The role of hydrogen in transporting offshore wind power to markets

- A techno-economic analysis

Dorthea Ting Arnø Sandvik

Lana Azad Tufeek

Bachelor's thesis in Energy Technology

Bergen, Norway 2024

Høgskulen
på Vestlandet

Western Norway
University of
Applied Sciences

The role of hydrogen in transporting offshore wind power to markets

Dorthea Ting Arnø Sandvik

Lana Azad Tufeek

Department of Mechanical Engineering and Maritime Studies

Western Norway University of Applied Sciences

NO-5063 Bergen, Norway

IMM 2024-M82

Western Norway University of Applied Sciences (Høgskulen på Vestlandet, HVL)

Faculty of Technology, Environmental and Social Sciences

Department of Mechanical Engineering and Maritime Studies

Inndalsveien 28

NO-5063 Bergen, Norge

Norsk tittel:	Hydrogen sin rolle i transport av offshore vindenergi til marked
Author(s), student number:	Dorthea Ting Arnø Sandvik, h602102 dorthea.sandvik@lyse.net Lana Azad Tufeek, h602104 lana-tufeek@hotmail.com
Study program:	Energy Technology
Date:	May 2024
Report number:	IMM 2024-M82
Supervisor at HHVL:	Velaug Myrseth Oltedal, HVL
Assigned by:	NORCE
Contact person:	Torbjørn Egeland-Eriksen Antonie Oosterkamp
Antall filer levert digitalt:	2

Preface

This bachelor's thesis marks the end of a three-year engineering education in Energy Technology at the Western University of Applied Sciences, campus Bergen. The work has been exciting and educational, but also challenging and demanding. It has given valuable insight into the transport of hydrogen, and hydrogen as an energy carrier.

First of all, we would like to thank our internal supervisor Associate professor Velaug Myrseth Oltedal, for the guidance and feedback. Your advice and support have been valuable and helpful. Thank you for your encouragement through the process.

We would also like to thank our external supervisors Researcher Torbjørn Egeland-Eriksen and Senior Researcher Antonie Oosterkamp, from NORCE. Thank you for your perspective, valuable advice and help in understanding the challenges in hydrogen transport. Your expertise has been of great help and has significantly enriched the thesis.

Abstract

In an effort to achieve net-zero emissions and meet the demand of energy, more renewable energy solutions are required. A topic that has gotten a lot of attention is offshore wind power and combining it with hydrogen production. Norway has great potential to contribute with new renewable power production given its wind resources in the North Sea and hydrogen can be key to the energy transition.

This bachelor thesis discusses offshore transport of hydrogen and electricity, with focus on levelized cost of hydrogen transportation (LCOHT) and levelized cost of energy transportation (LCOET). A wind area in the North Sea has been identified for the purpose of evaluating the most profitable transport method. This area has been chosen due to the strategic location and its high potential for power production.

Through an extensive literature study, information has been gathered on existing research and technological developments within hydrogen transport. This formed the basis for further analysis and calculations. In addition, this thesis presents a sensitivity analysis comparing lifetime of ship and submarine power cable, as well as pipe dimensions.

Detailed calculations have been performed to compare different transport methods. The results reveal that a 10-inch pipeline (0.004 USD/kWh) is the most cost-effective transport method, followed by submarine power cables (0.006 USD/kWh) and LH_2 ships (0.033 USD/kWh), with CGH_2 ships (0.077 USD/kWh) being the most expensive choice. This thesis recognizes the strengths and weaknesses of each method and underlines that the choice of transport method largely depends on investment costs, lifetime, material, and size. Lastly, it has been necessary to make certain simplifications and assumptions, given the scope of the study and available data.

Sammendrag

I et forsøk på å oppnå null-utslipp samt møte etterspørselen for energi, kreves det flere fornybare energiløsninger. Et tema som har fått mye oppmerksomhet er havvind og kombinasjonen mellom havvind og hydrogenproduksjon. Norge har et stort potensial til å bidra med ny fornybar kraftproduksjon gitt sine vindressurser i Nordsjøen og hydrogen kan være nøkkelen til energiomstillingen.

Denne bacheloroppgaven diskuterer offshore transport av hydrogen og elektrisitet, med fokus på *levelized cost of hydrogen transportation* (LCOHT) og *levelized cost of energy transportation* (LCOET). Det er identifisert et vindområde i Nordsjøen for å vurdere den mest lønnsomme transportmetoden. Dette området er valgt grunnet den strategiske beliggenheten og områdets høye potensial for kraftproduksjon.

Gjennom en omfattende litteraturstudie er det samlet inn informasjon om eksisterende forskning og teknologisk utvikling innen hydrogentransport. Dette dannet grunnlaget for videre analyser og beregninger. I tillegg presenterer denne oppgaven en sensitivitetsanalyse som sammenligner levetiden til skip og sjøkabler, samt rørdimensjoner.

Det er utført detaljerte beregninger for å sammenligne ulike transportmetoder. Resultatene viser at en 10-tommers rørledning (0,004 USD/kWh) er den mest kostnadseffektive transportmetoden, etterfulgt av sjøkabler (0,006 USD/kWh) og LH_2-skip (0,033 USD/kWh), med CGH_2-skip (0,077 USD/kWh) som det dyreste valget. Denne oppgaven anerkjenner styrker og svakheter ved hver metode og understreker at valg av transportmetode i stor grad avhenger av investeringskostnader, levetid, materiale og størrelse. Til slutt har det vært nødvendig å gjøre visse forenklinger og antakelser, gitt omfanget av studiet og tilgjengelig data.

Table of contents

Nomenclature

ABS	American Bureau of Shipping
CAPEX	Capital expenditure
CGH_2	Compressed hydrogen gas
CCS	Carbon capture and storage
CO_2	Carbon dioxide
°C	Degree Celsius
DSB	Direktoratet for samfunnssikkerhet og beredskap
DC	Direct current
EC	European Commission
EHB	European Hydrogen Backbone
FME	Environment friendly Energy research
H2	Hydrogen
HVL	Western Norway University of Applied Sciences
HDPE	High Density Polyethylene
HVDC	High voltage direct current
HVAC	High voltage alternative current
IMO	International Maritime Organization
°K	Degree Kelvin
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
LH_2	Liquid hydrogen
LHV	Lower Heating Value
LCOHT	Levelized cost of hydrogen transportation

LCOET	Levelized cost of energy transportation
LCOE	Levelized cost of energy
LOHC	Liquid organic hydrogen carriers
MW	Megawatt
MOU	Memorandum of understanding
NORCE	Norwegian Research Center
NVE	Norwegian Water Resources and Energy Directorate
NMA	Norwegian Maritime Authority
NOK	Norwegian Krones
OPEX	Operating expenses
O&M	Operation and Maintenance
PEM	Proton exchange membrane
ppm	Parts per million
SOEC	Solid oxide electrolyzer cell
SCH40	Schedule 40
TWh	Terawatt hour
USD	United States dollar
W	Watt
wt%	Weight percent
ρ	Density [kg/m^3]
η	Efficiency
V	Volume [m^3]
v	Velocity [m/s]
E	Energy
Δp	Pressure drop

1. Introduction

The increasing demand of energy still poses a dilemma in the world. Limiting fossil fuel resources and reducing carbon emissions entails a need for establishing more renewable power production. In addition, international cooperation is essential to ensure a sustainable future when addressing global challenges such as climate change [1] In Norway, Statnett have estimated an increased power demand of 50-90 TWh/year [2].

Among the promising alternatives is the combination of hydrogen production with renewable energy generation to achieve net-zero emission energy solutions [3]. Implementing a hydrogen infrastructure can create a structured energy transition from fossil fuel resources to more renewable energy methods. The global demand for pure hydrogen production was 70 million tons in the year 2019 [4]. The European Commission (EC) proposed a plan to phase out Europe’s dependence on fossil fuels from Russia. The proposed REPowerEU plan was presented in May 2022 and aims to reach 15 million tons of renewable hydrogen [5]. A potential method for hydrogen production is to utilize electricity from offshore wind power in combination with water electrolysis. Norway has great potential to contribute with new renewable power production given its wind resources in the North Sea.

Furthermore, producing hydrogen by offshore wind power is also evaluated in several countries such as Germany, Great Britain, Scotland, Denmark, and the Netherlands. Several scientific analyses have been published regarding this topic as well. The estimated levelized cost of hydrogen transportation (LCOHT) within a European context is ranging from 0.3 to 0.44 euros per kg. These variations are observed across transport distances from 25 to 500 km, influenced by hydrogen demand levels up to 100 000 kg per day [1].

The purpose of this thesis is to explore the use of energy from an offshore wind farm in the North Sea and search for different methods for transporting energy to shore in terms of transport costs from this location to shore. Local hydrogen distribution is left out of the scope in his thesis.

1.1 Literature review

In recent years, there has been significant attention on hydrogen and wind power. The following literature presents some of the scientific papers and projects related to the subject of this thesis.

In 2021, Greenstat published a detailed report on the possibilities of combining offshore wind power and hydrogen production at Sørlige Nordsjø II. The report concluded with results showing that offshore hydrogen production in Sørlige Nordsjø II is achievable at a competitive price. In addition, implementing a power cable to land combined with offshore hydrogen production resulted in lower LCOE from the wind farm, about 0.45 NOK/kWh, than in the case without hydrogen production. Estimated LCOH for a PEM plant (at 400 MW) showed a result between 36-41 NOK/kg H2 [2].

American Bureau of Shipping (ABS) has been engaged in many hydrogen projects. Among one of these projects there is a goal to design and construct an offshore platform for green hydrogen production by 2025. ABS published a paper that explores conditions such as technology that can be incorporated into offshore facilities and make green hydrogen possible in the maritime and offshore industries [6].

Gassco conducted a feasibility study with the German Energy Agency on the establishment of pipeline infrastructure for hydrogen transport from Norway to Germany. Two main scenarios have been evaluated regarding offshore hydrogen pipelines, and it is based on transport of large quantities of low-carbon hydrogen, and renewable hydrogen. The first concept is the combination of reusing existing infrastructure and new infrastructure and the second concept is only new pipeline infrastructure. The project is considered technically feasible within 2030 [7].

Lastly, the European Hydrogen Backbone (EHB), founded in 2020, has contributed to the development of a European hydrogen market. The contribution has been through publications of hydrogen infrastructure network maps. The EHB report involves 31 energy infrastructure companies from 28 countries, and supports the REPowerEU plan, an ambition to create and import a market for hydrogen [5].

1.2 Background

This project was suggested to Western Norway University of Applied Sciences (HVL) by the Norwegian research center (NORCE). The project is also a part of the Norwegian research center for hydrogen HyValue. HyValue is a center for Environment friendly Energy research (FME), dedicated to developing knowledge and innovative solutions to determine the role of hydrogen and hydrogen-based energy carriers in achieving a zero-emission energy economy [8].

This bachelor thesis presents the potential for green hydrogen production by utilizing large-scale wind power, focusing on a specific geographic area in the North Sea, this is relevant for Norway’s offshore wind. In addition, it explores attributes that enable a more beneficial and economically viable offshore hydrogen production. This thesis will also evaluate alternative methods of transporting hydrogen and assess which method will be the optimal solution. This involves evaluating the costs of transporting compressed hydrogen through pipelines or using ships to transport either compressed or liquid hydrogen. In addition to compare them to transporting the electricity by power cables from the wind farm to shore.

1.3 Aim and objectives

The aim of the bachelor thesis is to perform a techno-economic analysis of the role of hydrogen in getting offshore wind power to markets and end users, including a focus on possible transport methods. These following objectives are necessary to accomplish the aim of the thesis.

- Identify a wind area and compare different scenarios for offshore hydrogen production vs. onshore production for the selected wind area Sørvest B.
- Examine the characteristics of electrolyzers and estimate the hydrogen production.
- Explore different hydrogen storage methods and investigate their capacity for storage.
- Evaluate different transport methods available (pipelines, ships, power cables), perform an economic analysis and compare it with the levelized cost of hydrogen transportation and levelized cost of energy transportation.
- Perform a sensitivity analysis to evaluate the effect variations in the system variables such as lifetime and pipe dimensions.

1.4 Thesis structure

This thesis consists of seven chapters. First, an introduction that provides the background for the thesis and presents the aim and objectives. The subsequent chapters are as followed:

Chapter 2 – Theory

Chapter 3 – Case description

Chapter 4 – Methodology

Chapter 5 – Results of calculations

Chapter 6 – Discussion

Chapter 7 – Conclusion and further work

In chapter 2, the theory of hydrogen, electrolysis, transport methods, safety and storage of hydrogen, is explained. Then, in chapter 3, a detailed description of the case is presented, and limitations and assumptions. In chapter 4, the methods used in the study is described. Furthermore, in chapter 5, results of calculations are presented, followed by a discussion in chapter 6. Lastly, the conclusion and further work is summarized in chapter 7.

2. Theory

The purpose of this chapter is to provide the necessary theory for further reading. It will mainly contain information about hydrogen, electrolysis, various transport methods and safety. Furthermore, an introduction to various methods of storing hydrogen is given.

2.1 Hydrogen

Hydrogen is the first element in the periodic table and the most abundant element on earth. Hydrogen is very reactive, and rarely found in its pure form in nature. Most are chemically bound for instance as water molecules. Hydrogen is essential for our existence, and it is found in all living animals, plants and all parts of the body [9].

Hydrogen has several color codes, and these correspond to the extraction process. The three most common colors are blue, green, and grey. Green hydrogen is produced from renewable sources, making it more environmentally friendly. Blue hydrogen is produced from non-renewable sources for instance oil and gas, but with carbon capture and storage (CCS) to trap and store carbon dioxide (CO_2). Grey hydrogen, on the other hand, is also produced from non-renewable sources, but without CCS. This method therefore has higher carbon emissions. Almost all hydrogen produced today is grey [10].

In terms of production methods for hydrogen, steam reforming is the most common. Fossil fuels such as oil and gas are often used as fuel. However, this report will focus specifically on green hydrogen and production methods will therefore be limited to electrolyzers.

2.1.1 Hydrogen Gas

Hydrogen in gaseous form is mostly used for transport purposes. In passenger cars, hydrogen is often used under a pressure of 700 bar, while forklifts, buses and trucks usually use containers/tanks with a pressure of 350 bar. Hydrogen compressors are mechanical devices that increase the pressure of the gas by reducing its volume, often using a piston compressor [11].

It is crucial to have knowledge of the different properties of hydrogen. Hydrogen is known to be the lightest of all gases and will therefore rise quickly up in the air and blend with other gases. The gas is characteristically colorless, odorless, and tasteless. Hydrogen gas ignites easily and burns with a slightly bluish flame almost invisible in daylight [12]. These characteristics indicate that the handling and application of hydrogen requires special attention and caution.

2.1.2 Liquid hydrogen

Liquid hydrogen is most relevant for storage of large quantities and transport over long distances. Leakage of liquid hydrogen will form a white cloud on the ground and freeze surrounding gases. To liquefy hydrogen, it must be cooled to -253 °C (20 K) [11].

Claude cycle is a known method used for large-scale hydrogen production. Hydrogen is injected at 15-25 bar pressure, followed by precooling to -193 °C (80 K) using heat exchangers with liquid nitrogen (LN2). The hydrogen is then purified through an adsorption system to remove impurities. It uses recycled hydrogen for additional cooling, and through a Joule-Thomson valve, achieves a temperature of -253°C at atmospheric pressure. Although this process can be expensive with high capital costs (CAPEX), it is energy efficient with low operating costs (OPEX) [11].

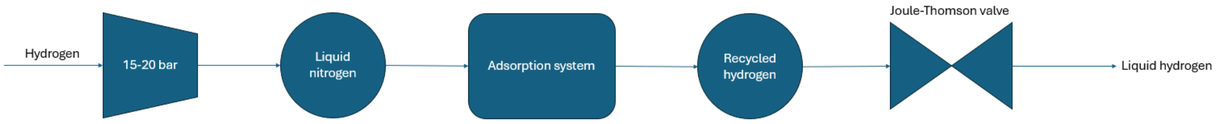


Figure 1: A simple figure of the Claude cycle. Shows the process, from hydrogen being injected until it is turned into liquid.

Converting hydrogen into liquid is a more energy demanding process compared to producing compressed hydrogen gas, as it requires 20-30 % more energy. In addition to being energy-demanding, it has higher operational costs. On the other hand, it is more scalable and has a higher volumetric energy density. It is therefore well suited for transportation by ships, as it can transport larger amounts of energy. According to the US Department of Energy, the current price for a liquefaction plant with a capacity of 300 000 kg H_2/day is 560 million USD, with an "ultimate goal" of 142 million USD [13].

2.2 Working principle of electrolyzers

Green hydrogen is produced using renewable resources and water electrolysis. The design of an electrolyzer has several common characteristics. They consist of an anode and a cathode separated by an electrolyte that permit different molecules to pass through. In the electrolyzer a reaction called electrolysis occurs where electricity is used to decompose water into hydrogen and oxygen. The chemical reaction is shown below.

$$H_2O \rightarrow H_2 + O_2$$

There are three designs of electrolyzers for hydrogen production, such as proton exchange membrane (PEM), alkaline and solid oxide. Each function in different ways depending on the type of electrolyte material and which ions it conducts [6] [14]. All the chemical reactions of the three electrolyzers are shown in table 1.

2.2.1 Proton exchange membrane electrolyzers

Proton exchange membrane or PEM electrolyzer have a solid electrolyte membrane that allow hydrogen ions to pass through it. At the anode water will react to form oxygen and positively charged ions. At the cathode hydrogen ions have travelled across the PEM and will combine with the electrons from the external circuit to form hydrogen gas [14].

In general PEM electrolyzers use more precious metals and precisely constructed techniques for their catalysts than alkaline, which causes them to be more expensive to produce and maintain. PEM usually operates at temperatures between 50 °C and 80 °C and the direct current (DC) density is between 10 000 A/m^2 and 20 000 A/m^2. Compared to alkaline electrolyzers, PEM operates at higher pressures and current densities. The increase in current density also makes PEM electrolyzers have great advantages when managing irregular renewable energy sources. This is because it enables a more rapid system response to changes in energy input [6]. In addition, PEM electrolyzers can be operated under different pressures and the general volume is smaller, about 1/3 of the alkaline electrolyzer [15]. The energy efficiency of PEM is approximately between 55-66% (LHV) [16]. These factors make PEM electrolyzer a preferred choice for further estimates of hydrogen production in chapter 4 calculations.

2.2.2 Alkaline electrolyzer

Alkaline electrolyzers use a liquid alkaline solution of 25 weight percent (wt%) sodium hydroxide (NAOH) or 30 wt% potassium hydroxide (KOH) as electrolyte [15]. Hydroxide ions (OH^-) are transported through electrolyte. Alkaline electrolyzers usually operate at temperatures between 60 °C and 90 °C, and the pressure is between 1 bar and 30 bar. Generally, alkaline electrolyzers require more space compared to PEM and the DC density is between 2000 A/m^2 and 4000 A/m^2 [6].

2.2.3 Solid Oxide electrolyzer

Solid oxide electrolyzers SOEC, use a solid ceramic membrane as electrolyte. The electrolyzer conducts negatively charged oxygen ions (O^{2-}). The operating temperature of SOEC must be high enough for it to function properly, usually around 700 °C. Compared to other electrolyzers, SOEC has a lower lifespan and does not require precious metals in their design. At the cathode, steam is combined with electrons from the external circuit to form hydrogen gas and negatively charged ions. Oxygen ions move through the solid ceramic membrane and react at the anode, where oxygen gas is formed, and electrons are generated, shown in table 1. SOEC are still under development, however there are advanced lab-scale research showing promising results for lowering the operating temperature based on proton conducting ceramic electrolytes [14].

Table 1: *Overview of chemical reactions for the three types of electrolyzers*

Electrolyzer	PEM	Alkaline	Solid oxide
At anode	$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	$4OH^- \rightarrow O_2 + 4e^- + 2H_2O$	$2O^{2-} \rightarrow O_2 + 4e^-$
At cathode	$4H^+ + 4e^- \rightarrow 2H_2$	$4H_2O + 4e^- \rightarrow 2H_2 + 4OH$	$2H_2O + 4e^- \rightarrow 2H_2 + 2O^{2-}$
Total reaction	$2H_2O \rightarrow 2H_2 + O_2$	$2H_2O \rightarrow 2H_2 + O_2$	$2H_2O \rightarrow 2H_2 + O_2$

2.2.4 Water desalination

About 97 % of the earth`s water resources consist of salt water, and conversion to fresh water is necessary for many applications. The traditional method of achieving this has been distillation, a process that requires a significant amount of energy. However, today`s progress in technology has led to an increasing use of membrane-based systems to separate salt from the water. This method has proven to be less energy-intensive compared to distillation and is therefore the most common approach in today`s offshore operations. Although water desalination is an important aspect as electrolysis need fresh water, it is not included in this thesis to delineate the study [17].

2.3 Transport methods and safety

This chapter will provide an overview of various methods for transporting offshore energy production to the demand at land, as well as examine safety considerations related to hydrogen. For instance, transporting hydrogen by a pipeline or a vessel by ship. In addition to transporting electricity by cable for an optimal conversion into hydrogen onshore [3].

2.3.1 Pipeline

Transportation via pipelines represents an important method for efficient distribution of hydrogen. To enable transport through pipelines, the hydrogen must be compressed. Hydrogen has unique challenges and opportunities for transport given its high gravimetric and low volumetric energy density. Pipelines make an ideal infrastructure for transferring hydrogen either onshore or offshore and could potentially play a key role in the future hydrogen economy. To understand fundamental principles of pipelines, such as safety procedures, dimensional standards, and material selection, it is essential to develop an efficient and secure hydrogen pipeline system. The following are some pipeline requirements about pressure loss, standard and materials.

Pressure loss in pipes will depend on the pipe's diameter, length, and material quality, as well as the pressure and amount of hydrogen transported through the pipe. Thus, this will also impact the energy loss within the pipes. For long transmission lines, hydrogen pipelines would need to be designed with larger diameters and operate at higher pressures. This will be necessary for cost effectiveness, since larger pipelines can transport more hydrogen and the higher pressures allow for more efficient transportation over longer distances [2].

The standard DNV GL-ST-F101, provides important content on structural assessment for submarine piping system. In addition, the standard covers important requirements and recommendations for development, design, construction, operation, and abandonment of pipeline systems [18]. Materials must be chosen carefully for hydrogen pipelines. This is necessary to improve resistance to hydrogen embrittlement (HE) and reduce diffusion leakage [3].

High Density PolyEthylene or HDPE is a polyethylene thermoplastic material made from petroleum and is composed of the chemical elements carbon and hydrogen atoms. HDPE has a linear molecular structure with minimal branching. The longer the main chain, the greater the molecular weight. The characteristics of HDPE make it a suitable material choice for piping across a wide range of applications. It presents a high resistance towards hydrogen embrittlement, corrosion, and impact. It can also withstand somewhat higher temperatures and is known for its impressive tensile strength [19].

Lastly, carbon steel and various grades of steel alloys are commonly used in hydrogen gas pipelines. Carbon steel is an iron-carbon alloy that contains up to 2.1 wt% carbon, and it is acceptable for lower temperatures and pressures [20]. American Petroleum Institute (API) 5L Grade X65 is a recommended carbon steel pipe material for sour service and is applied for pipelines in corrosive environment. Hydrogen sulfide, H_2S, can generate corrosion and cause leakage which is a threat to personal safety and the environment [21]. Further pipe calculations for this selected carbon steel pipeline are presented in chapter 5.3 results of calculations.

2.3.2 Submarine power cable

Submarine power cables are used to transport electric energy below the water surface. They can have a variation in diameter, anything from 70 mm to 210 mm. They come in two types of energy transmission, alternating current (AC) or high voltage AC (HVAC) and direct current (DC) or high voltage DC (HVDC) [22]. HVDC cables are often used as they provide lower transmission losses [23]. They are suitable for transferring more power over considerable distances, especially at distances exceeding 600 – 800 km on land, 50 – 95 km underground and 24 – 50 km underwater. HVDC lines are usually expected to be more efficient than HVAC lines [24]. They are often viewed as an efficient method for interconnection of different power grids with varying voltage and frequencies. These cables are suitable for the integration of renewables and play a vital role in connecting offshore wind farms to mainland grids. The number of HVDC projects in the world is estimated to grow further given the advantages of the DC transmission system. According to a report, subsea power cable CAPEX cost was around 2.0 €/MW/m and the energy loss was 3% per 1000 km [25]. Despite their vital role in power transmission, some concerns with equipment malfunctioning in power cables can cause fire and shock hazards, in addition to challenges in the visual impact of the landscape [24].

2.3.3 Ships

Hydrogen can be transported by ships either as a gas or a liquid. This is a relatively new technology and only exists to a limited extent, and still requires extensive testing and evaluation. Nevertheless, several companies have started to develop ships suitable for hydrogen transport.

In 2020, the first liquid hydrogen carrier ship was completed. The Suiso frontier is built by Kawasaki heavy industries (KHI) and has a cargo capacity of 1250 m^3 (75 tons of hydrogen). The ship is 115 meters and will transport liquid hydrogen from Hastings in Australia to Kobe in Japan [26]. KHI has also designed a ship with a total cargo capacity of 160 000 m^3 (12 700 tons of hydrogen), and in 2021 KHI achieved the Approval in Principle (AIP) from Nippon Kaiji Kyokai, also known by ClassNK. The ships consist of three tanks, each at 40 000 m^3 [27]. Furthermore, a ship called Jamila is under development. The ship is fueled by hydrogen and has a total capacity of 280 000 m^3. The total cost is estimated to be 480 818 160 USD, with a lifespan of 30 years [28].

The second company is the Australian company Provaris Energy Ltd. They are developing a ship, H2Max, for transporting compressed hydrogen. H2Max has two cylindrical tanks at 250 bar and a capacity of 2000 tons [29]. Provaris has signed a memorandum of understanding (MOU) with Norwegian Hydrogen. Together, they are working on selecting production and export locations in the Nordic countries. Additionally, developing a supply chain that serves the major hydrogenports in Germany and Netherlands [30]. One essential aspect to consider is how hydrogen will be stored at the sending and receiving ends. This topic will be described more in the next chapter.

2.3.4 Safety of transporting hydrogen

The safety challenges associated with the use of hydrogen differ significantly from conventional fuel and require alternative approaches and safety measures. The lack of experience, sufficient training material, as well as the need for stricter safety protocols when operating and handling hydrogen, reflect the knowledge gaps that need to be filled. This also includes the importance of establishing safety distances and defining danger zones to minimize the risk associated with hydrogen [31].

There are several organizations related to both offshore and onshore safety. The International Maritime Organization (IMO) is the United Nations (UN) agency responsible for the safety and the prevention of marine and atmospheric pollution from ships [32]. Furthermore, The Norwegian Maritime Authority (NMA) is the administrative and supervisor authority for safety related to life, health, material assets and the environment with the Norwegian flag, as well as foreign ships in Norwegian waters [33].The Norwegian Directorate for Civil Protection (DSB) has an overview of safety and vulnerability in society [34].

2.4 Storage

Hydrogen can be stored in various forms, including liquid, compressed gas and chemical. All methods have advantages and disadvantages. Hydrogen can be stored for long periods of time without significant losses [11].[11]. Prior to storage, hydrogen must undergo purification either as a gas, liquid, or chemical storage. For gas, the permissible level of impurities is around 4 parts per million (ppm), while for liquid it is recommended to be below 1 ppm. The reason liquid hydrogen has a lower ppm, is due to all other substances, except helium, have a freezing point above -253°C. At this temperature particles of other substances can be precipitated which can lead to clogged pipes [11].

2.4.1 Storage of compressed gaseous hydrogen

Once hydrogen is compressed, it must be stored into high-pressure vessels typically between 350 to 700 bar [35]. Hydrogen has a high energy density per mass and storage requires tanks capable of withstanding both high pressure and hydrogen. The major difficulty with storing CGH_2 is the needed volume and the energy required for the compression of the gas. Research continues to improve storage vessels and find efficient methods to maintain safety when handling compressed hydrogen [11].

Projects like Deep purple, led by Technip FMC, are looking to develop subsea storage options for compressed hydrogen offshore in order to limit the area required on top of the platform. They explore storage options for compressed hydrogen in tanks on the seabed, which can supply off-grid consumers such as oil platforms with stable power and for ships to be able to bunker hydrogen at sea [36].

Another possibility is using pipelines as a form of storage. Compared to storing natural gas, the capacity to store hydrogen in pipelines is 30% lower [7]. Line packing is a process of storing compressed gas within pipelines by altering the pipeline pressure. It involves exploring the storage capacity of various pipe dimensions, and at the hydrogen gas can be distributed when deemed necessary [37].

2.4.2 Storage of liquid hydrogen

A second method is storage of liquid hydrogen. Hydrogen can be stored in cryogenic vacuum insulated and double walled tanks. To minimize evaporation loss, the cryogenic equipment should be enclosed by single cold box with a vacuum and multi-layer insulation [11]. These storage methods have been used on land for decades, although their application has not been extensive.

Companies such as McDermott are working on tanks with capacities of 10 000 m^3, 20 000 m^3 and 40 000 m^3 [38]. Furthermore, Samsung C&T Corp achieved certification from DNV for their 40 000 m^3 tanks [39]. According to the US Department of Energy, the current price for a 3500 m^3 LH_2 storage tank is 6.6 million USD, with an "ultimate target goal" of 3.3 million USD [13]. This number is used to estimate the price for a 40 000 m^3 tank.

The offshore use of such tanks has been limited due to the complexity of the technology and the need for further development and optimalization. This thesis will therefore be based on storage tanks intended for land, but on an offshore platform.

2.4.3 Chemical storage

Ammonia, methanol, liquid organic hydrogen carriers (LOHC) and metal hydrides all function as temporary hydrogen carriers and must be converted back to pure hydrogen. These substances are liquids at atmospheric pressure and room temperature, which significantly reduces the risk compared to other storage methods for hydrogen [40]. They can also be stored and transported in the same way as other chemicals, which is known technology. The volumetric energy density for these substances is generally slightly higher than for liquid hydrogen [11]. These storage methods are not relevant for transport in pipelines as it is only possible to use compressed gas and will not be more elaboration on this method.

3. Case description

Sørvest B has been selected as a case study to determine available transportation methods. The hydrogen value chain infrastructure is illustrated in figures 1 and 2, presenting a windfarm, hydrogen production, storage, offshore and onshore transport, and consumption.

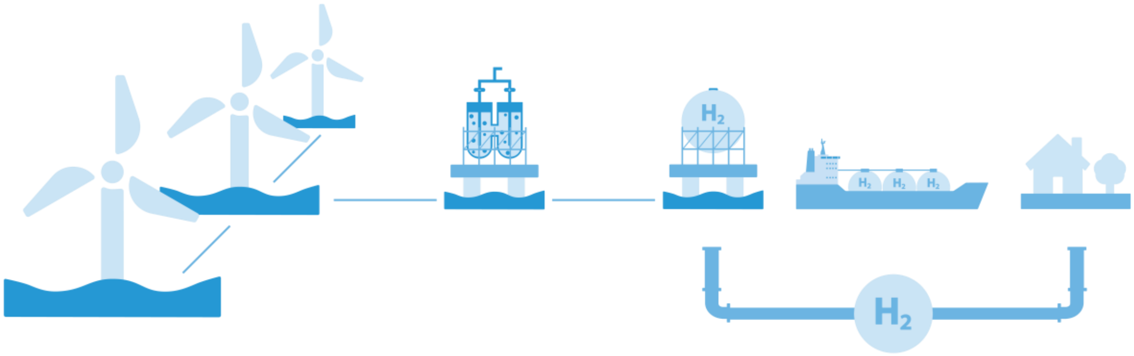


Figure 1: Offshore hydrogen value chain. Illustrates an offshore wind farm, offshore electrolysis, followed by offshore storage for further transport by ships or pipelines to shore.

Figure 1 illustrates the offshore hydrogen value chain. The electricity is generated by an offshore wind farm and then used in an offshore electrolysis process to produce hydrogen. After production, the resulting hydrogen is stored offshore, either in liquid or compressed form, for further transport to shore. Then, the hydrogen is transported to shore either as compressed in pipelines, or as liquid or compressed on ships. On shore, hydrogen can be used in a number of applications, from industrial use to fuel for vehicles.

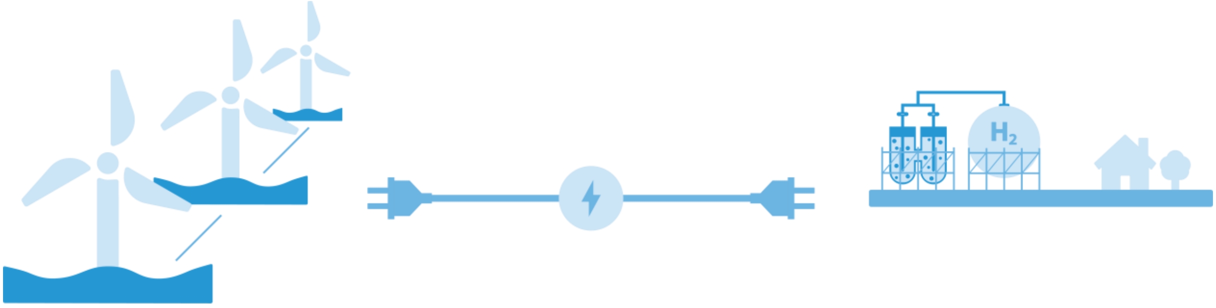


Figure 2: Onshore hydrogen value chain. Illustrates an offshore wind farm, transport of electricity to shore using submarine power cables, and onshore electrolysis and storage.

For onshore, there is an established grid connection which ensures transportation of electricity to the shore. The electricity can either be used directly or in electrolysis processes for production of hydrogen. It should be noted that this thesis does not include cost elements related to the electrolysis or storage of hydrogen for the onshore hydrogen value chain.

3.1 Sørvest B

NVE has suggested 20 areas outside Norway that may be relevant for the development for offshore wind. One of the areas is Sørvest B and is located in the middle part of the North Sea. NVE has defined the most techno-economic depth interval for bottom fixed foundations between 5-70 meters. The sea depth for Sørvest B ranges from 50-80 meters, but most of the study area has a depth of 60-70 meters. This makes it most suitable for bottom fixed foundations [41]. Figure 4 shows the geographical location of Sørvest B.

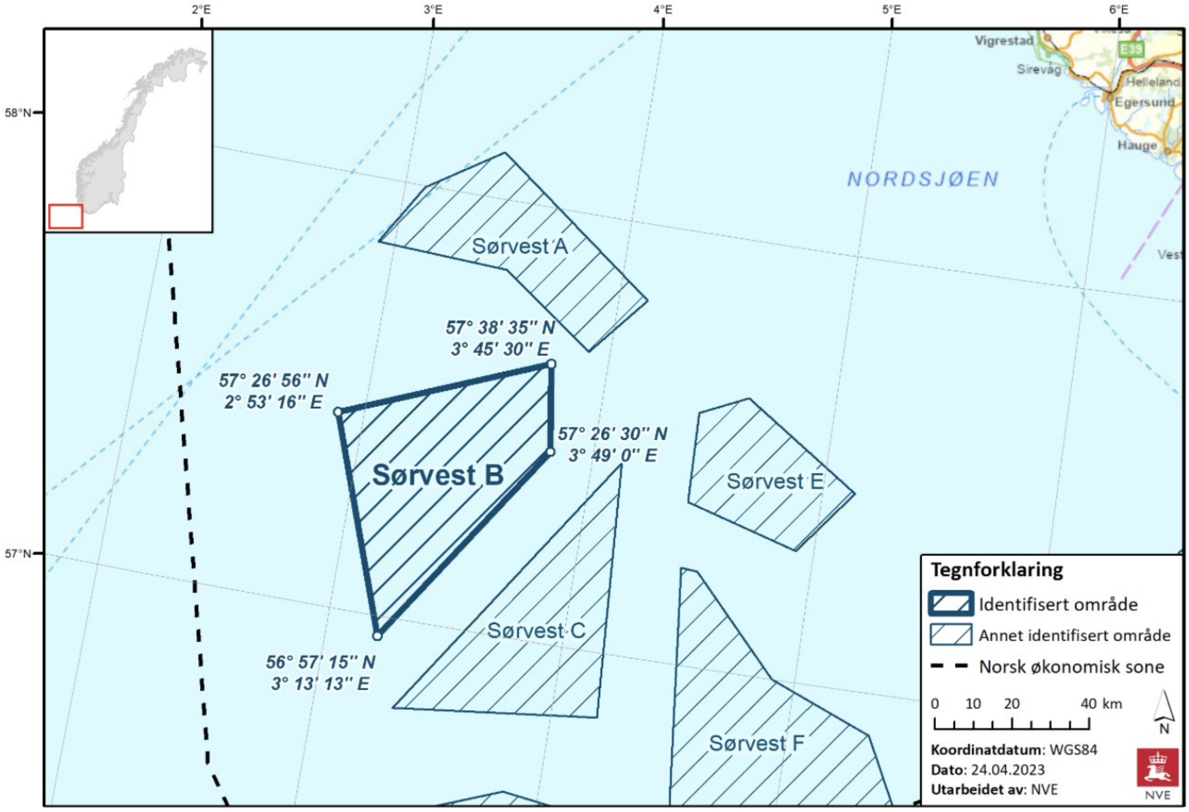


Figure 3: Geographical location of the area Sørvest B [41].

Sørvest B has a total area of 2179 km^2 and the distance from shore is about 152 km. The area has an average windspeed of 10.6 m/s. The windfarm is estimated to have an operational time of 4754 hours within a year and a yearly production of 4.75 TWh with loss. The operating time tells how many hours during the year the windfarm must run at full capacity to achieve the actual annual production. The yearly production is based on a reference project with a size of 1000 MW, and the losses are due to various factors such as downtime for maintenance and wake loss. Wake loss is turbulence that occurs behind a turbine [42]. Furthermore, these numbers are used to calculate the amount of hydrogen that can be produced from the windfarm, and an overview of these numbers are shown in table 2.

Table 2: Summary of geographical and wind data for the identified area, Sørvest B

Sørvest B	
Total area	2179 km^2 [41]
Yearly production from the wind farm (with loss)	4.75 TWh [41]
Average windspeed	10.6 m/s [41]
Sea depth	50-80 m [41]
Distance from shore	152 m [41]
Operational time (with loss)	4754 h [41]

Figure 3 shows that Sørvest B is in close proximity to the Ekofisk oil field, yet it avoids conflict with existing petroleum fields or areas where there are extraction permits.

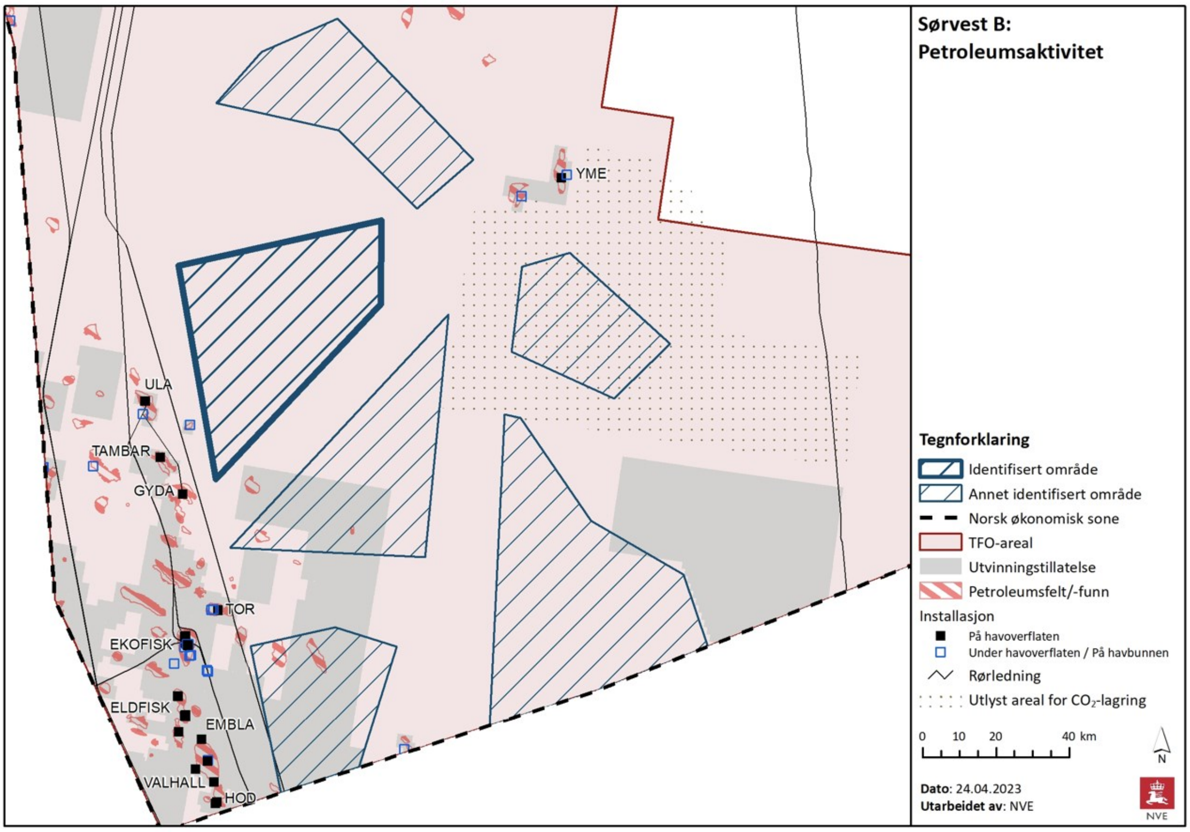


Figure 4: Activities related to petroleum and the storage of CO2 around Sørvest B. The selected area is hatched with dark blue lines. The light blue hatched lines are other identified areas. The grey fields are where there is an extraction permit. The red hatched areas are petroleum fields. The dotted area is a declared area for CO_2 storage [41].

On the other hand, an offshore windfarm can affect the fishing industry. Both the installation and noise from the turbine can alter fish migration patterns, potentially reducing the availability of fish. Given the fishing around Sørvest B, the distance from the wind turbines should be clarified to prevent significant safety risk, for instance collisions with wind turbines or the fishing gear getting stuck in anchorage [43].

Another important factor to consider is the presence of bird species. Sørvest B has a low sensitivity value in this area. Its location and distance from the coast mean a low number of species and individuals compared to areas that are more vulnerable. Nevertheless, summer is a period of increased vulnerability. Bird species that may be affected include seagulls, auks, and gannets [41].

The windfarm may also impact ship transportation. The sea is an important portal for export and imports. To ensure efficient and safe maritime transport, a system of navigation routes has been established. Wind turbines can potentially disrupt safe navigation and access, at the same time change the navigation routes and increase the distance. This can result in increased climate emissions for sea transport [44].

This area has been chosen because of its great potential and its high electricity production. Furthermore, the distance to shore makes it possible to compare onshore and offshore hydrogen production. The close location of the wind farm to shore also enables easier access to distribution networks and markets, which are crucial to achieve the potential of the hydrogen economy.

3.2 Existing European pipeline infrastructure

Figure 5 shows Norway’s existing network for natural gas transport via pipelines in Europe. The well-developed infrastructure connects the country with United Kingdom, Germany, Belgium, and France. The potential for blending hydrogen into existing natural gas pipelines could present an opportunity for transporting smaller volumes of hydrogen to the European market. There are two options for when the hydrogen gas reaches the receiving terminal. Either the hydrogen would need to be separated from natural gas through a separation process, or the gas could be utilized with a certain amount of hydrogen blended in [2]. The quality of steel is crucial considering hydrogen's properties, since a big challenge with blending hydrogen into natural gas is related to hydrogen embrittlement.

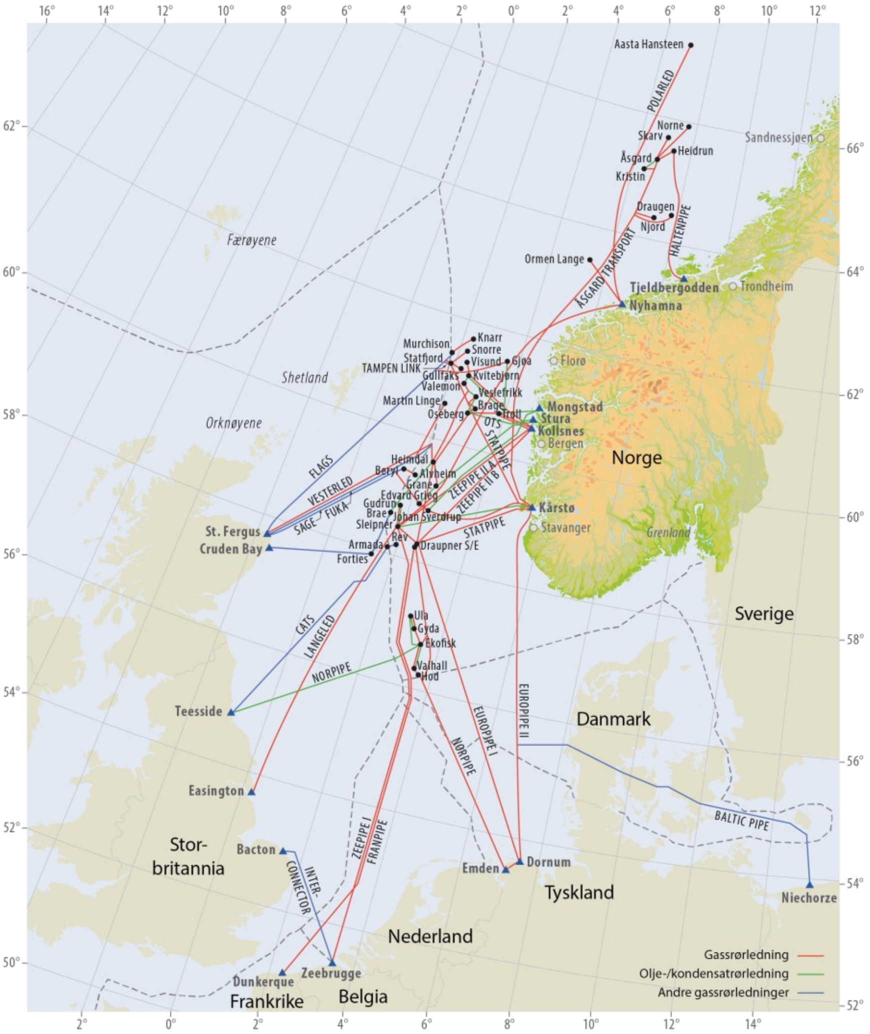


Figure 5: Pipelines on the Norwegian continental shelf [45]

For this study, only new offshore pipelines will be explored in all-new infrastructure will be explored. New pipelines can be designed to accommodate the desired capacity in nearby pipelines and offer future connections to other pipelines. Furthermore, there are opportunities to explore ongoing offshore hydrogen infrastructure projects and land-based hydrogen transport, but this will not be delved into for this case.

4. Methodology

The aim of this thesis is to perform a techno-economic analysis of the role of hydrogen in getting offshore wind power to markets and end users, with focus on possible transport methods. This chapter addresses the methods used to answer the aim. First, a literature study was conducted to establish a fundamental understanding of hydrogen technology and various transport methods. Relevant data was then collected, which formed the basis for the calculations presented in this chapter.

4.1 Literature study

A literature study was essential in writing this thesis. First and foremost, it provided a solid understanding of existing knowledge in the field, and an overview of theory. The literature study also helped to validate findings and results. In the initial phase, various offshore wind areas were examined. Furthermore, various production methods, transport methods, storage methods, and more, were investigated. The research included thorough searches through a variety of information sources covering a wide range of ships design, piping material and storage tanks, both existing and under development. The search portal Oria was also frequently used. This is a search engine that provides access to academic books and articles. The sources were carefully assessed with the aim of strengthening the validation of the thesis. The literature study also served as a key component in establishing a solid knowledge base. This basis was essential in order to place the aim in a the right context.

4.2 Data collection

Data in this study was collected from various research articles and literature, websites and meetings related to the aim of the thesis. All of the data was publicly available on the internet and URLs for download are given in references, chapter 8. Regular meetings were held with our external supervisors where they gave advice on articles with useful information, as well as data we could use in the thesis. A meeting was also held with Gassco. They expressed their interest in this bachelor thesis due to their knowledge about pipelines and gave valuable insight that was used in this thesis. All data collected in this process, as well as information obtained from Gassco was used as a basis for the calculations. After identifying relevant studies through the literature search, the data collected were then carefully assessed and compared.

4.3 Data analysis

Data collected was used to perform calculations necessary to determine the amount of hydrogen produced from the windfarm. This was further used to calculate levelized cost of hydrogen transportation (LCOHT) and levelized cost of energy transportation (LCOET). The calculations have been done in Excel.

In order to calculate and estimate the levelized cost of hydrogen transportation (LCOET) and levelized cost of energy transportation (LCOET), the amount of hydrogen or power which can potentially be transported was calculated. The amount of produced hydrogen at Sørvest B can be calculated by the given formula:

$$\text{Amount of hydrogen (kg)} = \frac{\mathrm{E} * \eta}{\rho} \tag{1}$$

Where E is the energy from windfarm (kWh), η is the efficiency for PEM electrolyzer and ρ is the energy density of hydrogen (kWh/kg).

Furthermore, based on the values found in this thesis, the formula below is used to calculate the amount of energy that can potentially be transported.

$$Installed\ capacity = \frac{Energy\ produced}{Operational\ time} \tag{2}$$

To find the material cost of pipelines, formulas 3, 4 and 4 are used. First, the inside diameter (ID) of pipe is calculated using formula 3.

$$\text{Inside diamter (ID)} = \mathrm{OD} - 2\mathrm{t} \tag{3}$$

Where, OD is the outside diameter and t is the nominal wall thickness. Furthermore, the volume of pipe was found using equation 4:

$$V = \pi * \frac{(OD^2 - \mathrm{ID}^2)}{4} * L \tag{4}$$

Where, V is the volume, OD is the outside diameter, ID is the inside diameter and L is the length of the pipe.

Finally, the weight of pipe calculated using formula 5:

$$Weight = V * \rho \tag{5}$$

Where, V is the volume and ρ is the density.

4.3.1 LCOHT and LCOET

LCOHT and LCOET measures lifetime costs for transportation divided by hydrogen or energy production. These calculations are essential for assessing whether to proceed with a project, and at the same time comparing different transport methods with varied lifetime, capital costs and sizes. They also represent the average minimum price that must be achieved to cover the total transport cost over the lifetime of electricity and hydrogen transport system [46]. The total minimum price must also cover the other parts of the value chain, such as production, storage etc.

$$LCOHT = \frac{\sum_{t=0}^{n} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{H_t}{(1+r)^t}} \tag{6}$$

$$LCOET = \frac{\sum_{t=0}^{n} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{7}$$

The investment cost (CAPEX), operating cost (OPEX) and the fuel cost for each year t are represented by the symbols I_t, O_t and F_t. The symbol n and r stand respectively for the total number of years (lifespan) and the assumed discount rate. H_t and E_t are the hydrogen production and energy production for each year [25].

4.4 Limitations and assumptions

There are various alternatives that can be considered for this case structure. To prevent the thesis from becoming overly complex, some factors have been disregarded. In addition, certain assumptions and limitations have been established to reduce complex calculations necessary to accomplish this thesis. This section aims to outline the alternatives considered for the bachelor thesis.

In the sensitivity analysis, the lifetime used is an assumption based on the lifespan relevant for each of the transport methods.

Losses from the wind farm to the electrolysis process etc. have not been considered in this thesis. The calculated amount therefore does not describe the actual amount that will be transported and used. To simplify the levelized cost of hydrogen transportation calculations, these factors are not included:

- The price for electricity from the selected wind farm
- The price for the hydrogen production platform
- The price for water desalination at the platform
- The price for electrolyzer

The PEM electorlyzer is a preferred option given the benefits such as faster response time and lower area requirements. PEM have an energy efficiency of 55-66% [16]. A lower efficiency of 55% takes account of possible losses and inefficiency in the system and has been applied for the calculation of hydrogen production at Sørvest B, chapter 5 results. The actual efficiency may vary depending on factors such as maintenance, temperature, pressure and other operating conditions.

4.4.1 Discount rate

An average discount rate of 6.75% for offshore wind projects were reported by Nordic respondents in a survey by Grant Thornton [47]. The discount rate of this thesis is assumed to be similar to those reported for offshore wind projects and has been rounded up to 7%. The discount rate of 7% has been applied to make a simplified estimation for all LCOHT and LCOET calculations in this study.

4.4.2 Alternatives for hydrogen transport via ships and storage tanks

McDermott and Samsung C&T are two companies developing liquid hydrogen tanks with a capacity of 40 000 m^3. Cost values from the U.S Department Energy (DOE) has been used to calculate LCOHT, with focus on "ultimate cost target". The goal aims to lower the capital costs associated with hydrogen as an energy carrier. This is assumed as it is expected that it will take a long time before this goal is realized. For compressed, the cost is approximately 600 USD/kg [13]. [13]. To calculate the total cost, it is based on the same amount of hydrogen in kg as a tank for liquid hydrogen can store.

For liquid hydrogen, the focus is on a ship called Jamila, with a capacity of 280 000 m^3. While there are ships for compressed hydrogen, all costs related to ships are the same as for liquid, as it is challenging to find specific values for compressed. Currently, there are no ships of sufficient size available.

4.4.3 Assumptions for pipeline estimations

The material cost estimates for pipelines are taken from a company called Trident Steel & Engg. Co. The head office is located in Mumbai, India and is a large global supplier of all kinds of piping solutions for oil and gas industries [48]. In this case study, only three pipe dimensions of 10, 12, 14 inches are examined and is a simplification of reality. The dimensions of offshore pipelines are assumed to be the same as for onshore pipelines.

A study on estimating the construction costs of natural gas pipelines indicated that the share of cost components was different for specific regions in the United States, where in the central region the material cost made up around 41 percent of total cost. Whereas, in the Northeast and

Southeast regions was only 24 percent of the total cost. In addition, offshore costs per mile for pipelines were about 1.96 times as high for onshore pipelines in the year 2000-2001 [49]. For this thesis, the material costs have been estimated to be around one third of the total costs and multiplied by two in an effort to convert it from onshore to offshore pipelines. Furthermore, a report by the title "Unit Investment Cost Indicators", published by ACER, indicated that there is a ten percent cost difference between hydrogen pipelines and natural gas pipelines. A multiplication factor of 1.1 is applied to adjust the technical, material and labor cost of gas pipelines [50]. This adjustment is made to estimate the costs of a hydrogen pipeline and has been applied to the calculation of CAPEX costs for this thesis.

Additional cost assumptions such as operating and maintenance costs are based on European Hydrogen Backbone (EHB) regarding European hydrogen infrastructure [5]. The estimates are conducted by comparing existing natural gas networks. Further calculations regarding pipelines will be shown in chapter 5.3 for this pipeline.

The number of compressors stations required in pipelines depends on the length, diameter, and mass flow rate. The assumption related to pressure drop is based on the research article (Cost optimization of compressed hydrogen gas transport via trucks and pipelines). The article estimated that larger pipe diameter resulted in less pressure drop for the same mass flow rate [1]. As mentioned before, the distance in this thesis is 152 km from the windfarm to shore. With such a short distance, it is assumed that only one compressor station is necessary for the pipeline.

4.5 Sources of error

Identification of potential sources of error is essential to ensure the validity and reliability of the thesis. This section mentions some sources of error that may have affected the results of this study. First, some assumptions have been made which may not have been optimal enough, such as disregarding losses in the value chain. For instance, the energy losses from the wind farm to the elecrolyzer and from the electrolyzer to storage. In addition to assumed prices for storage tanks and operating costs for pipelines. Furthermore, there may be errors or inaccuracies in the overall calculations. Information may have been registered or entered incorrectly, due to manual entry of numbers or incorrect format.

5. Results of calculations

In this chapter the calculated results are described and presented from this thesis.

To calculate and estimate levelized cost of hydrogen transportation (LCOET) and levelized cost of energy transportation (LCOET), the amount of hydrogen or power that is going to be transported must be found.

$$Amount\ of\ hydrogen = \frac{4.75 * 10^9\ kWh * 0{,}55}{33.3\frac{kWh}{kg} * 10^3\frac{kg}{ton}} = 78\ 454\ tons$$

Using Equation 1, the amount of hydrogen from the windfarm can be calculated. The power from the windfarm is multiplied by the efficiency of the PEM electrolyzer. This is divided by the energy density of hydrogen, which is 33.3 kWh/kg. Lastly, divided by 1000 to get the answer in tons. Annual hydrogen production is calculated to 78 454 tons, equivalent to approximately 215 tons/day.

5.1 Submarine power cable calculations

Before calculating the LCOET of a submarine power cable, it is necessary to determine the installed capacity of the wind farm.

$$Installed\ capacity\ (P) = \frac{4.75\ TWh}{4754\ h} = 9.992 * 10^{-4}\ TW = 999.2\ MW$$

Equation 2 tells us that the maximum capacity of the wind farm is 999.2 MW. This is based on the yearly production and the total operating time (with loss) obtained from the data of Sørvest B, here 4.75 TWh and 4754 hours.

Table 3 presents key parameters and assumptions used to calculate the levelized cost of energy transportation (LCOET) for a submarine power cable connecting the wind farm to shore. The following values are included:

Table 3 Summary of data for submarine power cable at identified windarea Sørvest B

Submarine power cables	
Yearly production from the wind farm	4.75 TWh [41]
Operational time of windfarm	4754 h [41]
Installed capacity of windfarm	999.2 MW
Distance to shore	152 km [41]
€/$ conversion rate	1.08 $/€ (obtained 06.05.2024) [51]
CAPEX	2 €/MW/m [25]
OPEX	0.67 %/CAPEX/year [3]
Discount rate	7 % [47]

The values in table 3 are used to calculate LCOET (7) by summing all the costs (CAPEX and OPEX) over the lifetime of the submarine power cable and dividing by the total amount of energy transported over the power cable during its lifetime. The investment cost (CAPEX) for the power cables is set at 2 £/MW/m and the annual Operation and Maintenance cost (O&M) is at 0.67% of the installation cost (CAPEX per year). It is important to note that the estimates for CAPEX and OPEX are obtained from reports that have made these calculations. The currency rate used for conversion between euros and US dollars, was obtained on May 6, 2024, to ensure that all costs are consistent in the same currency. The estimated discount rate, here 7%, is the rate of return used to discount future costs back to their present value.

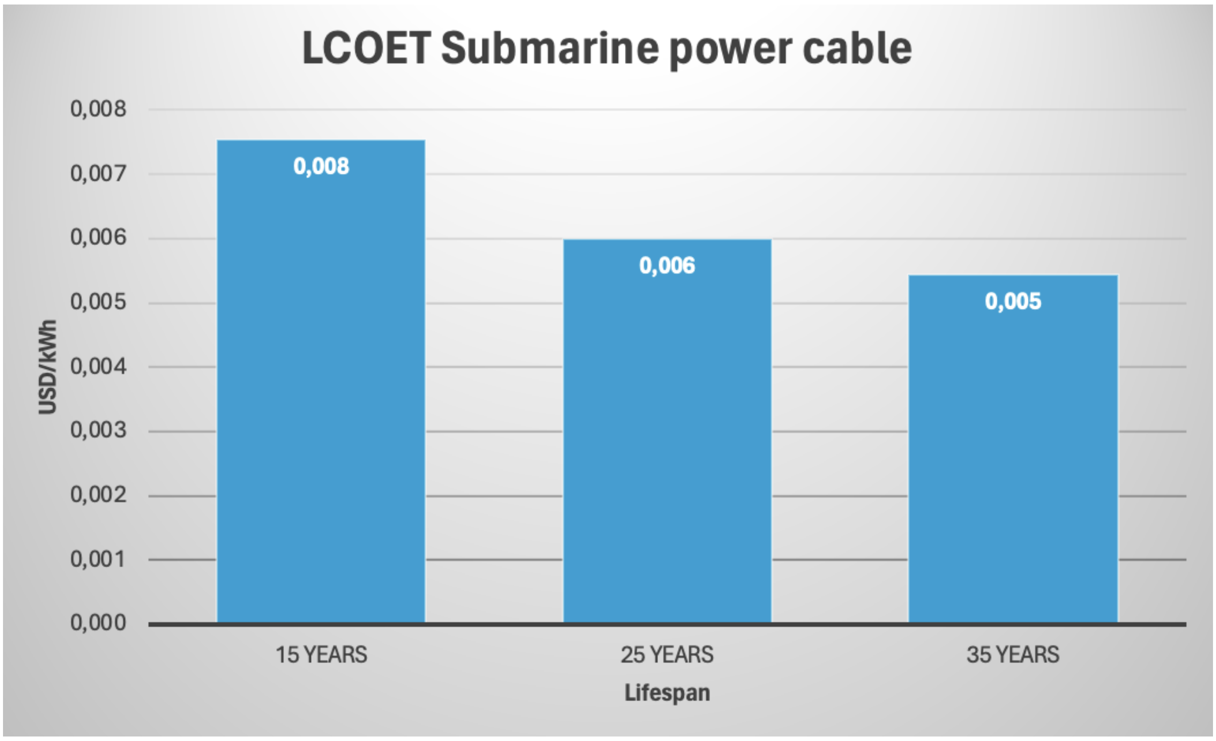


Figure 6: LCOET for submarine power cable with lifespan of 15 years, 25 years and 35 years

Figure 6 compares the cost per kWh (USD/kWh) for cables with three different lifetimes: 15 years, 35 years, and 45 years. The presented LCOET values are 0.008 USD/kWh, 0.006 USD/kWh, and 0.005 USD/kWh. The choice of the lifetimes presents an overview of the cost benefits by investing in power cables that have the potential to last longer. The cost per kWh decreases as the lifetime of the submarine power cable increases. This suggests that it is more economically favorable to invest in submarine power cables with longer lifespan.

For example, if we compare a cable with a lifespan of 15 years and one with 35 years, it is shown that the cost per kWh is lower for the cable with a longer lifespan (0.008USD/kWh vs. 0.005 USD/kWh). This indicates that a lifespan of 35 years for submarine power cables is more favorable. Furthermore, figure 6 shows that the costs are reduced by 0.002 USD/kWh from a lifetime of 15 years to 25 years. And a small difference in cost reduction of 0.001 USD/kWh is shown between 25- and 35-years.

5.2 Ship calculations

Ships for both LH_2 and CGH_2 are presented here. Cost values were only found for LH_2 ships in terms of ship costs, crew costs, fuel costs and operating and maintenance costs (O&M), and the same costs are also used for CGH_2. The discount rate is set as 7% to reflect the present value of future costs for both LH_2 and CGH_2 ships.

5.2.1 LH_2 ship

Table 4 contains key values used in the calculation of levelized cost of hydrogen transportation (6) for a ship that transports liquid hydrogen. The cost for liquefaction plant is obtained from the estimations of US Department of energy (DOE) and is based on the ultimate cost target. DOE have also estimated a price of 3.3 million USD for an LH2 tank with a volume of 3500 m^3. Based on this, a simplified assumption has been made that the price will increase proportionally with the size of the tank. Thus, the cost of the LH2 storage tank, shown in table 4, represents a capacity of 40000 m^3. The total CAPEX is the sum of the costs for the ship, liquefaction plant, and storage tank. The total OPEX is estimated to be the sum of fuel costs, crew costs and O&M costs.

Table 4 Key data and assumptions for the evaluation of LCOHT by LH_2 ship

Ship (LH_2)	
Yearly hydrogen production	78 454 tons
Liquefaction plant	142 000 000 USD [13]
LH_2 storage tank	37 700 000 USD
Cost of ship	480 800 000 USD [28]
Crew cost	1 460 000 USD/year [28]
Fuel cost	33 062 400 USD/year [28]
Operational & maintenance	2 800 000 USD/year [28]
Discount rate	7 % [47]

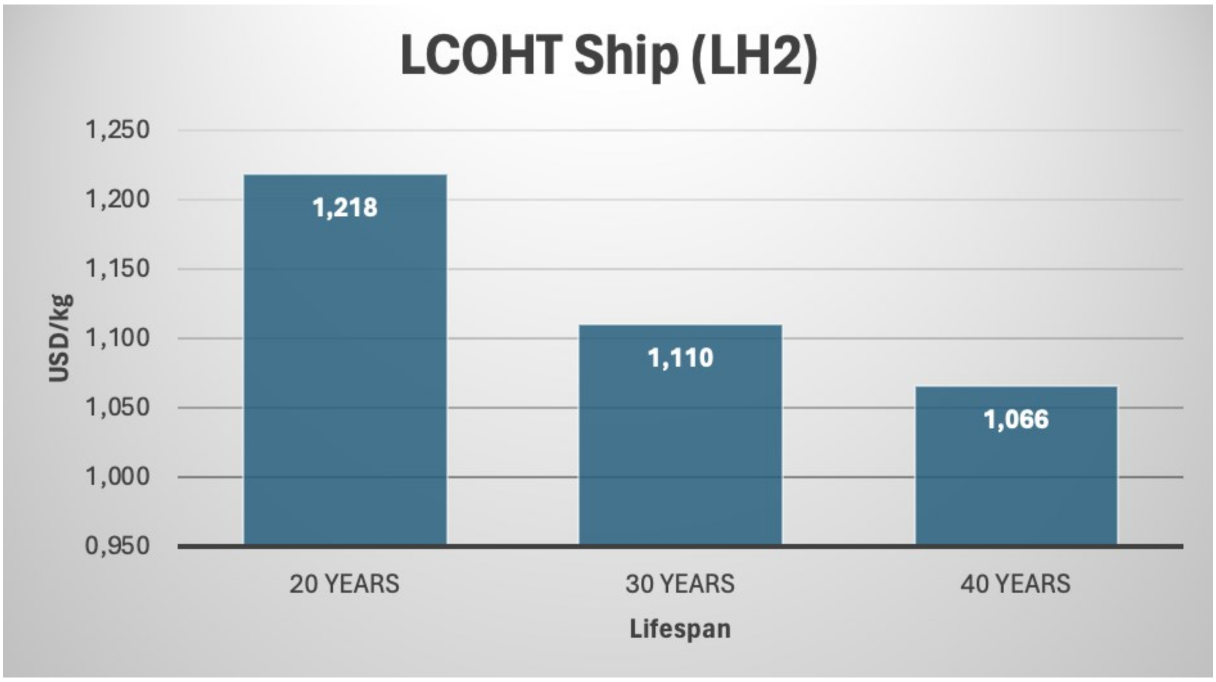


Figure 7: LCOHT for LH_2 ships with lifespan of 20 years, 30 years and 40 years

Levelized cost of hydrogen transportation represents the average cost of transporting LH2 over the lifetime of the ship, measured in USD per kg of hydrogen. Figure 7 shows that the highest LCOHT is 1.218 USD/kg for a lifetime of 25 year. LCOHT decreases with longer lifetime, where 30 years shows an LCOHT of 1.110 USD/kg. This is due to the yearly investments in liquefaction plants and storage tanks which are distributed over a longer period of time. Lastly, the lowest LCOHT is 1.066 USD/kg.

5.2.2 CGH$_2$ ship

Table 5 contains key values used in the calculations of levelized cost of hydrogen transportation (6). It is assumed the same values for total OPEX, and costs of ship as found for LH2 ships. The total OPEX is the sum of the costs for the ship, compression plant, and storage tank.

In order to calculate the price of storage tank for compressed hydrogen, some assumptions were made. First, it is assumed that the density of compressed hydrogen is 0.08988 kg/m^3 [52]. Furthermore, it is assumed that the energy content to be stored should be the same as liquid hydrogen. Therefore, it is first calculated how many kg 40 000 m^3 of liquid hydrogen corresponds to. Then this number is multiplied by 600 USD/kg, which is the price of a compressed hydrogen storage tank, shown in table 5 below.

Table 5 Key data and assumptions for the evaluation of LCOHT by CGH_2 ship

Ship (CGH_2)	
Yearly hydrogen production	78 454 tons
Compression plant	1 800 000 USD [13]
CGH_2 storage tank	600 USD/kg [13]
Cost of ship	480 800 000 USD [28]
Crew cost	1 460 000 USD/year [28]
Fuel cost	33 062 400 USD/year [28]
Operational & maintenance	2 800 000 USD/year [28]
Discount rate	7 % [47]

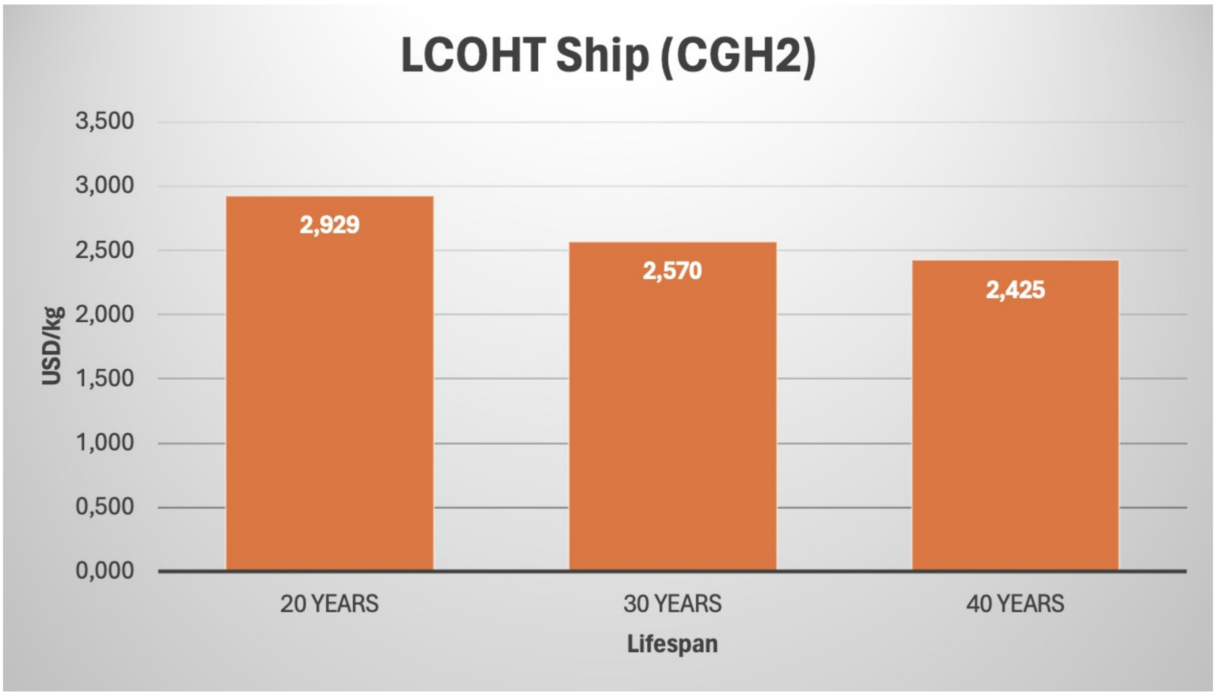


Figure 8: LCOHT for CGH_2 ships with lifespan of 20 years, 30 years and 40 years

LCOHT represents the average cost of transporting compressed hydrogen over the lifetime of the ship, measured in USD per kg of hydrogen. Figure 8 illustrates LCOHT of 2.929 USD/kg at 20 years, 2.570 USD/kg at, 30 years, and lastly 2.425 USD/kg at 40 years lifetime. The lowest alternative for CGH2 is when the lifetime is 40 years. This presents how the different lifetimes affect the cost of hydrogen transport.

Both types of ship present a reduction in LCOHT with increased lifetime. However, LH2 ships appear to have significantly more cost reduction compared to CHG2 ships, especially with the lifespan from 20 years to 40 years. Although the production of liquid hydrogen is more expensive than compressed hydrogen, due to the energy demanding process of liquefaction. LH2 ships can transport larger quantities of hydrogen per volume because of higher energy density. While CGH2 ships require more space for the same amount of energy, which increases the number of shipping trips required and therefore the costs as well.

5.3 Pipeline calculations:

A proposed concept for transport methods in this study involves a new pipeline stretching from the wind farm to the receiving terminal at shore. Table 6 and 7 provide a comprehensive overview of both the physical dimensions and material costs of a 10- inch pipeline at schedule 40 (SCH40). A pipe schedule is a measure of steel pipe's nominal wall thickness [53]. SCH40 steel pipe is commonly used due to its versatility and performance strength, and it is specified as 10.31 mm, shown in table 6 below. The pipe dimensions are obtained from a PSL2 wall thickness reference chart based on carbon steel specified API 5L X65 [54]. The inside diameter was calculated using equation (3) with the given values in table 6. Further calculations for volume and weight of pipe were solved using equations (4) and (5). The cost for a carbon steel pipe shown in table 7 is given in USD per ton for an API 5L X65 pipe [55]. To find the material costs for a pipeline of 10-inch the calculated weight of the pipe was multiplied with the price of steel pipe. Moreover, the share of material cost increased when the pipeline diameter increased.

Table 6: Key data for 10-inch dimension of carbon steel pipeline at SCH40.

Pipeline dimensions	
Outside diameter	232.8 mm [54]
Nominal Wall thickness SCH 40	10.31 mm [51]
Inside diameter	212.18 mm

Table 7: Key data for material costs for a carbon steel pipeline

Carbon steel pipeline	
Volume of pipe	1095.37 m^3
Weight of pipe	8598.7 tons
Price of steel pipe	1950 USD/ton [55]
Density of steel	7850 kg/m3 [56]

Table 8 provides key data for the basis for calculating the LCOHT (6) via H2 pipelines. The table includes yearly offshore hydrogen production, compressor cost, total CAPEX, operating costs, lifetime, and discount rate. The material costs have been estimated to be around one third of the total CAPEX and multiplied by a factor of two in an effort to convert it from onshore to offshore pipelines. A multiplication factor of 1.1 is applied to adjust an estimate to the cost difference between a natural gas pipeline and a hydrogen pipeline. The represented lifespan of 35 years is an assumption based on the pipeline life expectancy.

Table 8: Key data and assumptions for the evaluation of LCOHT by H2 pipeline

Pipeline	
Yearly hydrogen production	78 454 tons
Compressor cost	1 800 000 USD [13]
Total CAPEX	137 825 102 USD (10- inch pipeline)
OPEX/Year (O&M cost)	0.8 % CAPEX/years [3]
Lifespan	35 years
Discount rate	7 % [47]

Figure 9 shows the lowest LCOHT of USD 0.128 per kg of hydrogen for a pipe dimension of 10 inch. For a pipe dimension of 12 inch the LCOHT is USD 0.223 per kg and the highest LCOHT for a pipe dimension of 14 inch is USD 0.293 per kg hydrogen. The cost estimates all represent new infrastructure and are calculated with regard to the same distance of 152 km, a discount rate of 7% and a pipeline lifespan of 35 years. The LCOHT values show a clear pattern where the cost per kg of hydrogen increases with the diameter of the pipeline. This may be due to higher material and installation costs for larger pipelines.

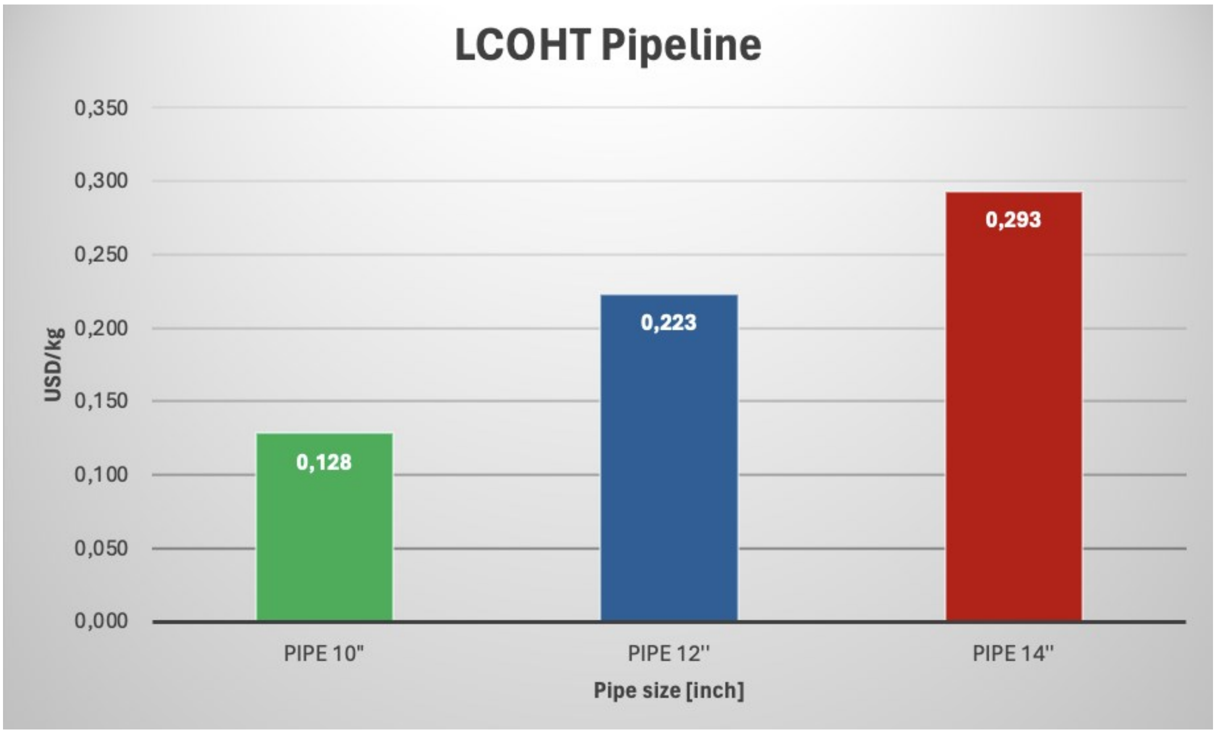


Figure 9: LCOHT for 10-inch pipe, 12-inch pipe and 14-inch pipe

5.4 Levelized cost of energy transportation (LCOET)

Previous figures, Figure 6, Figure 7 and Figure 8, show how lifetime affects LCOHT and LCOET. In addition, figure 9 shows LCOHT with different pipe dimensions. The most relevant options are included in figure 10. Discount rate is set to 7% for all transport methods to provide the best possible comparison. Furthermore, it is evident that 10-inch pipeline (0.004 USD/kWh) is the most cost-effective option, followed by submarine power cables (0.006 USD/kWh) and LH_2 ships (0.033 USD/kWh), with CGH_2 ships (0.077 USD/kWh) being the most expensive choice. Nevertheless, it is essential to consider that hydrogen technology is still in its development stage, which may lead to inaccuracies or deficiencies in the calculations.

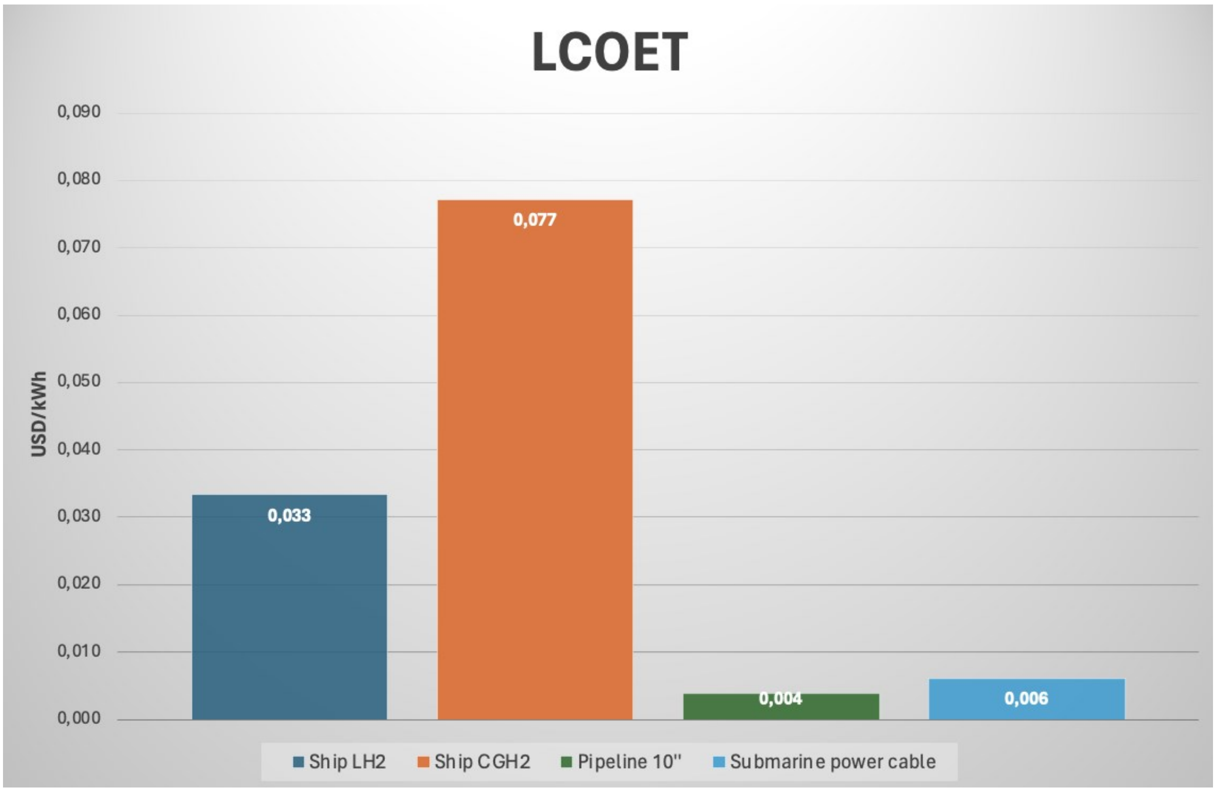


Figure 10: LCOET for LH_2 ship, CGH_2 ship, pipeline 10¨ and submarine power cable

6. Discussion

In the course of this bachelor thesis, the transport of hydrogen has been explored and analyzed. Calculations have been carried out the cost associated with it. Due to limited data, it has not been possible to go in-depth on all necessary technologies, and therefore simplifications and certain assumptions have been made. Furthermore, it has been necessary to omit certain aspects from the study. Chapter 6 will discuss the hydrogen value chain, choice of transport method, sensitivity analysis, off-grid wind farm and offshore hydrogen storage.

6.1 The hydrogen value chain

The hydrogen value chain is typically split into parts, such as production, storage, distribution, consumption, and application [57]. The choice of transportation method contributes to the various parts of the hydrogen value chain by ensuring efficient and reliable distribution from production to consumption, as well as affecting the choice of storage facilities. In addition, the method of hydrogen transport can influence cost effectiveness, safety, and sustainability in the entire value chain.

6.2 Off-grid wind farm

Although this thesis examines various transport methods, it is also important to draw attention to the wind farm. The establishment and operation of a wind farm will undoubtedly have an impact on the environment. This impact may include changes noise disturbances, changes in animal habitats and the landscape, and the need for infrastructure development.

Having a wind farm without connection to the power grid, also known as off-grid, have several challenges that can affect both operational efficiency and economics. A significant disadvantage of this approach is the limited flexibility in terms of power delivery. With the absence of connection to the power grid, the wind farm can only supply power locally or to any connected devices, which limits the opportunities to sell excess power or take advantage of the flexibility of the power grid.

Another disadvantage is the lack of power support at low production levels. Wind power production varies significantly with weather conditions, and there may be periods with low or no electricity production. Without connection to the power grid, it can be challenging to handle such periods without external power support. It can also have consequences for hydrogen production.

Technical challenges can also occur. Without access to the stability of the power grid, it can be more difficult to maintain a steady power supply to connected devices such as electrolysis plants. This can lead to inefficient operation and increase wear and tear on the equipment, which can again affect the operating costs.

6.3 Offshore hydrogen storage

This thesis has looked at transport methods for offshore hydrogen production. In order to be able to utilize all the energy from the wind farm, without having to connect to the grid, storage is essential. There are several advantages and challenges associated with offshore storage that are important to consider.

One of the prominent advantages of offshore hydrogen storage is the availability of large, unlimited storage areas. Marine area allows for large-scale storage, which can be important for countries that have limited land areas or who wish to avoid conflicts with other agricultural or development areas. Furthermore, the volumetric energy density of compressed hydrogen is significantly lower than for liquid hydrogen, and more tanks are therefore needed to store the same amount of energy. In addition, offshore storage can help relieve the pressure on land-based storage infrastructure and distribution networks, thus enabling more efficient and reliable handling of the hydrogen capacity.

At the same time, there are several challenges that must be solved in order to realize efficient offshore storage of hydrogen. One of the most significant challenges is the cost and complexity of building and maintaining offshore infrastructures. Construction and installation offshore require significant investments in technology, safety, and logistics. In addition, challenges related to corrosion, material wear and environmental impact can be significant and require careful monitoring and management.

It is also important to consider questions related to safety and risk management when storing hydrogen offshore. Hydrogen is highly flammable and can pose significant risks if not handled properly. Therefore, the development of offshore hydrogen storage facilities requires robust safety systems and careful risk assessment to ensure that potential hazards are effectively addressed.

Despite these challenges, offshore hydrogen storage represents a promising alternative to support the development of a sustainable hydrogen economy. With the right technology development, investment and regulation, offshore storage can play an important role in enabling reliable, scalable, and safe storage of hydrogen. Thus, helping to realize the potential for hydrogen as a key component in future energy systems.

6.4 Choice of transport method

The choice of transport method for hydrogen is a complex decision, that depends on several factors, including distance, volume, cost, infrastructure and safety aspects. This thesis examined the transport of offshore produced hydrogen in pipelines, and on ships as liquid or compressed hydrogen. In addition, transporting electricity to shore to produce hydrogen onshore has been discussed.

Based on the calculations carried out in chapter 5, it is clear that pipelines are the cheapest transport method (0.004 USD/kWh). It is important to note that the calculations are based on certain assumptions, as the data obtained are estimates based on available information. Nevertheless, one should not overlook the other methods. It is reasonable to assume that prices will decrease over time as the technology develops further and becomes commercially available. However, it is difficult to estimate exactly how much prices will fall. Each of these methods has its advantages and challenges that must be carefully considered.

Pipelines are an efficient transport method for large quantities of hydrogen. This method is cost effective in terms of operating costs and ideal for continuous transport. The challenges with pipelines include high investment costs, as well as potential technical challenges related to materials that can withstand the properties of hydrogen, which can lead to metallic embrittlement. Furthermore, there can be challenges related to safety and regulation, as leaks of hydrogen can be dangerous.

The question is whether it is applicable to build such a small pipeline. Another possible scenario for this study could be a combination of using existing and new infrastructure that could potentially reduce capex for offshore infrastructure. Norway can gain a significant competitive advantage if the existing pipelines in the North Sea can be used to transport hydrogen gas.

Transport by ships is another method that allows large quantities of hydrogen to be transported. Uncertainty about costs and technological development is a factor, as there are few existing examples of operational hydrogen transport ships. Safety is a critical concern and extensive safety protocols are necessary to prevent accidents. For liquid hydrogen transported by ship, the LCOET was 0.033 USD/kWh, while for compressed hydrogen the LCOET was 0.077 USD/kWh. Although it is more expensive and energy demanding to liquefy hydrogen, liquid hydrogen has a higher energy density per volume. This means that more tanks are required to store the same amount of compressed hydrogen in kg as for liquid hydrogen. The investment cost of these storage tanks constitutes as a significant part of CAPEX. The high energy density of liquid hydrogen allows more energy to be transported in a smaller volume compared to compressed hydrogen, meaning a ship can carry more energy as liquid hydrogen, reducing the number of trips required. Furthermore, it is more expensive to keep hydrogen liquid, and the OPEX will most likely be lower for CGH2, the question is whether it ever will be low enough to compete with LH2 ships, pipelines and power cables.

The choice between having the end-use as electricity or as hydrogen is a challenging decision that needs to be evaluated. One option could become more viable than the other, which will depend on the initial purpose for the use of the delivered energy.

Comparing submarine power cables and hydrogen pipelines, the cost ranges for hydrogen pipelines appear to be cheaper and more favorable. However, HVDC lines can efficiently transmit electricity from the windfarm over long distances [24]. Hydrogen has a lower volumetric energy density and takes up more space, which can affect the choice of transportation method and infrastructure. It will be beneficial to include energy storage components into power cables and hydrogen pipeline infrastructure, such as battery or hydrogen storage facilities.

6.5 Sensitivity analysis

In this study of hydrogen transport, a sensitivity analysis has been carried out to understand how different variables affect the levelized cost of hydrogen transportation and the levelized cost of energy transportation. Different lifespans for ships and submarine cables have been investigated, in addition to pipe dimensions.

The lifetime of a transport system has a significant impact on the financial calculations. Longer lifetime can reduce the costs by spreading investment costs over several years. In the sensitivity analysis, it has been investigated how variations in lifetime affect LCOHT and LCOET. The results show that an extension of the lifetime can lead to significant reduction in LCOHT and LCOET, which makes the investments more profitable over time.

Optimizing the lifetime of both ships and submarine power cables is essential to reduce LCOHT and LCOET. Regular maintenance, technological upgrades, and strategic planning to extend operational life can play a significant role in improving the cost efficiency. While both ships and submarine power cables benefit from longer lifetimes by reducing annual capital costs, the specific challenges and solutions are different from each transport method.

By analyzing lifetime and pipe dimensions, it appears that optimizing both factors can provide significant cost savings. By understanding how these variables affect the cost picture, decision makers can make informed decisions that can promote financial and operational efficiency.

In the early phase of development, it is challenging to determine the best solutions with certainty. Based on the calculations and research, a combination of the transport methods, such as submarine power cables and pipelines, may be the most optimal solution to ensure efficient and reliable transport of hydrogen and energy. Choosing a different wind area may significantly impact the case and result. For instance, an area with a greater distance to shore, the use of power cables may become more prominent. This is because submarine power cables are more suitable for transporting more power over longer distances.

7. Conclusions and further work

This chapter will discuss the conclusion and recommendations for further work.

7.1 Conclusions

This bachelor thesis has tried to fill a gap in knowledge in the field of hydrogen transportation, economic and green energy possibilities in the 21-century. The purpose for the thesis was to perform a techno-economic analysis of the role of hydrogen in getting offshore wind power to markets and end users, with a focus on possible transport methods. Local hydrogen distribution is not a part of this thesis.

This study explored different hydrogen transport methods at sea, such as compressed hydrogen (CH_2) by ship, liquid hydrogen (LH_2) by ship and hydrogen by pipeline. In addition to transporting electricity from one offshore wind farm by submarine power cables.

Although the cost results will likely deviate from reality, due to assumptions and simplifications, they offer a valuable insight for decision making. The results reveal that a 10-inch pipeline (0.004 USD/kWh) is the most cost-efficient transport method, followed by submarine power cables (0.006 USD/kWh) and LH_2 ships (0.033 USD/kWh), with CGH_2 ships (0.077 USD/kWh) being the most expensive choice. Further development will most likely reduce investment costs, and thus also provide a lower LCOHT and LCOET.

Overall, Sørvest B represents a strategically important location for renewable energy production. Its favorable geographical location, combined with the availability of ship routes and pipeline infrastructure, makes it a key in the transition to a more sustainable energy future.

7.2 Further work

Recommendations for further work are, among other thing, to look at critical minerals for the electrolysis, and explore other planned infrastructure projects of hydrogen.

Furthermore, LOHC should be considered as a method to transport hydrogen, as it can be transported as other chemicals. Investigating existing pipelines that are normally used for natural gas to transport compressed hydrogen should also be done. Retrofitting existing pipelines can potentially be more cost-effective solution compared to building entirely new pipelines dedicated to hydrogen.

In terms of sensitivity analysis, the distance to shore is another important factor that most likely will affect the LCOHT and LCOET. Especially where transport is dependent on cables or pipelines. Further distance from shore will lead to increased costs and increased complexity in the system. In addition, the use of ships should be explored in cases where hydrogen must be transported over longer distances, which can be an effective solution.

Storage of hydrogen should be investigated for both offshore and onshore. A wind farm the size of Sørvest B needs large storage tanks for hydrogen. It should therefore also be investigated whether a hybrid solution with both submarine cables and pipelines or ships should be used to avoid too large storage tanks.

8. References

[1] M. D. Solomon, W. Heineken, M. Scheffler, and T. Birth-Reichert, ‘Cost Optimization of Compressed Hydrogen Gas Transport via Trucks and Pipelines’, *Energy Technol.*, vol. 12, no. 1, p. 2300785, 2024, doi: 10.1002/ente.202300785.

[2] ‘Rapport om optimal utnyttelse av energi fra havvind’, Greenstat. Accessed: May 19, 2024. [Online]. Available: https://greenstat.no/nyheter/rapport-om-optimal-utnyttelse-av-energi-fra-havvind-offshore-h2-produksjon-og-kabel-til-land

[3] E. Saborit, E. García-Rosales Vazquez, M. D. Storch De Gracia Calvo, G. M. Rodado Nieto, P. Martínez Fondón, and A. Abánades, ‘Alternatives for Transport, Storage in Port and Bunkering Systems for Offshore Energy to Green Hydrogen’, *Energies*, vol. 16, no. 22, p. 7467, Nov. 2023, doi: 10.3390/en16227467.

[4] ‘Hydrogen Value Chain’, Ocean Hyway Cluster. Accessed: May 14, 2024. [Online]. Available: https://www.oceanhywaycluster.no/valuechain

[5] Rik Van Rossum, Jaro Jens, Genna La Guardia, Anthony Wang, Luis Kühnen, and Martijn Overgaag, ‘A EUROPEAN HYDROGEN INFRASTRUCTURE VISION COVERING 28 COUNTRIES’, *Eur. Hydrog. Backbone*, p. 36, Apr. 2022.

[6] ‘Offshore Production of Green Hydrogen’. Accessed: Feb. 26, 2024. [Online]. Available: https://absinfo.eagle.org/acton/media/16130/offshore-production-of-green-hydrogen

[7] Gassco and dena, ‘GER-NOR-Joint-feasibility-study-report-Hydrogen’, Nov. 2023. Accessed: Apr. 21, 2024. [Online]. Available: https://gassco.eu/wp-content/uploads/2023/11/GER-NOR-Joint-feasibility-study-report-Hydrogen-23.11.2023.pdf

[8] ‘About HyValue | HyValue’. Accessed: Mar. 11, 2024. [Online]. Available: https://hyvalue.no/about

[9] P. K. Kofstad, B. Pedersen, T. Kaland, and Allkunne, ‘hydrogen’, *Store norske leksikon*. Apr. 26, 2024. Accessed: Feb. 29, 2024. [Online]. Available: https://snl.no/hydrogen

[10] ‘The hydrogen colour spectrum| National Grid Group’. Accessed: May 19, 2024. [Online]. Available: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

[11] A. Léon, ‘Hydrogen Storage’, in *Hydrogen Technology: Mobile and Portable Applications*, A. Léon, Ed., Berlin, Heidelberg: Springer, 2008, pp. 81–128. doi: 10.1007/978-3-540-69925-5_3.

[12] ‘Hydrogen’, Linde (tidligere AGA) industrigasser. Accessed: May 20, 2024. [Online]. Available: https://www.linde-gas.no/no/products_ren/cutting_welding_gases/fuel_gases/hydrogen/index.html

[13] ‘DOE Technical Targets for Hydrogen Delivery’, Energy.gov. Accessed: May 19, 2024. [Online]. Available: https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery

[14] ‘Hydrogen Production: Electrolysis’, Energy.gov. Accessed: Feb. 26, 2024. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

[15] Y. Guo, G. Li, J. Zhou, and Y. Liu, ‘Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis’, *IOP Conf. Ser. Earth Environ. Sci.*, vol. 371, no. 4, p. 042022, Dec. 2019, doi: 10.1088/1755-1315/371/4/042022.

[16] ‘Lecture notes 3: Production methods: MAS539-1 23H Hydrogenteknologi’, Accessed: Apr. 30, 2024. [Online]. Available: https://hvl.instructure.com/courses/26144/pages/lecture-notes-3-production-methods?module_item_id=682740

[17] K. Hofstad, ‘avsalting’, *Store norske leksikon*. Aug. 22, 2023. Accessed: May 12, 2024. [Online]. Available: https://snl.no/avsalting

[18] 'DNV-ST-F101 Submarine pipeline systems'. Accessed: May 19, 2024. [Online]. Available: https://www.dnv.com/oilgas/download/dnv-st-f101-submarine-pipeline-systems/

[19] S. Kumar, A. K. Panda, and R. K. Singh, 'A review on tertiary recycling of high-density polyethylene to fuel', *Resour. Conserv. Recycl.*, vol. 55, no. 11, pp. 893–910, Sep. 2011, doi: 10.1016/j.resconrec.2011.05.005.

[20] 'Carbon Steel: Properties, Examples and Applications - Matmatch'. Accessed: Mar. 17, 2024. [Online]. Available: https://matmatch.com/learn/material/carbon-steel

[21] 'What is Sour Service Pipe and differences with Normal Pipes', Octalsteel. Accessed: Mar. 19, 2024. [Online]. Available: https://www.octalsteel.com/sour-service-pipe/

[22] 'Submarine Power Cables'. Accessed: May 21, 2024. [Online]. Available: https://www.escaeu.org/articles/submarine-power-cables/

[23] K. Hofstad, 'sjøkabel', *Store norske leksikon*. Jan. 04, 2024. Accessed: May 08, 2024. [Online]. Available: https://snl.no/sj%C3%B8kabel

[24] 'Hydrogen pipelines vs. HVDC lines: Should we transfer green molecules or electrons?', Oxford Institute for Energy Studies. Accessed: May 06, 2024. [Online]. Available: https://www.oxfordenergy.org/publications/hydrogen-pipelines-vs-hvdc-lines-should-we-transfer-green-molecules-or-electrons/

[25] Egeland-Eriksen, Torbjørn and Oosterkam, Antonie, 'Electricity transport vs. hydrogen production from future offshore wind farms', *NORCE Nor. Res. Cent. AS*, p. 7, 2024.

[26] 'The Suiso Frontier', HESC. Accessed: Mar. 18, 2024. [Online]. Available: https://www.hydrogenenergysupplychain.com/about-the-pilot/supply-chain/the-suiso-frontier/

[27] 'Kawasaki Develops Cargo Containment System for Large Liquefied Hydrogen Carrier with World's Highest Carrying Capacity—AiP Obtained from ClassNK | Kawasaki Heavy Industries, Ltd.' Accessed: May 19, 2024. [Online]. Available: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20210506_9983

[28] A. NFNR. Alkhaledi, S. Sampath, and P. Pilidis, 'Economic analysis of a zero-carbon liquefied hydrogen tanker ship', *Int. J. Hydrog. Energy*, vol. 47, no. 66, pp. 28213–28223, Aug. 2022, doi: 10.1016/j.ijhydene.2022.06.168.

[29] R. d'Amore-Domenech, V. L. Meca, B. G. Pollet, and T. J. Leo, 'On the bulk transport of green hydrogen at sea: Comparison between submarine pipeline and compressed and liquefied transport by ship', *Energy*, vol. 267, p. 126621, Mar. 2023, doi: 10.1016/j.energy.2023.126621.

[30] 'Provaris reckons it can crack the hydrogen export challenge | Provaris Energy'. Accessed: May 19, 2024. [Online]. Available: https://www.provaris.energy/news/provaris-reckons-it-can-crack-the-hydrogen-export-challenge

[31] Sjøfartsdirektoratet, 'Ny kunnskap for sikker bruk av hydrogen på skip'. Accessed: May 19, 2024. [Online]. Available: https://www.sdir.no/aktuelt/nyheter/ny-kunnskap-for-sikker-bruk-av-hydrogen-pa-skip/

[32] 'International Maritime Organization'. Accessed: May 20, 2024. [Online]. Available: https://www.imo.org/

[33] 'Kontakt oss - Sjøfartsdirektoratet'. Accessed: May 20, 2024. [Online]. Available: https://www.sdir.no/om-direktoratet/

[34] 'Om DSB', Direktoratet for samfunnssikkerhet og beredskap. Accessed: May 20, 2024. [Online]. Available: https://www.dsb.no/menyartikler/om-dsb/

[35] 'Compressed Hydrogen Storage - an overview | ScienceDirect Topics'. Accessed: May 19, 2024. [Online]. Available: https://www.sciencedirect.com/topics/engineering/compressed-hydrogen-storage

[36] 'Deep Purple^{TM} Pilot - TechnipFMC plc', Technip FMC. Accessed: May 19, 2024. [Online]. Available: https://www.technipfmc.com/en/what-we-do/new-energy/hydrogen/deep-purple-pilot/

[37] T. Pascal, 'Different methods of storing, transporting, and distributing Hydrogen', Structures Insider. Accessed: May 20, 2024. [Online]. Available: https://www.structuresinsider.com/post/different-methods-of-storing-transporting-and-distributing-hydrogen

[38] 'CB&I Receives Approval for Liquid Hydrogen Cargo Containment System for Gas Carriers from DNV'. Accessed: May 08, 2024. [Online]. Available: https://www.mcdermott-investors.com/news/press-release-details/2023/CBI-Receives-Approval-for-Liquid-Hydrogen-Cargo-Containment-System-for-Gas-Carriers-from-DNV/default.aspx

[39] 'Samsung C&T to build world's largest liquid hydrogen tank - KED Global'. Accessed: May 09, 2024. [Online]. Available: https://www.kedglobal.com/hydrogen-economy/newsView/ked202311130004

[40] Oltedal Myrseth, Velaug, 'Lecture 4 Storage of hydrogen: MAS539 Hydrogenteknologi', 2023. [Online]. Available: https://hvl.instructure.com/courses/26144/pages/lecture-notes-4-storage-of-hydrogen?module_item_id=682742

[41] 'Identifisering av utredningsområder for havvind: Sørvest B'. Accessed: Mar. 05, 2024. [Online]. Available: https://veiledere.nve.no/havvind/identifisering-av-utredningsomrader-for-havvind/nye-omrader-for-havvind/sorvest-b/

[42] 'Identifisering av utredningsområder for havvind: Beregning av kraftproduksjon'. Accessed: Mar. 08, 2024. [Online]. Available: https://veiledere.nve.no/havvind/identifisering-av-utredningsomrader-for-havvind/metode-og-vurderinger/beregning-av-kraftproduksjon/

[43] 'Identifisering av utredningsområder for havvind: Fiskeri'. Accessed: Mar. 08, 2024. [Online]. Available: https://veiledere.nve.no/havvind/identifisering-av-utredningsomrader-for-havvind/kunnskapsgrunnlag-om-virkninger-av-havvind/fiskeri/

[44] 'Identifisering av utredningsområder for havvind: Skipsfart'. Accessed: May 19, 2024. [Online]. Available: https://veiledere.nve.no/havvind/identifisering-av-utredningsomrader-for-havvind/kunnskapsgrunnlag-om-virkninger-av-havvind/skipsfart/

[45] 'Rørtransportsystemet - Norskpetroleum', Norskpetroleum.no. Accessed: Apr. 22, 2024. [Online]. Available: https://www.norskpetroleum.no/produksjon-og-eksport/rortransportsystemet/

[46] 'Levelized Cost of Energy (LCOE)', Corporate Finance Institute. Accessed: May 12, 2024. [Online]. Available: https://corporatefinanceinstitute.com/resources/valuation/levelized-cost-of-energy-lcoe/

[47] Grant Thornton UK LLP, 'Renewable Energy Discount Rate Survey 2018', p. 36, Jan. 2019.

[48] 'Trident Steel & Engg. Co. - Supplier of Steel Pipes and Tubes'. Accessed: May 11, 2024. [Online]. Available: https://www.tridentsteel.co.in/about-us.html

[49] 'Oil and Gas Pipeline Construction Costs', Global Energy Monitor. Accessed: May 08, 2024. [Online]. Available: https://www.gem.wiki/Oil_and_Gas_Pipeline_Construction_Costs

[50] 'ACER publishes a report on unit investment costs indicators and corresponding reference values of European energy infrastructure', www.acer.europa.eu. Accessed: May 08, 2024. [Online]. Available: https://www.acer.europa.eu/news-and-events/news/acer-publishes-report-unit-investment-costs-indicators-and-corresponding-reference-values-european-energy-infrastructure

[51] E. C. Bank, 'Euro exchange rates charts', May 2024, Accessed: May 21, 2024. [Online]. Available: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html

[52] S. S. Makridis, ‘Hydrogen storage and compression’, in *Methane and Hydrogen for Energy Storage*, R. Carriveau and D. S.-K. Ting, Eds., Institution of Engineering and Technology, 2016, pp. 1–28. doi: 10.1049/PBPO101E_ch1.

[53] N. Spira, ‘What is Schedule 40 Steel Pipe?’, Kloeckner Metals Corporation. Accessed: May 17, 2024. [Online]. Available: https://www.kloecknermetals.com/blog/what-is-schedule-40-steel-pipe/

[54] ‘API 5L X65 Pipe PSL2 and Gr X65 PSL1 Seamless/ ERW material supplier’. Accessed: May 11, 2024. [Online]. Available: https://www.tridentsteel.co.in/api-5l-x65-pipe.html

[55] ‘Carbon Steel Pipe Price List and API 5L Pipe Rates per meter’. Accessed: May 08, 2024. [Online]. Available: https://www.tridentsteel.co.in/carbon-steel-pipe-price-list.html

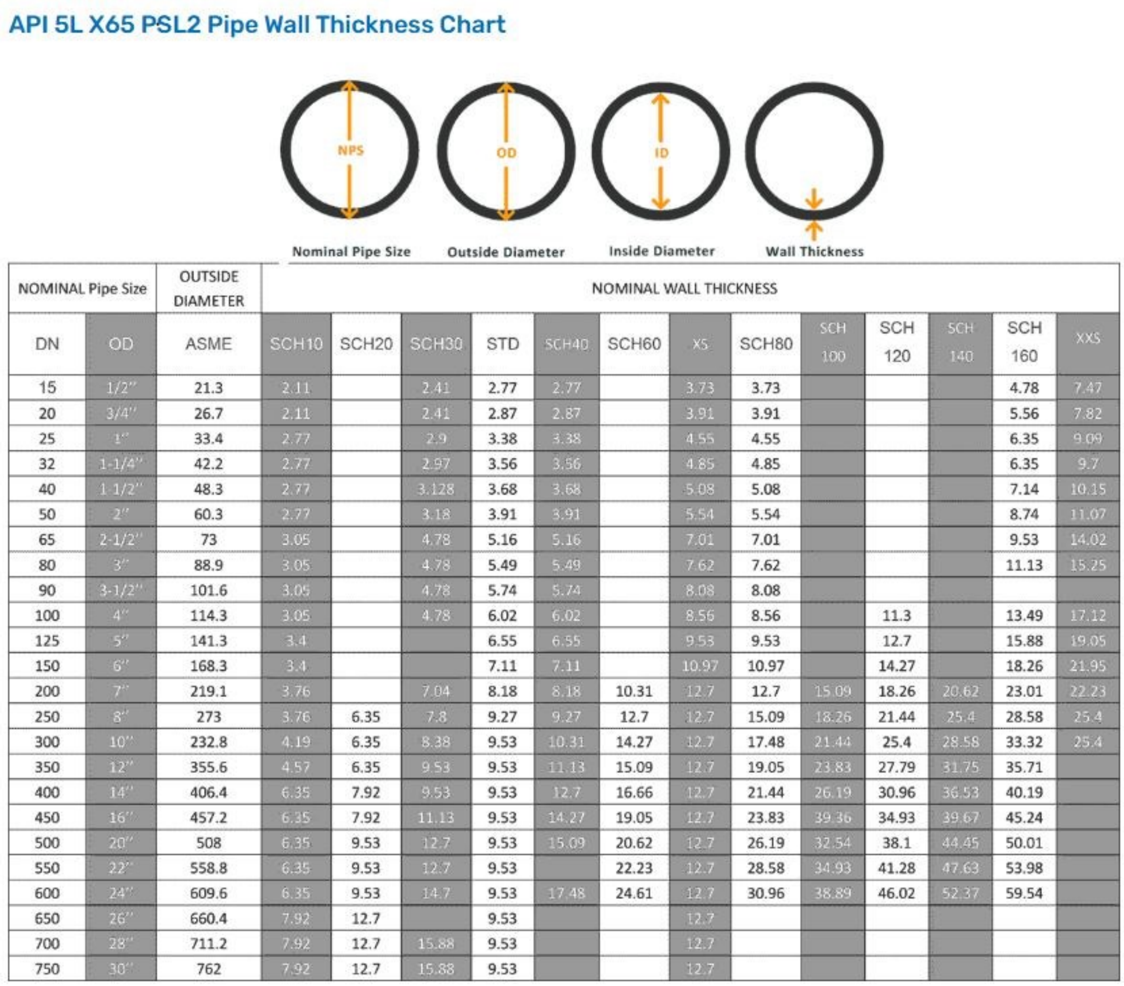
[56] R. Lutas, ‘How Dense is Steel? [2023 Guide]’, https://buyabeam.com/. Accessed: May 21, 2024. [Online]. Available: https://buyabeam.com/blogs/steel-beams/what-makes-steel-so-dense/

[57] ‘Safety and efficiency along the complete hydrogen value chain’, TÜV SÜD. Accessed: May 14, 2024. [Online]. Available: https://www.tuvsud.com/en/themes/hydrogen/explore-the-hydrogen-value-chain

List of figures

List of tables

Attachment 1



API 5L X65 PSL2 Pipe Wall Thickness Chart

NOMINAL Pipe Size		OUTSIDE DIAMETER	NOMINAL WALL THICKNESS													
DN	OD	ASME	SCH10	SCH20	SCH30	STD	SCH40	SCH60	XS	SCH80	SCH 100	SCH 120	SCH 140	SCH 160	XXS
15	1/2"	21.3	2.11		2.41	2.77	2.77		3.73	3.73				4.78	7.47
20	3/4"	26.7	2.11		2.41	2.87	2.87		3.91	3.91				5.56	7.82
25	1"	33.4	2.77		2.9	3.38	3.38		4.55	4.55				6.35	9.09
32	1-1/4"	42.2	2.77		2.97	3.56	3.56		4.85	4.85				6.35	9.7
40	1-1/2"	48.3	2.77		3.128	3.68	3.68		5.08	5.08				7.14	10.15
50	2"	60.3	2.77		3.18	3.91	3.91		5.54	5.54				8.74	11.07
65	2-1/2"	73	3.05		4.78	5.16	5.16		7.01	7.01				9.53	14.02
80	3"	88.9	3.05		4.78	5.49	5.49		7.62	7.62				11.13	15.25
90	3-1/2"	101.6	3.05		4.78	5.74	5.74		8.08	8.08					
100	4"	114.3	3.05		4.78	6.02	6.02		8.56	8.56		11.3		13.49	17.12
125	5"	141.3	3.4			6.55	6.55		9.53	9.53		12.7		15.88	19.05
150	6"	168.3	3.4			7.11	7.11		10.97	10.97		14.27		18.26	21.95
200	7"	219.1	3.76		7.04	8.18	8.18	10.31	12.7	12.7	15.09	18.26	20.62	23.01	22.23
250	8"	273	3.76	6.35	7.8	9.27	9.27	12.7	12.7	15.09	18.26	21.44	25.4	28.58	25.4
300	10"	232.8	4.19	6.35	8.38	9.53	10.31	14.27	12.7	17.48	21.44	25.4	28.58	33.32	25.4
350	12"	355.6	4.57	6.35	9.53	9.53	11.13	15.09	12.7	19.05	23.83	27.79	31.75	35.71	
400	14"	406.4	6.35	7.92	9.53	9.53	12.7	16.66	12.7	21.44	26.19	30.96	36.53	40.19	
450	16"	457.2	6.35	7.92	11.13	9.53	14.27	19.05	12.7	23.83	39.36	34.93	39.67	45.24	
500	20"	508	6.35	9.53	12.7	9.53	15.09	20.62	12.7	26.19	32.54	38.1	44.45	50.01	
550	22"	558.8	6.35	9.53	12.7	9.53		22.23	12.7	28.58	34.93	41.28	47.63	53.98	
600	24"	609.6	6.35	9.53	14.7	9.53	17.48	24.61	12.7	30.96	38.89	46.02	52.37	59.54	
650	26"	660.4	7.92	12.7		9.53			12.7						
700	28"	711.2	7.92	12.7	15.88	9.53			12.7						
750	30"	762	7.92	12.7	15.88	9.53			12.7						

Attachment 2

Calculations of levelized cost of hydrogen transportation (LCOHT) and levelized cost of energy transportation (LCOET)