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

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Final operational concept of hydrogen supply chain

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Document Type	
PRO	Technical/economic progress report (internal work package reports indicating work status)
DEL	Technical reports identified as deliverables in the Description of Work
MoM	Minutes of Meeting
MAN	Procedures and user manuals
WOR	Working document, issued as preparatory documents to a Technical report
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CO	Confidential, only for members of the consortium (including the Commission Services)	
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Abbreviations

CO2	Carbon dioxide
DBT	Dibenzyltoluene
GWP	Global warming potential
H2	Hydrogen
HySTOC	Hydrogen supply and transportation using liquid organic hydrogen carriers - EU-project
LOHC	Liquid Organic Hydrogen Carrier
LOHC-D	Liquid Organic Hydrogen Carrier in dehydrogenated form
LOHC-H	Liquid Organic Hydrogen Carrier in hydrogenated form
PSA	Pressure Swing Absorption
SMR	Steam methane reforming

1 Introduction

The need to decrease the release of greenhouse gases is one of the great challenges of our time. One promising way in achieving this goal is a hydrogen economy in which the main energy source for the industry, mobility and the private sector is hydrogen. On the way to a hydrogen economy one has to optimize the current supply chain of hydrogen in order to gain acceptance and to develop a CO2-free alternative energy system.

For the supply of hydrogen, the LOHC technology offers several big advantages compared to other state of the art technologies like compressed hydrogen or liquefied hydrogen. To name one of these advantages hydrogen is stored chemically in the LOHC material, which allows it to handle hydrogen at ambient conditions without the need for high pressures or very low temperatures.

Nevertheless, the LOHC supply chain will also have to take direct and indirect CO2 emissions into consideration. The HySTOC-Project (Hydrogen Supply and Transportation using Liquid Organic Hydrogen Carriers) addresses these topics and offers solutions to optimize the hydrogen supply chain via LOHC.

This deliverable will point out an optimized concept of hydrogen supply using LOHC based on the results of deliverable 8.1. (D8.1: Potential environmental implications of LOHC concepts). Deliverable 8.1 presents an environmental assessment using life cycle assessment methodologies. This assessment points out the impact of each step during the LOHC hydrogen supply chain. For example, the influence on the global warming potential or the photochemical ozone creation potential were examined and assessed. Thus identifying two main categories alongside the supply chain:

- Hotspot for greenhouse gas emissions and
- Potentials for minimizing impact on greenhouse gas emissions.

This report will study how to optimize the different sectors of the supply chain starting with the hydrogenation of the LOHC, transportation and dehydrogenation of LOHC.

2 Supply chain design in HySTOC

In the HYSTOC project the supply with hydrogen for the storage unit takes place in Kokkola, Finland at a hydrogen production site of Woikoski. In the HYSTOC project the system size of the storage and release units are at pilot scale (with 24 kg hydrogen/day). The LOHC-H and LOHC-D are stored in intermediate bulk containers (IBCs) and oil tanks. The IBCs obtain a storage capacity of 1m^3 each and the oil tanks are able to store up to 5m^3 of LOHC. The LOHC is transported from Kokkola via Voikoski and Järvenpäa to Espoo. At Espoo the release unit is stationed at VTT.
The release unit is equipped with electrical heaters to supply the required heat for the endothermal process of the dehydrogenation. The tanks are also heated electrically to ensure that in cold weather conditions LOHC remains pumpable. The stationary tanks are connected to a nitrogen supply to ensure strictly controlled conditions (SCC).
Figure 1 presents an overview of the LOHC supply and logistic concept designed in the HYSTOC project.

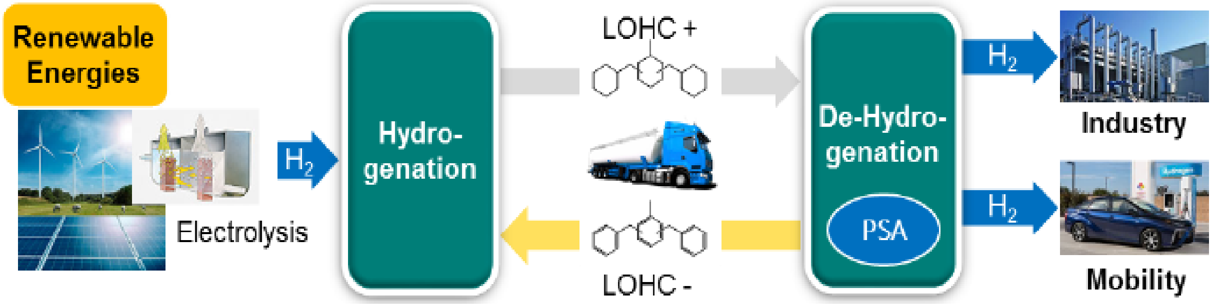

Figure 1: Hydrogen supply via LOHC Technology in the HYSTOC project

3 Hotspots of greenhouse gas emissions

The deliverable 8.1 (Potential environmental implications of LOHC concepts) assesses six categories for the life cycle assessment for the LOHC logistic concept. These categories are shown in Table 1.

Table 1: Environmental impact categories

Impact category	Abbreviation in the reporting	Reporting unit
Global warming potential in 100 year perspective	GWP	kg CO2 equivalents
Abiotic depletion potential of elements	ADP-E	kg antimony equivalents
Abiotic depletion potential of fossil fuels	ADP-FF	MJ
Acidification potential	AP	kg SO2 equivalents
Eutrophication potential	EP	kg PO4- equivalents
Photochemical ozone creation potential	POCP	kg ethylene equivalents

This report focuses mainly on the global warming potential (GWP) of each step during the LOHC concept. The impact on greenhouse gas emissions of each step depending on the overall process is ranked below:

1. Release unit (balance of plant, dehydrogenation process, PSA unit): 88 %
2. Transportation: 10%
3. Storage unit (balance of plant and dehydrogenation process): 1-2 %

The impact on GWP of the Release Plant is nearly 90 % of the overall impact due to the energy consumption of the dehydrogenation process. Therefore, tackling the energy distribution for the dehydrogenation process provides the strongest impact in reducing the carbon footprint of the LOHC concept. The second biggest impact occurs in reducing the CO2 emissions during transportation. Transportation is responsible for nearly 10 % of the CO2 emissions of the LOHC concept. The contribution of the storage unit and the PSA unit is below 1-2 %. Nevertheless, if the plants are scaled up to hundreds or thousands of tons of stored hydrogen in LOHC (e.g. seasonal storage) the total amount of CO2 emissions can still reach relevant amounts. As a result, specific efforts are assessed to reduce the carbon footprint of each step during the LOHC supply chain.

4 Optimized supply chain for LOHC logistics

This chapter describes an optimized strategy for the supply chain of hydrogen via LOHC to reduce greenhouse gas emissions based on the outcome of deliverable 8.1. This report distinguishes two scenarios. First, there is a mid-term scenario, which considers approaches based on technical state of the art solutions. Second, the long-term scenario assumes significant technological developments and a successful full energy transition to renewable energies.

4.1 Mid-term scenario

The following items below offer the biggest potential for reducing greenhouse gas emissions in a mid-term scenario:

- Energy supply for the dehydrogenation process
- Use of waste heat from the hydrogenation process

Energy supply for the dehydrogenation process

The dehydrogenation unit is the main source of CO2 when operating a hydrogen supply chain via LOHC. The greatest impact comes from the dehydrogenation enthalpy, which consumes around 10 kWh/kgH2. This energy consumption is thermodynamically given, but the source of the thermal energy supply can be changed. This study examined the following sources for heat production regarding their CO2 emission saving potential in comparison to electrical heating with the current power generation mix:

- Natural gas
- Biogas
- Power generation with renewable energies and
- Released hydrogen

The impact of the different sources is shown in Figure 2:

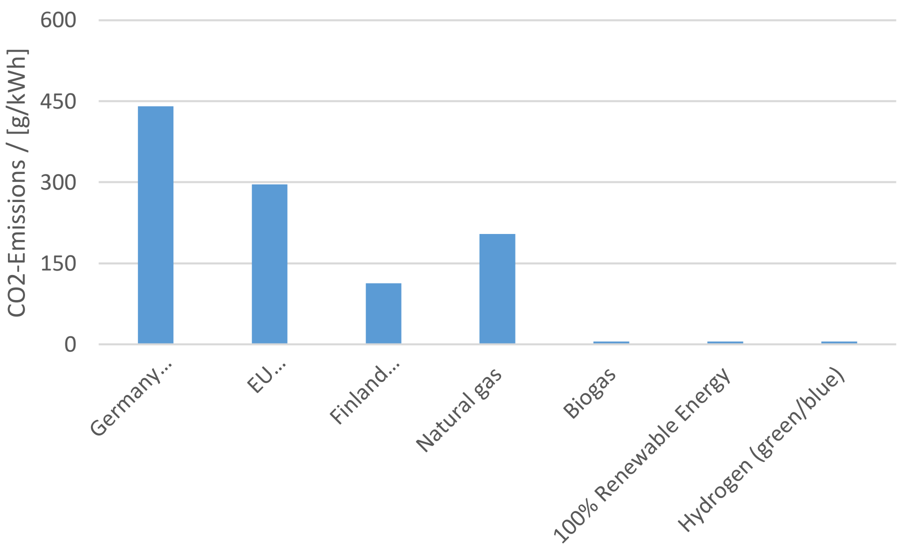

Figure 2: CO2 emissions depending on the source used for the thermal energy demand in the dehydrogenation process[1][2]

Figure 2 shows that the biggest impact on reducing CO2 emissions is achieved, when thermal energy is provided by burning biogas, by heating electrically using 100 % renewable power and by burning some part of the released hydrogen. If the first two options are not realizable (e.g. no biogas accessible), in countries like Germany one can use natural gas to reduce the CO2 footprint by about 40 – 50 % in comparison to electrical heating with standard power supply. In countries like Finland with a high amount of renewable energies (and nuclear power generation), this approach is not sensible as the CO2 emissions per kWh for power generation are already below the CO2 emissions of natural gas. Table 2 presents an overview of the different sources of power production in the EU, Germany and Finland.

Another way to reduce the CO2-footprint of the thermal heat supply for the dehydrogenation is using a part of the released hydrogen [5,6,7]. It is assumed that green or blue hydrogen is used. In burning hydrogen no additional CO2 is produced. However, due to the increased hydrogen demand at the release site, the delivery frequency to supply loaded LOHC has to be increased. This results in a higher output of CO2 because of the diesel combustion engines of today´s tank trucks. The calculations show, that this impact is relatively low as the increase of CO2 emissions is below 3 g CO2 per kWh (see Figure 2). Nevertheless, the use of the released hydrogen as a source for thermal energy faces several economical disadvantages, that lead to higher hydrogen selling prices [5]. First, one has to design and build a release unit that is about 1.3 to 1.5 times bigger to achieve a comparable output as a release unit that uses e. g. electricity. This will increase CAPEX and OPEX of a project. In addition, the needed amount of DBT increases by a similar factor, leading to significantly higher CAPEX, especially for large-scale projects. Furthermore, the increased number of LOHC deliveries increases the transport costs of LOHC.

Table 2: Overview of the different energy sectors for electrical power production in the EU, Germany and Finland in the year 2016 [1]

	EU [%]	Germany [%]	Finland [%]
Renewable Energies	29	29	44
Coal	21	40	15
Natural gas	20	15	6
Oil	2	1	0
Other Fuels	2	2	1
Nuclear	26	13	34

If in the mid-term scenario the heat for the dehydrogenation process comes from burning biogas (or natural gas), concerns of operators have to be overcome as it is more convenient to use electricity for any kind of usage. In addition, they have to accept a new infrastructure being installed at their site. The use of the released hydrogen may also get economically more attractive if the regulatory framework supports CO2-free energy sources compared to today.

Use of waste heat from the hydrogenation process

The hydrogenation unit offers the opportunity to use waste heat of the exothermal hydrogenation process of about 8 kWh/kgH2. Due to its temperature level of up to 250 °C, the waste heat is high value heat and can be used to heat up other industrial processes or buildings nearby, replacing energy sources with CO2 emissions.

In central Europe the average annual heating requirement of office facilities (e.g. office facilities of the operation staff at the hydrogen storage site) is around 200 kWh per m^2 [3]. Figure 3 shows the CO2 emissions of different energy sources that are used to meet the requested demand. The waste heat of the hydrogenation process offers an annual CO2 emission reduction for those facilities from about 40 to 80 kgCO2 per m^2.

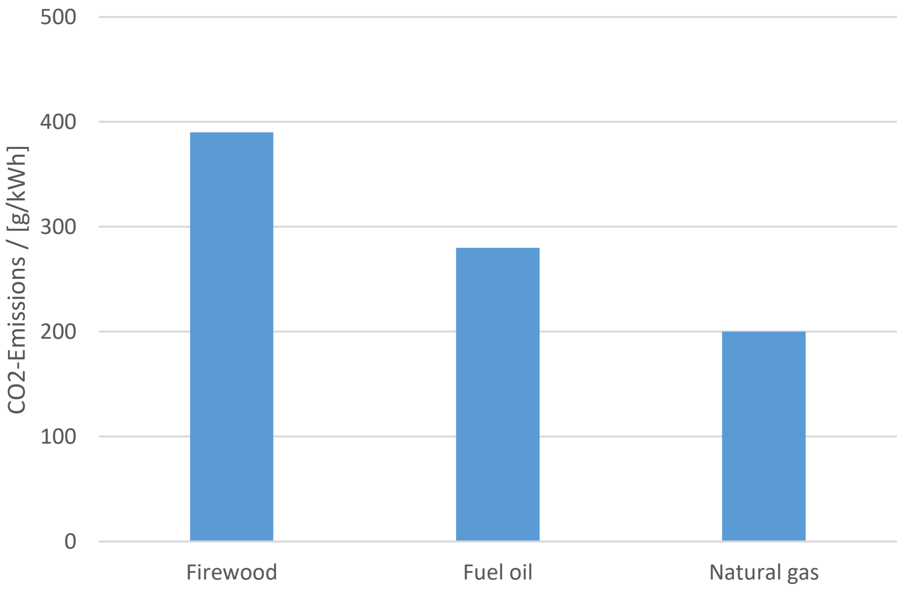

Figure 3: CO2 emissions of energy sources used for heating [2]

Other reduction potentials

For certain steps in the supply chain, a comparable quantification of CO2-reduction potentials is difficult. For transportation in the mid-term scenario it is assumed that the trucks still operate with a diesel combustion engine. To reduce CO2 emissions to a minimum it is ensured that all trucks are state of the art vehicles that observe the valid EU rules on combustion emissions. As the supply and demand for hydrogen grows, it is economically and environmentally reasonable to use further means of transportation. To overcome great distances over thousands of kilometers one uses tanker ships. For instance, tanker ships are used to supply costumers on the European continent with hydrogen stored via LOHC from hydrogen sources like Scandinavian wind farms in the North Sea, where hydrogen is produced directly via electrolysis. At the harbor the hydrogen rich LOHC is distributed by trucks and trains. Table 3 shows the CO2 emissions in the freight transport in 2017 depending on the greenhouse gas emissions per transported ton and kilometer.

Table 3: greenhouse gas emissions in freight transport in 2017 [4]

	Truck	Railway	Inland shipping
greenhouse gas [g/t km]	103	19	32

Using the LOHC technology to store hydrogen, it is possible to use todays fossil fuel infrastructure. This is why the technological readiness for transportation is already at commercial stage. Furthermore, the necessary infrastructure already exists and therefore saving energy during development and building of a new infrastructure.

4.2 Long-term scenario

In the long-term scenario all proposals of chapter 4.1 are already realized. In the long-term scenario the biggest impact on reducing the CO2 emissions alongside the LOHC supply chain is offered by the transportation sector.

Transportation

In 2018 the worldwide hydrogen production is estimated to about 600 billion Nm^3 - with up to 95 % of the production based on fossil fuels [7]. Hydrogen production using e.g. SMR produces 11 to 12 kgCO2 per kgH2 [8]. In the long-term scenario the installed capacity of renewable energies provides 100 % of global energy demand. The surplus of power provided by renewable energies can be used to produce hydrogen via electrolysis – making green hydrogen. In transportation fuel-cells have replaced the combustion engine as traction technology. Fuel cell trucks with zero emissions eliminate the combustion engine saving 700 g to 800 g of CO2 per kilometer compared to today (~2.6 kgCO2 per liter Diesel and a gas consumption of trucks of 30 l/100km).

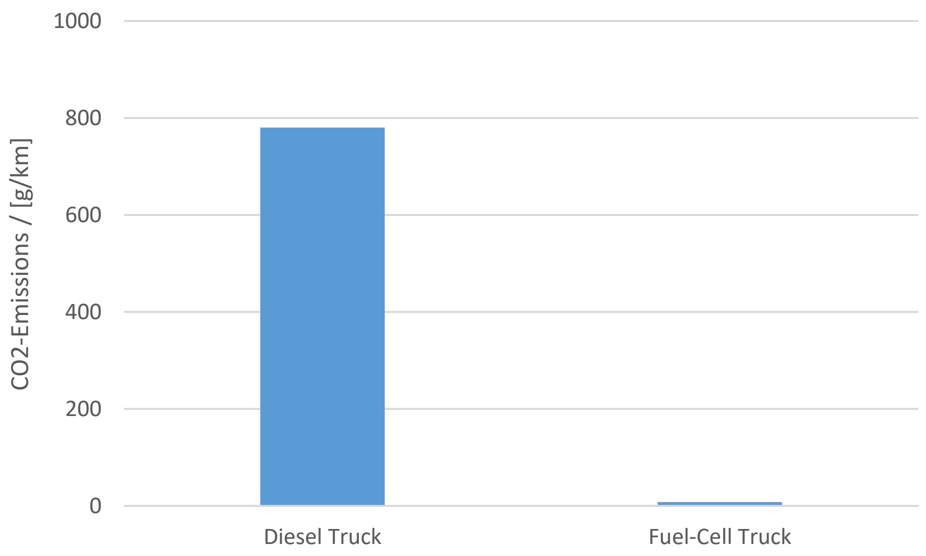

Figure 4: Comparison of CO2 emissions of trucks with different traction technologies

5 Conclusion

This study shows different possibilities to reduce the CO2 footprint of each step of the hydrogen supply chain via LOHC. Thus demonstrating that the LOHC technology is able to provide hydrogen in a sustainable way.

Two scenarios with different timescales were identified in this study. It is shown that it is possible to address the energy supply for the dehydrogenation process already in the mid-term scenario, which offers the biggest overall impact on reducing greenhouse gas emissions. Due to technological developments within the mobility sector and energy sector in the long-term scenario greenhouse gas emissions are reduced in every step during the supply chain of hydrogen via LOHC technology - in particular for applications in the transportation sector.

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