HYDROGEN SUPPLY AND TRANSPORTATION USING LIQUID ORGANIC HYDROGEN CARRIERS (HYSTOC)

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WP4 – LOHC logistics infrastructures

D4.1

Decision on LOHC storage and logistics concept

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Document Type	
PRO	Technical/economic progress report (internal work package reports indicating work status)
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1 Summary

The purpose of this deliverable is to present the opportunities, that are provided by hydrogen transport via LOHC. Furthermore, the LOHC logistic concept, that is designed for the HySTOC project, is explained. The technical solution is presented and a cost analysis for the chosen concept is included. This document also describes the needed environmental permits and practical solutions required to start operations in Finland. Potential risks and safety issues are described in this document as well.

2 LOHC logistics

The main idea of the LOHC technology is to store hydrogen in an oil. This allows hydrogen to be distributed easily and save in the existing infrastructure of the mineral oil industry. This is a huge advantage compared to other hydrogen technologies like compressed and liquefied hydrogen. The LOHC technology offers varies concepts to supply hydrogen to customers. As described, the overall concept is to use the well-known transport solutions of the mineral oil industry in order to supply hydrogen. As hydrogen is stored chemically-bonded in an oil, standard transportation systems like tank trucks, rail transport and oil tankers can be used. Figure 1 shows possible hydrogen sources, hydrogen distribution concepts and different demand sites.

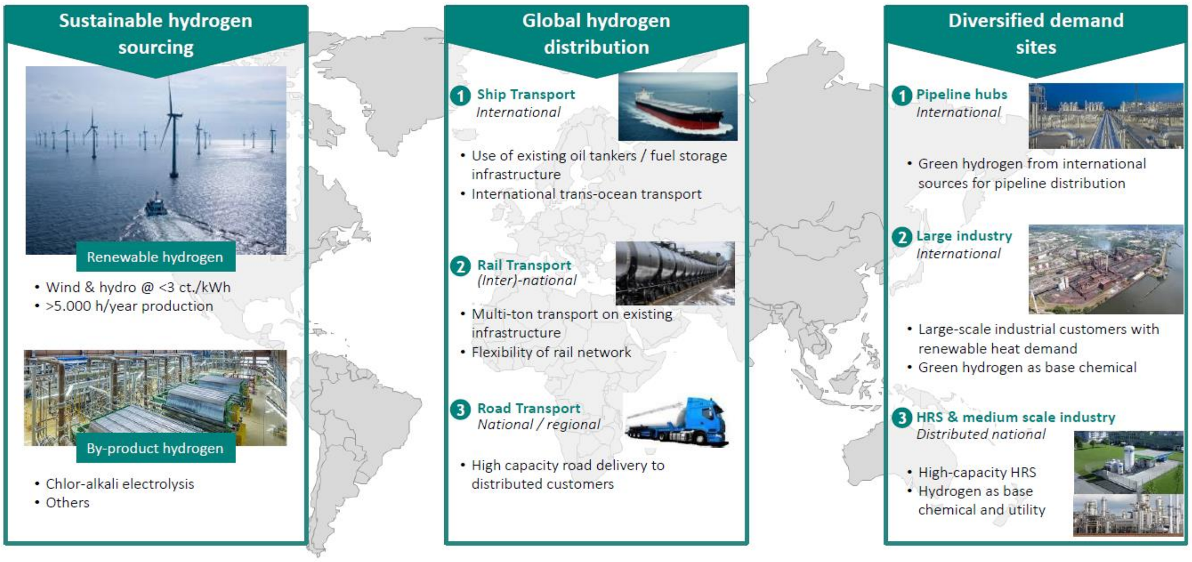

Figure 1: Overview of the different hydrogen logistic concepts via LOHC

The use of LOHC for hydrogen transport and storage has the following advantages compared to compressed and liquefied hydrogen:

- <u>High transport capacity:</u> With up to 1,800 kg/truck, LOHC allows an up to 5 times higher transport capacity per 40-to truck compared to 200 bar tube trailers and up to 3 times higher compared to 500 bar tube trailers, whilst storage, handling and transport of hydrogen, bound to LOHC, can be done at ambient conditions.
- <u>Low transport costs:</u> The higher transport capacity in LOHC reduces operating costs of hydrogen logistics by up to 80%. The possibility to use standard oil tank infrastructure

reduces investment costs significantly and allows for existing oil infrastructure to be used for LOHC-based hydrogen handling.

- Easy road transport: The LOHC of choice in the HySTOC project is dibenzyltoluene (DBT), which is a non-hazardous good according to ADR and all other relevant transport regulations.
- Availability: The carrier material DBT is a standard heat transfer fluid in industry and readily available in industrial quantities while its production process is not patented (patent expired). In Europe, the two chemical companies Eastman Chemical and Arkema provide the material ensuring supply security.
- High safety: As hydrogen is chemically bound, no molecular hydrogen has to be stored. The carrier material (DBT) is hardly flammable and non-explosive, allowing storage of large amounts of hydrogen at existing refuelling stations in standard underground tanks.
- Low footprint: The high storage density in LOHC and the possibility to use standard underground oil tanks give LOHC significant footprint advantages. HySTOC aims for a footprint reduction of 30 – 50% of the integrated LOHC-HRS systems comparted to conventional HRS designs with comparable capacities.
- Public acceptance: Handling liquids at ambient conditions encompasses a significantly higher public acceptance than handling a flammable gas at ultra-high pressures or a cryogenic liquid.

The different transport-systems for LOHC – tank truck, railway and ship – are beneficial depending on the setting of particular scenario. That´s why on-shore transports of LOHC for short to medium distances are realised on the road via tank truck. Using the railway may be an alternative, if the rails already exist. For large-scale LOHC transport between two continents only ship transport is sensible. The subsequent on-shore distribution is provided by tank truck or railway.

3 Logistics concept in the HySTOC project

One major target of the HySTOC project is to demonstrate the feasibility of hydrogen transport over long distances using a liquid organic hydrogen carrier (LOHC). Hydrogen is chemically bound to the LOHC, and in this way not classified as a dangerous good. This makes transportation and handling much easier compared to compressed or liquefied hydrogen. Two systems are required for the complete hydrogen supply chain. A storage system for hydrogenation of LOHC at the location of the hydrogen source, and a second system for hydrogen release at the consumer site. LOHC itself only serves as a liquid carrier, which is loaded and unloaded with hydrogen multiple times. The field test for the HySTOC project will be carried out with the storage system located at the Woikoski site in Kokkola, Finland. For the first period of field testing, the release system is located at the VTT-site in Espoo, close to Helsinki. The distance between these two locations is roughly 500km. In a second phase of field testing, the release system will be relocated further north to the hydrogen refuelling station in Voikoski. The distance between Kokkola and Voikoski is roughly 380km.

Logistical concept options for the project were limited by scaling of the pilot equipment with maximum hydrogen flow capacity of 10 Nm^3/h. This meant hydrogenation capacity to average 20 kg/h of LOHC. Scaling of stationary and transportation tanks was done with focus on optimizing cost effectiveness and ease of handling.

Suitable options were to transport LOHC with tank trucks designed for liquid transportation or use IBC containers in combination with existing truck transportation used for gas cylinder transportation.

In case of using liquid logistics concept, the use of big stationary tanks would be required to be able to fill liquid transportation trucks with a minimum capacity of 15 m^3. This option was unfeasible at this scale because of large capex expenses from LOCH liquid and stationary tanks as well as opex expenses of transporting liquid with half-filled trucks.

The selected concept was to optimize tank sizes and transportation equipment to fit weekly logistics from Kokkola to Voikoski. This option was easiest to reach with 1m^3 ICB containers in combination with 4m^3 stationary tanks.

3.1 Tank concept

Several aspects have to be considered in order to decide for the best suitable tank concept meeting the requirements of this HYSTOC project. These include the amount of required liquid organic hydrogen carrier (LOHC), the transport frequency, tank size, available and existing infrastructure assets, safety restrictions as well as environmental conditions. Depending on the actual application, the resulting concepts may vary in certain aspects. The boundary conditions of the HYSTOC project have been identified and are described in the following.

In general, a single transport vessel would be the most efficient solution for a large scale transport in order to minimize coupling of pipelines during filling/refilling steps, as well as instrumentation equipment and maximize the amount of LOHC and thus the amount of hydrogen transported. This will be evaluated and discussed in more detail in Section 3.

For HySTOC, the chosen logistic concept is however based on a combination of stationary tanks and the transportation of LOHC in intermediate bulk containers (IBCs). The decision for this setting is based on the side-condition of an existing infrastructure at the hydrogen production site of Woikoski in Kokkola. The existing regular truck transport between Kokkola and Bioruukki / Voikoski shall also be used for the LOHC transport to leverage synergies. The truck delivery takes place once a week, resulting in the required amount of roughly 3 m^3 LOHC per transport. To ensure easy handling with an existing forklift at site, IBCs with a volume of 1 m^3 each will be used for transport.

At each site, StorageBOX (SB) and ReleaseBOX (RB), there are two stationary oil tanks with a maximum capacity of 4 m^3. One is dedicated to the hydrogenated LOHC (LOHC-H) and one for the dehydrogenated LOHC (LOHC-D). At each stationary tank, there are pumps to empty and fill the IBCs.

After hydrogenation of the LOHC-D at the SB, the LOHC-H has to be filled into the IBCs and loaded with a forklift onto a truck to be transferred to the RB site.

Arriving at the RB site, the IBC have to be unloaded and the LOHC-H has to be transferred from the IBC to the corresponding stationary tank. After emptying, the same tanks can be used to transport the LOHC-D from the RB site back to the SB site. The filling of the IBC with LOHC-D works in an identical procedure as for the LOHC-H.

For the first transport-cycle an additional amount of LOHC-D has to be available at the SB site, to assure continuous operation of the plant.

Because of the high viscosity of the LOHC at low temperatures, heating to roughly 15 °C is required to enable pumping during filling and emptying of the IBCs. The time to heat the IBCs has to be considered in addition to the filling/emptying time.

General requirements for LOHC tanks:

Connections

- Emptying
- Filling
- Gas pendulum connection
- Electrical tank heating
- Over-/Underpressure valve
- Nitrogen supply (stationary tanks)

Instrumentation

- Temperature Sensor
- Filling level indicator
- Safety Valve
- Pressure sensor (stationary tanks)

Material requirements

In contact with media: Usage of DIN-EN listed materials of construction

Sealing: FKM, FFKM, PTFE, graphite, metallic

Cable Material in contact with LOHC: PTFE

Additional requirements for stationary tanks

Double-walled-leakage safe tanks with corrosion resistance (C4 according to DIN EN ISO 12944). Because of safety reasons, the intake of oxygen must be excluded. Therefore a slight nitrogen overpressure (~ 0,1 bar) atmosphere has to be applied above the liquid.

3.2 Transportation

Logistical concept is based on Woikoski gas logistics. This solution makes logistics cost effective. A truck comes once a week to Kokkola to pick up hydrogenated product containers with gas cylinders to Voikoski. From Voikoski the truck goes to Järvenpää from which it is possible to send the products to Espoo (VTT) with a delivery truck.

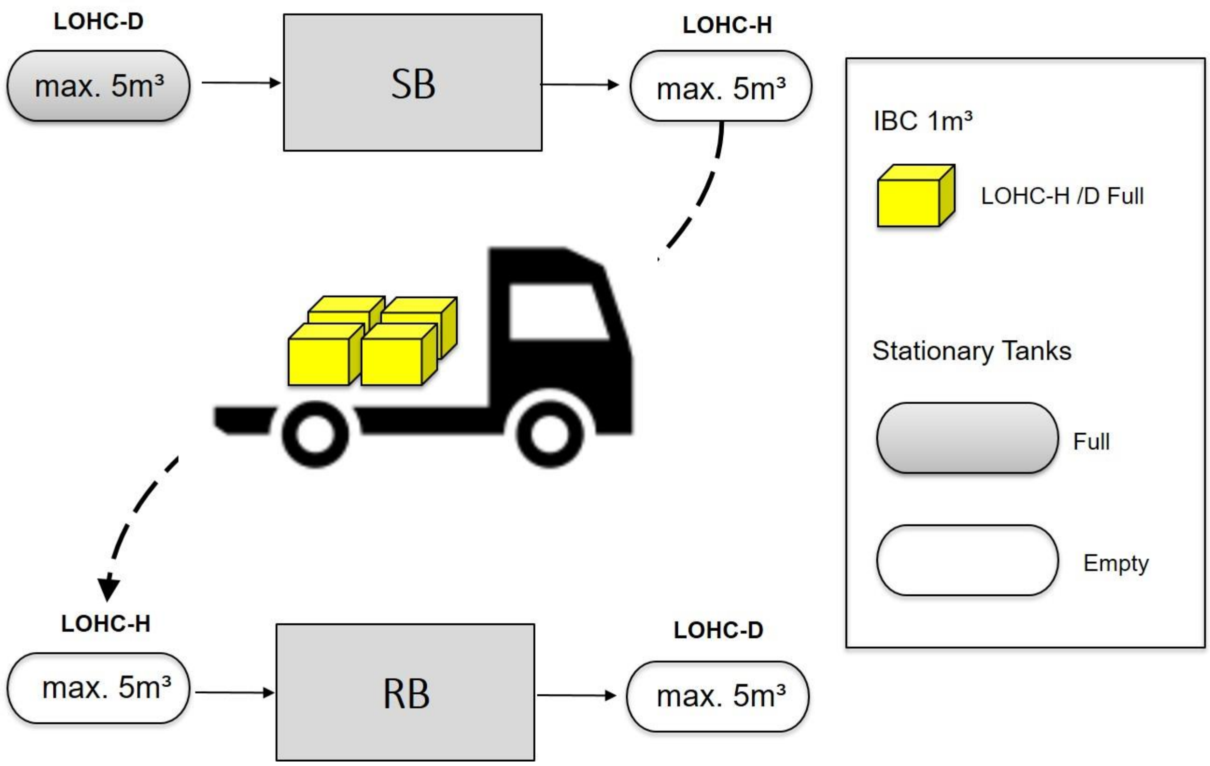

Figure 2: Scheme of logistic concept within HySTOC

The logistics will be done with 1000 l electrically heated IBC containers to ensure capability to operate in cold climate. At both ends of the logistical chain there is going to be max. 5000 l storage vessels for hydrogenated and un-hydrogenated LOHC material. LOHC material will be pumped from transportation.

3.3 Environmental permits

The hydrogen factory at Kokkola has an environmental permit. According to Finnish environmental law 527/2014 §31 there is no need to apply a new environmental permit. However there is a need to notify §119 the authorities 30 days before start of operation. The same applies with site at Espoo.

3.4 Safety

The LOHC materials are registered under REACH. LOHC-H is registered as transported, isolated intermediate while LOHC-D is registered under a PPORD registration. The co-registrations for Woikoski will be done as part of the project. Due to the registration as transported, isolated intermediate, the LOHC-H material has to be handled under strictly controlled conditions (SCC).

Strictly controlled conditions are defined in Article 18(4) (a) to (f) of REACH. The EU "*Guidance on intermediates*" (section 2.1) defines strictly controlled conditions as "a combination of technical measures that are underpinned by operating procedures and management systems". These measures include:

- Rigorous containment of the substance by technical means, supported by procedural and control technologies in place, used to minimise emissions and resulting exposure during the whole life cycle of the intermediate, i.e.:
    - manufacture of the intermediate and further purification steps
    - use in the synthesis of (an)other substance(s)
    - cleaning and maintenance,
    - sampling and analysis,
    - loading and unloading of equipment/vessels,
    - waste disposal/purification and storage

- Handling of the substance performed by trained, authorised and supervised personnel in accordance with well documented procedures
- Special procedures in place for cleaning and maintenance,
- Procedural and/or control technologies to deal with accidents and waste management.

All transportation units used on gas logistics chain have ADR approval, which is required for flammable liquids. All equipment that need approval according to either Finnish legislation or EU directives will be inspected by a notified body before use in Finland.

3.5 Costs – CAPEX and OPEX

Investment costs (Capex) and operational costs (Opex) of the tank and transport system for the LOHC and thus for the delivered hydrogen are crucial factors in the supply chain of LOHC as the hydrogen transport is the single most impactful and important advantage of the LOHC technology compared to compressed or liquid hydrogen distribution.

Capex:

The Capex assessment needs to be split into the Capex for stationary tanks, the Capex for the transport infrastructure and the LOHC material required to keep the infrastructure in smooth operations.

For the stationary part, it has to be taken into account that oil tanks encompass very high scaling factors. The max. 5m³ stationary oil tanks for LOHC described above have Capex of EUR ~6.000 – 8.000. In a fully commercial / industrial setting with large units, tanks with sizes around 100 m³ will be needed. The Capex for this sizes is in the range of EUR 35.000 – 42.000, i.e. only a 4-5x increase in price for 20x the capacity. Limited additional Capex might be required for insulation and pumps, however this very much depends on the actual site and the climate conditions.

For the transport part, standard oil delivery trailers can be used. Those are typically available as heating oil tank truck with 15 m3 capacity (corresponding to ~900 kg of hydrogen) or as dedicated trailers with up to 30 m³ capacity (corresponding to ~1.800 kg of hydrogen). These 30m³ trailers require investments of EUR ~80.000 – 100.000 (excl. the tractor) in Europe. Within the HySTOC project, simple 1m³ IBC are used to transport the LOHC as mentioned above. Such IBCs have costs of EUR ~400 per piece. Additional equipment requirements arising from the Finish climate conditions and required instrumentation are currently under clarification and might have an impact on the overall Capex. As the LOHC-D and the LOHC-H can be transported in the same trailers and tanks without any issue, a dual infrastructure is not needed.

For larger transport, e.g. by train, oil tank wagons can be considered. However, this application does not form part of this study and is therefore not assessed in more detail.

The amount of LOHC material needed is highly dependent on the operating and risk management strategy. For the HySTOC project, a total amount of at least 6 m³ is needed (3 m³ at each site). Each system processes ~0.5m³ per day, thus the planned amount of 3 m³ will allow for a weekly transport operation. The LOHC material costs ~ 4.5 EUR/kg (due to the low purchasing volume), thus EUR ~27.000 for the HySTOC project.

For larger projects, the amounts of LOHC material will be significantly higher, leading to predicted costs of around 3 EUR/kg. Together with the economies of scale for the larger tank system, the costs of storage capacity can thus decrease to as low as 60 EUR/kg of hydrogen.

Opex

The Opex of the storage and transport consist of the following items:

1. Opex of the stationary storage tanks: Pumps, heating, maintenance
2. Opex of the transport / delivery: fuel cost, driver salary, maintenance
3. Opex of the LOHC material: maintenance / replacement of degraded material

The Opex for the stationary tanks is neglectable as the pumping and trace heating of the liquid only requires very small amounts of energy. Furthermore, as the tanks are unpressurized and not operated at harsh conditions, maintenance is only required to a very limited extend.

The Opex of the transport has two main factors: Fuel consumption per km and driver salary. The total Opex then depend amnily on the distance transported. Average fuel consumption for (large) trucks is in the range of 35 l/100km. The drivers salary varies by region and country, but can be estimated between 30 – 40 EUR/h. As the LOHC material is not classified as a hazardous good, drivers do not need a special permit and are thus cheaper than qualified drivers.

The distribution Opex for the HySTOC project will not be representative due to the small amounts of hydrogen transported and the non-optimized transport solution with IBC. However, a more detailed assessment of the actual cost of transport will be an important part of the testing phase of the HySTOC project.

The third Opex factor is the replacement cost of degraded LOHC material. The material is expected to endure ~750 cycles, after which it will need to be regenerated by means of distillation. In this process, ~10% of the LOHC material will be lost. Assuming an estimated regeneration cost of 1 EUR/kg, the Opex from LOHC material can be calculated as follows:

Base data:

17 kg LOHC/ kg H2

1 EUR regeneration cost/kg LOHC after each 750 cycles

10 % loss each 750 cycles

((1 EUR*17 kg) + (17*10%* 5 EUR/kg))/750 cycles = 0.034 EUR/kg H2

At 3 EUR/kg LOHC, this cost of LOHC replacement and regeneration decreases to 0.029 EUR/kg H2.

Overall, it can be seen that the Capex of hydrogen storage and transport capacity with LOHC is low, especially compared to other storage technologies such as compressed or liquid hydrogen.

On the Opex, the absolute amount mainly depends on the transport distance, which will vary for each customer. Due to its high storage capacity, the cost advantage of LOHC will be especially relevant for longer distances (as will be demonstrated for the HySTOC project in Finland).

4 Scalability of LOHC tank and distribution system to full-scale operation at Hydrogen refueling stations

The described concept of stationary tanks in combination with LOHC transport focuses on small LOHC volumes (1 m^3 IBC tanks) due to the small scale demonstration and the existing infrastructure assets. However, this simple logistics concept can also be applied for large-scale hydrogen infrastructures. There are no special requirements in terms of construction material for the LOHC tanks. Suitable (underground) tanks with 100 m^3 capacity are readily available on the market at very low cost. The same holds true for tanker trucks with capacities of up to 30 m^3 (weight limits for road transport in certain countries might reduce the maximum transportable volume to around 28 m^3 LOHC, but this will not have a major impact on the scalability).

Furthermore, Dibenzyltoluene as hydrogen carrier is not classified as a dangerous good. It is thus also very easily transportable and storable in densely populated areas, which is an important factor for the application at hydrogen refueling stations.

These aspects enable easy scalability for the road but also the train and ship transport of hydrogen stored in LOHC.

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