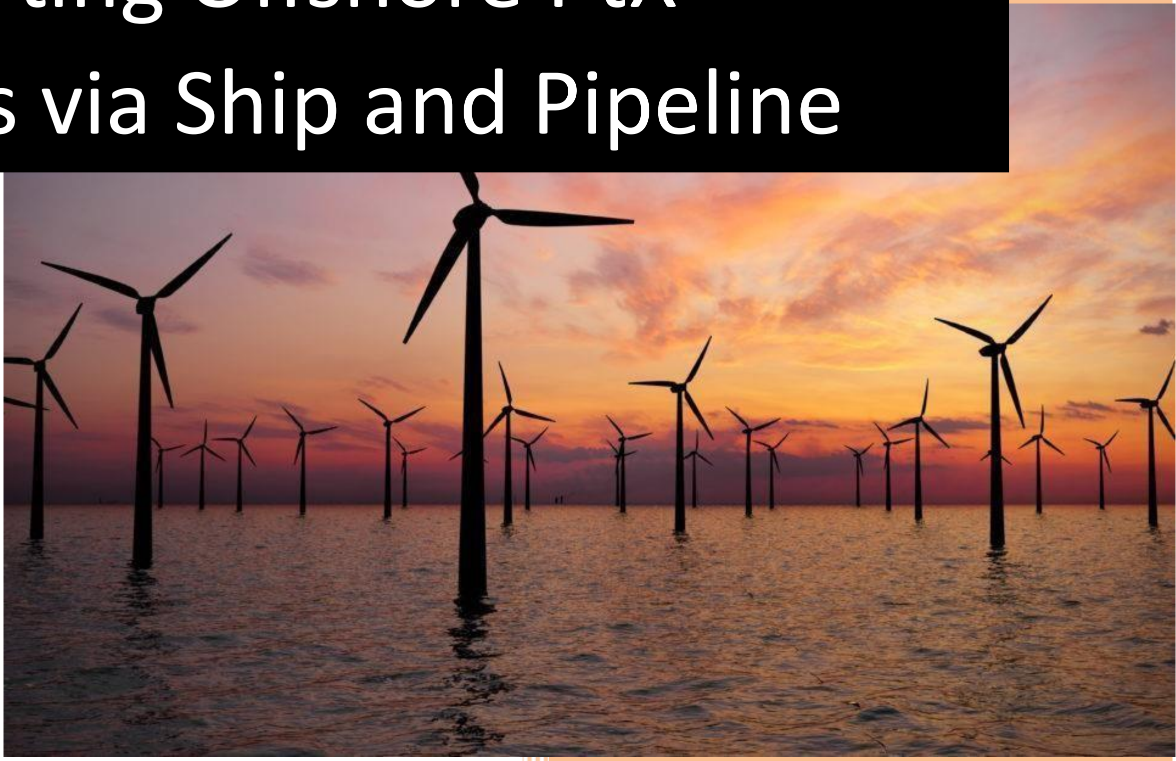
Techno-economic Analysis of Transporting Offshore PtX Products via Ship and Pipeline



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1.ABSTRACT

In recent times, there has been a growing global emphasis on alternative fuels such as hydrogen, ammonia, and methanol in the discourse surrounding climate change. Recognizing the strategic role of alternative fuels in achieving a net-zero carbon emissions economy, as highlighted in the IPCC report of 2018, (REPORT, 2018) this master's thesis undertakes a thorough techno-economic analysis of offshore power transportation to X products, with a specific focus on ammonia and methanol. The study explores both shipping and pipeline systems to evaluate their feasibility and economic viability.

Within the technical assessment of shipping options, the research encompasses the selection of suitable vessels, storage tank considerations, platform space requirements, fuel transfer options, and associated transfer times. Similarly, in the pipeline evaluation, a technical comparison is conducted, considering aspects such as material, insulation, flow rate, required storage, and pump specifications. This involves a comparison between a newly proposed pipeline and the repurposing of existing natural gas pipelines.

To determine the most economical transportation options for these fuels to a designated port in Germany, an economic assessment is carried out. With the given production rate, the containerized shipping solution emerges as the most economical option in terms of capital expenditures (CAPEX) However, in terms of the levelized cost of transport, the bunkering option proves to be more economical for transporting fuels.

This comprehensive analysis contributes valuable insights to the discourse on alternative fuel transportation, aiding stakeholders in making informed decisions aligned with the global transition towards a sustainable and low-carbon future.

2.INTRODUCTION

In recent years, there has been a discernible shift towards exploring and harnessing alternative fuels, particularly hydrogen, as a promising solution to address the escalating challenges posed by traditional fossil fuels. This growing focus is driven by a confluence of factors, including concerns over environmental sustainability, the imperative to mitigate climate change, and the realization of the finite nature of conventional energy resources. As the global community grapples with the need to transition towards cleaner and more sustainable energy systems, hydrogen and alternative fuels like Ammonia and Methanol has emerged as a key player in the quest for a low-carbon future (REPORT, 2018).

The rationale for this burgeoning interest in hydrogen and other alternative fuels is deeply rooted in the recognition of their potential to revolutionize the energy landscape. Hydrogen, in particular, stands out due to its versatility, high energy density, and zero-emission combustion, making it an attractive candidate for various applications, from transportation to industrial processes.

Through its Green Deal initiative, the European Union sets the ambitious goal of attaining carbon neutrality by 2050. In tandem, Germany has committed to reducing greenhouse gas (GHG) emissions by 65% by 2030 and achieving climate neutrality by 2045. The transition away from natural gas and other fossil fuels necessitates energy storage solutions coupled with on-demand power generation from renewable sources. At the core of the journey towards Net Zero lies the adoption of "green fuels," particularly focusing on green ammonia and other hydrogen derivatives. Germany anticipates the need for approximately 3.5 million metric tons per year (Mt/y) of green hydrogen by 2035, escalating to 11.3 Mt/y to achieve Net Zero (Constanze Leonie Fetting).

Europe boasts significant offshore wind resources, particularly in the North Sea and the Atlantic Ocean. Harnessing these resources allows for the generation of substantial amounts of renewable energy. According to the European Commission's "Offshore Renewable Energy Strategy" (2020), offshore wind energy has the potential to play a crucial role in achieving the European Union's renewable energy targets (European Commission 2020).

To realize the aforementioned aspirations, a paradigm shift in energy production is imperative. The solution lies in a transformative approach, with particular emphasis on the vast potential of offshore regions for energy generation. Several compelling reasons underscore the importance of focusing on offshore energy. Firstly, Europe possesses substantial offshore wind resources, notably in the North Sea and the Atlantic Ocean, offering a pathway to generate significant amounts of renewable energy. The European Commission's "Offshore Renewable Energy Strategy" (2020) underscores the pivotal role of offshore wind energy in fulfilling the European Union's renewable energy targets (European Commission 2020). Secondly, the consistent and high power production essential for the operation of electrolysers and other power-to-x products demands a continuous and stable energy supply. The offshore regions, with their abundant wind potential, possess the capability to fulfil this requirement (Dahiru et al.).

The primary objective of this master's thesis is to investigate diverse methods for transporting green fuels generated on offshore platforms to onshore locations, a critical aspect in fulfilling the growing demand for environmentally friendly fuels across various sectors. For example, In case of transport sector, particularly the maritime industry, more stricter rules are coming into force for reducing emission and achieve a zero emission state, which leads to future use of alternative marine fuels onboards ships like hydrogen, methanol and ammonia. These fuels can be produced from green electricity produced by offshore wind energy. In this thesis, different transport options such as ships and pipeline will be compared from technical and economic point of view to find the economical and feasible option for transporting the fuels to the onshore platform.

2.1 TECHNO-ECONOMIC ANALYSIS

Techno-economic analysis (TEA) is a methodology used to evaluate the economic feasibility of a technology or process. To evaluate the technical and economic performance of a system, TEA combines engineering and economic principles. A TEA's typical objective is to determine the most affordable solution to a certain problem, though this can be expanded by taking into account environmental and social factors. TEAs are frequently utilized in various industries to determine whether energy technologies are economically viable. The energy industry is confronting tough obstacles, like the need to cut greenhouse gas emissions, boost both guarantee energy security and energy efficiency. Therefore, a TEA can assist policymakers, To find the most affordable solutions to these issues, investors, and researchers are needed (Julian Ulrich Hausweiler).

2.2 BRIEF DESCRIPTION ABOUT P2X

P2X [power to x] is a revolutionary technology that transforms surplus renewable energy into hydrogen through an electrochemical reaction before reacting with carbon molecules to produce product 'X'. Power-to-gas (P2G), power-to-liquids (P2L), and power-to-chemicals (P2C) routes are a few of many P2X pathways that 'X' can address. In addition to the ones above listed, P2X technologies such as power-to-methane (P2M), power-to-heat (P2H), and power-to-hydrogen (P2H2) have also been mentioned (Dahiru et al.).

Two key processes in P2X technology are: CO2 hydrogenation to produce chemicals and fuels and H2 generation through water electrolysis utilizing renewable energy. As an alternative, CO2 can be directly converted into usable goods utilizing electrochemistry and renewable energy.

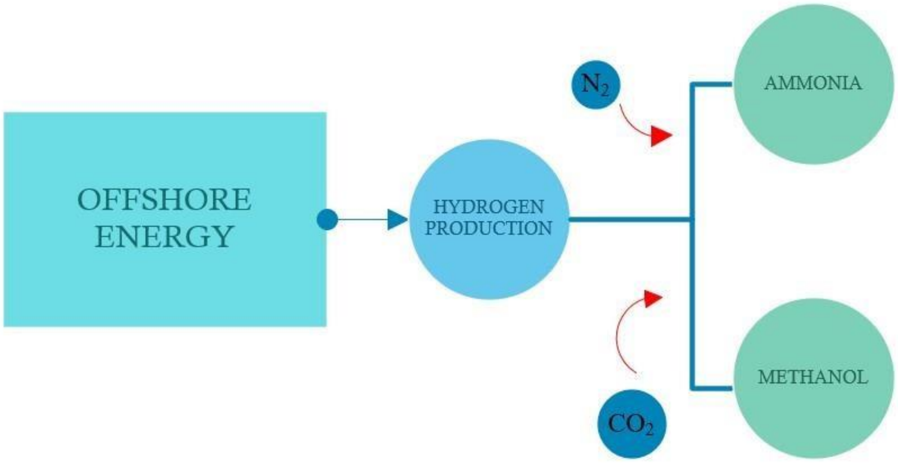


Figure 1- P2X PROCESS

2.3 WATER ELECTROLYSIS

Hydrogen supply is the first step for all the P2X systems, and this can be done by water electrolysis (WE). An overall electrochemical reaction is represented as.

$$H_2O\ (l) \rightarrow H_2\ (g) + \tfrac{1}{2}\ O_2\ (g).$$

Direct electric current is used to split the water into H2 and O2. Electrical or thermal energy can be used to meet the electrolysis process' energy requirements (S. Shiva Kumar, Hankwon Lim). The three most popular water electrolysis technologies are high-temperature electrolysis, which is aided by solid oxide electrolyte (SOEC), a polymer electrolyte membrane (PEM), and an alkaline electrolyser based on a liquid alkaline electrolyte (AEL). The efficiency, adaptability, and lifespan of an electrolyser technology determine which one to choose.

2.3.1. ALKALINE ELECTROLYTE (AEL) is thought to be the oldest and most established technique used in the water electrolysis process. As an electrolyte in AEL, an alkaline solution containing 30% aqueous potassium hydroxide (KOH) is frequently employed. A temperature of about 80 °C and either ambient pressure or high pressure can be used to run the operation (S. Shiva Kumar, Hankwon Lim).

2.3.2. POLYMER ELECTROLYTE MEMBRANE - Rather than using a liquid electrolyte, a solid polymeric membrane serves as the electrolyte in a conventional PEM system. PEM technology has several advantages over AEL, including quicker cold starts, greater flexibility, and better coupling with intermittent and dynamic systems. At the anode and cathode, respectively, noble metal catalyst supports based on iridium and platinum are utilized due to the proton exchange membrane's corrosive acidic susceptibility. However, a significant obstacle to the PEM process has been the high cost of these components and membrane materials (S. Shiva Kumar, Hankwon Lim).

2.3.3. SOLID OXIDE ELECTROLYTE CELL **-** An intriguing aspect of SOEC makes it a promising electrolysis technology for P2X applications. When compared to AEL and PEM, its efficiency is higher since it operates in the 800-1000℃ temperature range. Ionic conductivity and the speeds of electrochemical reactions on electrode surfaces both significantly rise under the high-temperature conditions of SOEC operation. As a result, there will be a decrease in overall power demand, which can be offset by providing thermal energy (S. Shiva Kumar, Hankwon Lim).

Hydrogen is produced by splitting water using an electrolysis process (WE), which is at the heart of the use of sustainable P2X technologies. It is challenging to store and transport hydrogen due to its low density (0.0813g/L) in its standard state. Hydrogen must be kept in a compressed or liquified state in order to overcome this difficulty. In specific tanks, compressed hydrogen is kept at a high pressure, while liquefied hydrogen is kept at a very low temperature in insulated containers and thus from the point of view of technical and economic aspects it a big challenge for the transport of hydrogen. Therefore, the production of alternative fuels formed by reactions between H2 and CO2 or N2 in the offshore platform and the transportation of resulting products like Ammonia and Methanol would be an attractive solution. For the production of Ammonia and Methanol, carbon dioxide and nitrogen needs to be extracted from the available resources in the offshore platform.

2.4. CARBON DIOXIDE EXTRACTION

From a sustainable point of view, the source of CO_2 used as feedstock is crucial for all P2X systems. Since it is very difficult to use the carbon dioxide from direct sources like industries, the most viable option is to either convert the carbon dioxide from carbonates from the ocean water and also in sites where the carbon dioxide is captured and stored in seabed or in the previously oil extracted sites (Nawaz et al.). There are several methods for the extraction of carbon dioxide from the atmosphere and sea water some methods are Direct Air Capture (DAC),Ocean-Based Carbon Removal, Algae-Based CO2 Sequestration, Mineralization (International Energy Agency).

The captured CO2 is combined with hydrogen produced, in the presence of a catalyst to produce methanol. The methanol synthesis reaction is known as the "Haber-Bosch process.

2.5. NITROGEN EXTRACTION

Extracting nitrogen from the atmosphere on offshore platforms for ammonia production serves as a strategic and environmentally conscious approach. The benefit is multifold, Firstly, Ammonia, produced from nitrogen extracted from the atmosphere, holds promise as a green fuel. Secondly, Extracting nitrogen on the offshore platform allows for on-site ammonia production, reducing the need for transporting nitrogen-rich materials and minimizing logistical complexities associated with importing feedstock. There are three standard methods used to extract nitrogen from air, the prominent methods are - Cryogenic distillation, Pressure swing adsorption, Membrane nitrogen generation (GENERON).

2.6. PROPERTIES OF AMMONIA AND METHANOL

A profound understanding of the physical properties of the green fuels like ammonia and methanol is essential for optimizing their utilization in energy systems. This knowledge informs the development of technologies, policies, and infrastructure to harness the full potential of ammonia and methanol, contributing significantly to the transition towards cleaner and more sustainable energy sources. Green fuels, such as liquid ammonia and methanol, exhibit unique properties that make them promising candidates for sustainable energy solutions.

At ambient conditions that is at the room temperature and atmospheric pressure, ammonia exists as a odorless gas. To facilitate bulk storage, it necessitates liquefaction through compression to 10 times the atmospheric pressure or cooling it to -33 degree Celsius. Second important factor is that the Liquid ammonia (NH3) contains a high percentage of hydrogen by weight, making it a potential source of clean hydrogen for fuel cells. With the increasing demand of hydrogen, the potential energy carriers like ammonia would be an ideal pathway for transportation. Finally, Ammonia can be combusted without producing carbon dioxide, offering a carbon-free energy option (Oscar Serpell et al.).

Methanol, with its high hydrogen-to-carbon ratio, emerges as an efficient hydrogen carrier, while its liquid state at ambient conditions simplifies storage and distribution. The versatility of methanol, derived from various renewable sources, underscores its potential as a sustainable feedstock. Furthermore, its lower toxicity compared to some traditional fuels enhances safety during handling and use (Song et al.).

There is a high level of maturity when considering storage and transportation infrastructure of ammonia and methanol due to the fact that it has been in widespread use in various industries like in the case of ammonia, as a feedstock for inorganic fertilizers. A globally established infrastructure, particularly in maritime trade is already in place. International shipping routes are well defined and a widespread network of ports worldwide efficiently handles large scale of alternative fuel operations (The Royal Society).

2.7. OFFSHORE PLATFORM

Offshore platforms are structures used for a variety of purposes in offshore environments, typically in bodies of water, such as oceans or seas. offshore platforms serve as strategic hubs for the production and storage of Power-to-X products, leveraging renewable energy sources to create sustainable and scalable solutions for the global energy transition. Their unique advantages, including space optimization, renewable resource proximity, and potential for energy storage, position offshore platforms as integral components in the pursuit of a greener and more resilient energy future (R Sharma 2019).

2.8. STORAGE TANKS

Storage tanks for liquid ammonia and methanol are typically designed and constructed with specific materials and safety features to ensure the safe storage of these chemicals. Below are the common types of storage tanks for liquid ammonia and methanol:

2.8.1. ATMOSPHERIC STORAGE TANKS:

Atmospheric storage tanks are typically made of carbon steel or stainless steel. These tanks are designed to operate at ambient pressure and temperature. Methanol can also be stored in these tank as it is transported under atmospheric conditions.

2.8.2. REFRIGERATED STORAGE TANKS:

For very low-temperature storage, especially for industrial or refrigeration applications, fuels like Ammonia is stored in refrigerated storage tanks. These tanks are equipped with insulation and refrigeration systems to maintain the ammonia at its required low temperature. (Cryospain, n.d.)

Figure 2- REPRESENTING THE CYLINDRICAL REFRIGERATED TANK FOR STORING LIQUID FUELS LIKE AMMONIA (eurotainer)

2.8.3. DOUBLE-WALLED TANKS: Double-walled tanks are used for the storage of hazardous materials like ammonia or methanol to provide an extra layer of protection against leaks or spills. The inner tank holds the chemical, while the outer tank serves as a secondary containment barrier. (Behaelter-kg, n.d.)

2.8.4. VERTICAL STORAGE TANKS - These tanks are typically constructed in a vertical orientation, with a cylindrical shape and a vertical axis. The design and materials used in these tanks are chosen to meet the specific requirements of storing alternative fuels safely and efficiently. These tanks are considered in the study for storing fuels for the bunkering or refueling options in shipping transport. (NORDIC, n.d.)

Figure 3- REPRESENTING THE VERTICAL TANKS FOR STORING FUELS IN OFFSHORE/ONSHORE PLATFORM (vopak)

2.9. MODES OF TRANSPORTING FUELS TO ONSHORE PLATFORM

Transporting fuel from offshore facilities to onshore locations is a critical operation in the oil and gas industry. Several methods are commonly used for offshore fuel transport to onshore:

2.9.1. TANKER SHIPS: Tanker ships designed for the transfer of alternative fuel are specialized vessel equipped to transport substances like hydrogen, ammonia and methanol. These vessels are specially designed to carry large quantities of liquid cargo. Offshore platforms load the fuel onto tankers, which then transport it to onshore facilities. In this study, the focus is given on tankers which carry ammonia and methanol, these tankers are designed by taking into consideration the safety measures like corrosion-resistant materials to prevent chemical reactions and containment systems to handle potential leaks. (Wartsila, n.d.)

2.9.2. OFFSHORE SUPPLY VESSEL: offshore supply vessels are specialized ships designed to support offshore exploration and production activities. These vessels are equipped to transport and deliver the essential supplies, equipment and personnel. In this master thesis, the offshore supply vessel is considered for the transport of storage container tanks filled with alternative fuels like Ammonia and Methanol to the onshore platform. (Guard, n.d.)

2.9.3. PIPELINE SYSTEMS: the pipeline transfer of alternative fuels from offshore to onshore involves a robust system of underwater pipelines, booster station, to keep the physical properties of the fuels to the desired level and storage facilities. These pipelines are used to transport the fuel directly from the platform to onshore locations. Pipelines are a cost-effective and efficient method for continuous transport.

The choice of method depends on factors such as the volume of fuel to be transported, distance to the onshore location, infrastructure in place, environmental considerations, and cost-effectiveness. Safety and environmental regulations also play a crucial role in determining the method of offshore fuel transport to onshore.

3.METHODOLOGY

In the master's thesis, the focus lies on investigating the transportation aspects of alternative fuels produced in the designated SEN 1 area, allocated for Germany. The production of hydrogen, as well as alternative fuels such as ammonia and methanol, is examined with a primary emphasis on transportation considerations. The study predominantly delves into the transportation of these fuels through two main avenues: shipping and pipelines. Through the examination of two cases for each mode of transportation, the thesis aims to provide a comprehensive analysis to ascertain the technical and economic feasibility of fuel transport, offering a better `understanding of the optimal choice for this purpose.

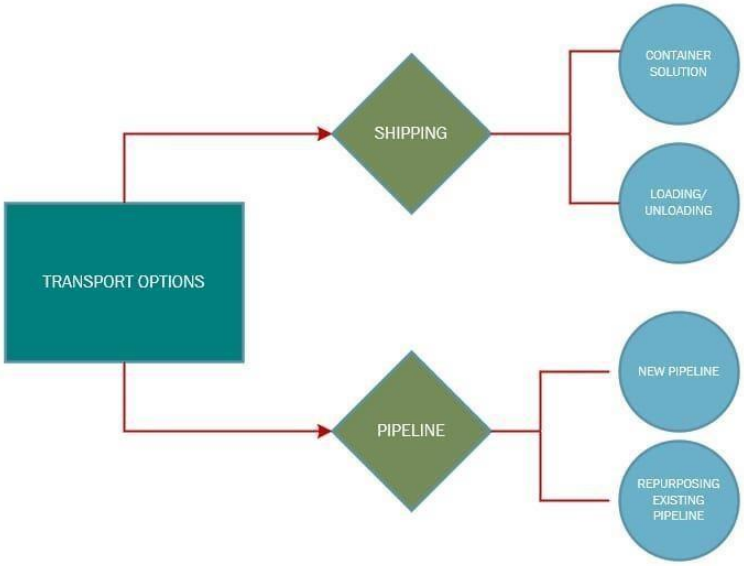


Figure 4- BLOCK DIAGRAM REPRESENTING THE DIFFERENT TRANSPORT OPTIONS STUDIED IN THESIS

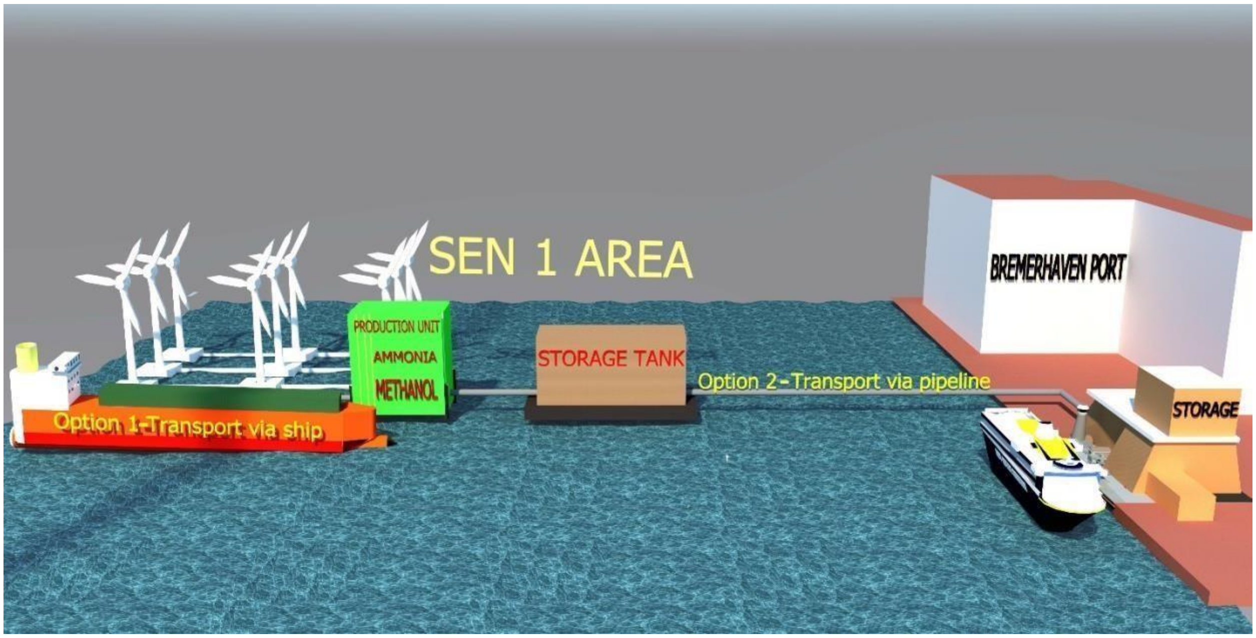


Figure 5- PICTORIAL REPRESENTATION OF TRANSPORT OPTIONS CONSIDERED IN STUDY FROM SEN 1 AREA TO BREMERHAVEN

3.1 SYSTEM BOUNDARY

The initial phase of the thesis involves defining the system boundaries to maintain focus and adhere to specific requirements. The study delves into assessment of two fuels, Ammonia and Methanol.

The assessment is carried out for one fuel (primary fuel) and an estimation is derived for the second fuel. The analysis primarily centers on Ammonia, which is considered as the primary fuel. The selection of fuel is solely based on the availability of literature sources. The physical properties of fuels considered for study are, temperature of -33 Degree Celsius for Ammonia and 25 Degree Celsius for Methanol. The pressure is 1 bar for both the fuels. The production rate of these fuels are nearly 112 tonnes per day. The transport options which is studied are containerized and bunkering in shipping solution and laying new pipeline and using repurposed pipeline for the pipeline transfer option.

3.1.1 CASE SCENARIOS FOR TRANSPORT VIA SHIPPING

The first case involves the examination of various shipping scenarios. This thesis explores two specific shipping transport options: a containerized solution and a refueling or bunkering solution. In the containerized approach, fuels produced are stored in cylindrical storage tanks with tailored design parameters for the specific fuels of interest. Subsequently, these storage tanks are transferred to a chosen vessel and transported to the designated onshore port, Bremerhaven. In the second shipping case, fuels are stored in a sizable storage tank on the offshore platform, and a designated tanker vessel is employed for the subsequent fuel transfer.

3.1.2 CASE SCENARIOS FOR TRANSPORT VIA PIPELINE

we analyze two distinct case scenarios for the transfer of fuels from offshore platforms to onshore facilities. The first case scenario involves utilizing the existing natural gas pipeline infrastructure for the transportation of fuels, while the second scenario explores the feasibility of laying an entirely new pipeline to cover the required distance.

In the first scenario, the establishment of a novel pipeline infrastructure becomes imperative to establish a connection with the pre-existing natural gas pipeline. Two natural gas pipelines available for the transport of fuels are NORPIPE and EUROPIPE II, both transfers natural gas from Norway to Germany. Retrofitting the incumbent natural gas pipeline for the conveyance of ammonia proves to be a multifaceted endeavor, demanding intricate modifications aimed at preserving the essential temperature and pressure parameters. Retrofitting may involve enhancing the insulation of the pipeline to prevent heat loss and maintain the temperature needed for ammonia transportation. Heat tracing systems can also be employed to ensure the ammonia remains in a liquid state. Natural gas pipelines usually operate at lower pressures compared to ammonia pipelines. Pressure control systems and regulators are installed to adjust the pressure to the appropriate level for ammonia transport

In the second case scenario, we undertake the installation of a brand-new pipeline, spanning a distance of approximately 170 kilometers from the offshore platform to the onshore facility. The selection of pipeline materials for this endeavor is a meticulously considered process, driven by several key factors. These include corrosion resistance, effective insulation to minimize heat ingress, and the overall durability of the chosen materials.

3.2. SHIP TRANSPORT – CONTAINER SOLUTION

Offshore platforms play a pivotal role in the safe storage of essential fuels. This section aims to present a structured method for determining the number of containers and storage area required to safely store fuels on offshore platforms. Notably, Ammonia and Methanol, with their distinct densities, present unique challenges and, therefore, demand specific considerations.

Container Dimensions: The research begins by utilizing fundamental container storage tank dimensions, laying the groundwork for further calculations. The dimensions for storage tank and respective volume considered in this study is shown below in table 1. The 20 foot container is selected with the assumption that it is easy to handle specifically during harsh weather conditions.

Table 1- DIMENSIONS OF COMMON TEU CONTAINERS

Length (m)	Width(m)	Height(m)	Internal volume (m^3)	Area m^2
6.1m (20 ft)	2.44m (8 ft)	2.59m (8 ft 6 inch)	33.2	14.88

Density: It is imperative to recognize that Ammonia and Methanol has different densities, which directly impact the storage requirements. This parameter is crucial in optimizing the storage solution for each fuel type. The density value of each of the fuels along with other similar energy fuels are shown in the table 2.

Table 2- FUELS AND CORRESPONDING DENSITY

Fuel type	Density(kg.m^{-2})
Methanol	791
Liquid Ammonia	678.5

Following the analysis of the fuel properties, the initial step involves determining the quantity of containers required to store the fuel, taking into account the production rate. This determination relies on the fundamental relationship between mass, density, and volume to quantify the amount of fuel each storage unit can hold.

Annual Production Rate: To determine the number of containers required per year, we use the equation

$$Annual\ production\ rate = \frac{Number\ of\ containers\ (per\ year)}{Mass\ in\ tonne} \qquad \text{Eq (1)}$$

This equation provides a practical method for optimizing storage solutions based on annual production rates.

3.2.1 CONTAINER STORAGE TANKS FOR AMMONIA AND METHANOL TRANSPORT

Material Selection: Containers for ammonia and methanol transport are typically constructed from materials that are resistant to corrosion, such as stainless steel or carbon steel. The material choice depends on the compatibility with the specific chemical.

Pressure Rating: Container tanks must have a suitable pressure rating to accommodate the pressure conditions associated with the transportation of fuels particularly ammonia, boil off gas phenomenon can increase pressure in the system. Pressure relief systems may also be incorporated.

Temperature Control: Temperature control is crucial for both ammonia and methanol. These tanks may feature insulation and heating/cooling systems to maintain the chemicals within safe temperature ranges and prevent freezing or overheating.

Capacity: Container tanks come in various sizes to match the volume of ammonia and methanol to be transported. The tank's capacity should be compatible with the vessel's space and weight limitations.

3.2.2 VESSEL SELECTION

After choosing the storage tank container, the subsequent crucial step involves selecting a suitable vessel for the fuel transportation. This decision hinges on factors such as daily production rates of fuels (i.e., the number of tanks to be filled per day) and to reduce the storage space required on the offshore platform as it is capital intensive.

3.2.3 TRANSFER OF FUELS

In the next step, the ammonia and methanol needs to be transferred to the container tank. For liquid ammonia, the transfer hose or a specialized transfer pump is used for transferring the fuels. Suitable pumps are used for both of the fuels as the density of liquid ammonia and methanol are different the specification of pump required for the purpose also varies. Materials used for the transfer these two fuels are typically made of stainless steel or Teflon due to corrosion and other risks that may occur (Simha, 2020).

3.2.4 LOADING OF CONTAINERS

The choice of crane depends on the platform or vessel's design and capacity. Offshore platforms may have pedestal cranes or gantry cranes, while offshore supply vessels typically use deck cranes or knuckle boom cranes. The crane operator uses the crane's hook or other lifting attachments to pick up the container from its initial position. The container is then raised and moved to the designated location on the vessel or platform. The crane operator, along with signalmen and spotters, communicates through hand signals or radios to ensure precise placement.

Figure 6- DEPICTS THE TRADITIONAL CRANE METHOD FOR TRANSFERRING THE CONTAINER TANKS TO VESSEL (wilson son)

3.2.5 BOIL OFF GAS ESTIMATION

BOG is the gas that is generated when the fuels stored in cryogenic tanks warms up and evaporates due to heat ingress. Boil-off gas (BOG) estimation is an important aspect of handling liquefied gases, particularly liquefied natural gas (LNG) or other cryogenic liquids. Unlike Ammonia or other cryogenic liquids, methanol is typically stored and transported at ambient temperatures and pressures, which do not cause the extreme temperature-related volume changes characteristic of cryogenic storage. As such, the concept of "boil-off" does not apply to methanol storage because it remains in a liquid state under normal storage and handling conditions thus in this section it is mostly focused on boil off gas estimation for Ammonia.

Heat ingress is the primary driver of BOG generation. It occurs when external heat is transferred to the cryogenic tank. Heat sources can include ambient temperatures, solar radiation, and heat from adjacent equipment. The rate of heat ingress must be determined, which is usually measured in kilowatts (kW)

The thermal properties of the Ammonia being stored, such as its heat of vaporization (latent heat), density, and specific heat capacity. These properties are essential for calculating the rate of BOG generation. The heat ingress, denoted as Q, is determined as the product of the overall heat transfer coefficient, the surface area of the storage container, and the temperature differential between the environmental temperature and the specific storage temperature of ammonia, which is -33 degrees Celsius (Song et al.).

$$Q = OHTC \times AREA \times \Delta T \qquad \text{Eq (3)}$$

Using the heat ingress rate, thermal properties of the Ammonia, and temperature profiles, calculate the rate at which BOG is generated. The basic equation for estimating BOG generation is:

$$BOG\ Rate\ (kg/hr) = \frac{Heat\ Ingress\ Rate\ (kW)}{\text{Heat of Vaporization of Ammonia (kJ/kg)}} \qquad \text{Eq (4)}$$

3.2.6 STORAGE

The critical factor influencing the choice of storage arrangement and the frequency of container loading on the offshore platform is the available space. The tank's area is derived from the dimensions of a single twenty-foot equivalent unit (TEU), as outlined in Table 2.

The study employs the fundamental equation:

$$\text{Area} = \text{Length} * \text{Breadth}, \qquad \text{Eq(5)}$$

to calculate the available area. It explores three distinct storage options: a single-layered arrangement, a two-layered stack configuration, and a three-layered stack arrangement.

3.3. SHIPPING TRANSPORT – LOADING/UNLOADING TYPE

Filling tanker ships with fuels at offshore platforms involves a complex process. First, the tanker arrives at the designated offshore loading point, then a loading arm or hose is connected from the platform to the ship's manifold. Fuel is transferred through these connections, typically using pump on the platform.

Once the tanker is filled, the connections are safely disconnected, ship departs for its destination. Regular inspections, maintenance and adherence to industry regulations are crucial to maintaining the integrity of the entire loading system.

3.3.1 SELECTION OF TANKER SHIPS

For research purposes, the initial step in implementing this transportation method involves securing a tanker ship designed to transfer fuels from offshore to onshore. Given the daily production rate of 112 ton of fuels, the choice of the vessel with the smallest capacity is preferred for fuel transport. The operational cost of smaller vessel would be less as limited resources would be sufficient for the fuel transfer.

3.3.2 STORAGE OF FUELS

The transfer of fuels from the production unit occurs into a range of storage tanks, including fixed roof tanks, floating roof tanks, spherical roof tanks, or cryogenic tanks. it is common to store liquid ammonia and methanol in tanks made of either carbon steel or stainless steel. In the context of ammonia, effective insulation is crucial to control temperature and reduce heat exchange with the surrounding environment. The area of the tank for storing the fuels in offshore and onshore is selected according to the capacity of the tanker ships. In the study the ammonia tanker and methanol tanker capacity is roughly around 22,000 m^3.

3.3.3 FUEL LOADING/UNLOADING FACILITIES

The process of loading tanker ships from an offshore platform is intricate and subject to rigorous regulation. The initial step involves positioning loading arms or hoses to facilitate the transfer from the platform to the ship, and securing the connections between these loading arms and the ship's manifold. Given the intricate nature of offshore conditions, this process often demands a considerable amount of time. The transfer of fuels is executed at an optimal rate, with a primary focus on safety considerations. In our study, we select two distinct flow rates for comparative analysis.

Figure 7- DEPICTS THE METHOD OF TRANSFERRING THE FUELS FROM OFFSHORE PLATFORM TO TANKER VESSEL USING PIPE AND PUMP SYSTEM (RBN)

3.3.4 BOIL OFF GAS ESTIMATION

In this specific case, the boil-off gas scenario closely parallels container-based transfer. The key distinction lies in the calculation of heat ingress, is the area of the tank . In the containerized solution, this area corresponds to that of a single container tank. The area of the storage tank considered in this case is $1257m^2$.

$$BOG\ Rate\ (kg/hr) = \frac{Heat\ Ingress\ Rate\ (kW)}{Heat\ of\ Vaporization\ of\ Ammonia\ (kJ/kg)} \qquad Eq\ (6)$$

3.4 PIPELINE TRANSFER

Transferring ammonia and methanol from offshore to onshore facilities through pipelines are less studied method for transporting these chemicals. The process begins at the offshore platform or facility where ammonia and methanol are stored in tanks. Loading facilities are equipped with transfer pumps and safety systems to ensure a controlled transfer process.

3.4.1 SELECTION OF MATERIAL

The selection of materials for pipeline transfer of ammonia and methanol is crucial to ensure the safe and efficient transportation of these chemicals. The carbon steel, stainless steel and duplex stainless (Simha, 2020)s steel are some of the common material which can be used for the transfer of transfer of fuels like Ammonia and Methanol. In addition to the base material, various coatings and linings can be applied to protect the pipeline's interior and exterior surfaces. Examples include epoxy, polyethylene, or ceramic linings. These protective layers enhance the material's resistance to corrosion and chemical attack. (Simha, 2020)

3.4.2 BOIL OFF ESTIMATION

The boil off gas is comparatively less in pipeline transport than shipping transport due to some of the reasons stated below (ITP INTER PIPE)

Insulation and Design: Offshore pipelines are typically well-insulated to minimize heat transfer between the transported cryogenic liquid and the surrounding environment. Insulation helps maintain lower temperatures, reducing the vaporization of the liquid (ITP INTER PIPE).

Continuous Flow: Pipeline transport involves a continuous flow of the cryogenic liquid, which reduces the exposure time of the liquid to higher ambient temperatures. This continuous flow minimizes the opportunity for significant boil-off.

Pressure Control: Offshore pipeline systems are designed with effective pressure control mechanisms. By maintaining the pressure within the pipeline at appropriate levels, the temperature of the liquid can be kept lower, reducing the tendency for boil-off.

Subsea Location: Offshore pipelines are often laid on the ocean floor, where the surrounding seawater acts as a natural heat sink, helping to maintain lower temperatures and reduce boil-off.

3.5 REPURPOSING NATURAL GAS PIPELINE FOR AMMONIA AND METHANOL TRANSFER

This section explores the feasibility of repurposing the existing natural gas pipeline for transporting alternative fuels such as ammonia and methanol. This section discusses in detail about the advantages of using existing natural gas pipelines and the challenges associated with it.

1) Relevance of repurposing existing natural gas pipeline

The North Sea region including Germany, has an extensive network of natural gas pipelines. These pipelines play a crucial role in supplying the energy resources in the region. However, the escalating global focus on mitigating greenhouse gas emissions and adopting cleaner energy sources as a response to climate change has stimulated a heightened interest in alternative energy carriers like hydrogen, as well as sustainable options such as ammonia and methanol.

Although natural gas is relatively cleaner than coal or oil, it remains a source of carbon dioxide emissions when combusted. In contrast, alternative fuels like hydrogen have the potential to deliver near-zero emissions, particularly when generated through the utilization of renewable energy resources.

The transition from natural gas to more environmentally friendly alternative fuels can be analyzed by reviewing the demand chart presented in Deloitte's collaborative natural gas demand projection for the future. The findings indicate that natural gas is losing momentum in the German and EU energy systems on the transition to net zero. By 2030, natural gas trend is projected to decrease by over a quarter from 2018 level and 80% decline is anticipated by 2050. This shift is driven by the improved share of renewables, rise in electrification and the higher demand for the hydrogen and its alternatives (Deloitte). In this study, this declining trend is considered as an opportunity to repurpose existing pipeline infrastructure for the transportation of greener fuels rather than decommissioning it.

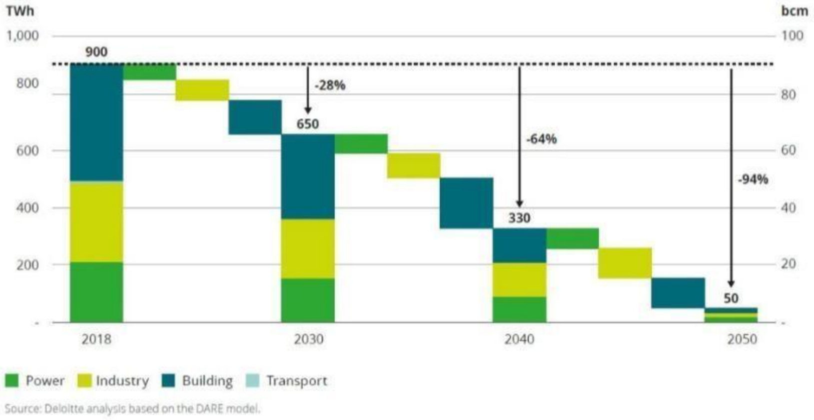


Figure 8- NATURAL GAS TREND IN GERMANY (Deloitte)

The primary benefits of utilizing the existing natural gas pipeline infrastructure are twofold (ACER):

1. Cost-Effectiveness: It is more economically viable to employ the existing pipeline network rather than investing in the construction of new pipelines for Ammonia or Methanol.
2. Social Acceptance and Efficiency: Natural gas pipelines already exist and have garnered societal approval, minimizing the likelihood of social conflicts and project delays.

Repurposing natural gas pipelines for the transportation of liquid ammonia and methanol can indeed present technical challenges.

1. Material Compatibility: The materials used in existing natural gas pipelines may not be suitable for the transportation of liquid ammonia and methanol, which have different chemical properties and may cause corrosion or other material-related issues. Thus technical remedies such as providing coating to steel pipe using material like Fusion Bonded Epoxy (FBE), Polyethylene (PE) Coating, Glass Reinforced Epoxy (GRE) Lining etc. are recommended. (Simha, 2020)

2. Pumping and Compression Requirements: Liquid ammonia and methanol require different pumping and compression systems to maintain flow and pressure within the pipeline. For instance, when dealing with liquid ammonia, the transfer of this fuel often involves the utilization of highly efficient magnetic drive pumps.
3. Pipeline Cleaning and Contamination: Residual natural gas and impurities in the pipeline may need to be thoroughly cleaned and removed to prevent contamination of ammonia and methanol. Pigging operations which refer to the process of using a device called a "pig" to perform various maintenance, cleaning, or inspection tasks within the pipeline are used for these operations.
4. Pressure and Temperature Requirements: Ammonia and methanol require different pressure and temperature conditions compared to natural gas, necessitating modifications to the pipeline system to ensure safe and efficient transportation. When dealing with refrigerated liquid ammonia, it is imperative to maintain a consistent temperature of -33 Degrees Celsius and low pressure throughout the entire pipeline distance.

3.6. ECONOMIC ASSESSMENT

In the economic analysis section the most critical consideration is to determine which transport option is economically viable and best for transporting the fuels from the offshore platform to the onshore. Calculating both the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) is essential for assessing the overall cost and financial feasibility of the transport option.

3.6.1. CAPEX CALCULATION

The CAPEX calculation, often regarded as the upfront, fixed expenditure incurred during the project's initiation, plays a pivotal role in assessing the project's feasibility. Specifically, for the shipping method of fuel transport, the assessment involves considering costs related to container tanks or storage tanks (in the case of refueling vessels), vessel procurement, and terminal infrastructure expenses. Conversely, for pipeline transfer, the evaluation encompasses the costs associated with pipelines, subsea equipment, including pumps.

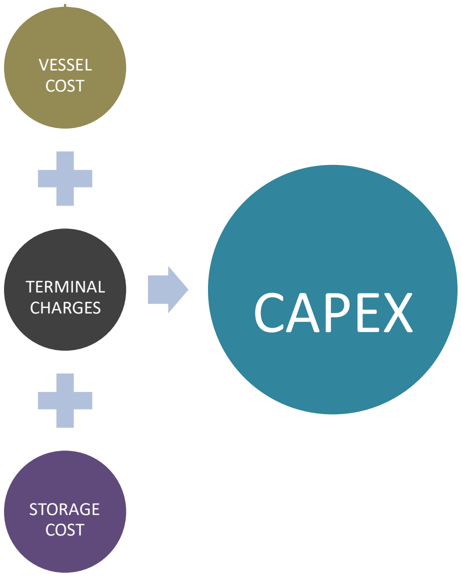


Figure 9- BLOCK DIAGRAM REPRESENTING COMPONENTS IN CAPEX CALCULATION IN SHIPPING

3.6.2. OPEX CALCULATION

The operational expenditure for the transportation of fuel encompasses the ongoing costs associated with managing and running the fuel transportation process. This includes crew wages, comprehensive insurance expenses, repair and maintenance outlays, and management-related costs. In this study fixed operational cost is considered so as to mitigate variations. (Julian Ulrich Hausweiler).

3.6.3. LEVELIZED COST OF TRANSPORTATION

The Levelized Cost of Transportation (LCOT) is a metric used to evaluate and compare the overall cost of transporting a unit of goods or energy over a specified distance. It is a concept analogous to the levelized cost of electricity (LCOE) used in the energy sector. LCOT provides a comprehensive perspective on the economic efficiency of transportation systems, incorporating various costs associated with the entire life cycle of the transportation process (Galimova et al.).

Key components and considerations in the calculation of Levelized Cost of Transportation may include:

1. Capital Costs: This encompasses the initial investment in transportation infrastructure, vehicles, or vessels. It considers expenses such as the purchase or construction of ships, trucks, pipelines, or any other transportation assets.
2. Operating and Maintenance Costs: These ongoing costs cover expenses related to fuel, maintenance, labor, and other operational aspects. It reflects the day-to-day expenditures necessary to keep the transportation system running.
3. Energy Costs: For modes of transportation that rely on fuel, the energy costs associated with propelling the vehicles or vessels are factored in. This includes the cost of the energy source, such as fuel or electricity.
4. Distance Traveled: The total distance over which goods or energy are transported is a crucial factor. Longer distances may affect the efficiency and cost-effectiveness of the transportation system.

Below are the two fundamental equations used to determine the levelized cost of transport for both shipping and pipeline transportation (Galimova et al.).

$$\mathrm{LCOT}_{\mathrm{SHIPPING}} = \frac{= (\,(\mathrm{CAPEX}*\mathrm{crf})+\mathrm{OPEX})}{FLH} + ELECTRICITY * LCOE \; + \; FUEL\ COST \qquad \text{Eq (7)}$$

In the investigation of the levelized cost of transportation for shipping in this study, key parameters considered include CAPEX (Capital Expenditure), OPEX (Operational Expenditure), CRF (Capital Recovery Factor), FLH (Full Load Hours), Electricity demand in the terminal port, LCOE (Levelized Cost of Electricity), and fuel cost.

$$LCOT_{\mathrm{PIPELINE}} \; = \; \frac{((CAPEX*crf)+OPEX)}{FLH} + PUMP * LENGTH * LCOE \qquad \text{Eq (8)}$$

Likewise, in the context of pipeline transport, the determination of the levelized cost of transportation involves considerations of CAPEX (Capital Expenditure), OPEX (Operational Expenditure), CRF (Capital Recovery Factor), FLH (Full Load Hours), pump electricity demand at the pump station, the length of the pipeline, and the levelized cost of transportation. Notably, this study omits the consideration of energy losses from the pipeline to align it with the shipping transport scenario. This deliberate exclusion of losses in both modes of transportation facilitates a more straightforward and comprehensible comparison.

The calculation of the capital recovery factor is determined through the following equation (Galimova et al.), primarily it depends on the weighted average of the capital cost (WACC) and the lifetime (N).

$$crf = \frac{WACC*(1+WACC)^N}{(1+WACC)^N-1} \qquad \text{Eq (9)}$$

4.RESULTS AND DISCUSSION

This section focuses on deliberating the outcomes derived from the technical and economic assessment conducted in the study pertaining to the transportation of alternative fuels. In technical assessment section, the study aims to compare the results between two shipping options as the first case and in the second case, the comparison is performed among the pipeline options. When it comes to the economic assessment, all the transportation options are considered and it is compared among each other on the basis of three major economic parameters.

4.1. TECHNICAL COMPARISON OF TRANSPORTING FUELS VIA SHIPPING

In the technical evaluation of shipping alternatives within this master's thesis, the two fuels under scrutiny exhibit nearly identical characteristics concerning the factors employed for comparison. Despite potential differences in their physical properties, the study assumes that both fuels share comparable requirements in terms of transportation demand. The table 4 provided below presents a comparison of fuel transport methods by shipping, encompassing several key aspects:

<u>Vessel Selection</u>: In the case of containerized fuel transport, the chosen vessel is an offshore supply vessel known as the "FS ABERGELDIE", both fuels are transported using the same offshore supply vessel. For bunkering solutions, both Methanol and Ammonia are transported using specialized tanker vessels, namely the "NEW WINNER" and "TRAMMO PARIS," respectively.

The initial phase of this study involves the selection of a suitable vessel for transportation, with a focus on minimizing offshore storage space requirements to enhance economic efficiency. To achieve this goal and optimize fund utilization, an offshore supply vessel which are widely used for supporting offshore activities, is chosen for the transportation of containerized fuels. The production rate of the alternative fuels which are of interest are also smaller favors the decision for selecting offshore supply vessel instead of large container ones.

The selection is also motivated by specific advantages over larger container vessels, including operational efficiency—where the maneuverability and ease of loading/unloading of offshore supply vessels are well-suited for transporting a smaller number of containers— and cost efficiency, as utilizing an offshore supply vessel for smaller cargo loads proves to be more economical than deploying larger vessels designed for extensive container transport. Likewise, in the context of tanker vessels, the study opts for the smallest capacity vessel. This choice is primarily driven by the objective of minimizing the storage space needed on the offshore platform. The selection of vessel is primarily based on the production rate of the fuels under consideration.

Figure 10- REPRESENTING THE OFFSHORE SUPPLY VESSEL CONSIDERED IN THE STUDY- FS ABERGELDIE

Figure 11- REPRESENTING THE AMMONIA TANKER VESSEL CONSIDERED IN THE STUDY- NEW WINNER

Figure 12- REPRESENTING THE METHANOL TANKER VESSEL CONSIDERED IN THE STUDY- TRAMMO PARIS

Storage Method: Fuel storage methods vary according to the type of fuel. Ammonia is stored in cylindrical refrigerated tanks This selection is primarily motivated by the incorporation of refrigeration systems within these containers, enabling precise control and regulation of temperature. This feature ensures that the ammonia is maintained in its liquid state throughout the transportation process, while Methanol is stored in double-walled cylindrical tanks. In the bunkering solution, vertical storage tanks are utilized, each designed according to specific criteria for Ammonia and Methanol. The vertical configuration allows for efficient use of space on the offshore platform while providing the necessary capacity for storing ammonia in its liquid form.

Platform Storage Area: Another crucial consideration is the space required on the offshore platform for fuel storage. In the case of containerized solutions for effectively utilizing platform space and reducing platform costs, containers from the Eurotainer brand are studied, which offers one layered, two-layered and three-layered stack arrangement options. This range of choices empowers project developers to select an arrangement based on the available space constraints on the platform. In single stack arrangement area required is $525m^2$ and in two layered arrangement the area required in offshore is $272.5m^2$.

Conversely, for loading/unloading solution, larger vertical tanks with a diameter of 40m is selected as this tank would have the capacity to store 22,000 m3 fuel which is the capacity of the vessel selected for bunkering option.

Boil off estimation: Investigating the boil-off rate for ammonia is imperative when analyzing the entire supply chain. The design of storage and transportation facilities must account for the specific boil-off characteristics of ammonia. With a calculated boil-off rate of 0.04%, a safety measure is implemented by not fully filling the tanks. Instead, the fuel capacity is maintained at 90 to 95 percent, leaving vacant space to ensure that pressure resulting from the boil-off remains within the allowable limit

Frequency of Voyage: The frequency of voyages determines how often a vessel visits the platform to transport fuels back to the onshore facility. In the containerized solution, an offshore supply vessel with a deck area of 700 square meters is chosen, allowing for the storage of 35 to 40 containers. Given the anticipated daily production rate, filling five containers per day, a weekly trip is deemed optimal. Conversely, for the loading/unloading solution, the vessel with a capacity of 22,000 m3, it is found that approximately 3 to 4 trips per year are adequate to transport the fuels produced annually.

Transfer of fuels: The concluding phase involves the transfer of fuels, and the results indicate that using the traditional crane system on the platform will require 1.5 to 2 hours for transferring 35 to 40 containers to the offshore supply vessel (Etsuko NISHIMURA, Akio IMAI, Bai ZHAO and Hitoshi KANEKO). Similarly, in the bunkering scenario, two flow rates (400 m^3/hr and 1000 m^3/hr) are considered, and the transfer occurs through a pipe and pump system. According to the vessel specifications, the fuel transfer involves 16 pipe systems, necessitating 1.2 to 3.2 hours. The primary challenge lies in connecting these 16 pipes, particularly in challenging offshore conditions. To enhance the study further, the exploration of pipes with larger diameters and corresponding flow rates is recommended for evaluation, aiming to address the difficulties associated with connecting multiple pipes in rough offshore conditions.

Table 3- REPRESENTING THE TECHNICAL COMPARISON BETWEEN TWO SHIPPING OPTION FOR AMMONIA

FACTORS	CONTAINERIZED	REFUELING (BUNKERING SOLUTION)
1.Type of vessel	Offshore Supply vessel	Tanker vessel
2.Storage method	Cylindrical containers	Vertical tanks
3.Storage space required	One layered- 525 sq. meter	1257 sq. meter
	Two layered- 262.5 sq. meter	
4.Boil off Rate	0.04%	0.04%
5.Voyage frequency	1 trip/1 week	3-4 trips/year
6.Fuel transfer method	Traditional platform crane	Using pump and pipe system
7.Duration for transfer	1.5 to 2 hours	1.2 to 3.2 hours (Depending on the pump, pipe specification).

4.1.1 RISK AND LIMITATIONS

Environmental Risks: Transporting fuels by vessel poses a significant risk of oil spills, which can have severe environmental consequences, harming marine life, ecosystems, and coastal areas.

Accidents and Collisions: Vessels transporting fuels are susceptible to accidents, collisions, and grounding, leading to potential leaks or spills, with the risk of fire or explosions.

Weather and Sea Conditions: Adverse weather conditions, such as storms or rough seas, can increase the likelihood of accidents during fuel transportation, making it a risky operation.

Human Error: The human element is a critical factor in fuel transport. Errors in navigation, miscommunication, or lapses in safety procedures can lead to accidents and spills.

Security Threats: Fuel-carrying vessels are vulnerable to security threats, including piracy and terrorism, which can result in hijacking, sabotage, or intentional spills with devastating consequences. (document)

4.2. TECHNICAL COMPARISON BETWEEN NEW PIPELINE AND REPURPOSING EXISTING NATURAL GAS PIPELINE

In scenarios involving pipeline transportation, akin to the shipping context, the factors considered for comparing the two methods are analogous for the two fuels under examination. This study investigates and compares the Ammonia pipeline in two case scenarios within the pipeline method. Given the constrained resources available for methanol pipeline transfer, the research assumes specific modifications to the pipeline selected for ammonia by incorporating measures to enable compatibility for methanol transfer.

In the technical comparison of pipeline transportation, various factors are considered, the detailed comparison is shown in the table 5.

Firstly, the choice of materials is paramount. The new pipeline is constructed using thick-walled Type 40 and Type 80 steel pipelines, purposefully designed for ammonia transfer (Gezerman). These pipelines are designed with a substantial wall thickness to ensure durability, strength, and safety during the transportation of ammonia, a chemical known for its corrosive properties. The designation "Type 40" and "Type 80" typically denotes the specific thickness and strength characteristics of the steel used in the construction of these pipelines. The robust nature of these pipelines is essential for containing and transporting ammonia under varying conditions, meeting both structural and safety requirements in the ammonia transfer process. This study assumes that same material can be used for the transfer of methanol with certain modifications. Conversely, the existing natural gas pipeline utilizes API X 42 and X52 lower-grade, more ductile steel pipes commonly employed in pipelines constructed between the 1980s and 2000s (ACER). Therefore, for the purposes of this study, it is assumed that the natural gas pipeline under consideration is also fabricated from similar materials. The mechanical properties of X42 and X52 grades, encompassing factors like yield strength, tensile strength, and impact resistance, render them highly suitable for meeting the requirements of transporting liquid ammonia.

Secondly, insulation requirements differ between these pipelines. The new pipeline, tailored for ammonia transfer, necessitates no additional insulation. In contrast, the natural gas pipeline typically requires insulation, with recommended options including Fusion-Bonded Epoxy (FBE), Polyethylene (PE) Coating, and Glass Reinforced Epoxy (GRE) Lining. In the case of utilizing above mentioned pipeline material for the transfer of methanol, certain modifications are required in the form of protective coatings or to blend the fuel with glycol or amine in order to reduce the corrosion effect.

Thirdly, the diameter of the pipelines plays a crucial role. A 12-inch diameter is chosen for the new pipeline for transferring Ammonia and Methanol in this study, driven by several factors. Firstly, anticipating an escalating demand for alternative fuels in the future, opting for a larger diameter pipeline is strategic to meet the anticipated increased demand. Additionally, the literature review suggests that a larger-diameter pipe is economically advantageous. Conversely, the existing natural gas pipeline employs a 36-inch diameter, in this study it is considered that the natural gas transmission is stopped completely for the transfer of alternative fuels the reason behind it is discussed in the above section about repurposing. To bridge the connection from the SEN 1 area to the existing pipeline, a 12-inch pipe is selected. The transition from a smaller to a larger diameter introduces velocity and pressure reductions in fluid flow, necessitating a detailed study to comprehend the flow characteristics through the pipe.

The fourth and fifth sections of technical analysis address the pipeline's capacity, encompassing considerations related to both flow rate and transmitted energy. For a newly constructed pipeline, the capacity ranges from 10,000 to 12,000 tons per day and boasts a transmission capacity of 1 GW. In contrast, the repurposed pipeline is anticipated to have significantly greater capacity, given that the diameter is nearly three times that of the new pipeline. Two key factors provide an explanation for this assumption:

Diameter Impact: The predominant factor influencing the higher capacity of the 36-inch pipeline is its larger diameter. The increased diameter allows for a greater cross-sectional area, facilitating the passage of a larger volume of fluid. This fundamental principle contributes to the enhanced transmission capacity, as the larger pipeline can accommodate a more substantial flow of materials.

Fluid Dynamics: Fluid dynamics, governed by principles such as Bernoulli's equation, plays a significant role in determining transmission capacity. In the case of a larger diameter pipeline, the physics of fluid flow results in lower frictional losses and a more streamlined flow. These characteristics contribute to an overall reduction in resistance, enabling the pipeline to handle a higher volume of materials with increased efficiency. This aspect further supports the assumption of a higher transmission rate in the 36-inch pipeline.

While these explanations are grounded in fundamental principles of fluid mechanics, it's important to acknowledge the assumptions are made in the absence of extensive studies on larger-diameter pipelines for alternative fuel transfer. Future research and empirical data could provide more accurate insights into the actual transmission capacities of pipelines with larger diameters, refining our understanding of the factors influencing their performance The energy transmission capacity for the repurposed pipeline is projected to reach 12 GW (cost of ammonia pipeline-WHEC2012Rev-H-Letter.doc).

The sixth factor under consideration pertains to the booster station pump. A booster station plays a crucial role in facilitating the transportation of ammonia and methanol from an offshore platform to an onshore facility. Its significance lies in optimizing the transfer process to meet the specific demands associated with extended distances or high-volume transport. Two key factors underscore its importance:

1.Pressure Boosting:

Purpose: The primary function of a booster station is to elevate the pressure of the transported fluids, including ammonia and methanol. This elevation is essential to ensure a consistent and reliable flow throughout the transfer from the offshore platform to the onshore facility.

Overcoming Friction: By boosting the pressure, the booster station effectively mitigates the impact of pipeline friction, a critical factor in maintaining the required flow rates. This is instrumental in preventing flow disruptions and ensuring a smooth transfer process.

2.Maintaining Physical Characteristics:

Fluid-Specific Tailoring: The booster station is meticulously designed to align with the unique physical properties of the transported fluids, taking into account factors such as viscosity, temperature, and chemical characteristics specific to ammonia and methanol.

Ensuring Compatibility: Tailoring the booster station to these specific fluid properties is crucial for ensuring compatibility and optimal performance throughout the transportation process. It prevents issues such as material degradation, phase changes, or other undesired alterations to the transported fluids.

Together, these two factors highlight the critical role of a booster station in enhancing the efficiency and effectiveness of the ammonia and methanol transportation process. By addressing pressure requirements and tailoring its design to the distinct physical characteristics of the fluids, the booster station contributes to a reliable and streamlined transfer from offshore to onshore facilities.

In the newly proposed pipeline, given the lower flow rate in comparison to the larger-diameter natural gas pipeline, a pump with reduced specifications is chosen for this investigation. The study opts for high-efficiency magnetic drive pumps, specifically selecting a mag drive multi-stage centrifugal pump for the new pipeline in case of Ammonia and vane pumps for the transfer of methanol and a mag drive process pump for the repurposed pipeline. The selection of pumps are specifically done by considering the fuels and its physical properties.

The seventh and eighth parameters address the physical properties of the fuel. For ammonia, the temperature is consistently maintained at -33 degrees Celsius in both pipeline options. Regarding pressure considerations, the new pipeline maintains a pressure range of 3 to 6 bar, whereas the repurposed pipeline, with its larger diameter, operates at a pressure value below 3 bar. Maintaining low pressure for the transfer of liquid ammonia at -33 degrees Celsius through a pipeline is crucial for several reasons, primarily related to the unique properties and behavior of ammonia at low temperatures. Here are key considerations for maintaining low pressure in this scenario:

Avoiding Phase Transition: At temperatures below its boiling point (approximately -33 degrees Celsius for ammonia), it remains in liquid form. However, if the pressure is too high, there is a risk of inducing a phase transition, causing the liquid ammonia to vaporize. Maintaining low pressure helps prevent this undesired transition.

Safety Concerns: Operating at low pressure reduces the risk of leaks or ruptures in the pipeline, enhancing safety. Ammonia is a corrosive and potentially hazardous substance, and controlling pressure mitigates the associated safety risks.

Pipeline Integrity: Low pressure conditions contribute to the integrity of the pipeline by minimizing stress on the pipeline walls. This is particularly important for pipelines transporting fluids at low temperatures, as material properties can be affected by both low temperatures and high pressures.

Temperature and Pressure Relationship: Ammonia, like many substances, follows the principles of the ideal gas law, where pressure and temperature are interrelated. By maintaining low pressure, the risk of temperature-related effects, such as unexpected increases in pressure due to temperature changes, is mitigated. In the case of methanol, it is transported in atmospheric conditions that is at 25 Degree Celsius and 1 bar pressure.

The final consideration pertains to the storage tank required on the offshore platform. In the case of the new pipeline with a smaller diameter, operating at full capacity necessitates a four-day annual operation for fuel transfer, requiring a storage volume of 17,000 m3. At half capacity, the storage requirement is proportionally reduced to 8,500 m3. Conversely, the repurposed pipeline, characterized by a larger diameter, only requires a single day for fuel transfer at full capacity, leading to a storage demand of 56,000 m3, and half that volume, or 28,000 m3, at half capacity.

Table 4- TECHNICAL COMPARISON BETWEEN THE TWO PIPELINE OPTIONS FOR AMMONIA

Factors	New pipeline	Repurposing Existing natural gas pipeline
1. Material	Thick-walled type 40 and 80 steel pipelines	API X42 and X52 lower grade more ductile steel pipe
2. Insulation	No additional insulation required	Required, as it is designed for natural gas
3. Diameter	12 inch	36 inch
4. Capacity of pipeline	10,000 to 12,000 tpd	>>>12,000 tpd
5. Rated transmission capacity	1GW	12GW
6. Pump(booster station)	mag drive multi-stage centrifugal pump	ISO 2858- ISO 5199 mag drive process pump
7. Operating pressure	3 to 6 bar	<3 bar
8. Temperature	240k	240k
9. Storage • Pipeline full capacity	17,000 m^3	56,000m^3
• Half capacity	8500m^3	28,000m^3

4.2.1 RISK AND LIMITATION

The transfer of ammonia and methanol from offshore to onshore locations via pipelines offers various advantages, such as efficiency and safety, but it also comes with inherent risks and limitations (Waskito et al. 2020).

Risks

Corrosion and Material Compatibility: Ammonia and methanol can be corrosive to pipeline materials, potentially leading to material degradation over time. Ensuring proper material selection and corrosion protection measures is crucial.

Leaks and Spills: The potential for leaks and spills during transfer poses environmental and safety risks. Effective leak detection systems and contingency plans are essential to mitigate these risks.

Health and Safety Concerns: Ammonia and methanol are hazardous chemicals that can pose health risks to workers in the event of exposure. Stringent safety protocols, worker training, and protective equipment are vital.

Environmental Impact: Spills or leaks can result in environmental contamination and damage to aquatic ecosystems. Compliance with environmental regulations and prompt response to spills is critical.

Regulatory Compliance: Adherence to various international and regional regulations and standards is mandatory for offshore-to-onshore transfer operations. Non-compliance can result in legal and financial consequences.

Limitations:

Cost of Infrastructure: Building and maintaining pipeline infrastructure can be costly, making it less feasible for smaller projects or in cases where other transportation methods are more economical.

Limited Routes: Pipeline routes are relatively fixed, making them less flexible compared to other transportation methods. This can be a limitation in cases where the location of offshore production sites or onshore facilities changes over time.

Maintenance Requirements: Pipelines require ongoing maintenance, inspection, and integrity management to ensure their safe operation. This can add operational costs and downtime.

Long Transportation Distance: For offshore locations that are far from the onshore receiving facility, the long transportation distance can increase the time and energy required for the transfer.

Extreme Environmental Conditions: Harsh offshore conditions, such as severe weather, ice, and deepwater environments, can pose challenges for pipeline operation and maintenance.

4.3. ECONOMIC ASSESSMENT

In this segment, the thesis endeavors to explore the economic contrasts among four distinct transportation alternatives. This evaluation involves an analysis of three pivotal factors: CAPEX, OPEX, and the levelized cost of transport.

4.3.1 CAPEX ESTIMATION

The capex estimation section delves into the factors taken into account for capital expenditure (capex) calculation and elucidates the assumptions underlying each factor employed in the capex calculation for the transport options considered in the study. The assessment is carried out for the primary fuel

Ammonia and the value for Methanol is assumed to be 30% less than the value for Ammonia (Ketan Gore).

The economic evaluation of loading/unloading type is presented below, CAPEX is determined as the sum of vessel cost, import and export terminal cost, and storage tank cost. In the assessment of capital expenditures (CAPEX) within the shipping transport, the costs taken into account include the market price of the product. Additionally, the alternative choices of leasing or renting out the products are viable and can be considered. However, it is important to note that, for the purposes of this study, the option of hiring will not be included in the analysis. The vessel cost is estimated at 44 million Euro, with the average cost derived from the reference to LPG carriers (Youngkyun Seo and Seongjong Han). The import and export terminal cost charges amounts to 4.2 million Euro as per the reference (Johnston et al.). The storage tank cost is assumed to be 9 million Euro, as indicated in the reference (AIT AIDER Cherif 2022).

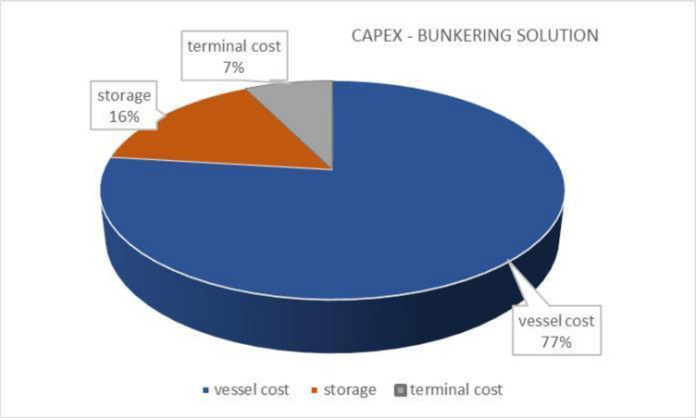


Figure 13- REPRESENTS THE CAPEX IN TERMS OF PERCENTAGE OF DIFFERENT COMPONENTS FOR LOADING AND UNLOADING TYPE

For the transportation of fuels in containerized form, the capital expenditure (CAPEX) calculation involves four primary factors, mirroring the bunkering scenario. These factors include the vessel cost, import and export terminal expenses, and the expenditure on storage tanks in the form of containers. The offshore supply vessel cost is projected to be 15 million euros based on the information provided in reference (ship selector). The estimated annual cost for import and export terminals is 4,2 Million Euro (Johnston et al.). In this study, the consideration is given to the cost of 280 containers, the quantity required for storing fuels over a two-month period. It is anticipated that these containers will be utilized for future fuel transfers. The estimated cost for the container tanks is 6 million euros (AIT AIDER Cherif 2022).

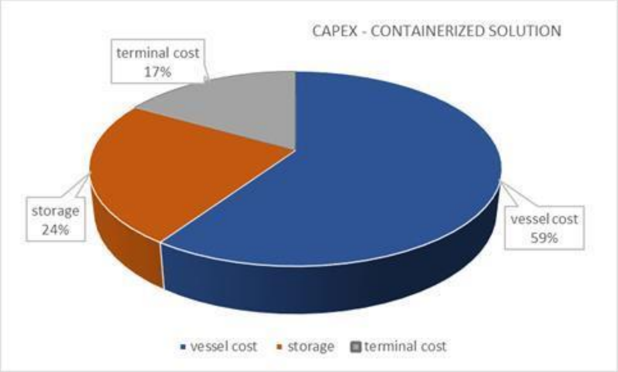


Figure 14- REPRESENTS THE CAPEX IN TERMS OF DIFFEREMT COMPONENTS FOR CONTAINERIZED SOLUTION

Table 5- REPRESENTING THE CAPEX AND PARAMETERS CONSIDERED FOR EACH TRANSPORT OPTIONS

Economic factors		Parameters included	Assumption	Final value	Reference
CAPEX	New pipeline	Cost of new pipeline per km and distance	Cost of New pipeline 0.3M€/km	51 M€	(a)
			Distance – 170 KM		
	Existing pipeline	Cost of repurposing existing NG pipeline , cost of laying new pipeline till joining existing one and respective distances	cost of repurposing Natural Gas pipeline- 30% of New pipeline CAPEX	25.8M€	(b)
			Cost of new pipeline = 0.3M€/km		
			Distance of New pipeline- 50 KM		
			Distance of using existing Natural Gas pipeline- 120KM		
	Shipping-containerized	container vessel cost, Terminal cost and storage container cost	Vessel cost- 15M€	25.2 M€	(c)
			Terminal cost- 4.2 M€		
			Storage cost-6M€		
	Shipping – Bunkering option	Tanker Vessel cost, Import & Export terminal cost and storage cost	Vessel cost- 44M€	57.2 M€	(d)
			Terminal cost- 4.2M€		
			Storage cost- 9M€		

REFERENCE (a)- (cost of ammonia pipeline- WHEC2012-Rev-H-Letter.doc)

REFERENCE (b)- (ACER)

REFERENCE (c)- (Johnston et al.), (AIT AIDER Cherif 2022)

REFERENCE (d)- (Youngkyun Seo and Seongjong Han; Johnston et al.; AIT AIDER Cherif 2022)

In the economic evaluation of constructing a new pipeline for the transportation of Ammonia and Methanol, the capital expenditure (CAPEX) is determined by the cost of the pipeline per kilometer (€300k) and total distance in kilometers between the offshore platform and onshore facility. This cost assumption is derived from the reference cited (cost of ammonia pipeline- WHEC2012-Rev-H-Letter.doc).

For the examination of repurposing existing natural gas pipelines, the calculation of capital expenditures (CAPEX) can be categorized into two primary domains. The first involves the installation of a new pipeline from the SEN 1 area to a specific point along the existing natural gas pipeline, incurring a cost of 0.3 million Euros per kilometer. The second aspect focuses on estimating the CAPEX for the repurposed pipeline, set at 30 percent of the cost of a new pipeline, as derived from the assumptions outlined in reference (ACER).

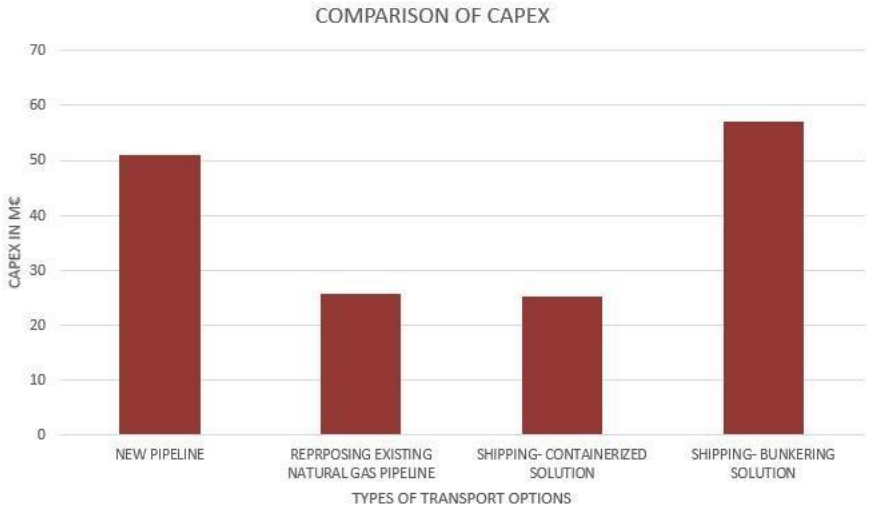


Figure 15- SHOWS THE COMPARISON BETWEEN CAPEX VALUE FOR DIFFERENT TRANSPORT OPTIONS

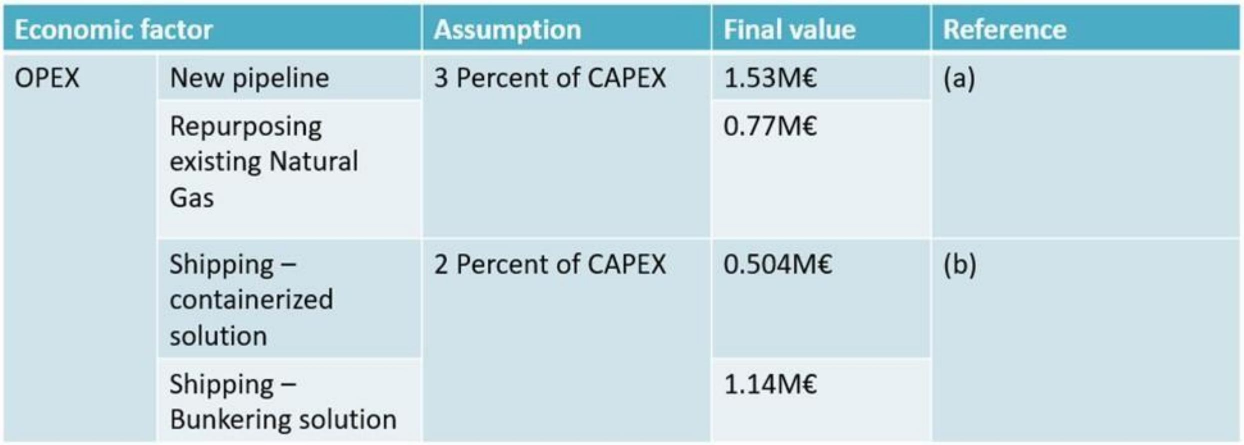
In the economic comparison segment, the pivotal determinant influencing the feasibility and financing of the project is the capital expenditure (CAPEX) cost. When assessing all four potential options explored in this study, with the given production rate of alternative fuels, the CAPEX is found to be the most economical for the containerized shipping scenarios which marks 25.2 million euro, followed by the repurposed natural gas pipeline option which amounts to 25.8 million Euros and 51 million euros for the installation of a new pipeline from SEN 1 area to Bremerhaven port. The most capital intensive is the bunkering solution, potentially attributed to the elevated cost of carriers. This study assumes the use of new tanker vessels, and one strategy to reduce costs could involve exploring alternatives such as chartering options or acquiring used vessels.

4.3.2 OPEX ESTIMATION

The second significant cost component, OPEX, representing operating costs, as depicted in the table is assumed to be 2 percent of the CAPEX for the shipping transport options. The OPEX factor is assumed to be 3 percent of the CAPEX for the pipeline cases. The assumptions are derived from the reference (Galimova et al.).

The Operational Expenditure (OPEX) for pipeline transport of fuels is often higher compared to transport via ship due to several factors inherent to each mode of transportation.one such factor is the maintenance. Pipelines require consistent monitoring, inspection, and maintenance to ensure the integrity of the infrastructure. This involves regular checks for corrosion, leaks, and other potential issues, contributing to ongoing operational expenses.

Table 6- OPEX ESTIMATION FOR DIFFERENT TRANSPORT OPTIONS



Economic factor		Assumption	Final value	Reference
OPEX	New pipeline	3 Percent of CAPEX	1.53M€	(a)
	Repurposing existing Natural Gas		0.77M€	
	Shipping – containerized solution	2 Percent of CAPEX	0.504M€	(b)
	Shipping – Bunkering solution		1.14M€	

REFERENCE (a)- (Galimova et al.)

REFERENCE (b)- (Galimova et al.)

In contrast to the Capital Expenditure (CAPEX) trends, the Operational Expenditure (OPEX) values for the four transportation alternatives exhibit a distinct pattern. The most cost-effective option in terms of OPEX is the containerized shipping choice, totaling 0.504 million euros, succeeded by the repurposed pipeline alternative at 0.77 million euros. Subsequently, the bunkering shipping option incurs an OPEX of 1.14 million euros. Finally, the new pipeline emerges as the costliest option in terms of operating costs, amounting to 1.53 million euros.

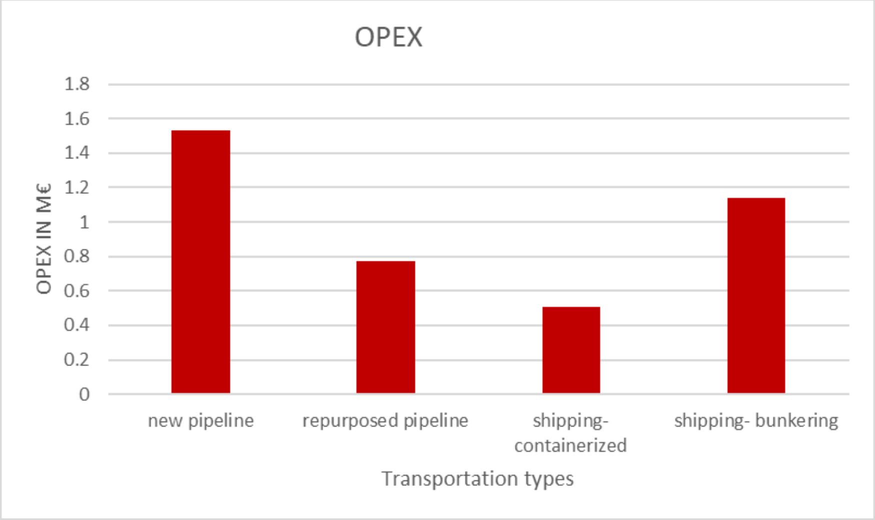


Figure 16- PLOTS THE COMPARISON OF OPEX VALUES FOR DIFFERENT TRANSPORTATION OPTIONS

The OPEX value for the case of Methanol also follows the similar assumption as that of CAPEX calculation that is nearly 30% decrease in cost compared to Ammonia transport (Ketan Gore).

4.3.3 LEVELIZED COST OF TRANSPORT

In the computation of the levelized cost of transport, factors beyond capital expenditure (CAPEX) and operational expenditure (OPEX) play a pivotal role. Various assumptions have been incorporated into the study to ensure the attainment of comparable results. Different factors that are considered in the study are detailed in the table presented below.

In the master thesis, several critical factors impact the calculation of the levelized cost of transport. The first factor is the capital recovery factor (CRF), determined by the weighted average of capital cost and lifetime, with the CRF value obtained using the provided equation [9]. The values for the weighted average cost of capital (WACC) and lifetime are assumed based on a review of the reference (Galimova et al.).

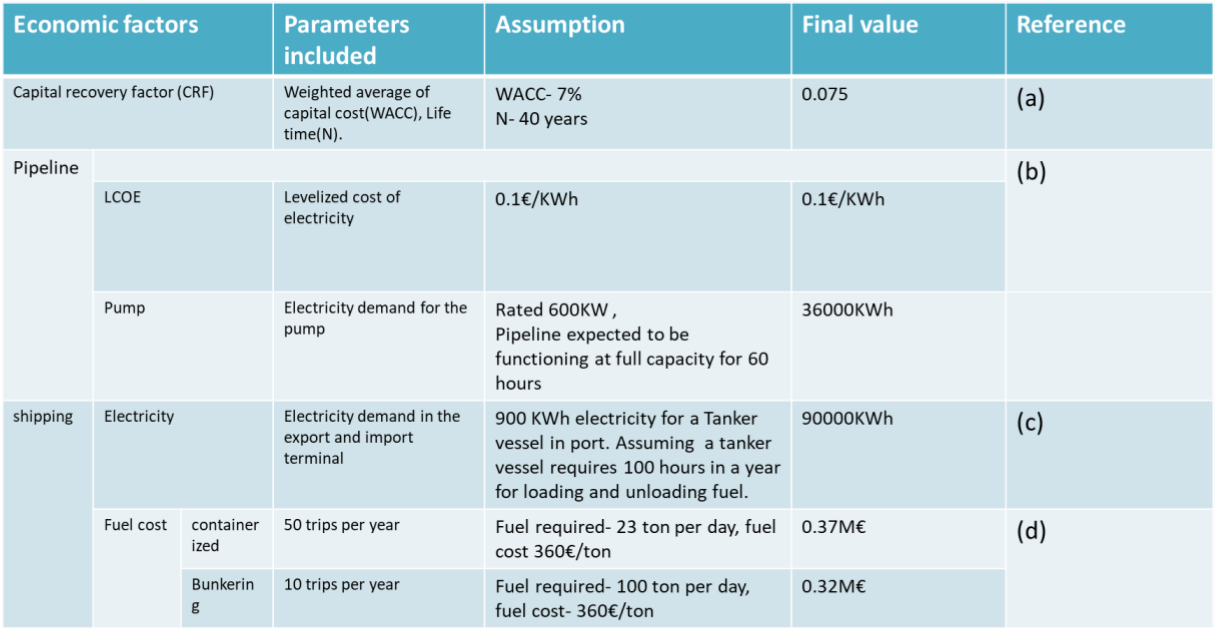
The second factor is the levelized cost of electricity, assumed to be 0.1 euros per kWh in this study. This assumption is made considering that all electricity demand in the scenarios will be met using renewable energy sources, and the value is drawn from the reference (Christoph Kost et al.).

The third factor involves the electricity demand in the pump station. For pipeline cases, the study assumes different pump systems with the same power ratings, specifically 600 Kw is assumed to be the power consumption for the pumps in booster station (Nayak-Luke et al.). Given the low production rate, these pumps are operational for 60 hours, resulting in an electricity demand of 36,000 kWh.

The fourth factor is the electricity demand in the terminals, with an assumption of 90,000 kWh required for both shipping cases, such as tanker vessels, as per the reference (PATRIK ERICSSON 2008). For instance, a tanker vessel requires 900 kWh of energy during the expected 100 hours in the port.

The final factor is fuel cost, with assumptions that a container tank requires 32 tons of fuel per day and a tanker vessel requires 100 tons of fuel per day, each costing 360 euros per ton. These assumptions are derived from a comprehensive literature review of the reference (Joris Kee, Malte Renz, Miralda van Schot, Finnbar Howell, Catrinus Jepma 2020).

Table 7- REPRESENT THE FACTORS CONSIDERED AND RESPECTIVE VALUES USED IN LCOT CALCULATIONS



Economic factors			Parameters included	Assumption	Final value	Reference
Capital recovery factor (CRF)			Weighted average of capital cost(WACC), Life time(N).	WACC- 7% N- 40 years	0.075	(a)
Pipeline						(b)
	LCOE		Levelized cost of electricity	0.1€/KWh	0.1€/KWh	
	Pump		Electricity demand for the pump	Rated 600KW , Pipeline expected to be functioning at full capacity for 60 hours	36000KWh	
shipping	Electricity		Electricity demand in the export and import terminal	900 KWh electricity for a Tanker vessel in port. Assuming a tanker vessel requires 100 hours in a year for loading and unloading fuel.	90000KWh	(c)
	Fuel cost	containerized	50 trips per year	Fuel required- 23 ton per day, fuel cost 360€/ton	0.37M€	(d)
		Bunkering	10 trips per year	Fuel required- 100 ton per day, fuel cost- 360€/ton	0.32M€	

REFERENCE (a) - (Galimova et al.)

REFERENCE (b)- (Nayak-Luke et al.)

REFERENCE (c)- (PATRIK ERICSSON 2008)

REFERENCE (d)- (Joris Kee, Malte Renz, Miralda van Schot, Finnbar Howell, Catrinus Jepma 2020)

The comparison of LCOT (Levelized Cost of Transport) for different pipelines is illustrated in the Figure (18). According to the reference (Galimova et al.), the levelized cost for transporting Ammonia through a pipeline in 2030 is estimated to be 12 euros per tonne. In this study, upon conducting calculations using equation [8], the LCOT value for the Repurposing pipeline scenario is 15.233 Euros per tonne, while for the installation of a new pipeline, the obtained LCOT is 15.266 Euros per tonne.

Despite a clear difference in the CAPEX value between the two pipeline options, the levelized cost of two options are almost similar with a small difference. This observation may be attributed to the impact of other factors such as capital recovery factor, full load hours and the electricity demand in the pump station in the LCOT calculation

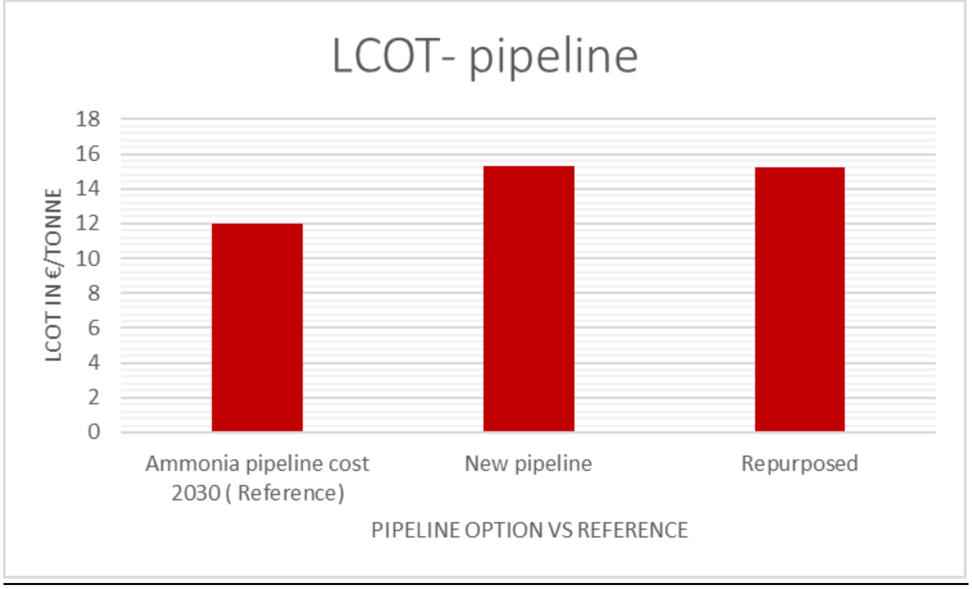


Figure 17- REPRESENTS THE COMPARISON OF LCOT BETWEEN AMMONIA PIPELINE OPTIONS VS AMMONIA PIPELINE 2030 REFERENCE

Similarly, a comparative analysis of levelized cost of transportation costs is undertaken, specifically focusing on shipping alternatives. The assessment involves benchmarking against a reference levelized cost of transportation (LCOT) for Ammonia transport in 2030, the value for LCOT is estimated to be 8 euros per tonne (Galimova et al.). Through the calculations performed for LCOT in the thesis, incorporating all data and assumptions for shipping transport, the obtained value for the loading and unloading type is 8.1 Euros per tonne and for the containerized solution, the LCOT value obtained is 9.4 Euros per tonne for transporting ammonia from the offshore platform to the onshore facility.

Similar trend can be observed in shipping option as well. Despite the loading/unloading ship's capital expenditure being nearly double that of the containerized solution, the investigation reveals that, in terms of LCOT, loading/unloading type emerges as the most economical choice. This observation can also be attributed to the impact of capital recovery factor and full load hours on both capital and operating expenses within the LCOT equation.

Another factor which increases LCOT for containerized solution compared to Loading/unloading type would be the practical aspect of the tanker vessel making only 10 trips per year compared to the containerized solution's 50 trips. This discrepancy significantly affects LCOT, as it exhibits a linear correlation with rising fuel costs. To mitigate expenses, potential strategies include opting for an offshore supply vessel with greater capacity or selecting a larger container vessel. These alternatives can be considered depending on the available space on the offshore platform for storing a substantial number of containers. Exploring stacking arrangements, whether in three or two layers, further contributes to the examination of viable cost-reduction measures.

Figure 18- REPRESENTS THE LCOT COMPARISON FOR THE AMMONIA SHIPPING OPTION VS AMMONIA SHIPPING 2030 REFERENCE

The observed trend in the levelized cost over a distance of 170 km aligns with the anticipated outcome based on the findings from the literature review. The estimated levelized cost of pipeline transport is higher when compared to the two shipping alternatives. The elevated levelized cost for pipeline transport can be attributed to its reliance on two major factor that is the electricity demand at the booster station and the distance between the offshore and onshore facility. The combination of these factors results in a higher LCOT in the equation [8], while the impact of fuel cost and electricity demand in the levelized cost of transport equation for shipping yields a much lower value for LCOT compared to pipeline. If the production rate increases, a different trend may emerge. With a higher volume of fuels, assuming the same vessel is considered, the number of required trips would rise, directly impacting both electricity demand in the port and fuel consumption. In such scenarios the pipeline would be more economical than the shipping option.

In this study Levelized cost of transportation for Methanol is assumed to be following a similar trend as that of the Ammonia. This assumption is considered because of the fact that on one side, the CAPEX and OPEX might be smaller for methanol but at the same time (Ketan Gore), the electricity demand considered in both transport options plays a crucial role in the LCOT calculation. The electricity demand particularly for the pump used in the transfer purpose will be higher for methanol, as the density of methanol is higher compared to Ammonia.

4.4.ANALYSIS OF SUPPLY CHAIN- UTILIZATION OF FUELS BY END USER

In this section, the goal is to provide a brief overview of the entire supply chain for transporting alternative fuels from offshore regions to end users. Realistic assessment of transport options necessitates considering the entire supply chain. Ammonia and methanol are versatile chemicals with a wide range of end users once they reach the Bremerhaven port (Emden port in case of using existing natural gas pipeline) in Germany. Alternative fuels (Ammonia and Methanol) supply chain from the offshore platform located in the SEN1 area to the end user, can be considered in two stages – transport phase and inland distribution phase.

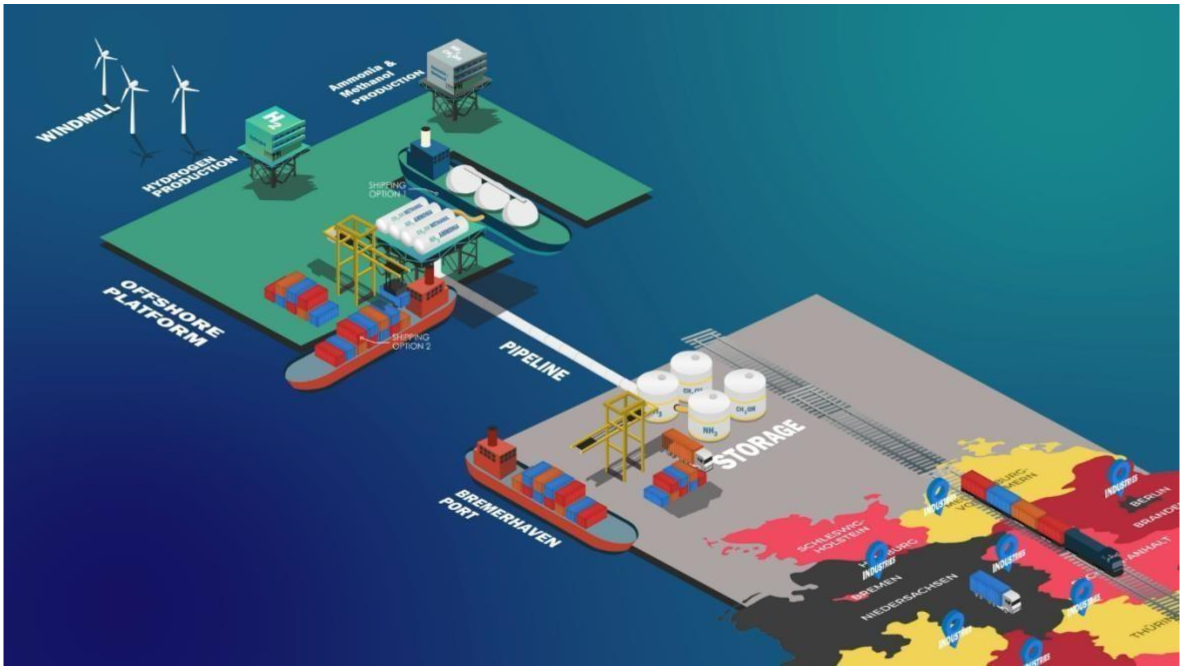


Figure 19- REPRESENTS THE WHOLE SUPPLY CHAIN OF TRANSPORTATION FROM PRODUCTION TILL END USERS

Transport phase -The import is for the transportation from the production phase which is located at the SEN 1 1 area to the port of country of origin which Bremerhaven in the case of the study. For these transfer of fuels, both pipeline and ships are seen as optimal choices considering the efficiency and costs. As larger amounts of fuels can be transported by them.

Inland Distribution Phase-Distribution is the phase of transportation to the end user. Different possible transport options for fuel distribution are available such as trucks, trains, pipelines as well as inland vessels. German public transport sector by providing more economical transport means, are favouring the faster inland distribution of fuels. Example, the Deutsche Bahn is getting ready to deliver 20 percent of the hydrogen demand by 2030 and also involved in the development of special containers for the transport of hydrogen (Bahn, n.d.). Thus, similar transfer of fuels like Ammonia and Methanol via rail line can be considered which provides a continuous flow of fuels to the end user at different locations. Depending on the distance, location of the end user, demanded amount of fuel as well as the fuel type, each of these transport options could be recommended.

Table 8- REPRESENTING THE LCOT VALUES ACROSS WHOLE TRANSPORTATION SUPPLY CHAIN

	Transport options	LCOT
Maritime transport	New pipeline	15.266 €/tonne
	Repurposed pipeline	15.233 €/tonne
	Shipping - containerized	9.4 €/tonne
	Shipping - bunkering	8.1 €/tonne
Inland transport	Rail	0.03€/tonne/km
	Truck	0.21€/tonne/km

This master's thesis primarily focuses on fuel transportation from offshore platforms to onshore regions. To comprehensively address the entire supply chain in the transportation sector, this section examines the costs associated with transporting fuels from onshore storage facilities to end users. The analysis predominantly considers two transportation pathways: rail and heavy trucks.

Rail and truck represent established means of transporting ammonia and methanol inland. Rail transportation proves efficient and cost-effective for distributing large fuel volumes inland, providing substantial capacities per journey and high fuel efficiency per tonne-km. However, its drawback lies in its limited flexibility, as it relies on existing railway lines. On the other hand, road transportation is a common method for fuel transport, offering greater flexibility for short distance transportation and ensuring last-mile connectivity. Nonetheless, it faces a significant drawback as it tends to be more expensive compared to other transportation modes.

The assumed costs for fuel transportation by rail and truck, as derived from the literature review of reference (Nayak-Luke et al.), are considered as 0.03 and 0.21 Euros/tonne/km, respectively, in this study.

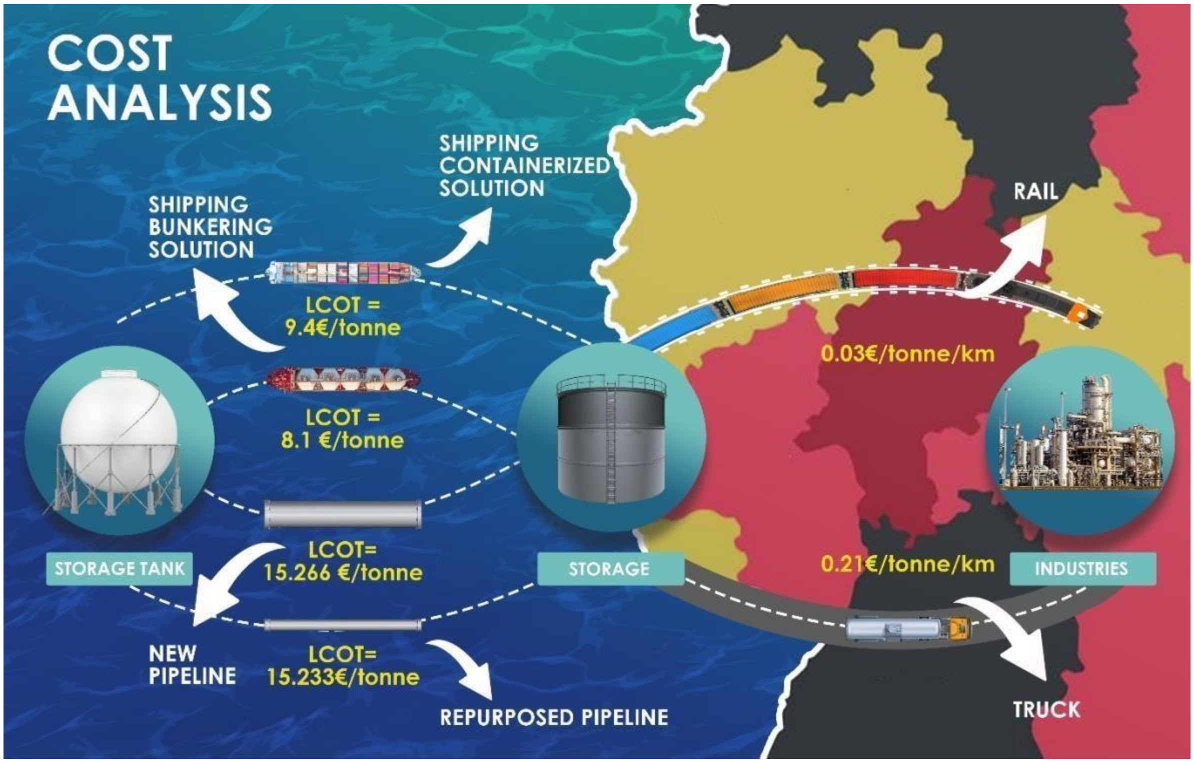


Figure 20- PICTORIAL REPRESENTATION OF LEVELIZED COST FOR DIFFERENT TRANSPORT OPTIONS FOR WHOLE TRANSPORT SUPPLY CHAIN

The determination of the most cost-effective transportation route extends beyond the sole consideration of the levelized cost of transportation. In practical scenarios, various other factors must be thoroughly examined. Pertinent parameters include the end user's location, the specific fuel type demanded by the end user, the volume of fuel required, the frequency of demand, and potential distribution alternatives from the port to the ultimate destination.

5.CONCLUSION

This master's thesis delved into a comprehensive techno-economic analysis of transporting offshore power to X products (Ammonia and Methanol) through both shipping and pipeline methods.

In the technical assessment section of the shipping option, the initial step in this study involved selecting two vessels for fuel transport, along with the corresponding storage tanks. Through an extensive literature review and certain assumptions, the offshore supply vessel and tanker vessel were chosen, taking into account the production rate and available storage space on the offshore platform. The smallest vessel are selected in both cases for the transfer since the production rate considered is low. Due to this reason, the number of trips in case of offshore supply vessel is 50 trips in a year while it is only 10 in case of tanker vessel, this points mainly to the fact that there are some margin of data discrepancies in this study.

Similarly, within the pipeline transport analysis, the focus shifted towards selecting an appropriate grade for the steel pipe and determining the diameter required for fuel transfer. The consideration extended to exploring the repurposing of existing pipelines, particularly in response to the declining trend observed in natural gas pipelines. This strategic approach was discussed as a means to mitigate future costs associated with transferring alternative fuels. By adapting and repurposing existing infrastructure, the study aims to contribute to a more cost effective and sustainable solution for the transport of alternative fuels.

When scrutinizing the results from an economic perspective, the containerized solution stands out as the most cost-effective option in terms of upfront expenses, amounting to 25.2 million euros. It is closely trailed by the repurposed pipeline option, which incurs a cost of 25.8 million euros. However, the portrayal shifts when considering the levelized cost of transport, where the bunkering solution, despite being the most capital-intensive option, emerges as the most economical, with a cost of 8.2 euros per tonne of fuels.

6.SCOPE FOR FUTURE STUDY

In the context of this study, various assumptions and considerations have been acknowledged, creating opportunities for further enhancements and broader research within these specific domains.

In the realm of shipping as a transportation option, there are several areas open to improvement.

Firstly, enhancing the accuracy of boil-off gas estimation under various conditions is crucial. Notably, the study does not currently consider the impact of sloshing, a factor identified in the literature to increase temperature and subsequently, boil-off gas emissions. Secondly, refining vessel cost estimation is possible by providing a comprehensive analysis of alternatives such as chartering or purchasing used vessels. Thirdly, exploring the use of greener fuels in shipping and utilizing boil-off gas for onboard power demand could significantly enhance the effective utilization of alternative fuels and mitigate greenhouse gas emissions.

In the case of pipeline transport, the study relies on repurposing existing natural gas pipelines by completely halting their operations for the transfer of alternative fuels. Future studies could explore the feasibility of utilizing the same pipeline for multiple products, potentially reducing capital expenditure.

Finally, beyond transport improvements, there is value in investigating the nature and quality of fuels reaching the port and exploring various methods of utilizing these fuels onshore, such as conversion to hydrogen to meet future demand.

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