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Cascade Tank LOHC System for Hydrogen Storage and Delivery

Phase 1 Feasibility Report (BEIS)

24 October 2022

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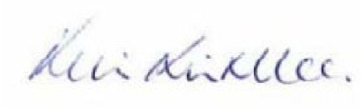

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Acronyms and Abbreviations

CAPEX	Capital Expenditure
OPEX	Operating Expenditure
LH_2	Liquid hydrogen
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
MCH	Methyl Cyclohexane
O&M	Operation & Maintenance
P&ID	Piping & Instrumentation Diagram
SOFC	Solid Oxide Fuel Cell
TRL	Technology Readiness Level

1. EXECUTIVE SUMMARY

The aim of the Low Carbon Hydrogen Supply Competition has been to determine the feasibility of low-carbon hydrogen solutions (Phase 1) that can be carried forward to demonstration trials (Phase 2). This report represents the findings of the feasibility assessment of the ERM Cascade Tank LOHC System for Hydrogen Storage and Delivery.

The ERM Cascade Tank System enables large quantities of hydrogen to be stored in the form of LOHC while minimising space requirements for tankage. The tank system is designed to be filled with ‘charged’ LOHC (i.e. LOHC carrying a high quantity of hydrogen) and can be coupled with a release unit to enable hydrogen to be released from the LOHC at point of use. In the cascade storage system the ‘dead’ LOHC (i.e. LOHC with hydrogen removed) is stored within the same tank system offering a high level of versatility, a wide range of applications, and minimising the volume of storage required. The storage footprint is reduced by a factor of two compared to the current systems, which need to use two separate tanks for live and depleted LOHC.

The key project objectives were as follows:

- Demonstrate the feasibility of using LOHC as a hydrogen carrier suitable for delivering hydrogen at scale based on financial modelling and assessment of regulatory constraints
- Perform engineering design for the cascade tank system
- Demonstrate the feasibility of the cascade tank for power generation applications, coupled with a fuel cell
- Develop a plan for Phase 2 of the project.

The key findings of the project are summarised below:

- The most promising market segment for the LOHC cascade tank is off-grid premises. It has been found that there are significant uncertainties about the use of LOHC in this context, and the technology of the associated systems such as the dehydrogenation release unit is relatively immature.

  The costs (both CAPEX and OPEX) are currently prohibitive for utilizing LOHC in this context. Although the gap could reduce over time (e.g. through a significant carbon tax), alternative technologies (e.g. heat pumps) may prove more favourable.
- Notwithstanding this market outlook, there are potential advantages of a cascade tank compared to the current two tank system for storing LOHC:
  - The lower energy density of LOHC introduces a requirement for larger storage than equivalent heating oil systems. However this is minimised by the cascade system and may make the use of LOHC feasible in locations where two tanks could not be accommodated.
  - A potential cost saving compared to the use of two tanks has been identified, however this is subject to significant uncertainty and would have a small cost impact compared to the overall cost of switching from heating oil to LOHC.
- The engineering design undertaken within this phase of the project has identified no significant technical challenges with regards to the cascade tank itself, however as discussed above, there is significant uncertainty around the operation of the dehydrogenation release unit.
- When using LOHC as a fuel source to provide power (e.g. through a solid oxide fuel cell) no drawbacks with cascade tank storage were identified. However, further work around heat recovery and hydrogen purity is required to assess whether it is feasible to use LOHC in this context.

- The following aspects of the design have been identified as requiring demonstration within Phase 2 of this project:
  - ease of operability;
  - confirmation of uninterrupted flow from tank compartments;
  - confirmation of adequate segregation of live and dead LOHC;
  - reliability and availability;
  - ease of emptying / refilling.
- These items have been prioritised as they are key to demonstrating the feasibility of the cascade tank system as an alternative to the simpler two tank system. It is currently proposed that trials with live LOHC will not be undertaken within Phase 2 for the following reasons:
  - The aspects of design discussed above are not specific to the material in the tank, and can therefore be demonstrated with any liquid. The use of a readily available, non-hazardous material such as water would reduce the cost of the trial significantly and eliminate difficulties with procurement.
  - The LOHC materials (Toluene / MCH) are relatively well understood given the large scale production / use of Toluene in industry. Separate projects have been commissioned to study the compatibility of existing tanks with LOHC.
  - The rollout of LOHC on a scale such that it would be commercially available to small users in off-grid locations is likely to be several years in the future and therefore the additional cost of demonstrating the tank with live LOHC would not be warranted within the next two years.
  - It will not be feasible to incorporate a dehydrogenation release unit into the trial at this stage, and therefore the benefit of using live LOHC would be limited.

Overall, it is foreseen that this technology could be deployed to decarbonise off-grid locations which currently rely on fuels such as oil or LPG for heat or power. However the use of LOHC more generally is commercially challenged in the market segments identified as favourable for a cascade tank. The benefits of using a cascade tank are relatively small compared to these commercial challenges.

2. INTRODUCTION

2.1 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 can transport hydrogen from point of origin to local demand centres via ship, rail or road transport.

The ERM *Cascade Tank LOHC System for Hydrogen Storage and Delivery* is a design for a multi compartment cascade tank system that can supply large quantities of hydrogen from an inventory of LOHC, while minimising space requirements for storage. The tank system is designed to be filled with ‘charged’ LOHC (i.e. LOHC carrying a high quantity of hydrogen) and can be coupled with a release unit to enable hydrogen to be released from the LOHC at point of use. In the cascade storage system the ‘dead’ LOHC (i.e. LOHC with hydrogen removed) is stored within the same tank system offering a high level of versatility, a wide range of applications and minimising the volume of storage required compared to the current two tank system for live and depleted LOHC.

The aim of this Phase 1 study is to determine the feasibility of using LOHC as a hydrogen carrier suitable for delivering hydrogen at scale, as well as developing an initial design for the unique cascade tank system that can be carried forward to demonstration trials in Phase 2. 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.

2.2 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 4: Net Zero Hydrogen Supply solutions”. ‘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.

2.3 Scope and Objectives

The key objectives of the project are to:

- Determine the feasibility of using LOHC as a carrier suitable for delivering hydrogen at scale
- Evaluate the feasibility of using a cascade tank system, and develop an initial design

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 examines the techno-economic and environmental, health, and safety case for the LOHC cascade tank system as a solution for implementation in locations off the gas grid.

The work completed to date comprises the following:

- Development of a basis of design;
- Development of equipment lists and key specifications;
- Development of indicative layout design;
- Process engineering, including development of piping and instrumentation diagrams;
- Control systems engineering;
- Reliability and maintainability analysis;
- Constructability and operability review;
- Hazard identification;
- Financial analysis; and
- Development of a regulatory compliance roadmap.

3. SUMMARY OF PHASE 1 RESULTS

3.1 WP2 – Option Selection

As part of WP2, a range of different industrial and non-industrial applications were assessed to identify different hydrogen storage and delivery applications that can be fulfilled by the proposed LOHC cascade system and develop the initial design for the selected application. These included:

- Remote distilleries
- On-site power generation
- Iron & steel manufacturing
- Hydrogen delivery via ship
- Refinery hydrocracking / hydrotreating
- Synthetic hydrocarbon production
- Commercial heating
- Residential heating

Screening was carried out against the following key criteria:

Table 3.1 Option Selection Criteria

Item	Criteria	Description
A	Safety	Are there any specific safety issues related to the selected application (storage, handling, transport etc.)
B	Environment	What is the potential impact to environment in the event of loss of containment for the selected application
C	Potential to Repurpose Existing Assets	For the selected application, could existing equipment or tanks be used
D	Space / Weight Constraints	For the selected application, are there constraints on space / weight for the system
E	Scale-Up	What are the scale / inventory requirements for the selected application. What is the potential for scaling up
F	Hydrogen Purity Requirements	Does the application require high purity hydrogen which would require a purification process following dehydrogenation
G	Reliability Requirements	What level of reliability is required for the selected application
H	Energy Requirements	How will the energy requirements for the system be met. High energy requirements?
I	Integration / Optimisation Opportunities	Are there opportunities for heat integration / optimisation for the selected application
J	Ease of Construction and Installation	How difficult / expensive will it be to install the system for the selected application
K	Ease of Operability / Maintainability	How difficult / expensive will it be to operate and maintain the system for the selected application. Any specific issues related to the mode of operation of the selected application

A workshop was undertaken to assess and rank the various options. The top applications selected to be taken forward for further review were:

- On-site Power Generation
- Iron & Steel Manufacturing
- Refinery Hydrocracking / Hydrotreating
- Residential Heating

Additional advantages / disadvantages were discussed as below to arrive at the final option to be pursued.

Table 3.2 Pros and Cons of Top Options

Option	Advantages	Disadvantages
Iron & Steel Manufacturing	▪ LOHC is a viable option as fuel source.	▪ Scale may be too large. Likely to use separate individual tanks rather than a cascade tank due to volume of LOHC required.
Refinery Hydrocracking / Hydrotreatment	▪ Refineries currently bring in H_2 supply from elsewhere. ▪ Option to repurpose out of service storage tanks for LOHC. ▪ H_2 currently used directly so no equipment conversion required.	▪ System would likely use separate individual tanks instead of cascade tank. ▪ Uncertainty around scale requirements.
Onsite Power Generation	▪ If solid oxide fuel cells were implemented then system could use heat from fuel cell to release hydrogen in case of shut down. However, this is already being looked at within the project elsewhere.	▪ High reliability requirement. Would need to ensure enough H_2 to power plant continuously. ▪ Would require a buffer tank and emergency power system (e.g. battery) in order to restart hydrogen release system in case of shut down.
Residential (or commercial) Heating	▪ Could top up hydrogen buffer tank by using electricity to power release unit during the night, when energy is cheap. ▪ Would require LOHC storage tank of comparable size to current oil tanks. ▪ Cascade system would work well here, otherwise two tanks would be required (one each for loaded and unloaded LOHC). ▪ Scale of tank required is good for trial purposes. Anything learned from this design could be easily scaled up for larger applications.	▪ Cost and reliability compared to current oil/LPG systems will be important ▪ Would require small release unit options from vendors. ▪ Conversion of household appliances to hydrogen operation will be required. ▪ Safety will be an even more important consideration as dealing with public.

The outcome of this discussion was that the Residential Heating application should be carried forwards for this phase of the design. This was on the basis that it will require the design of a cascade tank system of similar size to existing domestic oil / LPG storage tanks, which will be easy to build and trial in Phase 2 at modest cost. It is also an application that has significant scale up potential and wide range of end users both for residential and smaller scale commercial heating applications.

3.2 WP2 – Design Development (Domestic Heating)

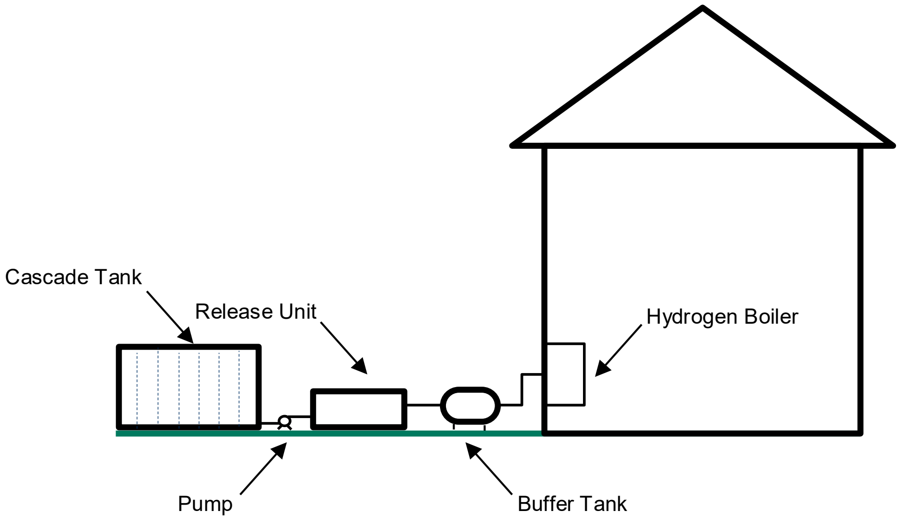
As outlined above, the application of residential heating was selected for the initial feasibility study. There are around 1.1 million fossil fuel heated homes in England which are not connected to the gas grid which currently use some of the highest carbon heating fuels including oil and coal (78% use heating oil, 13% use liquid petroleum gas, and 9% coal). Modern oil installations have become more efficient, however, oil remains the most carbon intensive heating option commonly used by those who do not have access to the gas grid.

Oil heating benefits from consumer familiarity, established supply chains, and, at present, from lower capital cost (as well as lower operating costs at current oil prices) than low carbon heating systems. Off the gas grid there is currently no strategic hydrogen option.

Replacing an oil-based system with LOHC would have the benefit of allowing use of hydrogen (a cleaner fuel) without the associated difficulties of transporting and storing hydrogen in gaseous state. Transportation and storage of LOHC can be done using the same types of tankers and storage tanks as oil and does not present any significant challenges from that perspective.

The overall system design for a typical domestic property was developed, including sizing of the key components. An overall illustration is shown below.

Figure 3.1 Schematic of Cascade Tank System for Domestic Heating



3.3 WP3 – Engineering Design (Non-Domestic Heating)

The initial design of the system in WP2 was based on the application of single-household domestic heating. While this remains technically feasible, discussions with dehydrogenation release unit vendors highlighted that very small scale applications like this are unlikely to be economically feasible to operate. Due to heat loss, the efficiency of the release unit decreases significantly with size and hence small scale applications are not currently being pursued by any of the main vendors of dehydrogenation technology.

A decision was therefore made to base the design on a larger consumer than the average UK home; for example, a block of apartments or non-domestic property such as hotel without gas grid connection.

There are currently ~280,000 non-domestic off-gas grid buildings in England. Of these buildings, ~60% have a floor area of 150-1,000 m^2 [6].

Non-domestic buildings in the hospitality sector have the highest median gas intensity of any sector, with a median of 284 kWh/m^2. Hospitality includes: restaurants, hostels, hotels, holiday homes / guesthouses, pubs.

The selected application is therefore a medium sized building in the hospitality sector. A complex of holiday apartments with 10 units averaging 40 m^2 would give a floor area of 400 m^2. Increasing this by 100 m^2 to account for communal areas gives a representative floor area of 500 m^2.

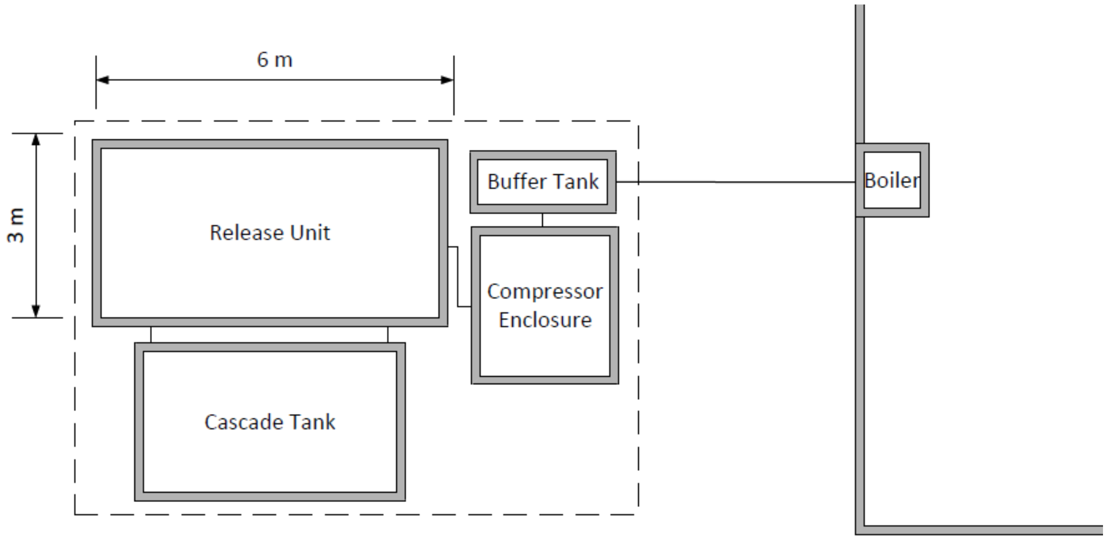
This gives an overall annual power usage of 511,200 MJ, which equates to:

- 3,600 kg/yr of hydrogen
- 60,000 kg/yr (78 m^3) of LOHC

Multiplying the overall demand figures by the number of off-grid properties gives a total potential hydrogen capacity for the sector of: (511,200 MJ / 3.6 MJ/kWh) x 280,000 properties ~ **40 TWh**. It is noted that applications of the system in other sectors is also feasible and these numbers could be higher depending on uptake. Use of LOHC rather than heating oil could completely eliminate CO_2 and other emissions locally where applied, and bring overall emissions close to net zero assuming green hydrogen is used to generate the live LOHC.

Initial engineering design was carried out for this application, including the production of indicative layouts as shown below.

Figure 3.2 Indicative Layout of Cascade Tank System



Assessment of this design lead to the following key conclusions:

- The relatively high energy demand associated with release unit and compressor operation would increase overall energy consumption of the property. However, the trade off compared to a heating oil system is a significant reduction in emissions. It is noted that a 3 phase power supply would likely be needed to power the compressor and release unit.
- It is noted that uncertainty remains about the efficiency and rate of heat loss from the dehydrogenation release unit. This technology is relatively immature and further optimisation of the design will be undertaken. Significant opportunities for heat integration with other users such as the hot water / heating system exist with the potential to reduce overall consumption.
- Hazards can be controlled to a similar level of risk to a conventional oil heating system, however some additional controls not required for a heating oil system would be needed.
- Initial RAM calculations indicate that the cascade tank system will have higher levels of unavailability than a standard two tank system. However the overall system reliability (based on availability of hydrogen supply to the boiler) will be improved due to the presence of the buffer tank; i.e. if repairs can be undertaken before the buffer tank inventory is depleted there is no impact on availability.
- The reliability will vary significantly based on the number of tank compartments and hence by reducing the number of compartments from the base case of 10, the reliability of the system can be improved further. It may be possible for a larger number of tank compartments to provide greater reliability by allowing single failures to be isolated, however this would require more complex control arrangements or manual intervention by users. As discussed above, the buffer tank is the primary means of ensuring continuity of hydrogen supply in the event of cascade tank failures.
- Constraints of space will likely play a role in the decision for each application of the system, in addition to considering the trade-off between the cost of a larger tank vs a reduction in the number of valves / instruments.
- Currently, loading / unloading of the tank using regular road tankers would require two tankers to attend (one to remove the depleted LOHC and one to dispense live LOHC). Modifications could however be implemented to compartmentalise a tanker in the same arrangement as the cascade tank, allowing for simultaneous loading / unloading by the same vehicle. This is beyond the scope of the current assessment, but transport applications such as tankers or ship bunkering could be important uses of the cascade tank technology as LOHC use / transportation becomes more widespread.
- Given the relatively small scale of the selected application, no issues are foreseen with the fabrication of equipment offsite, with transportation to site via truck. The cascade tank itself is anticipated to be of comparable size to standard heating oil tanks which are commercially available for commercial building applications and currently installed on many properties. The vendor-produced release unit will also be pre-fabricated prior to delivery to site and is anticipated to be no larger than a standard shipping container.
- Maintenance demanding systems have been kept at a strict minimum in order to ensure that the system has similar maintenance demands to a conventional gas or oil fired boiler; for which minor inspection and maintenance is generally undertaken annually.
- Corrosion concerns are expected to be no different to a standard storage tank used for hydrocarbon fuels for MCH / Toluene, and Non-Destructive Testing (NDT) of the tank shell could be carried out with no issues. NDT of the compartment dividers may be more difficult, however visual (camera) inspection should not present any issues. Loss of integrity of the partitions would not result in safety or environmental issues, only potential contamination. This would be detected

by analyser. Detailed consideration of inspection and maintenance regimes would be expected to be undertaken as the project moves to detailed design.

3.3.1 *Financial Feasibility*

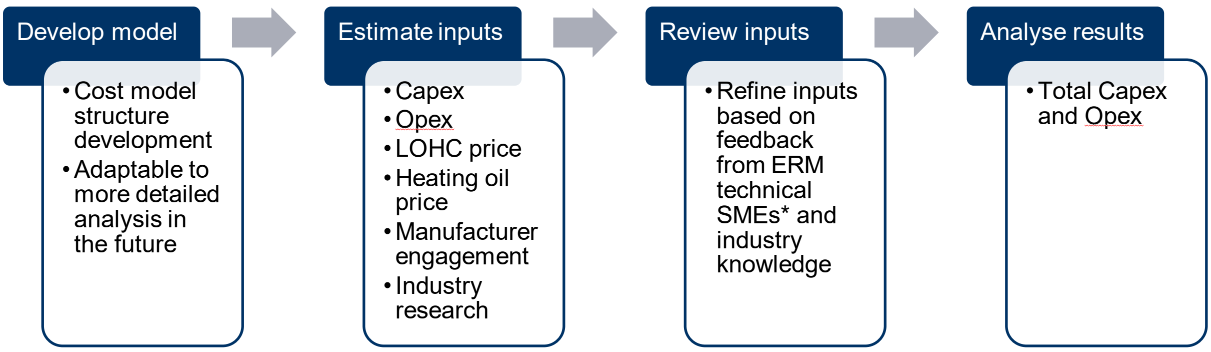
Financial modelling has been carried out for the cascade tank system based on the design completed within WP3.

3.3.1.1 Cost Modelling Approach

To evaluate the economic case for the system, a cost model was developed. The model includes Capex figures for all the key equipment types utilised in the concept design. The Capex and Opex for the model were developed by ERM based on industry and academic research, figures provided by industry bodies, ERM's experience from other hydrogen related projects and cost estimates from original equipment suppliers (OEMs).

The modelling process is summarised below in Figure 3.3.

Figure 3.3 Cost Modelling Approach



Project construction start date[1] is 2025 and it is assumed the heating system is to be operational for 15 years. There are several sensitivities considered in the economic feasibility analysis:

- The selected carrier for this project is the Methyl Cyclohexane (MCH) / Toluene (TOL) system. Toluene is mass produced and available at low prices, however, the production and use of MCH at scale as a hydrogen carrier is relatively new and mainly led by Japanese industry. At-scale demonstration projects are operational in Brunei and Australia [1]. At present, there is no Methyl Cyclohexane (MCH) / Toluene (TOL) system operational in Europe, and therefore, the future price of MCH is highly uncertain. A study from *Argonne National Laboratories for US Department of Energy [2]* estimated the cost of TOL hydrogenation to vary between 0.4 to 0.5[2] £/kg-H_2 depending on the scale of production. A study from *Johnstone et al.* [3] estimates MCH transportation cost between Japan and Europe to be around 1.14[2] £/kg-H_2. For simplicity, two price assumptions for MCH have been considered in the economic model:
    - Low case: 3.3 £/kg-H_2 (0.2 £ per kg of MCH), aiming to capture an optimistic case if MCH is produced at scale and low cost in Europe or the UK (cost of hydrogen production assumed around 2.5 £/kg-H_2, cost of hydrogenation[3] - around 0.4 £/kg-H_2 transportation cost – around 0.4 £/kg-H_2).

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[1] Essentially, this means the date when Capex starts being incurred.

[2,3] Prices converted using 0.83 USD to GBP conversation rate

[3] Including cost for buying TOL for the hydrogenation process.

  - Base case: 7.6 £/kg-H_2 (0.5 £ per kg of MCH), capturing a more pessimistic case of imported, long-distance MCH, and the cost of green hydrogen production at around 6 £/kg-H_2 (cost of hydrogenation[3] assumed around 0.5 £/kg-H_2, transportation cost – around 1.14 £/kg-H_2).

- The price of heating oil (kerosene) has changed significantly in the last few months. In the period 2018 to end of 2021, the price of kerosene was below 0.60 £/litre, while the current price is around 1.1 £/litre [4]. To explore future variations of the kerosene price, three assumptions have been considered:
  - Low case: 0.6 £/litre (~0.5 £/kg)
  - Base case: 1.1 £/litre (~0.9 £/kg)
  - High case: 1.5 £/litre (~1.2 £/kg)
- Electricity price assumptions are based on the historic rather than current off-peak tariffs due to the record high prices observed at the moment. The electricity price is assumed to be 0.0976 £/kWh [5]. Sensitivity analysis is not applied as the power consumption has a relatively limited contribution to total Opex.

3.3.1.2 Capital Expenditure

In order to model the Capex associated with the system, the potential costs were broken down into a number of elements, relating to the equipment required for the cascade tank system.

Baseline (present day) costs for each element were derived from a variety of sources, as follows:

- Publicly available reports, statements by manufacturers and industry projections; and
- ERMs experience of hydrogen projects.

The baseline costs were translated into future costs by applying learning rates based on projected cost decreases for key hydrogen production and conversion equipment, for example - the release unit, and benchmark learning rates for other, comparable industries. The baseline costs of mature technologies are kept constant through the years.

Other key assumptions used for the cost analysis are presented below:

- Installation costs have been assumed to be 10% of total Capex.
- Project management costs have been assumed to be 10% of total Capex.
- Development costs have been excluded from the model. It is assumed that funding will be available to cover these costs.
- Insurance costs have been assumed to be 2% of total Capex.
- Capex contingency costs have been assumed to be 20% of total Capex.
- Opex contingency costs have been assumed to be 30% Opex total.
- The FX rates used to convert manufacturers quotes are:
  - EUR to GBP: 0.84
  - USD to GBP: 0.83

The cost of the cascade tank has been approximated conservatively based on the cost of 10 individual bunded tank units (each with a volume 1/10th of the overall cascade tank size). The inaccuracy of this estimate is reflected in the ‘medium’ confidence level provided (+/- 35%). For comparison, the cost of a two tank system has also been estimated based on the costs of two tanks, each with a capacity equal to the overall LOHC storage capacity required.

A breakdown of the technical elements is provided below:

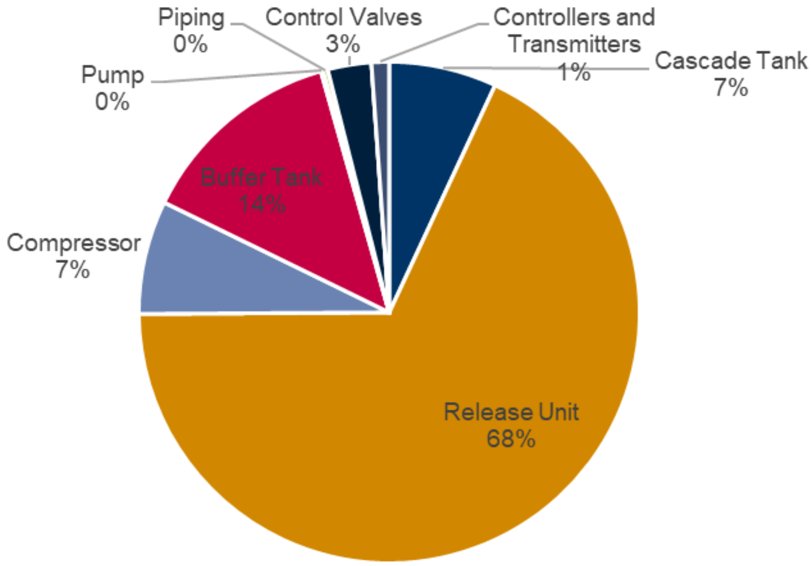
Table 3.3 Breakdown of Tank Costs

Key Technical Capex Element	Cascade Tank LOHC Storage	Conventional Configuration
Storage tank	10 compartment tank with total capacity of 23.6 m^3	2 storage tanks with total capacity of 47.2 m^3 (each 23.6 m^3)
Pumps	Flow rate 60kg/h (1 unit)	Flow rate 60kg/h (2 units; one pump for each tank)
Control Valves	Electric actuators valves (20 units)	Electric actuators valves (4 units)
Controllers and Receivers	Cascade Tank Level Transmitters (10 units) Cascade Tank Level Controllers (10 units)	Tank Level Transmitters (2 units) Tank Level Controllers (2 units)

The cascade tank was found to have a lower CAPEX than the equivalent standard LOHC storage configuration with two tanks (the difference is estimated to be around 36% of the tank CAPEX) for the selected application. However, due to the relatively low level of confidence in the cost estimates this figure may be inaccurate. Furthermore, as per the breakdown in Figure 3.4, this represents a small difference compared to the overall system costs.

The difference in capital cost between the LOHC system and a standard heating oil installation was found to be significant. The largest single contributor to the overall system CAPEX would be the hydrogen release unit. However it is noted that the technology is still a relatively new concept, currently at a conceptual stage and the cost of which is highly uncertain.

Figure 3.4 Breakdown of CAPEX by Category



3.3.1.3 Operating Expenditure

In order to model the Opex associated with each case, costs were broken down into the main contributing equipment types, listed below:

- Cascade tank
- Release unit
- Compressor
- Buffer storage

For the rest of the equipment, it is assumed that the Opex is insignificant.

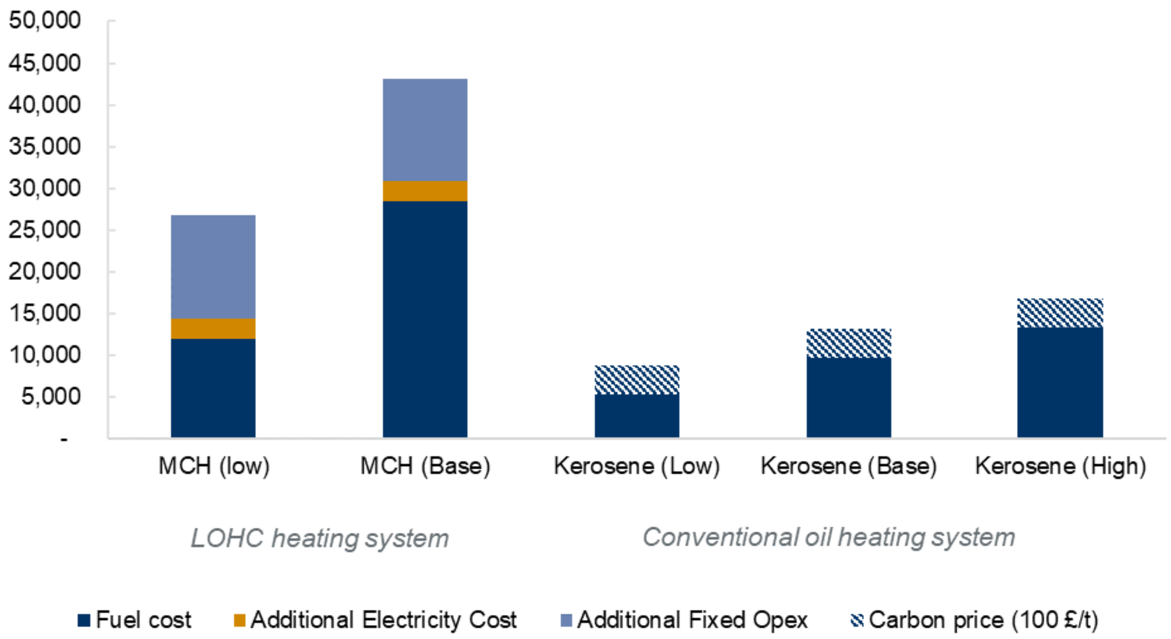
For simplicity, the baseline Opex for standardised equipment type was kept constant in the future. Future Opex related to the hydrogen release unit and hydrogen compression & storage equipment was based solely on industry research into learning rates, which was subsequently sense checked against ERM's knowledge of green hydrogen.

Given that the storage tank Opex is proportional to the Capex, Opex costs attributed to the cascade storage tank element will be lower than the conventional storage configuration (which has around 2x higher Capex – with the cascade tank costs based on the costs of 10 small bunded units for conservatism, as discussed above).

Currently, the running costs of an oil-based system are significantly lower than using LOHC as an alternative fuel. However, if the MCH is produced at scale and low cost in Europe and the price of kerosene continues to increase, the fuel costs of the LOHC system could eventually be lower than the conventional heating oil system. Low carbon policies such as increased carbon pricing, or funding support for low-carbon heating, could therefore make the use of LOHC in a commercial building a more attractive option in the future.

A carbon price above 100 £/tCO_2 will increase the Opex cost of the conventional system and put it in a comparable price range with the variable costs of a LOHC-run heating system (assuming MCH is available at scale).

Figure 3.5 Annual Operating Cost Comparison



Note that the aim of this analysis is to compare the proposed technology to the baseline for off-grid properties which is currently heating oil in the majority of cases. Other alternatives such as heat pumps may be an option for decarbonisation that is more economic (assuming the electricity grid continues to be decarbonised). However, it is noted that heat pumps may not be appropriate for all buildings.

3.3.1.4 Overall Conclusions

The overall difference in capital cost between the cascade tank system and a conventional heating oil system would be significant, with the largest contributor being the hydrogen release unit (68% of total technical Capex). The release unit is still a relatively new concept, currently at a conceptual stage and the cost of which is highly uncertain. The future cost of the release unit needs to be confirmed with the vendor before making final conclusions about the financial feasibility of the system.

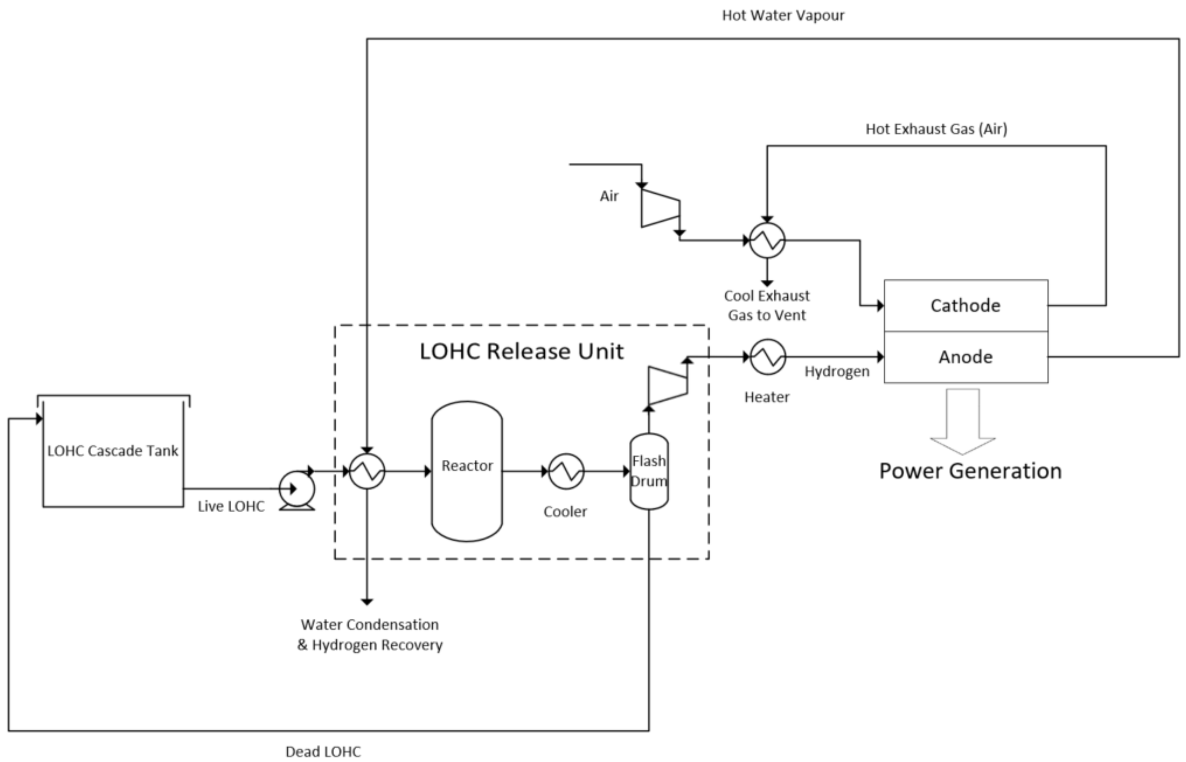
The cascade tank storage configuration is financially beneficial compared to the standard LOHC storage configuration, as the total Capex is around 36% lower, however it is noted that the cost estimates are uncertain at this stage and this represents a very small proportion of overall Capex.

The operational costs of the system are also found to be significantly higher than a conventional heating oil system.

3.4 WP5 – Power Generation (Solid Oxide Fuel Cell)

This work package produced a high level design for integration of the cascade tank system and release unit with a Solid Oxide Fuel Cell (SOFC) for power generation. A medium sized industrial application was selected for the purposes of initial equipment sizing. The overall process flow is shown below.

Figure 3.6 Process Flow for Integration with SOFC



A simple assessment of the heat integration opportunities indicates that the overall energy demand for operating the LOHC Release Unit could be supplied by waste heat from the SOFC. Further development of the heat exchanger network requirements however must be undertaken in order to confirm that this can be achieved in practice. Initial heat exchanger calculations suggest that integration with an exhaust stream of typical temperature alone would not cover the entire heating demand for the LOHC Release Unit Reactor inlet and hence direct removal of heat from the SOFC by other means will be required to maximise recovery.

Additional opportunities for recovery of lower grade heat for heating / hot water purposes also exist.

SOFCs are more tolerant of hydrogen purity than other types of fuel cell (e.g. PEM), and known issues such as sulphur poisoning are unlikely to be an issue with the hydrogen released from LOHC. However vendor supplied release units can be specified to incorporate hydrogen purification if required to meet end user specifications.

It was therefore concluded that the Cascade Tank system design is fully compatible with an LOHC release unit / SOFC system which could provide an efficient power generation system for applications currently met by diesel generators. This includes applications such as data centres back-up supply, open air events, etc. Although there is more work to be done on design of the LOHC release unit / SOFC system, outside of the scope of this project, the cascade storage tank arrangement is likely to be suitable for any final design that results.

3.5 WP6 – Regulatory Compliance

The storage amounts proposed for the applications studied within the Phase 1 project are sufficiently small that legislation such as COMAH or Hazardous Substances Consent would not apply.

A project to design, demonstrate, construct, commission, operate and maintain the cascade tank system would largely need to follow general health and safety legislation, including the following:

- Management of Health and Safety at Work Regulations 1999
- Dangerous Substances and Explosive Atmospheres Regulations 2002
- COSHH (Control of Substances Hazardous to Health) Regulations 2002
- Personal Protective Equipment Regulations 1992
- Classification, Labelling and Packaging of Substances and Mixtures
- Regulatory Reform (Fire Safety) Order 2005
- Provision and Use of Work Equipment Regulations (PUWER 1998)
- Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013 (RIDDOR)
- The Control of Noise at Work Regulations 2005 (the Noise Regulations)
- The Control of Vibration at Work Regulations 2005
- The Pressure Systems Safety Regulations 2000 (SI 2000/128) (PSSR)

External providers would also be responsible for adhering to the following legislation:

- Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009
- Construction (Design and Management) Regulations 2015
- The Pressure Equipment Safety Regulations 2016 (PESR)
- UK REACH Regulation

The UK legislative regime is largely non-prescriptive and compliance is generally achieved by following relevant good practice. Formal documentation required under the legislation listed above would include:

- Health and Safety File (CDM)
- Contruction Phase Plans (CDM)
- Health and Safety Management Report / Risk Assessment (HSWA, COSHH, DSEAR)
- Fire Safety Risk Assessment and Management Plan (Fire Safety Order)
- PPE Review (PPE Regs)

3.6 Overall Summary

The work undertaken in Phase 1 indicates that there are no significant technological barriers to the use of the cascade tank system as an alternative to a traditional two tank system for live and depleted LOHC. The application of supply to off-grid premises was selected as the most promising for the technology, however it is noted that there are significant uncertainties about the use of LOHC in this context, and the technology of the associated systems such as the dehydrogenation release unit is relatively immature.

The various work packages assessed the feasibility of using the system to supply hydrogen to a boiler for heating / hot water at a domestic or non-domestic off-grid property, and also for integration with a solid oxide fuel cell to provide power at an industrial site.

Key findings of this phase of the project are as follows:

- The costs (both CAPEX and OPEX) are currently prohibitive for utilizing LOHC in this context. Although the gap could reduce over time (e.g. through a significant carbon tax), alternative technologies (e.g. heat pumps) may prove more favourable.
- Notwithstanding this market outlook, there are potential advantages of a cascade tank compared to the current two tank system for storing LOHC:
  - The lower energy density of LOHC introduces a requirement for larger storage than equivalent heating oil systems, however this is minimised by the cascade system and may make the use of LOHC feasible in locations where two tanks could not be accommodated.
  - A potential cost saving compared to the use of two tanks has been identified, however this is subject to significant uncertainty and would have a negligible cost impact compared to the overall cost of switching from heating oil to LOHC.
- When using LOHC as a fuel source to provide power (e.g. through a solid oxide fuel cell) no drawbacks with cascade tank storage were identified. However, further work around heat recovery and hydrogen purity is required to assess whether it is feasible to use LOHC in this context.
- The following aspects of the design require demonstration within Phase 2 of this work:
  - ease of operability;
  - confirmation of uninterrupted flow from tank compartments;
  - confirmation of adequate segregation of live and dead LOHC;
  - reliability and availability;
  - ease of emptying / refilling.

The selected TOL / MCH system is a relatively new technology, however it is noted that Toluene is already produced on a large scale at present and therefore presents few novel issues or uncertainties with regards to its storage, safety, environmental or regulatory issues. Phase 2 of this project would therefore be focussed on demonstration of the operation of the tank system rather than material compatibility.

The use of heat pumps for homes which are connected to the electrical grid, but not the gas grid is a further potential option for decarbonisation; however this would rely on decarbonisation of the grid supply. Heat pumps are an effective solution for many off-grid properties, but may be unsuitable for some locations.

4. DEMONSTRATION PROJECT

The Phase 1 study has determined that the cascade tank system would be able to store and deliver LOHC for a range of applications, including the decarbonisation of off-grid commercial facilities. An initial design for the unique cascade tank system that can be carried forward to demonstration trials in Phase 2 has been developed.

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

4.1 Phase 2 Description

The cascade tank system uses a series of control valves and level controllers to supply live LOHC from the tank and store dead LOHC in separate compartments. The operation of the system does not vary with size and can be demonstrated with any liquid. It is also noted that connection to downstream equipment would not be required to demonstrate its performance. Furthermore, the system can be demonstrated with any number of tank compartments (>3).

The trial aims to evaluate the how level gauges and valves would work to control the flows and how it would be emptied and filled. A successful demonstration of the system would provide the design blueprint for commercial applications.

The trial would involve a controlled series of tests to demonstrate the performance of the system. Specifically, the proposed trial seeks to confirm the following, as a minimum:

- ease of operability;
- confirmation of uninterrupted flow of LOHC from tank compartments *(in order to ensure continuous flow to the release unit for efficient operation)*;
- confirmation of adequate segregation of flows representing live and dead LOHC *(in order to avoid contamination of live LOHC)*;
- reliability and availability;
- ease of emptying / refilling.

This will be achieved through the construction of a scale model in conjunction with a storage tank fabrication company and institution such as a university for instrumentation and testing. The specification of the trial tank is likely to be as below, although this shall be confirmed as part of the Phase 2 funding application:

- Volume: 5 m^3
- Number of Tank Compartments: 6
- Fluid: Water

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

- Filling of tank compartments with fluid representing live LOHC;
- Pumping of fluid out of tank and returning to separate compartments until all compartments have been cycled through;
- Interruption and re-start of tank / pump operation;
- Unloading and re-loading of tank.

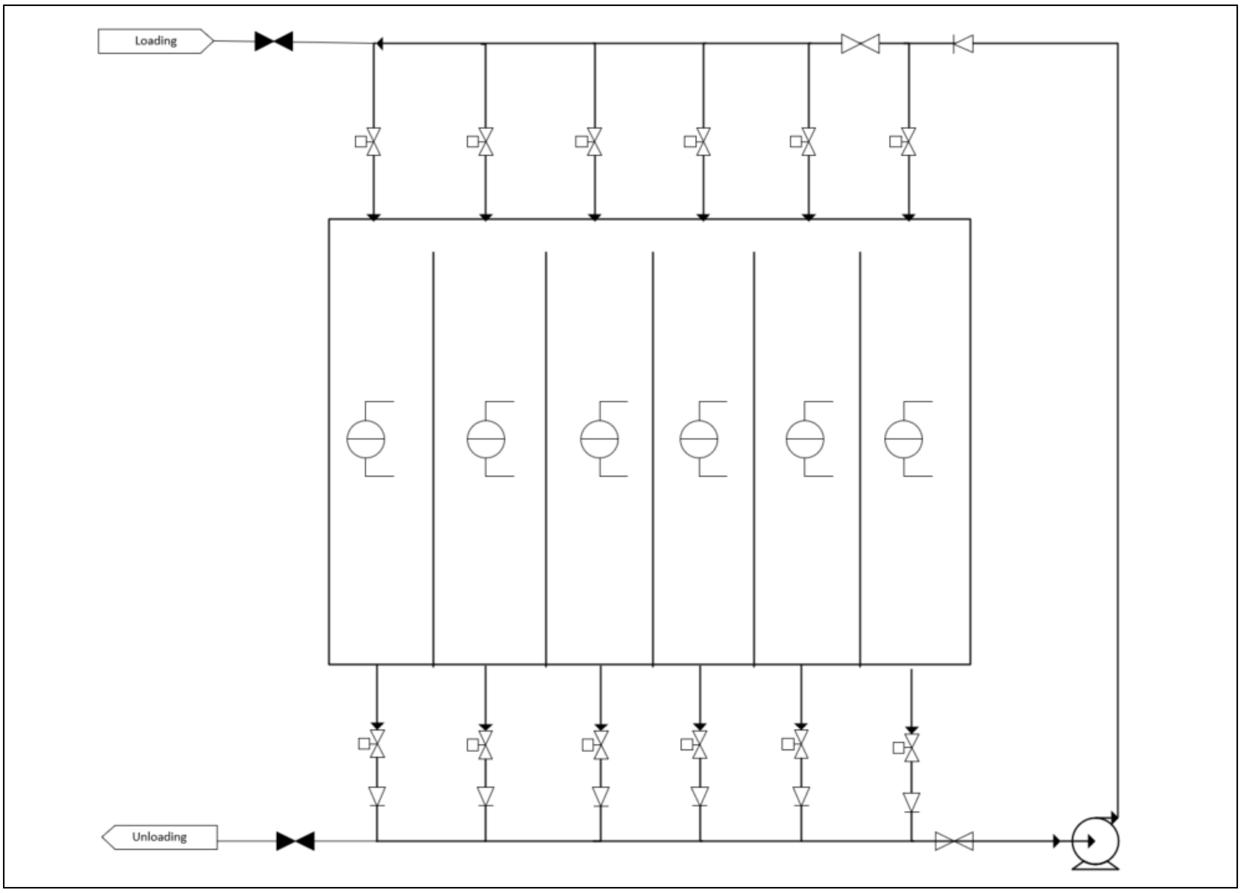
It is currently proposed that trials with live LOHC will not be undertaken within Phase 2 for the following reasons:

- The aspects of design discussed above are not specific to the material in the tank, and can therefore be demonstrated with any liquid. The use of a readily available, non-hazardous material such as water would reduce the cost of the trial significantly and eliminate difficulties with procurement.

- The LOHC materials (Toluene / MCH) are relatively well understood given the large scale production / use of Toluene in industry. Separate projects have been commissioned to study the compatibility of existing tanks with LOHC.
- The rollout of LOHC on a scale such that it would be commercially available to small users in off-grid locations is likely to be several years in the future and therefore the additional cost of demonstrating the tank with live LOHC would not be warranted within the next two years.
- It is unlikely to be feasible to incorporate a dehydrogenation release unit into the trial at this stage, and therefore the benefit of using live LOHC would be limited.

For the purposes of the trial, the tank could be operated as a closed loop system with a pump as illustrated below.

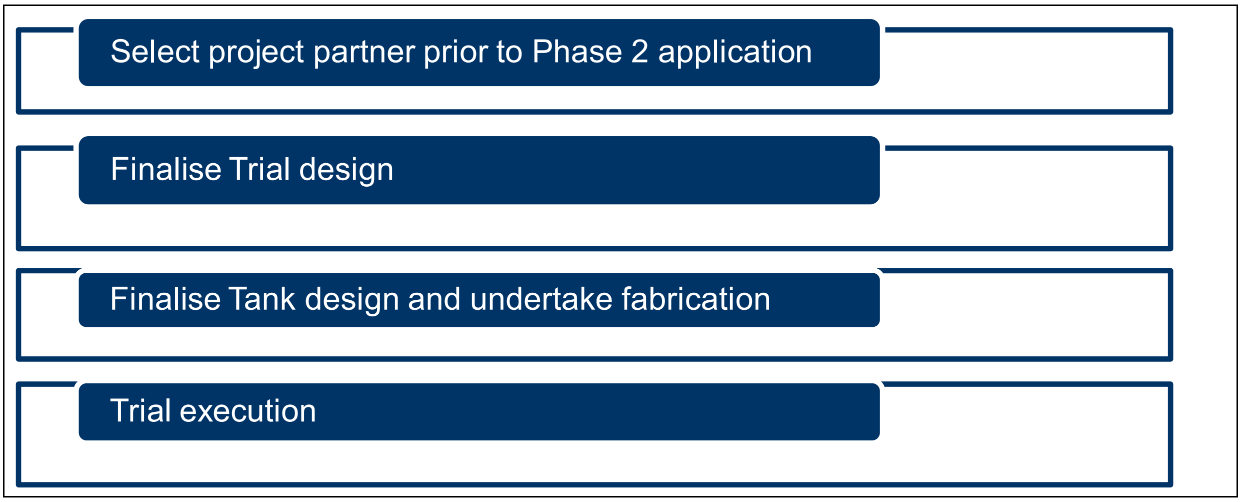
Figure 4.1 Proposed Trial Concept



4.2 Key Elements for Phase 2 Programme

The proposed trial would involve the demonstration of a scaled model of the tank system. The key elements required for the Phase 2 trial are shown below and discussed individually below.

Figure 4.2 Selection Process of Key Elements for Phase 2 Programme



Select Project Partner

This work involves the selection of project partner(s). Discussions have already been held with both storage tank fabricators and University Engineering Departments to find the best combination. Selection will be made prior to Phase 2 funding application to ensure the partner(s) can be involved in the application process. Support may be provided in the following activities, as examples:

- Engineering activities (including design and fabrication of the tank system);
- Procurement activities needed for the trial programme (e.g. provision of level controllers, control valves);
- Installation and testing of instrumentation;
- Operating the trial programme.

Trial Design

This work involves confirming the key aims of the trial and planning an appropriate series of test activities to meet these aims.

Tank Design and Fabrication

This work involves detailed design of the tank system, procurement, fabrication, installation and commissioning.

Trial Execution

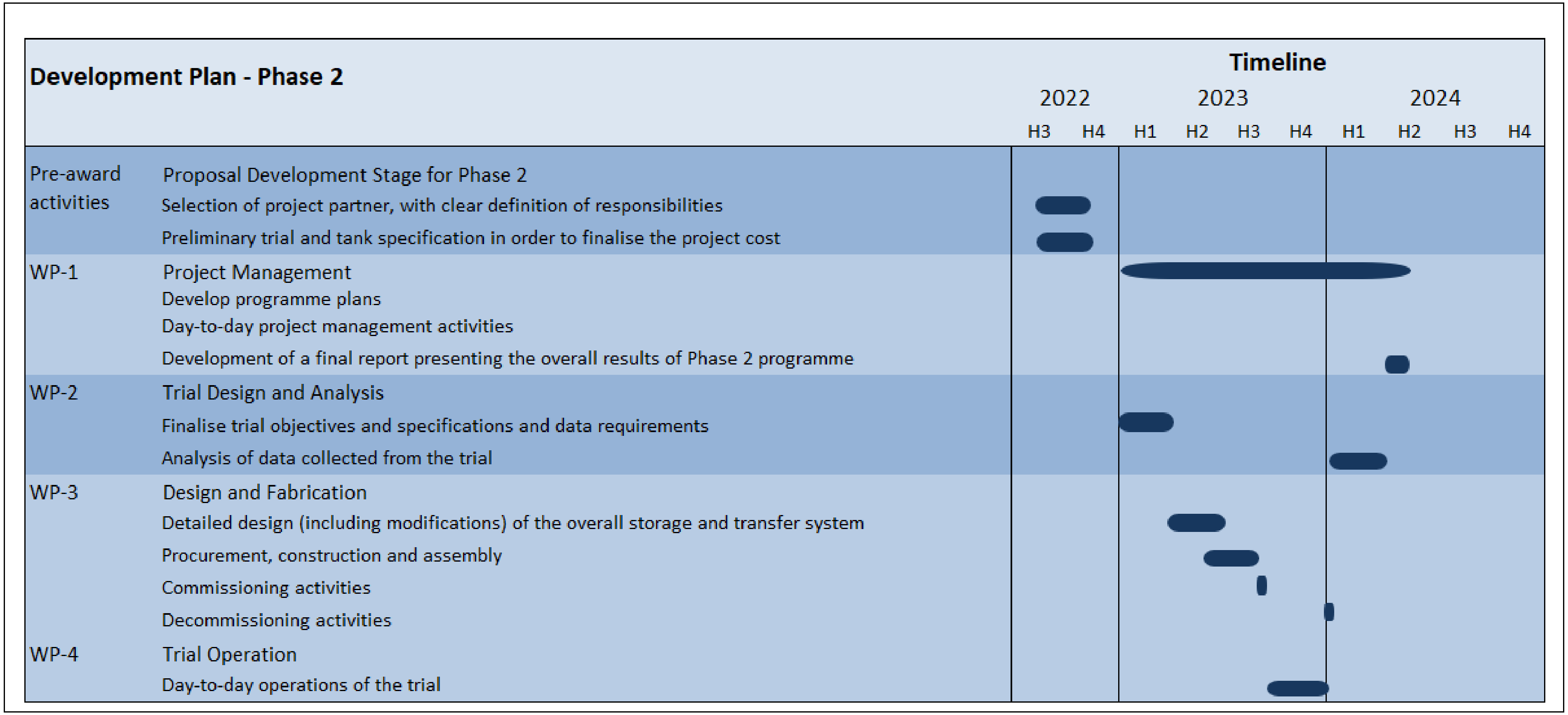
This will involve performing the trial as specified within the trial design.

4.3 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 4.3.

The schedule risks are low, as the materials and components to be procured for the trial are readily available with short lead times. The trial activities once the tanks has been fabricated / commissioned are also simple operations with no external dependencies.

Figure 4.3 Phase 2 Timeline



4.4 Estimated Costs for Phase 2

It is envisaged that the work required for Phase 2 will require the involvement of at least two organisations. Based on initial engagement with potential project participants, and high level cost estimates, it is envisaged that a Phase 2 programme will cost around £1.5 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. However, it is anticipated that the following breakdown to apply.

- WP-1 Project Management : 15%
- WP-2 Trial Design and Analysis : 25%
- WP-3 Design and Fabrication : 45%
- WP-4 Trial Operation : 15%

5. BENEFITS AND BARRIERS

An assessment of the benefits and barriers for the use of LOHC as a hydrogen carrier to deliver hydrogen at scale has been carried out, in addition to development and assessment of the cascade tank solution design. This work has included assessment of the technology, safety / environmental risks, RAM, capital and operating costs.

One of the key benefits from LOHC in this study is the potential speed and cost of the decarbonisation process for current users of fuels such as heating oil. Using LOHC to deliver hydrogen would have significant benefits as a decarbonisation solution, including the potential to re-use existing assets. It is expected that the technology could enable the use of LOHC in other 'high heat' industry sectors that are hard to decarbonise or those that need to store large volumes of hydrogen locally for uninterrupted supply (e.g. data centres back-up supply, open air events). 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.

As outlined above, there are no technical barriers foreseen to the development of the cascade tank itself, and the design could be progressed to commercial readiness relatively quickly. The main technological barriers to rollout of LOHC technologies relate to the dehydrogenation release unit required for the production of gaseous hydrogen from LOHC. The process is relatively well established, however the main developers of the technology have only operated plants on a trial basis, with the first commercial units likely to be available over the next 2-5 years. In the absence of commercially available release units which have been through significant development and testing, costs are likely to be high and publicly available information is limited.

The cascade tank arrangement would offer a space saving compared to the current two tank systems used for LOHC storage, and a cost saving compared to a two tank system has also been identified (although this is subject to some uncertainty). However, overall system costs are currently much higher than other systems such as heating oil, and the feasibility of the rollout of LOHC as a fuel source to the identified market sectors is highly uncertain at present.

The cascade tank itself is likely to be a highly scalable design, although for the largest scale applications a single tank may become unfeasibly large and therefore multiple tanks may need to be used in cascade arrangement instead. This may be a good alternative option for large storage sites where existing tanks were available for repurposing. It is also noted that for the largest users, the size and frequency of deliveries of LOHC required would be a challenge based on current supply chains.

It is recognised that other systems such as heat pumps may be a more attractive option if the electrical grid continues to decarbonise, however these may not be suitable for all buildings.

6. DEVELOPMENT PLAN

A development plan for the demonstration trial has been developed as outlined in Section 4 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. This is likely to involve partnership with industry to further develop the technology and roll it out on a commercial scale.

7. ROLLOUT POTENTIAL

As discussed above, the cascade tank is a highly scalable design, with a range of applications of different sizes studied as part of Phase 1 encompassing various domestic, hospitality and industrial installations. It can be used to provide compact hydrogen storage in a commercial or industrial setting both for heating and power generation (for example to supply industrial boilers or to provide back-up power for data centres or outdoor events) and at a larger scale can be used for hydrogen bunkering vessels or any system where available footprint for storage is restricted.

It is noted however that the use of LOHC is commercially challenged in the market segments identified as favourable for a cascade tank. The benefits of using a cascade tank are relatively small compared to these commercial challenges.

8. ROUTE TO MARKET

The key steps to commercialisation are outlined below:

- The Phase 2 trial described in Section 4 (to be completed in 2024) will demonstrate that the cascade tank design functions as intended, based on a medium scale unit under lab conditions. As discussed in in Section 4, live LOHC is not required for this stage of the project as the trial is focussed on the successful operation of the valves and level controllers to produce an uninterrupted flow of liquid and provide segregation between the tank compartments. This provides the design blueprint for a commercial system.
- Following on from Phase 2, the construction of a full scale tank coupled with a LOHC release unit would be undertaken to demonstrate that the overall system functions as intended to deliver gaseous hydrogen. The cost / sourcing of components required for the full scale trial will be developed further in Phase 2. The timescales for this phase will depend on the commercial availability of release units; anticipated to be within the next 2-5 years (i.e. 2025-2028).
- Upon successful completion of the overall system demonstration this will pave the way for installation of permanent facilities across a range of applications from supply of commercial heating through to remote power supply and even hydrogen refuelling facilities.

  It is noted that the rollout of the system for commercial use would depend largely on the availability of low cost LOHC at a large scale, and with comparable costs to other heating systems. As above, cost reduction and optimisation of the release unit technology would also be required.

9. DISSEMINATION

One or two dissemination activities were planned at the beginning of the project. However, 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.
- "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.

10. CONCLUSIONS

The work undertaken in Phase 1 indicates that there are no significant technical barriers, and a number of potential benefits to the use of the cascade tank system as an alternative to a traditional two tank system for live and depleted LOHC. The various work packages assessed the feasibility of using the system to supply hydrogen to a commercial boiler for heating / hot water at a commercial facility and also for integration with a solid oxide fuel cell to provide power at an industrial site.

- Based on the number of non-domestic off-gas grid properties in the country, the potential hydrogen capacity for the sector is ~40 TWh. It is noted that applications of the system in other sectors is also feasible.
- Off-gas grid properties in the UK currently rely largely on heating oil, which is one of the most carbon intensive heating options commonly used in the UK. The emissions factor of fuel oil is 0.27 $kgCO_2/kW_{th}$ [7], compared to zero for green hydrogen. For a total sector size of 40 TWh, there is a maximum decarbonisation potential of 10.8 $MtCO_2$/yr.
- There is the potential for job creation if a LOHC supply chain is established in the UK, with resources required to produce and transport LOHC in addition to supplying equipment such as tanks and release units.

The key findings of the Phase 1 project are as follows:

- The most promising market segment for the LOHC cascade tank is off-grid premises. It has been found that there are significant uncertainties about the use of LOHC in this context, and the technology of the associated systems such as the dehydrogenation release unit is relatively immature.

  The costs (both CAPEX and OPEX) are currently prohibitive for utilizing LOHC in this context. Although the gap could reduce over time (e.g. through a significant carbon tax), alternative technologies (e.g. heat pumps) may prove more favourable.
- Notwithstanding this market outlook, there are potential advantages of a cascade tank compared to the current two tank system for storing LOHC:
  - The lower energy density of LOHC introduces a requirement for larger storage than equivalent heating oil systems. However this is minimised by the cascade system and may make the use of LOHC feasible in locations where two tanks could not be accommodated.
  - A potential cost saving compared to the use of two tanks has been identified, however this is subject to significant uncertainty and would have a small cost impact compared to the overall cost of switching from heating oil to LOHC.
- The engineering design undertaken within this phase of the project has identified no significant technical challenges with regards to the cascade tank itself, however there is significant uncertainty around the operation of the dehydrogenation release unit.
- When using LOHC as a fuel source to provide power (e.g. through a solid oxide fuel cell) no drawbacks with cascade tank storage were identified. However, further work around heat recovery and hydrogen purity is required to assess whether it is feasible to use LOHC in this context.
- The aspects of the tank design required to demonstrate the feasibility of the cascade tank system as an alternative to a two tank system within Phase 2 of this project have been identified and incorporated into the development plan.

Overall, it is foreseen that this technology could be deployed to decarbonise off-grid locations which currently rely on fuels such as oil or LPG for heat or power. However the use of LOHC more generally is commercially challenged in the market segments identified as favourable for a cascade tank. The benefits of using a cascade tank are relatively small compared to these commercial challenges.

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