*.

[6] The Priming Public Financial Institutions for Green Innovation (PUFFIN) project is a three-year project which is funded by EIT Climate-KIC

Figure 3.1 Diagrammatic Representation of Proposed Trial to be designed during Stage 2



3.1.2.1 Stage 2 Costing

The cost/ sourcing of components required for the full scale industrial trial will be determined in Stage 2 as part of FEED. However, indicative costs (+/- 20%) for the three main components of the trial are as follows:

- LOHC Production and Storage Facility – £10m (sized for full distillery decarbonisation capacity; i.e. x3 greater than needed for 2MW trial)
- LOHC Release Facility – £3m
- LOHC Storage Tanks – £0.5m

It should be noted that these costs are for early stage developments and are expected to fall by around 50% by 2030 when the technology is manufactured at scale.

3.1.3 Stage 3 – Industrial Scale Trial using LOHC-Hydrogen to Fire a Distillery Boiler

This stage of the LOHC demonstration would involve the firing of a 2MW distillery steam boiler using hydrogen provided from LOHC. It would comprise the execution of the trial designed in Stage 2 at a host distillery and a separate LOHC production facility (coupled with green hydrogen production). Suitable sites for the production facility and distillery have been identified in Scotland and preliminary discussion have already been held with interested parties. The precise location of both the production facility and the receiving distillery would be confirmed during Stage 2 (FEED). The trial to be conducted would include:

- Building a separate fuel supply system to 2MW boiler at distillery with ability to swap easily between oil and hydrogen supply (utilising different burners)
- Daily production of 25te of charged LOHC and transport to site via road tanker
- Transport of up to 25te/day of H_nLOHC to site at distillery by road and storage in suitable storage tank (regular trips to deliver and return LOHC in line with usage)
- Provision of additional tank for receipt of H_0LOHC following hydrogen release

- Release of up to 1.5te of hydrogen per day to fuel the hydrogen burner via release unit with pre-heat facility utilising waste heat
- Continuous operation for a period of one month
- Record all data to illustrate overall performance and efficiency
- Ability to quickly revert back to oil supply at completion of the trial

The target date for this trial would be starting 2024.

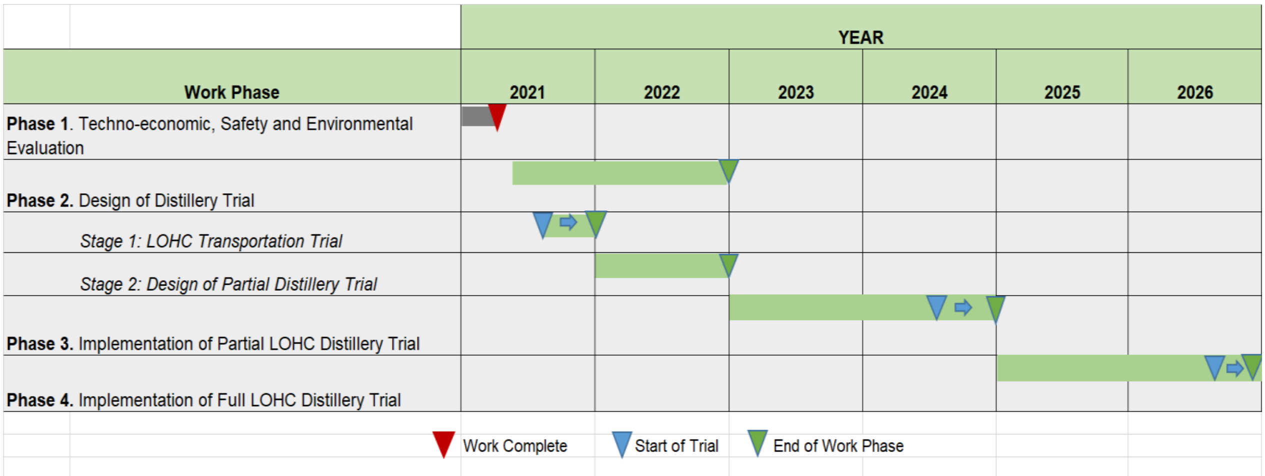
3.1.4 Stage 4 – Full Decarbonisation of Distillery by switching from Oil to Hydrogen.

This would be the final stage of the process and involve the installation of permanent facilities at the distillery to fully decarbonise heat and completing the transfer from oil to hydrogen, delivered via LOHC. To achieve this would require a successful Stage 3 trial and willingness of a distillery to undertake full fuel switching. The target date for this would be 2025/26.

3.2 Timeline for all 4 Stages of Demonstration Programme

The proposed timeline for all four stages of the LOHC demonstration programme is six years, with the key stages illustrated in *Figure 3.2.*

Figure 3.2 Proposed Schedule, Stage 1-4



3.3 Benefits and Barriers

An assessment of the benefits and barriers for the solution has been carried out including the sensitivity of capital and operating costs, process risks (in *Section 2.1,* and *2.2*), and how the process could be scaled (in *Section 2.2, 3.1.1* and *3.1.2*). One of the key benefits from evaluating LOHC in this study is the potential speed and cost of the decarbonisation process for the distillery industry. Using LOHC to provide hydrogen would have significant benefits as a decarbonisation solution, including the potential to re-use existing assets.

It is expected that the demonstration trial will not only inform the distillery industry but will also inform on the use of LOHC in other 'high heat' industry sectors that are hard to decarbonise and need to store large volumes of hydrogen locally for uninterrupted supply (e.g. steel, glass making, water treatment plant). A LOHC solution would be particularly valuable in the early years of a hydrogen economy where a pipeline infrastructure hasn't been established, particularly for industries in relatively remote locations.

3.4 Comparable Fuel Costs

In addition, consideration has been given to the amount of greenhouse gases that could be mitigated by an LOHC solution. The estimated potential CO_2 emissions savings for the UK by decarbonising heat used in the distillation process, across the country's 400 distilleries is around 643,000 tonnes per annum (2019 figures). The vast majority of this comes from the whisky industry that has around 160 distilleries, the majority in Scotland, and contributes around 530,000 tonnes per annum.

The use of green hydrogen, delivered by LOHC, to fully replace gas and fuel oil at distilleries has the capacity therefore to achieve a saving of around 600,000 tonnes per annum (taking out those distilleries recently converted to biomass). For the trials proposed in Section 3 of this report, the partial conversion of an average sized whisky distillery to hydrogen (2MW boiler) will result in a CO_2 saving of around 1,100 tonnes CO_2 per annum, whilst full conversion (6MW total) will result in a saving of 3,300 tonnes CO2 per annum.

An estimate for the change in distillery fuel costs when switching from oil or LPG to hydrogen (from LOHC) has been calculated from the economic analysis presented in *Section 2*. The calculation is based on a projected 2030 cost of hydrogen of £1.50/kg and a current day kerosene cost of £0.5/litre. It indicates that assuming current technology, manufacturing costs and performance for LOHC, the LOHC-Hydrogen option would result in increased fuel costs by a factor of x1.9 compared to oil. If the LOHC technology costs fall by the predicted 50% by 2030 this gap closes to around x1.5. Any increase in oil costs (perhaps due to Carbon pricing), additional reduction in hydrogen production cost or further LOHC technology developments would be expected to close this gap further.

3.5 Costed Development Plan

A costed development plan for the demonstration trial has been developed in the preceding sections. To summarise, this comprises:

- a detailed focus on the component(s) to be piloted in Phase 2 (*in Section 2.3*),
- a project delivery plan (*in Section 3.2*),
- cost estimates for the demonstration (in *Section 3.1.2.1*),
- a business plan for how the process will continue to be developed after the funding for the pilot ends (Stage 3 and 4 in *Section 3.1.3* and *3.1.4*).

3.6 Route to Market

The key steps to commercialisation have been reflected in the four stages of the Phase 2 demonstration project described in *Section 3.1* and *3.2*. The Stage 1 trial, to be held in Germany, will use renewable hydrogen to produce LOHC and provide the evidence to demonstrate that LOHC can be economically and safely used to transport and deliver hydrogen to fuel an operational distillery (in Stage 2). The cost/ sourcing of components required for the full scale industrial trial will be determined in Stage 2 as part of FEED working with a partner distillery. Stage 3 will execute the trial, designed in Stage 2, at the host distillery and a separate LOHC production facility. Upon successful completion of Stage 3 this will pave the way for Stage 4 and the installation of permanent facilities at the distillery to fully decarbonise heat and completing the transfer from oil to hydrogen will be set.

4. DISSEMINATION

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 over the next 3-4 months (with BEIS approval).

ERM are presenting at two events this month (March 2021) that are relevant to this study. These are:

- WBCSD. Vision 2050; Time to Transform, 25th March, and
- Ceres 2021. Transform Tomorrow Today, 22-25 March

In the first of these events, ERM will be holding a workshop on the transport and storage of hydrogen using LOHC and its potential use for delivering hydrogen for industrial heat.

In future, further presentations relevant to this study are expected, including:

- SPE Offshore Europe Conference and Exhibition, September 2021, speaking on the Commercial Case for Hydrogen as a Route to Market For Offshore Wind in the North Sea.
- Hydrogen workshop, Society of Petroleum Engineers, November 2021, speaking about hydrogen in the energy transition.
- NECCUS, April 2021, speaking on ERM Dolphyn Project; Green Hydrogen at Scale from Floating Offshore Wind.

ERM has an excellent track record of disseminating and promoting project work on behalf of projects for BEIS. ERM has given numerous presentations, conference papers and media articles on the Dolphyn project that was recently awarded **The 2020 Innovation Project of the Year** by 'The Engineer' magazine.

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

5. CONCLUSIONS

This Phase 1 study provides an evaluation of the technical, economic and EHS performance of LOHC as a hydrogen carrier with specific reference to its ability to replace fossil fuels at UK distilleries to decarbonise heat.

The conclusions from the study are as follows:

- A range of different LOHC and other hydrogen carriers have been assessed and the most suitable for decarbonising heat at distilleries was found to be the LOHC type dibenzyltoluene (DBT)
- DBT was found to have many advantages including; low flammability during transport, reasonable cost, low toxicity and ability to be transported and stored at atmospheric temperature and pressure using conventional oil facilities
- DBT was shown to be a viable option for supplying hydrogen to distilleries subject to the cost differential between it and current fuels (oil, LPG, etc.), decreasing to a level that is reasonably comparable
- Currently hydrogen, using DBT as a carrier, would increase fuel costs by a factor of x1.9 compared to the lowest cost, fuel supply option (kerosene). This decreases to around x1.5 allowing for the projected cost reduction of LOHC plant manufacturing by 2030. However, increases in future fossil fuel costs or further improvements in LOHC technology could close this gap further.
- The findings from the study, together with those from trials in Germany and Japan, indicate that it would be valuable to undertake an industrial scale demonstration project for LOHC as a hydrogen carrier for decarbonising heat at distilleries. Such a trial would not only inform the distillery industry but would also inform HM Government on the use of LOHC in other ‘high heat’ industry sectors (e.g. steel, glass making, water treatment plant).
- An outline development plan for a demonstration trial has been prepared which would involve an initial partial decarbonisation trial followed by full distillery decarbonisation. The initial stage of this plan would be completed in Phase 2 of this project and would consist of involvement in an already planned LOHC trial in Germany followed by the design (FEED) for an industrial scale UK trial at an actual distillery.
- The overall conclusion from this study is that LOHC is a viable option for transporting, storing and delivering hydrogen to a distillery (or other industrial facility) for heat production and that a demonstration trial is now warranted to demonstrate the technology under real-world conditions.

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