Concept analysis and life cycle assessment of large-scale, offshore hydrogen production, storage and distribution options

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I want to thank Greenstat, in which I have been employed for almost two years by the delivery of this thesis, for the inspiration to work with hydrogen technology, both during my master thesis and in the future. I have gained valuable professional insights through the employment. I also would express my gratefulness to my supervisors Martin Fernø, Velaug Myrseth Oltedal and Geoffrey Sean Gilpin, which have contributed to more knowledge, insights, and efforts than I could have asked for. I would also thank for the cooperation with the Western Norway University of Applied Sciences, which have contributed with both supervisors and the possibility to take relevant courses. I must express an extra gratefulness for the metaphors in which Geoffrey and Martin both are masters of, which have brought me a lot of joy and some frustration through the year – I think that I have managed to dig some gold out of the rocks by the deliverance of this thesis. I would also express my thankfulness to Vegard Lavik at HyFuel and Svein Kjenner at Deep Purple, which both have provided valuable insights to the thesis.

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Abstract

The world and its inhabitants are facing pressing challenges related to the global warming of the Earth. The increasing share of renewable electricity is forecasted to decrease emissions of greenhouse gases, but electrification is not suitable for all sectors. For the maritime and the industrial sector in particular, hydrogen made from renewable electricity is an alternative energy carrier with low emissions. Offshore wind is a renewable energy source with expected significant growth in the next decade and wind farms far from shore provide intensives to investigate hydrogen production offshore. The advantage of such system is that low-carbon fuels can be produced without stressing the onshore electricity system.

An offshore hydrogen production value chain includes the need for production, processing, storage and distribution to shore. This thesis identifies two large-scale hydrogen storage solutions for monthly production from a 500 MW offshore wind farm: compressed hydrogen in porous, underground formations and liquid organic hydrogen carriers stored on a floating vessel. A concept analysis outlines the data for the environmental analysis, which is performed by the standardized method of life cycle assessment (LCA), to compare the environmental impact of the studies storage solutions.

Generally, the results shows that hydrogen processing and storage part of the hydrogen value chain in a large-scale, offshore system are non-marginal and must be included to determine the environmental viability. A preferred storage solution from an environmental perspective cannot be determined, as the results overlap between defined scenarios. Nevertheless, UHS is generally related with a slightly lower emission, both greenhouse gases and other emission flows, has less deviation between defined scenarios and appear to have less system complexity. This combination leads the UHS case to appear as favorable within the boundaries of this thesis, but the LOHC case remains as an interesting alternative for further investigations for longer term hydrogen storage.

Content

Abbreviations	
ASME	American Society of Mechanical Engineers
BCC	Body Centered Cube
BOP	Balance of plant
BT	Benzyltoluene
CH_4	Methane
CO_2	Carbon dioxide
EIGA	European Industrial Gases Association
FCC	Face Centered Cube
FPSO	Floating production and storage offloading
GHG	Greenhouse Gases
GWP	Global Warming Potential
HHV	Higher heating value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LOHC+	Hydrogenated liquid organic carrier
LOHC-	Hydrogen-lean liquid organic carrier
LOHC	Liquid Organic Hydrogen Carrier
LHV	Lower Heating value
NVE	Norges vassdrag- og energidirektorat (Norwegian waterfall- and energy directory)
O&G	Oil and gas
P-BT	Perhydro benzyltoluene
R&D	Research and development
RE	Renewable energy
S&D	Storage and distribution
SMYS	Specified minimum yield strength/stress
Tkm	Ton*km
TPD	Ton per day
UHS	Underground hydrogen storage
WT	Wall Thickness

1 Introduction

1.1 Motivation

Climate change is one of the most pressing challenges humanity faces. It is driven by the rapid increase in global temperature and since the industrial revolution, human activities have led to a 1.1ºC increase in average global surface temperature. The temperature increase is expected to reach 1.5ºC warming within the next two decades and it is scientific consensus that human activities are driving global warming due to anthropogenic radiative forcing (IPCC, 2021). The greenhouse gases (GHG) most notably in a climate change perspective are carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2) and nitrous oxide (N_2O). Since 1750, the CO_2 content in the atmosphere has increased by 47% and combustion of fossil fuels is the main driver (IPCC, 2021). Despite decades of knowledge about climate change, global fossil fuel consumption reached a new record in 2019 and has been increasing annually since 1900 (with two exceptions, 1982 and 2009) (Ritchie and Roser, 2020). The commitments of the Paris Agreement, which the majority of the world's countries are committed to, state how countries shall cooperate to limit global warming to "well below" 2 ºC (compared to pre-industrial levels) (UNFCCC, 2015). The amount of GHGs that can be emitted to limit global warming to the stated policies, is referred to as the carbon budget. With the carbon budget defined by the Intergovernmental Panel on Climate Change (IPCC) accounted for by the yearly world emissions, we would have around 27 years of greenhouse gas emissions left with the emission rate we have today before the carbon budget is entirely spent[1].

The EU has led an ambitious climate strategy in the last years, with increased efforts on technology and investments related to reduction of emissions. In 2020, the EU redefined its climate target to reduce emissions by at least 55% by 2030 compared to 1990 levels, and aims to be "climate-neutral" by 2050 (European Commission, no date). Climate-neutrality is describing a society with net-zero GHG emissions – meaning that the GHGs that are emitted, must be captured, or compensated for. Norway has committed to the same targets as the EU, but in 2019[2], the reduction of emitted GHG was limited to under 1% compared to 1990

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[1] In 2019, around 33 GT of CO_2 equivalents were emitted (IEA, 2020), whilst the carbon budget is limited to 900 GT of CO_2 equivalents (IPCC, 2021)

[2] 2019 is used as reference year rather than 2020 or 2021 due to the global Covid-19 pandemic which leads to biased results for these two years.

(Miljødirektoratet, 2021). The Norwegian primary energy demand is based on 43% fossil fuels and biofuels (NVE, 2019), compared to 84% for the world's primary energy demand (Ritchie and Roser, 2020). If the Norwegian emissions are to be reduced by 55% by 2030, the fraction of fossil fuels and biofuels needs to be approximately halved. The fraction of fossil- and biofuels is dominated by the transport sector, followed by the industrial sector, which in 2020 utilized respectively 45 and 20 TWh of fossil fuels (Energifakta Norge, no date). These two sectors depend on high gravimetric energy density and use of hydrocarbons in chemical processes, which increases the challenge of electrification.

To meet the climate commitments in the following decades, fossil fuels need to be replaced with either electricity or fuels with significantly lower carbon intensity. Hydrogen is a proposed low-emission fuel, which can be burnt emission-free and produced from renewable electricity. Scientists have been pointing at the hydrogen economy for decades and as an example, pioneer environmentalist Lester R. Brown pointed out already in 1993 how hydrogen made from renewable electricity can replace fossil fuels in several sectors and reduce the emission of GHG through combustion of fossil fuels (Brown, 1993). Transition to a hydrogen economy suggests hydrogen made from renewable energy sources to a large extent replaces fossil fuels and contributes to energy storage for electricity generation (National Academy of Engineering, 2004; Webber, 2007). This is especially relevant in sectors where batteries are not expected to be a low-emission alternative due to the low gravimetric energy density, such as shipping, long-distance onshore transport and several industrial applications. This transition will however require significant implementation of new technology, which comes with an environmental footprint. The establishment of new infrastructure and production of new technology is critical for making the transition to renewables – however, our carbon budget is not unlimited in this phase, even if it is for the transition to a low-emission society. The pressing challenges of climate change, as well as the very limited carbon budget as earlier defined, emphasize the need to make informed decisions on the implementation of new technology, which limits the greenhouse gas emissions in all phases of its lifecycle.

1.2 Background

This chapter introduces important aspects of this thesis, including hydrogen, offshore wind, sustainability and an introduction to the life cycle assessment (LCA) methodology.

Offshore wind is introduced as a renewable energy (RE) source with vast potential for energy generation in Norway and Europe and a potential electricity source for hydrogen production. Furthermore, an introduction to sustainability, environment and LCA is made, as vital parts of a low-carbon society.

1.2.1 Introduction to hydrogen

Hydrogen can store electricity through electrolysis, a process where water is separated into hydrogen and oxygen molecules. When electricity is based on RE sources, as wind, this is referred to as green hydrogen. Energy is released by the reverse process, where hydrogen gas bonds with oxygen to form water, a process that does not emit any GHGs. In this way, hydrogen can work as an electricity storage medium that can be utilized emission-free, a crucial solution with an increasing share of unstable, renewable energy. Yet, the yearly production of hydrogen of around 70 million tons is primarily made by reformation of fossil fuels (98%), commonly referred to as grey hydrogen, which leads to emission of GHGs (IEA, 2019b). Around half of this production volume goes directly into oil refining, including methanol production, while the largest fraction of the other half goes into ammonia production (IEA, 2019b). In Norway, the biggest single emitter of GHG is the oil refinery on Mongstad, where grey hydrogen is produced for the oil refining (Miljødirektoratet, no date).

Due to hydrogen's potential as a low-emission energy carrier, industry actors are increasing efforts on research and development (R&D) and hydrogen-related projects and energy agencies declare that the transition to a net-zero society includes the hydrogen economy (IEA, 2019b; IRENA, 2019). However, there are several challenges linked to large-scale implementation of hydrogen in our energy system. It is the lightest atom on Earth and it therefore has low volumetric density, challenges in a material perspective and is an explosive gas. This combination leads to challenges for hydrogen handling and storage, and therefore the value chain is of particular interest when hydrogen is discussed (illustrated in Figure 1-1):

Figure 1-1 - Hydrogen value chain for production through electrolysis. This illustration shows the many steps related to the hydrogen value chain, which include production, processing, storage, transport, possibly re-processing and then either use directly in industrial processes or combustion, or in a fuel cell to produce electricity. Processing is indicated with a parenthesis after transport, as only some hydrogen carriers require re-processing.

Hydrogen has several options for useful, processed variations and two well-known processing technologies are compression and liquefaction (Rivard, Trudeau and Zaghib, 2019). Liquefaction requires a temperature of -253 ºC and increases the volumetric energy density (Michel, 2008). In addition to physical processing as compression and liquefaction, hydrogen can go through several forms of chemical processing. Processing of hydrogen to ammonia is a well-known process used for decades for fertilizer production (IEA, 2021). Other chemical alternatives such as liquid organic hydrogen carriers (LOHC) are gaining momentum and the technology is rapidly developing (IEA, 2019b). It can be stored either in physical storage (liquified or compressed) or chemical bonding (Andersson and Grönkvist, 2019), see Figure 1-2:

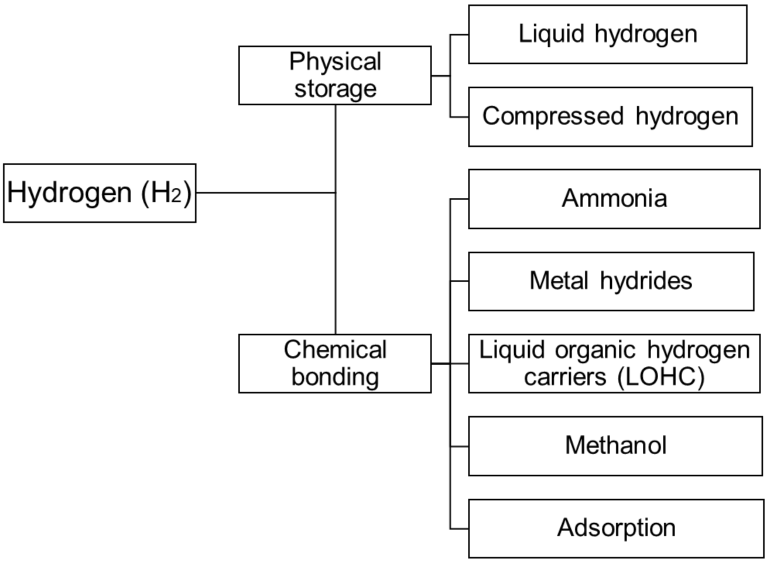

Figure 1-2 - Different hydrogen processing and storage techniques Figure inspired from Andersson and Grönkvist, (2019).

An established form for permanent hydrogen storage is in cryogenic tanks for space applications, where the largest cryogenic tanks have a capacity of about 270 tons (Perrin and Weber, 2008). In comparison, over 400 tons of hydrogen can be produced daily with electricity from a one GW wind farm, indicating that the largest tank storage solutions that exist commercially, are not sufficient for more than one day of large-scale hydrogen production.

Despite the large fraction of renewable electricity production in Norway, the GHG emissions from fossil fuels must be reduced and this is achievable by replacing a fraction of today's primary energy demand with (green) hydrogen. If 25% is of the yearly Norwegian fossil fuel demand is replaced with hydrogen (assuming the same efficiency for a fuel cell system as combustion of fuels including processing), this yields a yearly demand of close to 700 000 tons of hydrogen, corresponding to a daily production demand of minimum 2000 tons of hydrogen. Hence, existing storage solutions with a maximum capacity of 270 tons, are not sufficient and large-scale storage solutions are essential for large-scale hydrogen production. Large-scale is in this thesis defined as storage solutions for longer terms storage of hydrogen (minimum one month), that allow storage of minimum 270 tons of hydrogen.

1.2.2 Offshore wind and power-to-X projects

RE and large-scale energy storage options are important to reduce GHG emissions and decrease the warming rate of Earth. Offshore wind is a rapidly increasing RE source and several GW-scale offshore wind projects are planned in the North Sea in the coming decade. A more than 400% increase in installed offshore wind capacity is foreseen by IEA in Europe by 2030 (from 19 GW in 2018 to around 65-85 GW in 2030), with this exponential growth continuing towards 2050 (IEA, 2019a). This expansion is leading to interest in both fixed and floating wind farms and floating farms allow installation on increased water depths. It is estimated that offshore hydrogen production from a floating wind farm will be slightly cheaper than onshore hydrogen production with power cables to shore in 2040, due to the high cost of power cables (based on 80 km distance to shore) (Spyroudi *et al.*, 2020). This finding, combined with the complexity of power cables and the possible repurposing of already existing pipeline infrastructure, can explain the increasing interest in hydrogen production from wind farms on offshore facilities. A selection of such projects, are presented in Table 1-1:

Table 1-1 - Overview of ongoing projects which are combining wind energy and hydrogen production offshore (Danish Energy Agency, no date; EDP, no date; ERM, no date; Lhyfe, no date; PosHYdon, no date; TechnipFMC, no date; ZEEDS, no date).

Project name (Industrial actor)	**Country**	**Project type**	**Status**
Dolphyn (ERM)	Great Britain	Offshore hydrogen production with electrolysers directly installed in the wind turbine	Feasibility study is finished, plan pilot scale project by mid-2020.
Behyond (Consortium including EDP)	Portugal	Offshore hydrogen production on a platform with power from wind farm	R&D project, planned pilot without given date.
PosHYdon (Consortium including Neptun Energy)	Netherlands/ Northern Sea	Electrolyser with hydrogen production installed on an existing platform	Pilot is under development
Offshore H_2 production (Lhyfe)	France	Hydrogen production from an offshore wind farm on a jack-up rig	Pilot is under development
Energy Island (Not decided, ongoing tender)	Denmark	Denmark wishes to deploy the world's first energy Island, with a connected wind energy of minimum 3 GW. It is announced that hydrogen production is planned on the energy island.	Tender is expected to be announced in 2022
Zeeds (Aker Solutions, Equinor, DFDS, Grieg Star, Wärtsilä)	Norway/Northern Sea	Have outlined offshore bunkering stations for shipping vessels, provided by ammonia produced from wind energy.	Pilot project of green ammonia production in Berlevåg is planning to be fully commissioned in 2024.
Deep Purple (Technip FMC)	Norway/ Europe	A concept which is not specifically scoping hydrogen production from offshore wind, but which is focusing on the storage solutions of hydrogen offshore.	Pilot is under development

Increasing the share of RE in the energy mix will increase the fluctuation of energy production, meaning that the power situation must be adapted to larger variations. Large-scale energy storage is a critical factor to convert to an energy system with greater variability. Differentiation between the different renewables and thought-through planning on how energy availability can be secured even with fluctuating power, is crucial. Hydrogen production in surplus energy production periods is one way to contribute to stabilizing the energy system. Offshore wind can also be utilized as a differentiation source to produce hydrogen when the demand is lower. The produced and stored energy from the wind farm can provide energy by producing electricity through fuel cells, as shipping fuel or for industrial use. If the produced hydrogen (or another H_2-carrier) can be utilized in the winter months or when the demand is generally high, it can offtake a significant amount load on the grid onshore and thereby contribute to stabilize the energy system. Offshore wind can utilize an unstable, but vast energy resource for hydrogen production to adapt the load on the electricity system onshore.

1.2.3 Development and sustainability

An important aspect in the implementation of new technology, is to consider and estimate environmental impact through the whole lifecycle. This is related to environmental sustainability, which is one of three factors that was defined by the Brundtland commission in 1987 as essential for sustainable development, together with society and economy (see Figure 1-3). To develop our society sustainably, we need to minimize the emissions of establishment of the new energy solutions, secure that the solutions are sustainable in a societal perspective and secure economic viability. To build a hydrogen economy requires significant economical and resource investments and the acceptance of the society.

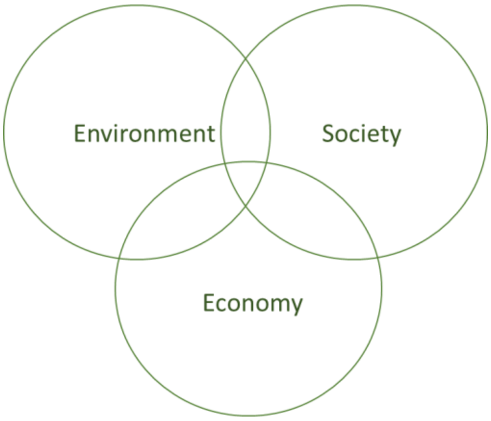

Figure 1-3 - The Brundtland commission defined sustainable development as the inseparable link between environment, society and economy (Store Norske Leksikon (SNL), 2022).

Impacts on society are challenging to measure and must be considered critically and carefully from case to case. It exists numerous methods for measuring both environmental and economic impact. Economic impact can be measured with a lot of different methodologies and levelized cost of energy is an example of an established method to quantify economic results. To quantify environmental impact is complex, but in the latest decades, several tools have been established. Life cycle assessments is one of such tools, which is a standardized methodology for determining the environmental impact of a product, system, or service.

1.2.4 Life cycle assessment

Life cycle assessment (LCA) is a well-defined methodology by ISO-14040 and 14044 standards and the standardization is made with great flexibility for the LCA practitioner (European Commission, 2010). The methodology includes four defined steps: goal and scope definition, life cycle inventory analysis (LCI), impact assessment (LCIA) and interpretation (ISO, 2006). The process is iterative and an important part of the methodology is to revise and re-evaluate the steps along the process (Figure 1-4):

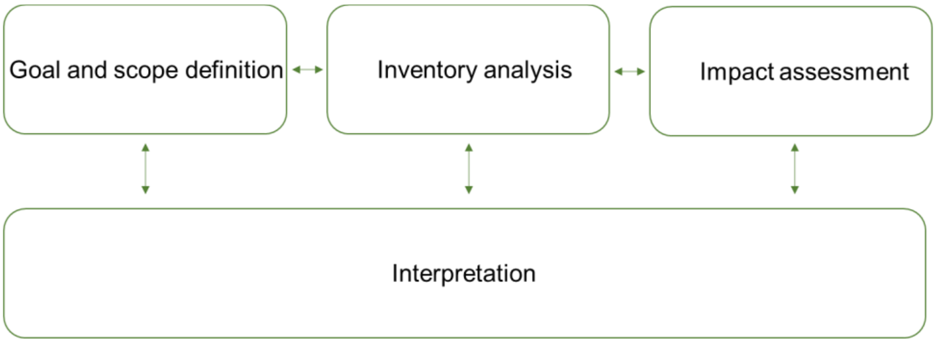

Figure 1-4 - The steps of the LCA methodology. The figure is made by inspiration from the ISO-14040 LCA standard (ISO, 2006).

LCAs include the whole lifecycle of the system or the product, called cradle-to-grave perspective (Figure 1-5). This perspective means that the manufacturing process from the mining of the resources that are needed for the manufacturing of products and systems, to the decommission or dismantling of the system, is considered.

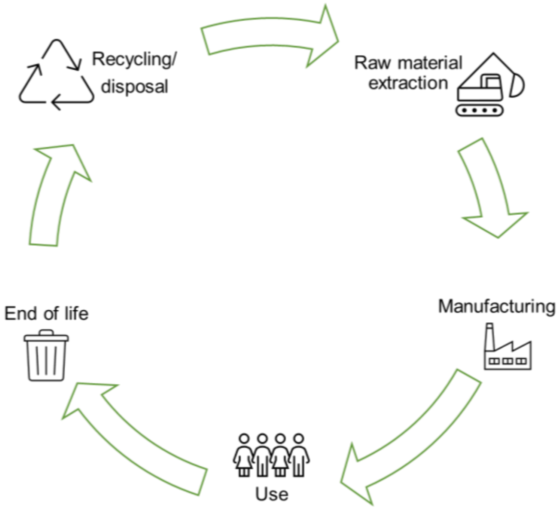

Figure 1-5 – Possible value-chain for the lifecycle of a system, inspired by (Baumann and Tillmann, 2004).

LCAs can be modified analyzing only cradle-to-gate, gate-to-gate, etc. and therefore the scope definition in an LCA methodology is an important part of the method. The LCA methodology is further described in chapter 3.2.

1.3 Literature review on hydrogen production/storage

In this chapter, a literature review on relevant LCA studies for this thesis is performed. LCA studies both covering wind production and hydrogen production from RE is presented.

1.3.1 LCA studies on hydrogen production

Wind energy has been excessively covered in LCAs and is one of the RE sources which yield the lowest GHG emissions, together with hydropower (Varun, Bhat and Prakash, 2009; Raadal *et al.*, 2011; Chipindula *et al.*, 2018). Offshore wind farms differ from onshore by the need for subsea electrical connections and ships for deployment, operation and maintenance (O&M) (Arvesen, Birkeland and Hertwich, 2013). For environmental calculations and comparison purposes, GHGs are often converted to CO_2 equivalents, meaning that all GHGs are added together using a factor that adjusts for the warming effect of the different gases (IPCC, 2018). When adjusted to CO_2 equivalents, the emissions are often referred to as global warming potential. The global warming potential (GWP) of an offshore wind farm has been estimated to 35 gCO_2eq./kWh in a cradle-to-grave perspective (Arvesen, Birkeland and Hertwich, 2013), which is within the range (4.6 – 55.4 gCO_2eq./kWh) presented in LCA review study for both offshore and onshore wind farms (Raadal *et al.*, 2011). Onshore wind farms has been estimated to a maximum of 39.4 CO_2eq./kWh for studies newer than 2000 in review LCA study by Varun, Bhat and Prakash, (2009). The low GWP from wind farms is assumably a driver for ongoing hydrogen production from wind projects (Table 1-1).

The GWP for wind energy is low per kWh, which leads to an expectation of low GWP related to hydrogen production from wind. However, the hydrogen value chain (Figure 1-1) increase the complexity of the system and may increase the influence on the overall GWP. Hence, the related environmental impact of the whole value chain must be carefully mapped to accurately evaluate the GWP from offshore wind (or other RE sources). A selection of analyses that evaluates hydrogen production from RE, conclude that hydrogen produced from wind energy emits between 20-85 g CO_2eq./kWh with an average of 46 g CO_2eq./kWh including compression (Simons and Bauer, 2011; Cetinkaya, Dincer and Naterer, 2012; Dufour *et al.*, 2012; Hacatoglu, Rosen and Dincer, 2012; Ghandehariun and Kumar, 2016; Suleman, Dincer and Agelin-Chaab, 2016; Zhang *et al.*, 2017). For comparison, 357 g CO_2eq./kWh is emitted when hydrogen is produced from natural gas (grey hydrogen) (Cetinkaya, Dincer and Naterer, 2012). Several of the results from the studies assessing hydrogen produced from RE imply that that the that GWP is dominated by the production and manufacturing of the plant/wind farm and that the operation phase (electricity production during the lifetime) has limited impact (Cetinkaya, Dincer and Naterer, 2012; Hacatoglu, Rosen and Dincer, 2012; Ghandehariun and Kumar, 2016). Half of the evaluated LCA studies does not include the whole hydrogen value chain and only consider cradle-to-grave on production (including electricity source) and processing (Dufour *et al.*, 2012; Suleman, Dincer and Agelin-Chaab, 2016; Zhang *et al.*, 2017), commonly known as gate-to-gate or well-to-tank (see Figure 1-6):

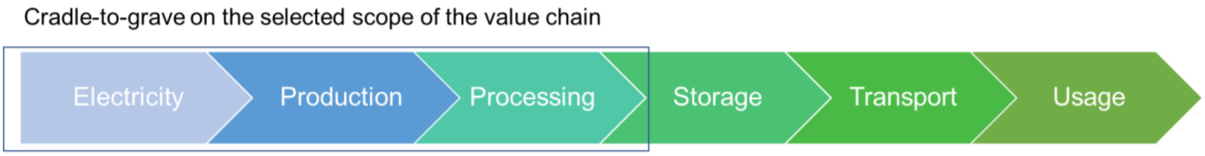

Figure 1-6 - Hydrogen value chain illustrated with the scope of the assessed LCAs.

The cited studies have in common that they either are well-to-tank studies and thereby omitting storage and distribution (S&D) or investigate hydrogen production on a rather small scale[3]. A perspective that is missing in the literature is therefore analyses that include large-scale S&D. Large-scale systems will require more complex S&D systems and seen in context with how the wind power plant dominates the GWP (Cetinkaya, Dincer and Naterer, 2012; Hacatoglu, Rosen and Dincer, 2012; Ghandehariun and Kumar, 2016), these aspects stand out as important to evaluate.

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[3] For Simons and Bauer (2012) and Hacatoglu, Rosen and Dincer, (2012) the assumption on small scale is not specifically stated in the articles but assumed due to consideration of road transport of compressed hydrogen. Road transport of compressed hydrogen is volume demanding and approx. 1 ton can be transported in a trailer. Therefore, small-scale (<<270 tons) is assumed as production volume for these cases. For Ghandehariun and Kumar, (2016), the daily production volume is given (~128 kg/d).

1.3.2 LCA studies on storage and distribution

A selection of LCA studies that directly address the storage and distribution (S&D) options has been evaluated, where the scope and limitations have been pointed out (Table 1-2):

Table 1-2 - LCA studies with focus on S&D-part of the value chain.

Reference	**S&D pathways addressed**	**Storage location**	**Remains to be investigated**
Wulf *et.al,* (2018)	CH_2 salt cavern + trailer	Onshore, German market (2050)	Detailed analysis related infrastructure to salt cavern storage, brine usage and disposal related to solution mining.
	CH_2 salt cavern + pipeline		
	LOHC tank + trailer		
Pérez and Vogt, (2014)	CH_2 salt cavern	All European salt caverns (2030)	A full-scale LCA, including production, manufacturing and dismantling of infrastructure related to the storage.
Wulf and Zapp, (2018)	LOHC transport	Onshore, German market (2050)	Temporary storage. Assessing production with frequent turnover rate
	LH_2 transport		
Paster, *et.al* (2011)	CH_2 salt cavern + pipeline	Onshore, Sacramento California (2020)	Storage has focus on the vehicle. Storage in salt cavern is assessed as pathway but has not included any emissions to it.
	CH_2 salt cavern + pipeline + truck		
	LH_2 storage + truck		

Several studies investigate reservoir storage in salt caverns as a possible hydrogen storage solution in an LCA perspective (Paster *et al.*, 2011; Pérez and Vogt, 2014; Wulf, et *al.*, 2018), but has several limitations. Study by Pérez and Vogt, (2014) only considerers direct emissions and is therefore not a holistic LCA on salt cavern storage. Study by Paster *et al.*, (2011) assumes that compressed hydrogen is delivered to a small-scale system (vehicle), after storage in cavern, but the cavern storage is out of the scope. Also Wulf *et.al*, (2018) have limitations in the investigation of the salt cavern underground hydrogen storage (listed in Table 1-2), meaning that all the presented studies have limitations related to the study of underground hydrogen storage (UHS) and it appears to be a literature gap on cradle-to-grave LCAs of UHS.

Green hydrogen production on larger scale systems including thorough assessments of the hydrogen value chain, is presented (Wulf and Zapp, 2018; Wulf *et.al*, 2018). These studies represent a scarce selection of such LCAs found in the literature. The transport pathway for the analyses is either by truck or pipeline. Truck transportation limits the transportation volumes and for the analyzed pathway of 80 ton H_2/d, this corresponds to the demand of respectively 44 (LOHC) and 74 (compressed hydrogen) transportation trucks, which is not feasible in an environmental perspective (Wulf *et.al*, 2018). With the defined limitations, the study concludes that UHS with pipeline transportation as the better environmental solution, whilst LOHC storage with truck transport is the less favorable environmental solution. Both studies present storage of hydrogen as LOHC, a storage perspective that is scarcely covered by LCA, despite LOHC being proposed as a hydrogen carrier with potential of efficient handling, transportation and storage (Markiewicz *et al.*, 2015).

1.4 Research question

Despite the importance of large-scale energy storage options, no literature that evaluates offshore hydrogen production, storage and distribution from a large scale (>100 MW), offshore wind farm in an environmental perspective is found. As seen in the literature review, the LCAs that include the whole hydrogen value chain, tend to scope small systems or are based on continuous turnover of the production hydrogen and thereby not including large storage volumes. A few relevant studies on large-scale storage systems are found for onshore systems, but no relevant LCA studies for offshore, large-scale storage of hydrogen is found. However, for increasing share of RE, combined with increasing energy demand, large-scale storage of hydrogen can be a key enabler to a zero-emission society. The research question that is raised in this thesis is stated in the following section:

Can large-scale, offshore hydrogen production (500 MW) powered by electricity from an offshore wind farm be practically stored on a monthly basis by LOHC or UHS, and if so, which of the solution yields least environmental impact?

To be able to answer to this research question, there are several objectives

1) Investigate and map LOHC and UHS processing and storage solutions
2) Define storage configurations for LOHC and UHS that allow storage of hydrogen produced by a 500 MW electrolyser system for one month by a concept analysis
3) Perform an LCA on the proposed storage configurations
4) Identify challenges within the scope

1.4.1 Scope

The concept of hydrogen production offshore may be questioned, in terms of the viability of offshore hydrogen production disconnected from shore vs. transportation of produced electricity to shore by cables. However, based on the high interest in projects for hydrogen production offshore as summarized in Table 1-1, combined with increased distance of windfarms from shore, the viability of hydrogen production offshore is defined as a prerequisite for the scope. The system boundaries were originally defined to exclude hydrogen production. However, by the iterative nature of LCA, it was uncovered that the hydrogen production was needed within the LCA scope, primarily due to lack of background data. The primary focus of this thesis remains on the parts of the value chain related to processing, storage, distribution and possibly reprocessing. The storage solutions investigated in this thesis are LOHC processing and storage and underground hydrogen storage (UHS) of compressed hydrogen (Figure 1-7):

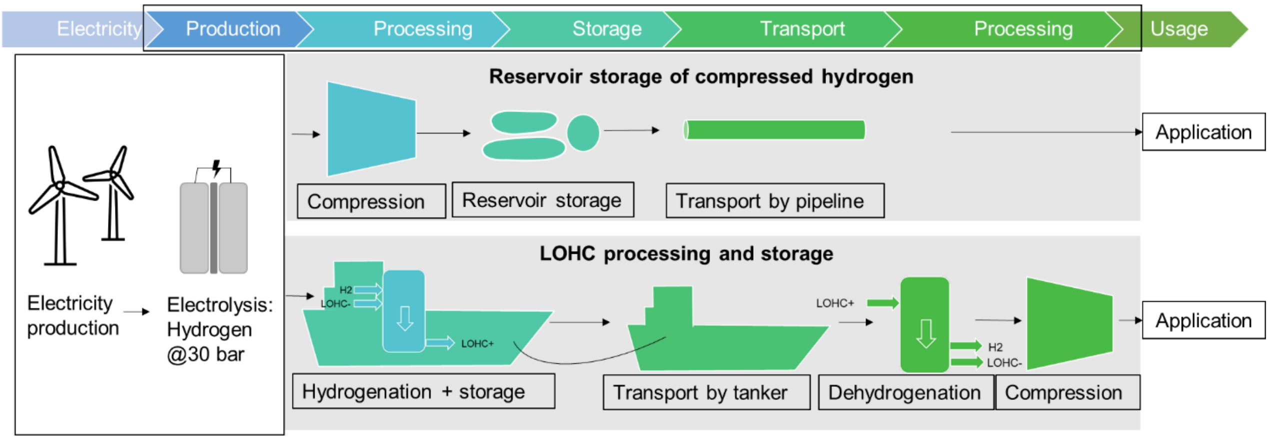

Figure 1-7 - Illustration of the processing and storage pathways for LOHC and compressed hydrogen. The grey box for each of the pathways illustrate the focus of the thesis. However, the upper flow chart indicates the LCA scope, as hydrogen production is included.

The storage solutions are further elaborated in Chapter 2. The storage solutions are investigated in detail in a concept analysis (Chapter 4), where space limitations, distribution pathways and production volumes are evaluated. Findings from the concept analysis, serve as basis to evaluate the environmental impact within the LCA framework (Chapter 5). The context of the analysis is in the Norwegian environment, specifically the Southern North Sea. The scope of the LCA analysis includes hydrogen production, processing, storage and transportation part of the value chain for a hydrogen production system offshore in a cradle-to-grave perspective.

2 Theory – hydrogen processing and storage

This chapter provides a description of hydrogen, hydrogen processing and hydrogen storage. Hydrogen is compared to traditional fossil fuels, as it is a low-carbon competitor. Hydrogen processing and storage are different parts of the value chain, but as the storage solutions require different processed variants, it is interrelated. Compressed hydrogen and liquid organic hydrogen carriers (LOHC), which will be assessed in the concept analysis and LCA, are thoroughly covered. Economic aspects are not assessed in detail, but some economical aspects related to the storage solutions are considered in this chapter. A justification for the chosen processing and storage variants is given by the end of the chapter.

2.1 Hydrogen and fossil fuels alternatives

The technology for hydrogen utilization today primarily focuses on the chemical reaction of hydrogen and oxygen in a redox reaction in a fuel cell. In contrast to the fossil fuels, that are combusted, hydrogen provides energy to an electric propulsion system through the chemical reaction in the fuel cell, where electrons are released (Li and Jensen, 2008). Hydrogen does not produce CO_2 when reacting in a fuel cell, as there are no carbon atoms present in the molecule. The hydrogen molecules react with oxygen and produce water. The reaction is shown in equation [1]:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O\ (g) \qquad \Delta H^{\circ} = -482\ \text{kJ (LHV)} \qquad [1]$$

To evaluate the impact of the value chain of fossil fuels, CO_2-emissions for combustion of 1 kg gasoline and natural gas (NG) is calculated. The results show that the direct combustion of gasoline generates a CO_2-emission of 3.2 kg/kg gasoline, whilst the combustion of NG generates a CO_2-emission of 2.2 kg/kg CH_4. The calculations are provided in Appendix I: Background data and calculations. Due to the lowered CO_2-emission by combustion of NG, it is suggested as crucial in the energy transition to abate emissions (IEA, 2019c). In addition to the emissions related to the direct CO_2-emission of combustion of the fuel, extraction, processing and emission of other GHGs during combustion increase the overall number of CO2eq. per combustion. An LCA review study of different fuels (Gode *et al.*, 2011) reports an emission of 3.7 kg CO_2 eq./kg (307 gCO_2 eq./kWh) for the overall life cycle of gasoline. This indicates that the emissions related to production and distribution are low compared with the emissions from combustion. An overall emission of 3.5 kg CO_2eq./kg (233 gCO2eq./kWh) is reported for NG (Gode *et al.*, 2011). Density and the related emissions in an LCA perspective for the different fuels are presented per kilogram and per kWh in Table 2-1. The average GHG emission from hydrogen is based on the presented articles for hydrogen production from wind energy in the literature review (Chapter 1.3). The average for gasoline is based on (Granovskii, Dincer and Rosen, 2006; Gode *et al.*, 2011; Simons and Bauer, 2011) and the average for NG is based on (Gode *et al.*, 2011; Simons and Bauer, 2011).

Table 2-1 - Gravimetric energy density and estimates for emissions for hydrogen, gasoline and NG. Estimates of emission are averages by the literature values presented. Energy density and fuel density is based on (Kircher and Braess, 2008).

Fuel	**Density [kg/m^3]**	**Energy density (LHV) [kWh/kg]**	**Emissions [kgCO$_2$ eq./kg fuel]**	**Emission [g CO$_2$ eq./kWh]**
Hydrogen (H_2) (350 bar)	23.4	33.3	1.5	46
Liquid* natural gas (CH_4)	392	14.0	3.6	257
Gasoline (C_8H_{18})	764	12.2	3.8	311

**) Characteristics for density and energy density is provided for liquid NG, whilst emission factors are for NG.*

2.2 Compressed hydrogen – technical aspects

Compression of hydrogen is a well-developed processing technology (Rivard, Trudeau and Zaghib, 2019), with several technical aspects linked to it. The most pronounced are the energy demand, combined with the requirements for material choices. This chapter presents several technical aspects related to compressed hydrogen, for further use in the concept analysis and in the LCA.

2.2.1 Compression

Hydrogen is compressed through a reciprocating or a diaphragm compressor and compressors adjusted for hydrogen compression are offered by a range of commercial actors[4]. Compression work is often simplified as either adiabatic or isothermal and hydrogen compression through reciprocating compressors is a mix. Hydrogen is compressed adiabatically stepwise and cooling is added between the steps to limit temperature increase, as isothermal compression is less energy demanding than adiabatic compression (Cengel, Boles and Kanoglu, 2020). The processes are characterized by not exchanging heat with the environment (adiabatic) and

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[4] A selection is found by the author; (Howden, no date; Mehrer, no date; Neumann & Esser, no date).

constant temperature (isothermal) and the stepwise gas compression requires energy between the adiabatic and isothermal processes (Makridis, 2016). By relations from the second law of thermodynamics, it can be shown that for constant entropy and the assumption of an ideal gas, the following isentropic relation can be shown (Cengel, Boles and Kanoglu, 2020):

$$\frac{T_2}{T_1} = (\frac{P_2}{P_1})^{\frac{\gamma-1}{\gamma}} \qquad [2]$$

where T_2 is the end temperature of the system after compression, T_1 is the initial temperature, P_2 is the pressure that is to be achieved by pressurization, P_1 is the initial gas temperature and γ is the adiabatic index, defined by the degrees of freedom of the compressed gas. Furthermore, it can be shown that the work for an adiabatic process can be expressed by equation [3], where $q_{rev} = 0$ due to the assumption of no heat exchange with the environment (Helbæk and Kjelstrup, 2006):

$$\Delta U = w_{rev} + q_{rev} = w_{rev} = C_v \Delta T \qquad [3]$$

Where ΔU is the entropy, w_{rev} is the compression work, q_{rev} is the heat, C_V is the heat capacity at constant volume and C_p is the specific heat capacity at constant pressure. The latter are related via specific heat ratio (adiabatic index γ) and it can be shown that:

$$\gamma = \frac{C_p}{C_v} \qquad [4]$$

$$C_p - C_v = R \qquad [5]$$

By combining the relations as showed in equation [3], [4] and [5], it can be shown that:

$$\Delta U = w_{rev} + q_{rev} = w_{rev} = C_v \Delta T \rightarrow \frac{nR}{\gamma - 1} \Delta T \rightarrow \frac{nR}{\gamma - 1} T_1 \left(\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \qquad [6]$$

The adiabatic compression work as expressed by equation [6] is plotted in Figure 2-1:

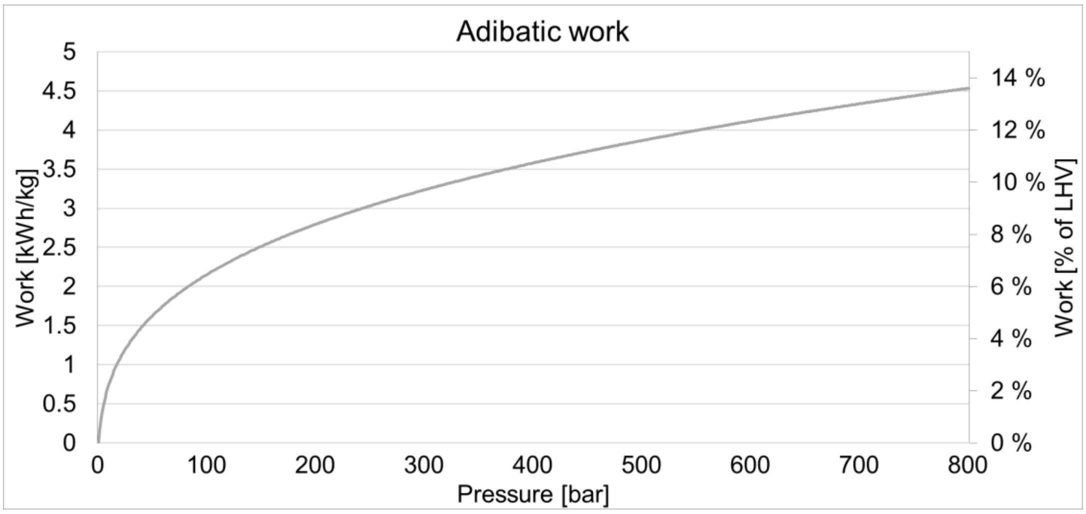

Figure 2-1 - Adiabatic compression work of hydrogen.

Adiabatic compression depends on ideal condition and is therefore only an approximation. Hydrogen compression work is generally characterized with high uncertainty, as limited real energy data is available and theoretical estimations are based on idealized processes. The DOE Fuel Cell Program have stated that measured data from a hydrogen refueling station has energy consumption between 1.7 kWh/kg (350 bars) and 6.4 kWh/kg (750 bars) for compression and the average energy consumption for these refueling stations is 3.1 kWh/kg (Gardiner, 2009).

Hydrogen has compressibility factor above 1 for ambient pressure and temperature, contrary to the behavior of many other gases. The compressibility factor for hydrogen is determined experimentally and can be calculated as follows (Suzuki, 2009):

$$Z = 1 + p(A + BT^{-1} + CT^{-2} + DT^{-3} + ET^{-4}) \quad [7]$$

Where p is the pressure [MPa], T is temperature [K], A = $4.93482 * 10^{-5}$, B = 2.04036, C = $8.15334 * 10$, D = $-65561 * 10^{4}$ and $E = 4.56516 * 10^{6}$. By the calculation of the compressibility factor, the density is calculated by the ideal gas law including compressibility (Makridis, 2016):

$$PV = nRTZ \quad [8]$$

There are several possible options for equation of state for hydrogen, but for the purposes of this thesis, the procedure introduced in this chapter is assumed.

2.2.2 Hydrogen embrittlement

Material compatibility for hydrogen is challenging due to its diffusive features. In this chapter, an introduction to hydrogen embrittlement and the challenges related to it is presented, relevant for both the concept analysis and the LCA.

Hydrogen embrittlement is a challenge the oil and gas (O&G)-sector has faced for decades, as hydrogen easily permeate through materials and make metals brittle. Hydrogen can be present in materials due to the following reasons (Tiwari *et al.*, 2000):

1) Free hydrogen atoms can be released through electrochemical processes (corrosion processes)
2) Hydrogen can be present from the production of the material
3) Free hydrogen atoms can occur due to hydrogen absorption on the surface area, especially in water.

Due to the knowledge of hydrogen embrittlement in the O&G-sector, there exists a range of standards in the sector for material choices. The practices defined in these standards are related to hydrogen released in the processes described from (1-3) and not based on pure hydrogen transport. However, both American Society of Mechanical Engineering (ASME) and European International Gas Association (EIGA) are offering standards specialized on hydrogen transport onshore (ASME, 2011; Eiga, 2014). Existing standards for the O&G-sector and on hydrogen transport, are today the best options for material planning related to hydrogen infrastructure offshore. For hydrogen embrittlement to occur, the following criteria's must be fulfilled (Pfeiffer, 2021):

1) The material has an infrastructure which is susceptible to hydrogen embrittlement (this is the case for steels, limited for polymers)
2) A high hydrogen concentration must be present
3) The material must be exposed to stress

Metals have different atomic structure that impacts the susceptibleness to hydrogen embrittlement. Ferritic steels have BCC (Body Centered Cube), a structure where one atom is placed in the middle of a cubic structure. Such structure allows more space for hydrogen occupation than the structure of austenitic steels which has FCC (Face Centered Cube), where the atoms are placed on the sides of the structure (Callister and Rethwisch, 2015). More space allows for permeated hydrogen atoms to cluster in the structure, which may lead to hydrogen embrittlement.

Standards ASME B31.12 and the EIGA IGC Doc 121/14 recommend carbon steel alloys API 5L X42 and X52 for hydrogen piping, which are related with a specified minimum yield strength (SMYS) of 42 000 (290 MPa) and 52 000 psi (360 MPa). The stress on the piping is generally kept lower than 30-50% of the material SMYS due to the embrittlement susceptibility and as of 2011 hydrogen had been operated at pressure up to 140 bar (ASME, 2011). High strength steel that exceeds the strength recommendations from ASME B31.12 are more susceptible to hydrogen embrittlement as they are less ductile and this can be compensated for by increasing the piping wall thickness. In ASME B31.12, an overview of compatible materials with hydrogen is presented in Table A-2.1, which displays how aluminum, austenitic steels, carbon steels, copper, low-alloyed steels and titanium and titanium alloys are assumed applicable for hydrogen transport (some of them with precautions) (ASME, 2011).

Several ongoing projects investigate whether higher strength steels than the recommendation limited to 52 000 psi SMYS can be accepted for hydrogen transport. The project "H21 North of England" seeks to repurpose old NG pipelines for hydrogen transport and has several ongoing projects with testing of hydrogen distribution (H21 North of England, 2021). DNV and Carbon Limits have made an extensive report of the possible reuse of North Sea infrastructure for hydrogen transport, where data from 65 pipeline operators has been collected, covering real data from 16 300 km of pipelines offshore and 58 000 km in total (Cauchois *et al.*, 2021). The report maps the material selection for the assessed piping and presents that the majority of installed offshore pipelines are API 5L X65 steel. The project concluded that minimum 2-25% of the existing infrastructure will be directly reusable for hydrogen transport and that 100% of the pipelines will be reusable with modifications. It is also stated in literature that the current restrictions on yield strength is conservative and that hydrogen safely can be transported in pipelines up to 70 000 psi when design pressure is limited to 20.7 MPa (207 bars) (Amaro *et al.*, 2018).

2.2.3 Pipeline transport of compressed hydrogen

The 70 million tons of hydrogen yearly produced are predominantly used *in situ*, transported short distances by pipelines or stored and transported by pressure vessels (IEA, 2019b). Thus, hydrogen pipelines are mature technology for transportation of compressed hydrogen shorter distances and around 5000 km of hydrogen pipeline exists in the world, compared to 3 million km NG pipelines (IEA, 2019b). Even though thousands of kilometers hydrogen pipelines exist onshore, none is yet to exist in an offshore environment (as of 2022). Repurposing NG pipelines for hydrogen transport is a subject of interest all over the world and several projects have recently been investigating this scenario. The EU-project NaturalHy ran for several years and aimed identifying whether hydrogen could be blended into the NG network safely (NaturalHy, 2009). The H21 North of England is a comprehensive project which is investigates whether NG pipelines can be repurposed for 100% hydrogen transport (H21 North of England, 2021). There are several challenges related to repurposing, chief amongst them the material challenges as presented in Chapter 2.2.2. Another challenge is hydrogen's low volumetric density, which will favor hydrogen transport under higher pressure than NG. ASME B31.12 (2011) states that high flow velocities should be avoided and that the flow velocity should be limited below the erosional velocity (Equation [9]):

$$Erosional\ velocity: u_e = \frac{100}{\sqrt{\frac{29GP}{ZRT}}} \qquad [9]$$

where P is the pressure [psia], Z is the compressibility factor, R is the ideal gas constant [ft^3*psia*°R^{-1}], T is the temperature [°R] and G is the specific gravity. The erosional velocity is a measure of the maximum velocity where no erosion-corrosion is expected to occur (Sani *et al.*, 2019). For a pressure of 200 bar and a hydrogen temperature of 4 ºC, this yields an erosional velocity of ~29 m/s. American Petroleum Institute (API) indicates by the standard RP 14E (Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems), that single-phase flow should be aware of noise problems related with high flow rate and that exceeding ~18 m/s may cause noise problems, but this is not defined as an absolute limit (API, 1991). The European standard for hydrogen transport does not suggest any specific limitation for velocity in pipelines, but points out the higher speed of sound of hydrogen compared to other gases as a potential problem, especially related to valves (Eiga, 2014).

High pressure transport pipelines could be limited to smaller pipeline diameter than traditional natural gas pipelines, due to low allowable material utilization (limited to 30-50% of SMYS) and the increased requirements for wall thickness when using carbon steel-types. For reel-laying of high-pressure transport pipelines, this leads to an apparent limitation of 12" diameter, as there both are challenges related to the reeling of pipelines with larger diameters and limitations on the access to pipelines with the necessary wall thickness (meeting with Svein Kjenner at TechnipFMC, 27.01.2022). The wall thickness can be calculated defined by equation [10] (ASME, 2011):

$$P = \frac{2St}{D} FETH_f \qquad [10]$$

where P is the design pressure [psig], S is the specified minimum yield strength [psig], t is the wall thickness [inch], D is the outer diameter of the pipeline [inch], E is the longitudinal joint factor, F is the design factor, T is the temperature derating factor and H_f is the material performance factor. The diffusive features of hydrogen increase the requirements for a hydrogen transportation pipeline. Based on the requirements in ASME B31.12, it is expected that hydrogen transportation pipelines must have thicker walls than natural gas pipelines and thereby smaller diameters.

Pressure drop specific for hydrogen transport can be calculated by equations based on natural gas. Pressure drop equations can be deduced from Bernoulli's law. Pressure drop for natural gas transport can be calculated by "General Pressure Drop Equation" (API, 1991) (equation [11]):

$$p_1^2 - p_2^2 = \frac{25.2\, S\, Q_n\, Z\, T_1\, f\, L}{d^5} \qquad [11]$$

where p_1 [psia] is the upstream pressure, p_2 [psia] is the downstream pressure, S is the specific gravity at standard conditions, Q_n [MMscfd] is the flow rate at standard conditions, Z is the compressibility factor, T_1 is the flowing temperature [°R], f is the Moody factor, D is the pipeline diameter [inch] and L is the length of the pipelines [feet]. No specific calculation for pressure drop on hydrogen is found, but as equation [11] consider the compressibility and the specific gravity factor, it is assumed to yield a valid approximation of pressure drop. The pressure drop over an orifice can be calculated by equation [12] (Bentley, 2005):

$$Q = CE\mathrm{eA}\sqrt{2\rho(\mathrm{P}_1 - P_2)} \qquad [12]$$

where Q is the flow rate [m^3/s], C is the discharge coefficient, E is the velocity of approach factor given by: $\frac{1}{\sqrt{1-\beta^4}}$, β is the flowmeter-pipe diameter ratio $\frac{d}{D}$, A is the flowmeter cross-sectional area [m^2], $e = 1 - (0.41 + 0.35 * \beta^4)\left(\frac{1}{\gamma}\right)\left(\frac{\Delta P}{P_1}\right)$, ρ is the density [$kg/m^3$], γ is the specific heat ratio, P_1 is the inlet pressure [Pa] and P_2 is the outlet pressure [Pa].

The report by Carbon Limits and DNV states that the maximum allowable operating pressure (MAOP) median of the assessed offshore natural gas network by is 160 bars (Cauchois *et al.*, 2021). Natural gas (NG) has higher energy density than hydrogen and it is beneficial with higher operating pressure or flow rate for hydrogen to maintain an acceptable energy transport. The pressure drop is proportional with the specific gravity and compressibility (see Equation [11]) and the compressibility is slightly higher for hydrogen compared to NG, but the specific gravity is close to 1/10. Hence, the expected pressure drop from hydrogen transport with the same volumetric flow rate can be estimated as roughly 1/10 of the pressure drop of NG. However, the volumetric energy density at same pressure is approximately 1/3 for hydrogen compared to NG, meaning that the volumetric flow rate must be increased three times to yield the same energy transport. This implies that the pressure drop of hydrogen and NG in pipelines for the same energy transport will be approximately the same (Haeseldonckx and D'haeseleer, 2007). If the volumetric rate is the same, then both the energy transport and the pressure drop is significantly lower for hydrogen than for NG.

2.2.4 State-of-the-art, compressed hydrogen storage

Compressed hydrogen storage tanks are designed to withstand a pressure between 100-700 bars, depending on usage. A lot of requirements are raised related to the mechanical properties for hydrogen storage, as it must withstand high pressure and a molecule with high permeation rate. There are several types of pressure vessels that are designed to meet the requirements that for a compressed hydrogen tank and the tanks consists mainly of either steel, composite, or a combination of the two. The five categories of hydrogen tanks are given in Table 2-2:

Table 2-2- Categories of hydrogen tanks, inspired by (Rivard, Trudeau and Zaghib, 2019).

Type	**Material** (Barthélémy, 2012)	**Gravimetric energy density [%]** (Rivard, Trudeau and Zaghib, 2019)	**Typical price [euro/kgH_2]**[5] (Rivard, Trudeau and Zaghib, 2019)
I	Steel/aluminum/other metal vessel	1.7	73
II	Metal lining with partly composite wrapping (main body of cylinder)	2.1	76
III	Metal lining fully wrapped with composite	4.1	616
IV	Polymer lining wrapped with composite	5.7	557
V	Composite	-	-

The tank types are used for different purposes and type I or type II type are normally preferred due to cost competitiveness for stationary appliances. For mobile appliances however, the three latter categories (III, IV and V) are generally the preferred due to weight considerations (Barthélémy, 2012). Established tank manufacturers, (e.g. Hexagon, UMOE, MaHyTec and Steelhead Composites) offers type III or type IV pressure vessels, whilst no manufacturer for type V pressure vessel was found. A carbon fiber tank increase the lifecycle GHG emissions in a fuel cell electric vehicle (Miotti, Hofer and Bauer, 2017; Benitez *et al.*, 2021) and is one of the main components of making fuel cell electric vehicles uncompetitive with battery electric vehicles in an environmental perspective (Miotti, Hofer and Bauer, 2017). Cited studies are on relatively small fuel cell systems, but composite vessels may be candidates for large-scale application in the future. The Deep Purple offshore hydrogen storage concept (see Table 1-1) is a large-scale, stationary concept based upon composite pressure vessels. Despite this concept being based on temporary storage which can favor steel, steel is related with significant corrosion challenges in an offshore environment and composite is therefore expected to increased long lifetime (Svein Kjenner at Technip FMC (27.01.2022).

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[5] Prices given in dollar, 0.88 euro/$ assumed (as of 24.01.2022).

2.3 Underground storage of compressed hydrogen

Compressed hydrogen requires a storage medium, which can withstand the pressure and the diffusivity. In the previous chapter, several technical aspects and state-of-the-art related to hydrogen compression was introduced. This chapter presents UHS, which is pointed out in literature as a crucial storage solution for large-scale and temporary storage of compressed hydrogen (Stone *et al.*, 2009; Amid, Mignard and Wilkinson, 2016; Tarkowski, 2019). Also energy agencies suggests geological storage as the best option for large-scale and long-term storage of hydrogen (IEA, 2019b; IRENA, 2019). In a future energy system with increasing fluctuations in power generation, UHS may be a key enabler to store energy. Proposed solutions for longer-terms storage of compressed hydrogen are presented.

2.3.1 Salt cavern compressed hydrogen storage

The largest hydrogen storage solutions that exist today, are test facilities in salt caverns in UK and Texas (Tarkowski, 2019). Geological gas storage is not a new concept and both CO_2 and natural gas have been stored in depleted gas fields, salt caverns and aquifers (Amid, Mignard and Wilkinson, 2016; Pfeiffer, Beyer and Bauer, 2017; Tarkowski, 2019). The thought of storing hydrogen in the same formations has therefore been investigated for several years, with special focus on salt cavern underground storage. In Teesside, UK, hydrogen has been stored in three different salt caverns since 1972 for industrial purposes. Furthermore, hydrogen has been stored in salt caverns in the US, one commissioned in 1983 and one in 2007 (Tarkowski, 2019). The caverns characteristics are obtained from (Tarkowski, 2019) and is reproduced in Table 2-3:

Table 2-3 - Proved salt caverns for hydrogen storage (Tarkowski, 2019).

	Clemens Dome (US)	**Moss Bluff (US)**	**Teesside (UK)**
Operator	Conoco Phillips	Praxair	Sabic Petroleum
Commission year	1983	2007	~1972
Depth	930	>822	350
Volume [m^3]	580 000	566 000	3x70 000
Pressure range [bar]	70-135	55-152	~45
Possible working gas capacity [MMkg]	2.56	3.72	0.83

Energy storage in salt caverns is a mature technology but remains to be implemented as an integrated part of the energy system. Preparation of a salt caverns include injecting water that mix with the salt and produce brine, which needs to be removed from the cavern. In addition to the physical preparation of the well, the considered well must be thoroughly mapped. Salt caverns are not well suited for seasonal storage for natural gas and is better suited as a peak-shaving storage medium (Mokhatab and Mak, 2019).

2.3.2 Underground porous hydrogen storage (UHS)

UHS in depleted O&G reservoirs is a proposed hydrogen storage technology, with less maturity level compared to salt cavern storage. The possible usage of depleted O&G-fields have been pointed out by a range of studies (Reuß *et al.*, 2017; Mouli-Castillo, Heinemann and Edlmann, 2021; Song *et al.*, 2021), with Underground Sun Storage in Austria as the first pilot project (publicly available) (Pestl, 2021). UHS in depleted hydrocarbon reservoirs is further referred to as porous UHS. One of few studies on the subject is a simulation study covering the technical feasibility of using a depleted hydrocarbon reservoir for hydrogen storage, focusing on storage volume, possible recovery rate and injection and withdrawal scenarios (Lysyy, *et.al*, 2021). The study is site-specific to the Norne-field in the North Sea and simulates a 4-year period with annual injection and withdrawal periods. The study investigating 4 different hydrogen injection scenarios:

a) 100% hydrogen injection
b) Mixing of hydrogen and formation gas in the reservoir, with formation gas injection prior to hydrogen injection to obtain the following pressure (formation gas as cushion gas rather than hydrogen):
    1. 220 bars
    2. 200 bars
    3. 160 bars
c) 70/30 mix of formation gas/hydrogen gas during injection (pre-mixed)
d) Other well, with vertical profile.

The results for scenario a) in a gas layer show that ~400 million Sm^3 of hydrogen can be delivered in withdrawal periods, with a total of 4.78 billion Sm^3 recovered over a 4-year period. When injecting hydrogen as a cushion gas, a large fraction was stored “permanently” in the first initialization (~85%), but this amount was largely recovered in a prolonged withdrawal period at final recovery. The overall recovery for storage case a) where hydrogen is injected as cushion gas, was 71% from the gas, oil and water zone. For scenario b)1., where formation gas is used as cushion gas, the overall withdrawal recovery rate was 94% in the gas zone and 85% in all zones, whilst a lower total volume is recovered over the period due to smaller initial hydrogen injection. The recovery ratios were lower in oil and water layers for all scenarios and the results demonstrate that storage in gas zone is the favorable solution. For case d), the overall recovery was limited to 58%, indicating that the well profile has significant impact on the overall withdrawal efficiency. The article is introduced with stating that they suspect the economic viability of an offshore hydrogen production to be improved with the use of existing offshore infrastructure.

Offshore porous UHS is investigated as an option to achieve contribute to a net-zero society, covering both advantages and challenges (Hassanpouryouzband *et al.*, 2021). The study highlights technical challenges outside the scope of this thesis, such as weakening of cap rock (impermeable layer), viscous fingering and microbiological growth. These challenges must be solved to realize porous UHS in depleted fields. It is pointed out how safety challenges, especially linked to leakage to ground water, is eliminated in an offshore storage. Furthermore, it is noted how it can be less socially controversial and relevant for this thesis – how environmental and economical expenses are reduced, using existing infrastructure from the O&G-sector (Hassanpouryouzband *et. al*, 2021).

Hydrogen storage in an O&G-field (a sandstone formation) is also investigated at an onshore storage reservoir in Northern Germany (Pfeiffer, Beyer and Bauer, 2017). This formation is shallower than most offshore environments (~500 m), but the Rhaetian sandstone formation which is investigated, makes the study relevant for offshore UHS. The study highlights how the heterogeneity is highly affecting the results of the injection and withdrawals and how the heterogeneity is making the different cycles unpredictable, as there will be different behavior from each cycle. This a finding that emphasizes the advantage of depleted O&G-fields, as one has thorough assessments of reservoirs done prior to hydrocarbon recovery. This can contribute to vital understanding of the heterogeneity and hence how fluids will act in the reservoir. The study investigates N_2 as cushion gas rather than H_2 and formation gas as Lysyy *et.al* (2021) did. N_2 yields an advantage in working as a possible barrier to formation water and thereby can hinder mixing with microbiological bacteria's, however N_2 can reduce the purity of the produced hydrogen, causing necessity for the hydrogen to be cleansed before usage in a fuel cell (Pfeiffer, Beyer and Bauer, 2017).

The Rough Gas Storage Facility in the Northern Sea, an partially depleted gas reservoir offshore outside the UK, is investigated by Amid, Mignard and Wilkinson, (2016). This study uncovers no technical barriers for hydrogen storage in a depleted gas reservoir, however, it aims at the possible biological reaction issues and suggests that this should be carefully examined. The study also aims at the same findings as Mokhatab and Mak (2019), that salt caverns have limited storage capacity for seasonal storage and that reservoirs with the storage capacity corresponding to depleted fields are more likely to yield an option for seasonal, large-scale storage. Similar to Hassanpouryouzband *et al.*, (2021), Amid, Mignard and Wilkinson, (2016) aims at the public opinion to possibly favor an offshore facility compared to an onshore facility. They expect losses from dissolution of hydrogen, as well as diffusion through the reservoir, to be limited to 0.1%. The overall withdrawal efficiency is not given.

The presented selection of studies on hydrogen storage in depleted O&G-fields (Amid, Mignard and Wilkinson, 2016; Pfeiffer, Beyer and Bauer, 2017; Lysyy *et al.*, 2021) are summarized in Table 2-4. It can be observed that the reservoirs assessed in the selection of studies have very varying conditions. Not all data is found on all the parameters, but the key characterization data that is found is presented in the table.

Table 2-4 - Reservoir characteristics of a selection of reservoir analyzed in different simulation studies, Norne-field;(Lysyy, et. al 2021), a fictive north German basin; (Pfeiffer, Beyer and Bauer, 2017) and Rough Gas storage facility; (Amid, Mignard and Wilkinson, 2016) .

	Norne-field	Fictive north German basin	Rough gas storage facility
Formation area [km^2]	27	~30	22
Well depth [m]	3000	~500	2743
Reservoir pressure (prior to injection) [bar]	130	40-55	-
Max. Pressure [bar]*)	270	30-65	313
Injection pressure [bar]	-	-	50-100
Temperature [ºC]		25	75
Porosity [%]	25-30	~5	20
Permeability [mD]	20-2500	-	75

*) *Equaling the initial bottom hole pressure prior to hydrocarbon recovery*

2.3.3 The North Sea

The North Sea is unique in a European context, containing around 6000 O&G-wells (Oljedirektoratet, 2017) and several areas with salt caverns. Especially the Southern North Sea is rich both in O&G-wells as well as salt formations (Caglayan *et al.*, 2020). The Southern North Sea is located over the reservoir formations Sandnes and Bryne, where it is located both O&G-fields and saline aquifers. According to the Norwegian Oil Ministry, the average depth of the saline aquifers in the Sandnes and Bryne formation is 1700 m (Halland *et al.*, u.d). Both reservoir zones are found in the Jurassic zone and the O&G-reservoirs are typically located at below 1500 meters depth, except in some elevated zones. The temperature gradient in reservoirs is highly dependent on location and no information about the specific temperature gradient of the Bryne and Sandnes formation were found. However, it is given that an average geothermal gradient is 25-30 ºC/km (Goldstein *et al.*, 2011).

2.4 Liquid organic hydrogen carriers

A general description about liquid organic hydrogen carriers (LOHC) and how they can store hydrogen is provided in this chapter. Theory relevant for determining the results is presented, as well more general description about LOHC's and how they work for completeness. The two chosen LOHC's for this thesis and how they can be stored will be described more in detail and a summary is provided.

2.4.1 General about liquid organic hydrogen carriers

LOHC's is an alternative way of storing hydrogen, which is yet to be fully mature as a hydrogen carrier alternative. Research has been done on LOHC for the last decades, starting in the early 1980's (Sekine and Higo, 2021). This has led to several commercial companies offering LOHC storage solutions and the world's largest LOHC plant with a planned capacity of storing 1800 tons of hydrogen yearly are currently under construction (Hydrogenious, 2021).[6] This plant is under development by Hydrogenious, a European actor who offers LOHC systems and has successfully deployed a pilot on their small LOHC container system related with the EU-funded project HYSTOC (HYSTOC, 2018). Another commercial actor within LOHC storage solutions is the Japanese company Chiyoda, which is involved in several projects where the technology

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[6] As of 2022.

is planned demonstrated (Kurosaki, 2018). A pilot project was successfully demonstrated in 2013 and the project is now on the commercialization step (Chiyoda Corporation, no date).

LOHC's are unsaturated hydrocarbons, mainly consisting of carbon and hydrogen, which has branches in the structure for hydrogen to bond into (Markiewicz *et al.*, 2015). When hydrogen is bonded into these structures, it is called hydrogenation and the molecule is thereby changing to a hydrogen-rich structure. It cannot be used directly as a fuel and the hydrogen needs to be released from the chemical bonding to be utilized, a process called dehydrogenation. A hydrogenated LOHC is henceforth referred to as hydrogenated LOHC or LOHC+, whilst a dehydrogenated LOHC is referred to as a hydrogen-lean LOHC or LOHC-. LOHC's are related with significant advantages; the complex characteristics of hydrogen is decreased when bonded in a LOHC and all different infrastructure which today carry liquid fuels (as tankers, tanks and pipelines) can therefore carry hydrogen in the form of LOHC (Markiewicz *et al.*, 2015). LOHC can be stored at ambient temperature and pressure, counter to compressed and liquid hydrogen, as hydrogen follows the LOCH characteristics when bonded. LOHC thus reduces the need for infrastructure development compared to liquid and compressed hydrogen. When bonded in LOCH the volumetric energy density of hydrogen is increased, whilst the gravimetric energy density is reduced, which is a challenge in LOHC solutions.

Hydrogeneration and dehydrogenation are chemical processes, respectively exothermic and endothermic reactions which are slightly different related to the choice of hydrogen carrier (Niermann *et al.*, 2019). Fixed bed reactors are typically used in these processes (Kwak *et al.*, 2021). This type of reactor which is commonly known for having the catalysts statically on a "bed" and the fluid is run through the catalysts bed (Hafeez *et al.*, 2018). In Figure 2-2, the LOHC processing scheme with typical reaction conditions is presented.

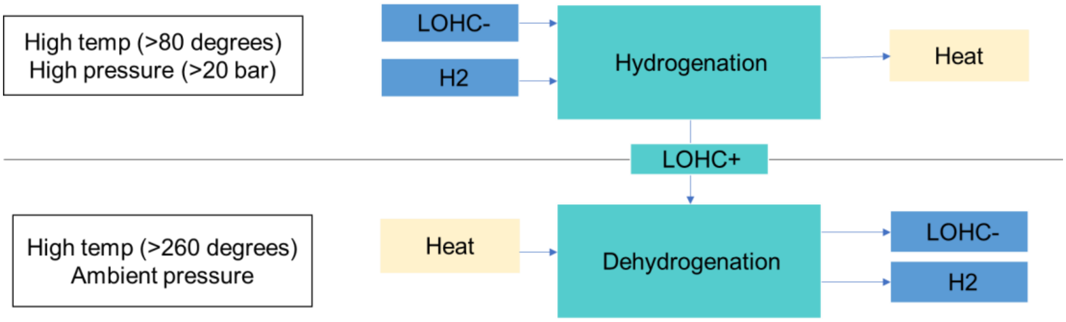

Figure 2-2 - Illustration of the LOHC processing scheme.

There are several chemicals which can serve as useful hydrogen carriers and Niermann *et al.*, (2019) provides information about a range of different LOHC and which carriers that are eliminated due to different reasons, such as toxicity, required process conditions, selectivity level, de-hydrogeneration rate, safety and energy demand. The two carriers' toluene and dibenzyltoluene are recommended as LOHC for further investigation in the study. Toluene is the chosen LOHC by Chiyoda, whilst dibenzyltoluene (DBT) is the chosen carrier for the HYSTOC project by Hydrogenious (HYSTOC, 2018). Hydrogenious is planning future projects based on Benzyltoluene (BT) as LOHC (Oestensjoe, 2021), as BT has preferrable viscosity features over DBT, which advantages BT especially in cold environments (Jorschick *et al.*, 2020). As toluene is the preferred LOHC by Chiyoda and BT is preferred by Hydrogenious, toluene/MCH and BT/perhydro benzyltoluene (P-BT) are further assessed in this thesis. Based on the safety data sheets of BT and toluene, they appear to be related with comparable challenges, which is related with toxicity to aquatic life and health hazard for humans by exposure. In addition, toluene is labelled as highly flammable, opposite to BT. Both substances are therefore believed to have complex features related to the physical handling.

2.4.2 Toluene/Methylcyclohexane

In this chapter, a more detailed description about the proposed LOHC toluene is given. Toluene consists of one benzene-ring linked to one methyl group and has the chemical formula $C_6H_5CH_3$ (National Center for Biotechnology Information, 2022c). One carbon-atom share in total four electrons with neighboring carbon-atoms and one hydrogen-atom. The carbon atoms, which in un-saturated form share total four electrons with neighboring carbon-atoms and one hydrogen-atom, has potential rather share two hydrogen-bindings. The molecule has space for six hydrogen bindings and if hydrogen is bonded to the molecule, toluene is changed into a methylcyclohexane (MCH) molecule (National Center for Biotechnology Information, 2022b). This is illustrated in Figure 2-3:

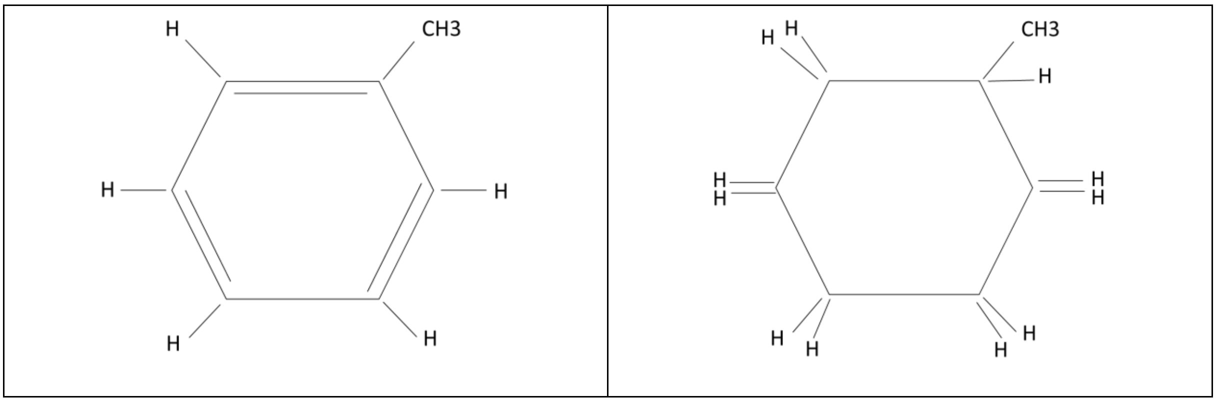

Figure 2-3 – Toluene (left) and methylcyclohexane (right).

The efficient storage of hydrogen in MCH is reported as 6.2 wt.% (Niermann *et al.*, 2019). Toluene is a by-product of oil refining and is therefore relatively easily available and commercial product, with an annual production of around 22 Mt (IEA, 2019b). Presented market prices range from 1-3 NOK2021/kg (IEA, 2019b; Niermann *et al.*, 2019). The hydrogenation/dehydrogenation reactions are illustrated in equation [13] and [14]:

Hydrogenation, equation [13]	Dehydrogenation, equation [14]
$C_6H_5CH_3 + 3H_2 \rightarrow C_6H_{11}CH_3 \;\; \Delta H^{º} = -205\,\frac{\mathrm{kJ}}{\mathrm{mol}}$	$C_6H_{11}CH_3 \rightarrow \; 6H_5CH_3 + 3H_2 \;\; \Delta H^{º} = 205\,\frac{\mathrm{kJ}}{\mathrm{mol}}$

The required energy for dehydrogenation is ~68 kJ/molH_2 (Niermann *et al.*, 2019; Rao and Yoon, 2020), 28% of the energy content of hydrogen (LHV), meaning that the dehydrogenation process is an energy demanding process. Hydrogenious estimates an energy demand of 12 kWh/kgH_2 for dehydrogenation, above the estimated energy demand solely based on reaction enthalpies as presented in this chapter (Hydrogenious, 2018). Lower energy demands of approximately ~1% of the energy content in hydrogen (LHV) is presented for hydrogenation (Teichmann, Arlt and Wasserscheid, 2012), where the energy is assumed to be needed for maintaining the activation energy and pressure, as well as cooling of the system. This means that the roundtrip efficiency of hydrogenation and dehydrogenation of LOHC (MHC) is approximately 70%.

Hydrogenation process typically requires pressurized conditions and elevated temperature, whilst the dehydrogenation requires significantly elevated temperature (minimum 250 degrees) and can be performed at ambient pressure (see Figure 2-2). MCH hydrogenation specifically requires a minimum of 30 bar and 120ºC and is typically performed using a platinum catalyst. Dehydrogenation requires minimum 250ºC (and can be improved by increased temperature) and is typically catalyzed by platinum (Pt) or nickel (Ni) supported on aluminum oxide (Al_2O_3) (Niermann *et al.*, 2019) (see Table 2-5).

Table 2-5 - Summary of main features of hydrogenation and dehydrogenation of toluene. Table is based on Niermann et.al, (2019).

	Temperature [C]	**Pressure [bar]**	**Suggested catalyst**	**Degree of storage/release**
Hydrogenation	>120	30	Pt/Zeolite	99%
Dehydrogenation	>350	Ambient	Pt/Al_2O_3, Ni/Al_2O_3	92%

Nickel as a catalyst for dehydrogenation in general provides low conversion rates and low toluene selectivity, but can achieve acceptable toluene selectivity when modified with zinc (Zn), tin (Sn) and indium (In) (Al-Shaikhali *et al.*, 2015). Generally, heterogeneous catalysts based on noble metals as Rh, Ru, Pd and Pt are considered as particularly effective catalyst materials for hydrogenation of organic hydrocarbons (Aakko-Saksa *et al.*, 2018).

2.4.3 Benzyltoluene/Perhydro Benzyltoluene

DBT is a proposed LOHC, but have challenges related to its high increase of viscosity with reduction of temperature, which can propose troubles especially in a North-European climate in terms of pumpability (Jorschick *et al.*, 2020). BT is an LOHC option which does not get a strongly increased viscosity with reduced temperature as DBT, which can contribute to favor BT or BT/DBT mixtures (Jorschick *et al.*, 2020). As the molecule name implies, it consists of one toluene molecule, with has one benzyl group added to it (see Figure 2-4) (National Center for Biotechnology Information, 2022a). In the dehydrogenated form, the molecule consists of 14 hydrogen atoms and 14 carbon atoms, while the hydrogenated molecule consists of 26 hydrogen atoms – meaning that 12 hydrogen atoms are added during the hydrogenation (see Figure 2-4):

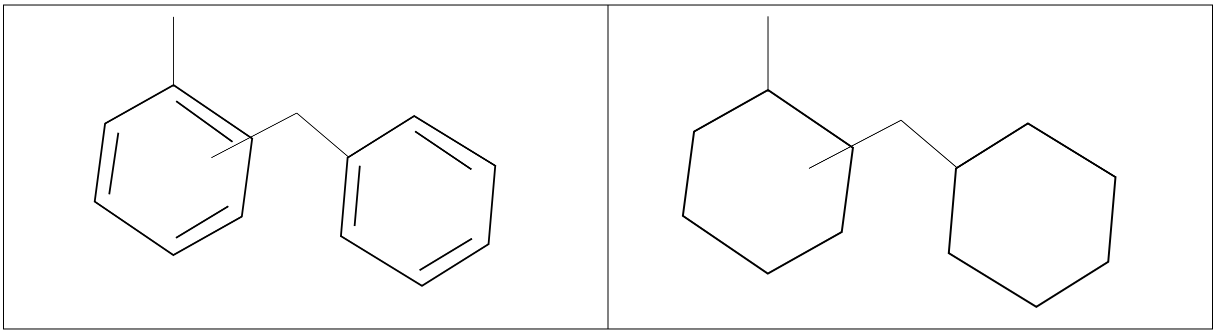

Figure 2-4 – Benzyltoluene (left) and perhydro benzyltoluene (right).

BT can be produced by different chemical processes with toluene as feedstock, in processes requiring intermediate heat (~100 ºC) and without noble catalysts (Barton *et al.*, 2003). It is a commercially available product for use as a heat transfer fluid, better known as Marlotherm LH (Müller *et al.*, 2015). Marlotherm SH (DBT) and Marlotherm LH (BT) are in the same price range and the price for Marlotherm LH is given as 30-50 NOK/kg by Siemens Energy (Grønt Skipsfartsprogram, 2022). 63.5 kJ/mol H_2 is reported as reaction enthalpy for the reaction (Müller *et al.*, 2015). The reaction enthalpy is illustrated in equation [15] and [16]:

Hydrogenation, equation [15]	Dehydrogenation, equation [16]
$C_{14}H_{14}(l) + 6H_2(g) \rightarrow C_{14}H_{26}(l)\ \ \Delta H^{\circ} = -381.2\frac{\mathrm{kJ}}{\mathrm{mol}}$	$C_{14}H_{26}(l) \rightarrow C_{14}H_{14}(l) + 6H_2(g) \rightarrow \Delta H^{\circ} = 381.2\frac{\mathrm{kJ}}{\mathrm{mol}}$

Ru/Al_2O_3 is found to be a well-working catalyst for BT hydrogenation, for conditions of 150ºC and hydrogen pressure of 50 bars and yields a 99% hydrogenation degree (Brückner *et al.*, 2014). They have furthermore concluded that platinum catalyst supported on carbon is the optimal dehydrogenation catalyst (Pt/C), (reaction conditions at 270ºC and ambient pressure), which yields a dehydrogenation degree of 96% (see Table 2-6). Platinum based catalyst supported on aluminum oxide is suggested both for hydrogenation and dehydrogenation of BT by Jorschick *et al.*, (2020), with estimations of full hydrogenation and ~ 99% dehydrogenation at sufficient temperature for BT. Corresponding efficiencies is estimated for DBT, with respectively 97% for hydrogenation and 99% for dehydrogenation (Reuß *et al.*, 2017).

Table 2-6 - Summary of features of hydrogenation and dehydrogenation of BT.

	Temperature [C]	Pressure [bar]	Suggested catalyst	Degree of storage/release
Hydrogenation				
(Brückner et al., 2014)	150	50	Ru/Al_2O_3	99%
(Jorschick et al., 2020)	220	30	Pt/ Al_2O_3	100%
Dehydrogenation				
(Brückner et al., 2014)	270	Ambient	Pt/C	96%
(Jorschick et al., 2020)	260	Ambient	Pt/ Al_2O_3	99%

Siemens Energy has performed a pilot study for Grønt Skipsfartprogram (Grønt Skipsfartsprogram, 2022) and they state that the BT must be re-processed after 300 cycles. Wulf and Zapp, (2018) assume a lifetime of 1000 cycles for the hydrogenation and the dehydrogenation of DBT expressed as a 0.1% loss in each process, the same assumption as Hurskainen and Ihonen, (2020) has obtained from Teichmann, Arlt and Wasserscheid, (2012). The assumption is based a comprehensive report made by Argonne National Laboratory that consider 0.1% LOHC degradation (Ahluwalia *et al.*, 2011). Degradation during use is an aspect related with high uncertainty, as LOHC yet is to be implemented commercially. It can also be expected some differences in degradation with different LOCH variants.

2.4.4 Summary of LOHC

In this chapter toluene/MCH and BT/P-BT has been investigated, which are two of the LOHC's that are suggested in commercial projects. Despite the many presented advantages of LOHC, it also has some related disadvantages. Chief amongst them is the low gravimetric energy. For every liter of LOHC that is carried, by a truck or by a shipping vessel, around 6-8% of the content that is carried is meant to be used, while the rest of the content needs transportation back to the hydrogenation plant. Another disadvantage is these processing steps that the carrier is related with, that decrease the roundtrip energy efficiency. Furthermore, hydrogeneration and dehydrogenation requires chemical reaction with catalyst. Catalysts are often based on noble metals and this is no exception for LOHC. Noble entities as platinum are a heavily processed metal with requires significant efforts and materials to produce (Classen *et al.*, 2009). The characteristics of the two LOHC's are summarized in Table 2-7:

Table 2-7 - Summary of characteristics for the presented LOHC's toluene/MCH and BT/P-BT.

	Methylcyclohexane (MCH) (Niermann et al., 2019)	**Perhydro benzyltoluene (P-BT)** (Brückner *et al.*, 2014; Müller *et al.*, 2015; Jorschick *et al.*, 2020)
Density [kg/m^3]	770	870
Liquid temperature range [°C]	-127 - +101	-30 +270
Ignition temperature [°C]	260	-
Hydrogen capacity [%]	6.2	6.2
Toxicit*y*	High (based on SDS)	High (based on SDS)
Availability	Stock available (dehydrogenated, as toluene)	Stock available (dehydrogenated, known as Marlotherm LH)
Catalysts	H: Pt/Zeolite DH: Pt/Al2O3	H: Ru/Al_2O_3, Pt/Al_2O_3 DH: Pt/C, Pt/ Al_2O_3
(De)hydrogenation, energy demand	68 kJ/mol	63.5 kJ/mol

2.5 Choice of storage solutions

There exists a range of different methods to process and store hydrogen (see Figure 1-2). There are challenges related to all the processing and storage options and therefore, assumptions have been made in thesis about which of the options that are considered favorable for large-scale storage in an offshore environment. The chosen processing solutions of this thesis is compressed hydrogen and LOHC. Other processed hydrogen forms, as ammonia, liquid hydrogen and metal hydrides, not are considered. This is due to the following reasons:

- Metal hydrides are by the author considered as a plausible option for stationary uses only, e.g. as a storage solution for industry. This is due to metal hydrides high weight and neither storage on a platform or transportation by maritime vessels seems feasible for a heavy metal storage solution (Fichtner, 2008).
- Liquid hydrogen poses great challenges related to the cryogenic nature. A temperature of -253ºC requires constant cooling in every part of the value chain, from storage tanks to pipelines. Liquid hydrogen is also related with a challenge related to boil-off, where an amount of the produced hydrogen is lost daily, as a fraction of the liquid is vaporizing. No large-scale storage solution that appears feasible for liquid hydrogen in an offshore environment is neither yet to exist.

- Ammonia is toxic and thereby complex to handle, in addition to needing processing either by cooling (-33ºC) or pressurization (10 bars) to become liquid (Hansen, 2020).

Note that the justifications that are listed here, are meant as arguments for why the chosen storage solutions are considered the most favorable and does not imply that any of the other listed storage techniques will not be feasible or favorable in the future. Both ammonia and liquid hydrogen is frequently suggested as future shipping fuels and it is suggested to implement ammonia, liquid hydrogen and possibly other hydrogen carriers in a future analysis. For the analysis performed in this thesis, a boundary had to be made due to time limitations and therefore, the boundary was cut at LOHC and compressed hydrogen.

2.6 Economy of storage solutions

This thesis does not perform any economical estimations. As economy is crucial for every technology development and implementation, this chapter will present a brief economic review of the described storage solutions based on existing literature.

Estimates for salt cavern storage are presented by net present value and payback period due to its assumed technological viability and is concluded to be as marginally profitable with a sales price of 3 €/kgH_2 and profitable at 5 €/kgH_2 for short withdrawal periods (Dinh *et al.*, 2021). The study estimates a linear increase in cost with increasing salt cavern capacity due to increased solution mining and brine disposal, thus short withdrawal periods yields more economic favorable results, in line with study by Mokhatab and Mak (2019). For porous UHS, the opposite findings of Mokhatab and Mak (2019) and Dinh *et al.*, (2020) will likely be the case. A hydrocarbon reservoir is a fixed size and as the preparation process of a reservoir requires the same effort independent of the storage volume, larger storage volumes are assumed to be more favorable. Other literature confirm the findings by Dinh *et al.*, (2020), with an estimated levelized cost of hydrogen stored by porous UHS found to be 4.5 €/kgH_2 (Song *et al.*, 2021).

LOHC is also described as a cost-competitive alternative in literature (Reuß *et al.*, 2017; Wulf and Zapp, 2018) and is presented as an economically reasonable carrier for the storage of large amounts of hydrogen at low charge cycles, especially where cavern storage is not available (Reuß *et al.*, 2017). LOHC is also defined as a cost-competitive alternative by IEA, which points to how the use of existing infrastructure increase the cost-competitiveness of LOHC (IEA, 2019b). The levelized cost of hydrogen for LOHC is estimated to ~7€/kg H_2 by Wulf and Zapp, (2018), slightly higher than for liquid H_2 (6.8 €/kg H_2) when green hydrogen is used as a heating source for dehydrogenation of LOHC. The estimations are lower (6€/kg H_2) when natural gas is used as heating source for the dehydrogenation, but this is related with higher GHG emissions. Note that all the listed studies on LOHC are for smaller volumes and not in an offshore environment but is listed to yield an insight to the economic viability of LOHC onshore. Further investigations are needed for cost estimates of UHS and LOHC for offshore production and distribution.

2.7 Summary of hydrogen carriers

In this chapter, hydrogen has been introduced as a possible fuel in the energy transition, due to its possible production by RE through electrolysis. The processed hydrogen variants assessed in this thesis, has been thoroughly introduced. In the following table, a summary of the energy characteristics for the two presented hydrogen carriers, as well as natural gas (CH_4) and diesel for comparison, is given. Safety issues is out of the scope of this thesis, but it is emphasized that hydrogen is related with challenging safety features compared to other carriers and hydrogen has a significantly lower ignition energy, a higher flammable range and a higher flame velocity than gasoline and diesel (Hansen, 2020). LOHC does not encounter these challenges but is related with toxicity (National Center for Biotechnology Information, 2022b).

Table 2-8 - Hydrogen carriers characteristics. Characteristics for compressed hydrogen, gasoline and liquid natural gas is given by (Kircher and Braess, 2008). Density characteristics for LOHC is obtained from (National Center for Biotechnology Information, 2022b), other characteristics are calculated.

	Compressed H_2 (350 bar)	LOHC[7] (MCH)	Gasoline (C_8H_{18})	Liquid natural gas (CH_4)
Gravimetric energy density [kWh/kg]	33.3	2.05[8]	12.2	14.0
Volumetric energy density [kWh/m^3][9]	780	1600	9300	5500
Density [kg/m^3]	23.4	770	764	392
Energy demand for production [kWh/kg][10]	3.4	1.7	-	-

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[7] Depends on organic carrier. Here illustrated with toluene bonding to form methylcyclohexane (MCH).

[8] Calculated by the gravimetric energy content of 6.2% hydrogen.

[9] Own calculations based on gravimetric energy content and density.

[10] Own estimations.

3 Methodology

In this chapter, the methodology for the concept analysis is presented and the LCA methodology for environmental assessment as introduced in chapter 1.2.4 is elaborated.

3.1 Concept analysis

A concept analysis has been performed to investigate the practical feasibility for compressed hydrogen and LOHC as proposed storage solutions in this thesis. The findings of the concept analysis contribute to define the storage configurations, determine if they fulfill the requirements of the research question and provide insights to in the life cycle inventory (LCI) for the LCA. The scope of the concept is limited by the scope of the LCA for the processing and storage solutions. Hydrogen production is not included in the concept analysis, as the processing and distribution pathways are the primary focus of this thesis. The structure of the concept analysis is presented in Figure 3-1, combined with the relation to the LCA:

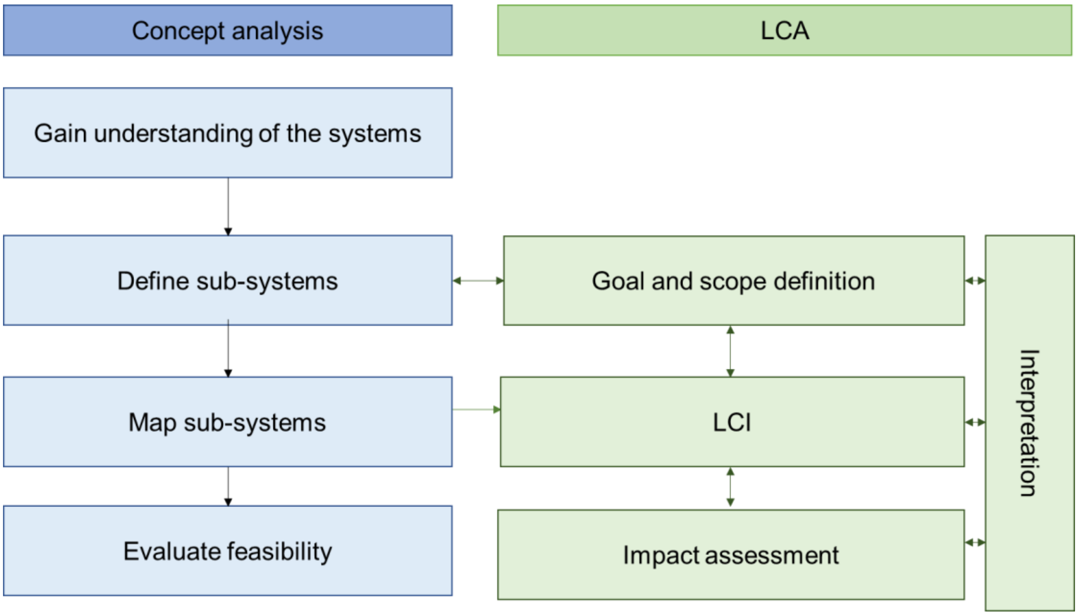

Figure 3-1- concept analysis.

Initially, an overall understanding of the storage solutions and the processing procedures was obtained by examining relevant literature for the two hydrogen carriers and the relevant storage systems. Sub-systems were then defined with the aim to acquire more detail and deeper understanding of the studied processes. The sub-systems were developed in synergy with the LCA goal and scope. Further, relevant calculations for to define the concept, as well as the LCI, were performed. Input data for calculation were obtained from manufacturers, vendors, standards and literature. The required data was specific for each sub-system and is therefore further described in the concept analysis. As an example, the mapping of the well equipment required theory understanding of hydrogen embrittlement and flow in a well, whereas mapping of the LOHC catalyst system required reviewing of existing catalyst studies and performing calculations based on existing, experimental studies with upscaling for the system investigated in this thesis. This workflow was important to be able to answer both aspects of the research question; both consider the systems feasibility for large-scale storage and make estimations necessary for the LCI. When the sub-systems were analyzed, they were seen in context with the overall system and the viability of the solutions were possible to investigate. The concept analysis chapter (Chapter 4), presents both the data material and method for estimation (the methodology) and therefore combines presentation of methodology and results.

3.2 LCA

The methodology of LCA is chosen for the environmental analysis performed in this thesis. It is chosen as methodology due to its standardized procedure and comprehensive coverage of environmental impacts with its life cycle perspective (ISO, 2006; European Commission, 2010). The method relies on comprehensive investigation, collection and analyzing of information related to the system in place and is thereby an engineering tool as it requires technical understanding of the systems in place (Baumann and Tillmann, 2004). As presented in the literature review, LCA is a method which is frequently used on identifying the environmental impact of hydrogen production and a formal definition is as follows (EAA; *et al.*, 1997, p. 9):

> *"Life cycle assessment (LCA) involves the evaluation of some aspects - often the environmental aspects - of a product system through all stages of its life cycle. It represents a rapidly emerging family of tools and techniques designed to help in environmental management and, longer term, in sustainable development."*

The methodology has been under constant development the last five decades (EAA; *et al.*, 1997) and there exists a range of software's specialized for LCA (Baumann and Tillmann, 2004). In this thesis, the software SimaPro is used for determination of the LCA results. SimaPro is a software developed by Pré and SimaPro has access to thousands of datasets on different systems and products (Pré Sustainability, 2020). EcoInvent is one of the databases that provide background data in SimaPro and is a comprehensive database which is based on continuous input and improvement from a LCI expert group from different Swiss institutions (Goedkoop *et al.*, 2013). LCA is based on linear algebra (Heijungs and Suh, 2002) and SimaPro (or other chosen software) executes the linear algebra which is behind an LCA analysis. The linear algebra behind LCA is based on the matrix equation, which was proposed in a mathematical model based on inputs and outputs by Wassily Leontif (Munroe and Biles, 2005). Years after implementing the economic model, Leontif extended the work of the economic model to account for environmental impact (Brown *et al.*, 2021). The linear algebra matrix is the foundation for LCA calculations (Equation [17]) (Munroe and Biles, 2005):

$$(I - A)^{-1} * f = X \tag{17}$$

Where X is the output vector, $(I_n - A)^{-1}$ is the Leontif inverse matrix including input-output matrix A and f is the demand vector. The output vector is further used to calculate the environmental emission vector based on a matrix with emission intensities. The calculated emissions vector is then calculated to a total impact vector, based on a characterization dataset or a normalization dataset. The chosen LCA software performs these calculations and multiplies the emission vector with a matrix with the chosen set of impact categories. The LCA methodology offers a set of different impact assessment (LCIA) methods.

The LCA methodology involves four steps (Figure 1-4, chapter 1.2.4) (ISO, 2006):

- Goal and scope definition
- Inventory analysis (LCI)
- Life cycle Impact assessment (LCIA)
- Interpretation

The goal definition includes six defined aspects by the standardized LCA procedure; intended application, limitations of the study, reasons for the study, target audience and type of audience, statement of eventual comparisons and definition of the commissioner of the study. A clear goal-definition is essential both to define the scope, as well as to make sure that the results are interpreted in the intended way (European Commission, 2010). The reasons for carrying out the study shall be unambiguously defined and the decision context should be clarified in the goal definition. LCAs can be used as decision supporting tools and it is differentiated between macro-level and micro-level decision support. LCAs can also be performed with the intention of accounting, hence share information about the analyzed system. Accounting studies are not implying which of the compared alternatives that are the preferred solutions, but rather displays the results and leaves the reader as the interpreter of "the better option".

The scope definition includes both the definition of which part of the lifecycle is included, as well as a clear definition of the boundaries for the system or product. The system's functional unit and function needs to be clearly defined in the scope definition. The functional unit is the reference unit of the system and all the quantified environmental impact is expressed per functional unit. The scope, together with the assumptions and scenarios defined by the practitioner also highly impacts the result and different scope definitions on the same system leads to different results.

The LCI is the analysis of the inventory related to the system and maps unit processes and the corresponding input and output flows of the unit processes (ISO, 2006). It includes the following steps: prepare for and perform data collection, validate of data, relate data to unit processes, relate data to the functional unit, perform data aggregation and possibly refining of the system boundaries (ISO, 2006). The LCI modelling framework can be either attributional or consequential, depending on the defined decision context. Attributional LCI modelling is quantitively focused on the reference flow, the functional unit and the input and outputs of flows to the analyzed system. A consequential LCA is not based on the functional unit and analyses the potential environmental impact based on changes in current systems or procedures (Schuller Martin Baitz *et al.*, 2020).

The LCIA is the life cycle inventory assessment, which assess and quantify the impact of the gathered inventory. The LCIA can be performed by different methods and the chosen impact method is ReCiPe Midpoint (H), including 18 impact categories that estimates potential environmental impact (further described in Chapter 5.1.2). ReCiPe LCIA method can also present endpoint perspective, which is gathering the impact categories to more comprehensive groups, Damage to human Health, Damage to Ecosystems and Damage to resource availability. As more information are gathered in the endpoint categories, the uncertainty rises (Goedkoop *et al.*, 2013). For interpretation, midpoint impact category is therefore preferred. The perspective H (hierarchist) is chosen as it is based on the most common policy principles and used a timeframe of 100 year for global warming potential (Pré Sustainability, 2020). Most LCA methodologies for the LCIA cover all the emission and footprint sources that are defined in planetary boundaries. Planetary boundaries are defined by the Stockholm Resilience Group as; " *the safe operating space for humanity with respect to the Earth system and are associated* *with the planet's biophysical subsystems or processes"* (Rockström *et al.*, 2009, p.472). These boundaries illustrate that anthropogenic emissions not only impacts climate change but contribute to other important areas which must be protected to develop in a sustainable way. The planetary boundaries are given in the following list:

- Climate change
- Novel entities
- Stratospheric ozone depletion
- Atmospheric aerosol loading
- Ocean acidification
- Biochemical flows
- Freshwater use
- Land-system change
- Biosphere integrity

GHG emissions impacts planetary boundary climate change, whilst other anthropogenic emissions and behavior impact the other eight boundaries, which also are defined as essential to maintain stability and resilience in the Earth system. Despite this, climate change is often the primary focus in LCAs and the environmental impact is frequently given only as global warming potential (GWP). Several of the other areas, such as ocean acidification, biochemical flow, biosphere integrity, will all be impacted if the global warming proceeds. In addition, climate change potential is a robust parameter to measure, as the effects of GHG emissions in the atmosphere is to a large scale understood, largely a result of the decades of effort on this impact by IPCC. Several of the other planetary boundaries, which can be covered in categories as terrestrial ecotoxicity and biosphere integrity are generally more challenging to quantify the effects of and these parameters are less robust. The interpretation of the LCIA is presented in the results chapter and aims to answer the goal defined in the study and thereby contribute to answer the environmental aspect of the research question.

LCA as a method has several limitations, amongst them is the dependency of high data quality, as well as sufficient understanding of the data material both for the practitioner and the reader of the analysis. Even though LCAs provide a quantification of environmental impact, every LCA must be read with great care, as the scope and goal definitions are crucial for the results. LCA is a tool which can help both industry, policymakers and politicians to choose new technology and investments that contribute with the lowest environmental footprint on our planet.

4 Concept analyses

In this chapter, the concept analyses of the two proposed storage solutions are presented. They aim to determine feasible storage solutions for the processed forms of hydrogen, to answer to the research question. Hydrogen production is assumed to be accommodated on a bottom-fixed platform located in Southern North Sea II (140 km from shore (Østenby, 2019)), with energy provided from a wind farm. Before deduction of the concept analysis for the storage systems, an area estimation for the electrolyser system was made and assured to fit on a platform structure (elaborated in chapter 5.2.1). This chapter henceforth focus on the sub-systems of the storage configurations. As presented in the methodology, this lies the foundation for evaluating the feasibility of the systems, as well as the inventory for the LCA. The sub-systems are assembled in a full system description in the LCA chapter (Chapter 5).

4.1 UHS concept analysis

Both salt caverns and UHS are proposed as a feasible offshore storage solution for hydrogen production (cf. chapter 2.3.1 and 2.3.2). Porous UHS is analyzed in a hypothetical depleted hydrocarbon reservoir in the Southern North Sea II (elaborated in chapter 4.1.2), investigated by the following sub-systems:

- Hydrogen production (Chapter 4.1.1)
- Storage - reservoir (Chapter 4.1.2)
- Material selection (Chapter 4.1.3)
- Well system (Chapter 4.1.4)
- Piping (Chapter 4.1.5)
- Compressor system (Chapter 4.1.6)
- Summary (Chapter 4.1.7)

The sub-systems are described more in detail in the following chapters and summarized in the UHS system description (Chapter 5.2.2).

4.1.1 Hydrogen production

A 500 MW electrolyser system is defined by the research question. Calculations for hydrogen production by a 200, 500 and 800 MW electrolyser system were performed for comparison (see Table 4-1). The calculations are performed based on the energy content (LHV) of hydrogen and the provided electricity to hydrogen production. The volumetric production is calculated based on a hydrogen density at 200 bars, calculated by Equation [7] and Equation [8] (Chapter 2.2.1). The wind farm capacity is based on the assumed needed energy for hydrogen production, compression and other auxiliaries and a more detailed overview of the background data for the calculations is given in Appendix I: Background data and calculations.

Table 4-1 - Maximum hydrogen production and the corresponding production volumes for the UHS storage case.

Wind farm capacity [MW]	Electrolyser capacity [MW]	Maximum H_2 production [t/day]	H_2 production [m^3/day]	H_2 production [Sm^3/month]
210	200	87	5573	29 407 474
526	500	218	13 932	73 518 684
841	800	349	22 292	117 629 894

4.1.2 Storage - Reservoir

This section provides a description of the hypothetical UHS reservoir, which is considered feasible for storing the produced amount of hydrogen in a month from a 500 MW electrolyser system. A depleted hydrocarbon reservoir has the capacity of storing large amounts of hydrogen (cf. chapter 2.3.2) and typically has stored in the order of ten to hundreds of million standard cubic meters of O&G. As an example, the Trym field in the Southern North Sea initially stored 1.8 million Sm^3 of oil and 4.3 billion Sm^3 of gas, i.e. the gas zone for hydrogen storage capacity is large (Olje- og energidepartementet, no date a). Only a selection of reservoirs on the Norwegian continental shelf has gas capacities below 73.5 million Sm^3, which is calculated as the monthly hydrogen production (see Table 4-1) (Olje- og energidepartementet, no date b). Salt caverns have more limited storage capacity (see Table 2-3) and the feasibility of storing the volumes calculated in this thesis is more uncertain. The research question states that the storage system shall enable minimum one month of hydrogen storage. Based on reported initial reservoir storage volumes, it can be concluded that most depleted hydrocarbon reservoirs on the Norwegian shelf fulfills this requirement. Another advantage of porous UHS, is the detailed mapping of the wells which have already performed. In addition, Norway has extensive experience in the offshore environment with hydrocarbon reservoirs and it can be favorable to repurpose both equipment, technology and competence into the energy transition. The scope of this LCA does not encounter social aspects as the repurposing of competence but aims to investigate the potential environmental advantage of repurposing equipment.

A hypothetic, depleted hydrocarbon reservoir with storage capacity that allow storage of one month of hydrogen production from an offshore wind farm is therefore assumed for this thesis. Based on the Bryne and Sandnes reservoirs, the reservoir is defined to be located at 2000 m depth, with a pressure of maximum 200 bars and temperature of approximately 60ºC (cf. chapter 2.3.3). The reservoir pressure after depletion and before hydrogen injection is 120 bars. It is assumed that the monthly stored hydrogen from the reservoir can be provided to shore in a seven-day timespan. The system is illustrated in Figure 4-1:

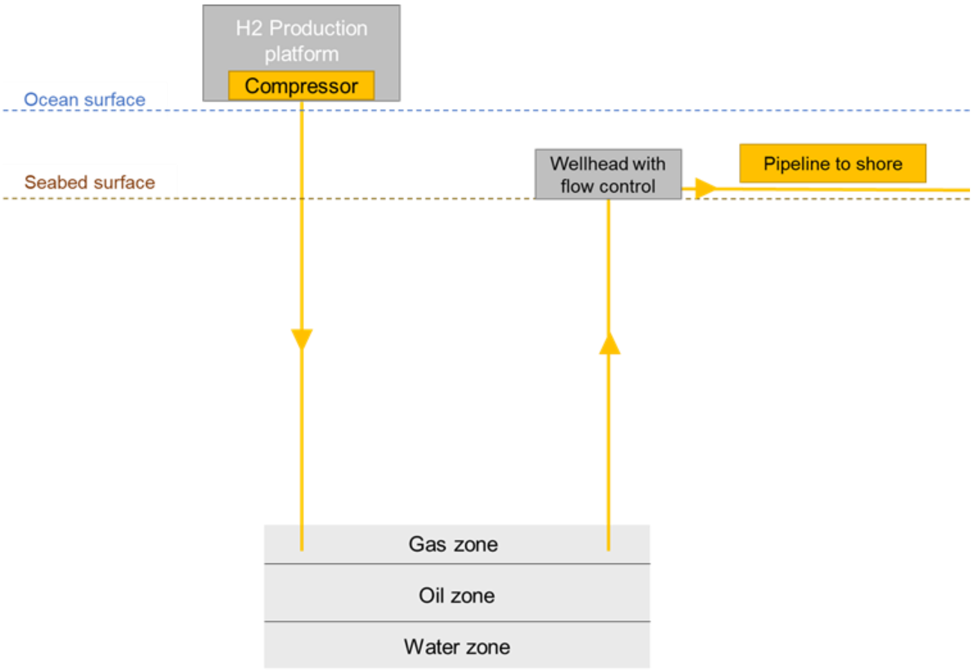

Figure 4-1 - UHS illustration. Hydrogen is injected to the reservoir from the production platform, where it can be stored for a month. It can be provided to shore in a seven-day timespan, via well outlet and transport pipeline.

4.1.3 Material selection

Material selections are important to determinate feasibility of the UHS system, as well as for the LCI and a summary of the material selection is provided in this chapter. There are challenges linked to the material use for hydrogen, as hydrogen has high permeation rate through most steels and occupation of space in the steel contribute to hydrogen embrittlement. Austenitic steel types have a dense structure with little space for hydrogen to occupy (FCC) and is assumed to be the best choice for hydrogen transport (cf. chapter 2.2.2). As summarized in chapter 2.2.3, hydrogen transport in repurposed NG pipelines is of high interest all over Europe and several projects investigates the potential use of existing NG networks for hydrogen distribution. For the purpose of this thesis, it is concluded to be no defined showstoppers from the material perspective for storage of hydrogen in reservoirs, even though modifications and adjustments may have to be established on existing technology. It is further assumed that steel up to 65 000 psi are applicable for transport pipelines. Besides the choice of a hydrogen-compatible steel types and defining that hydrogen storage is plausible in a material perspective (based on existing standards, reports and literature), further considerations regarding the material challenges is beyond the scope of this thesis. This is emphasized as material challenges linked with hydrogen is a complex matter, that must be more thoroughly investigated for a robust conclusion.

4.1.4 Well system

Detailed well design is a complex and comprehensive task and outside the scope of this thesis and estimations based on typical sizing made for the LCI (cf. chapter 5.2) is presented in this section. A typical well has a conductor length of 45 meters, a surface length of ~900 meters, an intermediate casing of ~3200 meters and a production casing of ~4300 meters (Byrom, 2015). This is dependent on the reservoir depth and reservoirs located on shallower depths, will have decreasing casing depths. The equipment is adjusted to the 2000m well that is assumed in this thesis, meaning that the conductor length is assumed to be ~25 meters, the surface casing ~450 meters, the intermediate casing ~1500 meters and the production casing ~2000 meter. The production casing typically ranges between 6-10 inches (152.4 to 254 mm) in diameter (Byrom, 2015). The dimensioning of the production casing affects the design of the outer casings and the corresponding ranges are 8-14 inches for intermediate casing, 11-20 inches for the surface casing and 16-30 inches in the conductor casing (in a hard rock environment). It is assumed that the cement layer is equal to the annuli between the casing diameters.

For the material selection in the down-hole, it is assumed that the injection and production tubing (inlet and outlet piping for the hydrogen) are exposed to most stress, because they are exposed to corrosive hydrogen at high pressure. Therefore, this tubing must be corrosion resistant alloy, especially resistant to hydrogen embrittlement. It is therefore assumed that the tubing consists of austenitic, stainless steel. If hydrogen leakages occur, it is advantageous that the (innermost) production casing can tolerate the hydrogen and not become brittle. It is assumed that the outer casings will not be exposed to hydrogen and thereby is only designed to balance the well and tolerate the increasing pressure with depth. API 5CT standard covers casing and tubing in O&G-wells and contains a range of different steel qualities, where steel selection must be chosen based on the specific well properties (API, 2005).

Casing thickness depend on the environment of the well, the characteristics of the well fluids, the material grade of the chosen steel and the manufacturing method of the pipeline (Byrom, 2015). API5CT standard provides a range of steel types that is specialized for well casings, from relatively low-strength steels (starting at 40 000 psi SMYS) to high-strength steels (up to 125 000 psi SMYS). High-strength, low-alloyed steel is assumed for the casings outside the production casing that is not exposed to hydrogen and more specialized material choices are outside the scope of this thesis. As detailed well design is beyond the scope of this thesis, estimations for wall thickness for use in the LCI is adapted from pipeline manufacturers. API5CT is the defined standard for the manufacturing of casing pipelines and by information from casing suppliers, the wall thicknesses given in Table 4-2 is summarized. As hydrogen yields challenging environment to the inner casings, it is assumed the wall thickness in the upper range of these suggestions for the LCI and for consistency, also the outermost casings are calculated in the upper range (extended calculation for amount is given in Appendix I: Background data and calculations).

Table 4-2 - Wall thickness of the casings[11].

Diameter [Inch]	Diameter [mm]	Wall thickness [mm]	Used WT for LCI
7	177.8	5.87-12.65	12.7
8 5/8	220	6.71-14.15	14.5
11 3/4	298.5	8.46-13.06	13.06
16	406.5	9.35-12.42	12.42
24	Not given	Assumed same as for 16 in.	12.42

At the wellhead, the hydrogen will pass a valve tree. This is a complex installation with several valves and the design depends amongst other factor on the reservoir environment, the expected flow, the production rates and the expected production fluids (Bai and Bai, 2008). To design the valve tree of a hydrogen injection and withdrawal is outside the scope of this thesis. However, a crucial component in the withdrawal valve tree is mentioned, the choke valve. The choke valve hinders uncontrolled gas expansion and limits the pressure loss during hydrogen

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[11] *These numbers are obtained by pipeline manufacturer Canada Steel and Casings Imports (Canada Steel and Casing Imports, no date)*

production. The choke valves are crucial to drive the gas from the well to the well head, as a pressure difference in induced.

4.1.5 Piping

This chapter presents considerations done for the well piping equipment, riser and transport pipeline. The wall thickness of the transport pipeline and the riser is determined for further use in the LCI. The flow rates are estimated based on different diameters to determine whether the dimensioning allow an acceptable flow rate. A simplified calculation of the pressure drop in the transport pipeline is performed, to determine whether a re-pressurization is necessary on the transport distance and that the dimensioning appear feasible.

Limitations provided by international standards (ASME, EIGA and API) has been assessed for hydrogen pipeline transport in Chapter 2.2.3. It is concluded that pipeline transport should be limited below the erosional velocity of ~29 m/s and that the sonic limitations are not assumed to be determining as hydrogen has higher speed of sound than comparable gases. It is also concluded that the pipeline diameter should be limited, as increased wall thickness is expected for hydrogen transport by high strength steels and are not recommended to exceed 12 inches (internal diameter) (cf. chapter 2.2.3). For the injection and withdrawal equipment, the inner tubing is suggested to be 7 inches. The current maximum hydrogen pressure in pipelines is limited to 140 bars (cf. chapter 2.2.3) and the hydrogen embrittlement challenges may be a showstopper for 200 bar transport pressure. The wall thickness for a 12" piping is calculated by equation [10] (chapter 2.2.3). More detailed explanation about the calculation procedure and the determination of the input variables is given in Appendix I: Background data and calculations. The result for this calculation is given in Table 4-3, for the assumption of a design pressure of 200 bars and a material yield strength of 450 MPa (corresponding to 65 000 psi):

Table 4-3 – Estimations of the hydrogen transport pipeline.

Material	**X65 (with cathodic protection)**
Density [kg/m^3]	7800
Internal pressure	>200 bars
ID	12" - 304.8 mm
OD	13" - 330 mm
Minimum wall thickness [mm]	25

A 12" (304.8 mm) diameter pipeline yields a wall thickness of approximately 25 mm at such high operating pressure.

The flow velocity in the 12" transport pipeline and the 7" withdrawal tubing in the well is determined based on the volumetric flowrate, the pipeline cross-sectional area and the pipeline pressure (see Table 4-4). The volumetric flowrate is defined by a month's production withdrawn in the seven days withdrawal period.

Table 4-4 - Overview of flow rate in pipelines as function of the pressure and the pipeline diameter. The flowrate is based on the average monthly production withdrawn in a seven-day period.

		Pipeline diameter [inch (mm)]				
		6 (152.4)	7 (177.8)	8 (203.2)	12 (304.8)	16 (406.4)
Pipe pressure [bar]	Flowrate [m^3/s]	Flowrate [m/s]				
140	0.64	35.05	25.75	19.72	8.76	4.93
180	0.51	27.82	20.44	15.65	6.96	3.91
200	0.46	25.29	18.58	14.23	6.32	3.56
250	0.38	20.74	15.24	11.67	5.19	2.92

The cells marked with orange is above the erosional velocity. The cells marked with yellow, is above the noise recommendation by API RP 14E, whilst the green cells are below both limits. A 12" pipeline therefore allow an acceptable flowrate of 6.3 m/s of hydrogen to shore, when a seven-day withdrawal period is assumed. The production tubing from the well, assumed to be 7", allow for transport below the erosional velocity for all given pressure levels. The calculations shown in Table 4-4 for the 7" pipeline accounts the outlet well piping, lower velocities are expected in the inlet well with lower flow rate.

Pressure losses determine if several compression steps are needed along the transport pipeline from outlet well to shore. The pressure drop in the well from reservoir to surface is not estimated and assumed to be minimal. The pressure drop for the transport pipeline is estimated by Equation [11], (Chapter 2.2.3) and omits pressure drop in joints and bends. Calculation based on Equation [11] indicates a low pressure drop related with hydrogen transport (see Table 4-5) based on the flow velocity of a seven-day withdrawal. Note that this equation includes the friction factor *f*, which has high impact on the results and is determined by the surface roughness of the piping. The surface roughness was determined to be 0.002 mm for stainless steel (White, 2017) , but this varies between steel qualities and wear. Further details about the input parameters for the calculation is provided in Appendix I: Background data and calculations.

Table 4-5 - Overview of pressure drop in the hydrogen transport pipeline, as a function of pipeline diameter and pressure.

		Pipeline diameter [Inch (mm)]		
		10 (254)	12 (304.8)	16 (406.4)
Pipe pressure [bar]	Flowrate [m^3/s]	Pressure drop [bar]		
140	0.64	43.6	16	4.8
200	0.46	28.6	11.4	3.8
250	0.38	22	9.3	3.3

The yellow cells indicate pressure drop that is too high to be assumed as alternative. The green cells indicate pressure drops assumed tolerated and object to more detailed estimation, including accounting for joints and bends. The pressure drops related to the choke valve between hydrogen outlet and transport pipeline, is calculated to 2 bars using equation [12] assuming a ratio 0.3 to the pipe diameter (cf. chapter 2.2.3). With an initial pressure of 198 bar after the choke valve, the pressure drop calculated by Equation [11] is limited to 12 bars in the transport pipeline (Further input details provided in Appendix I: Background data and calculations. A 12" transport pipeline is estimated with a limited pressure drop of 14 bars, equaling 7% of the original pressure of 200 bars. Based on these calculations and with some additional margin, an output pressure of 180 bars is assumed to shore. This calculation eliminates the need for re-pressurization along the hydrogen transport pipeline. This aligns with literature findings, which define a need for recompression of hydrogen for distances exceeding 250 km (Wulf, *et al.*, 2018).

The riser leads the produced hydrogen from the production platform to the wellhead. Conditions in the environment and operational conditions impact the riser design (e.g. diameter and wall thickness) but the riser is typically between 3" and 12" in diameter and made of X65 steel or higher grades for extreme conditions (Bai and Bai, 2019) The riser is designed to withstand stress from the surroundings and internal stress from the fluid flowing in the riser. It is assumed that high-strength carbon-steel with SMYS limited to 65 000 pris is suitable as riser material (cf. chapter 2.2.2), which is protected from sea water corrosion through cathodic protection. The pipeline must be designed with a sufficient wall thickness to resist corrosion both on the inside and the outside (Chakrabarti, 2005). The riser is a marginal, but crucial part of the system, in total under 100 meters, compared to the well system (2 km) and transport pipeline (140 km). The riser and the transport pipeline are experiencing comparable loads and for this analysis, it is assumed that the riser and transport pipeline must have comparable design in terms of diameter and wall thickness.

4.1.6 Compressor system

In this chapter, a short introduction of the general feasibility of the compressor system is given and the system is dimensioned. The energy necessary for hydrogen compression to 200 bars, is calculated to 2.7 kWh/kgH_2 (cf. chapter 2.2.1), yielding a compressor capacity of 25 MW (in context with the 500MW electrolyser system hydrogen production capacity). Reciprocating compressors are mechanical and piston-based and work by the same principle independent of which gas is present. The main adjustment that is assumed is an exchange in steel quality for the steel that is in contact with the hydrogen, due to the challenges related to leakage and hydrogen embrittlement (Sdanghi *et al.*, 2020). For the LCA, the inventory of the compressor system could be calculated based on the compressor capacity (25 MW). An area estimation of the compressor system had to be estimated by limited amount of information, as no public information, neither in literature nor by compressor manufacturers regarding area footprint were found. The estimated compressor capacity is 5% of the electrolyser capacity, but compressors are assumed to be space demanding equipment. Estimation by HyFuel (Vegard Lavik at Hyfuel, 18.01.2022) yields that a compression plant is approximately half the size of an electrolyser plant for compression to 350 bars (Grønt Skipsfartsprogram, 2022). Based on this and general assumptions of large area footprint per capacity for compressors, the area is assumed to be 60% of the electrolyser area as a conservative estimate.

4.1.7 Summary of UHS concept analysis

The concept analysis has outlined a possible UHS configuration for compressed hydrogen storage. It has defined a hypothetical, porous field in the Southern North Sea II, which enable minimum one month of hydrogen storage. Fundamental aspects related to equipment of the well has been identified to provide input to the LCI. The results from this analysis are foundation for the following LCA analysis on the proposed storage configuration. Some key findings from the concept analysis are summarized in Table 4-6:

Table 4-6 - Summary of findings of the concept analysis for porous UHS. Yellow boxes indicate medium feasibility, green boxes indicate favorable feasibility.

	Area	**Flow suitability**	**Energy efficiency**	**Material compatibility**	**Energy deliverance**
Estimation	System assumed to fit on a deck on a platform	Good	Possibly high, mainly depending on reservoir recovery	Challenging	43 500 MWh for the 7-days emptying period (sufficient for electricity provision to 88 000 households daily in the seven-day period)
Uncertainty	Medium	Low	Low	Low	Low

4.2 LOHC concept analysis

LOHC is a proposed energy carrier for hydrogen which allow efficient handling and storage of hydrogen and several LOHC's are suggested from different industrial actors (cf. chapter 2.4.1). For this thesis, benzyltoluene (BT) is analyzed, as this is a well-known chemical, it is related with same toxicity as other suggested LOHC's, it has acceptable hydrogen storage capacity and it is the chosen LOHC by commercial actors. The research question in this thesis concerns which storage solutions that allow energy from a 500 MW wind farm to be stored for minimum one month in a viable way. In this chapter, the ability of LOHC to fulfill the requirement defined in the research question is investigated and it was investigated with the following sub-systems:

- Hydrogen and LOHC production (chapter 4.1.1)
- Space requirements for the plant (chapter 4.1.2)
- Storage (4.1.3)
- Ship application (chapter 4.1.4)
- Catalysts (chapter 4.1.5)
- Summary (Chapter 4.1.6)

4.2.1 Hydrogen and LOHC production

The hydrogen production is defined to be performed by a 500 MW electrolyser system. Energy is needed also for the processing of the hydrogen, (hydrogenation) and other utilities and a larger windfarm than the electrolyser capacity is needed for the overall system. The calculations for hydrogen production rate are performed based on the energy content (LHV) of hydrogen and the defined electrolyser capacities. Based on background data presented in Appendix I: Background data and calculations, the wind farm capacity and daily hydrogen production at capacity factor and at rated power is presented (Table 4-7):

Table 4-7 - Overview of hydrogen production by wind farm and electrolyser capacity.

Wind farm capacity [MW]*)	Electrolyser capacity [MW]	H_2 production [t/day], 57% capacity factor	H_2 production [t/day], max. production
206	200	50	87
516	500	124	218
825	800	199	349

**) The wind farm capacity is as introduced in chapter 5.2.1 (see Figure 5-4) adjusted to the energy requirements for the osmosis and the hydrogenation.*

The daily production rate is 124 tons at 57% capacity factor and 218 at max production. Based on the hydrogen production presented in Table 4-7, the required amount of LOHC was calculated (see Table 4-8). A lifetime of 300 cycles as estimated by (Grønt Skipsfartsprogram,

2022) leads to a temporal lifetime of 25 years with a monthly recycling frequency. For a temporal lifetime of 20 years, the cycling lifetime is reduced to 240 cycles. The lifetime of the LOHC can arranged by two options; that all LOHC from the first cycles is new and is cycled through the lifetime of the system, or that a fraction is exchanged every cycle. In this thesis, the latter option is chosen and 1/240-part of the LOHC (0.4%) is assumed new in every hydrogenation process, henceforth referred to as virgin LOHC. The fraction of dehydrogenated LOHC which is re-used in the processes, is referred to as recycled LOHC.

Table 4-8- Overview of monthly hydrogen production, BT demand and possible P-BT production.

	Hydrogen	**BT**	**Virgin BT**	**P-BT**
Monthly production/demand [ton]	3568	54 114	226	57 646
Corresponding mol [-]	1 783 981 324	297 330 221	-	297 330 221
Volume [m^3]	-	54 994	-	65 806

In Table 4-8, the monthly hydrogen production based on the 57% capacity factor is displayed, together with the corresponding hydrogen-lean LOHC demand (BT), the virgin BT demand and the monthly production of hydrogenated P-BT.

4.2.2 Space requirements of hydrogenation/dehydrogenation plant

The area footprint of a five ton per day (tpd) hydrogenation plant is reported to be 196 m^2 (Vegard Lavik at Hyfuel, 18.01.2022; Grønt Skipsfartsprogram, 2022). LOHC hydrogenation and dehydrogenation systems are offered with predefined footprint of 30 m^2 (40-foot container) for hydrogenation and 20 m^2 (20-foot container) for dehydrogenation, both with a capacity of 11 kg/h (0.3 tpd) (Hydrogenious, 2018). The space requirements for the 5tpd plant is 0.75 of the 0.3 tpd plant. A scaling factor of 0.7 is used for further upscaling of plant size from 5 tpd to 218 tpd, which is the maximum hydrogen production from the wind farm. The area footprint of the hydrogenaton and dehydrogenation plant, is determined to be respectively ~6000 m^2 and 12 000 m^2 by these assumptions, summarized in Table 4-9:

Table 4-9 - Size estimations for hydrogenation and dehydrogenation plant.

	Upscaling	**Scaling factor**	
Hydrogenious' estimate	0.3 tpd to 5 tpd	0.75	
Upscaling to estimated H_2 production	5 tpd to 218 tpd	0.7	
Size estimation, hydrogenation [m^2]			6000
Size estimation, dehydrogenation [m^2]			12 000

4.2.3 Storage

LOHC can be stored in traditional, chemical tanks, which contribute to making LOHC storage a flexible alternative. For storage of minimum one month from a 500 MW electrolyser system, this would yield a volume of ~66 000 m^3, which assuming a tank height of 4 meters equals over ~16 000 m^2 for storage. This implies that the tank storage would yield a demand for another platform, or the platform that would be needed for both electrolysis, hydrogenation and LOHC storage would be amongst the largest platform in the world. Thus, tank storage is not considered feasible in the limitations of this analysis. However, LOHC stands out as a practical and safe way of storing hydrogen and as it is related with similar characteristics as crude oil, the systems for handling of crude oil were investigated.

An FPSO is an offshore production, storage and offloading facility of oil and natural gas, which can be formed as a ship and is comparable with an oil tanker. FPSO's are produced in a range of different sizes and can store from thousands to hundred thousand of liters of oil. An FPSO was investigated as a storage for the LOHC produced in a month from a 500 MW electrolysers, as LOHC can utilize existing equipment from the O&G-sector. Based on the monthly LOHC production volume of 57 646 tons (Table 4-8) and the estimated areal requirement of the hydrogenation plant of 6000 m^2, it is estimated that a medium/large sized FPSO (>220m x 40 m x 20 m) have sufficient surface space for the hydrogenation plant, sufficient hull for the LOHC and space for O&M-crew, if needed. All the required volume can then be stored in one, large, tank, instead of being dependent on a range of different tanks which both increase the complexity and the necessary area of the systems. The FPSO can be divided into two chambers, one containing hydrogen-lean LOHC and one containing hydrogenated LOHC. When approaching a month's storage, or before if energy is needed onshore, hydrogenated LOHC can be bunkered onto an oil tanker for transportation to shore (see Figure 4-2).

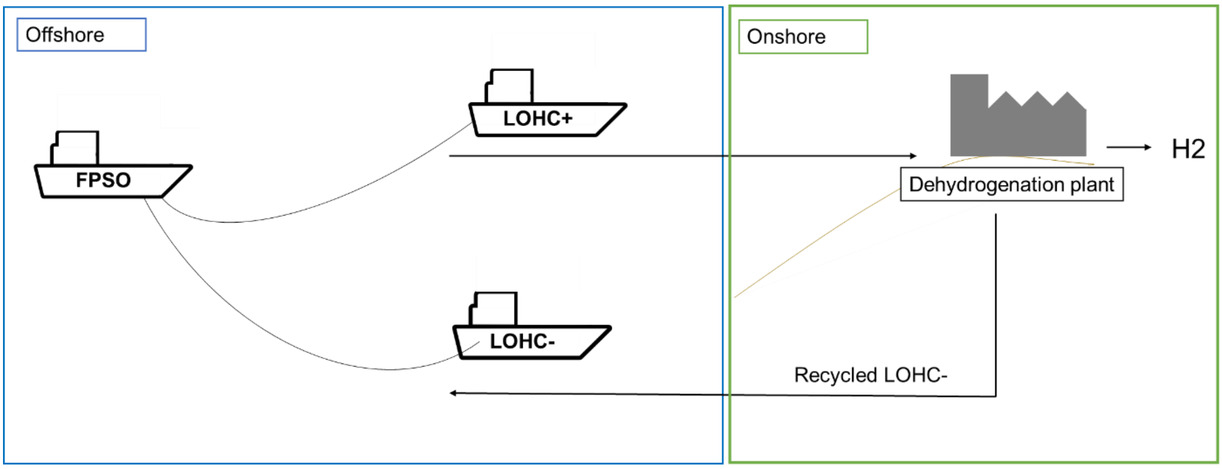

Figure 4-2 - Flow of LOHC to and from FPSO.

Two systems are considered, system A) where the hydrogenation plant is on the FPSO and system B) where the hydrogenation plant is on the platform (see Figure 4-3). System B) could be a relevant system if the hydrogenation plant will not fit on an FPSO (larger footprint than expected), if it is uncertain how the chemical process will be executed with more variable loads from the ocean, or if the deck on the FPSO will be needed for other purposes than storing the hydrogenation facility. Production on the platform can also be relevant if another storage methods is chosen. The two systems will be used for the presentation of two different results in the LCA, henceforth referred to as LOHC case A) (plant on FPSO) and LOHC case B) (plant on platform).

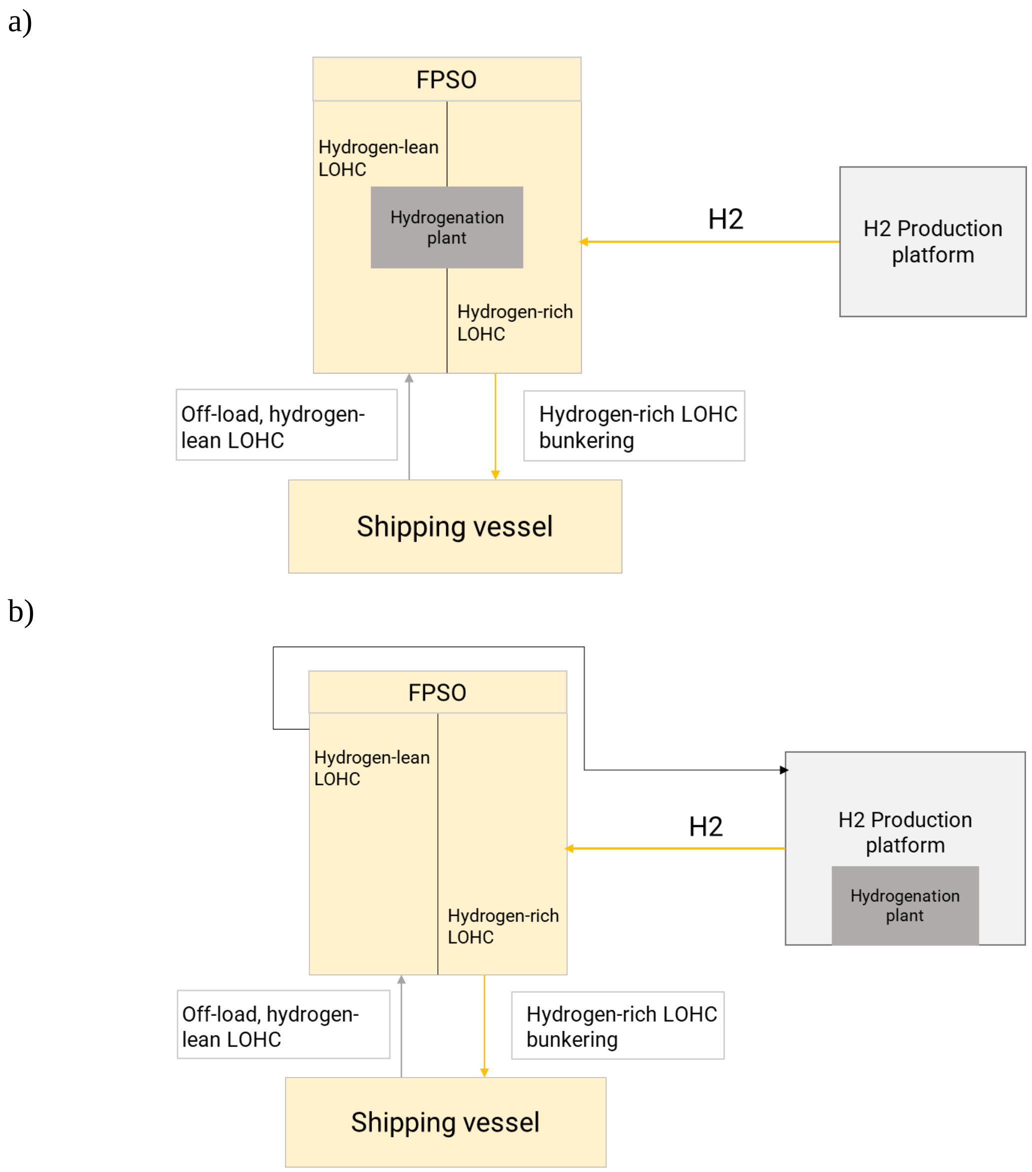

Figure 4-3 - LOHC FPSO storage configurations. a) LOHC plant on platform. b) LOHC plant on FPSO.

4.2.4 Ship application

Several industry actors are involved in pilot projects on LOHC release units combined with fuel cells onboard vessels as propulsion systems, for example pilot project for LOHC propulsion system by Østensjø and Hydrogenious, which plans to demonstrate the propulsion of a vessel with dehydrogenation onboard (Oestensjoe, 2021). HyFuel is another industry actor which aims to deliver hydrogenated LOHC as a shipping fuel. For use of LOHC in transportation purposes, especially for shipping, an interesting question is whether the dehydrogenation plant can be placed on the ship itself, easing the storage of hydrogen onboard to be in LOHC tanks at ambient pressure and temperature. A calculation for this is attached in Appendix I: Background data and calculations and the result indicates that a dehydrogenation plant can be placed onboard a ship corresponding to a Panamax ship and occupy around 2.2% of the storage capacity for the plant. As there is yet to be any consensus about the general hydrogen carrier that is to be utilized in the maritime industry, it is challenging to make an estimate about the potential of ships being able to bunker LOHC for its own propulsion. Therefore, direct utilization of LOHC to ships is not analyzed as a pathway in this thesis.

4.2.5 Catalysts

A detailed explanation of the procedure for calculating the catalyst amount is presented in this section, with reference to the most relevant studies that is found. The results are summarized in Table 4-10 at the end of this section.

Both hydrogenation and dehydrogenation require a catalyst and for the catalyzation of BT, platinum is assumed to be a favorable material (Brückner *et al.*, 2014, He, Pei and Chen, 2015, Aakko-Saksa *et al.*, 2018, Jorschick *et al.*, 2020), even though other catalysts may be suitable for hydrogenation and dehydrogenation (cf. chapter 2.4.1). Platinum is a part of the processing plants, but due to its high energy demand and crucial part in the system, it was decided to be analyzed as sub-system. As the parts of the catalyst which does not consist of noble quantities are more standard materials as Al_2O_3 or carbon, this are neglected from the analysis.

The amount of necessary platinum for hydrogenation/dehydrogenation of BT is based on the data given in two experimental studies (Brückner *et al.*, 2014; Jorschick *et al.*, 2020) and by an industry estimate presented by Ahluwalia *et al.*, (2011). The two experimental studies have in common that the need for catalyst for dehydrogenation is generally higher than for hydrogenation, mainly caused by longer reaction time of dehydrogenation. The calculations for hydrogenation yields larger variation and an almost ten times higher catalyst demand for hydrogenation is estimated by Brückner *et al.*, (2014) compared to Jorschick *et al.*, (2020). An estimation of 1 kg catalyst/500-ton processed material is presented as the industry estimate for hydrogenation (Ahluwalia *et al.*, 2011). Assuming 5 wt.% Pt of the catalyst, this yields an estimate of ~1500 kg Pt for the total hydrogenated amount studied in this thesis, based on the calculated LOHC production over the lifetime (see Table 4-10).

The estimation of catalyst demand by Brückner *et al.*, (2014) is in line with the estimation by Ahluwalia *et al.*, (2011) for hydrogenation, although the former suggests Ruthenium (Rh) for catalyst material rather than platinum for the hydrogenation. As platinum is frequently suggested as a hydrogenation catalyst for LOHC and has better data availability, platinum is assumed for the inventory of catalyst. For dehydrogenation, the estimations given by Jorschick *et al.*, (2020) is used, as a reaction temperature of 260ºC is used, within a safe margin from BT's boiling temperature of 280ºC (see Table 2-6). The calculations are based on the experimental procedure and upscaled to the hydrogen production estimated in this thesis, presented in Table 4-10.

Table 4-10 - Overview of the calculated amount of platinum for the hydrogenation and dehydrogenation plants.

	Hydrogenation (Bruckner et.al, 2014)	Dehydrogenation (Jorschick et.al, 2020)	Hydrogenation (Ahluwalia et al., 2011)
Experimental procedure			
Mol LOHC	0.76	0.15	-
Mol H_2	4.56	0.93	-
Mol Pt	0.002	0.001	-
g Pt/reaction time	0.37	0.01	-
g hydrogenated H_2/reaction time	9.04	1.86	-
Upscaled to daily capacity			
g Pt/day	0.37	0.01	-
g H_2 /day	144.62	1.94	-
Adapted to the H_2 production estimated			
Daily H_2 production [g]/ experimental production [g]	859 642	64 202 838	-
Pt upscaled to daily H_2 production [g]	318 843	645 338	-
Pt [kg] over 20-year, 1 year lifetime	6 377	12 907	2 095
Pt [kg] over 20-year, 3 years lifetime	2 126	4 302	1 466
Pt [kg] over 20-year, 5 years lifetime	1 275	2 581	733

The necessary amount of platinum for hydrogenation and dehydrogenation is related with high uncertainty. A direct upscaling from the laboratory experiments yield estimates outside the industry estimate of (Ahluwalia *et al.*, 2011) even for the maximum lifetime and exclude LOHC solution as a feasible option. Therefore, a scaled range which are in line with the industry estimate is assumed and a corresponding scaling factor as for the plants is assumed also for the catalyst (0.57). The scaled estimates are presented in Table 4-10.

A part of the concept analysis is to evaluate the feasibility of the system. The mapping of the sub-system related to catalyst for LOHC, uncovers challenges related to both estimation of the required catalyst amount for hydrogenation/dehydrogenation of hydrogen, as well as lifetime of the catalyst. Therefore, some assumptions based on this chapter had to be made for the inventory. The concept analysis uncovers that:

- The calculations performed on platinum demand is related with high uncertainty, as the estimations are upscaling based on low-scale laboratory experiments. The presented estimates yield a total demand of around 6 tons of platinum over the lifetime of the hydrogenation and dehydrogenation with 3 years lifetime for the catalyst, with the production of almost over 900 million kg of hydrogen. It is stated that the platinum production in 2021 was 180 metric tons and the average from 2010 to 2021 was 183 metric tons (Garside, 2022). Over the 20-year lifetime, with the yearly production of 183 metric tons, the demand from the LOHC system would equal around 0.2%. If the experimental estimations (Brückner *et al.*, 2014; Jorschick *et al.*, 2020) was directly upscaled with capacity to hydrogenate the maximum hydrogen production, and with conservative lifetime (1 year), an overall platinum demand of 33 tons was calculated, requiring around 0.9% of the world's platinum production in a 20-year perspective. The requirement of close to 1% of the world's platinum production for one single large-scale system appears as unfeasible, and as scaling factors are believed to be present also for upscaling of catalyst, the 0.57 scaling factor was added.
- The platinum demand may cause show-stopping challenges for large-scale LOHC systems if the platinum demand is in the upper range, combined with a low lifetime of the catalyst. It is further in this thesis assumed that these challenges are solvable and the inventory is investigated in a range where the LOHC solution is considered as feasible. This assumption is eliminating the lowest and the highest estimations for platinum need and is focusing on a broad range around the industry estimate presented by Ahluwalia *et al.*, (2011)

4.2.6 Summary of LOHC concept analysis

The concept analysis for LOHC has proposed a storage configuration in an offshore environment which allow storage of hydrogen produced by a 500 MW electrolyser system and processed to LOHC by an FPSO. Relevant feasibility aspects for the solution have been investigated, as production volumes and corresponding LOCH demand, space requirements for the plants, storage solutions and catalyst demand. The result from the concept analysis is based on several relatively uncertain estimates, as a lot of relevant information for such system is not publicly available. The results from this analysis are foundation for the following LCA analysis and yields insights to the LCI. A summary of the results is shown in Table 4-11:

Table 4-11 - Summary of findings from the concept analysis. Yellow boxes indicate medium feasibility, green boxes indicate assumed feasibility.

	Area	**Flow suitability**	**Energy efficiency**	**Material compatibility**	**Energy deliverance**
Estimation	Hydrogenation system estimated to fit on one deck of a platform or the surface of an FPSO	Good	High energy demand by dehydrogenation and high heat loss in hydrogenation	LOHC: Compatible, but toxic Catalyst: may be a showstopper, depends on material and amount	3425 tons of hydrogen, sufficient for providing ~800 roundtrips with a Panamax ship from Kristiansand to Southern North Sea II
Uncertainty	Medium	Low	Low	Low	Low

5 LCA

This chapter presents the formal steps of the determination of LCA results; goal and scope (G&S) definition and LCI. The LCIA and the interpretation is presented in the results chapter. The deduction of G&S and LCI is based on the ILCD Handbook and the ISO-14044 standard (ILCD, 2010, ISO, 2006). These references are recommended for clarifications of concepts and conceptions referred to in this chapter, if unfamiliar for the reader.

5.1 Goal and Scope Definition

5.1.1 Goal definition

This thesis aims to investigate the value chain related to offshore hydrogen production and specifically how the storage and distribution part of the value chain contributes to the overall environmental impact. The goal of the environmental study is to determine which of the analyzed offshore hydrogen storage and distribution options that yields the lowest environmental impact. This goal will contribute to answer the environmental aspects of the research question that is defined for this thesis. The LCA will analyze the storage solutions that are described in the concept analysis and aims to highlight "hot-spots" in the value-chain. The goal and scope definition are defined to be able to answer to the goal of the LCA, within the framework of the LCA methodology. The six aspects that defines the goal definition, are described in the following section.

The LCA will compare and define which of the analyzed alternatives that yields the better environmental option and it is therefore a micro-level decision supporting study. The chosen impact assessment method is ReCiPe Midpoint (H), which with 18 impact categories that estimate potential environmental impact (Further descriped in Chapter 5.1.2). The focus of this LCA is on impact category global warming potential (GWP) and is therefore limited in terms of analysis of other impact categories. A selection of assumptions has been made for the LCA, which has been stated through the concept analysis and system descriptions. The influence of major assumption has been tested by creating ideal and conservative scenarios, with altering of important parameters. As introduced in chapter 1.2.2, several ongoing projects that plans offshore hydrogen production, proposed with several different storage and distribution configurations, has limited literature coverage in an environmental perspective and this LCA can contribute to insights in the environmental impact of such solutions. Combined with the micro-level decision support assumed, the modelling framework adopted is attributional. The results are intended for an academic audience, but in a further perspective, these results may yield interest to politicians and policymakers, as well as project executers, for insights to environmental impact of different storage technologies in an offshore environment. The LCA is a comparative and compare the UHS and the LOHC offshore hydrogen storage and distribution options.

5.1.2 Scope definition

The deriving of the scope is presented in the following section. The functional unit of this thesis is 1 kWh hydrogen pressurized to 180 bars, delivered at shore. As a kg perspective can be more intuitive to understand and is often the given functional unit by LCAs the results will be presented both by the functional unit (kWh), as well as per kg. The system's function is to store hydrogen for minimum one month and allow distribution of the hydrogen to shore. A month is defined to propose a temporary storage solution for what has been defined as "large-scale" by this thesis; a production rate exceeding 270 tons for a month's storage period. Though various components have shorter lifespans and will need replacement, the overall lifespan of the system is assumed to be 20 years. The pressure output is defined by the expected output from reservoir storage, after pressure drops in production and transportation in pipeline is included. These calculations are provided in the concept analysis with an estimated output pressure of 180 bar. A compression unit is therefore added at the LOHC output, for hydrogen compression to 180 bars. Both systems are expected to deliver hydrogen which can be used in industrial processes or in a solid oxide fuel cell (SOFC) but needs to be cleansed for use in a PEM (Proton Exchange Membrane) fuel cell. As this is similar for the two systems and the scope is defined at hydrogen outlet, the cleaning unit is not included. The reference flow indicates the inputs and outputs to the system, based upon the outlet of one functional unit.

Two storage systems for hydrogen in an offshore environment is studied and compared. The studied systems are briefly summarized:

Porous underground hydrogen storage (UHS)

Hydrogen can be stored in several geological formations, but the focus of this thesis is on porous UHS, available from depleted O&G fields. Several actors are investigating the option of repurposing existing infrastructure from NG to hydrogen (cf. chapter 2.2.3). In this thesis, the environmental advantage of such scenarios will be investigated by analyzing the impact of the infrastructure when all is assumed new. UHS in the hydrogen value chain is illustrated in Figure 5-1:

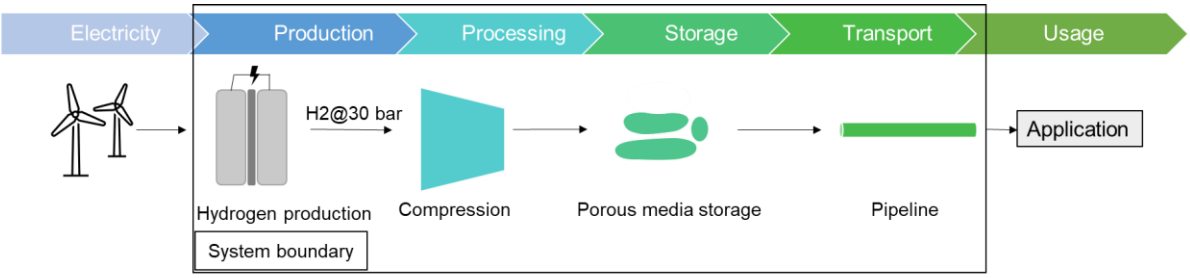

Figure 5-1 - Illustration of the value chain for a UHS storage case in an offshore environment, including system boundaries. The colors of the figure indicate different steps in the hydrogen value chain, based on Figure 1-1. Hydrogen production is indicated with grey color as it is has not been the primary focus.

LOHC storage in FPSO

For the LOHC storage case, hydrogen is assumed to be processed to liquid, organic hydrogen carrier, stored in a floating structure and transported by chemical tankers or used by shipping vessels, illustrated in Figure 5-2:

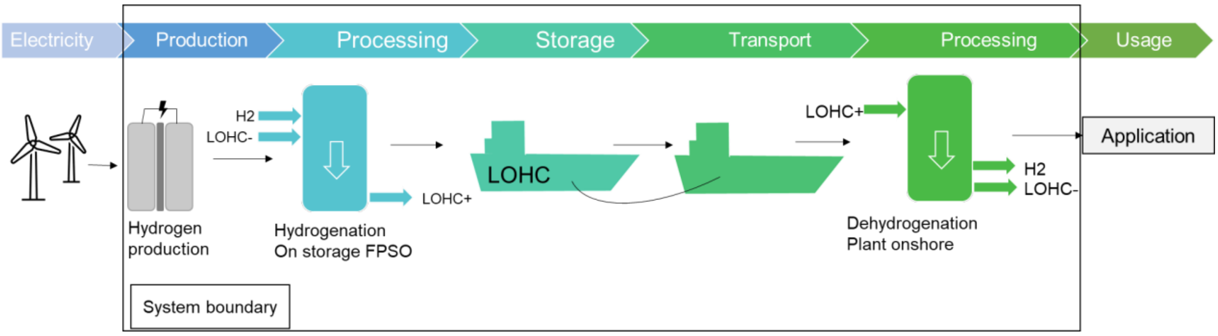

Figure 5-2 - Illustration of the value chain for an LOHC storage case in an offshore environment, including system boundaries. The colors of the figure indicate different steps in the hydrogen value chain, based on Figure 1-1. Hydrogen production is indicated with grey color as it is has not been the primary focus.

As described in chapter 4.2.3, the LOHC storage is proposed with two different configurations, case A) and case B). As the two LOHC cases are related with significant similarities, only separated by the location of the hydrogenation plant, the storage systems are in a comparison view mentioned as the *two* storage systems UHS and LOHC. When the cases are separated in the LOHC systems, it is specifically mentioned and defined as storage cases.

The LCA is based on a future scenario, accounting the year 2030. Some technology development and improvements are therefore expected. The two system are based on the common system for hydrogen production through electrolysis, provided by a wind farm. The system descriptions are thoroughly presented in chapters 5.2.1.1, 5.2.2 and 5.2.4.

The background processes are the windfarm (thus the electricity generation), the platform and the end-use of the hydrogen, whilst the foreground system consist of the unit processes hydrogen production, processing, storage and distribution systems (see Figure 5-3):

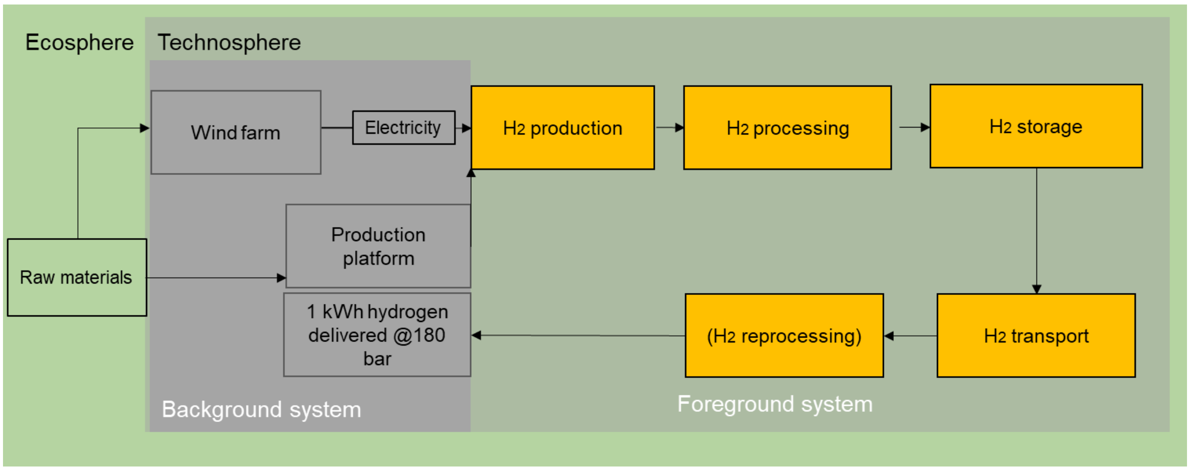

Figure 5-3 - Illustration of the foreground and background processes of the analyzed system. The background data is illustrated as inputs only to the background system as the inputs for each of the unit processes (orange boxes) is described in detail in the LCI.

Green hydrogen production was not found covered in any relevant LCA database and was therefore adopted from other LCA studies. Hydrogen production includes production of hydrogen, oxygen and heat. It is assumed that the surplus oxygen produced will be vented to the air and that the surplus heat is not useful in the offshore environment and therefore regarded as waste heat. The multifunctionality of the system is therefore eliminated and no system expansion is assumed. To make a comprehensive coverage of the environmental impact of the analyzed systems, the ReCiPe Midpoint (H) assessment method as chosen and the 18 environmental impact categories included in this method are summarized in Table 5-1 (Acero, Rodríguez and Ciroth, 2015):

Table 5-1 - impact categories used in ReCiPe (H), corresponding units and short description of impact indicator and endpoint damage area.

Impact category	**Unit**	**Impact indicator**	**Endpoint damage impact**
Climate change	Kg CO_2 eq.	Increase in global temperature and climatic phenomenon	Human health, ecosystems
Stratospheric ozone depletion	Kg CFC-11 eq.	Increase of UC radiation, illnesses caused by radiation	Human health, ecosystems
Ionizing radiation	Kg U235	Effects of radiation exposure (illness, etc.)	Human health
Ozone formation, human health	Kg NOx eq.	Ozone on the ground, creation of smog	Human health, ecosystems
Fine particulate matter formation	Kg PM	Increase in particulate matter in air	Human health, ecosystems
Ozone formation, terrestrial ecosystems	Kg NOx eq.	Ozone on the ground, creation of smog	Human health, ecosystems
Terrestrial acidification	kg SO_2 eq.	Reduction of pH, hence, increase of acidity in soil systems	Ecosystems
Freshwater eutrophication	Kg P eq.	Accumulation of nutrients	Ecosystems
Marine eutrophication	Kg N eq.	Increase of nitrogen, phosphorus and possible formation of biomass	Ecosystems
Terrestrial ecotoxicity	kg 1.4 DCB eq.	Biodiversity loss/extinction of species on the soil	Ecosystems
Freshwater ecotoxicity	kg 1.4 DCB eq.	Biodiversity loss/extinction of species in freshwaters	Ecosystems
Marine ecotoxicity	kg 1.4 DCB eq.	Biodiversity loss/extinction of species in the ocean	Human health, ecosystems
Human carcinogenic toxicity	kg 1.4 DCB eq.	Cancer	Human health
Human non-carcinogenic toxicity	kg 1.4 DCB eq.	Other severe diseases/health impact	Human health
Land use	m^2a	Different alterations on soil (for example loss of species)	Ecosystems
Mineral resource scarcity	Kg Cu eq.	Decrease of mineral resources	Resource availability
Fossil resource scarcity	Kg oil eq.	Decrease of fossil resources	Resource availability
Water usage	m^3	Decrease in water availability	Ecosystems, resource availability

Data from EcoInvent database and ILCD database is used as background data. Existing LCAs has been used for quantification of the environmental impact of hydrogen production from wind. For the foreground systems, data collection is performed by data gathering from standards, manufacturers, literature and with conversations with experts on the different storage solutions, to alter the background data to fit the foreground system. Details regarding the data that is used in the analysis, is provided in LCI chapter. The data has been evaluated in terms of their completeness, representativeness, precision and consistency and no major issues related to any of this evaluation categories has been uncovered. The most uncertain data material is linked to the adaption of a car catalyst regime for recycling of industrial catalyst, which may have issues related with technological representativeness. All the relevant data for the LCA is presented for reproducibility.

5.2 LCI

In this chapter, the system descriptions of the common system hydrogen production and the storage systems are provided. The data material used for the LCIA is presented. The common system, hydrogen production, is presented first, followed by the UHS and LOHC cases. The data material and the calculations are described quantitively in the sub-sections and summarized quantitative by table on the end of each section. The transport information is important for all the unit processes and all important information about assumed transportation routes and distances are assembled in Appendix II: Complementary LCI.

5.2.1 Common system – hydrogen production

5.2.1.1 System description

In this chapter, the assumptions and justifications for the hydrogen production, which is common for both storage systems, is presented. Hydrogen is assumed produced by a 500 MW electrolyser system provided with electricity from a wind farm. The processing of the hydrogen to compressed hydrogen and to LOHC has different energy demand, but the same electrolyser capacity (500 MW). The wind farm is therefore calculated to serve electricity for both the 500 MW electrolyser system, as well as other electricity requirements on the platform (see Figure 5-4). The wind farm is located in a shallow region in the Southern North Sea II 140 km from land, with a bottom-fixed structure and a capacity factor of 57% (Equinor, 2021, Sæbø *et al.*, 2020).

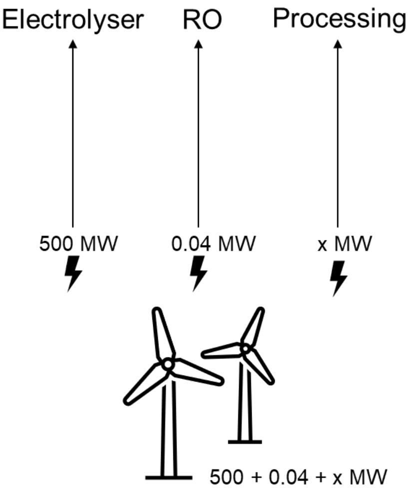

Figure 5-4 - Illustration of the energy system. The electrolyser capacity is assumed to be the same for the two systems, whilst the energy needed for processing is varying - and the wind farm capacity is therefore adjusted after this demand.

For the water requirement for the electrolysis, it is assumed that sea water is pumped to the platform deck and converted to freshwater by reverse osmosis (RO) (see Figure 5-5). The energy requirement for the RO system is included in the scope. Water demand is an important factor when determining the power consumption for the RO and is found to be 10 to 25 L/kg H_2 (ITM POWER, n.d; Siemens, n.d). The energy demand for RO is adapted as 4.5 kWh/m^3 water (Hank *et al.*, 2020). The environmental impacts resulting from heat and concentrated salt emissions to the natural environment are not within the scope of this LCA study.

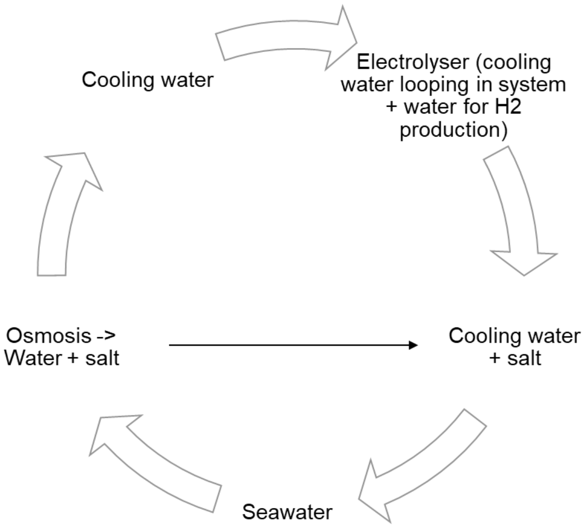

Figure 5-5 -Illustration of the pathways of the salt water pumped from the ocean through the cooling water loop.

Area estimations for a platform for accommodation of the electrolyser system is estimated to be 10 000 m^2, based on interpolated data from a 100, 200, 400 and 800 MW electrolyser system (Sæbø *et al.*, 2020). This area is out of the scope as it is common for the two systems but calculated to assure assumed feasibility. It is estimated that an additional deck of 6000 m^2 is needed on the platform, for accommodation of the hydrogenation plant (LOHC), compressors and pump equipment (UHS) and other necessary balance of plant (BOP). Based on a range of offshore platform structures, built both for hydrocarbon recovery and accommodation of AC/DC conversion equipment from windfarms (Aibel, no date; INPEX, no date; Tønnesen and Sandberg, no date), it is assumed that the electrolysers, the RO and the other relevant BOP fits on one deck of the platform, which is out of the scope. The processing equipment is assumed to fit a separate deck, which is included in the scope. It is further assumed that the platform tolerates the weight of the equipment.

PEM (Proton Exchange Membrane) electrolysers are assumed for hydrogen production, as they are characterized with faster response time than alkaline electrolysers, allow an output pressure of 30 bars[12] and requires less area than alkaline electrolysers (IRENA, 2019). The area requirements are the most significant feature for choosing PEM over alkaline electrolysers in an offshore environment where space occupation is crucial. An efficiency of 61% is assumed based on available data (Buttler and Spliethoff, 2018) and electrolysers of sufficient capacity is assumed available by 2030 (IRENA, 2019). An AC/DC converter is required as the electrolysers utilize direct current (DC), whilst wind farms traditionally produce alternating current (AC) (Spyroudi *et al.*, 2020). The converter is placed either subsea or on the platform, but is excluded from the scope. It is assumed no degradation on neither of the storage solutions. The lifetime of the electrolyser system is assumed to be 10 years for the stack and 20 years for the BOP, with constant capacity through the lifetime, which also yields constant hydrogen production rate through the lifetime of the system. A summary of the assumptions related to hydrogen production is presented in Table 5-2.

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[12] Based on commercial electrolyser brands (NEL, McPhy) deliver PEM electrolysers with a 30-bar outlet pressure.

Table 5-2 - Summary of assumptions regarding the hydrogen production scenario (common for both UHS and LOHC storage cases).

Input parameter	Value	Reference
Electrolyser capacity [MW]	500	Defined
Wind farm capacity factor [%]	57	Equinor (2021), Sæbø *et al.*, (2020)
Electrolyser efficiency [%]	61	Buttler and Spliethoff, (2018)
Electrolyser type	PEM	Defined
Production configuration	Centralized system, bottom-fixed	Defined
Distance to shore [km]	140	Østenby, (2019)
Sea depth [m]	40-70	Østenby, (2019)
Size of platform (surface area) [m^2]	10 000 (only electrolysers) 16 000 (including compressors/hydrogenation)	Own estimations
Lifetime of installation [years]	20	Defined
Temporal limitation	2030	Defined
LHV/HHV	LHV	Defined

5.2.1.2 Data description

Despite numerous LCA studies on green hydrogen production, it is not found as inventory in LCA databases. Therefore, the inventory of green hydrogen production from PEM electrolysers is adapted from literature (Bareiß *et al.*, 2019). The study estimates a 1 MW electrolyser system for existing technology and for "near future" and the estimate for near future is adapted as inventory. Neither heat, electricity, water or chemical flows are considered for the electrolysis assembly by the adapted study, but electricity demand is adapted by (Evangelisti *et al.*, 2017), which presents such estimate for the assembling of a fuel cell stack. The electrolyser area estimation of the near future estimate fits the estimate given in (Sæbø *et al.*, 2020) and is in a similar range as inventory given similar study (Zhao *et al.*, 2020).The process flow is shown in Figure 5-6 (inspired from (Lundberg, 2019)):

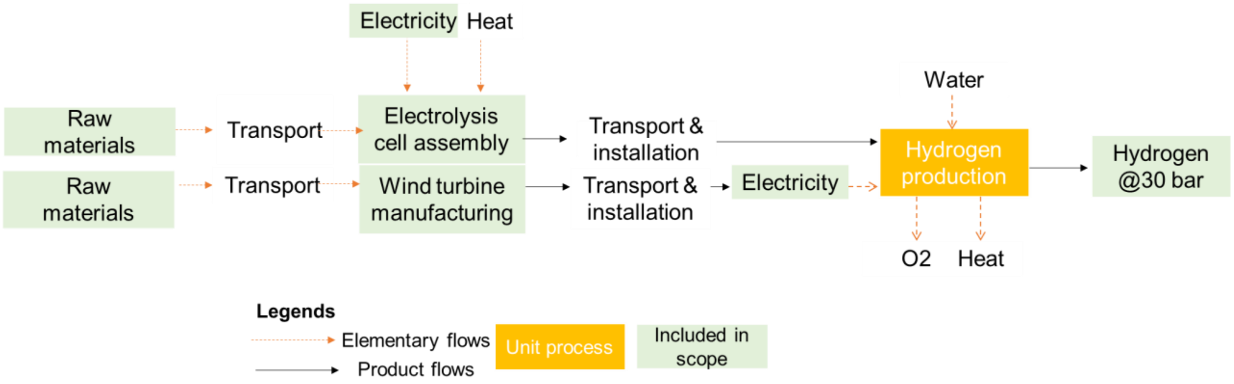

Figure 5-6 - Overview of the flows that is related to the unit process hydrogen production.

Hydrogen production from PEM electrolysers is requiring a lot of specific materials, as platinum, iridium and nafion. The last mentioned was not found in LCA databases and therefore, had to be adjusted to a more regular plastic (polyethylene) to be represented. This is a rough estimation, as Nafion is a specialized material. Iridium is not found in the EcoInvent database, but Iridium is a noble metal which is a co-product of platinum and is extracted in the same locations (Bareiß *et al.*, 2019). Therefore, the given amount of iridium is replaced with platinum as proxy. The input flows are presented in Figure 5-6 and quantified in Table 5-2Table 5-3:

Table 5-3 - Inventory of electrolyser system. Including BOP. BOP is given in tons, whilst stack is given in kilograms. The inventory is given for the whole 500 MW electrolyser stack. The inventory is directly adapted from (Bareiß et al., 2019) as "near future" and adjusted to the production volumes in this thesis.

Inventory, electrolyser stack	**Estimated value (assumed for 2030)**	**Unit**
Titanium	18 500	[kg/500 MW]
Aluminum	27 000	
Stainless steel	20 000	
Copper	4500	
Nafion®, modelled as polyethylene	1000	
Activated carbon	2250	
Iridium, proxy by platinum	18.5	
Platinum	5	
Sum	73273.5	
Energy requirement for stack assembly (Evangelisti et.al, 2017)	30 960	[kWh/MW stack]
Inventory, BOP		
Low alloyed steel	2400	[tons/500 MW]
High alloyed steel, modelled as low-alloy steel	950	
Copper	50	
Aluminum	50	
Plastic	150	
Electronic material, modelled as electronics for control units	550	
Process material	50	
Concrete	2800	

5.2.2 UHS – System description

The concept analysis of the reservoir case (Chapter 4.1), describe how the UHS case can look like practically and with quantified estimations of the different parts of the systems. In this chapter, the most important findings which lays the foundation for the inventory in the LCA is presented in a summarized system description. Furthermore, a detailed description of the data which is used for the inventory for the different part of the system is presented.

From hydrogen production outlet, the hydrogen is injected to a reciprocating compressor on the floating facility or rig and compressed to 200 bars. The hydrogen flows through the riser, through the well head and to the reservoir through the well. As the injected gas is assumed to be pressurized higher than the reservoir pressure, this will create a flow from the injection inlet to the reservoir. The withdrawal from the reservoir to the wellhead is driven by the pressure difference between reservoir and surface and no compression equipment is assumed to be necessary. From withdrawal wellhead, hydrogen can be lead either in pipelines to shore, or in riser to sea surface for bunkering vessels. For this thesis, transportation in pipelines to shore is assumed. Hydrogen transport by vessels would require significantly higher pressure, due to the low volumetric density of hydrogen. This would mean that a re-pressurization to either 350 or 700 bars would be necessary by well-head, before an eventual bunkering to a vessel. As it is a depleted field, the well mapping and drilling is excluded from the scope. The infrastructure in the downhole (casings and cement layers) may be reusable hydrogen injections and withdrawals. However, the infrastructure is included in the scope of this analysis to be able to determine which impact the infrastructure has, compared to e.g. the platform or the transportation pipeline.

5.2.3 Data descriptions, UHS

The inventory data that is utilized for the different parts of the LCI for the UHS system are presented in the following chapters. The unit processes for the UHS case are assembled in one process flow diagram (Figure 5-7), whilst the inventory tables are summarized by each unit process (sub-chapters).

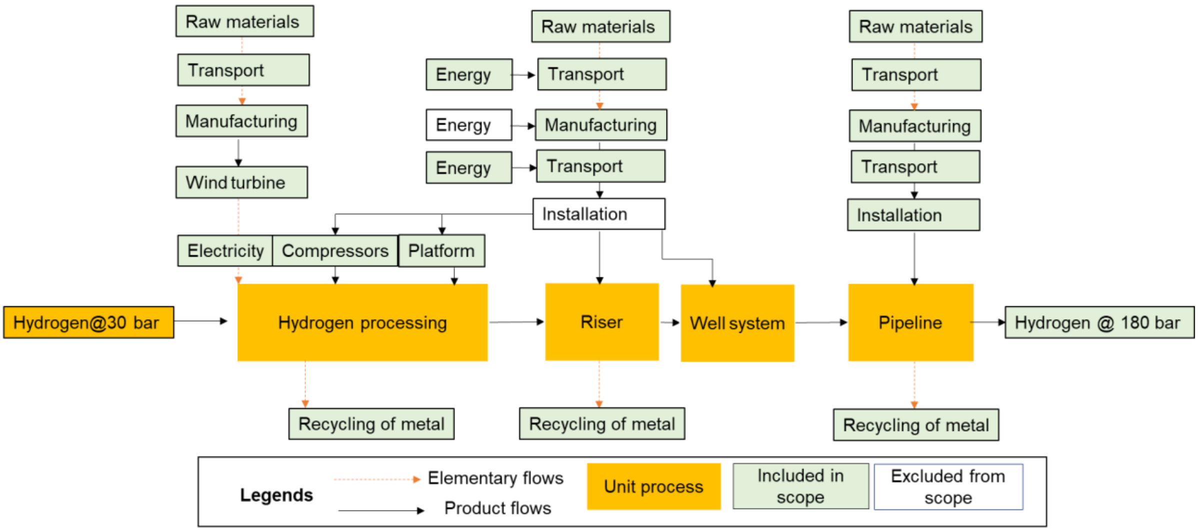

Figure 5-7 - Process flows for the UHS system

5.2.3.1 Hydrogen processing

Compressors

The energy necessary for hydrogen compression to 200 bars, is calculated to 2.7 kWh/kgH_2 (cf. chapter 2.2.1). Inventory specific for hydrogen compressors are not found and existing background data for air-compressors is therefore adapted. The existing background data accounts for a large fraction of stainless austenitic steel and is therefore assumed to be a valid approximation. The background data accounts for 300 kW compressors, whilst it is likely that hydrogen compressors for large-scale production will be of a significant larger scale. It is assumed that the relative material demand by capacity decreases when the compressor size increases, but this is not accounted for as no confirming data was found. Necessary BOP is assumed to be included for the compressor system. The preliminary iterations indicated that the compressor infrastructure equal a negligible part of the total system and further analysis regarding the compression system is therefore not performed. The compressor material is mainly steel, assumed to be recycled. Several manufacturers of hydrogen compressors are found and several of them manufacture their products in Germany and Germany is therefore defined as production location.

Platform

The platform impact is simulated by background data which covers a small natural gas production platform. To account for a deck area that can accommodate the hydrogenation plant/compressor system (6000 m^2), a number exceeding one platform that includes the jacket and subsea infrastructure must be assumed, as the background data cover a platform less than 6000 m^2 in surface area. Only the area estimated for accommodation of the processing equipment is included, as the electrolyser deck is common for both storage scenarios and therefore only contributes to increase the quantitative results but yields no comparative difference. Inventory for the hydrogen processing is summarized in Table 5-4:

Table 5-4 - Inventory for unit process Hydrogen processing for UHS storage case.

Inventory	Amount, total	Unit
Hydrogen for compression	907 531	Tons
Air compressor, 300 kW	321 (84)	Tons (Units)
Platform	3.75	Units
Transport of compressors (road)	160 753	Tkm
Transport of compressors (sea)	160 753	Tkm
Electricity for compression	253 478 399	kWh

5.2.3.2 Riser

As stated in the concept analysis (cf. chapter 4.1.5), high-strength, low-alloyed austenitic steels with adjusted wall thickness are assumed accepted for hydrogen transport in the riser and the well system. The diameter of the riser is defined to be 12" (304.8 mm) with a calculated wall thickness of 25 mm based on adjustments for hydrogen transport. Background data for low-alloyed steel, pipe manufacturing and hot-rolling is used as inventory for the riser (see Table 5-5). Zinc coating is assumed for cathodic protection and the amount is adapted from the inventory for the transport pipeline. The riser system is expected to be produced at in Egersund, Norway, where relevant industrial actors are located.

Table 5-5 - Inventory of the riser.

Inventory	Amount, total	Unit
Hydrogen	907 531	Tons
Low-alloyed steel	1.2	Tons
Hot rolling	1.2	Tons
Drawing of pipe	1.2	Tons
Transport of riser	3560	Tkm
Zinc	3.68	Kg

5.2.3.3 Well system

18/8 chromium steel, containing 18% chromium and 8% nickel, is a typical austenitic, stainless-steel type (Davis, 2001), assumed applicable for hydrogen transport (cf. chapter 4.1.4). 18/8 chromium steel is used as inventory for injection/production tubing and casing. Low-alloyed steel in the lower strength range (55 000 psi) as suggested in API 5CT, is assumed for outer casings. Low-alloyed steels exceeding 40 000 psi, are considered high-strength, low-alloy (HSLA) steels and can challenge conventional carbon steels in terms of both corrosion resistance and mechanical properties (Davis, 2001). Hot-rolling is not a claim for HSLA-steels, but increase the mechanical properties of the steel and is therefore assumed for the low-alloyed steel variants. Low-alloyed, hot rolled steel is assembled by the background data and this is used as inventory for surface casing, conductor casing and intermediate casing. The well equipment is not subject to recycling or dismantling, as it is assumed to be left in the well after operation. The inventory is summarized in Table 5-6. Nearly all wells are cementing using Portland cement (Nelson, 2011) and is therefore assumed in this inventory. Several of the Scandinavian countries produce Portland cement and Denmark is one of the biggest manufacturers. The cement production is therefore assumed in Aalborg, Denmark.

Table 5-6 - Inventory for the well system.

Inventory	Amount, total	Unit
Hydrogen	907 531	Tons
Low-alloyed steel	514.7	Tons
18/8 Chromium steel	514.3	Tons
Hot-rolling	1029	Tons
Drawing of steel pipe	1029	Tons
Portland cement	433.9	Tons
Transport of pipelines (sea)	514 515	Tkm
Transport of pipelines (road)	360 160	Tkm
Transport of cement (sea)	147 527	Tkm

5.2.3.4 Pipeline

High capacity, offshore natural gas pipeline is used as inventory for the transport pipeline. As described in the concept analysis, it is assumed that carbon steels, specifically X65 which dominates offshore pipelines today (Cauchois *et al.*, 2021) is to be allowed for hydrogen transport. It has been estimated that the transport pipeline should be limited to 12" (304.8 mm), keeping a minimum 24 mm wall thickness (1"). The 100 mm concrete wall coating the pipeline in the original inventory is kept. A coating may be applicable on the inside of the pipeline to further protect the pipeline from hydrogen embrittlement, but this is not accounted for. The pipeline is decommissioned at landfill. Recycling schemes could be considered but is not accounted for in this LCA. Subsea pipelines are assumed produced Wick, UK, as subsea manufacturers are found in Wick.

Table 5-7 - Inventory of transport pipeline.

Inventory	Amount, total	Unit
High-capacity natural gas pipeline (12", 1" WT)	140	Km
Transport of pipeline	16 373 125	Tkm

5.2.4 LOHC – system description

In the following chapter, a summary of the system description of the two LOHC storage configurations are given based on the concept analysis, which is described as LOHC storage case A) and B). The difference between the configurations is the location of the hydrogenation plant and except from this difference, the systems are similar. For the LOHC storage case, hydrogen is processed to liquid, organic hydrogen carriers, stored in a floating structure and transported by chemical tankers or used by shipping vessels. The specific separation of foreground and background of the LOHC system and the unit processes is illustrated in Figure 5-8:

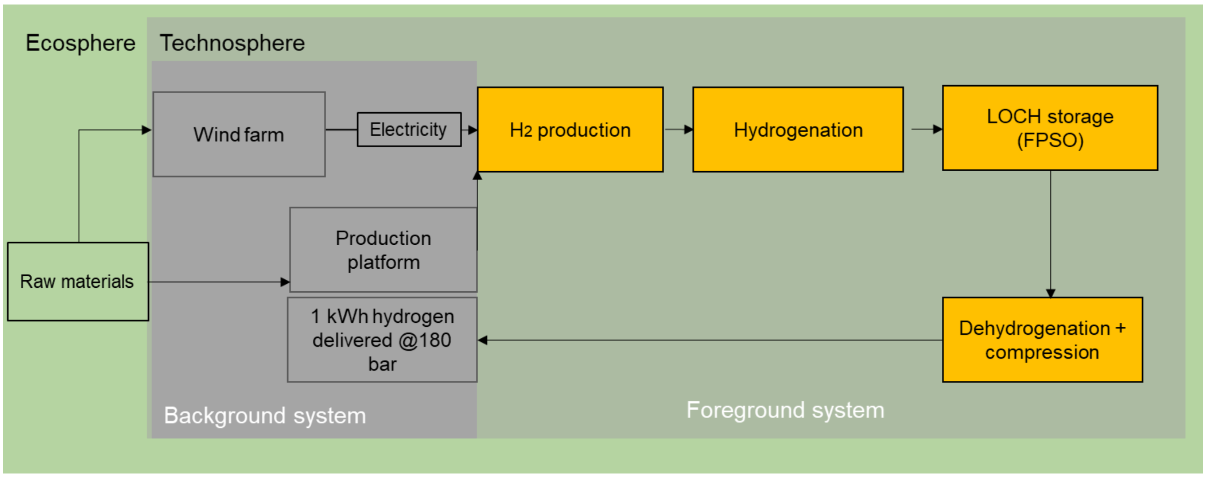

Figure 5-8 - Overview of the foreground and background processes in the LOHC storage scenario. Orange boxes indicate the unit processes.

The LOHC system configurations has been explained in detail in the concept analysis (Chapter 3.1) and summarized in Table 5-8:

Table 5-8 - Dimensions of inventory as defined by concept analysis.

Inventory part	**Amount**	**Unit**
Monthly hydrogen production	3568	Ton
Monthly BT demand	54114	Ton
Monthly P-BT production	57646	Ton
Size of FPSO [L x D x W]	220 x 40 x 20	m^3
Size of hydrogenation plant	6000	m^2
Size of dehydrogenation plant	12000	m^2

It is estimated that the hydrogenation facility fits one deck on the production platform, or the area of the FPSO. The hydrogenation plant receives hydrogen from the platform and hydrogen-lean LOHC from the hull (see Figure 4-3). In addition to the energy demand related to pumping of cooling liquid, auxiliaries and maintaining conditions for the activation energy, waste heat is generating an energy demand for cooling. Hydrogen can be stored in the LOHC storage facility for one month. Hydrogenated LOHC is transported to shore by an oil tanker for dehydrogenation, where hydrogen is separated from the hydrogenated LOHC and compressed. The dehydrogenation facility is in this thesis assumed to be onshore.

5.2.5 Data descriptions, LOHC

The data material that is utilized for the different parts of the LCI for the LOHC system are in the following chapters. The concept analysis is foundation of the inventory, and this chapter presents the background data material for the LCI based on the defined unit processes (Figure 5-8). Transport of LOHC to and from shore is included in the respective unit processes for hydrogenation and dehydrogenation.

5.2.5.1 Hydrogenation

The hydrogenation process is described in the concept analysis and in the system description (Chapter 5.2.4) and consist of a chemical plant which is located either on a platform deck, or an FPSO (see Figure 4-3). The hydrogenation unit process is shown in Figure 5-9:

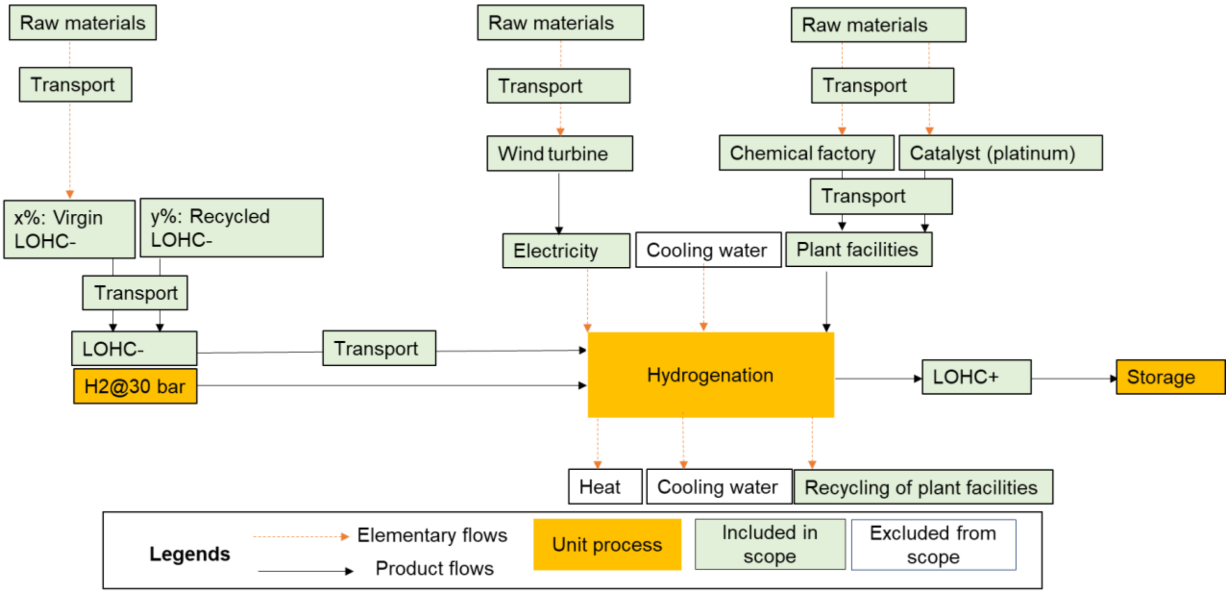

Figure 5-9 - Hydrogenation unit process

<u>LOHC</u>

Toluene is used as inventory for the LOHC system, as no primary data was found on BT production. Production of BT is assumed to be associated with low energy demand, no need for noble catalysts and toluene as feedstock (cf. chapter 2.4.3). Production of toluene is an energy-intensive process which is well-documented in EcoInvent database and it is therefore assumed that the environmental impact of the LOHC is expressed using toluene as inventory (based on uncovered similarities in toxicity features observed by the SDS, cf. chapter 2.4.1). For calculation of the necessary catalyst amount, the production and the related storage space the BT flow is used. As can be recalled from the concept analysis, the LOHC that is brought back from shore by shipping vessels for new hydrogenation is referred to as recycled LOHC, whilst newly produced LOHC is referred to as virgin LOHC. The monthly amount of virgin and recycled LOHC was calculated in the concept analysis (Chapter 4.2.1) and the lifetime amounts are defined in Table 5-9.

The produced hydrogen is affected by hydrogenation and dehydrogenation efficiency. Respectively 99% (hydrogenation) and 97% (dehydrogenation) efficiency is assumed (Brückner *et al.*, 2014; Jorschick *et al.*, 2020) (cf. chapter 2.4.3). This means that some of the recycled LOHC is saturated, which is accounted for by a slight reduction of the hydrogenation volume by the first hydrogenation cycle.

<u>Plant</u>

The size estimations of the hydrogenation plant have been described in Chapter 4.2.2 and this section describes the relevant data material for the LCA. The two most relevant LCAs found on LOHC systems, are by Wulf and Zapp, (2018); Wulf *et al.*, (2018). Like the article by Wulf and Zapp (2018), the chemical factory found in EcoInvent is adapted as inventory for the hydrogenation and dehydrogenation plant. The estimate for a hydrogenation plant of 320 mg/ kgH_2, presented by Wulf and Zapp, (2018) is adapted for weight estimation. On the FPSO, no area is turned in to industrial area and the only impact is related to the chemical factory in itself. The chemical factory for hydrogenation is assumed to be 288 tons, based on the weight estimates by Wulf and Zapp (2018).

For a 20 MW plant (~8 tpd), the energy demand for hydrogenation plant is stated to be around 400 kW (Grønt Skipsfartsprogram, 2022). Based on the daily production rate, this equals an energy demand of 1.2 kWh/kgH_2. It is assumed an additional energy demand of 0.5 kWh/kgH_2 due to the pumping necessary for cooling water. The input energy needed for hydrogenation is therefore assumed to be 1.7 kWh/kgH_2, which is powered by the wind farm and excess heat is assumed released to the air.

<u>Platinum</u>

Calculation of the necessary amount of platinum is described in detail in the concept analysis (Chapter 4.2.5). The largest fraction of the world's platinum reserves are in South Africa and most the production is today newly mined ore, but the amount of recycled platinum in the mix is increasing (Classen *et al.*, 2009). Platinum is therefore assumed mined as newly ore in South

Africa. The catalyst consists of the platinum coated on a regular catalyst material as carbon or aluminum oxide. Only the platinum, being a precious metal, is considered in the inventory. The platinum demand as calculated by the concept analysis for the hydrogenation and dehydrogenation plant and is given in Table 5-9 and Table 5-10.

Recycling schemes for platinum are in place as background data for car catalysts. No recycling scheme for more industrial appliances were found, neither in literature nor in the background data and recycling scheme for car catalysts were therefore adopted as. This recycling scheme is not optimized towards industrial catalyst recycling, however, the most important factors are that the processing of platinum is accounted for and that the recycled fraction is accounted for. This is assumed to be fulfilled by the autmobile recycling scheme.

Table 5-9- Inventory of hydrogenation.

Inventory of hydrogenation	Amount (over the lifetime)	Unit
Hydrogen	907 531	Tons
LOHC-	13 764 214	Tons
Virgin LOHC-	57 351	Tons
Transport of LOHC-	1 926 989 908	Tkm
Electricity	1 542 801 967	kWh
Chemical factory	290	Tons
Catalyst (platinum)	2.1	Tons
LOHC+	14 525 027	Tons
Recycling of platinum	50	%
For case B): Platform	3.75	Units

5.2.5.2 Dehydrogenation + compression

The dehydrogenation process is described in the concept analysis and in the system description (Chapter 5.2.4) and consist of a chemical plant located onshore in Kristiansand. In this chapter, the corresponding data material used for the LCA is presented. The inventory used for the dehydrogenation plant and the catalyst will be presented. The dehydrogenation unit process is shown in Figure 5-10:

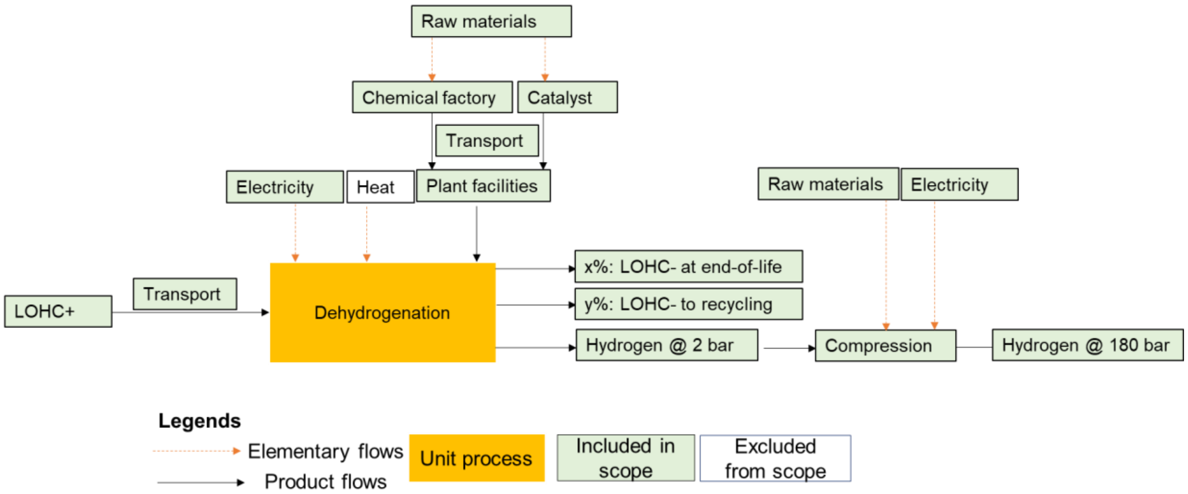

Figure 5-10 - Dehydrogenation unit process

Plant

For the dehydrogenation plant onshore, more impacts related to a chemical factory is included compared to the hydrogenation plant, as conversion of land to industrial area. The estimation of the dehydrogenation plant is 12 000 m^2 (cf. chapter 4.2.2). The background data is inventoried from EcoInvent's existing process "chemical factory, organics", based on the estimations made on plant size and weight. The heat demand for the dehydrogenation is assumed to be provided by electricity and the electricity demand of 12 kWh/kgH_2 for hydrogenation is provided by Norwegian electricity mix.

Compressor system

A compressor system is included as a part of the dehydrogenation system. The compressor system is included is to match the hydrogen output from the UHS case, which is assumed to provide hydrogen at 180 bar and require 2.6 kWh/kgH_2. The inventory for the compressor system is based on an existing inventory for an air compressor in EcoInvent and adjusted for the energy required for compression of the dehydrogenated hydrogen to 180 bars. Figure 5-10 illustrates the flows related to the dehydrogenation unit process. The input, LOHC+, is the last output from the illustration of the hydrogenation.

Platinum

As for the hydrogenation plant, the calculation of the necessary amount of platinum is described in detail in the concept analysis (Chapter 4.2.5) and all the other relevant data given for platinum in Chapter 5.2.5.1 accounts also for the dehydrogenation plant. The inventory of the dehydrogenation process is given in Table 5-10:

Table 5-10 - Inventory of dehydrogenation.

Inventory	Amount, total	Unit
Hydrogen	907 112	Tons
LOHC+	14 525 027	Tons
Transport of LOHC+	2 052 773 645	Tkm
Electricity for dehydrogenation	10 890 366 826	kWh
Chemical factory, organic	580.82 (0.046)	Tons (units)
Catalyst	4300	Kg
LOHC-, to waste	54 058	Tons
LOHC-, to recycling	13 764 214	Tons
Compressors	321 507 (74.6)	Kg (units)
Electricity for compression	2 340 830 869	kWh
Recycling of platinum	50	%

5.2.5.3 Storage (FPSO)

In this section, the data material for inventory of the storage unit process is presented, illustrated in Figure 5-11:

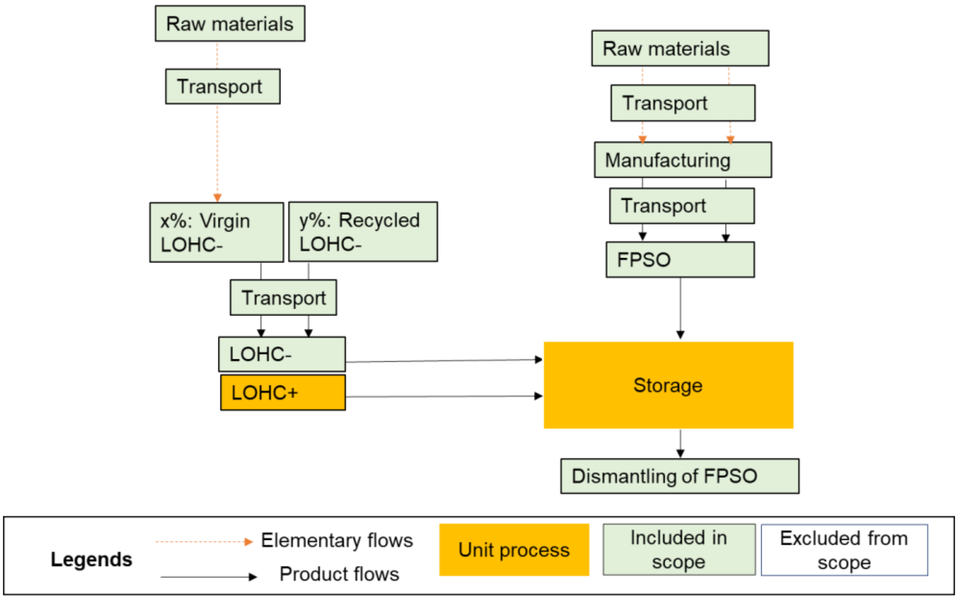

Figure 5-11 - Storage unit process

A petroleum tanker with a capacity of 36 000 DWT is assumed as inventory for the FPSO, which is given as background data in EcoInvent. For both analyzed cases (Case A and Case B), the hydrogenated and hydrogen-lean LOHC is expected to be stored in the FPSO. As described in the concept analysis, would storage tanks demand a large area and is not considered as a feasible option. The main difference between a FPSO and a tanker is mobility, where tankers are designed for transport, an FPSO can be designed for more stationary appliance. Therefore, an oil tanker is defined to be a valid estimate for a FPSO with a propulsion system.

36 000 DWT is smaller than a medium/large range FPSO as assumed for this system. A month's LOHC production equals about 50 000 tons of liquid, hydrogenated LOHC (see Table 4-8), meaning that approximately one and a half tanker in the size that is given in EcoInvent is needed for the storage of one month's hydrogen-lean LOHC to one month's hydrogenated LOHC. A reduction in the need for infrastructure per kg H_2 is assumed when upscaling the ship, but as the background data is given for a 36 000 DWT ship, this data is upscaled for inventory of the FPSO.

The ship is assumed to be produced in Turkey, a Turkey has grown to be a significant ship manufacturer in Europe and Turkish shipyards are producers especially of low-tonnage chemical tankers (OECD, 2021). Disposal scenario is included for the ship assessed in EcoInvent for disposal and recycling of the materials. The energy required for dismantling is not included and was sought in other LCAs. Some studies investigating ship LCAs were found, amongst them Ko (2015). The studies were not including the energy for dismantling as a part of the scope. Therefore, the dismantling energy is excluded from the scope.

Table 5-11 - Inventory of storage unit process.

Inventory	**Amount**	**Unit**
FPSO	1.39	Number of ships
Transport	57 045 600	Tkm

6 Results and discussion

This thesis evaluates technical and feasible aspects of the two analyzed storage systems UHS and LOHC and performs an LCA to assess the environmental impact. For a complex system such as hydrogen processing and storage in an offshore environment, there are several factors for the feasibility of a storage solution, in addition to the environmental viability. Selected feasibility aspects, defined by the boundaries of the LCA, has been assessed in the concept analysis (see Figure 6-1). The concept analysis has covered important parameters linked to the LCI and therefore yields a foundation for execution of the LCA.

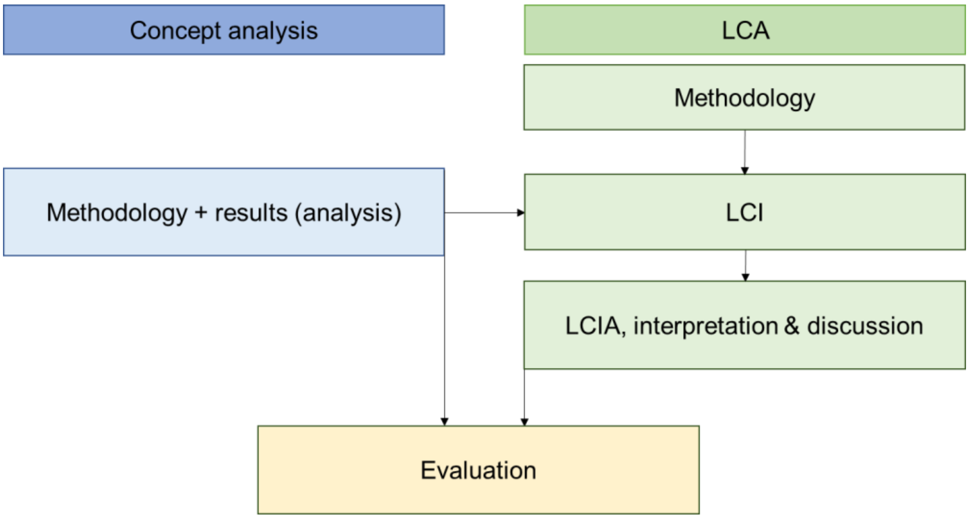

Figure 6-1 - Illustration of deducted results from the two analyses.

The results will present the defined LCA scenarios, results of GWP, general environmental impact results and reference flow. The common evaluation of the two presented analyses (Concept and LCA) will primarily be discussed in chapter for future work, as results and discussion for the concept analysis has been provided in its respective chapter (chapter 4).

6.1 Scenarios and data quality

In lack of adequate data availability, approximation and extrapolation from sparse data was performed for many parts of the system analyzed by concept analysis and LCI. It was also uncovered through theory and concept analysis that many of the assumed important parameters for the LCA are related with high uncertainty. The LCA data quality relies on background data from the EcoInvent database. This is one of the most comprehensive LCA databases in the world and if the right prerequisites are defined, it offers high data quality. All the data inputs used in the LCA has been investigated in terms of their completeness and representativeness and if not found sufficient, other alternatives have been sought. However, some of the background data was not specific for the chosen process, e.g., platinum recycling and similar background data had to be adjusted.

Generally, the quality of the analysis would increase with increased data availability and quality. Provided industry estimates covered smaller systems and upscaling was needed to evaluate larger systems. To account for some of the related uncertainty, three scenarios were defined for presentation of the LCA results: ideal, base and conservative scenario. The concept analysis provided important input to define such scenarios. As defined by the concept analysis, the LOHC storage system is divided in two storage solutions; Case A) where the hydrogenation plant is on the FPSO and Case B) where the hydrogenation plant is on the platform. For consistency, the storage systems (UHS, LOHC A and B) are called cases, while the parameter variation is called scenarios. The scenarios are abbreviated as follows; I - Ideal, B - Base and C – Conservative. Each storage case (UHS, LOHCA and LOHCB) is followed by the letter I, B or C to identify scenarios (see Table 6-1) and used throughout the chapter:

Table 6-1 – Overview of the abbreviation for the different storage cases and scenarios.

	Underground storage case (UHS)	**LOHC case A)**	**LOHC case B)**
Ideal	UHSI	LOHCAI	LOHCBI
Base	UHSB	LOHCAB	LOHCBB
Conservative	UHSC	LOHCAC	LOHCBC

The definition of the varying parameters in the scenarios are presented in the following sections. The results are presented based on these scenarios, due to the high uncertainty and to highlight the expected range rather than the result for one of the defined scenarios.

6.1.1 Porous UHS

Hydrogen pressure [bar], the reservoir recovery rate [%], the transport recovery rate [%] and the compression work [% of LHV] are chosen as UHS scenario parameters. The hydrogen pressure does not impact the LCA results but influences the flow rate of the system. The pressure range defined by the scenarios all maintains an acceptable well and pipeline flow rate and maintain an accepted pressure drop in the transport pipeline (cf. chapter 4.1.5).

The compressor capacity and energy demand vary between the different scenarios. Compression work of 2.7 kWh/kgH_2 is estimated for the base scenario from adiabatic work (see chapter 2.2.1), but real data for compression work has a wide range and is therefore varying parameter by scenarios. The injection regime is important for the final withdrawal in the reservoir storage case (cf. chapter 2.3.2). This thesis evaluates the overall hydrogen recovery based on the simulated results from Lysyy *et al.* (2021) and the fraction of the initial cushion gas is therefore assumed produced by the lifetime of the system. The parameters are summarized and displayed in Table 6-2:

Table 6-2 - Scenarios for UHS.

Parameters for UHS

Parameter	Conservative	Base	Ideal
Hydrogen pressure [bar]	140	200	250
Transport recovery rate [%]	75	90	95
Reservoir recovery rate [%]	50	70	90
Compression work [% of LHV]	12	8	5

6.1.2 LOHC

For the LOHC systems, scenarios are defined by the following parameters: platinum amount [kg] and recycling [%], LOHC lifetime (cycles) and hydrogen loss [%] in hydrogenation/dehydrogenation.

The LOHC lifetime has limited coverage in literature, but are defined in some studies (Ahluwalia *et al.*, 2011; Teichmann, Arlt and Wasserscheid, 2012) (cf. chapter 2.4.1). 240 cycles are defined as the base (based on (Grønt Skipsfartsprogram, 2022), cf. chapter 4.2.1), whilst 1000 cycles is defined as ideal (Teichmann, Arlt and Wasserscheid, 2012). To uncover impact of cycle lifetime, also a low number was investigated by the conservative case and the same relation as between 1000 cycles and 240 cycles was used to define the conservative case (58 cycles).

The platinum amount is upscaled from laboratory experiments on a very small scale and is therefore defined as a scenario-sensitive parameter. The scenario parameters spans a range which is adapted from experimental results (Brückner *et al.*, 2014; Jorschick *et al.*, 2020) scaled by 0.57 to fit the range of the presented industry estimate (Ahluwalia *et al.*, 2011) and assume respectively 1, 3 and 5 year lifetime of the estimated catalyst need by the experimental setup. The ideal platinum catalyst lifetime is based on the expected stack lifetime as presented in the adopted study for the PEM electrolyser stack, which also utilizes platinum (Bareiß *et al.*, 2019) (40 000 hours). A more modest lifetime is assumed for the base scenario and conservative scenario due to the uncertainty related to this factor and conversations with experts in the industry and by the conservative estimate of 1 year from lab test as presented by (Kurosaki, 2018).

Hydrogenation is defined with 99% (hydrogenation) and 97% (dehydrogenation) as base (Brückner *et al.*, 2014; Jorschick *et al.*, 2020). The scenarios were defined based on the range given by the two experimental studies (cf. chapter 2.4.3) and 99.5% was defined as an upper estimate and 98% as a lower estimate (hydrogenation), whilst dehydrogenation is defined with 99% as an upper estimate and 96% as a lower estimate.

The recycling scheme is based on background data for recycling of a car catalyst (cf. chapter 5.2.5.1). The platinum recycling fraction is based on reported up to 98% for an automobile catalyst (Classen *et al.*, 2009). An ideal scenario of 90% is therefore assumed, as a car catalyst and a (de)hydrogenation catalyst are not equal and it is uncertain whether the same recycling degree is valid. To observe the impact of recycling schemes, the conservative estimate assumes no recycling. This is conservative, as platinum is expensive and there will be economic intensives to recycle the catalyst. Between the extremes are therefore assumed for a base scenario. The scenario parameters for the LOHC system are summarized in Table 6-3:

Table 6-3 - Scenarios for LOHC cases.

Parameters for LOHC case A) and B)

Parameter	**Ideal**	**Base**	**Conservative**
Platinum in plants [kg] H/DH*)	1215/2580	2025/4300	6077/12902
Catalyst lifetime [years]	5	3	1
LOHC lifetime [cycles]	56	240	1000
Hydrogen loss hydrogenation [%]	0.5	1	2
Hydrogen loss dehydrogenation [%]	1	3	4
Platinum recycling degree [%]	90	50	0

*) H/DH for hydrogenation/dehydrogenation.

6.2 Global warming potential (GWP)

The study performed in this thesis is a comparative, attributional LCA study. Hence, the results are relative and not absolute and the goal is to compare key impact factors for the storage solutions. GWP is defined as the primary focus of the LCA and the GWP results will be presented per functional unit (kWh) and per kg H_2 in this chapter. An overview chapter with the main results are presented, followed by an in-depth analysis of the two chosen comparison cases. Finally, a comparative section of the GWP results is presented.

6.2.1 Case and scenario presentation

The results are presented based on the defined system unit processes for LOHC (hydrogenation, storage, dehydrogenation and hydrogen production) and UHS (riser, well, pipeline, processing and hydrogen production). The processing, storage and distribution are the parts of the value chain in focus of this thesis (see Figure 1-7), however, the hydrogen production is an essential part of the system and was included in the LCA. Hydrogen production is therefore marked with *grey* color for GWP figures. Transport is included in the respective modules, e.g., transport of LOHC from tanker to FPSO is included in hydrogenation, (cf. chapter 5.2). The results are presented by the defined functional unit of this LCA (kWh) (right axis), but for easier comparison with other LCA studies, also the impact per kg H_2 is presented (left axis) (see Figure 6-2 and Figure 6-3):

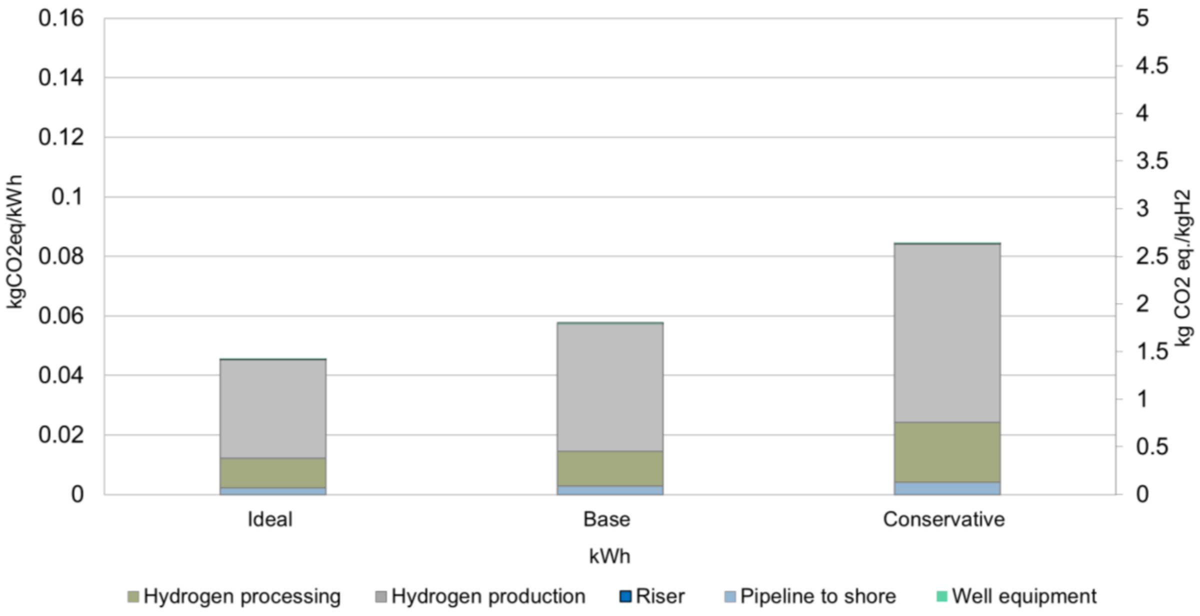

Figure 6-2- Results for ideal, base and conservative scenario for UHS case. The grey columns illustrate the GWP from the hydrogen production and as can be seen, this impact dominates the emissions from the UHS case. Hydrogen processing is illustrated by green columns, whilst pipeline to shore is by blue *columns. The well processing is contributing to a very low fraction of the overall results, but results to the upper line that can be observed over hydrogen production. The riser is of marginal impact and is not seen at the plot.*

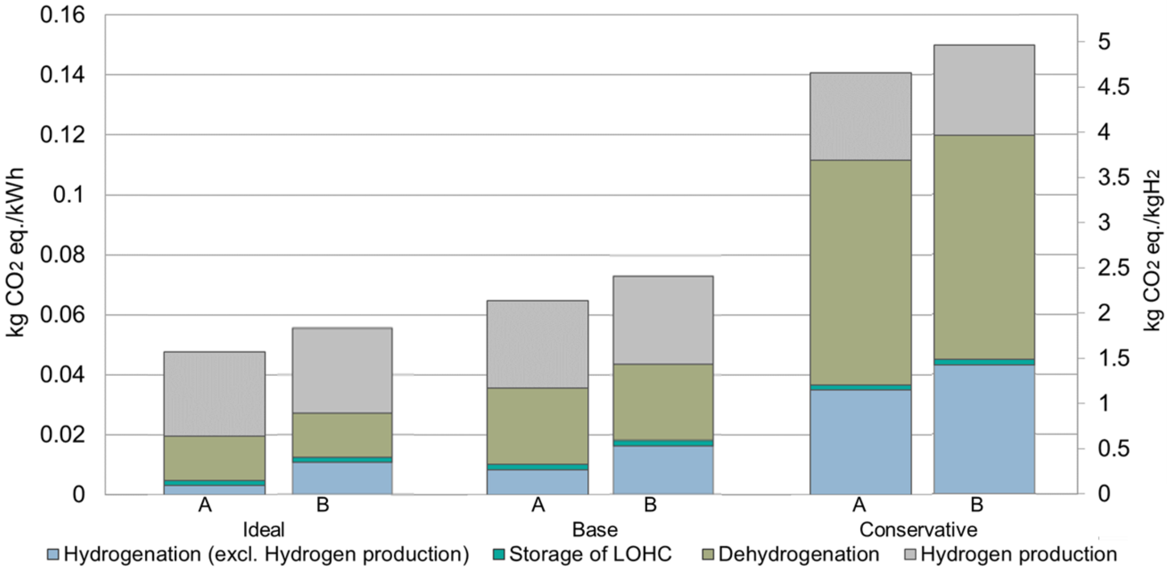

Figure 6-3 - Results for ideal, base and conservative scenarios for LOHC case A) and LOHC case B). LOHC case A) is presented as the left columns of each scenario and indicated with an "A". LOHC base B) is indicated correspondingly with a B.

The difference between the scenarios is larger for the LOHC cases than for the UHS cases and especially the difference between the base scenario and the conservative scenario is significant for the LOHC cases (see Figure 6-2 and Figure 6-3). This pronounced increase for the LOHC cases, is caused by the increased impact of hydrogenation and dehydrogenation processes. For LOHC case B) the hydrogenation generally has larger impact on the results than for LOHC case A (see Figure 6-3). This larger impact is caused by the platform structure, as this is the factor that separates the two cases. The platform structure is based on approximated background data (Chapter 5.2.3.1) and for a just comparison between the two storage cases with comparable prerequisites, it is further concluded to make comparison between the UHS case and the LOHC case B). As LOHC case B) and the UHS both have included parts of the platform to account for respectively hydrogenation plant and compressors, these cases are expected to yield a just comparison. If the platform impact biases the results, this bias is then equal for the two cases and does not impact the relative, comparative results. The results of the UHS scenarios and LOHC case B) scenarios are compared in Figure 6-4:

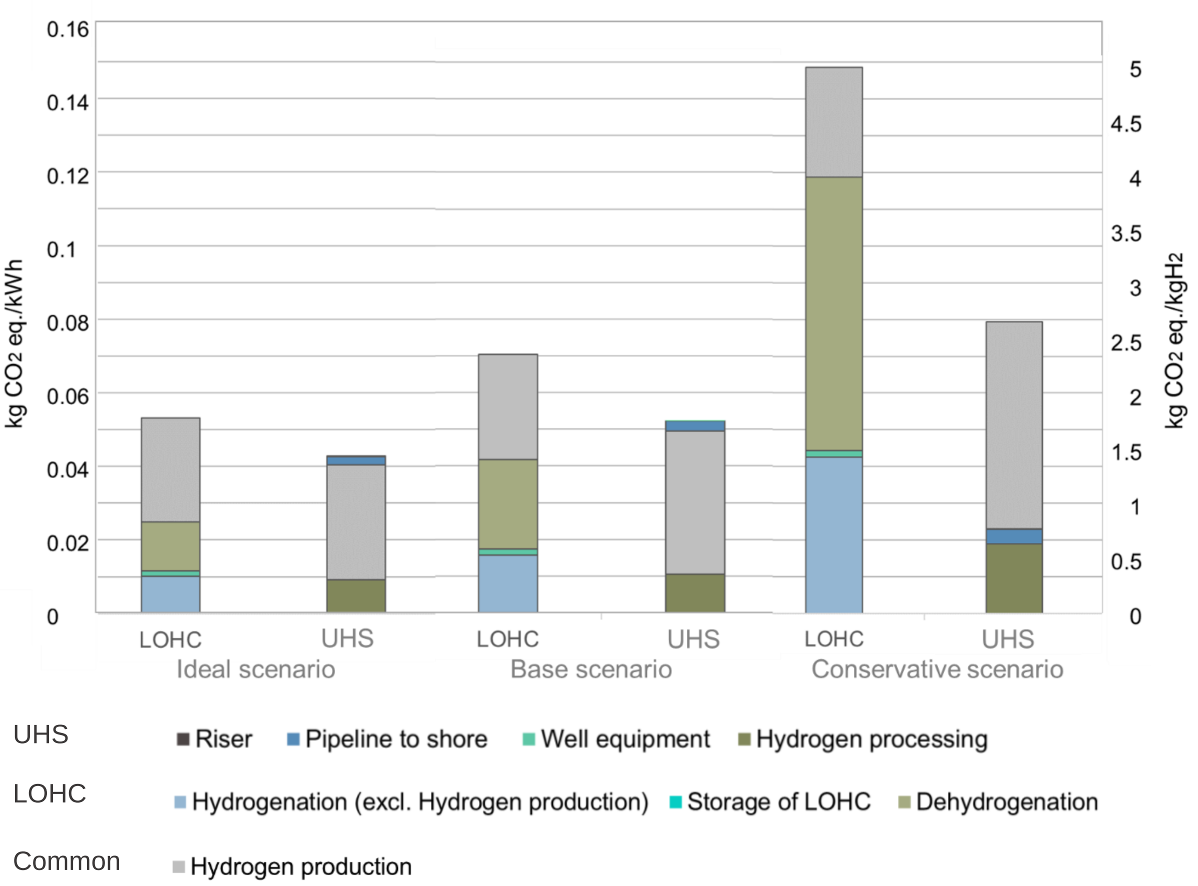

Figure 6-4 - Combined results for the UHS scenarios and the LOHC case B) scenarios. The colors for the UHS scenarios are indicated in a darker color shade to distinguish between UHS and LOCH, compared to Figure 6-2 for UHS.

UHS has lower GWP in all scenarios compared with LOHC, (See Figure 6-4) with largest difference observed in the conservative scenario. Despite the UHS case performing better in an environmental perspective for all the corresponding scenarios, the LOHCB) ideal scenario performs better in a GWP perspective than both the base case and the conservative case for UHS. An overview of the fractional difference between LOHCB) and UHS is given in Table 6-4:

Table 6-4 – Comparison of the related emissions to each of the two storage cases UHS and LOHC case B), including the fractional increase of LOHCB compared to UHS. Both the functional unit (kWh) and the impact per kg H_2 is included, to quantify the results displayed in Figure 6-4.

		Kg CO_2eq./ Kg (kWh)		
		Ideal	*Base*	*Conservative*
UHS	Pipeline to shore	0.07 (2.2E-03)	0.09 (2.8E-03)	0.13 (3.9E-03)
	Well equipment	0.01 (1.6E-04)	0.01 (2.1E-04)	0.01 (2.9E-04)
	Hydrogen processing	0.31 (9.2E-03)	0.36 (1.1E-02)	0.63 (1.9E-02)
	Riser	0.00 (5.4E-07)	0.00 (6.9E-07	0.00 (9.7E-07)
	Hydrogen production	1.04 (3.1E-02)	1.34 (4.0E-02)	1.87 (5.6E-02)
	Total	1.43 (0.04)	1.80 (0.05)	2.64 (0.08)
LOHCB	Hydrogenation (excl. H_2 production)	0.35 (1.1E-02)	0.54 (1.6E-02)	1.42 4.3E-02)
	Storage of LOHC	0.06 (1.7E-03)	0.06 (1.8E-03)	0.06 (1.8E-03
	Dehydrogenation	0.49 (1.5E-02)	0.84 (2.5E-02)	2.48 (7.4E-02)
	Hydrogen production	0.94 (2.8E-02)	0.98 (2.9E-02)	1.00 (3.0E-02)
	Total	1.84 (0.06)	2.42 (0.07)	4.96 (0.15)
GWP emission of LOHCB) compared to UHS [% difference]		29 %	34 %	87 %

LOHCB) is related to higher GWP than UHS for every scenario and the difference increases by scenarios (Table 6-4). LOHC case B) has almost 90% higher GWP than UHS in the conservative scenario, compared to the ideal scenario where the LOHC case B) has 29% higher GWP than UHS. This is explained by the non-linear increase of LOHC emissions determined by increased platinum demand, reduced platinum recycling and electricity demand for dehydrogenation, whilst the UHS emissions are linearly increasing. UHS is thus favorized when prerequisites are more conservative. In Table 6-6 and Table 6-5, the results are presented fraction wise for the different parts of the system, to illustrate where the emissions are coming from. A more in-depth analysis of the two storage solutions (UHS and LOHC case A and B) is presented and discussed in the respective chapters 6.2.2 (Porous UHS) and 6.2.3 (LOHC cases). Finally, a more comprehensive comparison between the UHS case and LOCH case B) is presented in chapter 6.2.4.

6.2.2 Porous UHS

The base scenario for the UHS have a global warming potential of 1.8 kgCO$_2$eq./kg H$_2$ (54 gCO$_2$eq./kWh) (see Table 6-4). One of the few relevant studies for comparison is summarized in Table 1-2 (Wulf *et.al*, 2018), where pipeline transport combined with salt cavern storage is assessed for a daily production volume of 80 tons and provide a comparable estimate of 1.8 kg CO$_2$eq./kgH$_2$. For both the LCA performed in this thesis and the comparison study (Wulf *et.al*, 2018), the pipeline distribution contributes to a significant fraction of the GWP. The impact of the distribution pipeline is higher by the comparison study, possibly caused by the addition of a coating in the pipeline system that prevents hydrogen diffusion. In this thesis, such modifications of pipeline were defined out of the scope, as the pipeline was adjusted by WT and steel material. In Table 6-5, the fraction of the related impact on the GWP is given, for a more in-depth perspective on the emissions from the UHS case (base scenario).

Table 6-5 – Fraction of related impact [%] of the UHS base scenario.

Unit process *Process*	**Fraction of related emissions**
Hydrogen production	74.3%
Well equipment	0.38%
Processing	20.1%
Platform	19.7%
Electricity	0.4%
Compressors	0.1%
Pipeline	5.13%
Riser	0.0001%
Sum	100%

For the UHS case, the hydrogen production has most significant GWP impact (74%), followed by the hydrogen processing (20%), the pipeline (around 5%) and the well equipment (0.38%). The riser system and compressors altogether contribute to less than 1% of the total impact on the system. The platform structure contributes to close to almost the entire fraction of GWP related to the hydrogen processing (19.7%). For the optimization of UHS in terms of environmental impact, the efforts must be sought in the value chain related to the hydrogen production, as this is the dominating impact factor.

The possible environmental gain that a repurposing can contribute to is described in literature (chapter 2.3.2). This analysis show that the platform and the offshore transport pipeline system dominates the environmental impact of the storage and distribution value chain, hence repurposing of the platform structure and pipeline, can contribute to positive environmental impact by reduction of the overall emissions related to a new system.

6.2.3 LOHC cases

An emission of close to 5 kg CO_2 eq./kgH_2 for LOHC transported 100 km by truck is presented (Wulf *et.al*, 2018), dominated by the truck transport (3 kg CO_2eq./kgH_2). Thus, without the transport module by truck (100 km), the emission is reduced to under 2 kg CO_2eq./kgH_2, in line with the base scenario of LOHCA) and the ideal scenario of LOHCB) (see Table 6-4).

An estimate of 3.5 kg CO_2eq./kg H_2 for LOHC (DBT) is given with hydrogen as heating source for dehydrogenation (Wulf and Zapp, 2018), a middle between the base scenarios for LOHC cases presented in this thesis (2.2-2.4 kgCO_2eq./kg H_2) and conservative scenarios (4.7-4.9 kg CO_2eq./kgH_2). In the compared study, the transport module is of significant impact and removal of the transportation module yields a result of slightly below 2 kgCO_2eq./kgH_2 comparable to the base scenarios results obtained by this LCA (both LOHC cases). The two presented comparison studies have in common that the transportation module have significant impact on the emissions. This distribution of emissions is thus different, as the results presented in this thesis have a very limited impact from transport. A more in-depth overview of the distribution of emissions is given for the base scenario is presented in Table 6-6.

Table 6-6 – Fraction of related impact [%] of the base scenarios for LOHC case A) and LOHC case B).

	LOHC A)	**LOHC B)**
Unit Process *Process*	Fraction of related emissions	
Hydrogen production	**45.3%**	**40.5%**
Hydrogenation	**12.9%**	**22.2%**
LOHC production and distribution	5.1%	4.54%
Electricity	1.35%	1.2%
Catalyst (platinum)	9.7%	8.7%
Plant	0.04%	0.03%
Platform deck	-	10.7%
Recycling of platinum	-3.9%	-3.5%
Storage: *FPSO*	**2.5%**	**2.4%**
Dehydrogenation	**39%**	**34.8%**
Catalyst (platinum)	19.6%	17.5%
Plant	0.07%	0.06%
Electricity	17.5%	14.9%
Transport of LOHC to shore	0.6%	0.6%
Disposal of LOHC	8.7%	7.8%
Recycling of platinum	-7.9%	-7%
Sum of unit processes	**100%**	**100%**

The transport is found to be marginal (>1%) for the LCA performed in this thesis, as the transportation module is divided by significantly larger quantities and is not a frequent event (monthly transport). The weight of chemical factories is adapted by Wulf *et.al*, (2018) however, as can be seen in the results, the chemical factories are contributing to a marginal part of the results when platinum demand is excluded. The catalyst and the corresponding recycling rate are important for the GWP, as the catalyst contributes to 28-30% of the overall emissions (before recycling), whilst the 50 % recycling factor contributes to a reduction to respectively 17.5% and 15.4% of the related emissions. This result emphasizes the importance of recycling schemes and stress that recycling schemes for the LOHC platinum must be in place for increased environmental performance for implementation of these systems. In Table 6-7, the increasing impact on GWP of the platinum by the LOHC cases is given (the results present the combined GWP fractional impact of the catalyst at both plants, including reduction of emissions related to recycling scheme):

Table 6-7 - Overview of the fractional impact of platinum on the GWP in the different LOHC configurations.

	Ideal	Base	Conservative
LOHCHA [%]	6.3	17.5	41.4
LOHCB [%]	5.4	15.4	39.2

The fractional impact of platinum on GWP is slightly lower in all scenarios for case B) compared to case A) as the overall emissions are higher with the included platform (Table 6-7). The difference between scenarios is exponentially increasing, despite the increase in platinum being linearly increasing. The catalyst demand estimated for the base scenario was of 7 mg Pt/kgH_2. A lower estimate of 0.3 mg Pt/kgH_2 is presented (Wulf *et.al*, 2018), which highlights the importance of detailed mapping of the catalyst demand for a hydrogenation/dehydrogenation system. However, the estimate of 0.3 mg/kgH_2 may include recycling and a comparative result of 0.4 mg/kgH_2 is estimated in this thesis for a lower platinum demand and including 90% recycling (ideal scenario). These findings emphasize the importance of recycling regimes for platinum-based catalysts.

Another parameter with large impact on the GWP for the LOHC cases, is the electricity for the dehydrogenation, which is related to a higher emission factor than the electricity from the wind farm. The electricity is from a Norwegian electricity mix and contributes to around 18% of the emissions. Despite the low GWP of electricity generation from renewables compared to electricity generation from fossil fuels, the results show how large electricity demands is related to emissions despite coming from renewable sources.

The LOHC is defined with a lifetime of respectively 57, 240 and 1000 cycles by ideal, base and conservative scenario. By a monthly LOHC cycling rate, the temporal lifetime of the LOHC increases, hence reduce the need for virgin LOHC. The storage configuration assessed in this this thesis appear as a favorable solution for large-scale storage of hydrogen in LOHC's, as the need for virgin LOHC is low and the LOHC has a low fractional impact of the overall GWP results (4.5-5.5%, see Table 6-6). This result is in line with the results presented by (Wulf and Zapp, 2018), which displays the LOHC production to be a low fraction of the overall results (around 2%).

6.2.4 Comparison

The hydrogen production contributes to a significant fraction of the emissions for the base scenario with 45.3% for LOHC case A, 40.5% for LOHC case B and 74.3% for UHS (Table 6-5 and Table 6-6). Emissions from hydrogen production is dominated by the electricity generation, which originates from the wind farm manufacturing. Studies suggest a range between 20 and 85 $gCO_2eq./kgH_2$ for hydrogen produced by wind (cf. chapter 1.3.1) and the background data suggest an impact in the upper range of these estimates (99 g $CO_2eq./kg$ H_2). By the comparative objective of this thesis, the hydrogen production only raises the emissions for the two solutions similarly, which leads to assumed viable background data for this parameter. A more comprehensive study on the wind farm could increase the quality of the absolute results.

As can be seen from the UHS results (see Figure 6-2 and Table 6-5), the platform deck of ~6000 m^2 contributes close to 20% of the GWP for the UHS. The platform had to be simulated by background data covering a small platform. This emphasizes that the most accurate comparison is assumed to be between UHS and LOHC case B, as a larger platform is likely to have less material per m^2 surface area, the GWP from the platform is assumed to be overestimated. If the whole platform structure were to be included, the emissions from offshore hydrogen production would have been higher, emphasizing the aspect of the relative results presented by the comparative LCA rather than absolute results. The platform area required for the electrolysers was defined outside the scope of the LCA, but the results show that the platform is an important environmental contribution to an offshore hydrogen production system and must be accounted for to obtain absolute results.

As the hydrogen production dominates the emissions related to the UHS case, there is limited room for improvement in the storage and distribution value chain for UHS. This is contrary to the LOHC cases, where the storage and distribution contribute to a significantly higher overall fraction (>50%) and therefore better prerequisites for enhancement in several parts of the value chain. The UHS case does also perform better in a GWP perspective than both LOHC cases, but the difference varies between scenarios (29-87%) and a clear result of the favored solution is not given. The ideal LOHC scenario is favored in terms of environmental impact over the conservative UHS scenario and is similar to the base scenario, despite LOHC appearing as the worst environmental option when only looking at comparable scenarios. The result from this analysis does therefore not present a robust conclusion that the UHS case is the better environmental option. However, some points can be highlighted:

- The UHS case does to a low degree depend upon energy-intensive materials or noble materials. The LOHC case accounts on both; both the toluene production and the platinum production are energy-intense and catalyst depends on a noble quantity. The LOHC case is also related with a higher electricity demand. Toluene is a by-product from oil refining, which is expected to decrease towards 2050. However, as seen in this analysis, even for large quantities, the need for the LOHC is very limited, if the LOHC can be recycled for several cycles.
- The UHS case does not depend upon the continued delivery of a medium for the processing, opposite to the LOHC cases which depend upon frequent delivery of lean LOHC to the system. The LOHC system is therefore more complex and has more parameters which can alter the production.
- Furthermore, the comparable result for UHS case and LOHC cases, is to a large degree dependent on the allocated platform deck. It can be expected when an additional platform is added to a whole platform structure, the effect of one additional deck as seen in this thesis, would be more limited.

The results presented in this chapter generally show that the processing, storage and distribution contribute to significant fractions of a large-scale hydrogen production and storage system, over 54-58% of the GWP for the base scenarios of LOHC cases and 26% of the UHS case. This finding emphasizes the importance of including the whole value chain in LCA of hydrogen production, as the processing, storage and distribution contribute to non-marginal parts.

6.3 General environmental impact results

The LCA uncovers other environmental impact categories than GWP, (cf. chapter 3.2). This chapter presents the environmental impact quantified by the other impact categories, but only for the two selected comparison cases UHS and LOHC case B) (see Figure 6-5 and Figure 6-6). The results are presented for the base scenario for the comparative aspect. The results for LOHC case A) are attached in Appendix III: Complete LCA results.

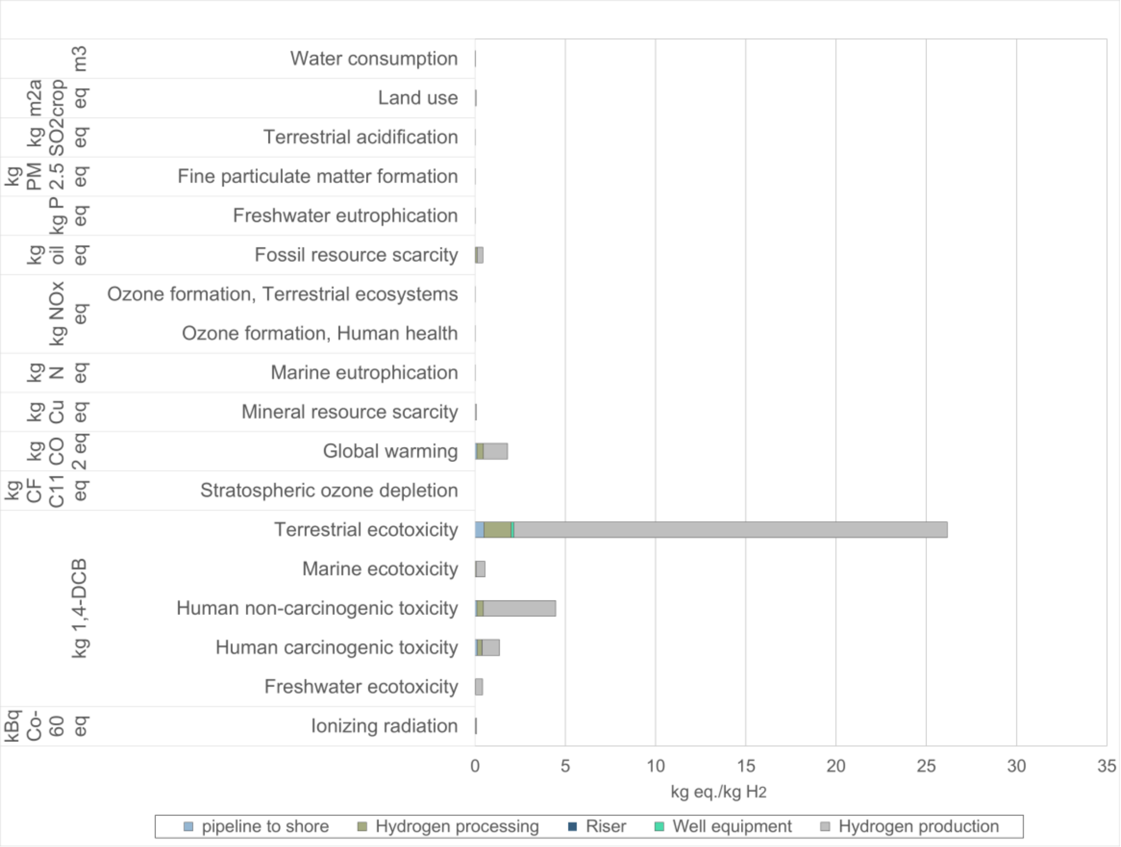

Figure 6-5- Results of all impact categories for UHS (base scenario), based on ReCiPe (H) Midpoint.

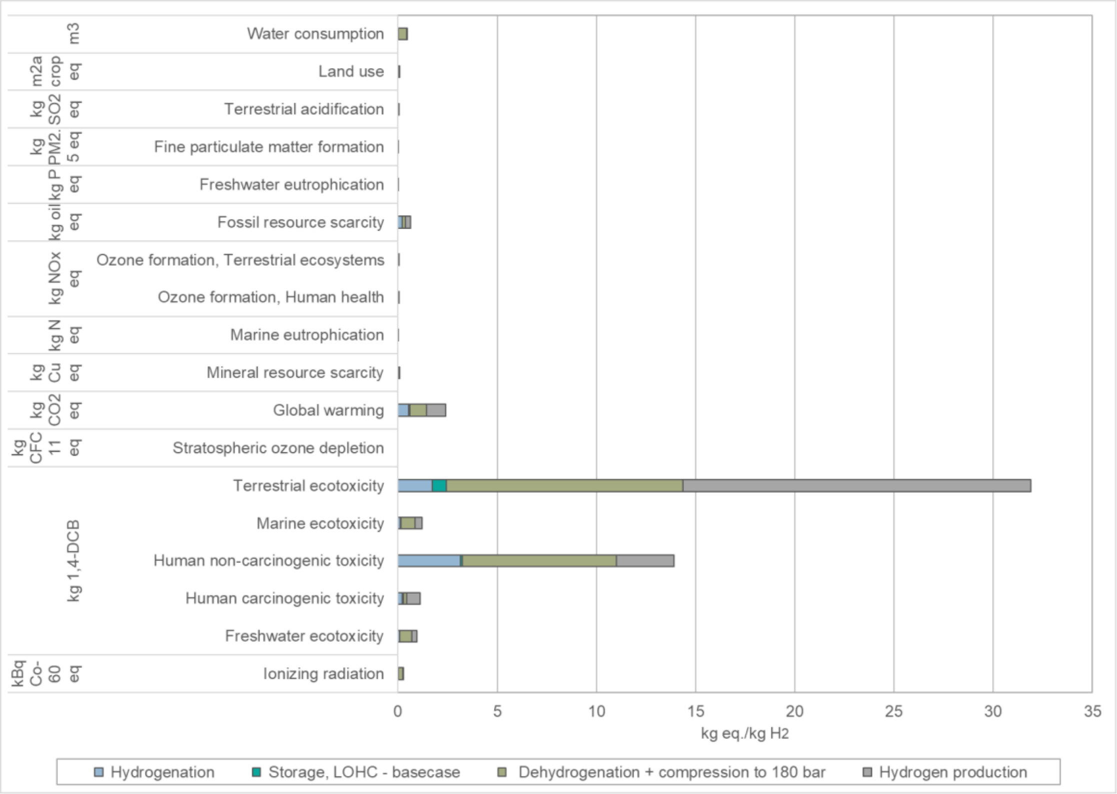

Figure 6-6 - Results of all impact categories for LOHC case B) (base scenario), based on ReCiPe (H) Midpoint

The systems are related with ecotoxicity, both affecting humans and ecosystems (see Figure 6-5 and Figure 6-6). The toxicity potential has not been the primary focus in this thesis and a more specific focus on toxicity flows is needed for a more thorough evaluation of the toxicity potentials. A large, quantified number for terrestrial ecotoxicity does not automatically mean that this is the impact category with most important environmental impact – the impacts of the flow must be interpreted and understood (cf. chapter 3.2). As we know from e.g., radioactive radiation, small amounts can cause great harm to human health and ecosystems and qualitative results are therefore not interpreted for other impact categories than GWP.

A comparative consideration can however be outlined. The toxicity impact is in all cases dominated by hydrogen production. Apart from the hydrogen production, the dehydrogenation process contributes to increased ecotoxicity impact of the LOHC cases compared to the UHS case. Terrestrial ecotoxicity is an impact category that potentially can impact planetary boundaries biosphere integrity and biochemical flows. These two planetary boundaries are already under high pressure, meaning that the value identified for the system may be an important consideration for offshore hydrogen production. The fossil resource scarcity impacts both systems and is related to the need for fossil fuels in the manufacturing processes, both by energy, manufacturing and materials. The other impact categories, where quantified impact is too low to be observed by figures are summarized in Table 6-8.

On average, from all the impact categories, hydrogen production accounts for 40% of the LOHC case B compared to 79% of the UHS and the impact of processing, storage and distribution is therefore significantly more dominating for LOHC than for UHS (see Figure 6-7 and Figure 6-8).

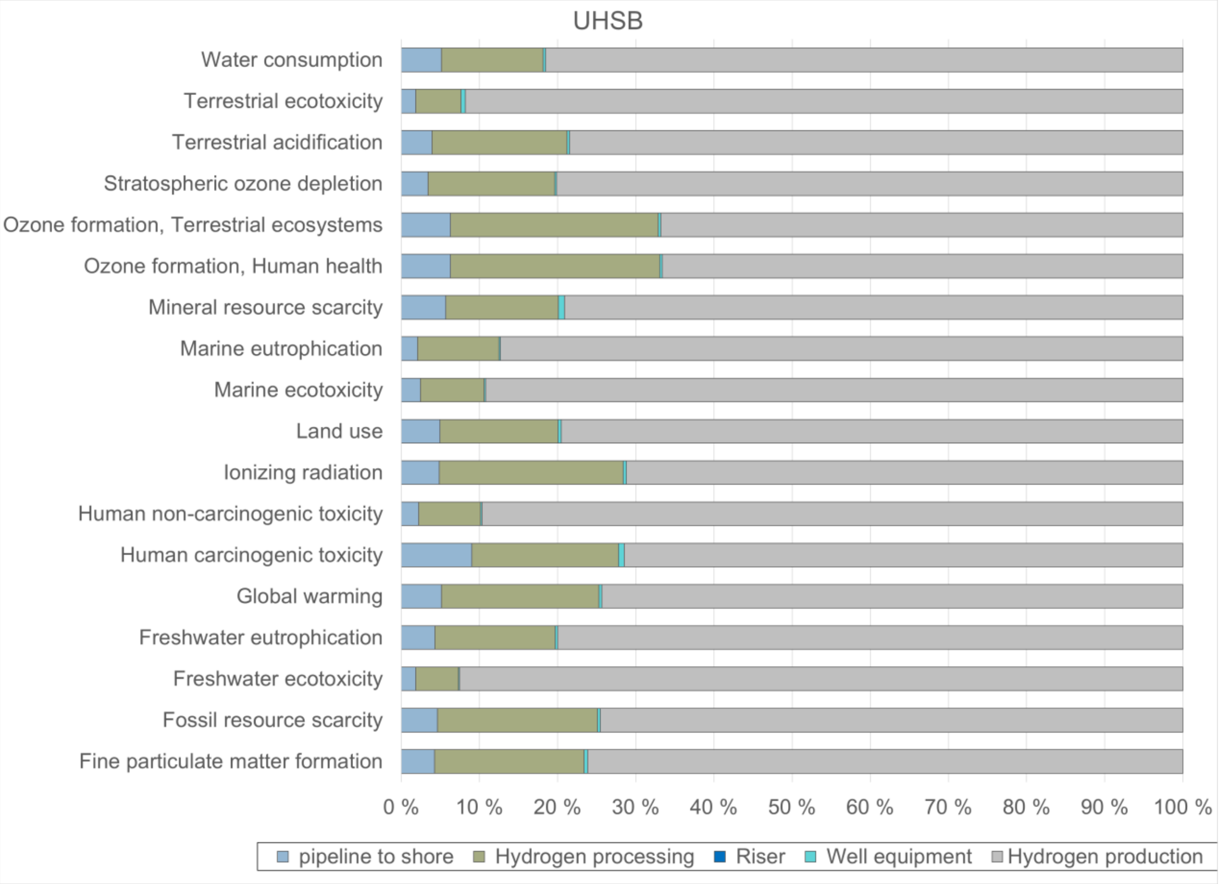

Figure 6-7 - Normalized results per impact category for UHS base scenario.

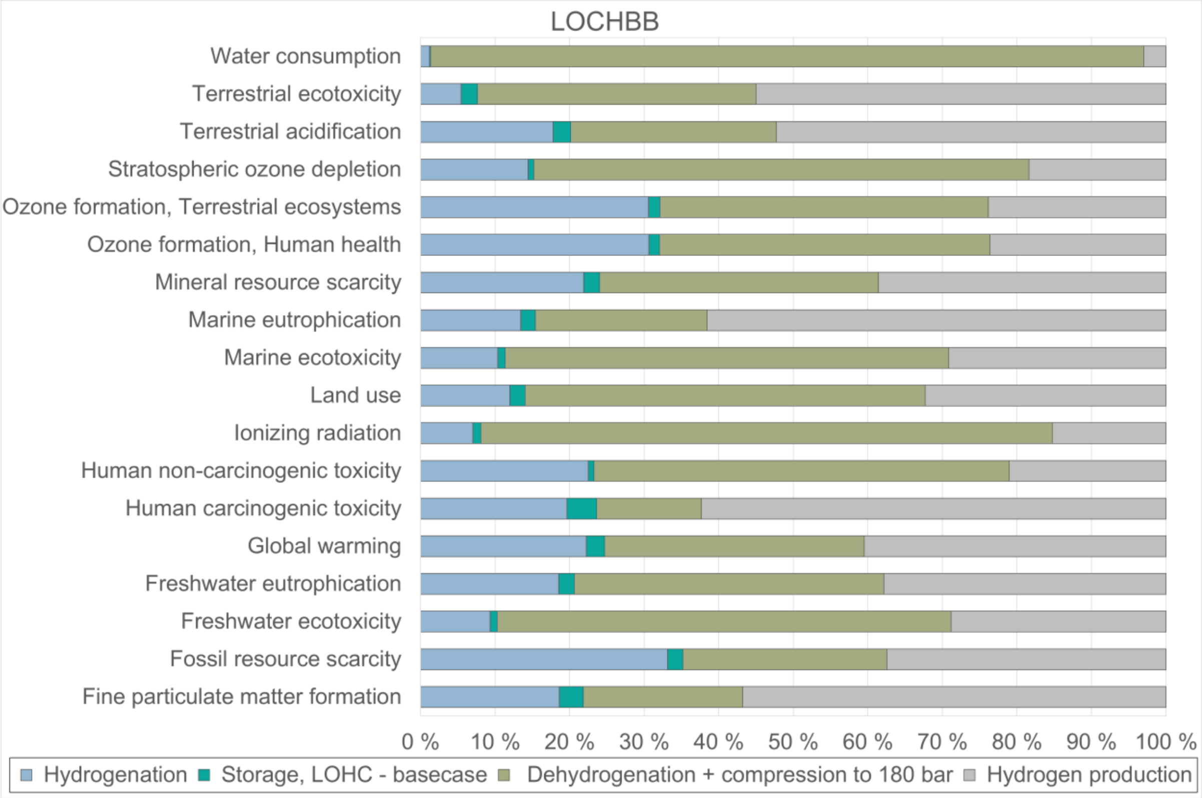

Figure 6-8- Normalized results per impact category for LOHC case B) base scenario.

For the UHS case, the fractional impact from the different sub-systems is in a similar range over the impact categories. In contrast, the variation of the fractional impact is more considerable for the LOHC case, primarily for the unit process dehydrogenation, which is related with large variation in fractional impact (Figure 6-8). The results indicate the same trend as for the GWP, that the LOHC cases generally is related with higher environmental impact than UHS. To investigate this result, the fractional difference between UHS base scenario and LOHCB) base scenario in all the impact categories is presented in Table 6-8.

Table 6-8 - Presentation of percentwise difference for UHSB and LOHCBB, with the quantified results of the environmental impact in the different impact categories. The results are given per functional unit (kWh hydrogen).

		UHS, base scenario	**LOHCBB, base scenario**	
Impact category	**Unit**	**Total**	**Total**	**Difference**
Global warming	kg CO_2 eq.	5.40E-02	7.25E-02	25.5 %
Stratospheric ozone depletion	kg CFC-11 eq.	2.33E-08	7.42E-08	68.6 %
Ionizing radiation	kq Co-60 eq.	2.47E-03	8.40E-03	70.6 %
Ozone formation, Human health	kg NOx eq.	1.65E-04	3.39E-04	51.4 %
Fine particulate matter formation	kg PM2.5 eq.	1.18E-04	1.15E-04	-2.1 %
Ozone formation, Terrestrial ecosystems	kg NOx eq.	1.70E-04	3.49E-04	51.1 %
Terrestrial acidification	kg SO_2 eq.	2.26E-04	2.47E-04	8.8 %
Freshwater eutrophication	kg P eq.	3.25E-05	5.02E-05	35.2 %
Marine eutrophication	kg N eq.	3.75E-06	3.89E-06	3.5 %
Terrestrial ecotoxicity	kg 1,4-DCB	7.84E-01	9.57E-01	18.0 %
Freshwater ecotoxicity	kg 1,4-DCB	1.23E-02	2.89E-02	57.3 %
Marine ecotoxicity	kg 1,4-DCB	1.63E-02	3.64E-02	55.3 %
Human carcinogenic toxicity	kg 1,4-DCB	4.05E-02	3.39E-02	-19.3 %
Human non-carcinogenic toxicity	kg 1,4-DCB	1.34E-01	4.18E-01	67.9 %
Land use	m^2a crop eq.	1.46E-03	2.63E-03	44.4 %
Mineral resource scarcity	kg Cu eq.	1.82E-03	2.72E-03	33.2 %
Fossil resource scarcity	kg oil eq.	1.28E-02	1.86E-02	31.2 %
Water consumption	m^3	6.95E-04	1.39E-02	95.0 %

For 16/18 impact categories, LOHCBB is related with a higher environmental impact than the UHSB. For toxicity indicators, the LOHC has the highest related emissions in 4/5 categories, where human carcinogenic toxicity is the exception. As briefly described in Table 5-1, the ecotoxicity indicators are related with damage to ecosystems and damage to human health. It is therefore advantageous for UHS to be related with lower ecotoxicity potential in 4/5 impact categories and combined with the lowered GHG emission, these results favor UHS case. The results are for all the categories, however, in a similar range, as the impact in these categories is mainly dominated by the wind farm. The higher results for LOHC, is for terrestrial ecotoxicity caused by the land-based electricity generation, for non-carcinogenic ecotoxicity caused by the platinum production and for marine and freshwater ecotoxicity dominated by electricity generation onshore (copper production and scrap handling), platinum production and by-product handling. The human carcinogenic impact, which has the highest impact from UHS, origin from the platform infrastructure. Platinum is not only an energy-intensive and material demanding to produce, but the results also uncover potential toxicity impact.

The land occupation is higher for the LOHC case than for the UHS case, as a land-based factory is assumed in the LOHC case. Both solutions will occupy a significant sea-bottom area, which is not reflected in the results. The UHS case will cover a larger sea-bottom area with the pipeline to shore and possibly impact ocean ecosystems in a large area. Both solutions will occupy the same ocean area by the platform and the FPSO solution will cover more specific spots related to the mooring of the system. The UHS case will cover some area where the injection and production wellheads are placed. The system has in common that the water consumption is low. However, a high water demand is expected from the electrolyser (cf. chapter 5.2.1), but this has been taken out of the scope, as this water is provided by salt water from the ocean. However, it may be an environmental issue related with outlet of the heated cooling water mixed increased salt concentration from the RO, which needs to be assessed thoroughly.

Summarized, the UHS case has a lower related impact over the 18 impact categories than the LOHC cases. This comes in addition to the generally lower results obtained for the GWP, but as for the GWP, the differences are marginal. The conservative scenario for both LOHC systems are not competitive with any UHS scenario and yields overall high GHG-emission.

6.4 Reference flow of the functional unit

Based on the efficiencies quantified for the unit processes, a reference flow based on the functional unit is presented (see Figure 6-9). The reference flows indicate the necessary energy input to provide the output of the functional unit (1 kWh hydrogen pressurized to 180 bars, delivered at shore). The figures illustrate the energy demand focused on the processing, storage and distribution (upper figures) and the energy demand for the whole value chain (lower figures).

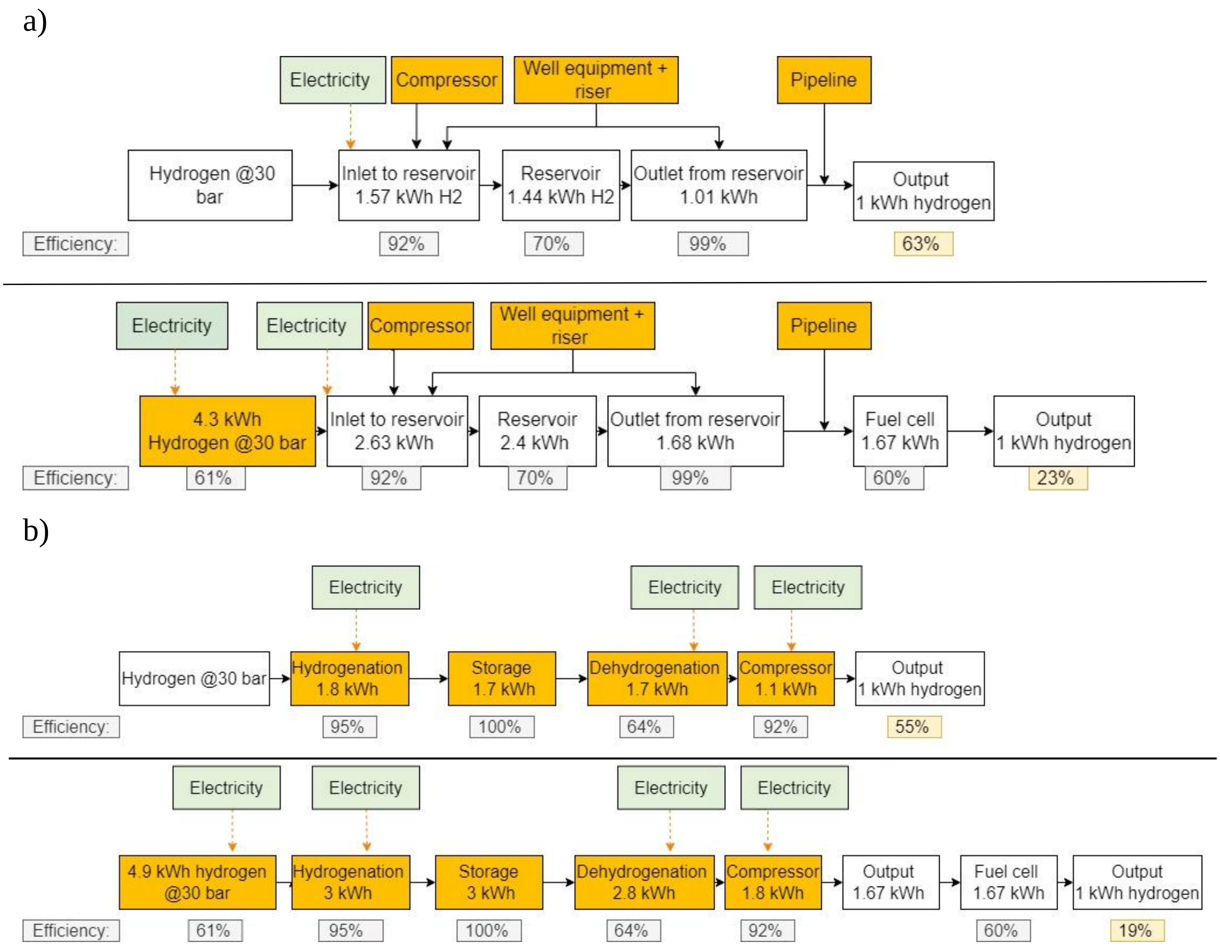

Figure 6-9 - Reference flow for the UHS and LOHC system based on the functional unit (presented for base scenarios). Flow over the indicated line illustrates the flow focusing on the storage and distribution (excluding electrolyser and fuel cell), flow under the line illustrates the flow including the whole hydrogen value chain. Green boxes indicate input electricity demand for the unit process, white boxes indicate input/output, orange boxes illustrate the unit processes (included in the presented flow), grey boxes indicate the efficiency of the corresponding process, whilst yellow box indicate the final efficiency.

The overall efficiency of these storage systems expressed as fractions of the energy content in the hydrogen (LHV) is defined to be 55% for LOHC storage and 63% for UHS case for the base scenarios (see Figure 6-9). Adding the electrolysis and a fuel cell with a related efficiency of around 60% utterly reduces the overall efficiency of hydrogen system with long term storage to around 19% for LOHC and 23% for UHS. To re-generate electricity through hydrogen produced by electrolysis is thereby an energy-demanding process, with low overall efficiency. This points at the importance both of considering storage solutions that are related to the minimum losses, as well as optimizing the processes linked to hydrogen production, processing and fuel cells. Note that 22% efficiency does not mean that 78% of 1 kg produced hydrogen is directly lost for the process. The loss is an expression of how much energy, in total, that is lost or is needed for producing 1 kWh of energy from a hydrogen production and storage system, expressed as a fraction of the energy content (LHV) in the hydrogen. A total of 4.9 kWh and 4.3 kWh is needed to produce 1 kWh of electricity regenerated in a fuel cell respectively for the LOHC storage systems and the UHS systems (see Figure 6-9). As stated in the introduction chapter, the optimal solution for a net-zero society is likely a large degree of electrification from renewables. However, not all sectors can be electrified with existing technology and low-emission carriers such as hydrogen are essential to maintain the living standards of today, while reaching expressed targets for a net-zero society within 2050.

6.5 Future work

Based on the result and discussion from the concept analysis and the LCA, suggestions for future work are presented. It is emphasized that this thesis covers aspects with sparse literature coverage and that the results presented in this analysis has very little comparable literature, both storage configurations and environmental results. To the authors knowledge, this is the first analysis which covers LOHC and UHS in a comparative LCA for large-scale, offshore hydrogen production. The scope therefore had to be limited and a range of future work is therefore identified.

6.5.1 Conceptual

The concept analysis is designed to provide the necessary input to perform the LCA of the systems and does not include all relevant parameters. In this section, an overview of omitted aspects suggested for further work is presented. Cost is a crucial parameter for implementation of systems and should be included for a holistic perspective on the presented concepts. Any challenges related to ocean movement or fluctuating power availability for electrolyser system or compressor system, is not accounted for. O&M is neither not accounted for. This is a clear lack, as e.g. the studies presented in the introduction by (Arvesen, Birkeland and Hertwich, 2013), points out that O&M is a main contributor to increase the emissions of an offshore wind farm compared to an onshore wind farm. The electrical system and umbilical cables are neither discussed. The systems also have in common that dimensioning has not gone in depth on balance of plant, safety distances and other eventual areal occupations. The practical solutions related to bunkering for the LOHC system is not discussed. Law and safety are aspects excluded from the scope of this thesis but are emphasized as crucial matters to investigate for the implementation of proposed systems. Safety is an extremely important aspect in a hydrogen perspective, due to hydrogens flammable and explosive features. Own, comprehensive safety evaluations of systems as proposed are therefore needed and this was outside the time limitations defined for this thesis. Implementation of such systems also rely on law regulations, grants and political aspects, also suggested for further investigation. There are numerous disadvantages and disadvantages by the concept of offshore hydrogen production offshore and these in themselves are not discussed, as it is defined as a prerequisite that offshore hydrogen production is viable. For future work, it is suggested to cover the concept of hydrogen production offshore in general thoroughly, compared with deliverance of electricity from the windfarm by power cables to shore.

The comparative LCA shows that LOHC (both cases) has higher environmental impact than the UHS case. Although the difference is low, other aspects of the LOHC solution contribute to increase the holistic complexity of such solution. The LOHC cases has inherent challenges such as need for continuous turnover, weather variations, logistics of ships, frequency of passing ships and bunkering schedules. The major challenge for porous UHS relates to the recovery efficiency. Furthermore, UHS is suggested as a seasonal storage solution (cf. chapter 2.3.2) and monthly storage may lead to too frequent withdrawal rate, that possibly lead to weakening of the impermeable layer (Hassanpouryouzband *et al.*, 2021), more wear and tear on the production equipment and possibly more uncertainty on production and withdrawal rates. Neither of these aspects, in-depth analysis of the practical solutions of LOHC cases nor the technical challenges related to reservoir recovery is investigated in this thesis, but is suggested for future work.

The concept of hydrogen production and compression from a wind farm utilizes the advantage of acute available power for production. When there is a lot of power available, there is power available both for compression and hydrogen production. This is the case for several hydrogen carrier production systems, as ammonia and liquid hydrogen. The LOHC cases has limited energy demand at the production location and depend on external delivery of hydrogen-lean LOHC, which possibly can contribute to favor the UHS storage case. The UHS on the other hand, rely on very specific locations related to where feasible reservoirs are found. Such aspects, related to the specific advantages of the storage cases in an offshore environment, should also be implemented for future work.

As this LCA is comparative, the results are relative and not absolute. However, a comparison of traditional fuels is presented in this chapter for discussion of the results in a comparative manner. Natural gas is estimated with a lifecycle emission (including production and combustion) of approximately 240 gCO_2eq./kWh (cf. chapter 2.1). This may be contrasted to the scenario with the highest emission (LOHC case B, conservative) with 150 gCO_2eq./kWh. Despite the limitation of not being absolute, the comparison points to the fact that all studied hydrogen storage cases have lower environmental footprint compared to NG. However, as this analysis was comparative for the two storage systems, aspects of the systems that were in common was omitted and further investigations are needed to conclude on the enhanced environmental performance of the systems compared to fossil fuels. Despite that the focus of this thesis is the comparison with UHS, it is worth noting how the difference between natural gas and LOHC shrinks at the conservative scenario and highlights that optimization of variables as platinum recycling are important to secure a competitive low-emission fuel in an environmental perspective.

H_2 is emission-free during combustion, but whether H_2 leakages affect the atmosphere as a GHG, is a crucial aspect to investigate (Warwick *et al.*, 2022). All large-scale hydrogen production systems will be likely to yield H_2 leakages, which emphasizes the need to uncover potential impact related to H_2 in the atmosphere, especially when aiming towards a hydrogen economy.

This thesis was written from 2021-2022, a year with large technology development related to hydrogen technology. Updates data manuals for the LOHC hydrogenation/dehydrogenation systems was found at the end of the study, pointing at the rapid development in this field and need for several studies which is up to date. The viability of offshore hydrogen production as a concept was defined as a prerequisite, but this concept in itself should also be subject to further analyzes, both in environmental perspectives, economic perspectives, social sustainability perspectives and law perspectives.

6.5.2 UHS

By the limitations defined, the well equipment is related with environmental impact, under 0.5% of the total GWP emissions. However, the mapping and drilling of the well was excluded from the scope due to time limitations and to include this process would have increased the quality of this result. Implementation of well equipment is a complex procedure which have the potential to impact the natural wildlife in the surrounding ocean area and all measures that limits the encroachment on nature, is expected to be favorable. Even though repurposing yields limited environmental gain by numbers in GWP, it should be considered as a positive measure to limit nature encroachment and inclusion of mapping and well drilling in the scope is suggested for future work to quantitatively measure this impact.

As described in the concept analysis (Chapter 4.1.5), the pressure drop in the transport pipeline is sensitive for the friction factor f and an increased friction factor could have yielded a need for a recompression along the transport pipeline. Note that the well pressure drop from reservoir to surface is not accounted for, which could increase recompression needs. However, as seen in Table 6-5 – Fraction of related impact [%] of the UHS base scenario., both compressors and electricity for compression have very limited environmental impact and it is assumed that the same results in the same range would have been identified also including recompression. The inclusion of a recompression was therefore not defined in the conservative scenario, but to add this impact is suggested for future work. Also, for a valid, conceptual estimation, more in-depth analysis on the pressure drop both in the well and in the transport pipeline should be performed.

The GWP from the pipeline is believed to be underestimated, as it is based on a point-to-point estimate. A more precise design of the pipeline is therefore suggested for future work, for better quantification of the impact from the transport pipeline.

6.5.3 LOHC

Platinum is used as a catalyst also for fuel cells and electrolysis, which means that a hydrogen economy is linked with challenges to the accessibility of this noble entity. As seen in the analysis presented in this thesis, the platinum is an important impact factor of the LOHC system. Investigations of alternative catalysts can be important for the implementation of LOHC as a viable hydrogen carrier alternative. More efforts both on the actual platinum demand, platinum recycling schemes and other catalysts are therefore crucial to make LOHC an attractive large-scale storage alternative.

LOHC is proposed used directly onboard ships and the estimation performed in chapter 4.2.4 show that a dehydrogenation plant is estimated to uptake a limited amount of space on a tanker ship. The possible use of LOHC directly on ships advocate to produce LOHC offshore and can contribute to make such a concept more attractive business case. It can also increase the environmental sustainability of the system, as the roundtrips solely for transportation of the LOHC to shore can be reduced and many of the bunkering's can utilize the fuel directly. This proposed solution should therefore be evaluated by LCA analysis, but was omitted for a better comparative result with UHS case.

Production of toluene has been used as a proxy for BT due to lack of data on the production process, contrary to (Wulf and Zapp, 2018), which has estimated an increased energy and chemical demand for DBT with toluene as reagent, which may contribute to increased emissions. This is a lack of the LCA performed in this thesis and a more specific LCA on BT is suggested for future work. It is suggested that a similar, independent LCA study that is performed in this thesis should be performed, to quality assure the findings.

7 Conclusion

The result shows that both LOHC storage in an FPSO and compressed hydrogen in porous UHS allow storage of hydrogen produced by wind from with a 500 MW electrolyser system for one month. This initial analysis points to several aspects both detailed and conceptual level, that are important for further investigations. The two analyzed hydrogen storage pathways have related low overall energy efficiencies, respectively 19% and 23% for LOHC and UHS systems with electrolyser and fuel cell utilization included. This is lower energy efficiency than combustion of fossil fuels and improvements of energy efficiency across the value chain are pointed out as important for hydrogen to yield a favorable option. However, transition from the fossil fuels is crucial to limit global warming and it is assumed that lower energy efficiencies in a preliminary phase must be accepted to make this transition.

A preferred solution from a GWP perspective cannot be identified because the ideal, base and conservative scenarios overlap between cases. However, the UHS case generally has lower related emissions, both by GWP and the other impact categories. It can also be drawn general conclusions related to the complexity of the systems. UHS can work independently from a shore system when installed, whilst LOHC is dependent on continuous deliverance of dehydrogenated LOHC. Hence, the combined effect of generally lower environmental impact and less complexity suggests that UHS storage is the preferred large-scale storage system within the scope of this thesis.

The general importance of LCA or similar environmental investigation for future energy systems is underscored and the results show how the processing, storage and distribution for a large-scale, offshore hydrogen system contribute to environmental impact. The thesis highlights the importance of accounting for these aspects ahead of system implementation. LOHC are frequently suggested as a promising hydrogen carrier, but its environmental impact is rarely mentioned. As this thesis uncovers, LOHC processing, storage and distribution may have a significant environmental footprint linked to it, that should be thoroughly investigated for future, large-scale implementations. It is presented several suggestions for further work that can contribute to increase the robustness of the presented conclusion and the LOHC case still stands out as an interesting alternative for longer term hydrogen storage.

Lastly, the results described in this thesis emphasize how we cannot solely rely on technology development to obtain a net-zero society. Despite investigating green hydrogen production from offshore wind, emissions are still dominated by the electricity production. This demonstrates that green technology development and implementations are only part of the solution to solve the climate crisis; adjustments of our lifestyle will be necessary to meet the commitments defined in the Paris Agreement.

8 References

Aakko-Saksa, P. T. *et al.* (2018) ‘Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion’, *Journal of Power Sources*, 396, pp. 803–823. doi: 10.1016/J.JPOWSOUR.2018.04.011.

Acero, A. P., Rodríguez, C. and Ciroth, A. (2015) *LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories*. Available at: https://nexus.openlca.org/ (Accessed: 14 April 2022).

Ahluwalia, R. K. *et al.* (2011) *Technical Assessment of Organic Liquid Carrier Hydrogen Storage Systems for Automotive Applications*. United States. doi: https://doi.org/10.2172/1219358.

Aibel (no date) *DolWin beta*. Available at: https://aibel.com/project/dolwin-beta (Accessed: 22 May 2022).

Al-Shaikhali, A. H. *et al.* (2015) ‘Non-precious bimetallic catalysts for selective dehydrogenation of an organic chemical hydride system’, *Chemical Communications*, 51(65), pp. 12931–12934. doi: 10.1039/C5CC04016G.

Amaro, R. L. *et al.* (2018) ‘Development of a Model for Hydrogen-Assisted Fatigue Crack Growth of Pipeline Steel1’, *Journal of Pressure Vessel Technology*, 140(2). doi: 10.1115/1.4038824.

Amid, A., Mignard, D. and Wilkinson, M. (2016) ‘Seasonal storage of hydrogen in a depleted natural gas reservoir’, *International Journal of Hydrogen Energy*, 41(12), pp. 5549–5558. doi: 10.1016/J.IJHYDENE.2016.02.036.

Andersson, J. and Grönkvist, S. (2019) ‘Large-scale storage of hydrogen’, *International Journal of Hydrogen Energy*, 44(23), pp. 11901–11919. doi: 10.1016/j.ijhydene.2019.03.063.

API (1991) ‘API RP 14E: Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems’. American Petroleum Institute (API).

API (2005) ‘API 5CT: Specification for casing and tubing’. American Petroleum Institute (API).

Arvesen, A., Birkeland, C. and Hertwich, E. G. (2013) ‘The importance of ships and spare parts in LCAs of offshore wind power’, *Environmental Science and Technology*, 47(6), pp. 2948–2956. doi: 10.1021/ES304509R.

ASME (2011) ‘ASME B31.12-2011: Hydrogen Piping and Pipelines’. New York: American Society of Mechanical Engineers (ASME).

Bai, Y. and Bai, Q. (2019) *Subsea Engineering Handbook (2nd edition)*. Elsevier. Available at: https://app.knovel.com/hotlink/toc/id:kpSEH00001/subsea-engineering-handbook/subsea-engineering-handbook.

Bareiß, K. *et al.* (2019) ‘Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems’, *Applied Energy*, 237, pp. 862–872. doi: 10.1016/J.APENERGY.2019.01.001.

Barthélémy, H. (2012) ‘Hydrogen storage - Industrial prospectives’, *International Journal of*

Hydrogen Energy, 37(22), pp. 17364–17372. doi: 10.1016/j.ijhydene.2012.04.121.

Barton, B. *et al.* (2003) 'Catalysts and Process for the Production of Benzyl Toluenes', *Organic Process Research and Development*, 7(4), pp. 571–576. doi: 10.1021/OP034043M.

Baumann, H. and Tillmann, A.-M. (2004) *The Hitch Hikers Guide to LCA*. Malmø: Studentlitteratur.

Benitez, A. *et al.* (2021) 'Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fi ber hydrogen tank', *Journal of Cleaner Production*, 278. doi: 10.1016/j.jclepro.2020.123277.

Bentley, J. (2005) *Principles of measurement Systems: 4th edition*. Harlow: Pearson Education.

Brown, L. R. (1993) *Jordens tilstand*. Oslo: Worldwatch Institute.

Brown, N. *et al.* (2021) *Producing environmental accounts with environmentally extended input output analysis*. Luxemborg. doi: 10.2785/172888.

Brückner, N. *et al.* (2014) 'Evaluation of Industrially Applied Heat-Transfer Fluids as Liquid Organic Hydrogen Carrier Systems', *ChemSusChem*, 7(1), pp. 229–235. doi: 10.1002/CSSC.201300426.

Buttler, A. and Spliethoff, H. (2018) 'Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review', *Renewable and Sustainable Energy Reviews*, 82, pp. 2440–2454. doi: 10.1016/j.rser.2017.09.003.

Byrom, T. (2015) *Casing and liners for drilling and completion : design and application (2nd edition)*. Elsevier. Available at: https://app.knovel.com/hotlink/toc/id:kpCLDCDAE8/casing-liners-drilling/casing-liners-drilling (Accessed: 14 May 2022).

Caglayan, D. G. *et al.* (2020) 'Technical potential of salt caverns for hydrogen storage in Europe', *International Journal of Hydrogen Energy*, 45(11), pp. 6793–6805. doi: 10.1016/J.IJHYDENE.2019.12.161.

Callister, W. and Rethwisch, D. (2015) *Materials Science and Engineering*. Singapore: John Wiley & Sons, Ltd.

Canada Steel and Casing Imports (no date) *API 5CT C90 Casing*. Available at: https://csacimports.com/api-5ct-c90-casing-2/ (Accessed: 4 May 2022).

Cauchois, G. *et al.* (2021) *Re-stream - Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe*. Oslo: DNV, Carbon Limits. Available at: https://www.carbonlimits.no/wp-content/uploads/2021/10/Re-stream-report-October-2021.pdf (Accessed: 23 March 2022).

Cengel, Y., Boles, M. and Kanoglu, M. (2020) *Thermodynamics: An engineering approach: Ninth Edition*. Singapore: McGraw-Hill Education.

Cetinkaya, E., Dincer, I. and Naterer, G. F. (2012) 'Life cycle assessment of various hydrogen production methods', *International Journal of Hydrogen Energy*, 37(3), pp. 2071–2080. doi: 10.1016/J.IJHYDENE.2011.10.064.

Chakrabarti, S. (2005) *Handbook of Offshore Engineering, Volumes 1-2*. Elsevier. Available at: https://app.knovel.com/hotlink/toc/id:kpHOEV0001/handbook-offshore-engineering/handbook-offshore-engineering.

Chipindula, J. *et al.* (2018) ‘Life cycle environmental impact of onshore and offshore wind farms in Texas’, *Sustainability*, 10(6). doi: 10.3390/su10062022.

Chiyoda Corporation (no date) *Performance of 10,000 hours of operation in Chiyoda’s demo plant*. Available at: https://www.chiyodacorp.com/en/service/spera-hydrogen/demo-plant/ (Accessed: 29 April 2022).

Classen, M. *et al.* (2009) *Life cycle Inventories of Metals*. Dübendorf. Available at: https://db.ecoinvent.org/reports/10_Metals_v2.1.pdf?area=463ee7e58cbf8 (Accessed: 18 April 2022).

Danish Energy Agency (no date) *Energy island in the North Sea*. Available at: https://ens.dk/en/our-responsibilities/wind-power/energy-islands/energy-island-north-sea (Accessed: 21 May 2022).

Davis, J. R. (2001) *Alloying : understanding the basics*. ASM International. Available at: https://app.knovel.com/hotlink/toc/id:kpAUB00001/alloying-understanding/alloying-understanding (Accessed: 11 May 2022).

DHL (no date) *Containership size: The Panamax*. Available at: https://www.dhl.com/content/dam/dhl/global/dhl-global-forwarding/documents/pdf/glo-dgf-cargo-sizes-infographic.pdf (Accessed: 14 May 2022).

Dinh, V. N. *et al.* (2021) ‘Development of a viability assessment model for hydrogen production from dedicated offshore wind farms’, *International Journal of Hydrogen Energy*, 46(48), pp. 24620–24631. doi: 10.1016/j.ijhydene.2020.04.232.

Dufour, J. *et al.* (2012) ‘Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources’, *International Journal of Hydrogen Energy*, 37(2), pp. 1173–1183. doi: 10.1016/j.ijhydene.2011.09.135.

EAA; *et al.* (1997) *Life Cycle Assessment (LCA) - A guide to approaches, experiences and information sources*. Available at: https://www.eea.europa.eu/publications/GH-07-97-595-EN-C/Issue-report-No-6.pdf/view.

EDP (no date) *BEHYOND: Bolstering the joint opEration of HYdrogen and Offshore wiND | edp.com*. Available at: https://www.edp.com/en/innovation/behyond-bolstering-joint-operation-hydrogen-and-offshore-wind (Accessed: 21 May 2022).

Eiga (2014) ‘IGC DOC 121/14: Hydrogen pipeline systems’. Brussel: European Industrial Gas Association. Available at: https://h2tools.org/sites/default/files/Doc121_04 H2TransportationPipelines.pdf (Accessed: 21 March 2022).

Energifakta Norge (no date) *Norsk energibruk*. Available at: https://energifaktanorge.no/norsk-energibruk/ (Accessed: 26 May 2022).

Equinor (2021) *Hywind Scotland fortsatt best blant havvindparker på britisk sokkel*. Available at: https://www.equinor.com/no/news/20210323-hywind-scotland-uk-best-performing-offshore-wind-farm.html (Accessed: 1 April 2022).

ERM (no date) *ERM Dolphyn*. Available at: https://ermdolphyn.erm.com/p/1https://ermdolphyn.erm.com/p/://ermdolphyn.erm.com/p/1/p/

1 (Accessed: 21 May 2022).

European Commission (2010) *General guide to Life Cycle Assessment (LCA): provisions and actions steps*. Luxemborg: Publications Office of the European Union. doi: 10.2788/94987.

European Commission (no date) *Paris Agreement*. Available at: https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en (Accessed: 24 November 2021).

Evangelisti, S. *et al.* (2017) ‘Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles’, *Journal of Cleaner Production*, 142, pp. 4339–4355. doi: 10.1016/J.JCLEPRO.2016.11.159.

Fichtner, M. (2008) ‘Scientific scope’, in Léon, A. (ed.) *Hydrogen technology*. Berlin: Springer-Verlag.

Gardiner, M. (2009) *DOE Hydrogen and Fuel Cells Program Record 9013: Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs*. Available at: http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage (Accessed: 14 May 2022).

Garside, M. (2022) *Mine production of platinum worldwide 2010-2021*. Available at: https://www.statista.com/statistics/1170691/mine-production-of-platinum-worldwide/ (Accessed: 24 May 2022).

Ghandehariun, S. and Kumar, A. (2016) ‘Life cycle assessment of wind-based hydrogen production in Western Canada’, *International Journal of Hydrogen Energy*, 41(22), pp. 9696–9704. doi: 10.1016/j.ijhydene.2016.04.077.

Gode, J. *et al.* (2011) ‘Miljöfaktaboken 2011’. Stockholm: Värmeforsk. Available at: https://energiforskmedia.blob.core.windows.net/media/17907/miljoefaktaboken-2011-vaermeforskrapport-1183.pdf%0Ahttp://www.sivl.ivl.se/download/18.372c2b801403903d2751c03/.

Goedkoop, M. *et al.* (2013) *Introduction to LCA with SimaPro*. Pré Sustainability. Available at: www.pre-sustainability.com (Accessed: 31 March 2022).

Goldstein, B. *et al.* (2011) *Geothermal Energy, IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, UK, New York, US. Available at: http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch04.pdf.

Granovskii, M., Dincer, I. and Rosen, M. A. (2006) ‘Life cycle assessment of hydrogen fuel cell and gasoline vehicles’, *International Journal of Hydrogen Energy,* 31(3), pp. 337–352. doi: 10.1016/j.ijhydene.2005.10.004.

Grønt Skipsfartsprogram (2022) *Maritimt utslippsfritt drivstoff. Infrastruktur for LOHC-flytende organisk energibaerer*. Available at: https://grontskipsfartsprogram.no/wp-content/uploads/2022/03/Maritimt-utslippsfritt-drivstoff.-Infrastruktur-for-LOHC.pdf (Accessed: 5 April 2022).

H21 North of England (2021) *H21 Phase 1 Technical Summary Report*. Available at: https://h21.green/projects/h21-nic-phase-1/ (Accessed: 14 May 2022).

Hacatoglu, K., Rosen, M. A. and Dincer, I. (2012) ‘Comparative life cycle assessment of hydrogen and other selected fuels', *International Journal of Hydrogen Energy*, 37(13), pp. 9933–9940. doi: 10.1016/j.ijhydene.2012.04.020.

Haeseldonckx, D. and D'haeseleer, W. (2007) 'The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure', *International Journal of Hydrogen Energy*, 32(10–11), pp. 1381–1386. doi: 10.1016/J.IJHYDENE.2006.10.018.

Hafeez, S. *et al.* (2018) 'Catalytic conversion and chemical recovery', in Al-Salem, S. M. (ed.) *Plastics to Energy: Fuel, Chemicals, and Sustainability Implications*. Elsevier, pp. 147–172. doi: 10.1016/B978-0-12-813140-4.00006-6.

Halland, E. K. *et al.* (2011) '4. The Norwegian North Sea', in *Co2 Atlas for the Norwegian Continental Shelf*. Norwegian Petroleum Directorate. Available at: https://www.npd.no/en/facts/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/4-the-norwegian-north-sea/ (Accessed: 28 January 2022).

Hank, C. *et al.* (2020) 'Energy efficiency and economic assessment of imported energy carriers based on renewable electricity', *Sustainable Energy & Fuels*, 4(5), pp. 2256–2273. doi: 10.1039/D0SE00067A.

Hansen, O. R. (2020) *Working together for a safer world Hydrogen and Ammonia Infrastructure Safety and Risk Information and Guidance Report for: Ocean Hyway Cluster*. Bergen: Lloyd's register. Available at: https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/5eb553d755f94d75be877403/158894183 (Accessed: 8 April 2022).

Hassanpouryouzband, A. *et al.* (2021) 'Offshore Geological Storage of Hydrogen: Is This Our Best Option to Achieve Net-Zero?', *ACS Energy Letters*, 6, pp. 2181–2186. doi: 10.1021/acsenergylett.1c00845.

He, T., Pei, Q. and Chen, P. (2015) 'Liquid organic hydrogen carriers', *Journal of Energy Chemistry*, 24(5), pp. 587–594. doi: 10.1016/J.JECHEM.2015.08.007.

Heijungs, R. and Suh, S. (2002) *The computational structure of life cycle assessment*. Dordrecht: Kluwer Academic Publishers. Available at: http://www.leidenuniv.nl/cml/ssp/software.html. (Accessed: 7 March 2022).

Helbæk, M. and Kjelstrup, S. (2006) *Fysikalsk kjemi: 2.utgave*. Bergen: Vigmostad & Bjørke.

Howden (no date) *Compressors for Hydrogen Fuel Cells*. Available at: https://www.howden.com/en-us/applications/compressors-for-hydrogen-fuel-cell (Accessed: 14 May 2022).

Hurskainen, M. and Ihonen, J. (2020) 'Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers', *International Journal of Hydrogen Energy*, 45(56), pp. 32098–32112. doi: 10.1016/J.IJHYDENE.2020.08.186.

Hydrogenious (2018) *Hydrogen infrastructure solutions* . Available at: https://www.hydrogenious.net/wp-content/uploads/2018/08/Hydrogenious_porduct_booklet_short_final.pdf (Accessed: 13 May 2022).

Hydrogenious (2021) *Kick-off for construction and operation of the world's largest plant for storing green hydrogen in Liquid Organic Hydrogen Carrier*. Available at: https://www.hydrogenious.net/index.php/en/2021/03/03/kick-off-for-construction-and-operation-of-the-worlds-largest-plant-for-storing-green-hydrogen-in-liquid-organic-hydrogen-carrier/ (Accessed: 6 January 2022).

HYSTOC (2018) *Hydrogen Supply and Transportation using Liquid Organic Hydrogen Carriers*. Available at: https://www.hystoc.eu/Public-deliverables/.

IEA (2019a) *Offshore Wind Outlook 2019: World Energy Outlook Special Report*. Paris . Available at: www.iea.org/t&c/ (Accessed: 13 May 2022).

IEA (2019b) *The Future of Hydrogen, The Future of Hydrogen*. Paris. Available at: https://www.iea.org/reports/the-future-of-hydrogen.

IEA (2019c) *The Role of Gas in Today's Energy Transitions*. Paris. Available at: https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions (Accessed: 23 May 2022).

IEA (2020) *Global CO2 emissions in 2019*. Available at: https://www.iea.org/articles/global-co2-emissions-in-2019 (Accessed: 3 September 2021).

IEA (2021) *Ammonia Technology Roadmap; Towards more Sustainable Nitrogen Fertilizer Production*. Paris. Available at: https://www.iea.org/reports/ammonia-technology-roadmap.

INPEX (no date) *Ichthys LNG*. Available at: https://www.inpex.com.au/projects/ichthys-lng/ (Accessed: 22 May 2022).

IPCC (2018) *Annex I: Glossary, Global warming of 1.5. An IPCC Special report on the impacts of global warming of 1.5 above pre-industrial levels and related global greenhouse gas emission pathways, in context of strenghtening the global response to the treath of climate change, sustain*. Edited by J. B. . Matthews et al. IPCC.

IPCC (2021) *Summary for Policymakers. Climate Change 2021: The Physical Science Basis Summary for Policymakers, Climate Change 2021: The Physical Science Basis*. Edited by V. Masson-Delmotte et al. Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report_smaller.pdf.

IRENA (2019) *Hydrogen: a Renewable Energy Perspective, Irena*. Abu Dhabi: International Renewable Energy Agency. Available at: https://irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective.

ISO (2006) 'Environmental management — Life cycle assessment — Requirements and guidelines'. Geneva: International Organization for Standardization (ISO).

ITM POWER (no date) *HGas3SP* . Available at: https://itm-power.com/products/hgas3sp (Accessed: 12 May 2022).

Jorschick, H. *et al.* (2020) 'Benzyltoluene/dibenzyltoluene-based mixtures as suitable liquid organic hydrogen carrier systems for low temperature applications', *International Journal of Hydrogen Energy*, 45(29), pp. 14897–14906. doi: 10.1016/J.IJHYDENE.2020.03.210.

Kircher, O. and Braess, H. (2008) 'Challenges and Requirements for Car Industry', in Léon, A. (ed.) *Hydrogen technology*. Berlin: Springer-Verlag.

Kurosaki, D. (2018) 'Introduction of Liquid Organic Hydrogen Carrier and the Global Hydrogen Supply Chain Project'. Chioyda Corporation. Available at: https://www.energy.gov/sites/prod/files/2018/10/f56/fcto-infrastructure-workshop-2018-32-

kurosaki.pdf (Accessed: 6 January 2022).

Kwak, Y. *et al.* (2021) ‘Hydrogen production from homocyclic liquid organic hydrogen carriers (LOHCs): Benchmarking studies and energy-economic analyses’, *Energy Conversion and Management*, 239, p. 114124. doi: 10.1016/J.ENCONMAN.2021.114124.

Lhyfe (no date) *Offshore renewable hydrogen* . Available at: https://www.lhyfe.com/our-production-units/offshore-ecological-hydrogen/ (Accessed: 21 May 2022).

Li, Q. and Jensen, J. O. (2008) ‘Fuel Cells’, in Léon, A. (ed.) *Hydrogen technology*. Berlin: Springer-Verlag.

Lohse-Busch, H. *et al.* (2017) *Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai Energy Systems Division*. Chicago: Argonne National Laboratory. Available at: https://publications.anl.gov/anlpubs/2018/06/144774.pdf (Accessed: 13 May 2022).

Lundberg, S. (2019) *Comparative LCA of Electrolyzers for Hydrogen Gas Production*. KTH Royal Institue of Technology. Available at: http://www.diva-portal.org/smash/get/diva2:1331089/FULLTEXT01.pdf (Accessed: 28 March 2022).

Lysyy, M., Fernø, M. and Ersland, G. (2021) ‘Seasonal hydrogen storage in a depleted oil and gas field’, *International Journal of Hydrogen Energy*, 46(49), pp. 25160–25174. doi: 10.1016/j.ijhydene.2021.05.030.

Makridis, S. S. (2016) ‘Hydrogen storage and compression’, in Carriveau, R. and Ting, D. S.-K. (eds) *Methane and Hydrogen for Energy Storage*. IET Digital Library.

Markiewicz, M. *et al.* (2015) ‘Environmental and health impact assessment of Liquid Organic Hydrogen Carrier (LOHC) systems-challenges and preliminary results’, *Energy and Environmental Science*, 8(3), pp. 1035–1045. doi: 10.1039/c4ee03528c.

Mehrer (no date) *H2 - hydrogen* . Available at: https://www.mehrer.de/en/applications/hydrogen (Accessed: 14 May 2022).

Michel, F. (2008) ‘Cryogenic reservoirs’, in Léon, A. (ed.) *Hydrogen technology*. Berlin: Springer-Verlag.

Miljødirektoratet (2021) *Norske utslipp og opptak av klimagasser*. Available at: https://miljostatus.miljodirektoratet.no/tema/klima/norske-utslipp-av-klimagasser/ (Accessed: 24 November 2021).

Miljødirektoratet (no date) *Norske utslipp - Utslipp til luft og vann og generert avfall, Karbondioksid fossilt*. Available at: https://www.norskeutslipp.no/no/Komponenter/Utslipp/Karbondioksid-fossilt/?ComponentType=utslipp&ComponentPageID=180&SectorID=600 (Accessed: 14 May 2022).

Miotti, M., Hofer, J. and Bauer, C. (2017) ‘Integrated environmental and economic assessment of current and future fuel cell vehicles’, *The International Journal of Life Cycle Assessment*, 22, pp. 94–110. doi: 10.1007/s11367-015-0986-4.

Mokhatab, S. and Mak, W. (2019) *Handbook of natural gas transmission and processing - Principles and Practices (4th edition)*. Elsevier. Available at: https://app.knovel.com/hotlink/toc/id:kpHNGTPPP5/handbook-natural-gas/handbook-natural-gas (Accessed: 14 May 2022).

Mouli-Castillo, J., Heinemann, N. and Edlmann, K. (2021) ‘Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study’, *Applied Energy*, 283(November 2020). doi: 10.1016/j.apenergy.2020.116348.

Müller, K. *et al.* (2015) ‘Liquid Organic Hydrogen Carriers: Thermophysical and Thermochemical Studies of Benzyl- and Dibenzyl-toluene Derivatives’, *Industrial and Engineering Chemistry Research*, 54(32), pp. 7967–7976. doi: 10.1021/ACS.IECR.5B01840/SUPPL_FILE/IE5B01840_SI_001.PDF.

Munroe, D. K. and Biles, J. J. (2005) ‘Regional Science’, in Kempf-Leonard, K. (ed.) *Encyclopedia of Social Measurement*. Elsevier, pp. 325–335. doi: 10.1016/B0-12-369398-5/00365-0.

National Academy of Engineering (2004) ‘The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs’, in *The Hydrogen Economy*. Washington DC: National Academic Press. doi: 10.17226/10922.

National Center for Biotechnology Information (2022a) *Compound summary: 2-Benzyltoluene | C14H14* . Available at: https://pubchem.ncbi.nlm.nih.gov/compound/2-Benzyltoluene (Accessed: 14 May 2022).

National Center for Biotechnology Information (2022b) *Compound summary: Methylcyclohexane | C6H11CH3* . Available at: https://pubchem.ncbi.nlm.nih.gov/compound/Methylcyclohexane (Accessed: 14 May 2022).

National Center for Biotechnology Information (2022c) *Compound summary: Toluene | C6H5CH3*. Available at: https://pubchem.ncbi.nlm.nih.gov/compound/Toluene (Accessed: 14 May 2022).

NaturalHy (2009) *Using the Existing Natural Gas System for Hydrogen*. Publications Office of the European Union. Available at: https://cordis.europa.eu/project/id/502661 (Accessed: 11 October 2021).

Nelson, E. B. (2011) *Well cementing, Oilfield Review*. Available at: https://www.slb.com/resource-library/oilfield-review/defining-series/defining-cementing (Accessed: 1 December 2021).

Neumann & Esser (no date) *Hydrogen Compressors*. Available at: https://www.neuman-esser.de//en/compressors/hydrogen-compressors/ (Accessed: 14 May 2022).

Niermann, M. *et al.* (2019) ‘Liquid Organic Hydrogen Carrier (LOHC) – Assessment based on chemical and economic properties’, *International Journal of Hydrogen Energy*, 44(13), pp. 6631–6654. doi: 10.1016/J.IJHYDENE.2019.01.199.

NVE (2019) *Samlet energibruk - NVE*. Available at: https://www.nve.no/energibruk-effektivisering-og-teknologier/energibruk/samlet-energibruk/?ref=mainmenu (Accessed: 10 May 2021).

OECD (2021) *Peer review of the turkish shipbuilding industry*. Available at: http://www.oecd.org/sti/ind/shipbuilding.htm (Accessed: 13 March 2022).

Oestensjoe (2021) *Hydrogenious LOHC Technologies and Østensjø Group join forces and tread a novel path towards safe zero-emission shipping*. Available at: https://ostensjo.no/hydrogenious-lohc-technologies-and-ostensjo-group-join-forces-and-tread-a-novel-path-towards-safe-zero-emission-shipping/ (Accessed: 1 May 2022).

Olje- og energidepartementet (no date a) *Felt: TRYM*. Available at: https://www.norskpetroleum.no/fakta/felt/trym/ (Accessed: 28 May 2022).

Olje- og energidepartementet (no date b) *Felt på norsk sokkel*. Available at: https://www.norskpetroleum.no/fakta/felt/ (Accessed: 29 May 2022).

Oljedirektoratet (2017) *6000 brønner på norsk sokkel*. Available at: https://www.npd.no/fakta/nyheter/generelle-nyheter/2017/6000-bronner-pa-norsk-sokkel/ (Accessed: 21 May 2022).

Paster, M. D. *et al.* (2011) 'Hydrogen storage technology options for fuel cell vehicles: Well-to-wheel costs, energy efficiencies, and greenhouse gas emissions', *International Journal of Hydrogen Energy*, 36(22), pp. 14534–14551. doi: 10.1016/J.IJHYDENE.2011.07.056.

Pérez, A. A. and Vogt, T. (2014) 'Life cycle assessment of conversion processes for the large-scale underground storage of electricity from renewables in Europe', in *EPJ Web of Conferences*. doi: 10.1051/epjconf/20137903006.

Perrin, M. and Weber, J. (2008) 'Distribution and storage', in Léon, A. (ed.) *Hydrogen technology*. Berlin: Springer-Verlag.

Pestl, S. (2021) *Underground Sun Storage 2030 - Press Releases - Public Relations*. Available at: https://www.uss-2030.at/en/public-relations-/-publications/press/details/article/unique-research-project-to-investigate-underground-storage-of-wind-and-solar-energy-2.html (Accessed: 16 May 2022).

Pfeiffer, W. T., Beyer, C. and Bauer, S. (2017) 'Hydrogen storage in a heterogeneous sandstone formation: Dimensioning and induced hydraulic effects', *Petroleum Geoscience*, 23(3), pp. 315–326. doi: 10.1144/petgeo2016-050.

PosHYdon (no date) *About PosHYdon*. Available at: https://poshydon.com/en/home-en/about-poshydon/ (Accessed: 21 May 2022).

Pré Sustainability (2020) *SimaPro database manual: Methods library*. Available at: https://simapro.com/wp-content/uploads/2020/10/DatabaseManualMethods.pdf (Accessed: 8 March 2022).

Raadal, H. L. *et al.* (2011) 'Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power', *Renewable and Sustainable Energy Reviews*, 15(7), pp. 3417–3422. doi: 10.1016/J.RSER.2011.05.001.

Rao, P. C. and Yoon, M. (2020) 'Potential liquid-organic hydrogen carrier (Lohc) systems: A review on recent progress', *Energies*, 13(22). doi: 10.3390/en13226040.

Reuß, M. *et al.* (2017) 'Seasonal storage and alternative carriers: A flexible hydrogen supply chain model', *Applied Energy*, 200, pp. 290–302. doi: 10.1016/j.apenergy.2017.05.050.

Ritchie, H. and Roser, M. (2020) *Energy*. Available at: https://ourworldindata.org/fossil-fuels (Accessed: 14 May 2022).

Rivard, E., Trudeau, M. and Zaghib, K. (2019) 'Hydrogen storage for mobility: A review', *Materials*, 12(12). doi: 10.3390/MA12121973.

Rockström, J. *et al.* (2009) 'A safe operating space for humanity', *Nature* , 461, pp. 472–475. doi: 10.1038/461472a.

Sæbø, A. *et al.* (2020) *Optimal utnyttelse av energi fra havvind i Sørlige Nordsjø II Offshore H2-produksjon og kabel til land*. Greenstat. Available at: https://greenstat.no/hvaskjer/rapport-om-optimal-utnyttelse-av-energi-fra-havvind-offshore-h2-produksjon-og-kabel-til-land (Accessed: 7 March 2022).

Sani, F. M. *et al.* (2019) 'Review of the API RP 14E erosional velocity equation: origin, applications, misuses and limitations', in *CORROSION2019*. Texas: NACE International.

Schuller Martin Baitz, O. *et al.* (2020) *Attributional vs. Consequential LCA, V2*. EUCAR. Available at: https://www.eucar.be/wp-content/uploads/2020/08/20200820-EUCAR-Attributional-vs-Consequential-updated-2.pdf (Accessed: 10 March 2022).

Sdanghi, G. *et al.* (2020) 'Towards non-mechanical hybrid hydrogen compression for decentralized hydrogen facilities', *Energies*, 13(12). doi: 10.3390/en13123145.

Sekine, Y. and Higo, T. (2021) 'Recent Trends on the Dehydrogenation Catalysis of Liquid Organic Hydrogen Carrier (LOHC): A Review', *Topics in Catalysis*, 64(7–8), pp. 470–480. doi: 10.1007/S11244-021-01452-X/TABLES/4.

Siemens (no date) *Silyzer 300, 2018*. Available at: https://assets.new.siemens.com/siemens/assets/public.1524040818.abae9c1e48d6d239c06d88e565a25040ed2078dc.ct-ree-18-047-db-silyzer-300-db-de-en-rz.pdf (Accessed: 12 May 2022).

Simons, A. and Bauer, C. (2011) 'Life cycle assessment of hydrogen production', in Wokaun, A. and Wilhelm, E. (eds) *Transition to Hydrogen: Pathways Toward Clean Transportation*. Cambridge: Cambridge University Press, pp. 13–57. doi: 10.1017/CBO9781139018036.006.

Song, H. *et al.* (2021) 'A novel hybrid energy system for hydrogen production and storage in a depleted oil reservoir', *International Journal of Hydrogen Energy*, 46(34), pp. 18020–18031. doi: 10.1016/j.ijhydene.2020.09.081.

Spyroudi, A. *et al.* (2020) *Offshore Wind and Hydrogen: Solving the Integration Challenge*. ORE Catapult. Available at: https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf.

Stone, H. B. J. *et al.* (2009) 'Underground hydrogen storage in the UK Underground hydrogen storage in the UK', *Geological Society, London, Special Publications*, 313(1), pp. 217–226. doi: 10.1144/SP313.13.

Store Norske Leksikon (SNL) (2022) *Bærekraftig utvikling*. Available at: https://snl.no/bærekraftig_utvikling (Accessed: 14 January 2022).

Suleman, F., Dincer, I. and Agelin-Chaab, M. (2016) 'Comparative impact assessment study of various hydrogen production methods in terms of emissions', *International Journal of Hydrogen Energy*, 41(19), pp. 8364–8375. doi: 10.1016/j.ijhydene.2015.12.225.

Suzuki, J. (2009) 'PRESSURIZED HYDROGEN STORAGE', in Ohta, T. (ed.) *Energy carriers and conversion systems, vol. II*. EOLSS Publications.

Tarkowski, R. (2019) 'Underground hydrogen storage: Characteristics and prospects', *Renewable and Sustainable Energy Reviews*, 105, pp. 86–94. doi: 10.1016/j.rser.2019.01.051.

TechnipFMC (no date) *Energy Transition, Deep Purple*^{TM}. Available at: https://www.technipfmc.com/en/what-we-do/subsea/energy-transition-deep-purple/

(Accessed: 21 May 2022).

Teichmann, D., Arlt, W. and Wasserscheid, P. (2012) ‘Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy’, *International Journal of Hydrogen Energy*, 37(23), pp. 18118–18132. doi: 10.1016/J.IJHYDENE.2012.08.066.

Tiwari, G. P. *et al.* (2000) ‘A study of internal hydrogen embrittlement of steels’, *Materials Science and Engineering A*, 286(2), pp. 269–281. doi: 10.1016/S0921-5093(00)00793-0.

Tønnesen, H. and Sandberg, F. H. (no date) *The Statfjord B platform* . Available at: https://statfjord.industriminne.no/en/category/platforms/ (Accessed: 22 May 2022).

UNFCCC (2015) *Paris Agreement*. Paris: UNFCC.

Varun, Bhat, I. K. and Prakash, R. (2009) ‘LCA of renewable energy for electricity generation systems-A review’, *Renewable and Sustainable Energy Reviews*, 13(5), pp. 1067–1073. doi: 10.1016/j.rser.2008.08.004.

Warwick, N. *et al.* (2022) *Atmospheric implications of increased Hydrogen use*. Department for Business, Energy & Industrial Strategy. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067144/atmospheric-implications-of-increased-hydrogen-use.pdf (Accessed: 27 May 2022).

Webber, M. E. (2007) ‘The water intensity of the transitional hydrogen economy’, *Environmental Research Letters*, 2(3). doi: 10.1088/1748-9326/2/3/034007.

White, F. (2017) *Fluid Mechanics*. Chennai: McGraw-Hill Education.

Wulf, C., Reuß, M., Grube, T., Zapp, P., Robinius, M., Hake, Jürgen Friedrich, *et al.* (2018) ‘Life Cycle Assessment of hydrogen transport and distribution options’, *Journal of Cleaner Production*, 199, pp. 431–443. doi: 10.1016/J.JCLEPRO.2018.07.180.

Wulf, C. and Zapp, P. (2018) ‘Assessment of system variations for hydrogen transport by liquid organic hydrogen carriers’, *International Journal of Hydrogen Energy*, 43(26), pp. 11884–11895. doi: 10.1016/J.IJHYDENE.2018.01.198.

ZEEDS (no date) *The ZEEDS Initiative – The start of something new*. Available at: https://zeedsinitiative.com/ (Accessed: 21 May 2022).

Zhang, X. *et al.* (2017) ‘Life Cycle Assessment of Power-to-Gas: Approaches, system variations and their environmental implications’, *Applied Energy*, 190, pp. 326–338. doi: 10.1016/J.APENERGY.2016.12.098.

Zhao, G. *et al.* (2020) ‘Life cycle assessment of H2O electrolysis technologies’, *International Journal of Hydrogen Energy*, 45(43), pp. 23765–23781. doi: 10.1016/J.IJHYDENE.2020.05.282.

Østenby, A. M. (2019) *NVE Faktaark - Dybde og kompliserte bunnforhold gjør havvind i Norge dyrere enn i Europa, Teknologianalyser 2019*. NVE. Available at: https://publikasjoner.nve.no/faktaark/2019/faktaark2019_15.pdf (Accessed: 26 May 2022).

9 Appendix

9.1 Appendix I: Background data and calculations

This appendix provides all the background data for presented calculations.

Calculation of hydrogen production

Table 9-1 - background data used for the calculation of hydrogen production in concept analysis.

Hydrogen production background data		
Input parameter	**Value**	**Reference**
Energy used for H_2 prod [kWh/kg H2]	55	Defined by efficiency
Water consumption [kg H_2O/kg H_2]	10	(Siemens, no date)
Energy consumption RO [kWh/m^3]	4.5	Hank et.al (2020)
Density hydrogen @200 bar [kg/m3], 10°C	15.34	Equation [7] and [8]
Density hydrogen @1 bar [kg/m3], 0°C	0.089	Equation [7] and [8]
Energy for compression/hydrogenation [kWh/kg]	2.79/1.7	Equation [6]/Defined
Fraction of energy for RO (UHS/LOHC) [%]	0.08 /0.08	
Fraction of energy for electrolyser (UHS/LOHC) [%	95.1 /96.9	
Fraction of energy used compression (UHS/LOHC) [%]	4.8 / 3.0	

Calculations of varying inputs by scenarios for LOHC cases

Table 9-2 - calculation of dehydrogenated hydrogen and LOHC for scenarios.

	Conservative	**Base**	**Ideal**
Loss, H_2, hydrogenation	0.02	0.01	0.005
Loss, H_2 dehydrogenation	0.04	0.03	0.001
H_2 production [kg]	907 530 569	907 530 569	907 530 569
BT need [kg]	13 764 213 627	13 764 213 627	13 764 213 627
H_2 in BT [kg]	889 379 957	898 455 263	902 992 916
Hydrogenated BT [kg]	14 378 309 312	14 525 026 754	14 598 385 475
Dehydrogenated H2 [kg]	853 804 759	871 501 605	902 089 923
Dehydrogenated LOHC [kg]	13 524 504 553	13 653 525 149	13 696 295 552

Calculations of varying reservoir recovery rate for UHS case

Table 9-3 – hydrogen output by recovery rate.

	Hydrogen output from reservoir		
	Conservative	**Base**	**Ideal**
Hydrogen produced [kg]	907536691.2	907536691.2	907536691.2
Hydrogen after reservoir [kg]	453768345.6	635275683.9	816783022.1
Recovery	0.5	0.7	0.9

Background data for calculation of produced BT in concept analysis

Table 9-4 - background data for calculation of produced BT in concept analysis (Table 4-7).

Input parameter	**Value**	**Reference**
C [g/mol]	12	Periodic table
H [g/mol]	1	Periodic table
Hydrogen weight [g/mol]	2	Own calculation based on atomic molweight
Perhydro benzyltoluene weight [g/mol]	194	Own calculation based on atomic molweight
Benzyltoluene weight [g/mol]	182	Own calculation based on atomic molweight
Mol benzyltoluene/mol H_2	0.167	Calculated
Density benzyltoulene @30°C [kg/m^3]	996	(Müller *et al.*, 2015)
Density hydrogenated BT @20 °C [kg/m^3]	876	(Müller *et al.*, 2015)
Relationship H_2/LOHC	15.17	Calculated

Calculation of the wall thickness for a hydrogen transport pipeline

The procedure for this calculation is based upon ASME B31.13, which is recommended as reference for more detailed information about the difference input parameters. E, the longitudinal joint factor, is based on the pipe class and given in the standard. The longitudinal joint factor is either 0.8 or 1.0 and for all API 5L steel it is defined as 1.0. F, the design factor, is based on the location class of the pipeline, which is related to the location of the pipeline close to industry, homes, buildings etc., or remote locations. In addition, it depends on the fracture control method, which can be either on a prescriptive design method or a performance-based design method. In this thesis, it is assumed that a prescriptive design method is used and hydrogen transport pipeline is assumed to be in location class 4, yielding 0.5 as design factor for an offshore hydrogen pipeline. T, the temperature derating factor, is tabulated in the ASME-standard for the right choice corresponding to the relevant temperature. In this thesis, it is assumed that the temperature does not exceed 150ºC, limiting the temperature derating factor T to 1.0. H_f, the material performance factor, is tabulated in the standard and is depending on the specified minimum strength (tensile/yield) and the system design pressure. Assuming a design pressure of close to 3000 psi (206 bar) and a yield strength of 450 MPa, the carbon steel material performance factor is 0.606. These variable definitions yields the following result, which is presented in Table 9-5:

Table 9-5 – results for calculations of the hydrogen transport pipeline.

Material	**X65 (with cathodic protection)**

Density [kg/m^3]	7800
Internal pressure	200 bars
ID	12" - 304.8 mm
OD	13" - 330 mm
Minimum wall thickness [mm]	25

Calculation of steel amount

Table 9-6 - calculation of steel amount for well LCI.

	Density [kg/m^3]	Length [m]	ID [in.]	ID [mm]	Material	WT [mm]	Amount [kg]
Well		2000					
Production string	7930	2000	7	177.8	18-18 Ch	12.7	112509
Production casing	7930	2000	9	228.6	18-18 Ch	14.15	161171
Intermediate casing	7850	1500	12	304.8	HSLA	13.06	147255
Surface casing	7850	450	16	406.4	HSLA	13.06	11255
Conductor casing	7850	25	24	609.6	HSLA	12.42	56015
Cement layer							
Conductor	*2400*	*25*		*203.2*	Portland c.	20.32	*15566*
Intermediate	*2400*	*1500*		*76.2*	Portland c.	7.62	*131339*
Surface	*2400*	*450*		*101.6*	Portland c.	10.16	*70047*

Calculation of space demand for a dehydrogenation plant on a Panamax ship

Key characteristics regarding fuel consumption, necessary hydrogen and thereby the necessary dehydrogenation capacity is summarized in Table 9-7. A Panamax ship is assumed, travelling a roundtrip distance of 280 km to and from shore to the hydrogen production platform.

The assumed efficiencies are 33% for a combustion engine and 60% for the fuel cell[13]. As fuel cells are more efficient than combustion engines, less energy is required for hydrogen-based propulsion systems.

Table 9-7 – Estimation of footprint of a dehydrogenation plan onboard a Panamax tanker for a round trip from shore to the Southern North Sea II.

Parameter	**Quantity**
Motor capacity [kW]	12 000
Distance estimated [km]	280
Time estimated [h]	12

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[13] Toyota Mirai FC has an efficiency between 50-66% depending on load (Lohse-Busch *et al.*, 2017)

Load capacity (containers)	2500
Energy consumption [kWh]	144 000
MDO, fuel consumption [ton]	12
Combustion engine efficiency	33%
Fuel cell efficiency	60%
H_2, fuel consumption [ton]	4,3
Hourly H_2 consumption [kg/h]	600
Area, dehydrogenation [m^2]	~1 600
Corresponding units of dehydrogenation containers	55
Requirement of ship capacity for dehydrogenation	2.2%

A dehydrogenation plant is by a rough estimation estimated to uptake the volume of 55 40-foot storage containers, corresponding to around 2.2% of the total storage capacity of a Panamax ship (DHL, no date).

Background data for calculation of pressure drop

Table 9-8 - input parameters defined for calculation of pressure drop.

Input parameter	**Value**	**Reference**
Dynamic viscocity [Pa*s] (μ)	9.0E-6	(White, 2017)
Kinematic vicocity [m^2/s] ($\frac{\mu}{\rho}$)	5.7E-07	Calculated
f (by Colebrook White equation) [-]	0.0106	(White, 2017)
Stainless steel, new (absolute roughness) [mm]	0.002	(White, 2017)
Pipeline length [km]	140	Defined
Temperature [C]	4	Defined
Z [-]	1.06	Equation [7]
S (spesific gravity) [-]	0.07	Calculated; (White, 2017)

Background data for calculation of pressure drop through orifice

Table 9-9 - input parameters for calculations of pressure drop over orifice.

Input parameters		
Q [m^3/s]	0.46	Based on 7-days empty period
C_d	0.9	(White, 2017)
β	0.3	Determined
A [m^2]	0.07	Based on 12"
Density	15.3	Equation [7] and [8]
Specific heat ratio	1.4	Equation [4]
P1 [bar]	200	Determined

Calculation of CO2-emissions from combustion of gasoline and natural gas

Table 9-10 - Molecule weights for gasoline, carbon dioxide and methane.

Molecule	Molar weight
$\boldsymbol{C_8H_{18}}$	$114{,}23\ g/mol$
$\boldsymbol{CO_2}$	$44{,}01\ g/mol$
$\boldsymbol{CH_4}$	$20\ g/mol$

$$9C_8H_{18} + 112.5O_2 \rightarrow 72CO_2 + 81H_2O$$

$$72\ mol * 44.01\ g/mol = 3.2\ kg \qquad [2]$$

$$50CH_4 + 100O_2 \rightarrow 50CO_2 + 100H_2O \qquad [3]$$

$$50\ mol * 44.01\ g/mol = 2.2\ kg$$

Calculation of erosional velocity and noise velocity recommendation by API RP 14E

Table 9-11 - Calculation of erosional velocity and conversion of noice recommendations in API RP 14E

	Original equation input	Imperial units	SI units	Units
G = Gas gravity	0.07	-	0.07	-
P = minimum pipeline pressure	2900	Psia	200	bar
R = universal gas constant	10.73	-	8.4	-
T = flowing gas temperature	497.5	Rankine	4	Celcius
Erosional velocity u	95.70	feet/sec	29.17	m/s
Z = compressibility factor	1.01	-	1.01	-
Noise recommendation (API 14E)	60	-	18.288	

9.2 Appendix II: Complementary LCI

This chapter provides important information about the transport for the unit processes. The transport information is provided per unit process.

9.2.1 UHS

Hydrogen processing

The compressors are therefore assumed transported from Cologne, Germany, to Rotterdam by road for shipping (250 km) and shipped from Rotterdam to Southern North Sea II by barge tanker (250 km). It is assumed the same transport distances for recycling of the compressors.

Riser

The riser is shipped from Egersund to the geographic center Southern North Sea II by bulk carrier, a transportation distance of 200 km.

Well system

Cement is transported by tanker from Aalborg to Southern North Sea II (340 km). The steel is expected to be produced in Sigen, Germany and assumed to be transported by lorry to Bremerhaven (500 km) and then by bulk carrier to Southern North Sea II (500 km).

Pipeline

Pipeline is transported by bulk carrier from Wick, UK, to Southern North Sea for reeling. The transport distance back to shore for recycling is included (500 km).

9.2.2 LOHC

Hydrogenation

The LOHC is assumed to be produced in Basel, Switzerland, a location known for production of chemicals. The virgin LOHC is assumed to be transported by Rhinen to Rotterdam by barge tanker (700 km). From Rotterdam, overseas transport by barge tanker is assumed to the geographic center of Southern North Sea II (550 km). It is assumed that all hydrogenated LOHC is transported to shore in Kristiansand. This transport is assumed as a part of the dehydrogenation. It is assumed that all recycled LOHC is transported from Kristiansand to the FPSO.

It is assumed that the hydrogenation plant is assemblied onto the FPSO in Bremerhaven, Germany, by the FPSO transported from Izmir, Turkey. Germany is chosen as manufacturer of the chemical plant as Germany is a large manufacturer in Europe and as Hydrogenious is german. The transportation of the plant is therefore accounted for by the FPSO.
The platinum is assumed transported from South Africa to Germany (12 000 km) (for plant assembling) by tanker.

Dehydrogenation

It is assumed that the dehydrogenation plant is assemblied at its location in Kristiansand, Norway. Material inputs to the plant is accounted for in the data and input materials are assumed to be produced in Europe or globally. Transport for dehydrogenation plant is therefore accounted by transport of raw materials.

Storage

FPSO is assumed assemblied in Turkey and transport from Turkey to Southern North Sea II (7000 km) is included in the unit process.

9.3 Appendix III: Complete LCA results

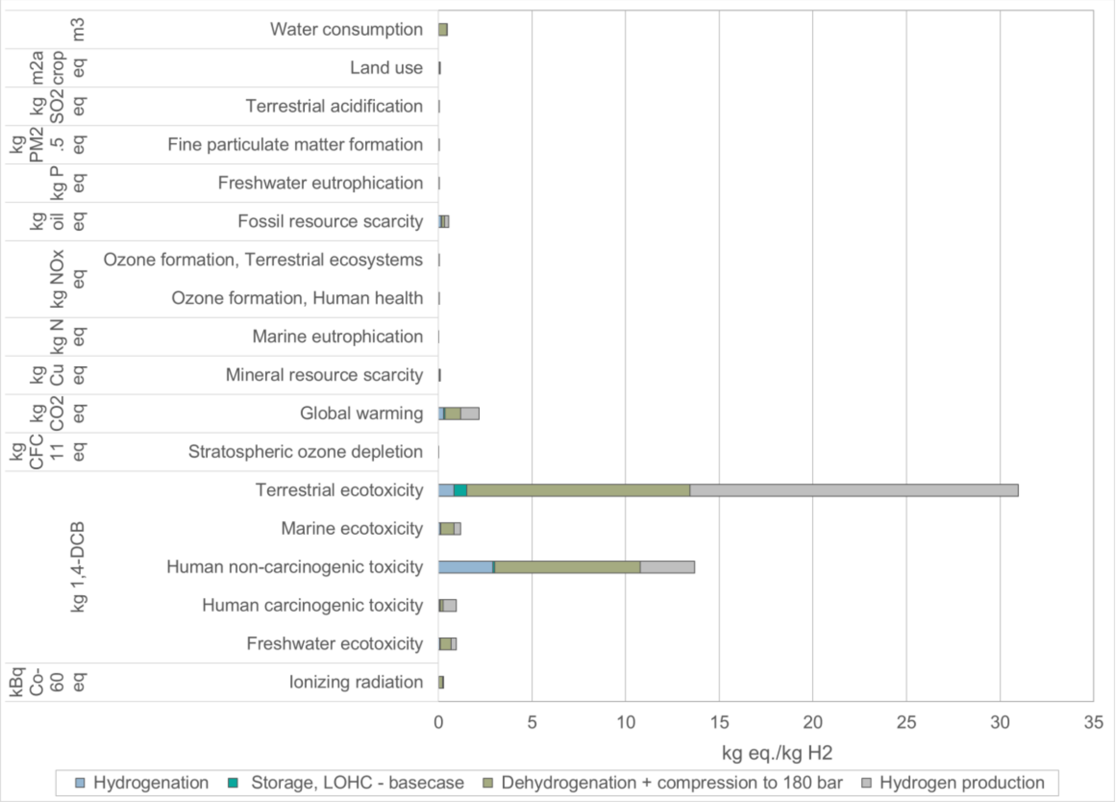

Figure 9-1 - Results of all impact categories for LOHC case A) (base scenario), based on ReCiPe (H) Midpoint

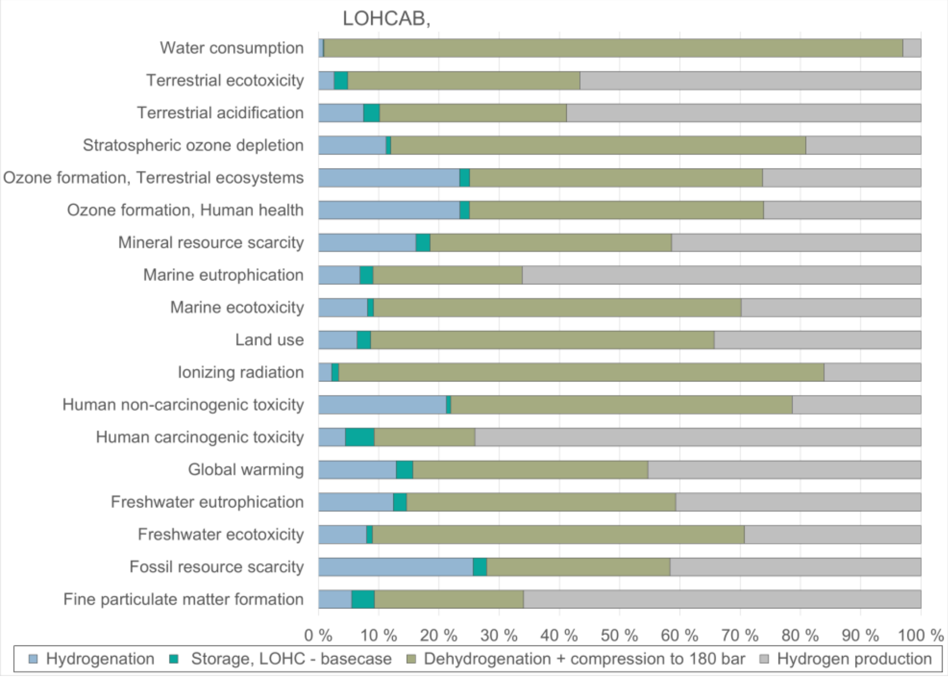

Figure 9-2 - Normalized results per impact category for LOHC case A) base scenario.