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Economical- and feasibility assessment of hydrogen storages

A Comparative Techno-Economic Analysis in Finland and Nordics

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ABSTRACT:

Decarbonization is one of the central challenges of societies today and in the future, and therefore, European Union has set climate neutrality goal by 2050. Greenhouse gas emissions can be reduced across the energy sector with various methods including renewable energy sources, such as wind and solar, and by enhancing energy storage methods. Hydrogen is considered one of the most promising ways to store fluctuating renewable energy due to sustainability and multiple end use applications.

In the case of Finland and Nordics there is a lack of research on feasibility of hydrogen storage. In this thesis techno-economic analysis is conducted to evaluate the current status of hydrogen storage technologies, both technically and economically, and to assess the feasibility in Finland and Nordics. An in-depth literature review indicates the most applicable storage technologies. Based on this, two storage technologies are chosen for further analysis, with two real-life case studies, to assess the feasibility of those technologies.

Lined Rock Cavern (LRC) and Hydrogen Refuelling Station (HRS) are the two cases chosen for further economic feasibility study and analysis. Economic feasibility is studied through Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP). These financial metrics are applied to LRC and HRS, where the data is based on literature, and sensitivity analysis for NPV and IRR values is conducted to evaluate the sensitivities and dependencies of the input parameters.

Results indicate that both cases are feasible within the framework of this thesis. For both cases the NPV and IRR values indicate profitability. Based on sensitivity analysis the most sensitive parameters of NPV calculations are price spread, cycles/utilization, CAPEX and WACC whereas for IRR calculations the most sensitive parameters are price spread, cycles/utilization and CAPEX. The price spread between bought and sold hydrogen indicates that in the case of HRS storing hydrogen is three times more expensive compared to LRC.

The in-depth literature review and techno-economic analysis of the two cases provide a foundation for future research of the hydrogen storage in Finland and Nordics. The results of the sensitivity analysis highlight key parameters that need to be considered for future real-life projects. By optimizing these parameters more profitable and feasible hydrogen storage projects can be achieved in the future.

KEYWORDS: Hydrogen, Hydrogen storage, Techno-Economic analysis, Renewable energy, Lined Rock Cavern, Hydrogen Refuelling Station.

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TIIVISTELMÄ:

Hiilidioksidipäästöjen vähentäminen on yksi yhteiskuntien keskeisistä haasteista nykyisin ja tulevaisuudessa, tästä syytä Euroopan unioni on asettanut tavoitteen olla ilmastoneutraali vuoteen 2050 mennessä. Kasvihuonekaasupäästöjä voidaan vähentää ympäri energiasektoria eri menetelmillä mukaan lukien uusiutuvilla energialähteillä, kuten aurinko ja tuulivoimalla, sekä parantamalla energian varastointimenetelmiä. Vetyä pidetään yhtenä lupaavimmista tavoista varastoida vaihtelevaa uusiutuvaa energiaa sen kestävyyden ja monikäyttöisyyden vuoksi.

Suomen ja Pohjoismaiden tapauksessa vedyn varastoinnin toteutettavuutta koskevia tutkimuksia on vähän. Tässä opinnäytetyössä suoritetaan teknillistaloudellinen analyysi vedyn varastoinnin nykytilan, teknillisen- ja taloudellisen tilan arvioimiseksi sekä toteutettavuuden arvioimiseksi Suomessa ja Pohjoismaissa. Syvällinen kirjallisuuskatsaus osoittaa käyttökelpoisimmat varastointiteknologiat. Tämän perusteella kaksi varastointiteknologiaa on valittu jatkoanalysointia varten, kahden todellisen tapaustutkimuksen kanssa, jotta voidaan arvioida näiden teknologioiden toteutettavuutta.

Vuorattu kalliovarasto (LRC) ja Vedyn tankkausasema (HRS) ovat kaksi tapausta, jotka valittiin jatkoon lisätaloudellista kannattavuustutkimusta ja - analyysiä varten. Taloudellista toteutettavuutta tutkitaan nettonykyarvon (NPV), sisäisen tuottoasteen (IRR) ja takaisinmaksujakson (PBP) avulla. Näitä taloudellisia mittareita sovelletaan LRC:n ja HRS:n tapauksiintutkimuksiin, joiden data perustuu kirjallisuuteen, ja NPV- ja IRR- arvojen herkkyysanalyysi tehdään syöteparametrien herkkyyksien ja riippuvuuksien arvioimiseksi.

Tulokset osoittavat, että molemmat tapaukset ovat toteuttamiskelpoisia tämän opinnäytetyön puitteissa. Molemmissa tapauksissa NPV- ja IRR- arvot osoittavat hankkeet kannattaviksi. Herkkyysanalyysin perusteella NPV- laskelmien herkimpiä parametrejä ovat hintaero, syklit/käyttöaste, CAPEX ja WACC, kun taas IRR- laskelmissa herkimmät parametrit ovat hintaero, syklit/käyttöaste ja CAPEX. Hintaero ostetun ja myydyn vedyn välillä osoittaa, että HRS:n tapauksessa vedyn varastointi on kolme kertaa kalliimpaa, kuin LRC:n tapauksessa.

Syvällinen kirjallisuuskatsaus ja teknillistaloudellinen analyysi näistä kahdesta tapauksesta tarjoaa pohjaa tulevalle tutkimukselle vedyn varastointiin liittyen Suomessa ja Pohjoismaissa. Herkkyysanalyysin tulokset korostavat keskeisiä parametreja, jotka tulee ottaa huomioon tulevissa käytännön projekteissa. Optimoimalla nämä parametrit tulevaisuuden vedyn varastointiprojektit voivat olla entistä kannattavampia ja toteuttamiskelpoisimpia.

KEYWORDS: Vety, Vety varasto, Teknoekonominen analyysi, Uusiutuva energia, Vuorattu kallioluola, Vedyn tankkausasema.

Preface

Writing this thesis has been a rollercoaster of emotions through uncertainty at times as well as success and joy. Writing process has taught me much from the subject itself as also from handling wide topics and keeping the project under control. Through this thesis I have had the opportunity to deepen my understanding of hydrogen storage technologies and their economic metrics, a topic that is both highly relevant and interesting.

I would like to express my gratitude to my thesis' supervisor, Professor Xiaoshu Lü, for this interesting topic and for the support of and guidance throughout this journey. Thank you for pushing me and this thesis to reach levels I could have not foreseen during the process. I thank you for the time and effort in helping me succeed.

Last but not least, I would like to thank all those who supported me and my fellow students for all the good memories and relentless encouragement. Special thanks go to my friends and family who motivated me through hard times and celebrated with me during success. Special thanks go to my girlfriend Sofia, without your support, reassurance and motivation this project would have been much harder.

Turussa, 16.4.2026

Juho Lahdelma

Contents

Tables

Figures

Abbreviations

Bar	Pressure
BOH	Boil-off hydrogen
CAPEX	Capital expenditure
CNT	Carbon nano tube
HDPE	high density polyethylene
HHV	higher heating value
HRS	Hydrogen refuelling station
IRR	Internal rate of return
Kg	Kilogram
kt	Kilotons
LCHS	Levelized cost of hydrogen storage
LCOE	Levelized cost of electricity
LCOH	Levelized cost of hydrogen
LHV	lower heating value
LOHC	Liquid organic hydrogen carrier
LRC	Lined rock cavern
MJ	Megajoules
mL	Millijoules
MLI	Multi-layer insulation
MOF	Metal organic framework
Mt	Megatons
NPV	Net present value
OPEX	Operational expenditure
P2X	Power-to-X (X is synthetic fuel)
PEM	Proton exchange membrane
TRL	Technology readiness level
TWh	Tera-Watt hours
UHS	Underground hydrogen storage

Symbols

%	Percentage
K	Kelvin
€	Euro
$	Dollar (USD)

Declaration of AI use

During the process of writing this Master thesis, Juho Lahdelma, the author of the thesis used (MOT Translator, MOT Proofing and Google Translate) tools to check grammatic errors and spelling. After using these tools, the author reviewed and edited the content and takes full responsibility for the content of this Master thesis.

1 Introduction

Decarbonization is a central challenge in contemporary energy systems. The EU has set a goal to be climate neutral by 2050 (European Commission, n.d.b) that requires substantial reductions in greenhouse gas emission across all sectors. With the rising demand for renewable energy sources such as wind and solar power, there is a growing demand for ways to store this energy (Andersson et al., 2019). Among various storage options, technologies, for example batteries, hydrogen is one of the most promising energy carriers for the future (Zhang et al., 2023).

There are various ways to utilize hydrogen in different sectors. According to IEA (2019) hydrogen is used mainly in industry such as ammonia, methanol and steel production. Additional applications include transportation, buildings and power generation (IEA, 2019).

Nordic-Baltic hydrogen corridor is one of these projects where hydrogen produced is gathered through the Finland and Baltic's and send to Europe (Gasgrid, n.d.a). Similar project is the Nordic hydrogen route a joint venture between Gasgrid and Nordion Energi to develop hydrogen pipeline between Finland and Sweden (Nordic Hydrogen Route, n.d.). For example, Finland has significant potential due to its growing renewable electricity capacity and availability of clean water for electrolysis. Finland is in the center of Nordic hydrogen development and therefore has a lot of potential to become the leader in hydrogen-based energy economy (Valtioneuvosto, 2023).

1.1 Motive of research

Finnish government has made a resolution on hydrogen in 2023. Valtioneuvosto (2023) resolution states that “Finland's goal is to become the European leader in the hydrogen economy across the entire value chain.” One of the main advantages stated in the resolution is that Finland has large network of clean electricity produced by wind power that is growing even larger in capacity. Finland also has abundant clean water that is needed in the electrolysis to make the green hydrogen (H_2 Cluster Finland, 2023).

For hydrogen economy, to realize in Finland and in Nordics, finding efficient ways of storing and transporting hydrogen remains as one of the biggest challenges (Gasgrid, n.d.b). While there are many different technologies to store hydrogen, none of them rise as the clear winner. According to Mulky et al. (2024) hydrogen is usually compressed or liquified to improve its low volumetric density. These storage technologies each have their own downsides and therefore materials-based hydrogen storages have gained attraction Mulky et al. (2024).

Despite extensive research on hydrogen technologies, there remains a lack of consistent and comparable economic assessment of different storage options, particularly in the Finnish and Nordic context. This creates uncertainty in investment and system design decisions. In Finland, for example, previous research focuses mostly on hydrogen storages as a part of a broader energy system, for example, hydrogen production with wind energy.

1.2 The objective and Scope

The main objective of this thesis is to create a comparable techno-economic assessment where an in-depth literature review, case study analysis and economic feasibility, assessed through net present value, internal rate of return and payback period, creates framework to assess feasibility of different hydrogen storage options. Main goals of the research are:

- **Conduct a literature review** on different hydrogen storage technologies, TRL’s and current state of those technologies both technologically and economically.
- **Perform a case study analysis** based on NPV, IRR and PBP of selected cases focused on Finland and the Nordics.

- **Evaluate economical and technological feasibility** of hydrogen storage technologies as a part of future energy systems in Finland and Nordics.
- **Assess the role** of hydrogen storage in future energy systems in Finland and the Nordic region.

The aim of this thesis is to evaluate the current state of the hydrogen storage and their economic feasibility through NPV, IRR and PBP. Cost is a crucial part when evaluating different storage options for the future energy system. Policy and regulatory aspects are not addressed in detail. This thesis contributes by providing a consistent and comparable framework for evaluating hydrogen storage costs across different technologies under unified assumptions.

The thesis structure is visually illustrated in Figure 1. First part of the thesis is a broad literature review on the current technical and economic state of hydrogen storage. This is followed by research methodology chapter that defines how the research on the topic is conducted. In the next phase the thesis splits into cases used as references and calculation results and analysis based on the research methodology chapter. Both cases and results are wrapped in the discussion chapter that is followed by conclusion and future work chapter.

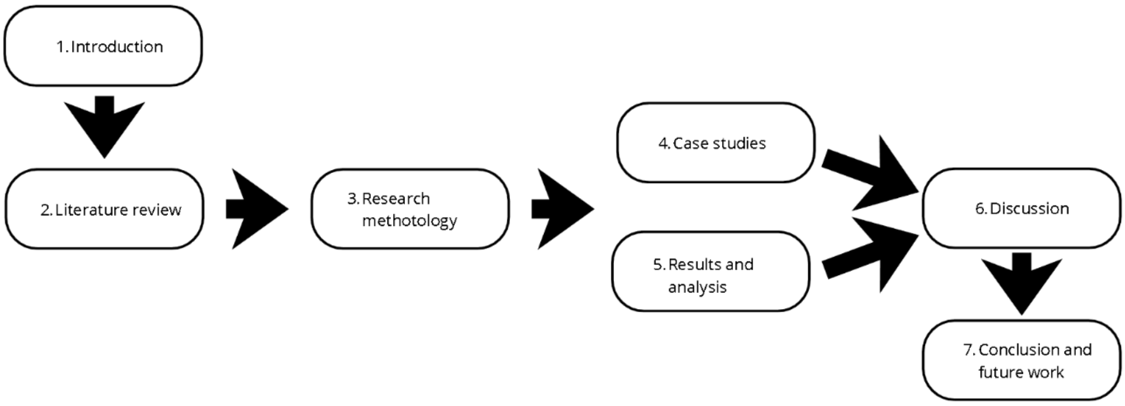

Figure 1. Flow chart of the thesis.

2 Literature review

This chapter provides broad literature review that handles properties of hydrogen, different storage technologies and current technical and economic status of hydrogen storages.

2.1 Key properties of hydrogen

Hydrogen is one of the most abundant elements in our universe. Even though 90 % of all atoms in our universe are hydrogen it is only accessible from deriving it from various compounds, for example, fossil fuels (Hamedani et al., 2024). Table 1 illustrates different thermodynamical properties of hydrogen as fuel compared to other currently more applicable fuels.

Table 1. Hydrogen properties comparison to other fuels (Adapted from Hamedani et al., 2024).

Property	Hydrogen	Methane	Gasoline	Diesel
Molecular weight	2.016	16.043	~110	~170
Boiling point (K)	20.3	111	298-488	453-633
Carbon content (mass%)	0	75	84	86
HHV (MJ/kg)	141.9	55.5	47.3	44.8
LHV (MJ/kg)	119.9	50	44.5	42.5
Auto-ignition temperature (K)	853	813	~613	~523
Volumetric energy content (@ 1bar & 273K; kJ/L)	10.7	33	33000	35000

Property	**Hydrogen**	**Methane**	**Gasoline**	**Diesel**
Density (@ 1 bar & 273 K; kg/m³)	0.089	0.72	730—780	830
Stoichiometry air/fuel mass ratio	34.4	17.2	14.7	14.7

As can be seen from the Table 1 hydrogen has many advantages compared to more traditional fuels. Nonetheless, hydrogen has its own weaknesses which makes it hard to utilize as a fuel and energy carrier (Bhuiyan et al., 2025).

According to Hamedani et al. (2024) main advantage of hydrogen as a fuel is its high energy density. According to Bhuiyan et al. (2025), this makes hydrogen a great option for transporting and as an energy storage. Other upsides of hydrogen as a fuel stated in their research are low boiling point and wide flammability range. Bhuiyan et al. (2025) states that low flashpoint of hydrogen (-231˚C) means that hydrogen can vaporize and ignite more easily. They state that this then leads to more simplified design of ignition and starting systems. Another benefit of hydrogen stated in their research is its wide flammability. Wide flammability ranges from 4—75 % allows hydrogen to be ignited in different concentrations of mixtures depending on the current need (Bhuiyan et al., 2025). Other advantage of hydrogen based on the Table 1 is its low carbon content. While hydrogen itself does not contain any carbon, in reality the amount of carbon in the lifecycle of hydrogen depends on the production method of hydrogen (Hamedani et al., 2024).

One of the biggest downsides of hydrogen is its poor volumetric energy density compared to traditional fuels (Bhuiyan et al., 2025). Table 1 illustrates that hydrogen has 10.7 kJ/l at atmospheric conditions, while gasoline and diesel have 33 MJ/l and 35 MJ/l. By compressing or liquefying hydrogen the volumetric energy density goes up to 4.9 MJ/l and 8.5 MJ/l (Usman, 2022). As can be seen from Table 1 hydrogen has a much lower volumetric density than, for example, diesel of gasoline at atmospheric conditions. This then results in the major challenge of storing hydrogen. In their research Bhuiyan et al. (2025) mentions that due to lower volumetric density of hydrogen, larger storage volumes are needed to compensate for the lower volumetric density compared to other fuels.

While low volumetric density makes storing hydrogen challenging in terms of viability and technology readiness, this challenge brings up many upsides. According to Bhuiyan et al. (2025) these problems drive innovation and design to realize the full potential of hydrogen as part of the future energy systems. As part of this thesis this is one of the main points of study. By comparing different storage options economically and technologically a more profound understanding of hydrogen storage technologies current and near future is achieved.

2.1.1 Hydrogen properties in different storage technologies

Low volumetric density of hydrogen in atmospheric conditions can be improved with storage technology. Table 2 illustrates gravimetric capacity, volumetric density and volumetric energy density of hydrogen in different storage technologies.

Table 2. Hydrogen properties based on storage technologies.

Storage technology	Gravimetric capacity (wt%)	Volumetric density (kg/m³)	Volumetric energy density (MJ/L)	Reference
Compressed gas (350—700 bar)	4—5	~25—30	2.94—4.9	Al Kareem et al. (2025); Usman, (2022).
Liquid hydrogen	~7	~70—80	8.5	Al Kareem et al. (2025); Usman, (2022).

Storage technology	Gravimetric capacity (wt%)	Volumetric density (kg/m³)	Volumetric energy density (MJ/L)	Reference
Cryo-compressed	~7—8	~80—100	9.6	Al Kareem et al. (2025); Usman, (2022).
Metal hydrides	1—7	~80—100	13.2—13.7	Al Kareem et al. (2025); Usman, (2022).
Liquid organic hydrogen carrier	5—7	~50—60	5.68—6.72	Al Kareem et al. (2025); Usman, (2022).
Ammonia	17.8	~107	n.d.	AlZohbi et al. (2025).
Ammonia borane	19.6	n.d.	n.d.	Bhuiyan et al. (2025).
Carbon based materials	5	~38.5	2.4	Usman, (2022).
Zeolites	2.55	~20	2.4	Usman, (2022).
Metal organic framework	5—10	~40—60	3.1	Al Kareem et al., (2025); Usman, (2022).
Glass microspheres	2.3	~36	n.d.	Dalai et al. (2014); DOE (2006); Usman, (2022).

Gravimetric capacity describes the mass of hydrogen stored as a percentage of the mass of storage (Broom et al., 2019). High gravimetric capacity is more crucial for an onboard storage application where high amount of hydrogen per the mass of the storage system is required (Usman, 2022). Volumetric density describes the amount of hydrogen stored in given space (kg/m³) as seen from Table 2. Low volumetric density leads to a need for larger storage systems to compensate for the lack of volumetric density (Al Kareem et al., 2025). Volumetric energy density describes the amount of energy stored in hydrogen (MJ/L) as seen fromTable 2. According to Usman (2022), low volumetric density directly translates to low volumetric energy density.

As stated in the previous chapter 2.1 by compressing or liquefying hydrogen the volumetric energy density is improved drastically and comes closer to gasoline and diesel. This is more important for onboard applications where hydrogen is used as a fuel source, to mitigate the need to refuel too often (Usman, 2022). Table 2 shows that metal hydrides have the highest volumetric energy density followed by cryo-compressed and liquid hydrogen.

To achieve properties indicated in Table 2 compressed hydrogen needs to be compressed to 350—700 bar pressure (Usman, 2022). Liquid hydrogen requires −253 °C and ambient pressure (Usman, 2022). Being a combination of two previous options cry-compressed hydrogen requires −253 °C and 350 bar pressure (Usman, 2022). Generally metal hydrides have gravimetric storage capacity between 1—2 wt% but exceptions like MGH_2 have higher 7.6 wt% capacity (Klopčič et al., 2023). Liquid organic hydrogen carrier (LOHC) has a higher gravimetric capacity compared to metal hydrides but doesn’t offer as good volumetric density (Usman, 2022). Ammonia and ammonia borane have the highest gravimetric capacities according to AlZohbi et al. (2025); Bhuiyan et al. (2025) and are therefore attractive hydrogen storage options. From the rest of the storage technologies listed in Table 2, metal organic framework has the highest gravimetric capacity and volumetric density. While MOF-120 can achieve gravimetric capacity of 7.9 wt%, at room temperature most of the MOFs have below 1 wt% capacity (Usman, 2022).

Understanding different gravimetric and volumetric properties of different hydrogen storage technologies is crucial in identifying the best available technology for different needs. For stationary applications volume is the biggest concern whereas in mobile applications both gravimetric and volumetric properties are crucial (Usman, 2022).

2.1.2 Colour codes of hydrogen

As stated in chapter 2.1, hydrogen production method affects the carbon content of the hydrogen. According to Incer-Valverde et al. (2023), there is deviation in the number of colours and naming of these in different sources. In their study, 10 most prominent colours are discussed. Figure 2 illustrates these 10 colours with the process and energy source.

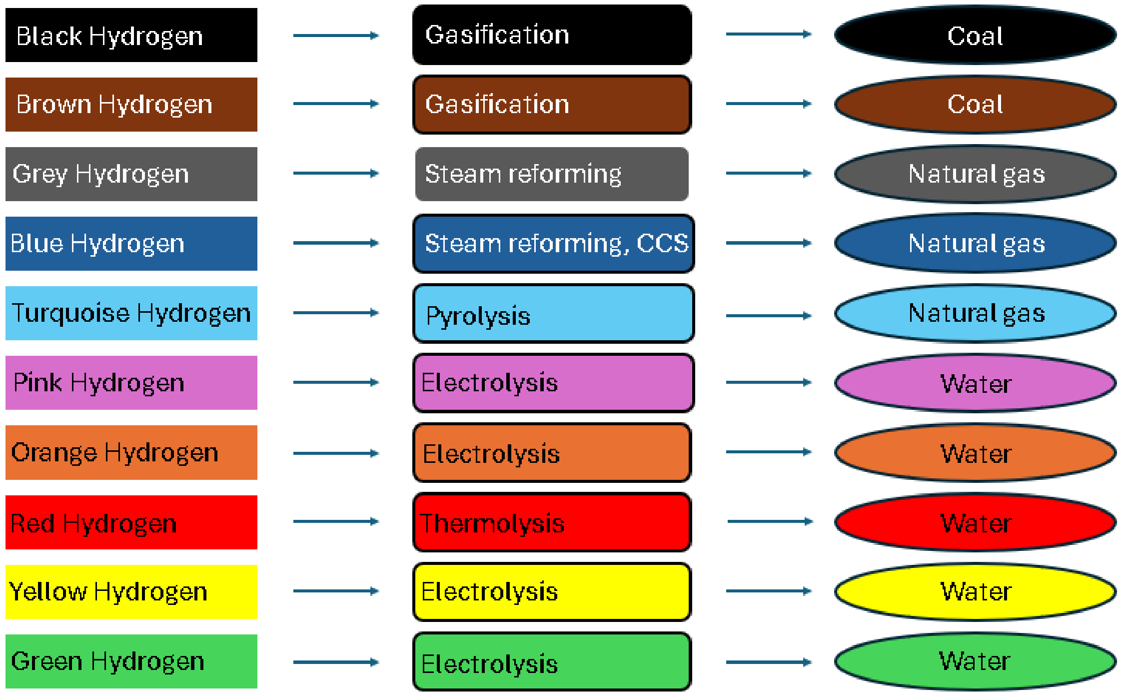

Figure 2. Hydrogen colour codes (Adapted from Incer-Valverde et al., 2023).

According to Incer-Valverde et al. (2023), the main factors contributing to carbon emissions are the source of hydrogen and energy. They state that, from pink to green the hydrogen is made from water via electrolysis or thermolysis. Their research suggests that pink and red uses nuclear energy, orange mixed grid electricity, yellow solar and green renewable energy. These production methods can be considered carbon free (Incer-Valverde et al., 2023).

The other end of the spectrum consists of black to turquoise hydrogen. Incer-Valverde et al. (2023) state that black to grey hydrogen types have the highest carbon emissions since fossil fuels are used to produce hydrogen. Their research suggests, that if carbon capture and storage is implemented to these processes, hydrogen can be called blue or turquoise. Additionally, electricity used for these processes is non-renewable affecting the carbon emission even more (Incer-Valverde et al., 2023).

Understanding the different colours of hydrogen production is important. While this thesis focuses on the storage aspects of hydrogen lifecycle, producing methods affects the overall price of the hydrogen during its lifecycle in form of LCOH (Kumar et al., 2024). Furthermore, LCOH contributes as a metric when assessing viability and implementation of hydrogen technologies, affecting greatly the implementation of hydrogen as a future energy source (Kumar et al., 2024).

2.2 Hydrogen storage technologies

As stated in chapter 2.1 hydrogen has high energy density per unit mass. The lower heating value (LHV) of hydrogen is 120 MJ/kg which is significantly higher compared to other fuels presented in Table 1. However, the problem of storing hydrogen comes from low volumetric density. In his research Usman, (2022) states that there are many different physical and chemical storage methods for hydrogen. It remains unclear which of these technologies is the most feasible. Hydrogen storages are divided into two main categories physical-based and material-based (Bhuiyan et al., 2025). In their study Bhuiyan et al. (2025) define that, physical-based storages consist of storing hydrogen as compressed gas, liquid or cryo-compressed while material-based storages consist of storing hydrogen through absorption via physical or chemical process. Figure 3 illustrates different storage methods for hydrogen. Physical-based storage methods are the most used ones at the moment while material-based storage options are still mostly in development phase (AlZohbi et al., 2023).

This chapter examines different storage methods used for hydrogen storage. All the storage methods shown in the Figure 3 are investigated in this thesis. Key aspects include pros and cons, safety and applicability. When it comes to storing hydrogen, different methods may be required. For this reason, it is important to have a good understanding of how different storage methods work and which are best for different applications.

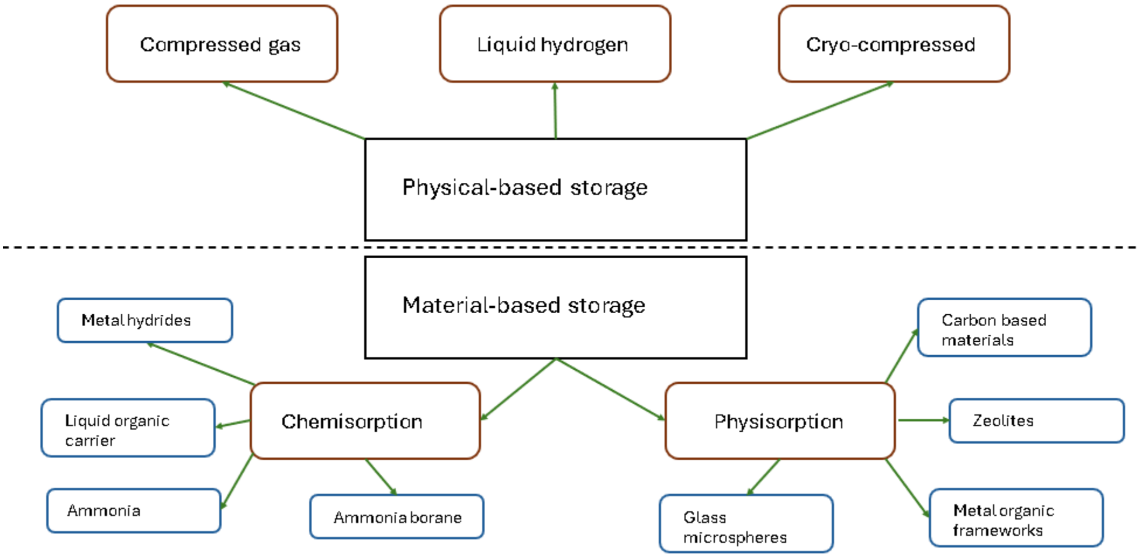

Figure 3. Hydrogen storage technologies (adapted from Bhuiyan et al., 2025).

2.2.1 Physical-based storages

Physical-based storage can be divided into three subcategories. In their research Bhuiyan et al. (2025) have divided the storages to compressed, liquid and cryo-compressed methods. They state that each method has its pros and cons while being suitable for different applications. Compressed hydrogen storages utilize compression as the name states. According to Usman (2022) this kind of compressed storage system is the most used hydrogen storage system. For liquid type storages hydrogen is cooled down below -253˚ C, under its boiling point (Usman, 2022). Cryo-compressed storage system combines both compression and cooling to get benefits of both storage systems (Bhuiyan et al., 2025).

2.2.1.1 Compressed hydrogen

According toUsman, (2022) compressed hydrogen is most used form of hydrogen storage. For this reason, it is also one of the most developed among the technologies (Usman, 2022). This type of storage offers good filling and release of hydrogen (Usman, 2022). According to Hjeij et al. (2022) in compressed hydrogen storages hydrogen is stored at 150 to 700 bar pressure. In his research Usman, (2022) mentions that there are five types of compressed hydrogen storage. Figure 4 illustrates the five different pressure vessel types. The storage types are divided based on the pressure requirement and application (Hjeij et al., 2022). In his research Usman, (2022) mentions that cylindrical vessels are favored over spherical for they are easier to fit in the applications.

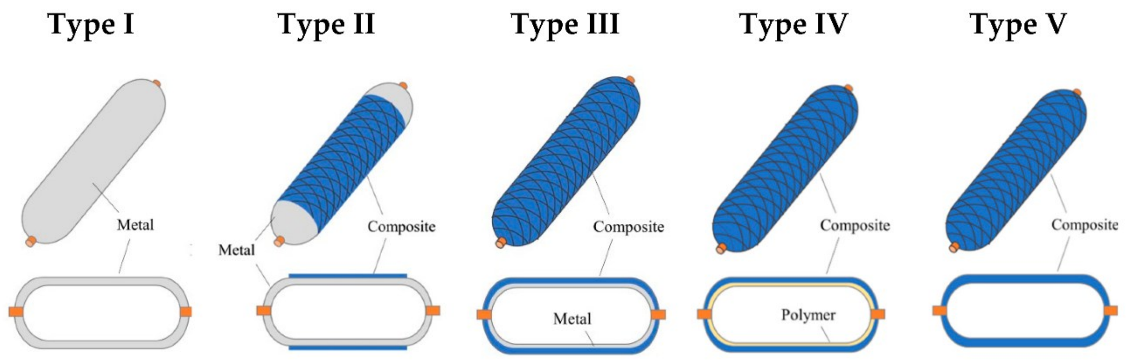

Figure 4 Illustration of different pressure vessels (Mikroni et al., 2024).

Type I vessels are made only from metal (Usman, 2022), as also shown in Figure 4. According to Cheng et al. (2024) type I storages are made from steel and aluminium alloys. Usually type I tanks are the cheapest option for they are easiest to manufacture (Cheng et al., 2024). Cheng et al. (2024) research states that type I tanks can withstand pressures up to 200 bar. But since these metals have high densities, this makes the tanks robust and heavy (Cheng et al., 2024). Therefore, they are mostly used for stationary applications such as industrial hydrogen or vessels like submarines where there are no restrictions for large tanks (Cheng et al., 2024).

According to Cheng et al. (2024) type II vessels are made of metal as type I, but they are strengthened with additional glass fiber or carbon fiber filament, as shown in Figure 4. Cheng et al. (2024) mentions that the working pressure of type II vessels goes up to 300 bar due to the added filament. Their research suggests that these vessels are still quite heavy and are therefore used for stationary applications. In their research (Cheng et al., 2024; Usman, 2022) states that type II tank weight around 30 % less than type I tank. These improvements raise the price of type II tank by about 50 % (Usman, 2022).

Type III is different from type I or type II storage. According to Usman, (2022) type III tanks are carbon fiber composites that are lined with different metal like aluminum, as shown in Figure 4. Cheng et al. (2024) research states that the liner seals the gas inside the tank while the composite layer handles the load. This allows the tanks to be lightweight and yet able to withstand higher internal pressures up to 700 bar (Usman, 2022). In their research Cheng et al. (2024) states that type III tanks can be over 50 % less thick than type I. Higher pressure and higher density of hydrogen allow type III tanks to be utilized in moving applications such as lightweight vehicles (Cheng et al., 2024).

Type IV tanks are like type III, but they have polymeric liner (Usman, 2022), as shown in Figure 4. According to Usman, (2022) the polymer is usually high-density polyethylene (HDPE). Similarly to type III, type IV stores hydrogen at pressure of 700 bars (Cheng et al., 2024). Similarly to type III tanks, type IV tanks are even less thick — approximately a third of type I — and are therefore good option for mobile applications (Cheng et al., 2024).

According to (Cheng et al., 2024; Usman, 2022) there is also type V tank. According (Cheng et al., 2024; Usman, 2022) these tanks are modification of type IV storage and fully made of composite, as shown in Figure 4. Cheng et al. (2024) states that this type of tank would be 20 % lighter than type IV tank, with higher hydrogen pressure up to 1000 bars. Their research suggests that the high cost of composite materials and early development restricts the commerciality of this application.

Compressed hydrogen can also be stored underground. According to Sambo et al. (2022) underground storage is attractive option for its safety, space usage and construction costs. While the storages would be undergroun d, they are less prone to catastrophes and wars (Sambo et al., 2022). Also, by being underground the storages won't reserve space aboveground which can be used for something more important (Sambo et al., 2022). By utilizing already existing reservoirs underground the construction costs for this type of storage is considerably lower (Sambo et al., 2022). According to Sambo et al. (2022), UHS include salt deposits, depleted gas/oil fields and aquifers. These storages are dependent on the formation location and are therefore only usable in given locations (Masoudi et al., 2024).

Another UHS option is lined rock cavern (LRC). According to Masoudi et al., (2024), LRC is excavated hydrogen storage technology where steel lining and hard rock around it creates the pressure vessel. LRC offers locational flexibility compared to the other UHS options, enhanced security and leakage proof (Masoudi et al., 2024). According to Kanto, (2022), LRC is viable option in Finland and Nordics where no other UHS formations are available.

Even though compressed hydrogen storage is the most common method of storage they have limitations. As shown in Table 2 volumetric density of compressed hydrogen is less than half of what is achieved with liquified hydrogen. The compression process for hydrogen requires approximately 13—18 % of the lower heating value of hydrogen (Usman, 2022).

2.2.1.2 Liquid hydrogen

In liquid hydrogen storage the hydrogen gas is cooled down to liquid form (Usman, 2022). According to Bhuiyan et al., (2025) the hydrogen is cooled down to -253˚C and stored in insulated tanks in ambient temperature. Insulation requires vacuum space between inner and outer shell and an insulation material based on the application (Simanullang, 2025). Liquefication improves the volumetric density of hydrogen drastically (Usman, 2022). Therefore, liquid storage is more applicable for high volume and long-distance transport (Simanullang, 2025). According to Usman (2022) in liquid form hydrogen is not corrosive. Therefore, the storage tanks can be made from stainless steel or aluminum alloys (Usman, 2022). In addition, the ambient temperature used in this storage type allows for thinner tanks (Usman, 2022). In the research Usman (2022) also mentions another advantage of cryogenic condition. As stated in his research, cryogenic hydrogen has low adiabatic expansion energy which helps in case of hydrogen releasing through opening. In these situations, the hydrogen's ability to expand in space and cause damage is lowered (Usman, 2022). Liquid hydrogen storages are divided into three subcategories based on the application: stationary, mobile and onboard (Simanullang, 2025).

According to Simanullang (2025), stationary type storages are used since 1960 to store rocket fuel. He states that, biggest one made by NASA has capacity of 4700 m^3 and bigger ones are already projected for the future. Based on his research, these storages are usually spherical shaped because they offer lowest boil-off rate. As stated in his research, insulation material for this type of tank is perlite powder or glass bubbles. He mentions that, nowadays insulation leans more towards the glass bubbles for additional mechanical resistance against thermal cycles and better insulation characteristics.

Simanullang (2025) also states that for mobile applications liquid hydrogen storages are used for distances over 300 km. One of the common methods stated in his research is to transfer liquid hydrogen on a barge or a carrier boat in a cylinder-shaped tank with hemispherical ends. He mentions that worlds first liq uid hydrogen carrier ship Suiso, carries hydrogen from Australia to Japan. He states that, for this type of application multi-layer insulation (MLI) is used, MLI means that multiple layers of insulation are wrapped around the inner shell of the tank. He suggests that using MLI allows for optimization of insulation affecting the boil-off rate and overall performance. While MLI offers better insulation and lighter tanks, it is more time-consuming to make and is not easily repaired (Simanullang, 2025).

Third subcategory of liquid hydrogen storage is the onboard storage tank. Simanullang (2025) mentions two projects based on this application H2FLY and Daimler truck. He states that, use of sustainable hydrogen for aviation and transportation sector is highly anticipated in the future. He mentions that onboard storage tanks also utilize MLI technology to achieve better insulation and lighter weight to reach the weight limits for road vehicles.

Clear disadvantages of liquid hydrogen storage are the cooling process and boil-off phenomena (Usman, 2022). In his research Usman (2022) states that the liquification process requires energy equivalent of 30—40 % of the net heating value of hydrogen. This significantly lowers the overall feasibility of this storage type. The boil-off phenomena occurs when the environment around the hydrogen heats it up to vapor phase and causes losses of 1.5—3 % a day (Usman, 2022).

2.2.1.3 Cryo-compressed hydrogen

Third and last physical-based storage method for hydrogen is cryo-compressed. As stated by Usman, (2022) in cryo-compressed storage method the hydrogen is both compressed and cooled down to -253˚C. By cryo-compressing higher volumetric density is achieved while lowering the boil-off losses (Usman, 2022). Moradi et al., (2019) states that cryo-compression allows also for fast and efficient filling and release and high safety caused by the double wall storage and vacuum. This technology is potentially the best option for future hydrogen storage because of its potential to meet targets for gravimetric capacity, volumetric capacity and losses while being dormant (Moradi et al., 2019).

This storage method also has its downsides. It is stated by Usman (2022) that type III vessels with double walls are required for cryo-compression, making the whole system more expensive. Additionally, higher energy demand and lack of hydrogen infrastructure remain an obstacle (Usman, 2022).

2.2.2 Material-based storage

The other main category of hydrogen storage is called material-based storage. According to Bhuiyan et al. (2025) material-based storages offer more compact and better capacity storage systems compared to physical-based storages mentioned above. Based on their research these types of storage are also considered safer than physical-based storage. Bhuiyan et al. (2025) have divided material-based storage into two subcategories physisorption and chemisorption. In physisorption hydrogen is absorbed on the surface of other materials via van der Waals forces while in chemisorption hydrogen atoms dissociate as atoms into storage material and form chemical bonds (Bhuiyan et al., 2025). Both technologies involve a lot of different possibilities as listed in Figure 3.

2.2.3 Chemisorption process

Chemisorption process involves multiple different subcategories. As shown in Figure 3 Bhuiyan et al. (2025) names metal hydrides, liquid organic carrier and ammonia borane. These types of storages allow high storage density and stability in ambient conditions (Bhuiyan et al., 2025). From these technologies metal hydrides are the ones with most recognition (Moradi et al., 2019).

2.2.3.1 Metal hydrides

According to Usman (2022) metal hydrides form when hydrogen and metal react chemically. In the process the hydrogen molecule separates into atoms and diffuses in the metals structure (Usman, 2022). Two mechanisms of the reaction are direct reaction and electrochemical dissociation with water (Usman, 2022). According to Usman (2022) the chemical process releases heat when hydride is formed and vice versa external energy is needed to release hydrogen for the end user. This can be done by heating the hydride or by lowering the pressure (Usman, 2022). These processes are illustrated in Figure 5.

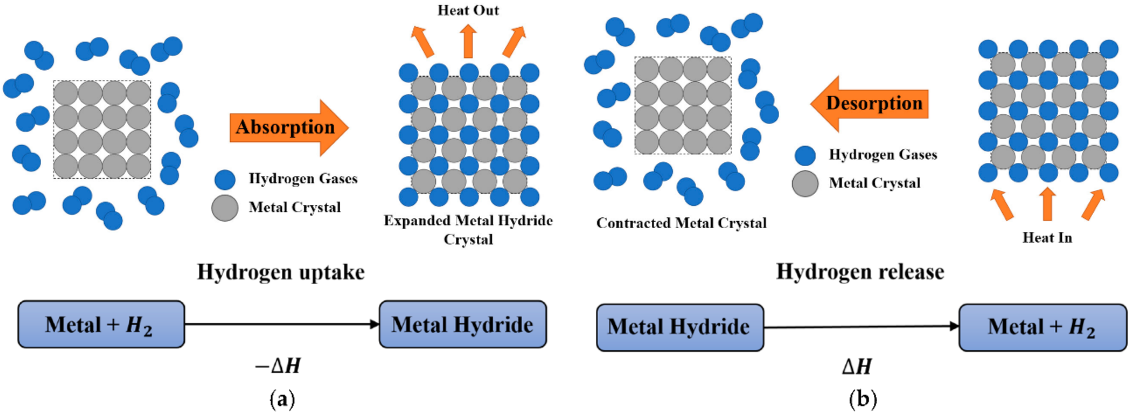

Figure 5. Absorption and desorption processes of metal hydride; (a) absorption and (b) desorption (Larpruenrudee et al., 2025).

As stated by Klopčič et al. (2023), metal hydrides have better volumetric energy densities than physical-based storages. With the additional safety due to hydrogen being chemically bonded to the hydrides at low pressures, makes metal hydrides very promising technology (Klopčič et al., 2023). Metal hydrides are applicable to both stationary and mobile applications (Klopčič et al., 2023). Metal hydrides can be divided into metal hydrides and complex metal hydrides (Usman, 2022).

Crucial factor of the metal hydrides is the desorption temperature. Usman (2022), states that desorption temperature means the amount of heat needed to release the hydrogen from the hydride. Understanding the desorption temperatures is crucial because some applications, for example Proton exchange membrane (PEM) fuels cells cannot provide high temperatures required for the desorption process (Usman, 2022). For example, MgH_2 isn't suitable for PEM fuel cells due to its over 300˚C desorption temperature (Usman, 2022). Magnesium hydride can also be alloyed with other metals to improve its kinetics and desorption temperature (Usman, 2022). Other hydrides mentioned by Klopčič et al. (2023), are TiFe, $TiMn_2$ and $LaNi_5$. These have low gravimetric densities, but they have significantly lower desorption temperatures (Klopčič et al., 2023). According to Usman (2022), magnesium hydride is mostly used in stationary applications due to its limitations. Metal hydrides are good mid- to long-term storages because of high energy density, scalability and minimal losses (Klopčič et al., 2023).

Another form of metal hydrides is complex metal hydrides. According to Usman (2022), in complex metal hydrides the hydrogen is covalently bonded with the central atom. Complex metal hydrides consist of alanates, borohydrides and amides-imides (Usman, 2022). These complex metal hydrides offer higher gravimetric capacities with lower desorption temperatures (Usman, 2022). Gravimetric capacities range from 5.6 to 18.5 wt% compared to previous metal hydrides and desorption temperatures range from 150˚C to 380℃ (Usman, 2022).

Even though metal hydrides have many advantages over compressed and liquified hydrogen storage they have also disadvantages. According to Klopčič et al. (2023), the biggest disadvantage is the filling and extraction times caused by slow kinetics of the hydrides. Also, high desorption temperatures create problems for the applicability of the hydride for on-board applications (Usman, 2022).

2.2.3.2 Liquid organic hydrogen carrier

Another form of chemisorption storage is liquid organic hydrogen carrier (LOHC). According to Usman (2022), in this storage type hydrogen is chemically bonded to hydrogen deficient organic molecule. Figure 6 illustrates LOHC cycle adapted from Usman (2022. In the cycle the LOHC carries hydrogen from hydrogenation facility to end-users, for example, reactor of the power plant or vehicle where the hydrogen is released (Usman, 2022). Dehydrogenation releases water that can be used, for example to produce green hydrogen (Usman, 2022). The LOHC then goes back to hydrogenation facility where it is hydrogenated again with hydrogen (Usman, 2022). One big upside of this process is that carbon stays within the cycle and carrier liquid remains unconsumed (Moradi et al, 2019). Based on Moradi et al. (2019) research, LOHC works in ambient conditions and low storage pressures. LOHC offers reasonable high hydrogen storage capacity compared to some of the metal hydrides and other hydrogen storage options as can be seen from the Table 2. Current gasoline infrastructure can be used for LOHC processes (Usman, 2022).

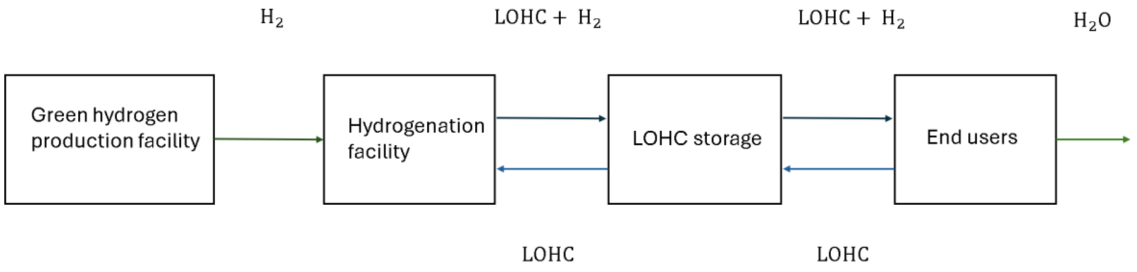

Figure 6. LOHC cycle concept (adapted from Usman, 2022).

According to Usman (2022), among the most studied LOHC are cyclohexane, methylcyclohexane and decalin. Dehydrogenated products of these include benzene, toluene and naphthalene (Usman, 2022). While benzene is carcinogenic and naphthalene solid at ambient temperature, toluene is neither of these (Usman, 2022). Therefore, toluene is regarded as one of the easiest starting points of using LOHC to store hydrogen (Usman, 2022). Other viable dehydrogenated products involve benzytoluene and dibenzytoluene which are more commonly used as heat transfer oils (Usman, 2022). LOHC process can be used for stationary and on-board applications (Bhuiyan et al., 2025).

According to Bhuiyan et al. (2025), LOHCs are one of the preferred options for long distance sea transport and large-scale applications. Due to simpler process compared to liquid hydrogen LOHC offers safer and cheaper option (Bhuiyan et al., 2025).

Even though LOHC has many upsides it still has limitations. Bhuiyan et al. (2025), states that hydrogenation and dehydrogenation process where hydrogen is bonded and released require energy. For the LOHCs mentioned above the dehydrogenation temperatures are 325˚C which prevents their use with PEM cells (Usman, 2022).

2.2.3.3 Ammonia

Even though ammonia is not presented as a hydrogen storage option in Figure 3 it is a viable alternative. Hydrogen is used to produce ammonia via Haber-Bosch process (Bhuiyan et al., 2025). Haber-Bosch process requires high temperature of 400—500 and pressure of 100—300 bar (Menefee et al., 2024). Ammonia requires -33˚C temperature and 1 bar$_a$ pressure or 20℃ and 7 bar$_a$ to be in liquid phase (Lamb et al., 2019). According to Lamb et al. (2019), ammonia can be used as fuel itself or decomposed back to hydrogen and nitrogen. This allows hydrogen to be then used in, for example, PEM fuel cells (Lamb et al., 2019). Ammonia value chain discussed above from production to end users is illustrated in Figure 7. Keeping ammonia liquified requires significantly less energy compared to hydrogen (Lamb et al., 2019). 70 % of the energy used to produce liquid ammonia can be later used, making ammonia efficient storage method (Lamb et al., 2019). Ammonia is used in many different processes and transported vast amounts every year around the world and this combined with absence of carbon in ammonia, makes ammonia interesting possibility (Lamb et al., 2019).

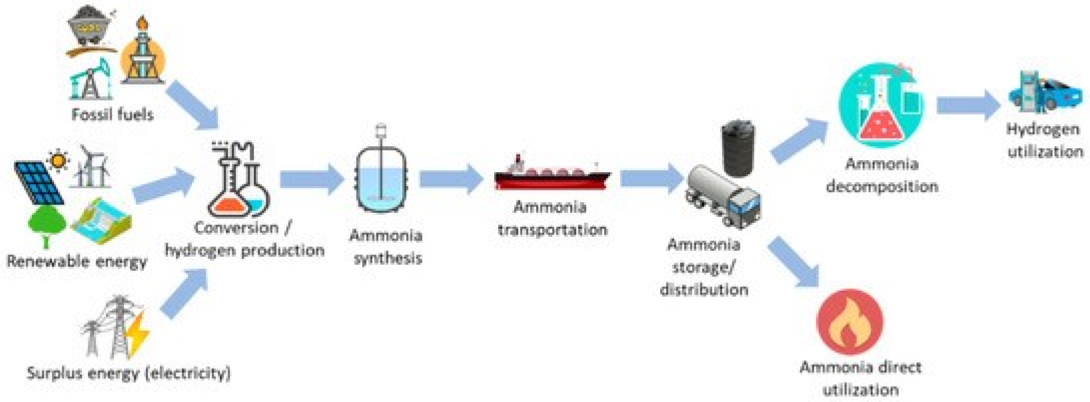

Figure 7. Ammonia as hydrogen storage value chain (Aziz et al., 2020).

Challenges of ammonia as storage are toxicity and purity concerns after decomposition (Bhuiyan et al., 2025). Lamb et al. (2019) also mentions the separation and purification of hydrogen processes challenge for their lack of efficiency, reliability and scalability.

2.2.3.4 Ammonia borane

Ammonia borane (NH_3BH_3) is chemical hydride (Bhuiyan et al., 2025). According to Bhuiyan et al. (2025), unlike LOHCs and metal hydrides, ammonia borane is irreversible. While offering high hydrogen content they have many challenges, for examples high temperatures (Bhuiyan et al., 2025). Due to these issues applicability of this technology is limited to lightweight high-capacity storage for portable- and emergency applications (Bhuiyan et al., 2025). Dehydrogenation of ammonia borane at room temperature requires catalytic material (Akbayrak et al., 2018).

Bhuiyan et al. (2025) states that, main challenges for ammonia borane and other chemical hydrides are needed for catalysts, high production cost and unwanted byproducts that require recycling. Release process requires high energy input which furthermore limits the applicability (Bhuiyan et al., 2025).

2.2.4 Physisorption process

Physisorption is the other subcategory of material-based storage. According to Bhuiyan et al. (2025), in physisorption hydrogen is absorbed to solid material via van der Waals forces. These solid materials include carbon-based materials, zeolites, metal organic frameworks (MOF) and glass microspheres (Bhuiyan et al., 2025). Advantages of physisorption are high rates of adsorption and desorption, relatively low enthalpy, efficiency and non-existing hydrogen losses (Usman, 2022). According to Usman (2022), high surface area is required for the materials. Materials mentioned above meet those requirements and are the most developed (Usman, 2022).

2.2.4.1 Carbon based materials

Carbon based materials consist of many different options. According to Mulky et al. (2024), these include graphene, carbon hollow spheres, carbon fibers and carbon nanotubes (CNTs). Porous structure of carbon materials offers good efficiency to store hydrogen, but the storing process require approximately -200˚C temperatures and 30—60 bar pressures (Usman, 2022). Cryogenic conditions required to obtain, adequate storage densities require energy and make carbon-based materials not suitable for large scale applications (Bhuiyan et al., 2025). Mulky et al. (2024), mentions graphene and carbon nanostructures as possible option for nanoscale applications.

2.2.4.2 Zeolites

Zeolites offer high surface area like the other physisorption materials (Usman, 2022). As stated by Usman (2022), zeolites are aluminosilicates. Zeolites have theoretical storage capacity of 9.2 wt% (Mulky et al., 2024). The storage capacity is lower as illustrated in Table 2. According to Usman (2022), zeolite CaX requires storage conditions of 15 bar and -200˚C temperature and in ambient temperatures the capacity drops to 0.4 wt%. While zeolites offer quick adsorption and desorption process the cryogenic conditions require vast amounts of energy making it less applicable for large scale hydrogen storage (Bhuiyan et al., 2025).

2.2.4.3 Metal organic framework

One promising physisorption based storage method for hydrogen is metal organic framework (MOF). According to Usman (2022), modifiable and versatile MOF offer the highest surface area of all hydrogen storage materials. By modifying MOFs, structure higher surface areas are created which leads to higher hydrogen storage density (Qiao et al., 2024). In his research Usman (2022) states that MOF-120 shows highest experimentally measured area of 6240 m^2/g at 80 bar and -200˚C temperature. According to Qiao et al. (2024), there are more than 100000 different MOFs each with their unique structure and properties. Recent breakthroughs in MOF development involve crystal engineering and decoration methods to further improve performance of MOFs (Qiao et al., 2024).

While recent development of MOFs shows promise in the future of hydrogen storage there are still obstacles on the way of this technology. Qiao et al. (2024) states in their research that MOFs have unsatisfactory hydrogen capacity at ambient conditions. Another challenge of MOFs is the desorption temperature which causes thermal management issues especially in on-board applications (Qiao et al., 2024).

2.2.4.4 Glass microspheres

Glass microspheres are a storage option for gaseous hydrogen. According to Usman (2022), hydrogen gas is stored within 5—500 µm size glass microspheres which offers an option for hydrogen transportation. High pressure hydrogen (350—700bar) is stored in the glass microspheres while the storage pressure is much lower and therefore this storage technology offers safe option to store compressed hydrogen due to lower storage pressure (Usman, 2022). At 10 bar pressure and 200˚C capacities mentioned in Table 2 can be reached (Dalai et al., 2014). Another benefit of this storage technology is the availability of the materials for the glass microsphere which is often recycled cullet (Dalai et al., 2014).

Glass microspheres have also drawbacks. Usman (2022) states that glass microspheres offer low volumetric energy density. Releasing hydrogen from storage requires lots of energy and temperatures up to 200—300˚C (Usman, 2022). Release of hydrogen in ambient temperatures and possibility of breaking during the processes are other drawbacks mentioned by Usman (2022). This leads to restrictions on applicability of this storage method.

2.3 Technical status of hydrogen storage technologies

This chapter focuses on the current technical status of hydrogen storage technologies. Technical status is studied through technology readiness levels, safety, technical challenges and applicability. Evaluating hydrogen storage status through these viewpoints creates foundation for the latter part of the thesis where feasibility is evaluated.

2.3.1 Technology readiness levels

Technology readiness level (TRL) indicates the maturity of given technology (Manning, 2023). There are nine TRLs levels indicating the maturity where first level is the lowest while ninth is the most mature (Manning, 2023), but According to Revinova et al. (2024) IEA has also added levels 10 and 11. Their study states that, level 10 means that technology is implemented in energy systems on a large scale while level 11 means that technology has achieved predictable growth and maturity. TRL evaluation is critical, so research and resources are dedicated to the most prominent storage options (Boretti, 2023). Table 3 summarizes the eleven different levels of technological maturity.

Table 3. Technology readiness levels (adapted from Revinova et al. 2024 & IEA 2025).

Level of readiness	**Description**
TRL 11	Predictable growth
TRL 10	Implemented in energy systems at large scale
TRL 9	Technically ready for sale or licensing
TRL 8	First-of-a-kind commercial scale commissioned
TRL 7	Validated at pre-commercial scale
TRL 6	Prototype operated in real conditions
TRL 5	Large prototype tested
TRL 4	Early prototype tested
TRL 3	Components tested
TRL 2	Application formulated
TRL 1	Initial idea reported

According to IEA (2025), levels 1 to 3 are ideas or concepts. To reach levels 4 to 6 the technology must have a prototype in some level (IEA, 2025). Levels 7 and 8 are commercial level technologies and from 9 onward the technology is mature enough to be implemented in applications (IEA, 2025).

Physical-based storage technologies have been used for a while. As stated, most common hydrogen storage technology is compressed. According to Revinova et al. (2024), compressed hydrogen can be categorized as TRL 11. Second highest TRL of physical-based storage goes to liquid hydrogen storage and cryo-compressed hydrogen storage (IEA, 2025; Boretti, 2023). Underground storages have TRL levels ranging from 3 to 10 (Revinova et al. 2024). Physical-based storage technologies are mature technologies that have high technology readiness levels and are therefore more feasible options for hydrogen storage.

Material-based storage offers wider spectrum of technology readiness levels. According to Revinova et al. (2024), highest TRL of material-based storage goes to ammonia. This is mature and widely used technology which gives it TRL 11 (Revinova et al., 2024). Second highest TRL 6 to 7 goes to LOHC (Revinova et al., 2024). As can be seen from Table 3, levels 6 to 7 seven indicates that this technology is somewhere between final prototype and precommercial product. Metal hydrides have TRL of 4 to 5 which means that at these levels the concept has developed into a prototype and improvements need to be made to reach commercial status (IEA, 2025). According to Revinova et al. (2024), storage technologies using adsorption into materials have the lowest TRLs. These include MOFs, carbon-based materials and zeolites which have TRL from 2 to 3 (IEA, 2025). At this stage the concept of these storages needs validation to reach prototype status (IEA, 2025). Ammonia borane has TRL level between 3—4 (Demirci, 2020).

Overall, the most developed technologies are physical-based storage methods with ammonia as an exception widely used at large scale. However, there are still challenges within these technologies that affect the overall applicability of hydrogen storage. Technologies like LOHC and metal hydrides are promising options for the future of hydrogen storage.

2.3.2 Safety

Due to hydrogen characteristics storage generally requires high pressures, high or low temperatures or toxic carrier materials resulting in safety concerns. According to Li et al. (2022), these characteristics are small size – which leads to leakage –, low minimum ignition energy, wide flammability range and wide explosion rate. Small size causes hydrogen to pass through materials causing embrittlement while low density causes it to spread across the open space fast (Li et al., 2022). Minimum ignition energy of 0.02 mJ and wide flammability range 4—75 vol% makes hydrogen prone to ignite (Li et al., 2022). Auto ignition temperature of 560˚ C means that hydrogen needs higher temperature for ignition compared to for example gasoline (Li et al., 2022).

Characteristics of hydrogen mentioned above can cause fire or explosion (Tukes, 2024). According to Tukes (2024), the severity of the accidents correlates with the amount of hydrogen leaked. Additionally based on the guide, the severity of the accident depends on if the ignition is immediate or delayed. It is stated that accumulation of hydrogen rises the concentration which can cause ignition. Therefore, a leak in confined space is more dangerous than in open space. Ammonia is toxic and corrosive substance and exposure to it can even cause death (Työterveyslaitos, 2025).

There are several techniques to minimize or prevent these safety issues. According to Tukes (2024) guide, pressurized hydrogen storage can be built underground to remove exposure to weather and physical damage that can cause explosions. Based on the guide, liquid hydrogen storage requires safety valves and boil-off regulation system to avoid pressure build up within the tank. Guide stated that, usage of inert gas – usually nitrogen – is required for the piping to prevent air-gas mixture formation. Hydrogen has characteristics that can cause static electricity and fires within the piping and therefore the storage system requires grounding (Tukes, 2024). For ammonia, sufficient ventilation is used to mitigate problems caused by leakages (Yang et al., 2025). Ammonia leakages can also be mitigated with water sprays as ammonia is soluble in water (Kojima, 2024).

In Finland safety and handling of hydrogen is regulated through various legislations (Tukes, 2024). According to Tukes (2024) these include, chemical safety legislation, environmental legislation, explosive atmospheres legislation, pressure equipment legislation, rescue legislation and land use and building legislation. These legislations with other relevant legislations and standards ensure safe handling of hydrogen in Finland.

2.3.3 Technical challenges

Technology readiness level indicates the maturity level of a technology. However, even if a technology has a high TRL, it does not necessarily mean it is optimal. All storage technologies have their own issues regarding system properties that affect their ability to maximize hydrogen storage capacity. The low volumetric density of hydrogen is the main reason for these different challenges. To mitigate the issue, high pressure and/or low temperature conditions are required to improve the volumetric density. These processes introduce technical challenges for storage affecting the applicability and efficiency of the hydrogen storage systems. Implementing pressurization and/or low temperature directly affect the price of the storage solutions.

As stated in chapter 2.1 compressing hydrogen gas to 700 bars improves the volumetric energy density approximately 50 times. This improvement comes with drawbacks regarding the storage system, safety and efficiency. According to Bhuiyan et al. (2025) these challenges involve overall safety, material fatigue and leakage. They state that high pressure poses risk for explosions and material fatigue, whereas small size of hydrogen poses risk for leakage. To mitigate these challenges the storage tank materials and leakage detection systems need to be chosen correctly (Bhuiyan et al., 2025). According to Hassan et al. (2023), compressed storage tanks require high-strength materials that can be often expensive and/or hard to manufacture. These materials should also be lightweight and able to withstand diffusion and hydrogen embrittlement (Usman, 2022). Compared to other storage methods, compressed hydrogen occupies larger volumes within the tanks and therefore limits the amount of hydrogen stored (Hassan et al. 2023). Another challenge comes from energy required to pressurize hydrogen which is around 13—18 % as stated in Chapter 2.2.

While underground hydrogen storage (UHS) offers large storage volumes they have also challenges. According to Alfarge et al. (2025) challenges for UHS are well integrity, design and structure requirements, purity of extracted hydrogen and chemical reactions. Based on their research, well integrity is crucial factor and the UHS needs to be selected carefully to withstand various loads and corrosion. They state that, design and structure requirements involve suitable materials – steel and cement – to be used to protect from hydrogen leakages. Hydrogen stored in UHS is prone to get mixed with other substances negatively affecting its purity (Alfarge et al., 2025). Lastly, UHS storages have issues regarding chemical reactions where the hydrogen is chemically reacting with other gases, forming toxic compounds and these compounds can be corrosive and damage the well (Alfarge et al., 2025). LRC tackles most of the problems present in the other UHS technologies (Masoudi et al., 2024). Lining used in LRC reduces the risk of leakage, enhances purity and provides overall structural strength making it good choice as a UHS storage (Masoudi et al., 2024).

Liquification is other method used to improve the volumetric energy density of hydrogen. As stated in Chapter 2.1 liquifying hydrogen improves the volumetric energy density approximately 100 times. Liquifying hydrogen by cooling it down to -253˚C creates challenges with insulation of the tank, energy consumption and boil-off (Bhuiyan et al., 2025). Energy consumption and boil-off can be mitigated by using high performance insulation materials (Simanullang, 2025). Proper insulation reduces heat transfer which lowers the power required to cool the hydrogen while also reducing boil-off phenomena (Simanullang, 2025). According to Usman (2022), cooling of hydrogen is energy intensive process. Approximately 30 – 40 % of hydrogens lower heating value is used in the cool down process (Usman, 2022). Waste heat, for example, can be used as an energy source for this (Hassan et al., 2023).

Boil-off gas is a phenomenon where the temperature of liquid hydrogen rises causing it to gasify due to heat transfer from the environment (Simanullang, 2025). According to Morales-Ospino et al. (2023), in context of hydrogen this can be called boil-off hydrogen (BOH). They state that there are also other reasons that cause BOH involving ortho- to para hydrogen conversion, sloshing and flashing. According to them, these BOH losses are result of atomical level movement and movement while. Size of the tank can significantly reduce the amount of BOH (Morales-Ospino et al., 2023). The BOH can cause daily losses of around 3 % (Usman, 2022). According to Morales-Ospino et al. (2023), BOH phenomena also causes rise of pressure inside the tank. They state that overpressure can be managed by venting to atmosphere but there are other techniques – reliquification and compression – that eliminates wasting fuel.

As stated in Chapter 2.2.3.2. limitations with LOHCs are the hydrogenation and dehydrogenation temperatures. According to Lin & Bagnato (2024), dehydrogenation process requires 25—30 % of the lower heating value of the stored hydrogen while the same amount of energy is released during the hydrogenation process. Dehydrogenation temperatures are more crucial for the system than the hydrogenation temperatures (Lin & Bagnato, 2024). Their research suggests that dehydrogenation process requires temperatures ranging from 50—420˚C while most of the carriers had temperatures above 300˚C. Achieving these temperatures without external source of energy leads to additional hydrogen being used as an energy source further increasing the energy demand (Lin & Bagnato., 2024). Various catalysts are being studied to reduce the energy needed for dehydrogenation (Lin & Bagnato., 2024).

While LOHC suffers from dehydrogenation temperatures, other material-based storages, for example metal hydrides suffer from desorption temperatures. As stated in Chapter

2.2.3.1 desorption is the reaction where hydrogen is released from the surface of the storage material. According to Klopčič et al. (2023), high desorption temperatures cause similar problems as dehydrogenation. High temperatures required for desorption limits the applicability of these technologies for mobile applications (Klopčič et al., 2023). PEM fuel cells cannot be used since the waste heat from them is not adequate (Klopčič et.al., 2023). Enhancing the hydride is possible by using different catalyst options, further changing the characteristics (Klopčič et.al., 2023).

2.3.4 Applicability

As stated in chapter 2.2 there are various storage types for hydrogen. All these storage types have their own advantages and disadvantages (Bhuiyan et al., 2025). These characteristics results in different storage options being best fit for different applications (Hassan et al., 2021). Table 4 summarizes suitable applications for different storage types based on the research of Hassan et al. (2021).

Table 4. Suitable applications for different hydrogen storage type (adapted from Hassan et al., 2021).

Storage type	**Application**
Compressed type I	Stationary
Compressed type II	Stationary
Compressed type III	Mobile
Compressed type IV	Mobile
Liquid hydrogen	Aerospace

Storage type	Application
Cryo-compressed	Mobile
MOFs	Stationary Mobile (near targets)
Elemental hydrides	Stationary
Intermetallic hydrides	Stationary applications
Complex hydrides	Stationary applications
Chemical hydrides	Energy/hydrogen carrier

As can be seen from the Table 4 above, the suitable applications can be divided roughly into stationary and mobile applications. Stationary applications have less requirements for the storage system than mobile applications and therefore more storage options are available (Hassan et al., 2021).

In their research Hassan et al. (2021, p. 4) state, “Transportation applications require high gravimetric and volumetric capacities, moderate working pressure and temperature, fast kinetics, less heat during uptake and release, multi cycle reversibility, high safety and less infrastructure expenditure for recharge and recycling”, while the same applies for mobile applications. According to Usman (2022), stationary applications are less challenging and the main concern for stationary applications is the volume not the weight or size.

For stationary applications best options are compressed hydrogen, MOF, and metal hydrides as can be seen in the Table 4. As stated in chapter 2.2.1.1. compressed storage types I and II are usually large and heavy while UHS are naturally stationary. MOFs require high pressure and cryogenic conditions to be efficient enough and therefore are more suitable for stationary applications or vehicles near targets (Hassan et al., 2021). While metal hydrides are safe and have moderate operating temperatures, they suffer from weight, slow kinetics and high dehydrogenation temperatures and are therefore better suited for stationary applications (Hassan et al., 2021).

For transportational and mobile applications there are less storage options because of the requirements mentioned by Hassan et al. (2021) cited in the previous paragraph. According to Hassan et al. (2021), compressed type III and IV storages have high gravimetric energy density due to high pressure resistance and light weight. Especially type IV storage is favored in mobile applications (Hassan et al., 2021). Toyota and Hyundai are utilizing type IV tanks for their fuel cell vehicles running on compressed hydrogen (Usman, 2022). According to Hassan et al. (2021), chemical hydrides such as LOHCs and ammonia are potentially good hydrogen carriers. They state that due to high gravimetric densities and easy hydrogen release they are good option for long distance transport and offer cheaper options compared to liquid hydrogen. They also regard cryo-compression as a good option for mobile applications. By combining both cryogenic conditions and moderate pressure cryo-compressed storage can be optimized and therefore for example BMW have adopted this technology for their hydrogen cars (Hassan et al., 2021). Verne also utilizes cryo-compression in its heavy-duty trucks (Verne, 2024).

In their research Hassan et al. (2021) regards liquid hydrogen storage suitable for aerospace applications. In aerospace applications high gravimetric and volumetric densities are required and therefore high energy consumption is not considered as a barrier (Hassan et al., 2021). As stated in chapter 2.2.1.2. liquid hydrogen can be used for both stationery and mobile applications. In his research Simanullang (2025), divides liquid hydrogen storage into stationery, mobile and onboard tanks. He mentions that both stationery and partially mobile tanks are used in aerospace industry whereas mobile tanks are used to transport hydrogen over large distances by NASA as well as between continents by carrier ship. Other than that, liquid hydrogen storage is utilized for on board applications for example H2FLY and Daimler trucks (Simanullang, 2025).

2.4 Economic status of hydrogen and hydrogen storage technologies

Similarly to previous chapter, this chapter focuses on the current economic status of hydrogen storage technologies. This chapter handles economic status of hydrogen and hydrogen storages through demand, levelized cost of hydrogen, levelized cost of hydrogen storage.

2.4.1 Demand and supply

Hydrogen demand is rising in the coming decades (Jayawardhana et al., 2025). Hydrogen storages are needed to balance the variation of production caused by renewable energy sources such as wind and solar (Irena, n.d.). Additionally, to being used as storage in energy sector, hydrogen storage has demand for vehicular applications (Hamedani et al., 2024). Hydrogen storage is key enabler for hydrogen implementation in vehicular applications, but it has its drawbacks that needs to be overcome (U.S. Department of Energy, n.d.).

According to European Hydrogen Observatory (2025), in 2024 hydrogen demand in Europe was 7872 kt. 58 % of hydrogen is used in refineries and 25 % is used in ammonia production followed by the methanol production and chemical industry with 11 % (Hydrogen Observatory, 2025). Other end users listed include industrial heat, steel production and mobile applications (Hydrogen Observatory, 2025). By 2030 Europe’s hydrogen demand would be approximately 10 Mt and by 2050 42 Mt (European Hydrogen Observatory, n.d.). Europe has strategic aims to produce 10 Mt of renewable hydrogen and another 10 Mt of hydrogen for import (European Commission, n.d.a). Based on their study Jayawardhana et al. (2025) projects green hydrogen demand in

Europe to reach 5.376 Mt, so just over 50 % of the initial target. They state that clearer legislation needs to be executed to support the development of hydrogen transition and thus meet the targets set by 2030. They suggest that more realistic timeframe would be meeting these targets by 2040.

Nordic countries are set to be major contributors of European hydrogen in the coming decades (Nordic Energy Research, 2024). According to European Hydrogen Observatory (2025), in 2024 Nordic hydrogen demand was 496 kt. Raising demand of green hydrogen in Europe means more production is needed. In Finland and Sweden, the wind capacity has potential to exceed national demand in the coming decades and therefore contribute to production of green hydrogen for import (Nordic hydrogen route, n.d.). According to *Nordic Hydrogen – Poised for Lift-off, but Still on the Runway* (2025), also Denmark is set to be one of the key players producing green hydrogen with its large capacity of wind power. In the article Norway is also mentioned for its highest available renewable energy capacity in Europe from hydro power. The expected hydrogen demand in Bothnia Bay region is expected to be 65 TWh or 1.95 Mt by 2050 (Nordic hydrogen route, n.d.).

Within Nordic countries Finland has substantial potential to be one of the leading countries when it comes to hydrogen (Valtioneuvosto, 2023). In 2024 Finland consumed approximately 156 kt of hydrogen (European Hydrogen Observatory, 2025). According to Jayawardhana et al. (2025), most of the hydrogen is made of natural gas and around 88 % is consumed by biofuel- and oil processing. They state that by 2030 steel industry would dominate hydrogen demand and after 2030 e-fuel production will take the lead. Finnish government made resolution in 2023 on hydrogen stating that Finland could produce 10 % of EUs total green hydrogen demand in 2030 (Valtioneuvosto, 2023). According to research made by Jayawardhana et al. (2025), Finland expects over 5 GW electrolyser capacity by 2030. This would mean that Finland reaches around 8 % of the EU’s 40 GW electrolyser target. Jayawardhana et al. (2025) study suggests that even though the target of 10 % is almost reached the end-products would be P2X products and green steel instead of direct supply to Europe. Hydrogen has the potential to be significant business opportunity for Finland (Business Finland, 2024). According to Business Finland (2024), by 2035 hydrogen economy could bring revenue of 34 billion € and by 2045 approximately 69 billion €. In 2024 Finland's GDP was 276 billion € according to Tilastokeskus (2025), and therefore projected revenues from hydrogen would be significant to Finnish economy.

2.4.2 Levelized cost of hydrogen

Levelized cost of hydrogen (LCOH) is one way to evaluate economic viability of hydrogen. Levelized cost is used to calculate the overall cost of electricity generated during the lifetime of the generating system and used to compare different technologies (Li et al., 2025). While this study focuses more on the cost of storage for hydrogen, it is necessary to understand where it is coming from, and that there are other aspects affecting the overall economic viability of hydrogen.

Levelized cost of hydrogen is adapted from the formula of levelized cost of electricity (LCOE) (Li et al., 2025). They have used equation (1) as an example in their study.

$$LCOE = \frac{I_0 + \sum_{t=1}^{N} \frac{A_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{M_t}{(1+r)^t}} \tag{1}$$

In the equation (1) I_0 is the initial investment, also known as CAPEX. A_t is the annual operating cost also known as OPEX. M_t is the annual electricity generation. N is the total years of usage and t the set year. Discount rate is defined as r. The unit can vary depending on the input units used, for example, €/MWh.

$$LCOH = \frac{COST_{Initial} + \sum_{t=1}^{N} \frac{COST_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{Q_{ht}}{(1+r)^t}} \tag{2}$$

Equation (2) illustrates the LCOH as used by (Li et al., 2025). Same elements are present in the levelized cost of hydrogen as in LCOE. $COST_{initial}$ represents the initial investment also known as CAPEX. This is the amount of capital invested to the said project in the start (Li et al., 2025). $COST_t$ represents here the annual operating and maintenance costs. This includes not only the cost of operation and maintenance but also the cost of raw materials (Li et al., 2025). Q_{ht} is the annual hydrogen produced in kg (Li et al., 2025). The *N, t* and *r* are the same as in equation (1). Therefore, LCOH is expressed as € per kg.

Levelized cost of hydrogen varies from case to case and hydrogen production type changes LCOH significantly. There are multiple colours of hydrogen each with different production methods affecting the LCOH calculations. In his thesis Arachchi (2024), has calculated LCOH values for different production methods in Finland. His calculations show values for five different cases. Two of which are green, one turquoise, one grey and one blue. Arachchi (2024), study shows that green hydrogen production is the most expensive with values of 6.56 /$\mathrm{kgH_2}$ for grid powered electrolysis and 5.82 €/$\mathrm{kgH_2}$ for wind powered electrolysis. By 2030 LCOH in Sweden and Denmark is projected to be 4—7 €/$\mathrm{kgH_2}$ and 4—6 €/$\mathrm{kgH_2}$in Norway (*Nordic Hydrogen – Poised for Lift-off, but Still on the Runway,* 2025). Based on Arachchi (2024) thesis, turquoise hydrogen had LCOH of 4.75 €/$\mathrm{kgH_2}$ with the thermal decomposition of methane production and grey hydrogen had the lowest LCOH with 3.69 €/$\mathrm{kgH_2}$ produced with steam methane reforming. With the additional carbon capture system steam methane reforming plant produced blue hydrogen with LCOH of 4.02 €/$\mathrm{kgH_2}$(Arachchi, 2024).

2.4.3 Levelized cost of hydrogen storage

Levelized cost of hydrogen storage (LCHS) indicates how much the storage technology costs per kg of hydrogen over the project’s lifetime (Abdin et al., 2022). Levelized cost of hydrogen storage is abbreviated also as LCOHS or LCOS depending on the literature (Lou et al. 2026; León et al., 2024). According to Abdin et al. (2022, p. 3), LCHS is the “net present cost of the storage system divided by its cumulative hydrogen storage over the plant's entire lifetime.” They calculated LCHS values for seven different storage types in their research by using equation (3).

$$LCHS = \frac{C_{CapEx} + \sum_{n}^{N} \frac{(C_{OpEx} + C_{DeCom})}{(1+i)^n}}{\sum_{n}^{N} \frac{M_{H_2}}{(1+i)^n}}. \qquad (3)$$

In equation (3), numerator illustrates the net present value. It consists of C_{CapEx} that is the initial capital investment (Abdin et al., 2022). C_{OpEx} and C_{DeCom} (operation cost and decommissioning cost) form the annual cost for operation and maintenance (Abdin et al., 2022). N is the lifetime while n is the number of years and i is the interest rate (Abdin et al., 2022).

In their study Abdin et al. (2022), they have compared different stationary hydrogen storage applications by projecting LCHS. They have compared compressed, liquified, salt cavern (compressed), metal hydride, LOHC, ammonia and methanol storage technologies. Their study illustrates how storage efficiency, CAPEX, OPEX per storage cycle, storage cycle and storage time affect the LCHS. Their calculations use fixed values of 5000 tonnes as installed capacity and 4000 tonnes as capacity per storage cycle to get comparable results. Storage size is a parameter affecting the LCHS but for the sake of comparison fixed value is needed.

One key parameter affecting the LCHS in Abdin et al. (2022)’s study is the efficiency of the storage system. Their study suggests that by improving efficiency, the storage system OPEX can be greatly reduced. It is stated that this is due to the decrease in the energy required for storing. Their study illustrates that compressed gas storage has the highest efficiency while ammonia and methanol have the lowest. Their study indicates that even though liquid, metal hydride and LOHC have less efficiency than compressed hydrogen storage there are ways to improve it.

CAPEX is another key parameter affecting the LCHS (Abdin et al., 2022). According to Abdin et al. (2022), CAPEX consists mainly of system components. Their study shows that ammonia, methanol and liquified hydrogen storages are the most expensive CAPEX wise while compressed storages are the cheapest option. They suggest that storage system complexity due to hydrogenation and dehydrogenation properties of said storages results in high CAPEX. Based on their study salt cavern storage is clearly the cheapest option and LOHC is close second, but there is uncertainty due to it being immature technology.

OPEX is the yearly cost component of LCHS (Abdin et al., 2022). According to Abdin et al. (2022), OPEX is significantly affecting LCHS. Their study indicates that OPEX is divided into variable and fixed cost with a ratio of approximately 70/30. Their study suggests that fixed costs are greatly influenced by the CAPEX while the utility cost is the main component of the variable cost. Results of their calculations show that OPEX costs follow the same pattern as CAPEX costs between the storage technologies compared. They state this to be the result of energy intensive storage processes.

Abdin et al. (2022), research suggests that storage cycle and time are greatly affecting OPEX and LCHS. The results show that longer storage cycle length drastically decreases the OPEX while simultaneously raising the LCHS. They state that it is due to variable OPEX cost decreasing due to less hydrogen stored over the lifetime. For the LCHS the storage cycle works other way around since daily cycle means more hydrogen stored in the same timeframe and thus distributes the lifetime cost over a larger amount of hydrogen (Abdin et al., (2022). Based on the results Abdin et al. (2022) state that hydrogen storage is very expensive as long-term storage.

Table 5. LCHS of hydrogen storages (adapted from Abdin et al., 2022).

Storage type	**LCHS ($/kg) Daily cycle**	**LCHS ($/kg) 4-week cycle**
Compressed	~0.33	~25

Storage type	LCHS ($/kg) Daily cycle	LCHS ($/kg) 4-week cycle
Salt cavern	~0.14	~3
Liquid	~0.94	~61
Metal hydride	~0.7	~44
LOHC	~1.2	~16
Ammonia	~3.51	~137
Methanol	~2.25	~104

Table 5 shows the LCHS values for different hydrogen storage types calculated in their study by Abdin et al. (2022). While these LCHS values cannot be used straight in assessing LCHS in Finland and Nordics they indicate the variation between the storage types. Since LCHS is calculated with equation (3) it varies between projects due to different parameters used. Abdin et al. (2022) study offers anyhow valuable insight into comparable LCHS data. This data is valuable to this thesis where qualitative differences of the different storage applications are compared and analyzed.

In their study Abdin et al. (2022) project that in the future the LCHS would go down. Their explanation for this is that hydrogen storage is relatively new technology and the learning rate would go up in the coming decades. Based on this they state that the CAPEX would go down thus decreasing LCHS. Their projections show decrease of approximately 0.5 $/kg of LCHS for daily cycle. Storage technologies that have higher LCHS would have more significant decrease in the LCHS in the future (Abdin et al., 2022).

Abdin et al. (2022) state that energy demand is another crucial factor that influences LCHS. They project that reducing energy demand of the discharging process would improve the efficiency of the storage technologies and lower the LCHS. They state that energy demand influences OPEX and thus reducing it would lower the LCHS, especially for the ammonia and methanol which suffers from large energy demand during discharge.

3 Research methodology

Research part of this thesis consists of two real life case projects demonstrating viability of hydrogen storages in Finland and in Nordics. After demonstrating these cases economic calculations and analysis is made to analyze and compare the feasibility of these hydrogen storage technologies in Finland and in Nordics.

Economic calculations in this thesis are based on the two existing projects in Nordics. The calculations consist of NPV, IRR and PBP calculations and sensitivity analysis for the first two. Due to lack of actual project data, assumptions are made and therefore the calculations are estimations of similar projects and their feasibilities.

3.1 Net Present Value, Internal Rate of Return and Pay Back Period

Net present value (NPV) is one of the most widely used formula when assessing storage project profitability. According to Lin et al. (2024), NPV model is more applicable to energy storage projects than LCOE. Therefore, NPV is used in this thesis to assess the profitability of hydrogen storage projects. NPV describes the time value of money over the project lifetime considering future risks, capital costs, future cash flows and cost of equity and debt (Lin et al., 2024). NPV values over zero are considered profitable projects and higher NPV indicate higher the profit (Lin et al., 2024). Therefore, NPV is valuable tool in decision making when choosing if the project is worth considering or not.

$$NPV = -C_{inv} + \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{4}$$

Equation 4 adapted from Lin et al. (2024) describes the NPV formula used in the research where $-C_{inv}$ is the total capital investment, n is, the project lifetime, t is the given year, R_t is the yearly revenue and i is the discount rate. NPV sums yearly discounted revenues and subtract capital investment cost from the summed-up revenues.

$$R_t = (H_{2,sold} - H_{2,bought} - OPEX) * (1 - Tax\ rate) \qquad (5)$$

Revenues are calculated with equation 5 adapted from Lin et al. (2024), by subtracting bought hydrogen and OPEX from sold hydrogen, and multiplied by correcting parameter where tax rate is considered. OPEX includes both fixed O&M costs and variable electricity costs.

Internal rate of return (IRR) is the discount rate that causes NPV to go to zero (Lin et al., 2024). Therefore, IRR needs to be higher than the discount rate for the NPV to be positive and for the project to be profitable (Lin et al., 2024). In this thesis IRR needs to be calculated with annuity for there are different lifetimes for different components. Equation 6 describes the relation between NPV and IRR.

$$NPV = -C_{inv} + \sum_{t=0}^{n} \frac{R_t}{(1+IRR)^t} = 0 \qquad (6)$$

Payback period for a project can be calculated discounted or undiscounted. Payback period describes the time required for the project to pay back the initial investment costs (Mensah et al., 2024). Discounted payback period is used in this thesis because it uses the same discounted cashflows as the NPV calculation.

3.2 Component cost parameters

Due to LRC and HRS being very different technologies the cost parameters will differ between the two. Therefore, parameters for these two technologies are discussed in their separate sub-chapters.

3.2.1 Lined rock cavern cost parameters

Cost parameters used in the NPV and IRR calculations for LRC are illustrated in Table 6. These parameters create capital and operational costs for the LRC.

Table 6. LRC economic calculation cost parameters.

Parameter	Unit	Value	Reference
CAPEX	€/kg	55.4	Vendt et al., (2022).
OPEX	% of CAPEX	2.0	Vendt et al., (2022).
Size	tons	500	Papadias, D., & Ahluwalia, R. (2021).
Cushion gas	%	8.0	Kanto, (2022).
$\mathbf{OPEX_{fix,comp}}$	% of comp CAPEX	4	Yousefi et al. (2023).
$\mathbf{OPEX_{var,comp}}$	€/kg	0.0795	Calculated
Electricity price	€/kWh	0.05	Nord pool (2025)
Compression power	kWh/kg	1.59	Weiss, R. & Ikäheimo, J. (2024)

As can be seen from the Table 6 CAPEX, OPEX and OPEX$_{\text{fix, comp}}$ values are dependent on the size of the storage tank. CAPEX value is multiplied with the size to get the initial cost of the storage, and OPEX and OPEX$_{\text{fix, comp}}$ are percentages of the initial cost. OPEX$_{\text{var, comp}}$ is calculated from electricity price and power required for the compression multiplied by the amount of hydrogen stored in a year.

Size of the storage tank is based on literature. Capacity of 500 tons is at the lower end of the spectrum in the literature, for example Kanto (2022). The amount of cushion gas is subtracted from the storage size to get the actual working gas cycle. The cushion gas ensures minimum pressure within the storage that is needed for the system to work properly (Kanto, 2022). Working gas cycle is then used in cashflow calculations.

The size of the storage used in the calculations is higher compared to one used in HYBRIT project. The calculations are used to estimate NPV and IRR values for larger LRC storage.

3.2.2 Hydrogen refuelling station cost parameters

Parameters used in the NPV and IRR calculations for HRS are illustrated in Table 7. All the values presented affect the initial capital and operational costs of HRS.

Table 7. HRS economic calculation cost parameters.

Parameter	Unit	Value	Reference
CAPEX	€/kg	100	Barhoumi et al. (2022).
OPEX	% of CAPEX	1.0	Barhoumi et al. (2022).
Tank capacity	kg	2200	Pagano, A. (2023).
$\mathbf{CAPEX_{comp}}$	€/kW	10800	Pagano, A. (2023).
$\mathbf{OPEX_{fix,comp}}$	% of CAPEX	4	Di Micco et.al. (2023).
$\mathbf{OPEX_{var,comp}}$	€/kg	0.15	Calculated
Electricity price	€/kWh	0.05	Nord pool (2025)
Compression power	kW	60	Pagano, A. (2023).
Compression work	kWh/kg	3	Pagano, A. (2023).
$\mathbf{CAPEX_{cooler}}$	€/kW	5374	Minutillo et al. (2021).
$\mathbf{OPEX_{fix,cooler}}$	% of CAPEX	3	Minutillo et al. (2021).
$\mathbf{OPEX_{var,cooler}}$	€/kg	0.015	Calculated
Cooling power	kW	5.5	Pagano, A. (2023).
Cooling work	kWh/kg	0.3	Pagano, A. (2023).
$\mathbf{CAPEX}_{\boldsymbol{disp}}$	€	65000	Minutillo et al. (2021).
$\mathbf{OPEX}_{\boldsymbol{disp}}$	% of CAPEX	3	Minutillo et al. (2021).
Land cost	€/m²	120	Maanmittauslaitos (2026)
Site size	m²	260	Stein et al. (2025).

As illustrated in the Table 7, HRS CAPEX and OPEX are dependent on the size of the storage tank. Size of the tank is based on reference literature where similar refueling capacity was used. $CAPEX_{comp}$ is multiplied with compressor power and $OPEX_{fix,\ comp}$ is then calculated as a percentage of the compressor initial cost. Same principle applies also for the cooler CAPEX and fixed OPEX. Dispenser CAPEX is fixed value and OPEX is calculated as a percentage of that. Variable OPEX for compressor and cooler is calculated by multiplying electricity price with the work required. This value is then multiplied by the yearly hydrogen demand illustrated in Table 9 to get the actual yearly variable OPEX.

Additionally, land cost is calculated for this HRS size. According to Stein et al. (2025), small HRS with one dispenser requires 260 m² as average. This is then multiplied by the land cost approximately 120 €/m².

3.3 Financial parameters

Deviating from component cost parameters, financial parameters are more similar between the LRC and HRS. There are few differences in each other and therefore the parameters are discussed in separate sub-chapters.

3.3.1 Lined rock cavern financial parameters

Table 8 illustrates the financial parameters used for the lined rock cavern NPV and IRR calculations.

Table 8. Lined rock cavern financial parameters.

Parameter	Unit	Value	Reference
Lifetime	years	30	Kanto, T. (2022).
Cycles	Per/year	10	Assumed
H_2 price spread	€/kg	1	Assumption
Tax rate	%	20	Vero.fi

Parameter	Unit	Value	Reference
WACC	%	8.0	Kanto, T. (2022).

Lifetime for the lined rock cavern project is assumed to be 30 years based on literature. Number of cycles depends on the supply and demand. In this thesis 10 cycles per year are assumed, approximately once a month.

H_2 price spread is assumed to be 1 €/kg. The price spread is the difference between bought/produced and sold hydrogen. As LRC is commonly used as a seasonal storage or as a balancing energy storage for the grid, hydrogen is stored at lower electricity prices and to minimize the cost when electricity price rises. Therefore, maximum profit is not intended in this calculation and price spread is kept low. Tax rate of 20 % is the corporate tax rate in Finland. WACC is used as the discount rate and derived from relevant literature referenced in Table 8.

3.3.2 Hydrogen refuelling station financial parameters

Financial parameters of hydrogen refuelling station NPV and IRR are presented in Table 9.

Table 9. Hydrogen refuelling station financial parameters.

Parameter	Unit	Value	Reference
Lifetime	years	20	Minutillo et.al. (2021).
Fleet size	Per day	30	Pagano, A. (2023).
HRS capacity	Kg/day	150	Pagano, A. (2023).
Total demand	Kg/year	54750	Calculated
H_2 price spread	€/kg	4	Assumption
Tax rate	%	20	Vero.fi
WACC	%	8.0	Minguez et.al. (2026).

HRS capacity is defined by multiplying average hydrogen fuel cell electric vehicle tank size by number of refueling vehicles per day. Average storage capacity for hydrogen fuel cell electric vehicles is 5 kg (Minutillo et al., 2021). Therefore, capacity of this thesis predicts 30 refueling vehicles per day. This number is quite high considering the current amount of hydrogen vehicles but is a commonly used figure in literature used to assess HRS feasibility. Yearly hydrogen demand is calculated by multiplying the daily capacity by 365 days. Utilization is 100 % for the base case.

Since HRS is more complex system compared to LRC hydrogen storage system, the CAPEX and OPEX cost per kg of stored hydrogen are much higher. In addition to the compressor, HRS system also consists of cooler/chiller and dispenser further adding to higher initial- and operational costs. Therefore, for the NPV to be positive the price spread needs to be higher. In this thesis 4 €/kg price spread is used as the baseline value. This value follows trends in literature, for example Pagano, A. (2023).

Lifetime of the HRS is assumed to be 20 years which is common figure in relevant literature. Tax rate and discount rate are same as the ones used for LRC calculations.

3.4 Data sources and assumptions

Most of the parameters used in the calculations are derived from scientific literature and few are assumed. Table 6 to Table 9 illustrate the references from where the data used in the calculations is derived. Lack of actual project data limited the available literature to ones clearly describing parameter values useful in this thesis. Relevant literature, especially for LRC, is dependent on only a few studies on the subject. For HRS there is broader range of research but only a few with relevant data useful in this thesis.

As stated earlier in chapter 3, assumptions were needed in assessing net present value, internal rate of return and payback period without actual project data.

NPV and IRR calculations for LRC required following assumptions:

- No salvage value is assumed.
- Compressor lifetime is 15 years, after which it’s replaced.
- Construction in year 0, production starts in year 1.
- WACC is used as the discount rate.
- No carbon emission compensation calculated.
- Electricity price is fixed.
- Hydrogen price assumed as price spread.
- Demand and supply are assumed to be maximum.
- No subsidies assumed.

NPV and IRR calculations for HRS required following assumptions:

- No salvage value is assumed.
- Cooler and dispenser lifetime is 15 years, after which they are replaced.
- Construction in year 0, production starts in year 1.
- WACC is used as the discount rate.
- No carbon emission compensation calculated.
- Electricity price is fixed.
- Hydrogen price assumed as price spread.
- Demand and supply are assumed to be maximum.
- No subsidies assumed.

Similar assumptions are used in the calculations for both cases except for the component lifetimes.

3.5 Sensitivity analysis method

After the initial calculations, sensitivity analysis of eight parameters affecting each storage type NPV and IRR is made. Sensitivity of each parameter is evaluated individually with a sensitivity spread of ± 10 %. A tornado chart is then created from the results to visually illustrate how changes in the parameters affect NPV and IRR values. The sensitivity analysis gives valuable insight into which parameters affect the storage project feasibility the most. The parameters used in the sensitivity analysis are listed in Table 10.

Table 10. Parameters used in sensitivity analysis.

Sensitivity analysis parameter	
Lined rock cavern	**Hydrogen refueling station**
CAPEX	CAPEX
OPEX	OPEX
Size	Tank size
WACC	WACC
Price spread	Price spread
Electricity price	Electricity price
Cycles	Utilization 90 %
Cushion	Utilization 80 %

As can be seen from Table 10, sensitivity parameters are similar for both cases. Since tank size doesn’t affect the amount of hydrogen going through the HRS in a year utilization percentage of the station is used to assess similar parameters as the cycles and size for the LRC.

4 Cases studies

In this thesis two types of hydrogen storages applicable in Finland and Nordics are studied. For underground, longer storage periods and larger volumes, LRC storage is selected and for aboveground, shorter storage periods and smaller volumes, compressed hydrogen storage is selected. Both technologies are already in use in Nordics and therefore they are the most meaningful to study.

4.1 Selection of cases

For this thesis, two cases are chosen to be studied based on few criteria. Most importantly, both cases are already implemented in Nordics and are therefore applicable, and within the scope of this thesis. Secondly there are lack of available cases within the framework of this thesis.

As stated, the two storage technologies are used in a different way. These different storage technology cases are selected to get broader, more insightful analysis on the subject. Both cases have similarities but also their own unique features allowing comparison between the two technologies. HYBRIT lined rock cavern project is chosen for the large-scale underground storage and Hynion/Vireon hydrogen refueling stations for the shorter and faster injection storage.

4.2 HYBRIT Lined rock cavern

According to Hybritdevelopement.se (2025), The HYBRIT Lined rock cavern hydrogen storage is a part of the HYBRIT project in Luleå, Sweden where LRC storage is a part of fossil-free steel production value chain. The project took place between 2019-2024 and was a joint venture of SSAB, LKAB and Vattenfall (Hybritdevelopement.se, 2025). The fossil-free steel production process utilizes green hydrogen instead of fossil coal to reduce the iron ore (Hybritdevelopement.se, 2025). By using green hydrogen to reduce the iron ore up to 90 % of the total carbon dioxide emissions of the steel production can be mitigated (Hybritdevelopement.se, 2025). Figure 8 shows an overview of the LRC storage system used in the HYBRIT project.

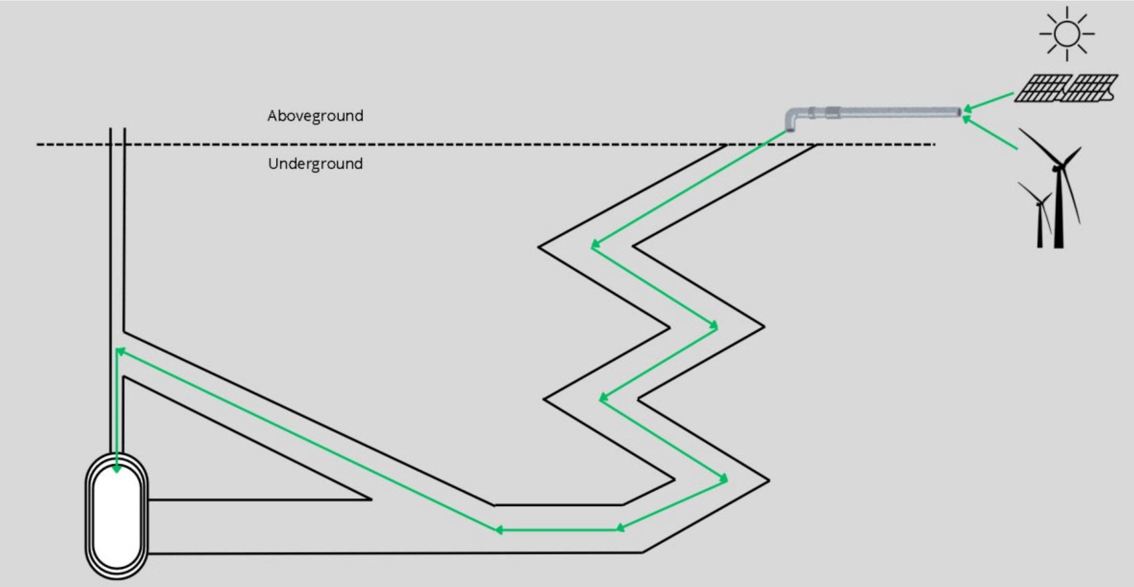

Figure 8. Overview of the LRC storage system used in Hybrit project (Adapted from Hybritdevelopement.se, 2025).

As stated by Hybritdevelopment.se (2025) and seen from Figure 8, In HYBRIT project the green hydrogen is produced 3 km away from the steel production facility with an electrolyzer and brought to the storage station via pipeline. The hydrogen storage is located underground in an excavated cavity and consists of inner steel liner, sliding layer and concrete layer. Transported hydrogen is pressurized from 7—9 bar to 250 bar storage pressure with compressor from on top of the vertical. The LRC is located 30 m underground and can hold up to 100 m^3 of hydrogen with a maximum capacity of 2000 kg.

While reducing carbon emission of steel production the pilot project also enabled testing of LRC storage and gave valuable data for future work (Hybritdevelopement.se, 2025). The project gathered almost 4000 hours of operational data and proved the functionality and performance of such technology (Hybritdevelopement.se, 2025). The design proved to be safe with no leakage during the testing and the mechanical stress test showed that the storage can last over 50 years (Hybritdevelopement.se, 2025).

According to Hybritdevelopement.se (2025), the LRC storage within the steel production value chain showed operational and economic benefits. Operational wise the LRC supports the end user as a buffer tank to ensure reliable supply and as a backup system in case of hydrogen production malfunction (Hybritdevelopement.se, 2025). This creates flexibility for the end user while also providing stability to the electricity grid (Hybritdevelopement.se, 2025). Economic benefits come from the flexibility to produce and store hydrogen depending on the electricity price. During periods of excess production of wind or solar energy it can be transformed into hydrogen and stored (Hybritdevelopement.se, 2025). This significantly decreases the variable operation cost up to 25—40 % (Hybritdevelopement.se, 2025).

HYBRIT project in Sweden has demonstrated the applicability of a LRC storage as a part of steel production. Based on this pilot project the future of LRC looks promising in the Nordics. In the future commercial large-scale RLC storage size can range from 50000 to $100000\mathrm{m}^3$(Hybritdevelopement.se, 2025). LRC storage offers large variety of end uses in the future not limiting only to steel production but also as an example large-scale energy storage.

4.3 Hynion & Vireon hydrogen refueling stations

Compressed hydrogen storage vessels are widely used in hydrogen refueling stations (HRS). In Finland and Nordics there are many companies and projects based on hydrogen refueling. Hynion has one working station in Høvik, Norway and other opening soon in Porsgrunn, Norway (Hynion, 2025a; Hynion, 2025b). In Finland Vireon built the first HRS in the summer of 2025 to Jyväskylä (Suomenvetylaakso, 2025; P2X Solutions, 2026).

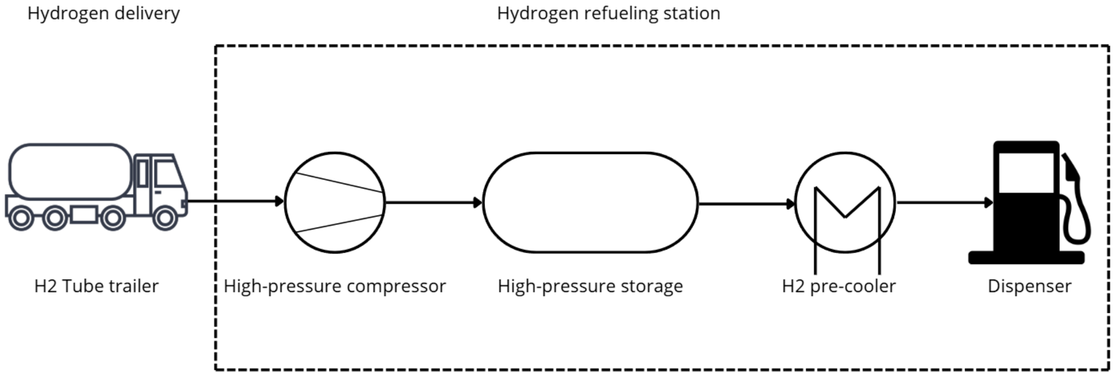

Figure 9. Schematic drawing of off-site hydrogen refueling station (adapted from Pagano, 2023).

HRS can be divided into two categories based on the hydrogen production method, on-site or off-site (Minguez et al., 2026). Figure 9 illustrates the simplified layout of the off-site HRS. General components of HRS are high-pressure compressor, storage tank, chiller and dispenser (Minguez et al., 2026), these components are presented in the schematic Figure 9. Depending on the end-user the hydrogen is dispensed at 350 bars or 700 bars (Minguez et al., 2026). This defines also the storage pressure either 500 bars or 900 bars (Minguez et al., 2026). Dispensing pressure of 350 bars is used for heavy-duty vehicles like buses or trucks whereas 700 bar pressure is used for regular passenger cars (Minguez et al., 2026).

Hynions HRS in Høvik operates at 700 bars (Hynion, 2025a). It serves both passenger cars and heavy-duty vehicles with a dispensing capacity of 200 kg/day (Hynion, 2025a). According to press release by Hynion (2025c), Høvik HRS is temporarily closed. The press release describes this to be outcome of hard market conditions affected by the political and financial landscape. Vireon HRS in Jyväskylä is in pilot phase where it supplies hydrogen to busses and limited number of passenger vehicles (P2X Solutions, 2026). According to Blekhman (2024, Forbes) Vireon's standard HRS design includes three tube trailers, medium and high-pressure storages, compressor, cooler and two dispensers. Based on the article the stations can dispense hydrogen at pressures of 350 bar and 700 bar. Since the design involves tube trailers as the supply method these stations are off-site production HRS’s. Current supplier of the hydrogen to Jyväskylä HRS is P2X Solutions whose hydrogen is produced in Harjavalta production plant (P2X Solutions, 2026). In the next phase of the Jyväskylä Hydrogen Hub a 5 MW electrolyzer with a production capacity of 700 tons per year will be built in the same site as the HRS (Vireon, 2024). This enables direct supply of hydrogen without the need for transportation via tube trailers. According to Blekhman (2024, Forbes) Vireon’s strategy in Finland involves three more HRS in Vantaa, Liminka and Tornio. Based on the article these four stations would create a 750 km long corridor from Helsinki to Tornio providing sufficient refuelling distances. This corridor would link Finland to be part of the Nordic hydrogen network (Helen, 2024, April 18). Letter of intent signed by Vireon and Helen aims to build a heavy-duty hydrogen refuelling station next to Helen’s Vuosaari production plant (Helen, 2024, April 18).

5 Results and analysis

This chapter presents the results of the economical calculations defined in chapter 3. The results illustrate key economic parameters to evaluate the feasibility of the selected storage types. In chapter 5.1.1 NPV, IRR and PBP results for LRC storage are presented where as in chapter 5.1.2 NPV, IRR and PBP results for HRS are presented. Chapter 5.2 sums up the technologies mentioned in the chapter 2.2 to provide further feasibility analysis. In chapter 5.3 sensitivity analysis for both NPV and IRR are presented for both LRC and HRS. The differences, constraints and simplifications between the reference case projects defined in chapter 4. and the calculations are discussed further in chapter 6.

5.1 Net present value, internal rate of return and payback period

NPV, IRR and PBP are essential economic parameters when assessing feasibility of hydrogen storages and are therefore straightly linked to the objectives of this thesis. From the formulas defined in chapter 3.1 and parameters defined in chapter 3.2 and 3.3 following results have been calculated.

5.1.1 NPV, IRR and PBP of LRC

For the LRC hydrogen storage the calculated NPV resulted in 2811889.87 €. The yearly revenue of 2815005.02 € was discounted over every year of the project which resulted in positive NPV. Figure 10 illustrates the cumulation of the NPV during the project's lifetime. Year 0 was the construction year, and the summed-up CAPEX was 27700000 €. As can be seen the value of money was higher in the first years of the project and declined every year since then. After year 15 the NPV went down because of replacing the compressor which resulted in negative revenue. The NPV went above 0 after year 22 so therefore the discounted payback period for the LRC in this case is 23 years when rounded up. Breakeven point of the price spread was 0.93 €.

IRR calculated with annuity resulted in 9.05 %. IRR value higher than the discount rate – in this thesis WACC – which means the project is profitable and generating value. Calculated IRR value is quite close to the discount rate value which is explained by the price spread being close to the break-even value of price spread.

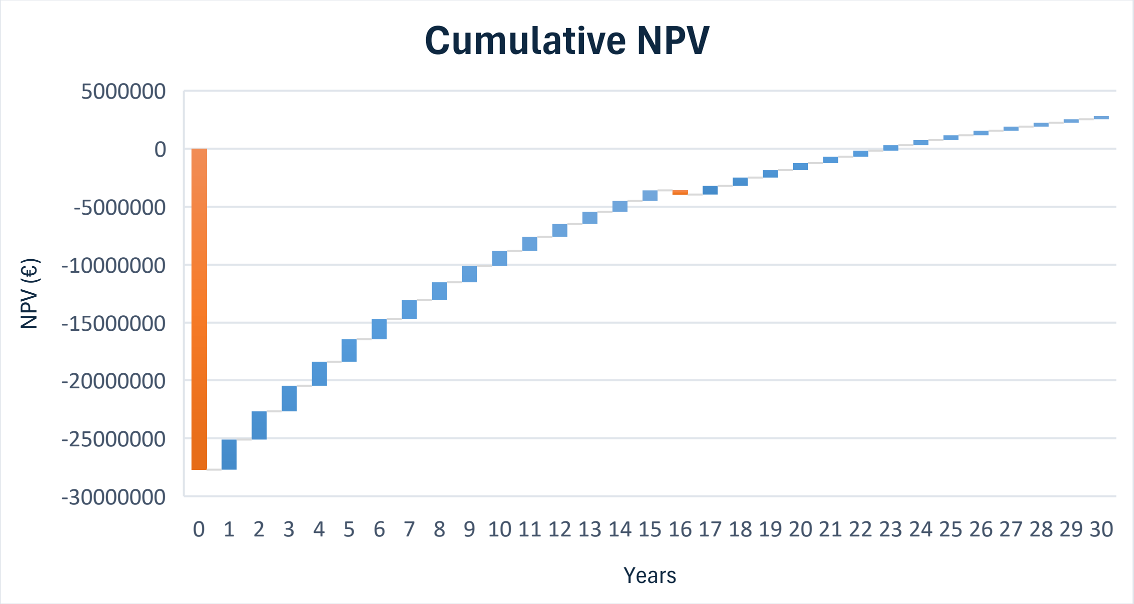

Figure 10. LRC Cumulative NPV.

5.1.2 NPV, IRR and PBP of HRS

For the HRS hydrogen storage the calculated NPV resulted in 384676.35 €. Yearly revenue calculated from the cashflows resulted in 143207.6€. This yearly revenue discounted over the whole project lifetime results in positive NPV value. In Figure 11 the cumulative NPV curve is presented. As in the LRC, year 0 illustrates the summed-up CAPEX 993757€. At year 1 when the project starts, the cumulation of the discounted revenues starts to build up. Also, in this calculation cooler and dispenser needed replacement after 15 years, which explains the smaller revenue in year 16. As can be seen from the NPV curve in Figure 11 the value goes positive before year 11 so therefore the discounted payback period for this project was approximately 11 years. Breakeven point for the price spread was 3.11 €

IRR calculated with annuity resulted in 13.07 %. IRR value is much higher than the discount rate – in this thesis WACC – which means the project is profitable and generating value. High IRR value compared to LRC calculations is explained by the bigger difference between the price spread and the break-even price spread.

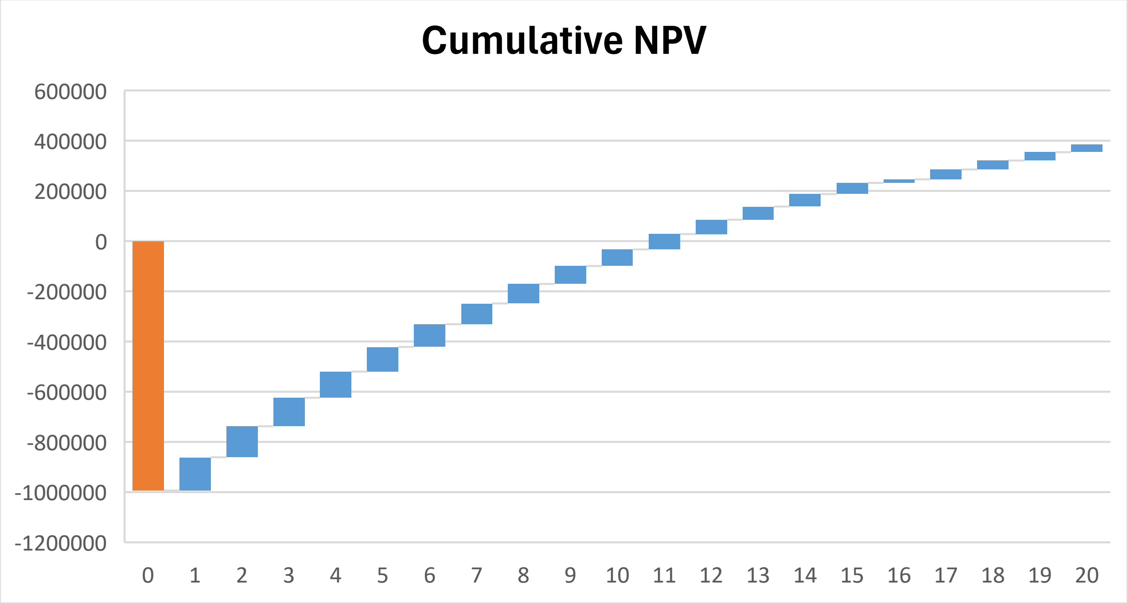

Figure 11. HRS Cumulative NPV.

5.2 Comparison of technologies

As illustrated in chapter 2.2 there are many different types of storage options for storing hydrogen. None of these options are perfect and all of them have their own drawbacks. Main attributes of different storage options discussed from chapter 2.2 to chapter 2.4 are collected in Table 11.

Table 11. Hydrogen storage technology parameter comparison.

Storage technology	**Gravimetric capacity (wt%)**	**Volumetric density (kg/m^3)**	**Pressure (bar)**	**Temperature (°C)**	**Energy loss (%)**	**Application**	**TRL**
Compressed gas	4—5	~25—30	150—700	atm	13—18	S & M	11
UHS	4—5	~25—30	50—300	atm	13—18	S	3—10
Liquid hydrogen	~7	~70—80	atm	-253	30—40	M	9
Cryo-compressed	~7—8	~80—100	250—350	-253	n.d.	M	9
Metal hydrides	1—7	~80—100	n.d.	30—350	n.d.	S	4—5
LOHC	5—7	~50—60	1	150—325	n.d.	M	6—7
Ammonia	17.8	~107	1—7	-33—20	30	M	11
Ammonia borane	19.6	n.d.	n.d.	atm	n.d.	M	3—4
Carbon based materials	5	~38.5	30—60	-200	0	nano	2—3
Zeolites	2.55	~20	15—40	-200	0	n.d.	2—3
MOF	5—10	~40—60	80	-200	0	S & M	2—3
Glass microspheres	2.3	~36	10	200	0	M	n.d.

In Table 11, applications are defined as stationary (S) or mobile (M).

Most desired attributes for hydrogen storage are high gravimetric capacity and volumetric density. On the other hand, TRL cannot be overlooked when deciding storage options that can be applied. Therefore, based on Table 11, best options for hydrogen storage would be compressed, UHS, liquified, cry-compressed or ammonia. These can be further narrowed down based on the desired application and other attributes like energy loss, temperatures, pressures etc. For this thesis compressed and LRC storage were chosen as they have proven applications in use in the Nordics. Both applications are considered as stationery which supports the choice for these storage types. Liquid cryo-compressed and ammonia would be good options for mobile or transportational applications but were not chosen for this thesis. Compressed hydrogen storage is one of the cheapest options as can be seen in the Table 5, and while LRC is not as cheap of an option it is the only available UHS in the Nordics and Finland.

Hydrogen storage technologies are rapidly developing and in the future the applicability of the different options mentioned in the Table 11 might be substantially increased. Especially, metal hydrides and LOHC have good potential due to relatively high TRL numbers.

5.3 NPV and IRR sensitivity analysis

As stated in chapter 3, sensitivity analysis is used to illustrate how the change in parameters affects the NPV and IRR values. Figure 12 illustrates the NPV sensitivity for LRC and Figure 13 shows the NPV sensitivity for HRS. The figures illustrate how much ± 10 % change in each parameter affects the baseline NPV value. As can be seen from Figure 12 and Figure 13 there are 2 different parameters between the two storage options due to differences between the two storage technologies.

Four parameters affecting LRC NPV the most were price spread, cycles, CAPEX and WACC and NPV calculations were therefore highly sensitive to those parameters. Parameters affecting NPV the least were cushion and electricity price. Price spread, number of cycles and CAPEX were the only parameters where the -10 % change caused NPV to go below 0. In such cases the project would not be considered profitable. Breakeven point of the price spread was 0.93 €. Figure 12 clearly shows that price spread, cycles and size are parameters that causes the NPV to decrease when the parameter values decrease. Reducing these parameters causes decrease in the amount and price of hydrogen therefore affecting negatively on yearly revenue. For the other parameters this logic worked vice versa.

For the HRS NPV sensitivity analysis, utilization percentage was chosen as one of the parameters. 80 % utilization, price spread, and 90 % utilization were parameters affecting NPV the most followed by CAPEX and WACC. Parameters affecting NPV the least were OPEX and electricity price. As can be seen from the Figure 13, NPV in this case doesn't go below zero with any parameter. Breakeven point for the price spread was 3.11 € indicating higher system cost compared to LRC. Similarly to LRC sensitivity analysis, utilization and price spread were the only parameters that decreased the NPV as the value of the parameter decreased in the HRS. As for the LRC, decreasing these parameters causes the revenue to decrease as well.

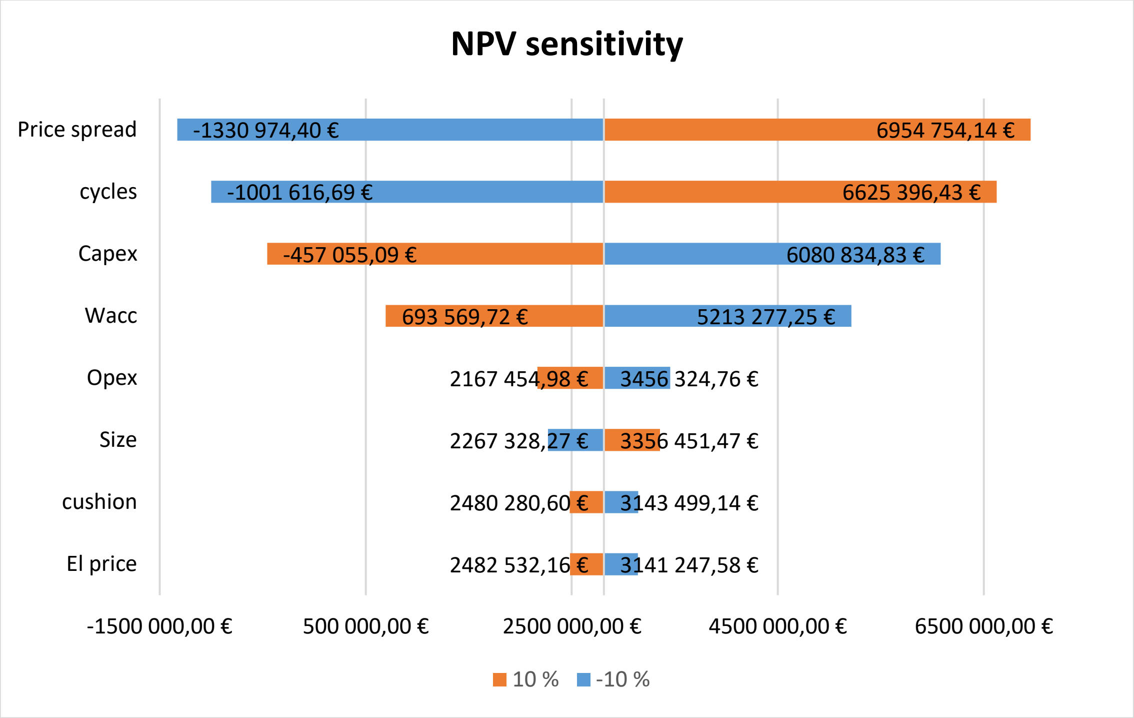

Figure 12. LRC NPV sensitivity.

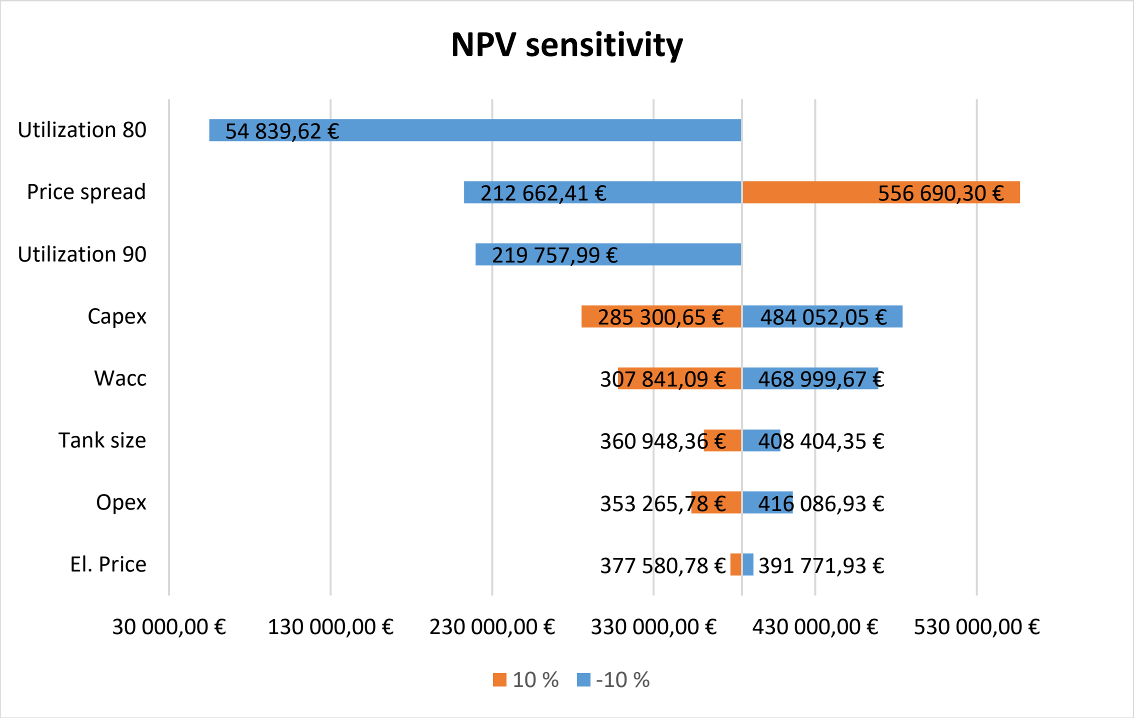

Figure 13. HRS NPV sensitivity.

Sensitivity tornado charts were also done for the IRR sensitivity. Figure 14 shows IRR sensitivity for LRC and Figure 15 IRR sensitivity for HRS. These figures illustrate how much ± 10 % change in each parameter affects the baseline IRR value. Identical parameters were evaluated as in the NPV sensitivity analysis for both storage options.

Price spread, number of cycles and CAPEX were the most sensitive parameters in IRR calculation for LRC. Size had clearly smaller impact on IRR than on NPV. Similarly to LRC NPV sensitivity price spread, number of cycles and CAPEX are the only parameters going below the 8 % WACC. As stated in chapter 3.1, IRR values below discount rate means that project isn’t profitable.

IRR sensitivity to HRS followed same trend as the NPV sensitivity. Utilization, price spread and CAPEX were the most sensitive parameters while the others had much lower impact. None of the parameters affected the IRR to go below 8 % WACC. Therefore, this project is profitable within these parameter sensitivity frames.

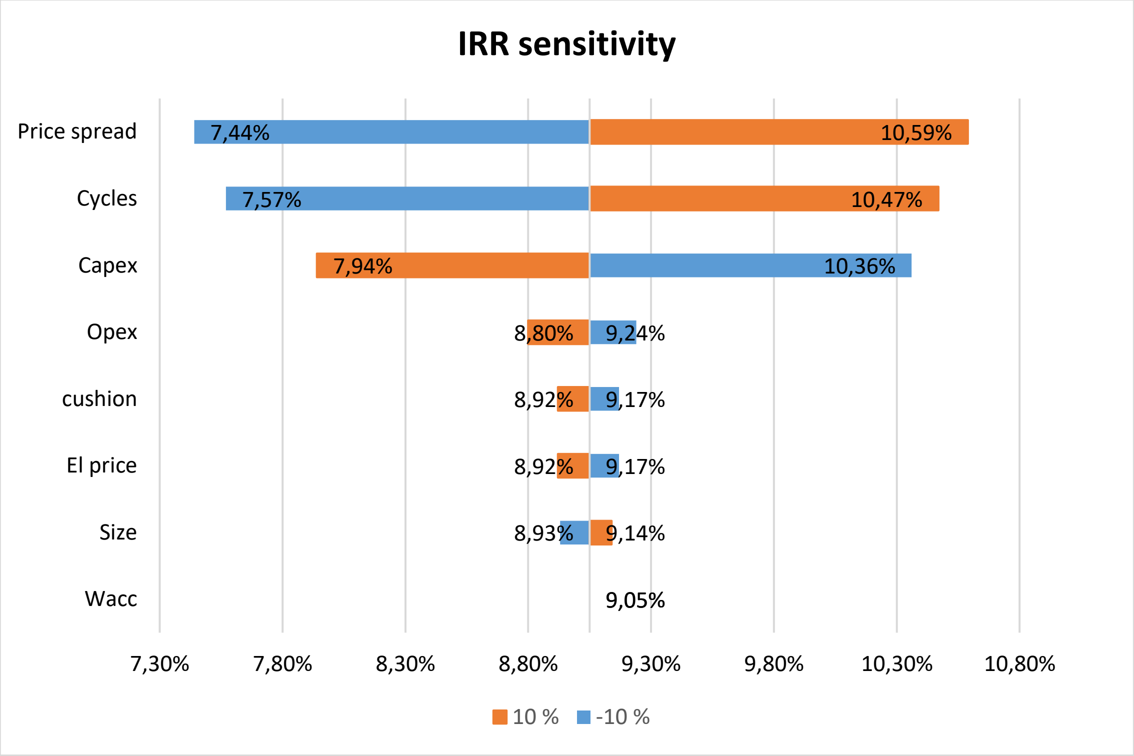

Figure 14. LRC IRR sensitivity.

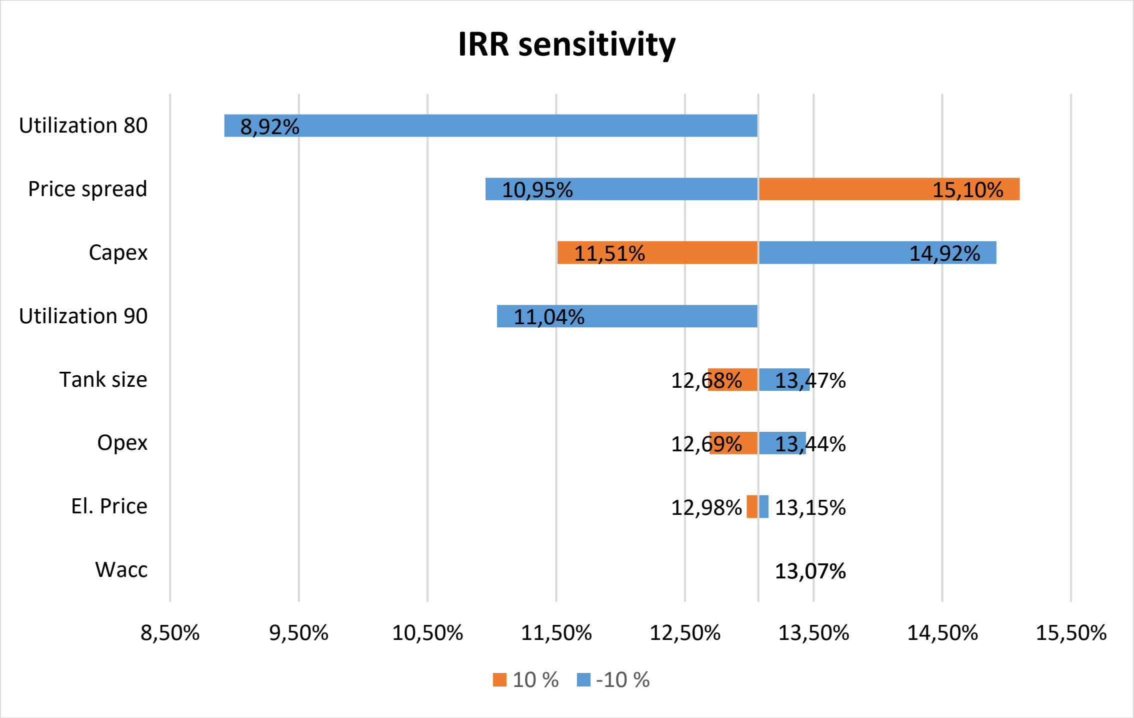

Figure 15. HRS IRR sensitivity.

6 Discussion

Aim of this thesis was to evaluate the levelized cost and feasibility of hydrogen storages in Finland and in Nordics. LRC was chosen as the large-scale hydrogen storage and compressed hydrogen storage as part of the HRS as stated in chapter 5.2. While this thesis focused solely on hydrogen storage and not production, NPV and IRR are chosen to evaluate the profitability and economic feasibility instead of LCOH or LCHS. These calculations were conducted based on literature and not actual project data. Therefore, there were constraints and simplifications that needed to be made. These resulted in differences between the actual reference cases and the two selected storage types.

6.1 Feasibilities

Based on the economic calculations and the framework of this thesis, hydrogen storages can be feasible in Finland and in Nordics. The result suggests that the chosen storage types are not only technologically relevant in Finland and in Nordics but are also economically feasible. Positive net present value and internal rate of return in both cases indicate that both cases are feasible with the parameters and simplifications used. With actual project data the calculations could be either more or less feasible depending on the conditions of such project and data used.

Even though the constraints and simplifications made the results less applicable to real life scenarios, the sensitivity analysis gave valuable insight into how sensitive the storage projects are to different input parameters. As discussed in chapter 5.3 the LRC is most sensitive to price spread, number of cycles, CAPEX and WACC and the HRS is most sensitive to utilization, price spread, CAPEX and WACC. Understanding the sensitivity of the dependencies between the input parameters and results is crucial for the optimization of the hydrogen storage. Maximizing the utilization and price spread results in higher profits and so does decreasing the capital investment costs.

6.2 Limitations, uncertainties and challenges

Biggest constraint for the calculations in this thesis was available data. Due to lack of actual project data in Finland and in Nordics, data for the calculations were derived from the literature. Within the literature there was only few research done where techno-economic assessment for LRC and HRS were applicable to this thesis. Therefore, most of the literature used for the economic calculations were not in the Finnish or Nordic context. This resulted some of the parameters used in the calculations to not be the most accurate for the Finnish and Nordic setting. The constraints regarding availability of data led to simplifications within the calculations.

Another constraint of this research was the lack of simulation tools. All the calculations in this thesis were conducted with Excel where no modelling could be done. This meant that no modelling or component sizing could be done and therefore everything is dependent on the data retrieved from the literature. Better alternatives to Excel could be, for example, Homer Pro where modelling and simulations could be made.

Because of the constraints mentioned earlier many simplifications were needed for the economic calculations. Due to constraints, no actual load models or component sizing could be done in the calculations and those were dependent on literature. For the LRC and HRS, demand and supply were assumed 100 % at all times, which in reality is not always the case. Due to component sizing being dependent on literature no straight comparison between each storage option could be done. Modifying component parameters would result in the other input parameters being not valid anymore. As a result of that, and due to technological differences between the two storage options storage sizes, components and storage pressures vary between the two.

Other simplifications for the economic calculations include no salvage value assumed, fixed electricity price, no carbon emission compensation and no subsidies assumed. These simplifications were used to make the calculations simpler and chosen due to the constraints mentioned above. In literature there were a lot of variations of these simplifications being used or not. Rounded up fixed electricity price resulted in simpler calculation but as a result does not show accurate real-life values. But as can be seen from Figure 12 to Figure 15 electricity price has the lowest impact on NPV and IRR in these calculations.

Since no salvage value, carbon emission compensation and subsidies are assumed in the calculations the results can be considered as worst case scenarios. By implementing some or all these parameters, results would be more positive. As all these parameters have positive effect on the revenue this would result in more positive NPV and IRR values.

As a result of constraints, the calculations made and reference projects had differences. As mentioned above, the constraint of data affected the comparison between the two storage types. Other than that, the two storage options analyzed in this thesis were technology and application wise different.

When comparing the calculations the biggest difference is the size and therefore the amount of hydrogen. The LRC storage had size of 500 tons compared to 2.2 tons of the HRS. Annual amount of hydrogen going through the LRC storage was 4600 tons whereas for HRS it was 54.75 tons. More comparable storage size was limited by the availability of data and in the other hand would not be purposeful. Larger LRC storage can be used as seasonal storage or as larger energy storage whereas smaller HRS storage needs to be able to deliver daily demand of hydrogen.

Other differences between the two storage types can be clearly seen from the Table 6 to Table 9. LRC as a storage system consists of the excavated storage and compressor whereas HRS has additional cooler and dispenser in addition to the tank and compressor. More complex system of HRS leads to higher CAPEX and OPEX per kg of stored hydrogen compared to LRC. As can be from the Table 6 and Table 7, CAPEX of HRS storage is almost double the amount of LRC. Relative OPEX values between the two storages were quite similar but the additional components of HRS cumulated in higher fixed and variable OPEX per kg. Figure 16 and Figure 17 illustrate the breakdown of OPEX for LRC and HRS. Compressor variable OPEX was over two times the amount of the fixed OPEX for LRC. The high LRC OPEX was due to large capital costs of the storage system where the OPEX was taken as percentage. As shown in Figure 17 compressor fixed OPEX was over half of all the OPEX values. Both fixed and variable compressor OPEX contributed over 75 % of the total OPEX for HRS. Compressor variable OPEX was in HRS case smaller than the fixed OPEX due to small yearly hydrogen demand. Compressor variable OPEX per the yearly hydrogen demand resulted in twice as high value for the HRS than for the LRC.

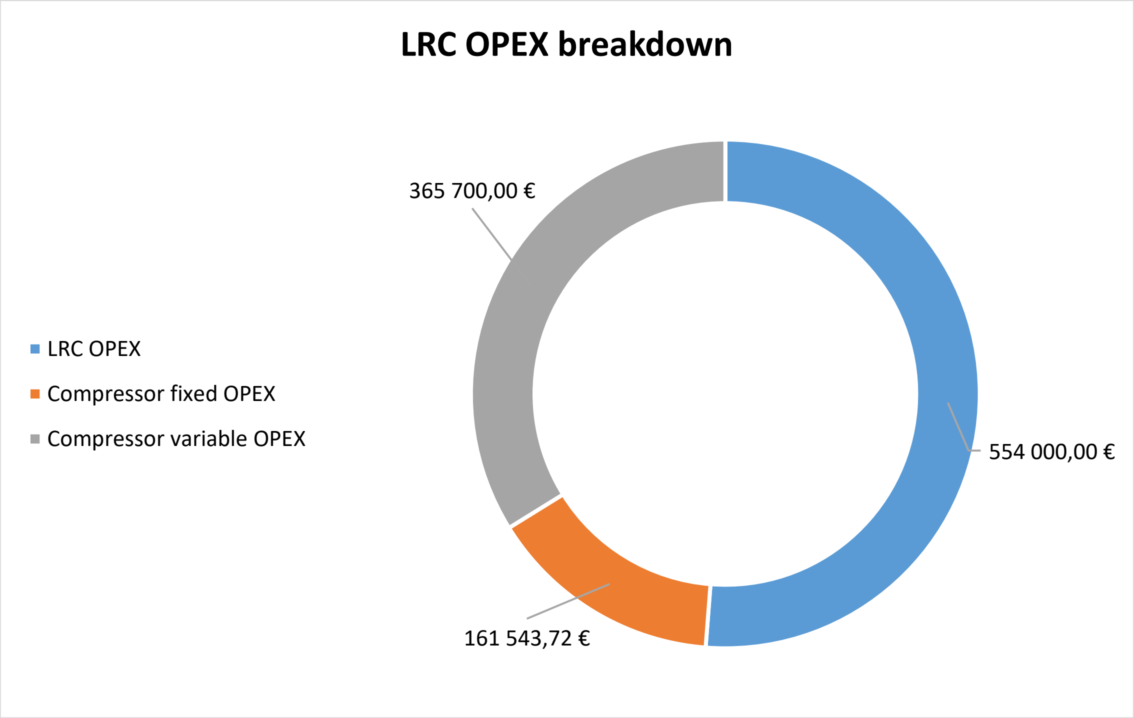

Figure 16. LRC OPEX breakdown.

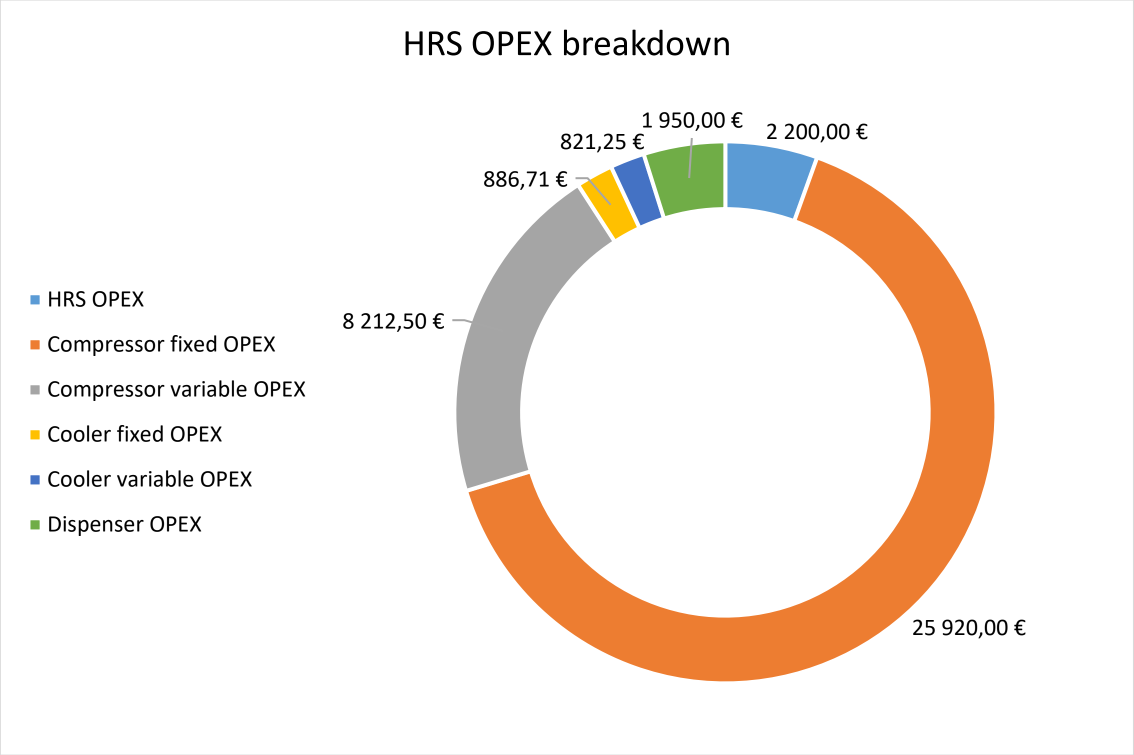

Figure 17. HRS OPEX breakdown.

Size and cost differences resulted in very different price spreads. As stated in chapter 5.3 break-even price spread for LRC was 0.93 € and 3.11 € for the HRS. Due to lower yearly hydrogen demand and higher costs per kg of hydrogen, HRS had over three times higher break-even price spread compared to LRC. Based on this LRC seems to be cheaper storage option compared to HRS with less negative cashflows. This is in line with the LCHS values presented in Table 5. Price spread was chosen to indicate the difference between the sold and bought hydrogen due to lot of fluctuation between LCOH. In addition to LCOH values, distributing hydrogen from the production plant to the storage site adds costs. As the market price of hydrogen could fluctuate, price spread indicates how high the sold hydrogen price needs to be to have profitable storage project. Since the aim of this thesis was not to evaluate the production and distribution of hydrogen to the storage facilities, using price spread is justified.

Reference case projects handled in chapter 4 and actual calculations performed had different input parameters. As mentioned earlier, lack of reference case data forced calculations to be made with data derived from literature. For the LRC the reference case size was 2 tons compared to calculation 500 tons. Size difference is drastic but as stated in chapter 4.2 in the future LRC storages have potential to be much bigger in size. The reference case project for HRS was in the pilot phase and thus supplying hydrogen to only a few buses and other passenger vehicles. Therefore, the fleet size of 30 refuelling's per day used in the calculation was quite high. Anyhow in literature refuelling capacity of 150 $\mathrm{kg_{H_2}}$ per day is often used. Due to this and lack of data, using such high value was justified in the calculations.

6.3 Implications for hydrogen development

Findings derived from literature review and economic calculations gives foundation for future development of hydrogen storages and therefore hydrogen economy in Finland and in Nordics. Key findings indicate that compressed hydrogen storage can be feasible option in different parts of the energy sector. To be more competitive, price of the hydrogen value chain needs to be reduced. Technology wise, appropriate materials are crucial in case of compressed hydrogen storage. To enhance the efficiency of the storage the energy required for compression needs to be minimized.

Enhanced compression also affects the economic feasibility of storage. Enhancing compression efficiency can lower variable operating costs of the storage. As the capital investment costs are dependent on the size of the storage and components, correct sizing is recommended. Additionally, maximal utilization of storage is recommended to further increase feasibility by lowering costs per kg of stored hydrogen. Finally break-even price spreads indicate that compressed hydrogen storage as part of a hydrogen refueling station requires around three euros to operate and therefore lowering production costs would make hydrogen more competitive alternative fuel source.

Hydrogen storage feasibility is strongly dependent on integration with surrounding energy systems, particularly electricity markets and hydrogen production facilities. Colocation of production and storage for example, electrolyzers and LRC or HRS systems can significantly reduce logistics costs and improve overall system efficiency.

The results also indicate that electricity price dynamics play a critical role in hydrogen storage economics. Electricity prices directly affect the variable OPEX and therefore contribute to overall cost of the storage system. Efficient components, including compressors and coolers, are therefore suggested to minimize the variable OPEX caused by the electricity costs. As sensitivity analysis was conducted with only 10 % change the effect of it is minimal on the electricity price. In reality, electricity prices fluctuate much more resulting in higher variable OPEX.

Policy frameworks and potential subsidies can significantly influence hydrogen storage deployment. While this thesis did not focus on policies or subsidies it is evident that these play big role in the implementation of hydrogen storage systems. Straight forward and clear policies help implementation of hydrogen storages and subsidies affect the economics of hydrogen storage in a positive way, bringing additional revenues.

This study is based on literature-derived parameters and simplified assumptions due to the lack of detailed real-world project data from Finland and the Nordics. As a result, the economic calculations should not be interpreted as precise predictions of project feasibility. In particular, assumptions such as constant electricity prices, full system utilization, and simplified revenue structures may lead to deviations from real operational conditions. Furthermore, the use of deterministic sensitivity analysis with limited variation ranges does not fully capture the uncertainty and variability present in real hydrogen storage projects. Consequently, while the results provide useful directional insights into the relative feasibility and key cost drivers of hydrogen storage technologies, they should not be interpreted as definitive investment evaluations.

From future research perspective, data from actual projects is required to further validate and optimize hydrogen storages in Finland and Nordics. In the Nordics there are abundant numbers of hydrogen refuelling station projects on going, but there is a lack of lined rock cavern projects at the moment. Actual component and hydrogen price data would give more accurate results on the feasibility of hydrogen storages in Finland and Nordics.

7 Conclusions

This thesis reviewed hydrogen storage technologies and assessed which of the options would be feasible in Finland and in Nordics. Based on the in-depth literature review and reference cases there seem to be multiple possible ways to store hydrogen. From these options LRC and compressed HRS were chosen for further economic feasibility analysis based on their attributes and applicability in the Finland and Nordics with existing reference projects. The economic feasibility calculations consisted of NPV, IRR and PBP calculations to assess the profitability of such projects. From these calculations sensitivity analysis was made for the NPV and IRR input parameters.

The results from the calculations indicated that both storage options can be economically feasible within the framework of this thesis. Key findings were that for both storage options the NPV values were positive. This resulted in the IRR values also to be above the discount rate. Also, the payback periods were less than the actual project lifetime further strengthening the hypothesis of profitable projects. Another crucial result was the price spread break-even points that indicated how much the price spread needs to be to achieve profitable storage project.

Sensitivity analysis gave important insight into the relation between the input parameters and NPV and IRR results. Understanding the most sensitive parameters is crucial when assessing new build projects. By identifying the most sensitive parameters and by optimizing these, more profitable and feasible storage projects can be made in the future.

Based on the calculations and results no real-life conclusions could be obtained. The calculations and sensitivity analysis gave valuable insight into how the different input parameters affect the economic feasibility of the storage projects. Furthermore, these results provide framework for future research on the subject and can be used for example as a preliminary profitability assessment.

The calculations in this thesis had many constraints and simplifications. Within the framework of this thesis the results are in line with the research that has been done previously on the subject. List of improvements include:

- Use of actual project data if possible
- Usage of simulation tools, for example Homer Pro
    - Actual component sizes
    - Demand and supply load models
    - Electricity price fluctuations
- Assume salvage value, carbon emission compensation and subsidies

There remain many possible research opportunities based on this topic. First, implementing some or all the improvements listed above would improve the research on the topic. Most importantly, simulation tool that would enable component sizing and load models. Additional topics include, how would salvage value, carbon emission compensation and subsidies affect the calculations? How would the legislation around the hydrogen storages affect the calculation? How would modelling the production and delivery of hydrogen influence the calculation? What would be the most optimized solution? How would the different operation mode or end user affect the calculations? Also, a broader analysis where other feasible options such as liquid hydrogen, cryo-compressed and ammonia are studied.

8 Summary

This thesis started by addressing the need for decarbonizing the future energy system. Due to the nature of renewable energy sources, such as wind and solar, storage systems are needed to balance the fluctuating energy production. Hydrogen is considered to be one of the most promising storage options in the future energy systems. Aim of this thesis was to evaluate the current state and feasibility of hydrogen storage in the context of Finland and Nordics. This was done by conducting broad literature review on different hydrogen storage options, where technical and economical attributes of each storage technology were evaluated. Based on the literature review two storage types were chosen for the feasibility analysis. Feasibility was assessed through economic calculations and two real-life case studies. Economic calculations consisted of net present value, internal rate of return and payback period for two reference cases, similar to the real-life cases. Based on these calculations' sensitivity analysis was conducted to further analyze which parameters affect the economics of hydrogen storage the most.

Hydrogen is seen as good option for future energy systems because of the abundance of it and high energy density. Anyhow, it suffers from low gravimetric capacity and low volumetric density therefore requiring storage options that enhance those attributes. There are many ways to store hydrogen, and the most used ones are compressed, liquified, cryo-compressed and ammonia. From these options compressed hydrogen storage was selected for further feasibility analysis, as part of the lined rock cavern and hydrogen refueling station. This was mainly result of similar real-life projects in Finland and Nordics. Additionally, compressed hydrogen storage is simpler and cheaper option compared to the other methods further indicating feasibility.

The economic calculations were conducted in Microsoft Excel and used data derived from relevant literature because no actual project data was available. This created limitations and uncertainties, to the calculations and results, for no actual modelling or component sizing could be done. Anyhow, the calculations resulted in positive NPV and

IRR values for both cases indicating profitable projects and therefore feasibility. While these values are not definitive and not straightly applicable for assessing actual feasibilities they provide direction. Additionally, sensitivity analysis highlights key parameters that should be considered in the future.

The aim of this thesis was to evaluate the feasibility of hydrogen storage in Finland and in Nordics. Based on this thesis compressed hydrogen storage can be feasible in the context of Finland and Nordics. Anyhow, it is important to note that the results do not give definite answers and can only be used as guidance and as a foundation for future research on the topic. Therefore, it can be conducted that this thesis answered to the research question whether hydrogen storage can be feasible in Finland and in Nordics while keeping in mind the limitations and uncertainties mentioned above.

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