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SCALE DEPENDENCY OF LEVELIZED COST OF HYDROGEN STORAGE

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Tämä opinnäytetyö toteutettiin Wärtsilä Finland Oy:n toimeksiannosta. Molekyylisen vedyn paikallinen varastointi on harvinaista. Saatavilla on kuitenkin useita teknisiä ratkaisuja, joiden kustannukset vaihtelevat suuresti kokoluokasta ja käyttökohteesta riippuen. Tutkimuksen tarkoituksena on selvittää, kuinka varaston kapasiteetti, sekä purku- ja latauskapasteettien koko vaikuttaa kustannustehokkaimpaan varastoratkaisuun, sekä varastoinnin elinkaarikustannuksiin vetykiloa kohden. Tutkimuksessa selvitetään myös, kuinka varaston käyttötapa vaikuttaa varastoinnin energiankulutukseen, varastointikustannuksiin, ja kustannustehokkaimman varastoteknologian valintaan.

Tutkimus on kaksivaiheinen. Kirjallisuuskatsauksessa selvitetään vedyn varastointiin vaikuttavat ominaisuudet, varastointimenetelmät, niiden energiankulutus, sekä kustannukset. Tieteelliset artikkelit, sekä alan yritysten julkaisut antavat riittävän tietopohjan tutkimuksen toiseen vaiheeseen. Toinen vaihe käsittää varastointimenetelmien vertailutyökalun kehittämisen, sekä tutkimuskysymyksiin vastaamisen työkalun antamien tulosten pohjalta.

Vedyn varastointi on kehittyvä ala, ja toteutuneita projekteja on vähän. Tulosten validointi on siksi haasteellista. Epävarmankin tiedon pohjalta suuret trendit ovat havaittavissa. Pienimmissä järjestelmissä paineistettuna varastointi on todennäköisesti selvästi edullisin ratkaisu. Suurissa kokoluokissa varaston käyttötiheys, purku- ja latausnopeudet, sekä komponenttien todelliset hinnat vaikuttavat edullisimpaan vaihtoehtoon huomattavasti herkemmin. Jokaiselle tarkastelluista varastoteknologioista on reunaehdot, joilla teknologia on edullisin vaihtoehto.

Asiasanat	Vetyvarasto, elinkaarikustannukset, nestevety, paineistettu vety, LOHC

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ABSTRACT

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This thesis was commissioned by Wärtsilä Finland Oy. Stationary storage of physical hydrogen is not commonplace. Costs of the many available technologies vary greatly depending on scale and application. The purpose of this research is to find out how storage size and input and output capacities affect the most cost-effective storage solution and levelized cost of hydrogen. The effect of storage usage pattern on energy consumption and choice of technology is also explored.

The research consists of two parts. Properties of hydrogen relevant to storage, storage methods and related energy consumptions and costs are covered by a literature review. Scientific articles and publications by businesses in the industry give a sufficient factual basis for the second phase of the research. The second phase includes developing a tool for comparison of storage technologies and answering the research questions based on results obtained from the tool.

The results from a calculation tool are only as good as the starting values given to it. This must be considered when viewing the results of this thesis. Hydrogen storage is a developing industry, and finished projects are scarce. For this reason, validating the results is challenging. Despite the numerous uncertain parameters, general trends are clear. In small installations pressurized storage is likely most cost effective by a fair margin. In large capacities the usage pattern, loading and unloading capacities and the final cost of components determine which storage type provides the lowest cost of hydrogen storage. Each type of storage in this comparison has a set of conditions under which it is the lowest cost solution.

Keywords	Hydrogen storage, liquid hydrogen, compressed hydrogen, and LOHC

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ABBREVIATIONS

LCOH	levelized cost of hydrogen
LCOHS	levelized cost of hydrogen storage
LOHC	liquid organic hydrogen
$\mathrm{LH_2}$	liquid hydrogen
$\mathrm{CH_2}$	compressed hydrogen
LHV	lower heating value
HI	heat integration

1 INTRODUCTION

1.1 Objective

Hydrogen plays a major role in the energy sectors transition off from fossil sources. It has long been utilized in process and chemical industries as part of processes. Large scale stationary storage of hydrogen is not commonplace, and the existing applications serve special use cases, such as space launches, hydrogen fuelling stations and hydrogen production. As demand for renewable energy storage solutions increases, the question of cost-effective hydrogen storage for each scale and application must be answered.

Many hydrogen storage methods involve binding hydrogen into other materials, or processing hydrogen into other, more easily stored substances such as ammonia or methane. This thesis will concentrate on storage of physical hydrogen, meaning the methods that do not rely on further processing after hydrogen production. Technologies, such as storage in salt caverns, other geological structures and repurposed structures are also excluded, as they may not be commercially available, and equally applicable to every location. This thesis will cover the challenges in hydrogen storage, introduce the mature technologies for storing hydrogen in physical form and explore the link between different properties of a storage system, and levelized cost of hydrogen. As part of this thesis a tool to compare physical hydrogen storage technologies is developed.

1.2 Research Gap

A tool for comparing different storage solutions is developed based on currently available information. The tool will be able to calculate the levelized cost of hydrogen storage based on the physical properties of hydrogen, performance data from component manufacturers and cost information. In this thesis, early results from the comparison tool will give an indication of where each storage methodology is likely to be most cost effective. The tool will aid in planning of hydrogen storage solution for a specific project.

1.3 Scope

This thesis covers mature hydrogen storage technologies of molecular hydrogen, in terms of the costs and energy consumption associated with them. Costs and energy consumption of hydrogen compression and liquefaction are covered, but the details of the technologies are not included. Hydrogen as a molecule and substance is introduced to better understand the challenges related to its storage. Different technologies and their components are described briefly to introduce their properties, special features, strong points, and challenges. The development of the comparison tool is covered, as is the source data used in the tool development. Figure 1 illustrates the scope of this thesis and comparison tool development.

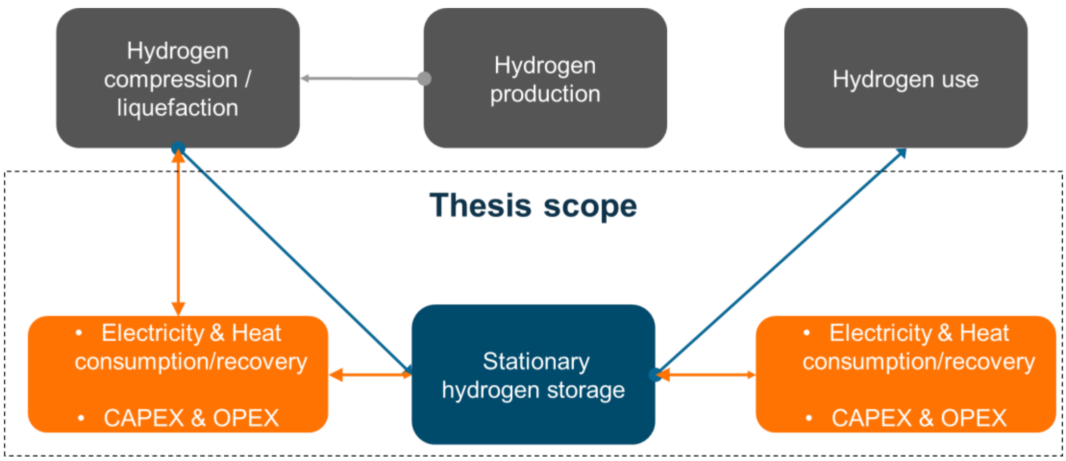

Figure 1. Scope of the thesis

The major topics immediately outside the scope of this thesis are hydrogen safety, storage technologies other than compressed hydrogen (CH_2), liquid hydrogen (LH_2), and liquid organic hydrogen carriers (LOHCs). Combinations of the storage technologies are excluded, as are hydrogen end use and production. Most notable exclusion is the validation of the calculation tool results. This is due to the scarcity of completed hydrogen storage projects and unavailability of detailed data related to them.

1.4 Methodology

The first part of this thesis is a literature review concerning past research into hydrogen storage. Mature storage technologies of hydrogen are identified, and the costs and energy consumption involved with them are explored.

A part of the thesis consists of developing a tool to compare the energy usage of different technologies under different usage parameters. Hydrogen storage in liquid organic hydrogen carrier is added to the comparison tool based on prior research into the subject by an expert in the case company, thus, only briefly described here. The calculation tool development will be based on the findings made in the first portion. The results of the tool will aid in answering the research questions.

2 PROPERTIES OF HYDROGEN

The challenges in hydrogen storage stem from the physical properties of the gas. Properties most relevant to challenges faced in storage solution are introduced in this chapter. Hydrogen molecules are small compared to other gases and have a strong repulsive interaction. Table 1 lists properties relevant to hydrogen storages under consideration in this thesis.

Table 1. Properties of hydrogen. (Najjar, 2013)

Property	**Value**
Molecular weight	2,01594
Density of gas at 0°C and 1 atm	0,08987 kg/m^3
Density of solid at -259°C	85,8 kg/m^3
Density of liquid at -253°C	70,8 kg/m^3
Melting temperature	-259°C
Boiling temperature at 1 atm	-253°C
Critical temperature	-240°C
Critical pressure	12,8 atm
Critical density	31,2 kg/m^3
Heat of fusion at -259°C	58 kJ/kg
Heat of vaporisation at -253°C	447 kJ/kg
Lower heating value	119,9 MJ/kg

The low molecular weight of hydrogen indicates a small size of the molecule, which leads to the gas being prone to leakages. The densities of both gas and liquid phase are remarkably low. The density of gaseous hydrogen is only about a 14^{th} of the density of air in standard temperature and pressure. The density of liquid hydrogen is only about a tenth of more common liquid fuels, such as diesel or methanol. The gravimetric energy density of hydrogen is exceptionally high at 119,9 MJ/kg or 33,3 kWh/kg, compared to other fuels such as methane at 50MJ/kg, diesel at 42,5MJ/kg or methanol at 18,0 MJ/kg. Due to the low density of hydrogen, the volumetric energy density is low. The volumetric energy density of LH_2 for example, is only about 23% of the volumetric energy density of diesel. The lower heating value (LHV) is used when referring to the energy content of hydrogen in this thesis.

A low boiling temperature of hydrogen sets high requirements for liquefaction, and insulation of LH_2 storage vessels.

2.1 Density of Hydrogen

As the focus is on physical hydrogen storage, the differences between storage methods fundamentally stem from differences in storage temperature and storage pressure. Figure 2 represents the density of hydrogen at several pressures as function of temperature.

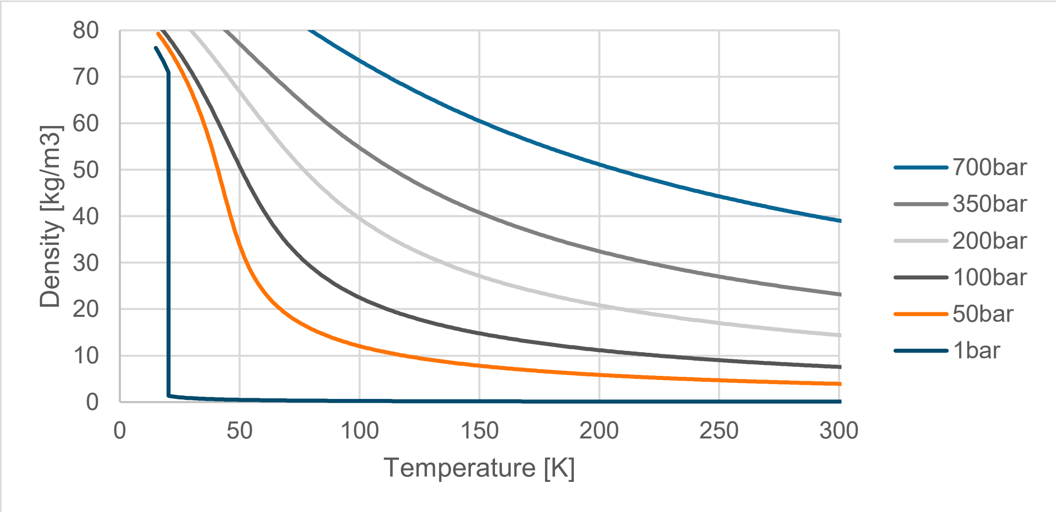

Figure 2. Hydrogen density as function of temperature in various pressures. (National Institute of Standards and Technology, 2022)

2.2 Compressibility

The amount of hydrogen in a storage vessel cannot be accurately calculated using the ideal gas law, because like all real gases, hydrogen deviates from ideal gas behaviour. With the high pressures involved in hydrogen storage, the compressibility factor of hydrogen causes a significant deviation from the linear behaviour of an ideal gas. In this thesis, the issue of calculating density is circumvented by using density data directly. The density data used in the calculation tool developed in this thesis is sourced from the National Institute of Standards and Technology.

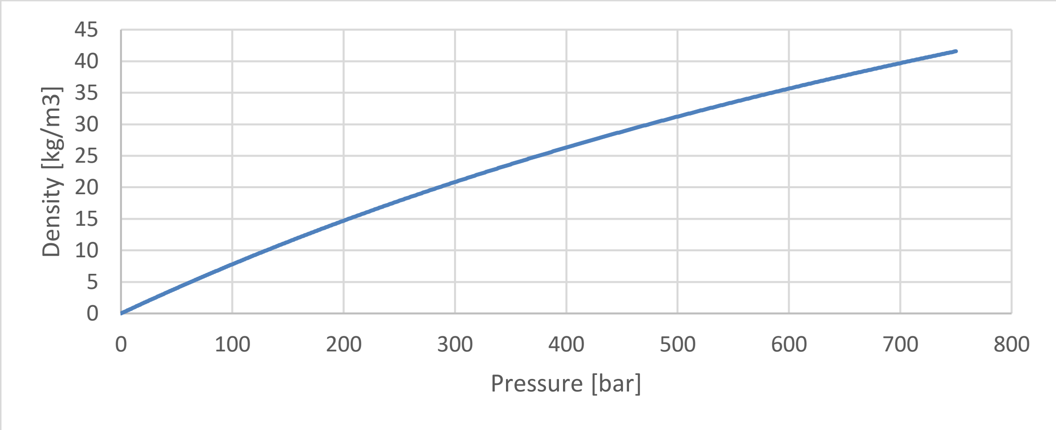

Figure 3. Density of hydrogen at 20°C as function of pressure. (National Institute of Standards and Technology, 2022)

2.3 Spin Isomers of Hydrogen

Hydrogen has two spin isomers, ortho- and parahydrogen illustrated in Figure 4. Hydrogen in room temperature, called normal hydrogen consists of 75% ortho-, and 25% parahydrogen. As illustrated in Figure 5, the equilibrium changes in cryogenic temperatures equalizing to 99,8% parahydrogen in the liquid phase. The conversion from 75% ortho- and 25% parahydrogen to 99,8% p-H_2 releases 527 kJ/kg of heat. This is an issue in liquefied storage because the heat of vaporisation of hydrogen at 20K is only 447kJ/kg (Aziz, 2021). If the composition of normal hydrogen is retained after liquefaction, this will result in the entire liquefied mass of hydrogen boiling off entirely, even without any heat leakage. (Asadnia & Mehrpooya, 2018)

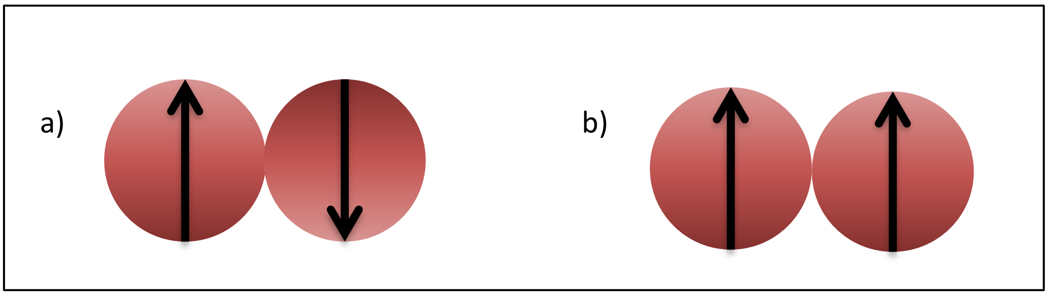

Figure 4. Illustration of parahydrogen (a), and orthohydrogen (b).

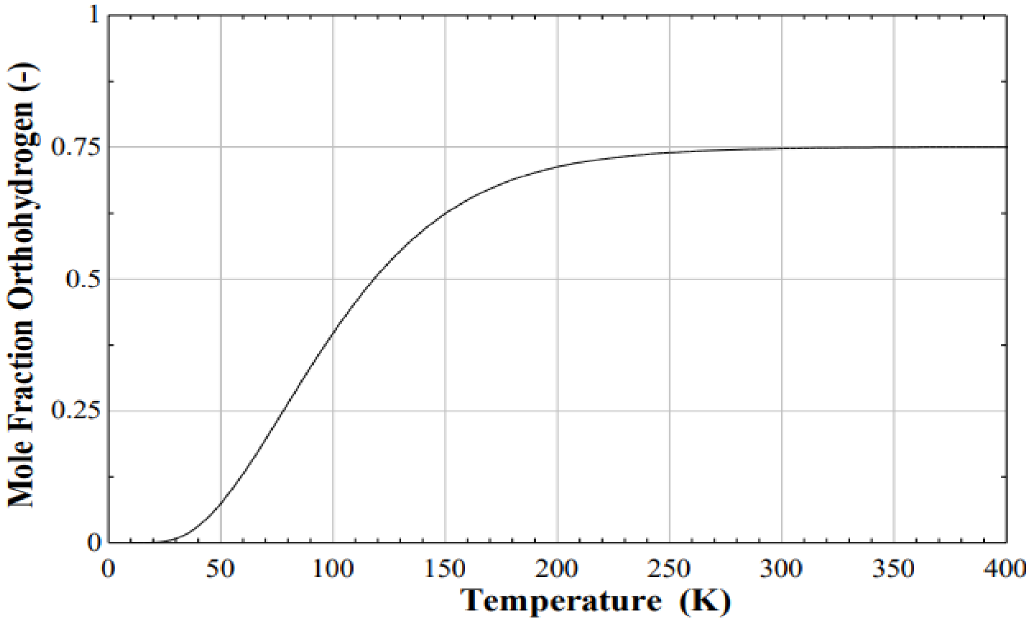

Figure 5. Equilibrium orthohydrogen percent composition in relation to temperature. (Bliesner, 2013)

The conversion from ortho- to parahydrogen can be attained during liquefaction (Linde Engineering, 2023). This prevents the need for excessive capacity of active cooling of the storage, or boiloff reliquefication. This phenomenon does not affect the development of the comparison tool in this thesis, as it is assumed that liquefaction expenses include the appropriate provisions for handling the ortho- to parahydrogen conversion.

2.4 Joule-Thomson Effect

Hydrogen liquefaction processes require pre-cooling of hydrogen. This is due to Hydrogens Joule-Thomson inversion temperature of only 202K. The Joule-Thomson effect describes the temperature change of a gas forced through a restriction, without heat exchange with the environment. The Joule-Thomson coefficient does not apply in isentropic expansion, where internal energy is conserved meaning that the gas does work as it expands. An ideal gas has a Joule-Thomson coefficient of zero. Real gases have an inversion temperature, where the coefficient turns from positive to negative as temperature increases. Figure 6 illustrates this for hydrogen. For the Joule-Thomson liquefaction cycle to be effective, hydrogen needs to be cooled down below the inversion temperature. Above this temperature hydrogen heats up as it passes through a restriction rendering the liquefaction process ineffective without pre-cooling. Liquid nitrogen is commonly used to pre-cool hydrogen for liquefaction.

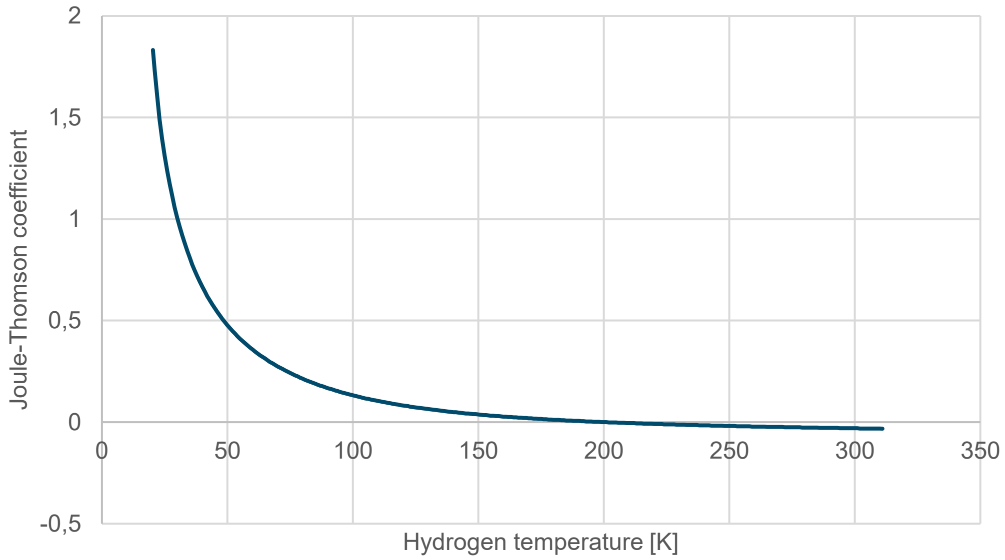

Figure 6. Joule-Thomson coefficient of gaseous hydrogen at 1 bar. (National Institute of Standards and Technology, 2022)

2.5 Hydrogen Embrittlement

Material selection is extremely important in hydrogen storage. The physical stresses of pressurisation and depressurisation also set high requirements for the materials used in compressed storage vessels. Cycle life refers to the number of pressurisation and depressurisation cycles a vessel can safely withstand. Some materials degrade when in contact with hydrogen. The effect called hydrogen embrittlement is most prominent in metals, though some metal alloys are more resilient than others.

The embrittlement of metals in direct contact with hydrogen negatively affects the lifecycle of hydrogen storage equipment. Hydrogen embrittlement is caused by hydrogen diffusion and dissolution into the microstructure of the metal. Brittle materials shatter or crack instead of showing plastic deformation when subjected to stresses. This phenomenon affects the lifespan of storage vessels, and associated components. As of the year 2023, lifespan of 25 years and over are advertised for composite cylinders with a polymer inner liner (UMOE Advanced Composites, 2023). Research to the mechanisms of hydrogen embrittlement is still ongoing. (Demaco cryogenics, 2021)

3 STORAGE TECHNOLOGIES

This thesis concentrates on mature technologies of physical hydrogen storage, LOHC being the exception to those criteria. For storage of physical hydrogen, the differences between technologies are thus limited to what can be altered in terms of temperature, and pressure of the stored hydrogen. Emerging technologies such as cryo-compressed storage, or slush hydrogen could eventually be added to the comparison tool, should they present some unique benefits to stationary hydrogen storage.

3.1 Liquid Hydrogen Storage

Liquid hydrogen storage has the highest volumetric density of hydrogen of the options compared in this thesis. A famous example of a large-scale $\mathrm{LH_2}$ storage system is in the Kennedy Space Center Launch Complex 39B, Florida, United States, where over 550 tons of hydrogen can be stored across two spherical vessels. The larger vessel has an internal diameter of about 21 meters. (Fesmire & Swanger, 2021).

The main downsides to storage in liquefied form are the high energy consumption of liquefaction processes, and potential boiloff losses of hydrogen from the storage as heat inevitably leaks into the storage vessel. Hydrogen must be cooled down to 21K to liquefy it. Heat leakage into the storage is inevitable. If there is consistent usage of hydrogen from the storage, boiloff losses can be used, unless liquid hydrogen is required in the use case. Other options are to venting to atmosphere or reliquefication. Boiloff can be avoided entirely by actively cooling the hydrogen in the storage vessel. Testing on a smaller scale integrated refrigeration and storage system has revealed that roughly seven times the cost of energy is saved in liquid hydrogen, in a zero-boiloff storage. (Adam Swanger, 2022)

All other gases are solid at the temperatures of liquid hydrogen, except helium, which can be used as coolant in this application. In addition to reliquefying or preventing boiloff, a vacuum pump may be needed to maintain the vacuum in insulation used in cryogenic storage tanks and pipework.

3.1.1 Energy Consumption of Liquefaction

The theoretical energy requirement to liquefy hydrogen is only 3,23 kWh/kg. In real applications liquefaction takes approximately 10 to 15 kWh of electricity per kilogram of hydrogen, which is a significant portion, about 30% to 42% of the LHV of hydrogen. Small capacity and intermittent operation results in higher energy consumption. (Züttel, 2003), (Aziz, 2021) Linde lists the energy consumption of liquefaction to be between 7,5 and 14 kWh/kg in the capacities explored in this work (Linde Engineering, 2023).

Hydrogen needs to be cooled below its Joule-Thomson inversion temperature of 202K, after which multistage Joule-Thomson expansion can cool it further, eventually liquefying a fraction of it. The end temperature is about 20K (-253°C), and pressure is close to atmospheric. (Züttel, 2003)

3.1.2 Dormancy Period

The dormancy period is the length of time a liquid hydrogen storage can stay full, or partially full without boiloff being lost. Hydrogen has a global warming potential of 6 to 33 times that of carbon dioxide (Warwick, et al., 2022). In this thesis, it is expected that the boil-off is reliquefied, or the storage is actively cooled to prevent hydrogen loss. Unless preventing the escape of boil-off gas produces more emissions, releasing the boil-off hydrogen into the atmosphere would be counterproductive, given that the move towards hydrogen economy is largely motivated by the need to cut down on greenhouse gas emissions.

3.2 Compressed Storage

3.2.1 Tank Types

Compressed storage relies on high pressure to increase storage density. Pressure vessels are differentiated by their materials and construction into types I to V. Figure 7 describes the construction and materials of four most common vessel types.

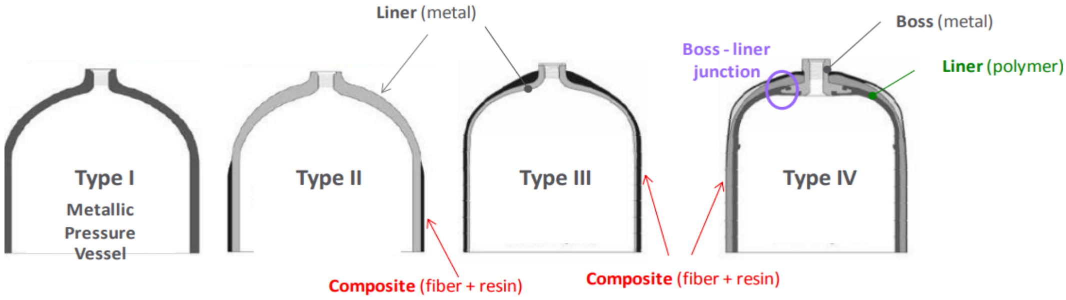

Figure 7. Pressure vessel types I, II, III and IV. (Barthélémy, et al., 2016)

In this thesis, the most commonly available types, type I and IV were compared in the comparison tool. The most notable differences between these two are the higher maximum working pressure achievable with composite construction, and the somewhat lower cost of the metallic pressure vessel type. The cost of vessel becomes important as capacities increase. Higher maximum working pressure requires more energy for compression but yields a smaller footprint. Typical maximum working pressure for type I vessels is 250bar. Type IV vessels can be manufactured to various specifications, but maximum working pressures between 350bar and 700 bar are most common. Such high pressures may not be necessary for stationary compressed storage unless footprint is limited. Higher pressures require more energy for compression.

3.2.2 Cascade Storage

Cycling the storage at low fill levels requires significantly less energy for compression than cycling the storage at near its maximum capacity. When the storage system needs to perform shallow cycles near its full capacity, cascade storage can save a significant amount of energy.

A compressed storage system consisting of several gas cylinders can be partitioned with valves to allow for sequential filling and discharging of the storage partitions. This is called cascade storage. All partitions may initially be filled up to the maximum working pressure. Discharging the storage is done one partition at a time, so that if more hydrogen needs to be stored, the partition with lowest pressure can be filled up first, saving some energy compared to a system with only one gas volume.

3.2.3 Energy Consumption of Compression

Compression in multi-stage compressors does not correspond to any theoretical calculation method, but data from a compressor manufacturer suggests that the actual energy consumption curve lies between adiabatic and isothermal compression curves as illustrated in Figure 8. The multistage curve in this figure is used as a basis for calculating energy required for compression in the storage comparison tool.

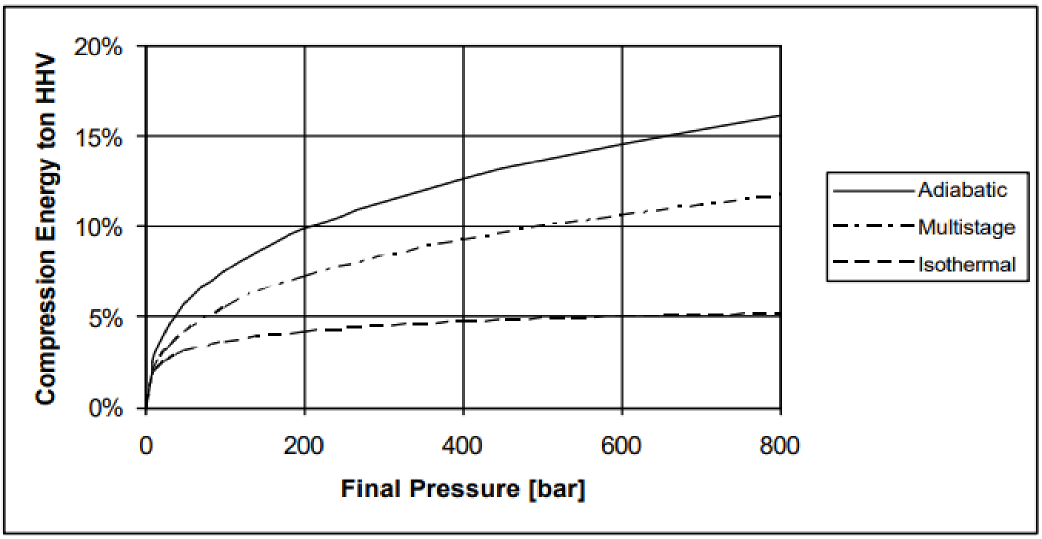

Figure 8. Energy required for compression of hydrogen compared to its higher heating value HHV (Bossel & Eliasson, 2003).

Input pressure to the compressor has a significant effect on how much energy is required to reach the final pressure. As presented in Figure 8, compressing a kilogram of hydrogen from atmospheric pressure to about 50 bar takes roughly the same amount of energy, as compressing it from 50 bar to 500bar. In the comparison tool developed as part of this thesis, any compression work done before the compressor is considered essentially free, as in having no energy consumption.

3.2.4 Cushion Gas

Cushion gas is the amount of gas required to maintain output pressure. Cushion gas will remain in storage once the vessel or partition of a system is considered empty (Elberry;Thakur;Santasalo-Aarnio;& Larmi, 2021). The minimum output pressure required from the storage system is effectively the pressure at which the storage can be considered empty. This discrepancy between the full capacity, and usable capacity of the storage must be considered when performing calculations involving the storage capacity.

The lower the maximum pressure of the storage is, the higher is the percentage of storage capacity in kilograms required for cushion gas. The amount of cushion gas at a set output pressure is proportional to the internal volume of the $\mathrm{CH_2}$ storage system. The density of hydrogen at 12 bar and typical outside temperatures varies between 1,0 and 1,1 kg/m3 (National Institute of Standards and Technology, 2022).

3.3 Liquid Organic Hyrogen Carriers

In terms of volumetric density of hydrogen, liquid organic hydrogen carriers, or LOHCs, such as benzyltoluene are somewhere between compressed storage, and liquefied hydrogen storage in terms of volumetric density of hydrogen. Given the unimportance of system weight in stationary storage, potentially low gravimetric density is not an issue in this application. Handling LOHC is comparatively safe and easy. No pressurisation or refrigeration is needed, and it can be stored in low-cost tanks. Some LOHC is lost in the process, needing to be topped up to retain storage capacity.

Two tanks are needed for LOHC storage, each of them large enough to hold the entire liquid volume of LOHC in the system. One tank holds the dehydrogenated liquid, and the other holds hydrogenated liquid. Hydrogenation unit takes liquid form the de-hydrogenated tank when storing hydrogen, recovers heat which is released upon hydrogenation, and releases the liquid into the hydrogenated liquid tank. De-hydrogenation unit works in the opposite way. It takes hydrogenated liquid from the hydrogenated liquid tank, applies heat into the liquid to release the hydrogen, releases the hydrogen to the output line, and dehydrogenated liquid into the dehydrogenated liquid tank. (Hurskainen, 2019)

3.4 Requirements of Hydrogen Storage System

Hydrogen may be stored for various use cases, for which the requirements vary greatly. The main variables are storage capacity, input and output capacities, and the depth and frequency of fill cycles, which set requirements for storage cycle life, and define the importance of energy consumption and specific capex of input output and storage capacity when choosing a technology. The choice of technology is limited to $\mathrm{LH_2}$, $\mathrm{CH_2}$ or LOHC in this thesis. Compressed storage has several options for maximum working pressure, the lowest pressure being with a type I vessel, and other with type IV. Results for LOHC are calculated with, and without heat integration in terms of energy consumption. Qualitative requirements pertaining to the types of storage are entirely omitted here.

3.4.1 Storage Capacity and Downtime

Storing hydrogen solves the problem of production and consumption happening at different times. The production must match consumption on some period and vice versa, for the storage to suffice as a solution. The shorter the period, the smaller the required storage capacity. In the scope of this thesis, downtime refers to the time that storage in not being filled or discharged. Some use cases may have essentially no downtime, especially when the hydrogen feeds into a process of some kind. When hydrogen is stored for energy use as backup power, or for a peaking application, there is likely significant downtime.

3.4.2 Input and Output Capacities

Hydrogen storage systems can have vastly different input and output capacities depending on the application. In applications that have constant hydrogen demand, the storage output capacity is likely small compared to the input capacity. The expectation here being that the storage is filled quickly when needed, or when economical, and hydrogen is then discharged slowly over a longer period.

At the other end of the spectrum are applications such as hydrogen storage as fuel for peaking power plants, or backup power. The storage is filled slowly when hydrogen is inexpensive to produce and used fast to make electricity or heat when demand is high. In these applications the input capacity of the storage may be significantly smaller than the output capacity.

3.4.3 Heat Integration

Vaporising liquid hydrogen requires the application of heat, but low-grade heat from sources, such as seawater or ambient air is sufficient. The liquefaction processes do not produce significant high-grade recoverable heat, though regassification could provide some cooling when the storage is discharging. However, this was left out of the comparison due to the challenge of quantifying the potential benefit, and the end use of hydrogen being outside of the scope.

The availability of heat integration is a factor in whether LOHC is a suitable storage solution. Heat integration could mean the utilisation of industrial waste heat in dehydrogenation, or connection to district heating at the point of hydrogenation.

This is highly case specific but boils down to cutting the waste heat and heat demand of the processes as much as possible. In the case of stationary storage, both processes would take place at the same location making integration with a system such as heat storage a possibility.

3.4.4 Storage System Footprint

Storage density is subject to a sanity check, ruling out low pressure solutions from the comparison. Storage technologies differ in the amount and shape of space they require. In practical applications, the components can be made to fit various shapes and locations. It is possible that footprint of single components may be lowered by increasing cost, or system footprint may be lowered by stacking components vertically.

The volume occupied by the stored hydrogen itself, and the storage vessel can be estimated with some accuracy. Data for compressor footprint, liquefier footprint, LOHC hydrogenation and dehydrogenation must be acquired from a reputable source before including them to the footprint calculation. These parameters, and footprint cost will be set to zero as default in the comparison tool.

In the storage comparison tool vessel footprints for $\mathrm{LH_2}$, $\mathrm{CH_2}$ and LOHC are estimated based on the net volume required in in each storage method. Only floor area is considered. Liquid hydrogen storage sphere is expected to occupy a rectangular area with a user adjustable percentage of extra area, to account for insulation and associated componentry. LOHC vessels are assumed to be vertical cylinders with equal height and diameter, occupying a rectangular area with a user adjustable percentage of extra area. These components benefit from the free upward expansion in this calculation tool. Compressed storage is given an approximate footprint requirement per unit of net storage volume based on a storage module offered by an industry leading manufacturer, and a multiplier to account for access ways and safety structures. Compressed storage modules may be stackable, in which case the former parameter must be calculated again.

4 CAPEX ESTIMATES

As hydrogen storage technologies are not widely used, and most manufacturers do not publish the prices of their components, this thesis will cover the costs on a very general level. Little data is available about the cost break down of systems, and the effect of design parameters to the costs involved. The values discussed in this chapter are used as starting values and must be updated based on offers from manufacturers and suppliers before making decisions based on the comparison tool results. The usage of storage undoubtedly affects the operating expenses of each component. Energy use is calculated separately, as is the cost of makeup LOHC. The remaining maintenance costs are simplified to a percentage of capital expenses, default values in the comparison tool are 2% for storage vessels and 4% for other components.

4.1 Liquefied Storage

The main components involved in liquefied storage systems are the liquefaction system, storage vessel and evaporator. The cost of the liquefaction system is treated as one, though it consists of compressors, heat exchangers and valves. The cost of this system is perhaps the most elusive. For a 27 ton-per-day system the capital cost was described to be 104 million in 2018 United States dollars (Connelly;Penev;Elgowainy;& Hunter, 2019).

In inflation adjusted euros that would be approximately 110 million euros in 2023. Dividing this by the plant capacity gives a cost 4,07 M€/tonH2/day. A scaling factor if 0,67 was used in the model to account for the economics of scale. Values for the liquefaction capacity, and liquefaction system cost per capacity can be adjusted in the model inputs to better correspond to most recent information.

Vacuum insulated storage vessels in the scales under consideration in this thesis are without exception made to order, and one-off examples. The method of calculating capital cost with a scaling factor. The contract for NASAs latest liquid hydrogen storage expansion, which included an $\mathrm{LH_2}$ storage sphere, vaporizers, fill manifold, piping, valves, and controls, had a potential total value of $60.3 million (Hambleton & Harland, 2018). The volume of the sphere in question is 4732 cubic meters. Adjusted for inflation, this would be about 66 million euros, or almost 14000 euros per cubic meter of storage. This will serve as a starting value in the comparison tool, bearing in mind, that it includes other associated componentry, such as vacuum insulated transfer lines, and evaporators.

4.2 Compressed Storage

The costs involved in compressed storage essentially have three components. Some portion of costs is proportional to the storage capacity, some portion of the cost is proportional to the operating pressure of the storage, and some proportion of the cost is proportional to the input and output capacities.

The cost of compressed storage vessels increases as storage volume, and storage pressure increase. The effect on the cost per kilogram of storage capacity is comparatively small, as the gravimetric capacity also increases with both volume, and pressure. The cost of type 4 storage vessels operating at 700 bars is in the range of 13 to 19$/kWh (Houchins, Cassidy; James, Brian D.; Strategic Analysis Inc., 2020), which adjusted for inflation and calculated for a kilogram of storage capacity is between 500 and 740 euros per kilogram of capacity. The system in the example utilises carbon fibre as the composite material. In more recent examples fibreglass has replaced the expensive carbon fibre composite. The cost for these vessels is estimated at 400 to 500 euros per kilogram of storage capacity. 450 euros per kilogram of capacity is used in the calculations for type 4 vessels, regardless of the pressure. Type 1 vessels are less costly to produce, per unit volume, but the difference is small for a given gravimetric capacity. A quote for a type 1 storage unit was obtained for this thesis, at 395 euros per kilogram of storage capacity. Storage capacity of the unit in question is 320kg of hydrogen at 20°C.

There are several types of hydrogen compressor, each with their benefits and disadvantages. Cost and capacity are the only parameters regarding the choice of compressor in this thesis. 130000€ for a 60kg/h compressor was provided as the reference cost and capacity. A scaling factor of 0,67 is used when estimating compressor cost at different capacities.

4.3 Liquid Organic Hydrogen Carrier

Hydrogen storage in LOHC was included in the comparison because of recent significant interest in these solutions, and good availability of data from recent studies. Hydrogen storage in liquid organic hydrogen carrier requires two tanks. One for the hydrogenated liquid, and one for dehydrogenated liquid. In addition, a hydrogenation and dehydrogenation equipment is needed. The specific capex values of hydrogenation and dehydrogenation are quoted as having high uncertainty. This is to be expected, as hydrogen storage in LOHC is an emerging technology.

$\mathrm{LH_2}$ and $\mathrm{CH_2}$ share a basic distribution of capital expenses for input and output capacities, where the input capacity carries a high specific capex, and the output capacity is relatively inexpensive. The case is the exact opposite for LOHC, which has a relatively low specific capex for the input capacity and high specific capex for the output capacity. This leads to the ratio between the input and output capacities being the defining factor in whether $\mathrm{LH_2}$ or LOHC is the lower cost solution for a specific use case.

The liquid tanks are remarkably simple compared to other storage solutions. The tank cost is estimated based on 125€/m^3 at the scale of 50000m^3, and a scaling factor of 0,77 is used when calculating storage tank capex. The difference in the required size of storage tank for hydrogenated and dehydrogenated LOHC is considered in the comparison tool. (Hurskainen, 2019)

5 DEVELOPMENT OF COMPARISON TOOL

The tool logic has three distinct parts illustrated in Figure 9. A small number of input values entirely dependent on storage requirements and subject to change when exploring how the LCOHS changes with alterations to storage specifications. These main input values change based on storage specifications and expected cycling information.

The tool uses dozens of additional input values for properties of hydrogen, LOHC, liquefaction, energy consumptions, costs, and data tables for density and compression energy information. These values change with inflation, as technologies develop, as more accurate information becomes available, and as supply and demand and economies of scale affect the costs of components. For values such as liquefaction energy consumption a data lookup table, or formula could be implemented, should a reliable source of information become available.

The most interesting results such as LCOHS are listed at the top of the tool dashboard. Intermediate results that further combine to form the end results are clearly labelled and visible in case a specific parameter is of interest. Troubleshooting and verification or modification of formulas is also made simple this way.

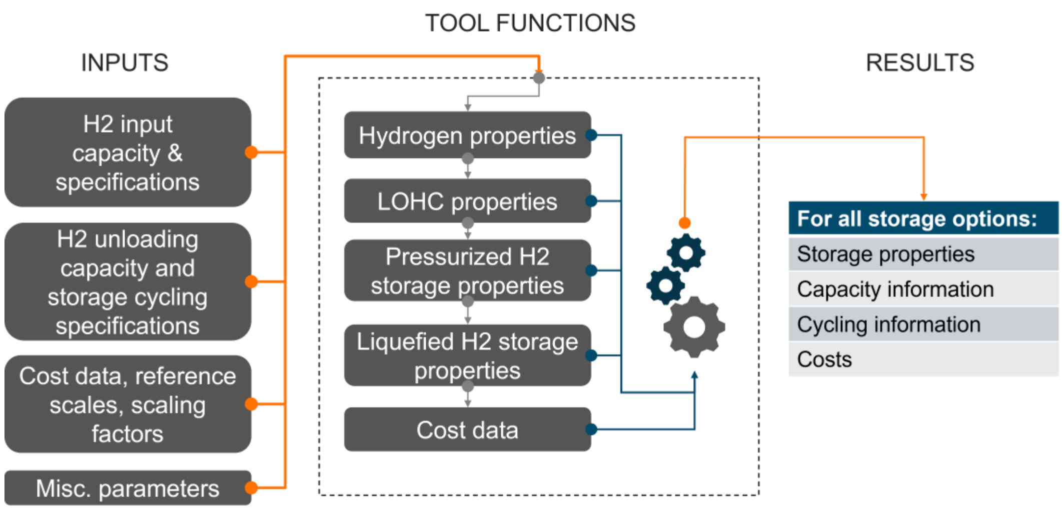

Figure 9. Visualisation of comparison tool logic.

5.1 Input Values

The primary function of the tool is to provide a framework to which most recent specifications and parameters of each system type can be fed to. Input parameters and their units are listed in Table 2. The default values have varying degrees of accuracy, and many are subject to change in the future, and based on case specifications. Common specifications and storage requirements are the primary inputs that are varied to produce the conclusion of this thesis. Compressor energy consumption is discussed separately in section 5.1.1 as it requires a separate table of data.

Table 2. List of input values and adjustable parameters in the comparison tool.

Variable	Unit
Common specifications & storage requirements	
Storage capacity (gross)	kg
H2 input pressure from production	bar
System storing capacity	kg/h
Storage min output pressure	bar
Storage max output	$MW_{H2\ (LHV)}$
Average fill cycle starting point	% of usable capacity in kg
Average fill cycle end point	% of usable capacity in kg
Average fill cycle depth	% of usable capacity in kg
Fill cycles per year	pcs
Electricity cost	€/MWh
Heat cost	€/MWh
Footprint cost	€/m2
Heat recovery rate	%
Heat reusage rate	%
Liquefaction	
Liquefier cost	€
Reference scale	t/d
Scaling factor	-
Liquefaction energy consumption	kWh/kgH2
System electrical efficiency	%
System maintenance cost	% of CAPEX
Footprint	m2/(t/d)
LH2 Storage	
Storage vessel cost	€
Reference scale	m3
Scaling factor	-
Active cooling of storage	kW_el
System maintenance cost	% of CAPEX
Footprint multiplier	m2/m2
Compression	
Compressor cost	€
Reference scale	kgH2/h
Scaling factor	-
Compressor maintenance cost	% of CAPEX
System electrical efficiency	%
Compressor footprint	m2/(t/d)

Variable	Unit
CH2 Storage	
Type 1 vessel cost	€/kgH2
Type 4 vessel cost	€/kgH2
System maintenance cost	% of CAPEX
Storage cylinders footprint	m2/m3_net
Storage footprint multiplier	m2/m2
LOHC	
LOHC cost	€/kg
Hydrogenation heat production	kWh/kg_{H2}
Hydrogenation electricity demand	kWh/kg_{H2}
Dehydrogenation heat demand	kWh/kg_{H2}
Dehydrogenation electricity deman	kWh/kg_{H2}
Degradation/make up needed	%/cycle
Holding tank cost	€/m3
Hydrogenation specific CAPEX	$€/kW_{H2}$ LHV
Reference scale hydr.capex	MW_{H2}
Scaling factor hydr.capex	-
Dehydrogenation specific CAPEX	$€/kW_{H2}$ LHV
Reference scale dehyd.capex	MW_{H2}
Scaling factor dehyd.capex	-
Hydrogenation annual OPEX	% of CAPEX
Dehydrogenation annual OPEX	% of CAPEX
Holding tank OPEX	% of CAPEX
Dehydrogenation rate	%
LOHC holding capacity	mass%
Oil tank cost	€/m3
LOHC density (hydrogenated)	kg/m3
LOHC density (dehydrogenated)	kg/m3
Hydrogenation footprint	$m2/kW_{H2}$ LHV
Dehydrogenation footprint	$m2/kW_{H2}$ LHV
Footprint multiplier	m2/m2
Miscellaneous	
Hydrogen LHV	kWh/kg
Interest rate	%
Years of payments	a

Hydrogen pressure and density data is fetched using excels xlookup -function from several separate tables imported into the tool from the National Institute of Standards and Technology website.

Heat and electricity cost both remain at 50€/MWh throughout the tool runs. Though they do affect the absolute value of LCOHS, varying the values between 30€/MWh and 50€/MWh did not disproportionally hurt or benefit the performance of any technology, or have consistent and significant effects to the choice of lowest cost technology at any given scale. If two technologies are close in LCOHS, changing the energy costs can influence which one has the lowest LCOHS.

5.1.1 Compressor Energy Consumption

The ability to calculate the energy use of hydrogen compression is a key part of the tool. The energy consumption is calculated considering the different start and end pressures when cycling parameters are varied. For this reason, a fixed value cannot be used. The multistage graph from Figure 8 is used as the basis for compression energy calculation. The figure was expanded in a photo editing application, and the multistage graph was traced with 2000 points of resolution at suitable intervals. The gaps were then interpolated to form a continuous table of data. More accurate data can be substituted for the input values should accurate performance information become available.

When calculation energy consumption of partial fill cycles, the compressor compresses the added amount of hydrogen from production output pressure to the end state pressure of the storage. In addition, the mass of hydrogen already in the storage is compressed from the starting pressure before filling, to the end state pressure. Compression of this cushion gas and partial fill is assumed to take the same amount of energy per kilogram of hydrogen as compressing the added portion of gas took. The actual energy consumption may be lower, due to the compression behaving closer to an isothermal compression as the gas is compressed slowly and has ample time to release heat to the cylinder walls.

5.2 Downtime

Annual downtime for each system is calculated as part of the comparison. This functions as verification for adequate input and output capacities in relation to storage capacity, and specified cycling pattern. Instead of trying to keep downtime constant across different comparison cases, annual hydrogen usage compared to storage capacity is kept constant, if there is downtime to spare. The cycle depths are set to 90% with 5% reserves at the top and bottom of an average fill cycle, unless otherwise specified. The aim of this is to aid the mutual comparability of different sets of results.

5.3 Exclusions and Assumptions

It is assumed that when storage pressure is below the pressure of incoming hydrogen, it flows directly into storage. Any compression work by an electrolyser or other means before the compressor is outside the scope of this thesis and does not count towards the calculated compression energy. Calculated compression energy only accounts for the electricity requirements of the compressor. To include an estimate of the energy consumption prior to the compressor, the electrolyser output pressure to one bar.

Storage capacities of the compressed storage systems in this comparison are calculated at 20°C. This was decided for the total capacity to meet or exceed the specification throughout the year. Were the capacities calculated at lower temperatures, the required storage volume would be slightly smaller. The effects of outside temperature to storage capacity, and cushion gas are disregarded in this calculation tool. Should 20°C not be representative of the expected operating temperatures of a planned storage system, the calculation tool must be modified to use density data better corresponding to the expected operating temperatures.

The total capacities of the storage options are set equally. The lowest pressure compressed storage option loses approximately 7% of its total capacity to cushion gas at 20°C, and the minimum output pressure of 14 bar. For the storage comparison to be fair, a reasonable decision would be to compare useful capacities after cushion gas has been accounted for, but this was decided against based on permitting or regulations potentially having a set limit for total storage capacity, which is expected to be taken full advantage of by each storage technology. The notion of limiting the quantity of LOHC on the premises to the same kilogram amount as hydrogen does not work, and permits would likely be more lenient towards the storage of LOHC. In the calculation tool, the gross hydrogen storage capacity of LOHC was set equal to the gross capacity of the physical hydrogen storage systems yielding a very similar usable capacity for hydrogen storage in LOHC.

LOHC has two columns of results in the tool. One without, and one with heat integration. Heat integration parameters are the heat recovery rate, which is set at 87%, and the heat reusage rate, which is set to 50%.

5.4 Limitations of the Tool

The exact value of several variables used in the comparison tool are subject to change based on the situation. All capital and operational expenses reported, are based on estimates, which can be highly inaccurate considering the relative immaturity of the technologies in question. Properties of hydrogen are well known, but their application to compression and liquefaction would require accurate performance data of the exact system which would be installed. Big leaps in the technologies involved are unlikely, but theoretically possible, in which case the tool would need adjusting to produce results of any relevance.

One guiding principle in this thesis was the focus on physical hydrogen storage. Where other storage methods are not ruled out, the technologies not mentioned in this tool will need separate consideration, unless not ruled out based on qualitative reasons.

To calculate the energy consumption of an average, a typical fill cycle needs to be defined. This is a straightforward process for LOHC and liquefied storage, but there are several options regarding pressurized storage. It was decided to use the usable capacity in kilograms as a base range, and percentages of that capacity in kilograms as start and end points of a typical fill. This results in a small difference in the calculated hydrogen mass of a typical fill cycle of each storage method in the comparison.

6 SCALE DEPENDENCY OF LCOHS

Most importantly, the levelized cost of hydrogen storage is directly affected by two values: the annual sum of costs involved with a storage system, and the annual amount of hydrogen that flows through the storage system. If one kilogram of hydrogen flows through an expensive storage system, even if just to avoid division by zero, the LCOHS is understandably astronomical. In the interest of producing at least plausible values for LCOHS, the average fill cycle depth is kept at 90% with a 5% margin at each end of the cycle.

Though the numerical value of LCOHS indicated by the comparison tool is not accurate, the general trends can certainly be pointed out. LCOHS as function of storage capacity was plotted with various configurations of input and output capacity, energy costs and cycling patterns to identify where each storage method is competitive, and how changes in the cycling pattern affect the LCOHS.

The ratio between storage capacity, charging capacity and discharging capacity is kept constant in this the first graphs. The effect of scale is thus displayed. The effect of increasing only the storage capacity and keeping the annual hydrogen throughput constant is explored separately in Chapter 6.7.

6.1 Equal Input and Output Capacity

As Figure 10 illustrates, LCOHS generally decreases when storage capacity increases. With all the assumptions and prerequisites mentioned in this thesis, the lowest pressure compressed storage is the most cost effective across the entire scale with these parameters. Charging and discharging capacities in this example were set to 10% of the storage capacity per hour. The order of technologies from lowest cost to highest cost does not change over this capacity scale. The average annual downtime for these results is 28%, and the average annual hydrogen consumption is 320 times the storage capacity.

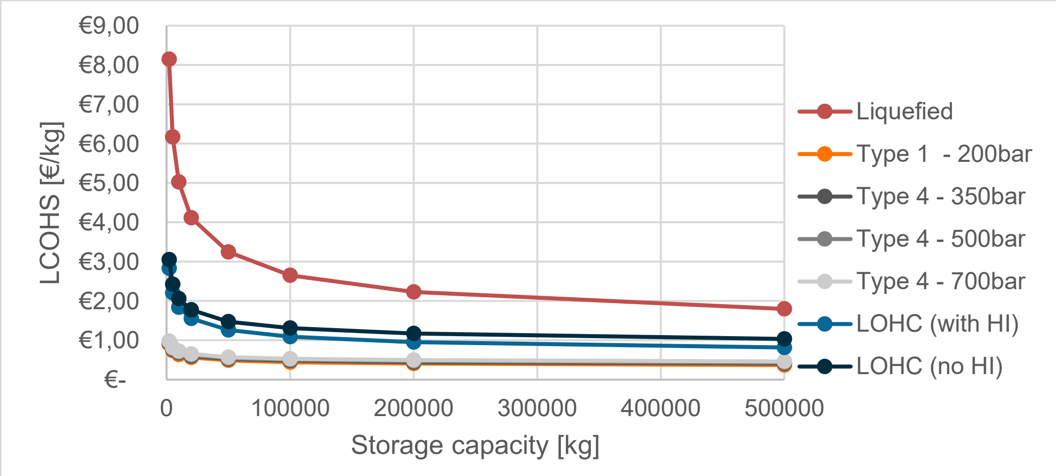

Figure 10. LCOHS as function of storage capacity, even charging and discharging capacities.

6.2 Input Capacity Biased Storage

In Figure 11, input capacity and output capacity are 20% and 5% of the storage capacity in an hour respectively. The annual hydrogen throughput remains at about 320 times the storage capacity, and the downtime is down to 10%. The comparatively high input capacity, and low output capacity favours LOHC, and hurts LH_2, though the order least to most expensive stays unchanged. Lowering the cost of heat to 30€/MWh and increasing the cost of electricity to 100€/MWh gives LOHC with HI a cost advantage over the highest pressure compressed storage when the storage capacity is in the hundreds of tons.

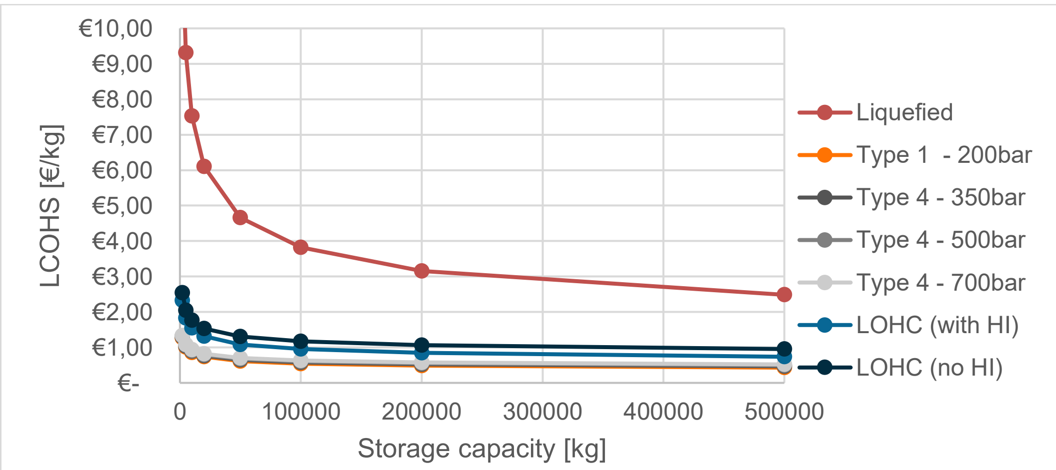

Figure 11. LCOHS as function of storage capacity, larger input capacity.

6.3 Output Capacity Biased Storage

Figure 12 represents a storage system, where the input capacity is 5% and the output capacity 20% of the storage capacity per hour. The average downtime and the annual hydrogen usage remain unchanged at 10% and 320 times the usable capacity. Notably, the decreased input capacity has benefited LH_2 storage, to where changes in energy costs and small adjustments can give LH_2 the lower LCOHS.

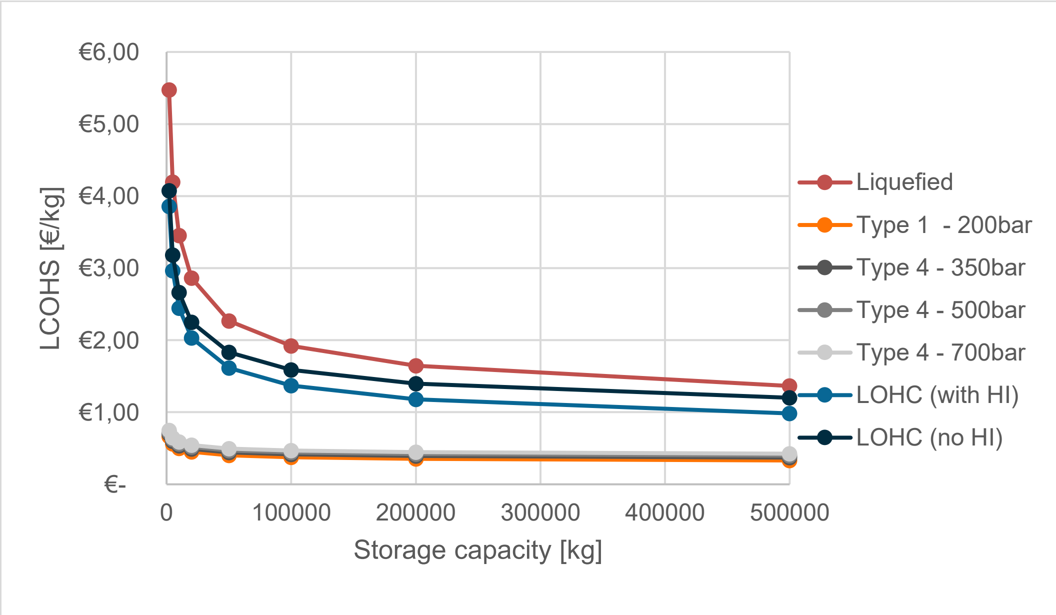

Figure 12. LCOHS as function of storage capacity, larger output capacity.

6.4 Case for LH2

Finding a case for each technology by trial and error is very simple in the tool. It appears that for LH_2 to be competitive, the hourly input capacity, which translates to hourly liquefaction capacity must be mere fractions of a percent of the storage capacity. The output capacity should be large, which keeps LOHCs costs up. Then it is a case of increasing the storage capacity, until the non-linearly growing storage costs of LH_2 undercut those of CH_2s. The liquefied curve in Figure 13 has

200W/m3 of active cooling power added to it. The point at which LH_2 storage vessel costs no longer scale with the same scaling factor is not known here, and the subject needs more thorough research. Based on this comparison tool, the most likely application for LH_2 is a large-scale backup energy storage that must be able discharge rapidly.

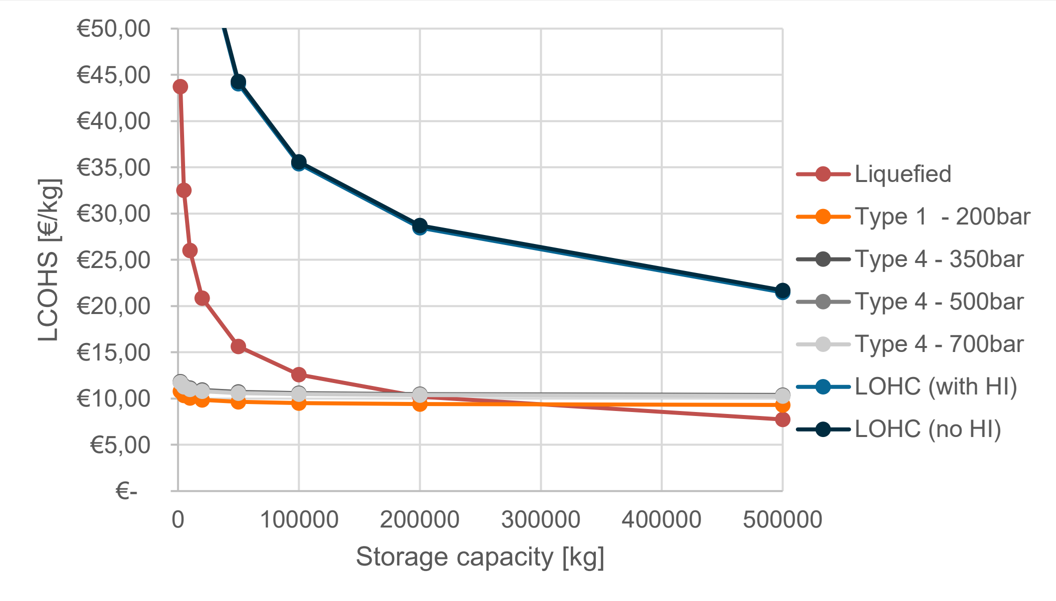

Figure 13. LCOHS as function of storage capacity, a case for LH_2.

Results in Figure 13 have been achieved with an hourly input capacity of 0,1% of the storage capacity, and an output capacity 100 times that, able to empty the storage over 10 hours. The downtime here is 40%, with annual hydrogen usage of 5,3 times the storage capacity. Reducing the number of annual cycles raises the LCOHS of each storage type but does not significantly affect which technology has the lowest costs at each storage capacity.

6.5 Case for LOHC

Figure 14 presents the LCOHS when the system can fill up entirely in four hours, but only discharges slowly, 0,5% of the storage capacity per hour. The annual average downtime for the systems is 33%, and the annual hydrogen throughput is 29 times the usable capacity, which is achieved with 30 cycles at 90% cycle depth.

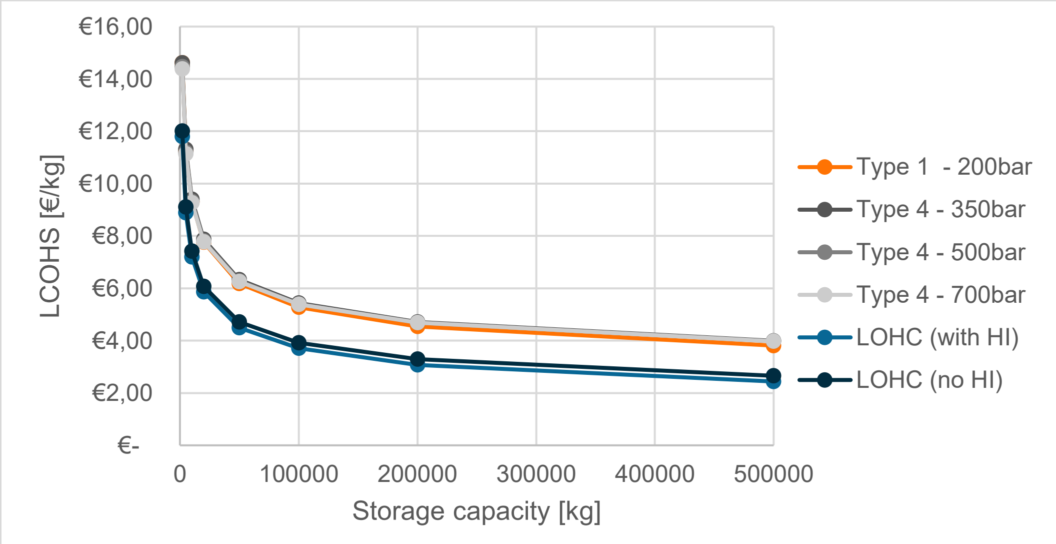

Figure 14. LCOHS as function of storage capacity, case for LOHC.

6.6 Cycle Depth, Frequency and Downtime

Due to the logic of the comparison tool, increasing the cycle frequency while simultaneously decreasing the annual cycle count so that the hydrogen throughput remains constant does not affect the LCOHS. More frequent starts and stops would likely increase the energy consumption of liquefaction, and LOHC hydrogenation and dehydrogenation. However, the effect of cycle depth and how full the storage is when experiencing shallow cycle has a distinct effect to LCOHS in compressed storage.

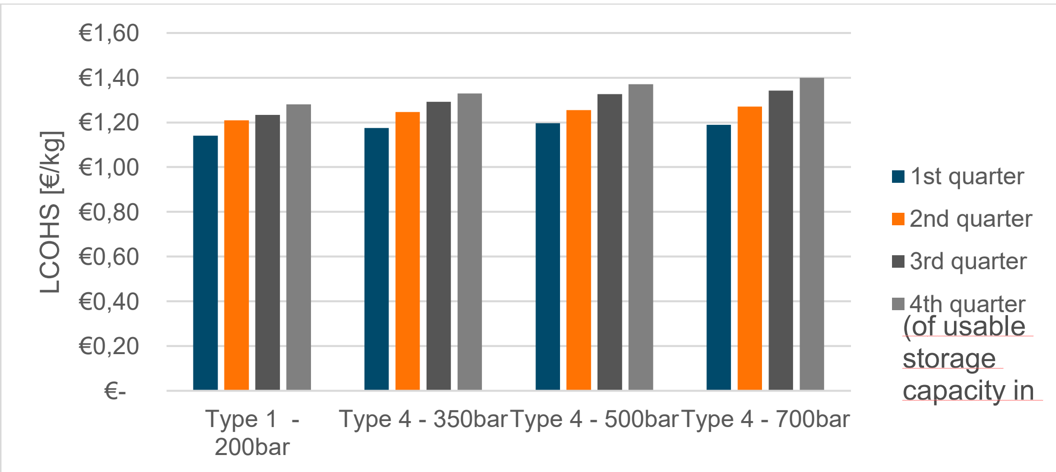

Figure 15. LCOHS with 25% cycle depth taking place at different fill levels.

LH_2 and LOHCs are left out of Figure 15, due to this effect only being modelled for and relevant to the pressurized storages. The results presented demonstrate that a shallow fill cycle in a near empty storage takes less energy than a shallow cycle at a near full storage. The abnormal behaviour of 1st quarter cycle of 700 bar storage having lower cost is due to the differences in annual hydrogen throughput. Shallow fill cycles exacerbate the issue stemming from the differences in usable capacities, and the cycle depth being set based on the usable capacities. Cascade storage could yield similar savings, depending on the exact storage configuration and cycling parameters.

6.7 Only Increasing Storage Capacity

The previous figures have retained the ratio between storage capacity, input capacity and output capacity at each scale, with a constant number and depth of cycles, which results in the annual downtime staying constant, and the annual hydrogen use increasing as capacities increase. If only the storage capacity is increased to increase the downtime, the number of cycles, and the annual hydrogen throughput stays constant, LCOHS can be expected to increase as storage capacity is increased, as illustrated by Figure 16.

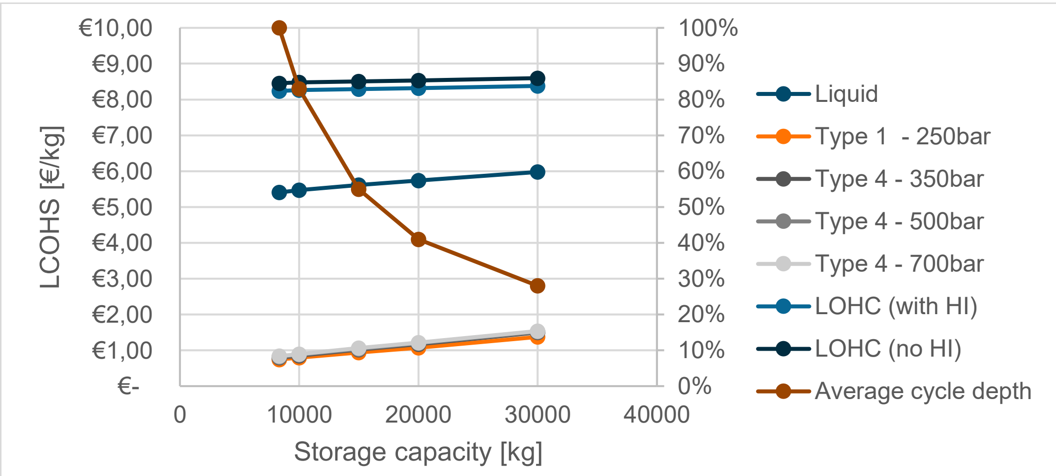

Figure 16. LCOHS as function of storage capacity. Constant annual H2 throughput by decreasing cycle depth.

If the average fill cycle is shallow compared to the storage capacity, the result is an increased LCOHS. This may be necessary to cover the gaps between intermittent production and consumption but should be avoided in applications where the extra capacity is never utilized. Percentagewise the effect is most prominent in LH_2 where increasing storage capacity increases the capital expenses linearly, and the cost of storage vessels is often more significant portion of all expenses.

7 CONCLUSIONS

According to the results obtained from the comparison tool, the LCOHS decreases logarithmically as storage capacity, input capacity and output capacity are increased. This is due to the scaling factors utilized in estimating the capital expenses in the tool. The LCOHS in $\mathrm{CH_2}$ does not display the effect to a similar extent, due to it only having a compression specific scaling factor.

Every type of storage compared in this thesis has its ideal application. The decision is largely driven by the specific costs of input-, output-, and storage capacity of each storage technology. In the case that two technologies have otherwise similar costs, qualitative factors, and the cost of energy may sway the decision either way, though in most cases the energy consumption is not a significant factor.

In small and frequently cycled storage applications $\mathrm{CH_2}$ is likely the lowest cost solution by a fair margin. The situation changes when storage capacity is increased, as the cost of storage capacity in $\mathrm{CH_2}$ increases linearly as opposed to benefitting from a scaling factor like $\mathrm{LH_2}$ and LOHC do.

In large, less frequently cycled storage systems $\mathrm{CH_2}$ remains a competitive option into the hundreds of tons of storage capacity, but the relationship between the ratio of input capacity to output capacity is a major factor in deciding between $\mathrm{LH_2}$ and LOHC is the more likely competitor. In applications where the storage needs to be filled quickly, and discharged slowly, the high specific capex of liquefaction rules out $\mathrm{LH_2}$, and makes LOHC the more likely choice. If the storage is filled up slowly and discharged quickly, LOHC has the disadvantage of high specific capex of dehydrogenation, which makes $\mathrm{LH_2}$ the more likely choice. In both cases the annual hydrogen throughput is low compared to the storage capacity, as the duration of one fill cycle can be significantly increased when either filling or discharging is very slow.

7.1 Points of Improvement

Dynamic modelling of different usage patterns would yield more accurate information about energy consumption of the different storage options under a specific usage pattern. This would be especially useful in the case that the expected operating expenses and energy consumption for two competing technologies are similar.

Cascade storage is a relatively simple addition to a compressed storage system. Dynamic modelling could estimate the energy savings achievable by cascade storage in a compressed storage system.

Adding other storage technologies would be the logical next step to reach wider applicability for the comparison tool. Though the most common technologies are covered, some maturing technologies may prove unexpectedly suitable based on safety aspects or unique heat recovery and reuse possibilities.

Safety is paramount in hydrogen storage, and all storage methods have their set of safety requirements and precautions. The inclusion of safety related costs varies between applications and cannot be reliably predicted. Further research into the parameters that dictate the need for safety precautions would aid in estimating the costs of spillways, fire sensors and suppression systems, isolating structures, and increased system footprint due to safety distances.

While the field on hydrogen storage develops, legal guidelines regarding the storage of hydrogen are subject to develop as well. Possible advantages of energy storage in the form of hydrogen due to legal guidelines and trade policies may affect the expenses beyond what is estimated here. Similarly, any incentives that may now or in the future apply to a specific application must be considered separately.

7.2 Final Word

It is sometimes difficult to notice when proponents of one storage technology omit mentioning its shortcomings. The fact that hydrogen is difficult to store and can be stored with various methods of varying maturity, is ripe for sensationalist news of breakthroughs in the field of hydrogen storage. From this crudely simplified look into a couple of hydrogen storage methods, it is evident that the problem of one storage technology may barely be a factor at all in some specific use case, while other, usually less costly approaches struggle to perform. Every tool has its limits, and most certainly, the levelized cost of hydrogen storage is most dependant on the specific use case, realized system parameters and cycling characteristics.

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APPENDICES

APPENDIX 1

Figure 17. Screenshot of the comparison tool. (Classified)