Aalborg University

Implementing E-ammonia Bunkering Infrastructure in Port of Esbjerg

Master's thesis in Sustainable Energy Planning and Management

Ditte Stougaard Stiler
02.06.2023

Preface

This report constitutes my master's thesis compiled during Spring 2023 at Aalborg University from the study programme "*Sustainable Energy Planning and Management"*. The topic "*Introducing E-ammonia Bunkering Infrastructure in Port of Esbjerg*" is inspired by the research and work regarding developing both Nordic and international green shipping corridors that aim at decarbonising the shipping sector. Thank you to keynotes at the conference, "*The Green Future of Maritime Operations*", that was held in Nuuk 2022, co-hosted by Naalakkersuisut and Nordic Energy Research. Their presentations and speeches have encouraged me to investigate this topic.

In that regard, a special thank you must be forwarded to my great colleagues at Nordic Energy Research for having contributed with scientific inputs and advice to the investigation as well as been a great support during the process of compiling this report. I look very much forward to start working full-time with you after Summer.

Furthermore, a valued thank you forwards to the three interview respondents that have contributed to this report by sharing knowledge, providing data, and perspectives on the topic. The three interview respondents are senior consultant at DNV, Nathaniel Frithiof, CEO at Port of Esbjerg, Dennis Juul Pedersen, and Head of Offshore Energy at ELOMATIC, Ted Bergmann.

Lastly, I want to thank my supervisor, David Maya-Drysdale, for his brilliant supervision during this process. It has been both instructive and constructive to have you as a supervisor.

I hope that you as a reader find this report interesting. Please enjoy the readings.

Project: Master's Thesis

Project Period: February 2023 – June 2023

Student: Ditte Stougaard Stiler **Student no.**: 20183982

Supervisor: David Maya-Drysdale

Pages: 80 (incl. list of reference)

Appendices in total: 6

Appendix 1: Page 81 - 82

Appendix 2 – 6: Attached the report.

Table of Content

Abbreviations

AIS: Automatic identification system

ASU: Air Separation Unit

CAPEX: Capital cost

CCS: Carbon Capture and Storage

CCUS: Carbon Capture Utilisation and Storage

E-ammonia: Electrochemical ammonia

E-hydrogen: Electrochemical hydrogen

E-methanol: Electrochemical methanol

EU: European Union

EU ETS: European Union Emission Trading System

GT: Gross tonnage

KPI: Key performance indicator

LCA: Life-cycle assessment

LCOA: Levelized Cost on Ammonia (Nayak-Luke et.al., 2021)

LNG: Liquefied Natural Gas

IMO: International Maritime Organization

MGO: Marine Gas Oil

MGO eq.: Marine Gas Oil equivalent

Mtoe: Millions ton of oil equivalent

OPEX: Operational cost

UN: United Nations

1. Abstract (Danish)

Denne rapport indeholder en teknoøkonomisk gennemførlighedsanalyse vedrørende implementeringen af e-ammoniak bunkering infrastruktur i Esbjerg Havn, som udvalgt kritisk casestudie, i henhold til en større udvikling af Nordiske grønne skibskorridorer. Dette udføres ved at besvare følgende problemformulering:

Hvordan kan e-ammoniak bunkering infrastruktur gennemførligt implementeres i Esbjerg Havn fra et teknoøkonomisk perspektiv til at understøtte udviklingen af Nordiske grønne skibskorridorer?

Problemformuleringen besvares med afsæt i en teoretisk tilgang, der omfatter *teknologiforståelse*, *multi-level perspective teori* og *stategic niche management*. Disse rammesætter en forståelse af, hvordan demonstrering af innovative teknologier på niche-niveau kan medvirke til omstillingen af en sektor på samfundsniveau. Det leder til udvælgelsen af et kritisk casestudie, der bidrager med en teoretisk og metodisk forståelse af, hvordan fænomener gældende for en kontekst kan sige noget om den generelle virkelighed og i hvilken grad ud fra et validt synspunkt.

I gennemførlighedsanalyse, som udgør rapportens hovedmetode, undersøges hele forsyningskæden af e-ammoniak til bunker anvendelse. Det indbefatter produktion, transport, lagring og bunkering. To alternativer arbejdes der med, som e-ammoniak bunkering løsninger, som er *lastbil-til-skib* og *skib-til-skib bunkering*. Gennemførligheden af de to alternative bunkering løsninger vurderes på baggrund af deres evne til at opfylde to gennemførlighedskriterier: *ønsket om høj bunkering udførelse* og *lav medført pris på e-ammoniak per ton*. Dette bliver gjort med afsæt i hele e-ammoniak bunkering infrastrukturen. Analysen baseres på nuværende skibsaktiviteter i Esbjerg havn og pris på marine fossile brændsler til sammenligning og behandlet som en baseline. Både kvantitativt og kvalitativt data er indhentet i form af sekundær litteratur og primære data gennem udførelsen af tre interviews. Kvantitativt data behandles i en udarbejdet energimodel i Excel, som simulerer efterspørgsel, produktion og lagringskapacitet af e-ammoniak samt bunkeringudførelsen af de to alternativer. Dertil udføres økonomiske beregninger i modellen. GIS anvendes som supplerende data indsamlings- og analyseredskab til at processere data med geografiske forhold og information.

Resultatet af analysen peger på, at skib-til-skib bunkering kan bidrage med højeste bunkering udførelse, hvortil lastbil-til-skib bunkering medfører laveste priser på e-ammoniak per ton. Ingen af alternativerne er konkurrencedygtige med eksisterende pris på marine fossile brændstoffer. Ikke desto mindre bidrager analysens resultater til udviklingen af grønne korridorer ved at demonstrere teknoøkonomiske parameter og usikkerheder relateret til e-ammoniak bunkering infrastruktur, der tilfører viden ny viden til fremtidigt arbejde indenfor feltet. Der påpeges væsentlige barrierer, som på løses på samfundsniveau samt bør demonstreringen af den teknoøkonomiske gennemførlighed understøttes ved lignende analyser for andre Nordiske havne. Det er med hensigten at styrke modenheden af den innovative teknologi.

2. Introduction

Inventing carbon-neutral solutions for international shipping can be argued as a necessity. Approximately 2 % to 3 % of today's global greenhouse gas emissions originate from the sector (Global Maritime Forum, 2023). Additionally, international shipping constituted almost 90 % of the global trade by volume in 2020 (Baresic & Palmer, 2022) , which implies a heavy dependency on shipping to generate economic value by trading goods (OECD, 2023). International shipping is, furthermore, predicted can triple in size by 2050 compared with 2008 due to increased freight demands (OECD, 2023). With this prognosis, greenhouse gas emissions can increase by 90 % to 130 % in 2050 compared with 2008 from the sector (Faber & et.al., 2021).

In response to the movement, 24 member states of the United Nations signed a memorandum of understanding during the 26th Conference of the Parties (COP26) in 2021. The memorandum of understanding concerned an agreement to establish international coalitions that contribute to decarbonising international shipping. The declaration is called "the Clydebank Declaration for green shipping corridors" and refers to as the Clydebank Declaration. (UK Government & United Nations Climate Change, 2021)

The Clydebank Declaration targets to develop carbon-neutral shipping routes between at least two ports, defined as green shipping corridors. The aim is to have at least six of them operating in 2025 and more by 2030 to accelerate the transition to carbon-neutral shipping. (UK Government & United Nations Climate Change, 2021) A challenge is, however, that the green shipping corridors must replace existing infrastructure that has dominated since the industrial revolution in the 1800's century with the intervention of fossil fuel-based technologies that could increase the efficiency of maritime freight. (Takahiro, 2021)

The initiative intends to support the target of the Paris Agreement for retaining the global temperature increase below 1,5 degrees compared with pre-industrial levels. It obliges, additionally, to the goal of the International Maritime Organisation's (IMO) "Resolution MEPC.304" to reach at least 50 % greenhouse gas emission reduction by 2050 compared with 2008 from international shipping. (UK Government & United Nations Climate Change, 2021)

The status of developing green shipping corridors is in focus for the next chapter.

3. Problem Analysis

For this problem analysis, a state-of-the-art provides concerning the progress of developing green shipping corridors and the application of carbon-neutral fuels for shipping. Firstly, announced international green shipping corridors become explored to gain insight into recent activities in the field. Subsequently, characteristics of Nordic ship traffic are disseminated since the Nordic Region constitutes a node of regional corridors with ongoing initiatives for developing Nordic green shipping corridors. Recently adopted European policy measures are described to update on the newest regulation and the role of ports. Lastly, three carbon-neutral fuels that are assessed with a convincing potential for substituting marine fossil fuels for Nordic ship traffic are elaborated on. It leads to formulating a research question based on a relevant challenge to overcome for introducing electrochemical ammonia (e-ammonia) as bunker fuel, cf. Chapter 4.

3.1. Status on Green Shipping Corridors

The development of international green shipping corridors is thriving (Talalasova, 2022). The Getting to Zero Coalition under the Global Maritime Forum has gathered green shipping corridors in a map announced before November 2022 (Talalasova, 2022) that presents in Map 1. The map illustrates that green shipping corridors centre on regional and international shipping routes, which implies inside and among continents (Talalasova, 2022). International shipping routes are characterised as ocean-going shipping routes (Hammer, et al., 2023).

Map 1: Announced green shipping corridors before November 2022. The map is prepared by the Global Maritime Forum Getting to Zero Coalition (Talalasova, 2022).

Ocean-going shipping routes concern deep-sea shipping. Deep-sea shipping comprises ships that overcome (long) intercontinental distances. Ships included in the segment are characterised by having a predictable and stable energy consumption per voyage because primary energy consumption relates to propulsion. A challenge is, however, that deep-sea ships rely on the global accessibility of fuels. (Hammer, et al., 2023) Hence, international coalitions and cooperation are necessary for inventing deep-sea green shipping corridors. (Global Maritime Forum and Mckinsey & Company, 2022)

On the contrary, short-sea ships perform shorter distances inside continental, regional, or domestic seas (Eurostat, 2022). These have variable consumption rates due to utilising fuels for operational purposes besides propulsion to a higher degree, which encompasses port- and offshore operations, for example. Primary green shipping corridor-related pilot projects and initiatives concern short-sea shipping because less comprehensive port-to-port investigations are required. (Hammer, et al., 2023).

A characteristic of announced green shipping corridors is that they are in the initiating implementation phase. It implies that partnerships are becoming established, and the pre-feasibility of implementing carbon-neutral fuel production, storage, and bunkering infrastructure assesses. (Talalasova, 2022)

Pre-feasibility assessment of green shipping corridors shall encompass technological, regulatory, and economic considerations, according to the Global Maritime Forum, because fulfilling such conditions can demonstrate *"scalable, carbon-neutral fuels and associated technologies"* that are the initial objective with green shipping corridors. (Global Maritime Forum and Mckinsey & Company, 2022)

Today, ship designs run as pilot projects on carbon-neutral fuels from a well-to-wake perspective. From a well-to-wake perspective implies that carbon is not emitted from fuel consumption onboard ships. 30 pilot projects are identified globally regarding ships that can consume hydrogen, ammonia, biofuels, or methanol. (Hammer, et al., 2023).

With approaching target deadlines related to green shipping corridors for 2025 and 2030, it is appropriate to discover regional green shipping routes for accelerating the transition because short-sea ship pilot projects are primarily tested (Talalasova, 2022). The regional perspective still requires cross-border cooperation for the development to reinforce (Global Maritime Forum and Mckinsey & Company, 2022). Therefore, focusing on a region with close cross-country cooperation (Kronvall, 2023) and identified as a cluster for announced regional green shipping corridors, cf. Map 1, is reasonable to investigate. Consequently, the Nordic Region examines with a dissemination of Nordic ship traffic characteristics.

3.2. The Nordic Region

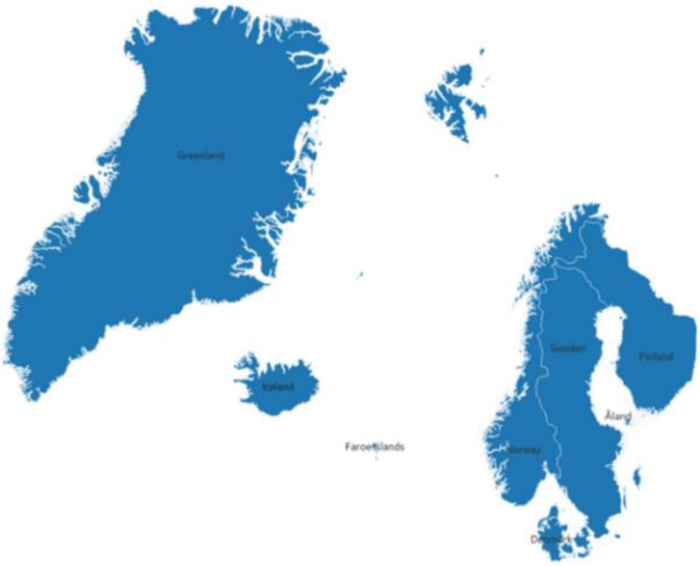
The Nordic Region constitutes the countries: Denmark, Norway, Sweden, Finland, and Iceland, as well as Greenland, the Faroe Islands, and Åland (Herning, 2018). Map 2 provides a geographical overview of the countries. The region's cooperation is politically bound to the Nordic Council of Ministers and the Nordic Council, which describes in Textbox 1 (Herning, 2018).

Textbox 1: The Nordic Cooperation

The Nordic Region embodies the world's oldest regional partnership, politically amended in the Helsinki Treaty from 1962. The institutional setting of Nordic cooperation constitutes two political entities. The Nordic Council of Ministers represents inter-governmental cooperation, where national ministries discuss political matters of common interest to generate Nordic added values of political decision-making. The Nordic Council is the inter-parliamentary cooperation entity constitutes 87 elected parliamentarians from the Nordic countries.
(Herning, 2018)

The focus is set on developing Nordic green shipping corridors under the Nordic Council of Ministers. It underlines the programme, "The Nordic Roadmap" funded by the Nordic Council of Ministers. "The Nordic Roadmap" acts as a knowledge-sharing platform for Nordic cooperation on the development of Nordic green shipping corridors. It provides studies and research on carbon-neutral fuels and supply infrastructures, life-cycle assessments, and ship traffic activities in the region. (Frithiof, 2023)

Ship segments and activities that characterise Nordic ship traffic accentuates to apprehend the types of ships to transition (Rivedal & et.al., 2022).



Map 2: The Nordic countries: Denmark, Finland, Sweden, Norway, and Iceland as well as Aaland, the Faroe Islands, and Greenland (Herning, 2018). The map is compiled in GIS.

3.2.1. Statistics on Nordic Ship traffic

Table 1 presents ship segments represented in Nordic ship traffic in 2019. Nordic ship traffic involves ships that call in at least one Nordic port, and in 2019, around 12 500 ships voyaged in Nordic maritime territories, according to AIS data, whereas above 70 % entered at least one Nordic port. (Rivedal & et.al, 2022)

Dominating ship types constitute cargo and wet and dry bulk ships, which indicates a high share of freight-related ship activities (approx. 50 %). Regarding fuel consumption, approx. 8.6 million tonnes of oil equivalent (Mtoe) were consumed in 2019, and due to few passenger ships operating on low-emission electricity, carbon emissions reached 26,6 million tonnes as marine fossil fuels have highest consumption share. (Rivedal & et.al, 2022)

60 % of the ships had a weight below 5 000 gross tonnages (GT), but ships above 5 000 GT constituted a share of 75 % of total carbon emissions. It underlines the necessity to discover solutions for transitioning large ship segments to carbon-neutral alternatives. (Rivedal & et.al, 2022)

Table 1: Ship traffic, fuel consumption, and CO_2 emissions divided on ship segments constituting Nordic ship traffic in 2019. The table is prepared by DNV (Winje & et.al., 2022).

Ship category	No of vessels	Sailed distance (mill. nautical miles)	AIS observed time, sailing and in port (mill. hours)	No. of voyages	Energy consumption (Mtoe)	Share of CO_2 emissions (%)
Cargo vessels	2584 (29%)	227	490	130 200	2.39	28 %
Wet and dry bulk vessels	2160 (24%)	136	247	42 300	2.24	26 %
Passenger vessels	804 (9%)	29	375	298 600	1.66	19 %
Cruise vessels	155 (2%)	8	24	9700	0.54	6 %
Work / service vessels	1972 (22%)	538	610	124 200	1.27	15 %
Fishing vessels	1211 (14%)	214	490	59 300	0.55	7 %
Totals	**8886 (100%)**	**1152**	**2235**	**664 300**	**8.64**	**100 %**

[6] CO_2 factors (tonne CO_2 per tonne fuel) used in this estimate is MGO/MDO: 3.206; electricity from grid (battery-powered ferries): 0; LNG: 2.75

[7] Cargo vessels are ships carrying *unitized cargo*, such as containers, while wet and dry bulk vessels carry solid or liquid *loose cargo*, such as grain or oil products. In this report, the category *cargo vessels* include the ship types *container ship, general cargo ship, refrigerated cargo ship* and *ro-ro cargo ship*. The category *wet and dry bulk vessels* include the ship types *bulk carrier, chemical tanker, crude oil tanker, gas tanker* and *oil product tanker*.

Ongoing Nordic pilot projects on ship designs that can operate on carbon-neutral fuels are in that regard clarified.

3.2.2. Nordic Pilot Projects and Research Programmes

Pilot projects on ships that can operate on carbon-neutral fuels are tested in the Nordic Region to mitigate carbon emissions related to ship operations. The "Green shipping programme" is an example of a public-private partnership that provides funding and accommodates knowledge sharing on pilot projects tested in Norway to navigate industries for the transition and as the basis for recommending national policy measures. Pilot projects comprise innovative ship designs, fuel infrastructures, and port operations. (Mjøs & Eide, 2023)

Tested short-sea ship design pilot projects are an ammonia-powered trawler (Lerøy Havfisk, 2022) and a carbon-neutral passenger ferry (Color Line, 2022). Tested deep-sea ships comprise a green methanol container ship (Thome Group, 2022), an ammonia-powered tanker (Equinor, 2022), and a green ammonia bulk carrier (Grieg, 2022). Beyond the Green Shipping Programme, the Norwegian offshore company, Eidesvik Offshore, evaluates an ammonia-powered offshore supply ship (Eidesvik, 2023). These diverse examples highlight an extensive focus on developing carbon-neutral ship designs in the Nordic Region.

However, barriers exist for maturing carbon-neutral ship solutions in the region (Hansson & Jiven, 2023). Certain barriers are emphasised by the consortium under the "Nordic Maritime Transport Energy Research programme" funded by Nordic Energy Research. The consortium called "Hydrogen fuel cells solutions in shipping in relation to other low carbon options" (HOPE) investigates hydrogen fuel cell applications for a short-sea Stena ferry, conveying between Frederikshavn, Denmark, and Göteborg, Sweden. (Nordic Energy Research, 2023)

Project findings show that hydrogen fuel cell applications are cost-effective solutions for short-sea ships (Hansson, 2023), but barriers must abate for commercialising them. These barriers concern economic incentives because of deficient hydrogen supply chains, high investment costs of new ship designs, and uncertainty linked with procuring innovative technologies. These parameters disincentivise investments from a business economic perspective. In that case, policies emphasise as crucial. (Hansson & Jiven, 2023)

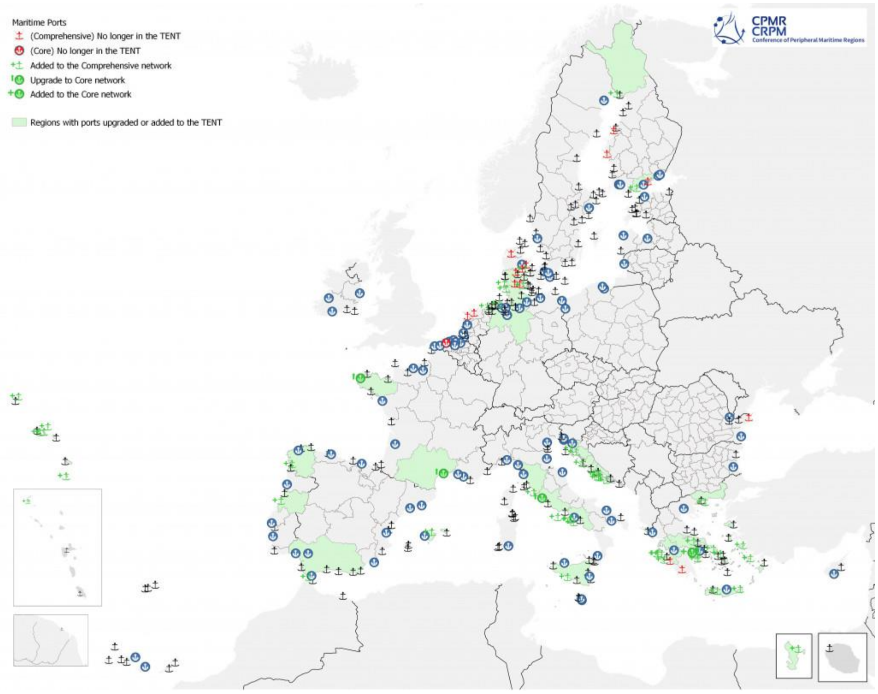
New and updated policy measures under the European Union (EU) are underway to mitigate some of the barriers from a broader perspective that influence conditions the Nordic Region (European Commission, 2023).

3.3. EU Policy Measures and Regulation

The incentive for transitioning heavy shipping recognises by the European Union (EU). In 2022, the EU adopted ships with a weight equal to or above 5 000 GT in the EU Emission Trading System (EU ETS) as an economic response measure to abate the consumption of marine fossil fuels. The policy measure is a part of the European Green Deal, "the Fit for 55' package", that constitutes proposals on updated EU legislation to reach a 55 % net greenhouse gas emission reduction by 2030 compared with 1990 in the EU. (European Commission, 2023)

Furthermore, the FuelEU Maritime initiative is a policy measure attempting to accelerate the employment of renewable fuels for shipping in the EU. The provisional political agreement undertakes an approval process in the recent year (2023) at the EU Council. Measures included expected to amend requirements for abating marine fossil fuel consumption, advancing on-shore power supply, and provision of carbon-neutral technologies for shipping. (European Council, 2023)

Moreover, a regulation proposal, Directive 2021/0223, by the European Commission was presented in 2021. It manifests an interest in deploying alternative fuel infrastructure for shipping and other modes of transport in "Trans-European Transport Network" (TEN-T). The TEN-T is a transport network that connects member states in the EU by identified transport junctions to accommodate increased import, export, and mobility inside the EU. Map 3 manifests ports and regions designated in the TEN-T, including Nordic ports. (Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council, 2021)



Map 3: European ports and regions included in the European TEN-T network.
The map is compiled by the Conference of Peripheral Maritime Regions. (CPMR, 2023)

Concludingly, it emphasises that ports play an important role for providing economic wealth, mobility among regions, and for the transition of short-sea connections inside the EU and Nordic Region, since they facilitate the bunkering infrastructure needed for ships to operate (Jakobsen & et.al., 2022).

3.4. The Role of Ports

The role of ports is principal for introducing Nordic green shipping corridors since ports facilitate the energy needed for ships to operate through bunkering infrastructure (Jakobsen & et.al., 2022). Bunkering comprises the process of ships becoming refuelled with (bunker) fuels for propulsion and operation purposes. Three types of bunkering infrastructure are performed in ports: pipeline-to-ship, truck-to-ship, and ship-to-ship. The difference concerns whether the bunkering ship becomes refuel led by a vehicle, a bunker barge ship, or a fixed pipeline. (International Transport Forum, 2023)

Requirements and facilities linked with bunkering infrastructure depend on the distributed fuel type (International Transport Forum, 2023). Currently, the bunkering infrastructure of carbon-neutral fuels is inadequate, which places a barrier for Nordic green shipping corridors to reinforce. (Jakobsen & et.al., 2022)

Regarding the Nordic Region, ports are appointed by *"the Nordic Roadmap"* as potential energy hubs for ships due to having high local energy production and consumption related to ship operations and bunkering. These are ports in Goteborg, Helsinki, Hanko/Hangö, Oslo, Stockholm, Trelleborg, Åbo/Turku, Esbjerg, and Malmö. (Rivedal & et.al., 2022) Six of them have, with four other Nordic ports, signed a commitment to cooperate for progressing sustainable operations of port activities. These ports comprise Esbjerg, Goteborg, Helsinki, Malmö, Oslo, and Stockholm Port. (Pedersen, 2019)

A includes to facilitate carbon-neutral bunker fuels that can become supplied for ships with high combability (Jakobsen & et.al., 2022).

3.5. Prominent Carbon-neutral Fuels

Carbon-neutral fuels with prospected high capability for decarbonising Nordic ship traffic are hydrogen, methanol, and ammonia. These can be produced in two ways for being classified as carbon-neutral which are distinguished into *blue* or *green*. (Winje & et.al., 2022).

Textbox 2 provides information on the two ways of producing respectively blue and green versions of the fuels.

Textbox 2: Hydrogen, Methanol, and Ammonia Production

Blue hydrogen, methanol, and ammonia:

Hydrogen produces from a steaming process of fossil fuels with application of Carbon Capture and Storage (CCS) or CCUS (Carbon Capture Utilisation and Storage) to capture emitted carbon from the process. Methanol synthesises from hydrogen and a carbon source from either carbon capture or biogenic. Ammonia synthesises from hydrogen and nitrogen, which can be absorbed from ambient air by an Air Separation Unit (ASU).

Green hydrogen, methanol, and ammonia:

Hydrogen produces from an electrochemical process (electrolysis), where renewable electricity is used for separating water molecules (H_2O) to obtain the element (H_2) (Danish Energy Agency, 2017). Methanol and ammonia can be synthesised subsequently by following the same procedure as for blue versions. Green fuels are also defined as electrochemical fuels: e-hydrogen, e-methanol, and e-ammonia.

(Winje & et.al., 2022)

Methanol and ammonia are incidental products of hydrogen hence, they dependent on hydrogen production and supplies for becoming utilised for ships. The potential of upscaling hydrogen production assesses high in the Nordic countries and particularly regarding e-hydrogen. (Winje & et.al., 2022) However, infrastructures for transporting and distributing e-hydrogen are, as previously emphasised, inadequate, which places a barrier for producing e-ammonia, and e-methanol (Winje & et.al., 2022).

However, carbon emissions related to the electrochemical versions prove the best results compared with blue ones. Figure 1 presents an investigation of the well-to-wake carbon emission footprint of marine fuels related to consuming them in different onboard ship engines. Here, e-fuels score the lowest carbon-emission content for fuel cell consumption at 0,2 kg CO2-equivalent/kWh in 2030. None of the fuel alternatives can support carbon-neutral ship operations by 2030. It is a consequence of the share of electricity produced from fossil fuels in Nordic power grids. (Brynolf & et.al., 2023)

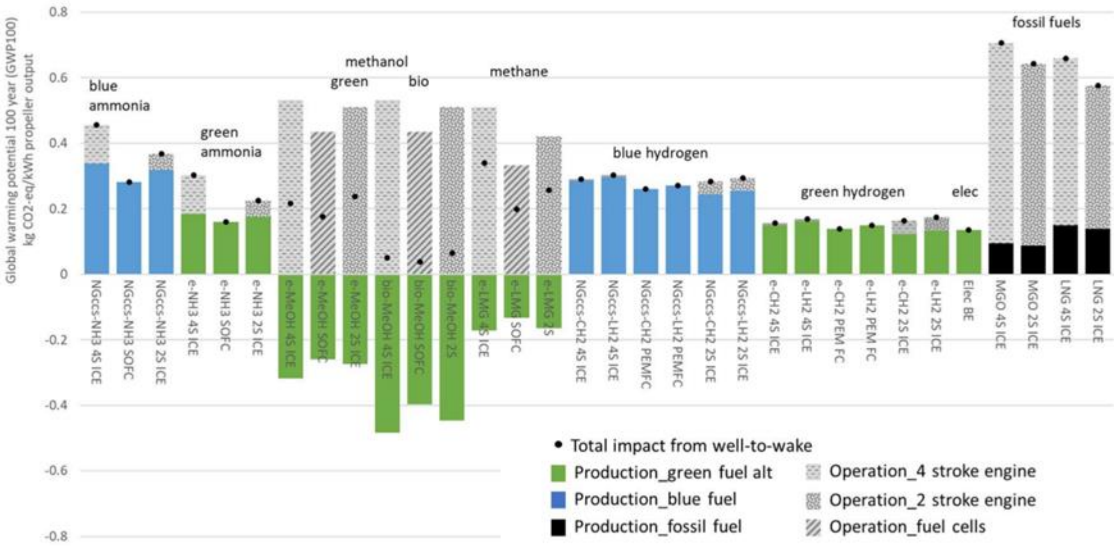


Figure 1: Well-to-wake carbon emission level of alternative marine fuels in the Nordic Region by 2030. Results reflect the entire life cycle of fuels from production, transportation, distribution, and consumption. The figure is compiled by Chalmers University and IVL Swedish Environmental Research Institute. (Brynolf & et.al., 2023)

Regarding ship-type combability, hydrogen is suitable for ships overcoming short distances with an opportunity to refuel frequently. It concerns domestic and regional ferry connections, for example. (Winje & et.al., 2022). The opportunity for frequent refuelling is a prerequisite, because of the low energy density of hydrogen (Brynolf & et.al., 2023). Additionally, hydrogen has a boiling point of –253 degrees Celsius (Brynolf & et.al., 2023) hence, it must be stored under high pressure or refrigerated to keep it in gas or liquid form. Together, it places a prerequisite on further space allocated for storing purposes than on marine fossil fuel consuming ships. (Winje & et.al., 2022)

The combability of methanol and ammonia is, in comparison, high for deep-sea ships due to their higher energy density and the lower boiling point at respectively 65 degrees Celsius and -33 degrees Celsius (Brynolf & et.al., 2023). Hence, less storage space requires onboard ships, which results in an estimation that they can cover up to 80 % of total fuel consumption for Nordic ship traffic (Winje & et.al., 2022).

However, methanol and ammonia contain less gravimetric energy density than diesel at -50 % and -30 %, respectively (Winje & et.al., 2022). It implies increased refuelling and space allocated to perform same distances and operations as today on marine fossil fuels (Jakobsen & et.al., 2022). Additionally, ammonia has chemical properties that place a risk on providing adequate safety standards related to managing it, as it contains high toxicity and flammability (Jakobsen & et.al., 2022).

In Figure 2, the maturity level of the three electrochemical fuels, fossil fuels, and biofuels are summarised. It highlights that e-hydrogen and e-ammonia have lowest maturity level for marine applications today. It is a result of lacking evidence of safe onboard fuel conversion, safety standards, regulation, and bunkering infrastructure, despite its high feedstock availability that indicate abundant resource utilisation potentials of these fuels for shipping. (Mærsk Mc-Kinney Møller Center, 2021)

Figure 2: Maturity level and challenges for maritime fuel applications today. The figure is prepared by Mærsk McKinney Møller Centre for Zero Carbon Shipping. (Mærsk Mc-Kinney Møller Center, 2021)

With e-ammonia as one of two marine fuel alternatives with the potential for transitioning the largest share of Nordic ship traffic and being the most carbon-neutral fuel solution for ammonia, it is relevant to discover challenges to overcome for introducing it for ship propulsion purposes.

3.5.1. Summary: Challenges of E-ammonia as Bunker Fuel

Most significant barriers related to e-ammonia as bunker fuel concern lack of technological maturity onboard ships, safety regulation and requirements, high investment costs, and fuel bunkering infrastructure and logistics (Mærsk Mc-Kinney Møller Center, 2021). These are barriers that comprise both technical, economic, and regulatory challenges that must be assessed for evaluating the feasibility of e-ammonia projects concerning its use as bunker fuel and for green shipping corridors in general (Svendsen, 2023).

The concept of green shipping corridors embraces a transition of not just a single technology but entire infrastructures of carbon-neutral fuel supplies that include production, distribution, storage, bunkering, and consumption in upgraded or new ship designs. Under the Nordic cooperation, programmes and projects run that enable knowledge sharing based on research, tests, and evaluations of pilot projects with the purpose to designate feasible port connections as Nordic green shipping corridors.

The role of ports is crucial since new bunkering infrastructure must become constructed for distributing carbon-neutral fuels for ships. Particularly e-ammonia requires, due to its chemical properties, that new ship designs and bunkering infrastructures become established (Jakobsen & et.al., 2022). Since e-ammonia is appraised as an alternative carbon-neutral fuel with convincing potential for decarbonising Nordic ship traffic, investigating the feasibility of introducing e-ammonia as bunker fuel is of interest. It leads to the formulation of a research question regarding the implementation of e-ammonia bunkering in a Nordic port.

4. Research Question and Design

With point of departure in a significant barrier for developing Nordic green shipping corridors with supply and distribution of e-ammonia as bunker fuel, the following research question is formulated to become answered in this report:

How to feasibly implement e-ammonia bunkering infrastructure in the Port of Esbjerg from a techno-economic perspective, to support the development of Nordic green shipping corridors?

The research question emphasises an intrinsic focus on e-ammonia as potential carbon-neutral fuel for shipping. The limitation of dealing with e-ammonia is not performed to neglect other carbon-neutral fuel potentials such as hydrogen, methanol, and blue ammonia. It decides to limit the scope of the investigation, and because of due its lower maturity level compared with methanol sharing the same promising combability for shipping, cf. Section 3.5.

Bunkering infrastructure solutions comprise only these that can be used in ports, which can concern *pipeline-to-ship*, *truck-to-ship*, and *ship-to-ship*, cf. Section 3.4. Additionally, e-ammonia production, transport, storage, and distribution are embraced to reflect the entire supply chain of e-ammonia that is lacking today, cf. Section 3.5, and to discover these components impact on the techno-economic feasibility of e-ammonia bunker fuel, cf. Section 7.3.

The phrase, to feasibly implement, underlines that assessing the practicability of e-ammonia bunkering infrastructure and its characteristics are in focus. Feasibility recognises as a broad term. Hence, a techno-economic perspective is applied to scope the feasibility assessment. It indicates that the regulatory aspect associated with determining the feasibility of green shipping corridors is not in focus, cf. Section 3.5.1.

Port of Esbjerg is selected because the port is designated a potential energy hub for developing Nordic green shipping corridors, cf. Section 3.4. It is, furthermore, located in one of the TEN-T areas, which underlines its prominent role for European transport, cf. Section 3.3.

It prioritises deliberate on how this analysis can support the development of Nordic green shipping corridors to orientate the scope and reflect on the potential contribution of the results to an ongoing regional programme that requires increased knowledge of the investigated field (Jakobsen & et.al., 2022).

The research question leads to structuring a research design that is visualised in Figure 3. It provides an overview of the research content with applied theories and methods that orientate the ontological, epistemological, and analytical approaches for answering the research question.

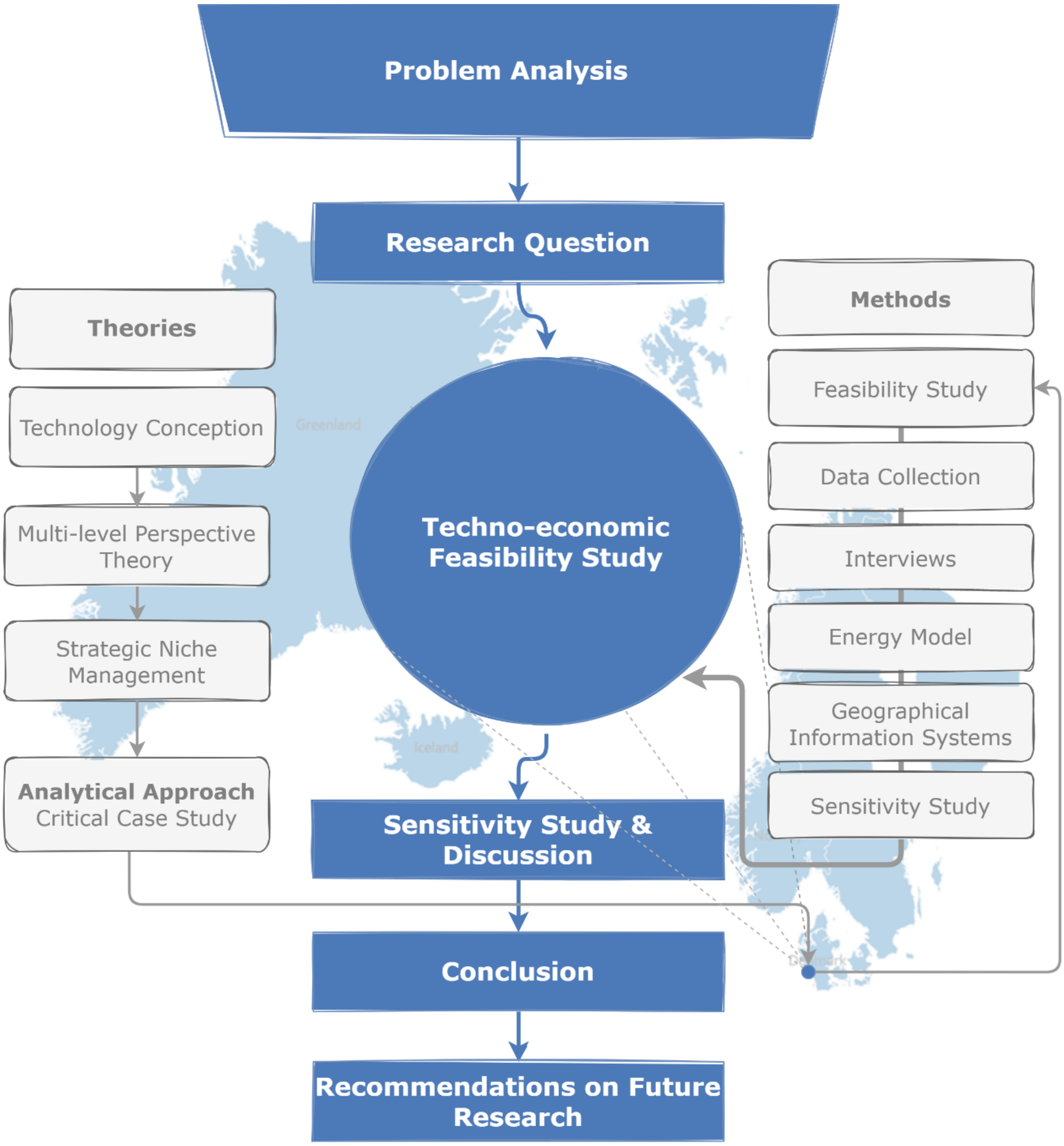


Figure 3: Visualisation of the research design. The background map is compiled in QGIS and the figure in Google Diagrams.

Contemplations behind the structured research design are elaborated on in the following sections starting with the theoretical approach and subsequently the methodological approach.

5. Theories

A theoretical *technology conception*, *multi-level perspective theory* and *strategic niche management* are configurated as they provide ontological and epistemological conceptions for dealing with the implementation of an innovative technology in a niche level. It implies that the background for comprehending e-ammonia bunkering infrastructure as an innovative technology, which most advantageously shall be tested in niches to demonstrate successful implementation of the technology within the societal context, clarifies for this chapter. It begins with a description of the technology conception to understand the components that e-ammonia bunkering infrastructure consist of.

5.1. Technology Conception

Technology can be interpreted constituting four components: technique, knowledge, organisation, and product. The technique encompasses raw materials, natural resources, and energy consumed to fabricate and construct the technology. Knowledge concerns the requested scientific and practical skills for producing and designing the technique. For the technology to become procured, an organisation around it shall promote the technology and manage internal labour among workers. Lastly, the product is the intermediate result of the relation between the three components. Consequently, it frames the purpose and use-value of the technology that must be present for the technology to be demanded by consumers. (Müller, 2011)

The technology conception relies on the ontology that one component cannot change the technology because the other components must adapt to the change for it to intervene. (Müller, 2011)

Additionally, it recognises that a technology exists based on a demand for functionality by human agencies that the product provides. Human agencies can comprise consumers, behavioural patterns, legislation, etc., constituting and characterising a society. Societal structures are the product of interrelations between technologies, legislation, political interests, behavioural patterns, market structures etc. (Van den Bosch, 2010). By their interrelation societal functions can be provided, such as fuel infrastructures (Geels, 2004). Hence, the demand for functionality also impacts the opportunity of changing technology (Müller, 2011).

Multi-level perspective theory provides a comprehension of how new technologies can emerge and intervene in societal structures and their nested interrelations (Van den Bosch, 2010).

5.2. Multi-level Perspective Theory

The multi-level perspective theory explains the nature of society, its dynamics, and how *transitions* can emerge in societal structures (Van den Bosch, 2010). Figure 4 presents the framework of societal dynamics that distinguishes society into three levels: landscape development, socio-technical regime, and technological niches that are characterised by different dynamics (Geels, 2004).

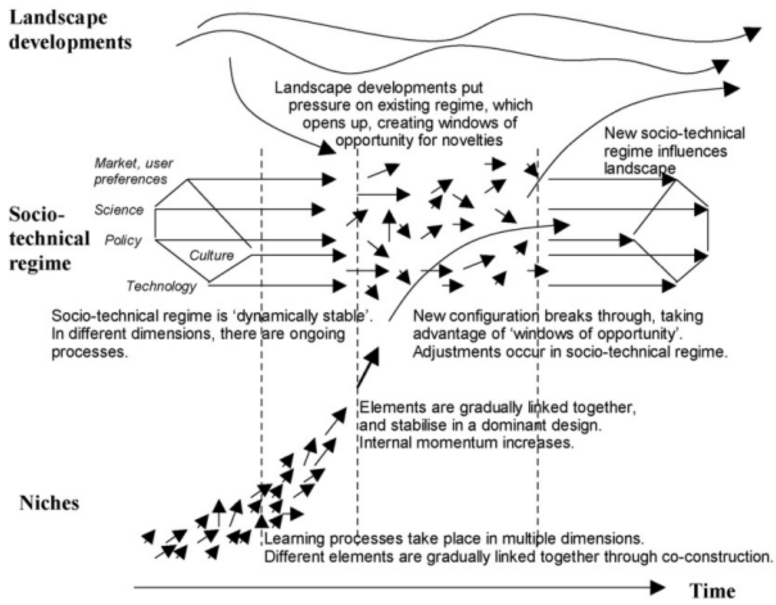


Figure 4: Visualisation of societal dynamics according to the multi-level perspective theory. The figure is performed by Genus & Coles (2008).

The *landscape development* constitutes the macro-level of society (Van den Bosch, 2010), which defines stability because it builds on solid structural trends in society, such as cultural values, standard political coalitions, and paradigms, like political ideologies. Only extensive occasions can encourage changes in the landscape, like wars or rapidly increasing energy prices. (Geels, 2004)

The socio-technical regime level represents the meso-level of society (Van den Bosch, 2010). It contains sub-regimes being *the market and user preference regime*, *the science regime*, *the policy regime*, *the technology regime*, and *the culture regime*. Regimes create the lock-in effects of socio-technical systems because they build on (re)produced activities in society and configure standard procedures, routines, or planning practices. An example can be standard requirements for fuel functionality that have been adopted based on current policies, technology practices, and user preferences. (Genus & Coles, 2008) Transitions in the socio-technical regime(s) occur(s) but only incrementally since they are the product of repetitive behaviour (Geels, 2004).

Lastly, *technological niches* represent the micro-level of society (Van den Bosch, 2010), where transitions can emerge rapidly (Geels, 2004). The niches provide small contexts perceived sheltered from societal structures at the regime hence, they can be testbeds for new or so-called *innovative technologies* (Geels, 2004). Innovative technology is characterised as technology that requires new knowledge and practices to become adopted in societal structures. Consequently, a transition intervenes over a long time and expects to meet opposition from existing societal structures since it tries to alternate or substitute current practices. (Edquist, 1997)

The relation between the three societal system levels is a nested hierarchy (Geels, 2004). It implies that the socio-technical regimes dictate the niche activities because activities on niche levels provide solutions to meet societal needs, such as marine fuel demands (Van den Bosch, 2010). Conversely, socio-technical regimes are embedded in landscape developments where paradigms and ideologies appear. The nested hierarchy emphasises the ontology of how society reaches consistency. (Geels, 2004)

Windows of opportunity for transition processes to become adopted at the regime level can emerge, which is visualised by the arrows in Figure 4, inside socio-technical regime structures. The windows of opportunity can force by change dynamics in the landscape, such as a new paradigm evolving or continuous implementation of innovative niche projects. It points out that non-linear implementation of the same innovative niche project can reinforce radical changes in society. (Scot & Geels, 2008)

The strategic niche management theory provides an ontology on how these niche projects can drive change.

5.2.1. Strategic Niche Management

Strategic niche management points out that transitions reinforce through experimentation (Van den Bosch, 2010). Experiments perform to gain insight into successful implementation processes of respective technology for it to be adopted (Scot & Geels, 2008).

Experimentation performs on niche levels, where technologies assume sheltered from market structures and competition of mature technologies for radical changes to emerge. It recognises that policymakers, consumers, industries, and other social groups can facilitate the experiment. (Scot & Geels, 2008) Ordinarily, strategic niche management strives to contribute to the practical decision-making of policymakers or project managers so they know how long-term visions can be met by executing experiments (Van den Bosch, 2010).

The societal context must be considered despising the intrinsic focus on innovative technology because external societal processes, such as political agendas, either support or neglect the introduction of the technology. Consequently, the co-evolution of innovative technology, user practices and regulatory structures must exist for the technology to intervene. (Scot & Geels, 2008)

Summarised, strategic niche management conceptualises the management of innovative technologies that experiment to serve long-term goals and is inconsistence with existing infrastructures and user preferences (Scot & Geels, 2008).

This forms a basis for comprehending the theoretical framework.

5.3. The Theoretical Framework

Based on the technology conception, e-ammonia bunkering infrastructure is considered more than consisting of techniques but requires knowledge, an organisation, and a product to define its consumer functionality. It implies that switching techniques in current bunkering practices accepts inadequate for the technology to reinforce. Primarily, the demanded functionality of the current bunkering infrastructure will be in focus since it constitutes a determining factor for the practical feasibility of the technology.

E-ammonia bunkering infrastructure contemplates, in that regard, as an innovative technology because it will require changes in societal practices and regulations to manage it, cf. Section 3.5. Therefore, the recognition of technology and societal functions being interrelated adopts to assess the feasibility of the innovative technology validly.

A niche perspective applies as it might provide room for testing the innovative technology. With departure in the strategic niche management approach, it comprehends that by demonstrating e-ammonia bunkering infrastructure in a niche level such as Port of Esbjerg, its user value can be identified to potentially serve the long-term vision of introducing Nordic green shipping corridors. Therefore, the objective is to guide decision-making based on an analytical demonstration of consequences related to implementing e-ammonia bunkering infrastructure from a techno-economic perspective.

Multi-level perspective theory configures to underline which regime structures in society must be considered to assess the practical feasibility of e-ammonia bunkering infrastructure from a techno-economic perspective. Regimes that will be in focus are current marine fossil fuel bunkering infrastructures entangled in the market and user preferences, current science/knowledge, policy and regulation, and technology. Here, technology perceives existing marine fossil fuel based bunkering infrastructure. These regimes comprise the socio-technical conditions that will be emphasised for the analysis. It is visualised by Figure 5 that frames the theoretical framework based on the applied theoretical perceptions.

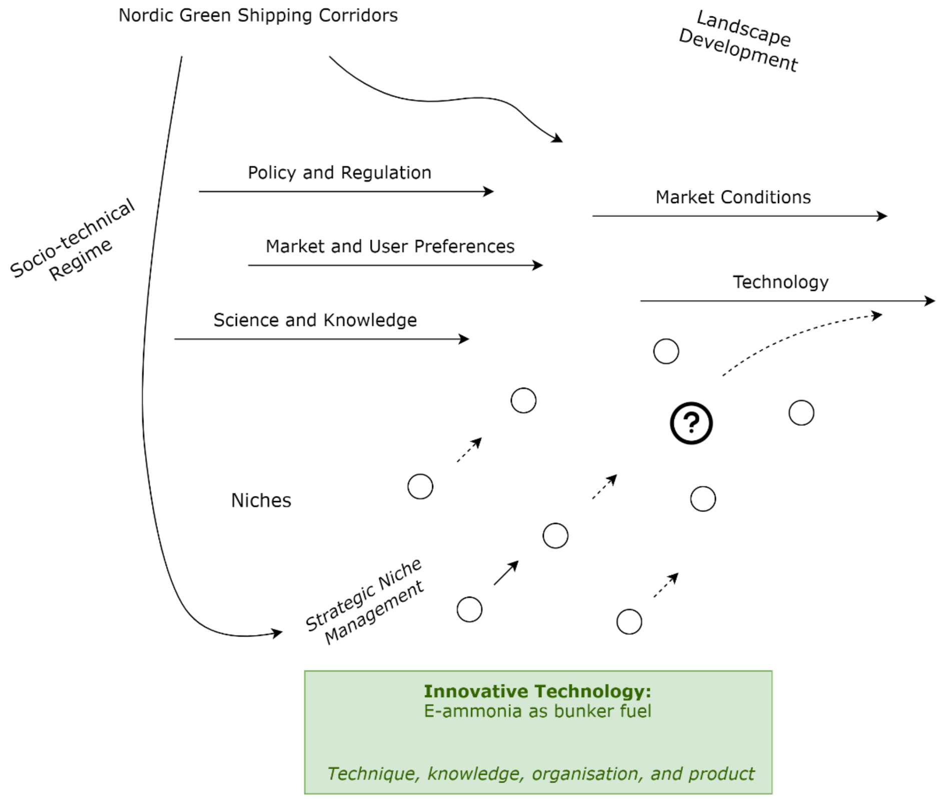


Figure 5: Visualisation of the theoretical framework. The figure is compiled in Google Diagrams.

Strategic niche management can be stated forming an explorative and inductive analytical approach based on its emphasis on experimenting with unexplored technologies. This approach adapts to the analytical approach based on the recognition of dealing with innovative technology, cf. Section 3.1.

However, the applied theories have limitations that must be emphasised.

5.3.1. Limitations to the Theoretical Framework

A limitation of strategic niche management is that it does not provide practical tools and procedures for managing innovative technologies at a niche level. Neither a definition of criteria on how to facilitate niche experiments to ensure that they are sheltered from societal structures, which can allow for its experimentation. (Van den Bosch, 2010) It prevents processing the analytical demonstration of e-ammonia bunkering infrastructure in Port of Esbjerg under conditions that allow for the implementation, why societal conditions are considered.

Additionally, the multi-level perspective theory usually applies for analysing hindsight events (Genus & Coles, 2008). In contrast, strategic niche management deals with the implementation of future projects. It indicates a contradiction in the provided analytical approaches of the theoretical framework.

Multi-level perspective theory can also be argued does not present an ontology but an analytical framework for analysing the dynamics of transitions on three levels (Geels, 2004). However, the definition of transition dynamics that facilitate niches in reinforcing is missing. It adds complexity to understanding in which phase a niche development project appears in an incremental transition of society. (Genus & Coles, 2008) Hence, it makes it difficult to perceive the role of this project in conjunction with other similar projects based on applied theories.

Instead, a case study applies to the analytical approach to understanding how the results compiled for Port of Esbjerg can be processed and potentially applied to other niches to cope with the experimentation of e-ammonia bunkering infrastructure.

6. Case Study Approach

Following an explorative approach, case studies can be used to compile in-depth analyses of contemporary phenomena of a context and their characteristics (Flyvbjerg, 2010). A case study builds on the epistemology that phenomena can only be comprehended and investigated by considering the context because these are context dependent. Phenomena can be current implementation practices of a technology or stakeholder behaviour that define the given context. (Yin, 2018)

Two paths of epistemological orientations can apply to a case study. Either a realist approach that assumes only one reality exists hence results related to one context appeal to all other cases or a relativist perspective that acknowledges the existence of several realities. (Yin, 2018) The relativistic perspective reflects the pragmatism research approach that builds on the epistemology that no single case, research, or viewpoint can provide adequate information on reality because several realities exist (Saunders & Tosey, 2013). It corresponds to the multi-level perspective theory perception of multiple niche realities. Hence a pragmatic relativistic research approach follows, also to recognise that the results of this investigation might not be applicable to other cases, such as other Nordic ports.

A critical case study strategy selects in that regard (Flyvbjerg, 2010), to underline for which other cases or niches the results of a single case study, Port of Esbjerg, can potentially be used. Following a critical case study selection strategy implies that the context and its phenomena are emphasised transparently to set up criteria that must be present in other cases for the results to be assessed as applicable and valid. (Flyvbjerg, 2010). The analytical approach follows a falsification emphasis that argues that if the results apply to this case, they apply to other similar cases and vice versa, which the critical case study relies on (Yin, 2018).

Based on these contemplations, Figure 6 illustrates how the applied critical case study approach is used for dealing with a niche context, Port of Esbjerg, to demonstrate the techno-economic feasibility of e-ammonia bunkering infrastructure and to understand how it can support the development of Nordic green shipping corridors.

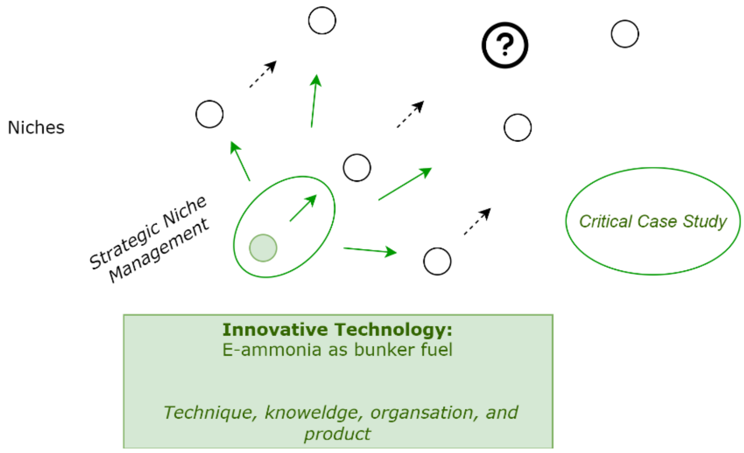


Figure 6: Analytical approach for dealing with one niche project and comprehend the validity of results in other cases. The figure is structured in Google Diagrams.

It leads to describing phenomena and characteristics of Port of Esbjerg to set up the criteria.

6.1.1. The Port of Esbjerg

The Port of Esbjerg selects as a critical case study because it fulfils a set of criteria that reflects the research objective. These comprise criteria that underline the validity of investigating the Port of Esbjerg as part of Nordic green shipping corridors. The criteria are summarised in the forthcoming:

Selection criteria

- Placed in the Nordic Region.
- Designated potential energy hub for ships.
- Part of the TEN-T network.

These selection criteria indicate the relevance of choosing the Port of Esbjerg because it anticipates a preliminary validity for accommodating e-ammonia bunkering infrastructure. It recognises that the techno-economic feasibility of e-ammonia bunkering infrastructure in the Port of Esbjerg can be different from other cases or niches, implying that a lack of techno-economic feasibility does not necessarily indicate infeasibility for other cases. Hence, the explorative research approach underlines once again, but in this regard, to emphasise that the aim is not to determine an optimal techno-economic implementation process of e-ammonia bunkering infrastructure but to explore the characteristics enabling a feasible implementation concerning the potential context dependency of results.

Characteristics and phenomena that are specific to the niche context, Port of Esbjerg, specifies further for the core methodological approach, which is a feasibility study, cf. Section 6.1.1.

6.1.2. Limitations

Case studies have been opposed to criticism due to their context dependency on results, which does not allow for objective information, according to natural science (Flyvbjerg, 2010). Consequently, choosing a single-case study design is at risk of obeying this criticism because results build on one context.

The case study has also been criticised for not providing a valid and reliable methodology. It argues that they are context dependent and do not provide objectiveness and representativeness of results as quantitative data such as statistics. It reflects another critical point that results can, to a certain extent, be subjective due to the researcher's normative selection process (Flyvbjerg, 2010). Hence, this is considered for the choice of methods and collected data, cf. Section 7.4.

Ordinarily, case studies deal with historical events to clarify and evaluate phenomena characterising previous events (Yin, 2018). It does not support the inductive approach of strategic niche management and might limit the understanding of phenomena relevant for assessing the feasibility of e-ammonia bunkering infrastructure in Port of Esbjerg since tools for understanding context-dependent future conditions of case studies are lacking.

Despite the raised critics and limitations to a case study, the critical case study applies to provide an epistemology that enables an understanding of how the feasibility study results can be used for other cases and niches and forms an analytical approach to the core method that constitutes a feasibility study.

7. Methods

It requires a valid method to demonstrate and assess the techno-economic feasibility of implementing e-ammonia bunkering infrastructure as an innovative technology in the critical case study context, Port of Esbjerg. Therefore, the methodological approach builds on a feasibility study that frames strategies for conducting techno-economic feasibility assessments of an innovative technology compared with current technologies (Hvelplund & et.al., 2007).

Methods used for collecting and processing required data to compile the feasibility study are described in association with respective analytical parts of the feasibility study. These methods include interviews and techno-economic data collection, an energy model and Geographical Information Systems (GIS). The validity, credibility, and reliability of applied methods and their application are considered to follow the pragmatistic philosophy recognition of using methods that can provide credible results to be used in practice (Saunders & Tosey, 2013). In response, a sensitivity study applies as part of the feasibility study design to examine the sensitivity of the feasibility results.

Firstly, an elaboration on a feasibility study's ordinary aim and content follows.

7.1. Feasibility Study

A feasibility study aims to identify the most combability alternative solution, such as an innovative technology, for solving a problem in a given context. Two approaches can be applied to assess the feasibility of an alternative technology, which comprises a business and a public one. The selection of each depends on the respective decision-making perspective. (Hvelplund & et.al., 2007)

Based on the critical case study approach, a business-economic feasibility study considers most suitable since its scope transpires on a micro-level, usually indicating a niche-level (Edomah & et.al., 2017) (Hvelplund & et.al., 2007). In contrast, for public decision-making that has a larger scope, where consequences on society related to an investment are assessed, such as the environment, public, and institutions. (Hvelplund & et.al., 2007)

For techno-economic feasibility studies, the feasibility assessment builds on an evaluation of cost and benefits related to an investment for evaluating its profitability and advantages for a private business or stakeholder (Hvelplund & et.al., 2007). Therefore, decision-making will build on the technical specifications' costs, reflecting a techno-economic perspective (Edomah & et.al., 2017) Techno-economic parameters can concern fuel prices and investment payback time that stands ground for the feasibility assessment (Edomah & et.al., 2017).

However, feasibility studies regarding innovative technologies require considering the societal context and tendencies for compiling a valid feasibility study. It is a consequence of the recognised impact that societal structures, such as legislation and current planning practices, have on the feasibility of new technologies. (Hvelplund & et.al., 2007) It emphasises the same notion as for the theoretical framework, why societal structures are considered for the feasibility study.

The content of a feasibility study follows three formal steps presented by professors at the Institute of Planning at Aalborg University, Dr Frede Hvelplund and Dr Henrik Lund (1998), which follow for this feasibility study.

7.2. Steps of a Feasibility Study

Steps to follow for preparing a feasibility study constitute the forthcoming:

1. *Considering and answering what should be studied, for whom, and why it should be studied (WWW-analysis).*
2. *Clarification on how it should be studied based on formulated feasibility criteria and applied methods.*
3. *Feasibility study design that comprises the analysis structure and its preparation.*

   (Hvelplund & Lund, 1998)

The two first steps scope the analytical content of the feasibility study and are conducted as part of the method. The last step comprises the structure of the feasibility study, which consequently constitutes the analysis structure.

To add validity and reliability to the feasibility study scope and approach, the Danish fund, Maersk Mc-Kinney Møller Center for Zero-Carbon Shipping's "Pre-feasibility Phase Blueprint" (Blueprint) (Svendsen, 2023) is used for consolidating associated content. The blueprint provides a framework for studying and assessing the feasibility of green shipping corridor activities to assist industries and stakeholders in practicable decision-making (Svendsen, 2023). It distinguishes between pre-feasibility and feasibility activities defined according to the implementation phase and demonstrated with respective green shipping corridor(s) (Svendsen, 2023). For this study, feasibility assessment criteria and activities are considered since the Port of Esbjerg recognises pre-feasibility assessed under "the Nordic Roadmap" as a potential energy hub for green shipping corridors, cf. Section 3.4. Hence, a detailed demonstration of one activity is compiled for this analytical feasibility study approach.

With this settled, the scope of the feasibility study's content, audience, and context is contemplated based on step 1 of a feasibility study (Hvelplund & Lund, 1998).

7.3. The Feasibility Study Scope

E-ammonia bunkering infrastructure is an innovative technology that provides an alternative solution to Port of Ebsjerg's existing marine fossil fuel bunkering infrastructure (Port Esbjerg, 2023). Therefore, existing bunkering infrastructure constitutes a baseline that frames the status quo of current techno-economic conditions of the port, which considers represents demanded functionality of bunkering processes of ships laying in port. Therefore, the baseline is a comparative foundational measure for the feasibility assessment of alternatives comprising two e-ammonia bunkering infrastructure solutions. They comprise the forthcoming:

Bunkering Alternatives:

1. Truck-to-ship: A road carrier transports and distributes e-ammonia for ships at quayside by a flexible mounted hose that can connect to the ship directly for refuelling.
2. Ship-to-ship: A ship with mounted hose refuels bunkering ships along the quayside. The bunker supply ship loads with e-ammonia by a loading arm at quayside.

(Zakariyya et.al., 2021)

The two bunkering alternatives represent existing bunkering facilities in the port. A third exists being pipeline-to-ship bunkering. (Port Esbjerg, 2023) However, due experienced lack of data on technical specifications of small e-ammonia pipeline distribution network for enabling a valid analysis (Danish Energy Agency, 2017) (Salmon & et.al., 2021), and well-known high investment costs of small distribution networks by pipeline (Salmon, et al., 2021), only the two mobile bunkering solutions considers for this study.

Formulating bunkering alternatives based on current practices complies with the incentive of discussing comparative solutions to existing practices in port. The two e-ammonia bunkering solutions comprise just part of the entire infrastructure that concerns bunkering. Hence, the two alternatives are visualised in Figure 7, which concretises the defined innovative technology, *e-ammonia bunkering infrastructure.* Additionally, the baseline is shown in the figure.

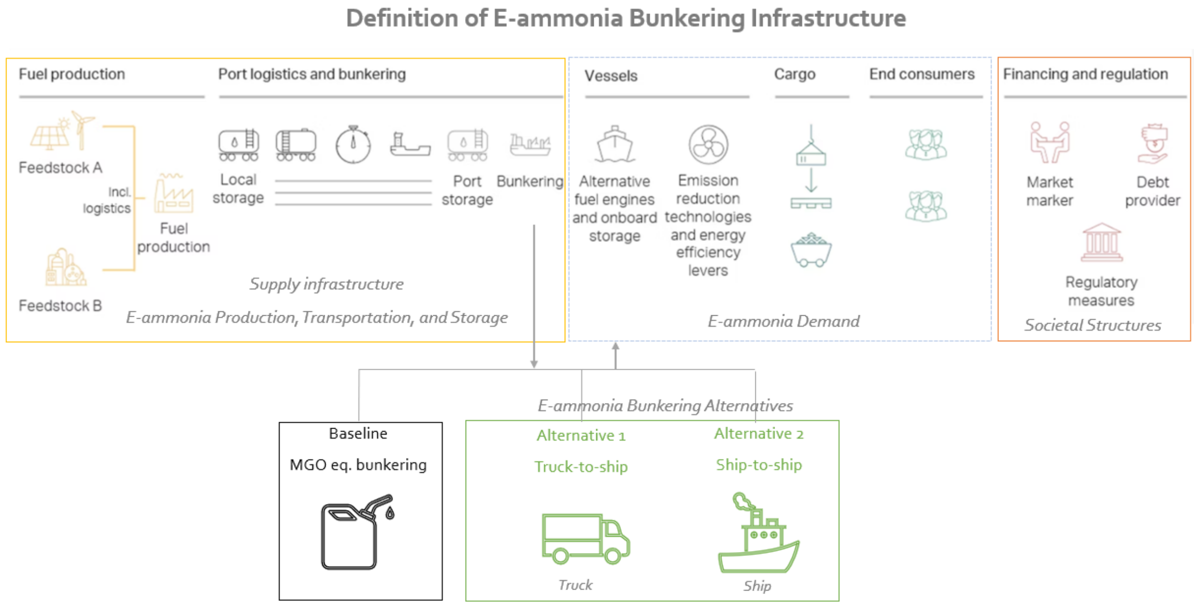


Figure 7: Visualisation of the baseline and two bunkering alternatives. The image is compiled in PowerPoint and with background figure gathered form the "Pre-feasibility Blueprint", which presents the green maritime supply chain (Svendsen, 2023).

Figure 7 indicates that most parts of the defined green maritime supply chain in the Blueprint is considered for the feasibility study (Svendsen, 2023). It concerns fuel production, fuel transportation to the port, storage facilities, and bunkering with the two alternatives. In addition, cargo activities, emission reductions, market makers, and debt providers are out of the scope (Svendsen, 2023). Besides, the critical case study approach suffices that this study has departure in a *single point* green corridor investigation, where focus on one port hub within the transition of port connections examines (Svendsen, 2023).

Figure 8 provides a visualisation of considered e-ammonia feedstock and fuel production. It includes use of raw materials being water, oxygen, and nitrogen, and consumable products as electricity and hydrogen. Technologies considered are alkaline electrolysis as most used electrolyser technology today and the Haber-Bosch process for e-ammonia synthesis and ASU (Wolter & Jensen, 2021). These technologies represent the *technique components* of the e-ammonia bunkering infrastructure, cf. Section 5.1.

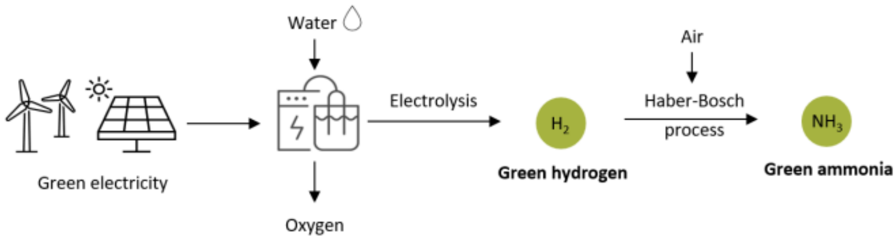


Figure 8: Considered e-ammonia fuel production process for the conceptualised e-ammonia bunkering infrastructure. The figure is compiled by the Danish Energy Agency (Wolter & Jensen, 2021).

The aim is not to select the best option out of the two alternatives based on the epistemology that several realities exist that influence the feasibility of projects, cf. Section 5.3. Techno-economic characteristic explores, instead, to provide knowledge and assist the decision-makers in implementing e-ammonia bunkering infrastructure. It leads to answering who the audience is.

Audience

Based on the baseline and two alternatives, three audiences consider relevant: the e-ammonia producer and supplier, Port of Esbjerg, and ship owners bunkering their ships in the port. Techno-economic consequences will be studied for these stakeholders related to the investment. Division of ownership related to the investment comprehend as follows:

- E-ammonia producer: Investment in e-ammonia production capacity and transportation.
- Port of Esbjerg: Investment in e-ammonia storage tank and bunkering alternatives.
- Ship owners: Consumers of e-ammonia.

The comprehended interest of the audiences is based on the business economic feasibility approach that relies on the epistemology that the core interest of stakeholders is to obtain profitable investment and perform economically feasible operations. Due to different audiences that aspire to different organisations, the organisation component of the innovative technology is not emphasised, cf. Section 5.1.

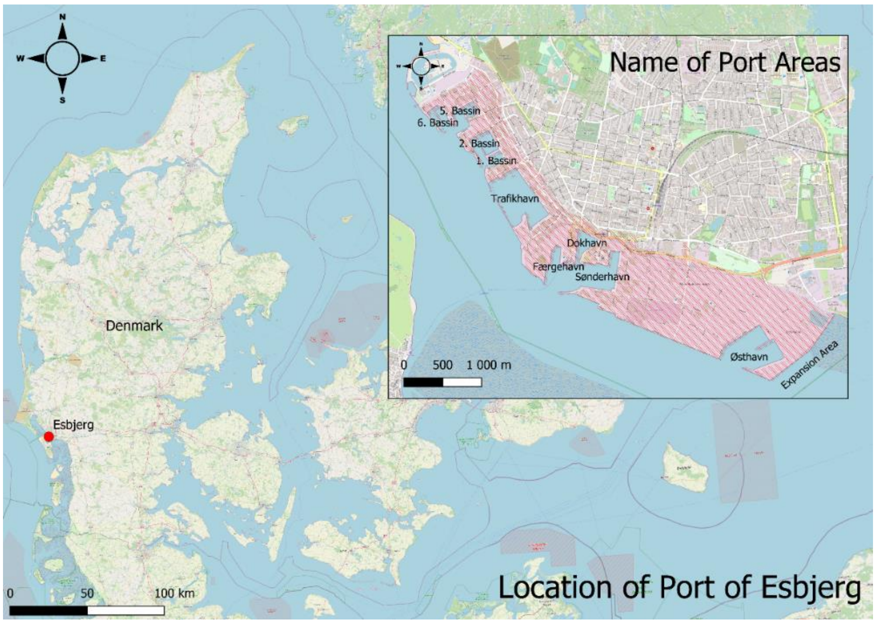
Purpose

The purpose is to demonstrate the techno-economic feasibility of e-ammonia bunkering infrastructure in Port of Esbjerg for relevant stakeholders to make feasible implementation decisions. In addition, it envisages supporting the development of Nordic green shipping corridors. It requires further understanding of the critical case study context, visions, societal context, and development trends. (Svendsen, 2023) (Hvelplund & Lund, 1998) Core assumptions linked to the feasibility study perform based on that.

The Context

Port of Esbjerg covers an area of 4 500 m^2 (Port Esbjerg, 2021) and contains five quay sections (Port Esbjerg, 2023). An overview of its geographical area is shown in Map 4. It is a public self-governing port owned by the Municipality of Esbjerg and opened in 1874 as a transport centre for international trade and sea carriage in Denmark and is an international transport centre for Scandinavian ships today. (Holländer, 2023)

The port authority envisions increasing its sustainability profile by progressing sustainable port operations in cooperation with ten other Nordic ports, cf. Section 3.4. Furthermore, Esbjerg Municipality is designated as the Energy Metropolis of Denmark by the World Energy Cities Partnership due to the facilitation and testing of innovative energy technologies in the area as a part (WECP, 2023). Combined, it indicates that a local incentive for demonstrating, and knowledge sharing applies to Port of Esbjerg, enabling a potential willingness to implement e-ammonia bunkering infrastructure.



Map 4: Overview of the location of Port of Esbjerg and name of port areas. The map is prepared in GIS.

Local e-ammonia production is on the board. The company, Høst PtX Esbjerg, plans to construct a hydrogen and e-ammonia plant close to the port, which will start operating in 2028 or 2029. (Høst PtX Esbjerg, 2023) It points to a driver for implementing e-ammonia bunkering infrastructure in the Port of Esbjerg (Svendsen, 2023). Consequently, Høst Ptx Esbjerg chooses as the supplier of e-ammonia.

Port of Esbjerg is a work/service port since it performs operations in offshore wind turbines and oil and gas trace-related activities in the North Sea (Jakobsen & et.al., 2022) (Holländer, 2023). . In response, it is reasonable to investigate the demand for e-ammonia from work/service ships that bunker in the port to embrace a characterising element of the case (Appendix 3). Furthermore, a work/service ship design is tested running on e-ammonia as a pilot project in Norway by the offshore supply company Eidesvik Offshore, cf. Section 3.2.2. Hence, it considers valid to investigate this ship type. Additionally, an ammonia tanker runs as a pilot project in Norway (Equinor, 2022). Hence, it also considers relevant to embrace the prospected demand of the ship type.

With the adoption of ships with weight above 5 000 gross tonnages (GT) in the EU ETS, ships in this weight segment consider for counting on the new political measure (Pandey & et.al., 2022). Ships operating on short-sea routes in distances orientate for the scope because these are primarily in focus for the first phase of decarbonising shipping, cf. Chapter 4.

Port of Esbjerg, as part of the European TEN-T, implies it is entitled to decide on its development of provided bunkering infrastructure according to EU regulation 2021/0420 (Appendix 5). It underlines an opportunity for demonstrating e-ammonia bunkering infrastructure in the port which accounts for.

These phenomena characterising the critical case study, Port of Esbjerg, concentrate the scope of the feasibility study. Consequently, data collection performs to investigate the techno-economic feasibility of e-ammonia bunkering infrastructure in this context.

7.4. Data Collection

The techno-economic perspective requires quantitative data collection, which comprises obtaining numeric information such as statistics and technical specifications (Byrne, 2023), e.g. regarding e-ammonia. Additionally, qualitative data that is non-numeric information, such as written articles and recordings (Byrne, 2023), can provide insight into the newest research, the critical case study phenomena and characteristics, as well as the socio-technical context (Byrne, 2023).

Hence, both quantitative and qualitative data are collected for the feasibility study. It emphasises a mixed-method approach (Saunders & Tosey, 2013). Specifically, a mixed method simple design follows as a data collection strategy that implies, firstly, a collection and processing of qualitative data to understand status-quo in the research field and phenomena of the critical case study, to formulate valid feasibility criteria, and assess the socio-technical context. Secondly, quantitative data is gathered and processed to analyse the techno-economic parameters by calculating and simulating numeric values that can indicate the feasibility of the alternatives. (Saunders & Tosey, 2013)

It underlines performed method triangulation that considers increases the validity and reliability of results because different data types can prove the representativeness of results and evidence to conclusions and vice versa (Byrne, 2023). It is essential to the pragmatic research philosophy and limitations linked with the critical case study approach (Saunders & Tosey, 2013).

The credibility of quantitative and qualitative data sources is assessed to ensure the application of valid and reliable data. It accomplishes by credibility checking the source of origin, which includes evaluating the author's validity and reliability based on her or his background, affiliation, and motive for providing the information. (Sandström, 2018) Therefore, articles, publications and statistics processed by authorities and researchers are employed due to their considered expertise and credibility.

Quantitative data can be based on large samples, which underlines the representativeness of results and their reliability. (Sandström, 2018) Qualitative data is, on the other hand, processed with a recognition that, e.g., an individual interview does not necessarily reflect the general opinions of society (Brinkmann & Kvale, 2007).

Secondary data that involves data achieved and processed by secondary parties (Byrne, 2023), are used from the internet as a data gathering technique. Google Scholar is primarily employed as a search browser because it provides an open search platform for collecting academic literature and research (Google Scholar, 2023). Hence, it considers a reliable search function. Additionally, official websites are employed being ResearchGate (ResearchGate, 2023), , Aalborg University Library (Aalborg University, 2023), the Nordic Roadmap's website (Frithiof, 2023), Nordic Energy Research's website (Nordic Energy Research, 2023), as well as websites of Danish Energy Agency (Danish Energy Agency, 2023), EUROSTAT (Eurostat, 2023), and Danish TSO, Energinet (Energinet, 2023). The credibility of official websites relies on the reliability of the institutions and organisations that assess high for used websites.

Primary data collection is also performed by performing interviews that is a self-employed data collection method (Brinkmann & Kvale, 2007).

7.5. Interviews

Interviews provide a methodological framework for collecting qualitative data through dialogues and forwarding questions to selected respondents (Brinkmann & Kvale, 2007). The verbal interaction enables an understanding or perspective on the topic from the respondent's point of view (Brinkmann & Kvale, 2007), which is essential for comprehending the phenomena that characterise the critical case study. Three interviews are conducted for which respondents with names and affiliations are mentioned in Table 2 with the attached interview purpose for each.

Table 2 Name of interview respondents, their affiliation, and the purpose of respective interview.

Respondent	Affiliation	Purpose
Nathaniel Frithiof	Consultant and Project manager *"the Nordic Roadmap"*, DNV (Frithiof, 2023)	Validate the state-of-the-art assessment and relevance of the research question.
Dennis Juul Pedersen	CEO, Port of Esbjerg (Port Esbjerg, u.d.)	Insights in the case study area, the Port of Esbjerg's development, and for quantitative data collection.
Ted Bergman	Vice-President for International Business, ELOMATIC (ELOMATIC, u.d.)	Technical and economic specifications of e-ammonia production and distribution as well as analytical assumptions to consider for the energy model, cf. Section

The process of performing interviews is inspired by the seven stages by the professor in applied phycology and qualitative methods, Dr Svend Brinkmann, and professor in educational psychology, Dr Steinar Kvale (2023). These stages comprise: thematising, designing, interviewing, transcribing, analysing, verifying, and reporting (Brinkmann & Kvale, 2007). The seven stages are assembled into two to follow a simplified version distinguishing data gathering and processing. These two stages encompass a design and execution stage that embraces thematising, designing, and interviewing, whereas transcribing, analysing, and verifying are performed in an interview data processing stage. Reporting is part of the feasibility study analysis as qualitative data results (Brinkmann & Kvale, 2007).

7.5.1. Design and Execution

The purpose of the interview determines the structure, format and raised thematises (Brinkmann & Kvale, 2007). All interviews are conducted to gain *expert* insights and perspectives on different parts of the e-ammonia bunkering infrastructure, cf. Figure 7, to validate the research design and execute valid conclusions and analysis on alternatives. Consequently, expert interviews are performed with respondents that recognised as experts to gain information about the topic from their experiences and perspectives, which can be difficult to gather from secondary literature (Döringer, 2020). Recognising the respondents as experts emphasises an applied epistemology that their statements are credible (Döringer, 2020).

An exploratory expert interview is executed with respondent Mr Nathaniel Frithiof to receive information on how to investigate an activity related to Nordic green shipping corridors validly based on his practical experiences that characterise as processual knowledge. (Döringer, 2020) The same applies to the interview with respondent Mr Pedersen, where the objective is to gain expert insight into e-ammonia bunkering considerations of the Port of Esbjerg and perspectives on the transition to alternative fuel bunkering in ports. Using the Port of Esbjerg as a case study can also be approved (Appendix 5). The interview with Mr Bergman targeted receiving technical knowledge regarding e-ammonia production and supply to understand the supply side of e-ammonia bunkering infrastructure, Figure 7 (Döringer, 2020). It includes information on analytical considerations, assumptions, and characteristics of e-ammonia.

All interviews are carried out following a semi-structured interview design. A semi-structured design is selected as it allows the respondent to raise or follow up on topics during the interview. It gives room for raising awareness of unascertained themes and considerations of the interviewer to broaden the perspectives on the topic. (Brinkmann & Kvale, 2007) It corresponds advantageously with performing expert interviews (Döringer, 2020). The interview guide is sent to the respondents before the interview for they to be prepared and confident with the content (Brinkmann & Kvale, 2007). All interview guides initiate with introduction questions, asking about the respondent's background to engender a relaxed and trustful atmosphere between the interviewer and the respondent (Brinkmann & Kvale, 2007). Interview guides can be found in (Appendix 4) (Appendix 5) (Appendix 6).

The respondents are contacted by e-mail as request technique (Brinkmann & Kvale, 2007). Two other respondents were reached out to but had no time to participate or replied too late to have time to process the data. Microsoft Teams is used for interviews due to the distance between the respondent and interviewer. Additionally, it allows for English recording of meetings (Microsoft Teams, 2023). However, the Norwegian language settings in the applied Teams account makes it impossible to use the feature. Hence, another transcription approach is used for interview data processing.

7.5.2. Interview Data Processing

Interviews are processed into summaries due to the inability of recording. Summarises constitute, therefore, the transcription of interviews that is a data processing preparation method that allows for compiling a written format of an oral interview to easier analyse points to report (Brinkmann & Kvale, 2007). The Interview summaries can be found in the following appendices:

- Appendix 4: Interview with Nathaniel Frithiof (Confidential)
- Appendix 5: Interview with Dennis Juul Pedersen (Confidential)
- Appendix 6: Interview with Ted Bergman (Confidential)

Used information from interviews in the report is sourced by (Appendix X) depending to the respondent. Coding is exercised as an analytical data processing method as it provides a simple, structured format for identifying information relevant to the feasibility study. It comprises determining keywords that emphasise themes of interest to illuminate. (Brinkmann & Kvale, 2007) The keywords are the followings that are formulated ahead of interviews:

- *Research gaps and barriers to introducing Nordic green shipping corridors.*
- *Techno-economic specifications and considerations of e-ammonia bunkering infrastructure.*
- *Phenomena and characteristics of the Port of Esbjerg.*
- *Incentives of the audience related to the e-ammonia alternatives.*

Ethical issues may arise for the conduction of interviews. It concerns, e.g. processing and using information that might be confidential but of interest to share in the protected space that an interview can accommodate. (Brinkmann & Kvale, 2007) Therefore, interview summaries and guides are kept confidential. The respondents have verified selected points used for the analysis to ensure acceptance of its use and reliability of how the information is processed.

Additionally, limitations belong to the interview design and procedure.

7.5.3. Limitations

One of the limitations linked to the performed interview method is that the interviewer formulates the interview guide hence, she or he settles the agenda and can navigate the conversation (Brinkmann & Kvale, 2007). It limits the opportunity for having spontaneous conversations, where knowledge and perspectives are exchanged, which can foster an explorative interview approach that this report entails, cf. Section 7.5 (Brinkmann & Kvale, 2007). The semi-structured interview format does, however, provide some room for an explorative interview process.

Advantageously, the respondent can feel confident and prepared for the interview when sending the interview guide ahead of the interview. However, it can also be disadvantageous since well-prepared answers might be favoured above personal opinions (Brinkmann & Kvale, 2007).

The inability to compile transcriptions due to recording issues limits the extent of data gained from the interview because recordings enable memorising the entire conversation (Brinkmann & Kvale, 2007). Consequently, there might be a need for more information by the transcription method. The techno-economic data collection and processing method can be elaborated on with the qualitative data methodology described, following the simple mixed method approach.

7.6. Techno-economic Data Collection

The method used for gathering techno-economic data is inspired by a literature study which is an academic demonstration of current knowledge undertaken by examining and comparing existing research studies and industrial reports (The University of Edinburgh, 2022).

Studies and technology catalogues on green shipping corridors, marine fuels, bunkering infrastructure, and fuel production are examined that constitute secondary data. These are distinguished into three categories depending on their scope: *international studies*, *Nordic studies*, and *data from Port of Esbjerg*. It is performed to evaluate the validity of applied techno-economic data since the scope influence reliability of information for the critical case study context.

An examination of studies follows divided into categories with an explanation of how they are considered for the analysis and what data they and analytical approaches they provide.

International studies:

A) Wang H., et.al. (2023), *"Ammonia-based green corridors for sustainable maritime transportation"*, article, University of Minnesota, volume 6.
B) Yang M. & Lam J. S. L. (2023), *"Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective"*, article, Nanyang Technological University, Elsevier, 1361-9209.
C) Nayak-Luke, et.al. (2021) *"Techno-Economic Aspects of Production, Storage, and Distribution of Ammonia"*, chapter in book, *"Techno-Economic Challenges of Green Ammonia as an Energy Vector"*, Elsevier, pp. 191 - 207.

Wang H. et al. (2023) examine sites for e-ammonia production and refuel stations from the global scope. It follows an energy model optimisation principle where ports are selected as candidates for ammonia bunkering based on an estimated balance of ammonia production potentials and demands from international shipping. *If statements* are used to measure ammonia demands, production capacities and costs that are location-dependent (Wang & et.al., 2023) The model is used as inspiration for the energy model compiled for this feasibility study, cf. Section 7.8, and for verification of applied assumptions. However, the associated energy model approach differs from Wang H. et al. (2023) by only investigating one context and following a simulation technique rather than an optimisation, cf. Section 7.8 Additionally, e-ammonia production is not determined by wind and solar electricity production profiles (Wang & et.al., 2023) but based on electricity prices, cf. Section 7.9.2. Lastly, bunkering solutions are considered in this study, whereas Wang H. et al. (2023) do not emphasise bunkering procedures. Instead, it is investigated by Yan & Lam (2023).

Yang & Lam (2023) analyse operational and economic conditions of marine fossil fuel and ammonia for ship-to-ship bunkering infrastructure in the Port of Singapore to evaluate and compare their *bunkering supply chain performance*. Additionally, a numeric model is developed for simulating the operational and economic characteristics of the bunkering infrastructure. Two processes are simulated loading and bunkering operations. (Yang & Lam, 2023) The level of detail regarding bunkering supply performance of ship-to-ship bunkering is not employed because one other alternative, e-ammonia production, transport, and storage, is also considered for this study. However, parameters and assumptions are applied that include technical specifications of bunker supply ships and measures on bunkering performance, cf. Section 7.9.2. Applying data might, though, not be valid to some extent due to the Port of Singapore's geographical scope and size differences between the two ports since the Port of Singapore is one of the world's largest ports (Talalasova, 2022). It stresses a need for more validity of applied data, potentially.

Nayak-Luke et al. (2021) outline analytical components and considerations for assessing techno-economic conditions of e-ammonia production, storage, and distribution that, for this feasibility study, referred to as transportation. Costs are measured by appraising the lifetime of investments. Hence, the Levelised Cost of E-ammonia (LCOA) is calculated by a net present value formula (NPV) divided by total e-ammonia production:

$$LCOA = \left(\frac{\sum_{t=0}^{n}\left(\frac{OPEX_t}{(1+i)^t}\right) - CAPEX_{t=0})}{Total\ e - a\ production}\right)$$

The same calculation attempts this feasibility study for each alternative to accounting for the lifetime that is vital (Hvelplund & et.al., 2007). Technology prices connect to the United Nations (Nayak-Luke et.al., 2021) Hence data is only applied from the study in case of lacking data specifications on technologies in a Nordic context. It concerns prices on the e-ammonia storage (Nayak-Luke et.al., 2021) and measures of its size that are gathered from the Belgian company, Gedolf, (Geldof, 2023). Besides, numeric estimates are primarily employed from Nordic sources.

Nordic studies:

- Frithiof N. (2023), "*The Nordic Roadmap – Future Fuels for Shipping*", DNV, project website: futurefuelsnordic.com.
  - Basso, M. N., & et.al. (2022), "*Screening of Sustainable Zero-carbon Fuels"*, Menon Economics, Nordic Roadmap Publication No. 1-A/1/2022.
  - Rivedal, N. H. & et.al. (2022), "*AIS Analysis of Nordic Ship Traffic*", DNV, Nordic Roadmap Publication No. 2-A/1/2022.
  - Basso, M. N., & et.al. (2022), "*Infrastructures and Bunkering Challenges for Zero-Carbon Fuels"*, Menon Economics, Nordic Roadmap Publication No. 2-B/1/2022.
  - Brynolf, S., & et.al. (2023). "*Life Cycle Assessment of Marine Fuels in the Nordic Region – Task 1C"*, Chalmers University of Technology, Nordic Roadmap Publication No.1-C/1.1/2023.

- Zakariyya K., & et. al. (2021), *"Ammonia Bunkering of Passenger Vessel – Concept Coastal Shipping Programme"*, DNV.
- Danish Energy Agency (2017), *"Technology Data for Energy Transport"*, Version number: 0004: Danish Energy Agency and Energinet.
- Danish Energy Agency. (2017). *"Technology Data for Renewable Fuels"*, Version number: 0010: Danish Energy Agency and Energinet.

Primarily, techno-economic data is gathered from four studies belonging to *"the Nordic Roadmap"* project. These concern a screening of e-ammonia applications for shipping with assigned technical specifications and considerations (Winje & et.al., 2022), an outline of infrastructure considerations for e-ammonia and other alternative fuels (Jakobsen & et.al., 2022), an AIS analysis of Nordic ship traffic (Rivedal & et.al, 2022), and lastly, a life cycle assessment of e-ammonia and marine fossil fuels (MGO eq.). These studies are considered providing high validity since they concentrate the Nordic Region.

A study by DNV (Zakariyya et.al., 2021) investigates e-ammonia bunkering for a case in the Port of Oslo, where ship-to-ship and pipeline-to-ship bunkering are investigated from a safety requirement and technical perspective. Technical specifications are used that concern the two alternatives and a hose belonging to the ship-to-ship bunkering alternative (Zakariyya et.al., 2021). Data validity is also considered convincing because it applied to the Port of Oslo, cf. Section 3.4.

Technological and economic specifications of e-ammonia production are gathered from the Danish Energy Agency's *"Technology Data for Renewable Fuels"* (Danish Energy Agency, 2017). The technology catalogue contains information on fuel technologies in a Danish context. Hence, the validity assumes to be high. Furthermore, the *"Technology Catalogue for Energy Transport"* also by the Danish Energy Agency is studied to receive technological and economic specifications and perspectives on ammonia transportation (Danish Energy Agency, 2017). The specifications do not necessarily apply to bunkering infrastructure but to general fuel transportation, distribution and storing purposes (Danish Energy Agency, 2017). However, technical and economic data considers valid.

Data from the Port of Esbjerg:

- Ship activity data for 2022 and map of port quays (Appendix 3).

Data is gathered by e-mail from the Port of Esbjerg as secondary quantitative data on monitored ship activities in the port in 2022 and a map of the port area with designation of quay numbers. Respective data can be found in Appendix 3. The informative and quantitative data is collected as input to the energy model that is contemplated for compiling the techno-economic analysis of the feasibility study. Methodology behind the data processing method is described in Section 7.8.

Based on obtained qualitative and quantitative data, the feasibility criteria are formulated, and an energy model is structured to respectively base the feasibility assessment on and perform the processing of techno-economic data.

7.7. Feasibility Criteria

Feasibility criteria are formulated to emphasise criteria that the e-ammonia bunkering infrastructure alternatives must fulfil to be assessed as feasible compared with the baseline (Hvelplund & Lund, 1998). Two feasibility criteria are formulated based on interviews and the techno-economic data collection method, which is why they are sensitive to the specific data. Hence, they could have been different in the case of interviewing more or other respondents as well as other or more studies. The two criteria are presented in Textbox 3.

Textbox 3: Feasibility criteria

- High bunkering performance
  Parameters:
  - *Bunkering time*
- Lowest price of e-ammonia per tonne
  Parameters:
  - *Production prices: Electricity prices and variable operational costs*
  - *Transportation: From the Høst PtX Esbjerg e-ammonia plant to the e-ammonia storage tank/terminal*
  - *Storage costs: Investment, maintenance, and operational costs*
  - *Bunkering costs: Investment, maintenance, and operational costs*

Bunkering performance is assumed to be the functionality demanded by ships that bunker in the Port of Esbjerg. Yang & Lam (2023) stress that bunkering performance depends on the fulfilment of key performance factors that influence bunkering service time and efficiency. These factors involve:

- *Average bunkering time*
- *Bunker barge usage*
- *Berth utilisation efficiency*
- *Supply waiting time*
- *Mean waiting time*
  (Yang & Lam, 2023)

Based on provided data, the time ships lay in port can be identified (Appendix 3). Hence, the bunkering performance assesses only based on the measure, which implies a limitation to the results.

The second feasibility criterion embraces the economic part that centres on low prices of e-ammonia. Mr Pedersen emphasises the necessity of considering bunker fuel prices to distribute e-ammonia as bunker fuel. He states that the shipping industry, due to high fuel consumption rates, depends on fuel prices for performing profitable operations to a high extent (Appendix 5). Therefore, e-ammonia prices are assessed as the second feasibility criterion. Estimate on e-ammonia price per tonne considers for the investment period (Hvelplund & et.al., 2007).

Investment period

The lifetime of e-ammonia bunkering infrastructure follows the lifetime of an e-ammonia plant, including an electrolyser and Haber-Bosch unit, which is 30 years (Wolter & Jensen, 2021). The investment year is settled in 2028 when the Høst PtX Esbjerg e-ammonia plant operates. In connection with this, it assumes that ammonia-designed pilot projects of involved ship types are commercially viable same year. Therefore, the time horizon of the investment runs from 2028 to 2059, with 2028 as year 0. It implies that the techno-economic data of the Danish Energy Agency relate to 2030 values instead of 2020. Lastly, a discount is applied at 5 % due to applied techno-economic data (Nayak-Luke et.al., 2021) (Danish Energy Agency, 2017).

It leads to an investment period timeframe as follows:

- Investment year: 2028
- Lifetime of investment: 30 years starting from 2028 (year 0)
- Discount rate: 5 %

Risks and uncertainties related to the long-term investment period will be assessed in a sensitivity study, cf. Section 7.11 (Hvelplund & et.al., 2007). Results on the feasibility criteria are simulated and calculated in an energy model.

7.8. Energy Model

An energy model is structured for processing the quantitative data and, by calculations and simulations, measuring techno-economic parameters of the baseline and two alternatives to assess the feasibility of e-ammonia bunkering infrastructure in the Port of Esbjerg. The energy model is compiled in Microsoft Excel since it provides a tool for processing quantitative data, calculations, and visualisations (Microsoft, 2023). The methodology and analytical approach behind the energy model is inspired by a bottom-up energy model and simulation model approach (Herbst & et.al., 2012).

A bottom-up energy model approach is followed because it concentrates investigation of technical and business economic conditions of technology locally (Herbst & et.al., 2012) Demand and supply balances are the foundation of such an approach (Herbst & et.al., 2012), which is the objective identified for understanding the supply and demand of marine fossil fuels and e-ammonia, cf. Figure 7. Additionally, societal context is analysed based on qualitative data for the feasibility study that is also not accounted for in the ordinary energy model, such as changes in political frameworks, market conditions, and resource adequacy (Herbst & et.al., 2012). However, it indicates a limitation to the energy model because of the investment period where market conditions and public regulation can change (Hvelplund & et.al., 2007).

A simulation approach is applied since it provides a flexible and strategic modelling framework where technical and economic characteristics can be demonstrated (Herbst & et.al., 2012). It goes well in hand with the *inductive* research approach and the objective not to identify most cost-effective (feasible) alternative that applies for an optimisation model (Herbst & et.al., 2012). The simulation framework can be argued to outweigh, to some extent, the limitation of not considering societal changes because an optimal solution is not pointed out based on an indirect recognition that technical conditions, market failure, and unpredictability of future costs are a reality (Herbst & et.al., 2012). Instead, it stimulates the explorative research approach of the research framework.

Figure 9 shows the flow diagram of the energy model that indicates the steps followed for compiling the feasibility study. Applied simulations and methodology are inspired by the studies elaborated on for the techno-economic data collection, cf. Section 7.6.

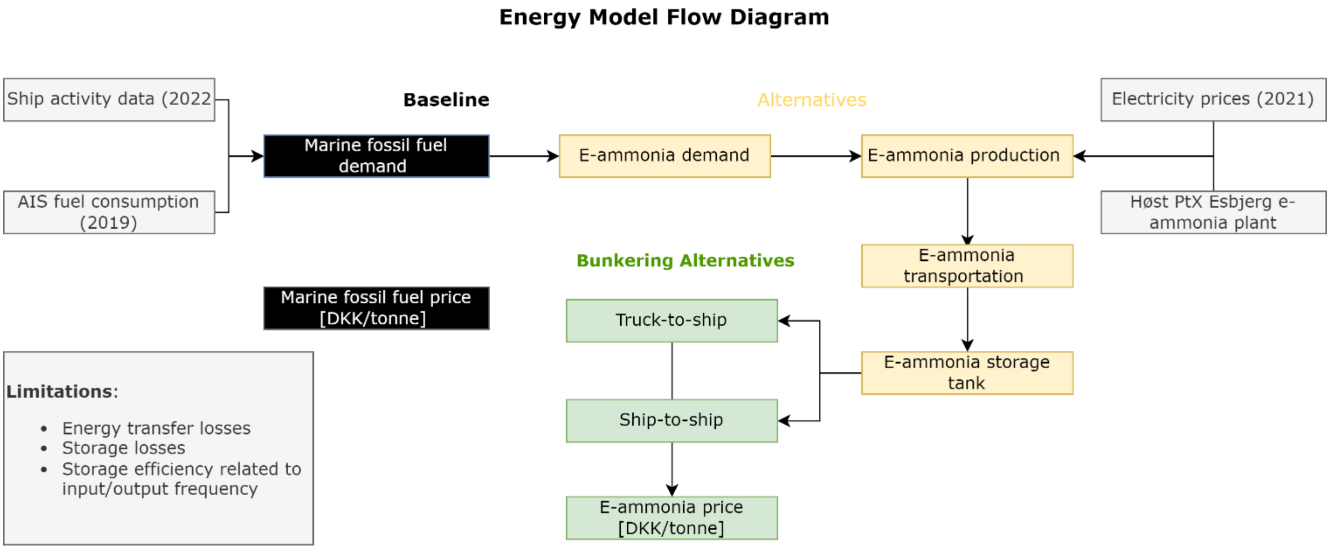


Figure 9: Flow diagram of the energy model simulation process divided into steps according to the feasibility study framework. Grey boxes indicate applied data. Black boxes belong to the baseline, yellow boxes to the supply infrastructure, and green boxes to the two bunkering alternatives. Colour codes refer to those used in the energy model, cf. Appendix 2, "Introduction". The flow diagram is compiled by using Google Diagrams.

Two primary tools are used in Excel for the energy model to simulate baseline and alternatives. These are if statements and pivot table analyses. If statements are applied to simulate and extract ship types, data values etc., based on a logistical test that measures if a statement is true or false for processing data and calculation on, e.g., included ship types (Microsoft, 2023). Primary if statements used are presented in Appendix 1 and referred to in the analysis, when applied and simulated, cf. Appendix 1. A pivot table is a tool for analysing and summarising data to identify patterns, e.g., ship activities, and compare results (Microsoft, 2023).

Respective parts of the feasibility study analysis are represented in Figure 9 by a baseline and analytical steps regarding the alternatives. These analytical parts are structured within the third step of a feasibility study, namely the feasibility design (Hvelplund & Lund, 1998).

7.9. Feasibility Study Design

The feasibility study design contemplates the analytical structure of the feasibility study (Hvelplund & Lund, 1998), for which results will be presented in a baseline and two alternatives that additionally scope the analysis structure. A sensitivity study is carried out in relation to the feasibility study, which methodology presents in Section 7.11.

7.9.1. Baseline

Existing techno-economic conditions and ship activities in Port of Esbjerg are concretised and examined for the baseline. It involves an examination of current bunker fuel demand of mapped ship segments and activities (Svendsen, 2023). Data used involves monitored data on ship activities from 2022 that is provided by Port of Esbjerg (Appendix 3). Fuel consumption of ship segments are estimated based on Nordic ship traffic AIS data from 2019 (Rivedal & et.al., 2022).

Historical data were impossible to obtain on marine fossil fuel consumption and prices in the Port of Esbjerg because data is not publicly available on bunker fuels (Esbjerg, 2023) , and an answer has yet to be received from the fuel supply company by e-mail. Therefore, the baseline's reliability is limited to average consumption measures from 2019 and monitored ship activity data from 2022. The difference in years is assumed not to impact the results since consumption estimates reflect average measures and not historical data. It is because historical data is more context-dependent since the practical fuel consumption of ships depends on internal and external factors (Rivedal & et.al., 2022). With the Nordic region constituting the scope and data used processed for Nordic ship traffic (Rivedal & et.al, 2022), ships that overcome distances that can be reached from the Port of Esbjerg to the other Nordic countries are considered.

The baseline builds on a selection of assumptions and delimitations. Existing bunkering infrastructure assumes not to require reinvestment during the investment period. Additionally, it anticipates that expenditures related to operation and maintenance are reflected in current prices on marine fossil fuels, implying a limitation to the results. Demand and prices of marine fossil fuels are considered to apply to the investment year 2028, emphasising a frozen development. Additionally, it assumes that all ships calling in Port of Esbjerg have a bunkering fuel demand to enable security of supply. The assumptions are summarised in the forthcoming:

Baseline Assumptions:

- All ships calling in the Port of Esbjerg have a bunkering demand.
- Ship activities (2022) and marine fossil fuel consumption rates (2019) apply to investment year in 2028.
- Ship segments demanding e-ammonia in 2028
    - Ship type: Domestic and regional work/service ships and domestic and regional tankers.
    - Size: Equal to or above 5 000 GT.
    - Overcome Nordic distances that can be reached in the Nordic Region from Port of Esbjerg.
- Existing bunkering infrastructure does not require reinvestment during the investment period.

The analysis of alternatives builds on the result of the baseline.

7.9.2. Alternatives

The feasibility assessment of the e-ammonia bunkering infrastructure initiates with an analysis regarding e-ammonia demand, production, transportation, and storage that are similar for the two bunkering alternatives, cf. Figure 7. Following data sources and assumptions are contemplated for the respective parts of the e-ammonia bunkering infrastructure:

- E-ammonia demand:
    - According to marine fossil fuel consumption for the baseline.
    - Technical specifications on e-ammonia (Wolter & Jensen, 2021) (DNV, 2019)

  - Onboard ship energy efficiency (Brynolf & et.al., 2023)
- E-ammonia production:
  - E-ammonia production capacity (Høst PtX Esbjerg, 2023)
  - Technical specifications of e-ammonia production and costs (Wolter & Jensen, 2021)
  - Spot market electricity prices for DK2 for 2021 (Energinet, 2023)
- E-ammonia transportation (refrigerated liquid tank):
  - Transportation by truck (Danish Energy Agency, 2017)
- E-ammonia storage tank (refrigerated storage tank)
  - Storage size (Geldof, 2023)
  - Storage costs excl. cost of terminal services (Nayak-Luke et.al., 2021)

Prices and technical specifications refer to 2030 prices to reflect the investment year 2028 if possible. Onboard ship energy efficiency refers to an e-ammonia fuel cell, SOFC, because it has the lowest carbon-emission profile from a well-to-wake perspective, cf. Section 3.5. Electricity prices only embrace spot market electricity prices excl. electricity deduction costs and tariffs. It is chosen due to prospected changing in tariff structures (Energinet, 2022) and to reflect the Nordic Region being reliant on same electricity spot market (Nordpool, 2023). Spot market prices in 2021 for DK2 are used, because prices in 2022 was affected by an energy crisis resulting in significantly high prices (IEA, 2022). Hence, referring to 2021 prices considers increase validity of standard years. However, it is an important delimitation that electricity price prognoses, tariffs etc. are not included in the electricity prices.

The choice of refrigerated storage options is decided because refrigerated storages provide higher safety measures compared with pressurised storage tanks (Zakariyya et.al., 2021). However, no conversion losses or leakage measures are considered for the feasibility study, implying an essential limitation.

The feasibility of bunkering alternatives studies is based on settled feasibility criteria. Technical specification of the two alternatives gathered respectively from:

- Truck-to-ship: (Danish Energy Agency, 2017) (Zakariyya et.al., 2021)
- Ship-to-ship: (Yang & Lam, 2023) (Danish Energy Agency, 2017) (Zakariyya et.al., 2021)

Two events are designated to base the feasibility assessment of feasibility criterion 1. The comprises:

- Event 1: Annual peak demand of bunkering performance by one ship according to its demand and time spending in port.
- Event 2: Daily peak demand of e-ammonia of ships.

The events are framed because an assessment based on total annual bunkering events is considered too comprehensive within this report's scope. Instead, the methodology follows the falsification approach of the employed critical case study that emphasises that if the bunkering solutions can fulfil the demand with respective specifications and conditions, it can fulfil the demands of any other event.

Feasibility criterion two is measured based on a levelized cost of e-ammonia (LCOA) formula that calculates by following *Equation 1*:

Equation 1: LCOA

$$LCOA = \left(\frac{\sum_{t=30}^{n}\left(\frac{OPEX_t}{(1+i)^t}\right) - CAPEX_{t=0})}{Total\ e - a\ bunkered}\right)$$

One variable is different from the one applied by Nayak-Luke et. al. (2021). The total amount of e-ammonia bunkered accounts for instead of the produced amount of e-ammonia since the variable shall reflect the amount of e-ammonia distributed through the e-ammonia bunkering infrastructure in Port of Esbjerg relative to the costs.

Included in the equitation is a net present value calculated, which ordinarily employs to estimate the profitability of an investment by discounting annual cashflows during the investment period and comparing it to the initial investment. If it turns positive, it implies the profitability of the investment but is sensitive to the applied discount rate that represents the employed interest rate. (Lund & Østergaard, 2010). The levelized cost of e-ammonia is not applied to indicate profitability but rather the required cost of e-ammonia as bunker fuel in Port of Esbjerg to enable a profitable investment in e-ammonia bunkering infrastructure given the investment period. Included investment costs concern those of Port of Esbjerg that, according to the Blueprint, are the e-ammonia storage and bunkering infrastructure (Mæsrk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022).

Sensitivity related to the feasibility study results is estimated for a sensitivity study. The method behind the sensitivity study describes after an elaboration on how GIS is used for conducting the feasibility study.

7.10. Geographical Information Systems (GIS)

The open-source desktop version, QGIS, is used, which provides analytical tools to perform geospatial investigations (QGIS Documentation, 2023). It is used to collect and process data with geographical information needed for the feasibility study, including vector data such as transport distances and quay activities. Besides its analytical purposes, maps are produced to visualise the locations and spatial conditions of the Port of Esbjerg. The prefixed background layer in QGIS is linked with Google Street Map, which enables the updated use of vector data, such as road connections and buildings, to be referred to and processed for the investigations (QGIS Documentation, 2023).

The project coordinate reference, *ETRS89 / UTM zone 32N*, is applied since it centres onshore and offshore areas of Europe that encompass Denmark (espg.io, 2023). Analytical tools and features are employed, which comprise *georeferencing, vector points and line drawing and measuring.* The methodological use of them describes respectively by the following.

Georeferencing

Georeferencing uses to assign coordinates to a drawn map that constitutes of raster or pixel data (Gandhi, 23). It provides an opportunity for with great detail to identify and point out features and locations from the drawn map in Port of Esbjerg.

For the feasibility study, georeferencing applies to identify quay locations in the port. It accomplishes this by marking four points constituting a rectangle on the drawn map, processed in the georeferencing tool window, corresponding to GPS coordinates in the background layer. Results are verified by clicking the raster layer (drawn map) on and off to compare it with the background layer. Map 5 shows a visualisation of the result of georeferencing the drawn map that is provided by Port of Esbjerg by e-mail, cf. (Appendix 3)

Map 5: Visualisation of the georeferencing tool applied for the GIS analysis. The map is a screenshot of the used tool.

Additionally, vector points are designated to visualise the preliminary sites of the Høst PtX Esbjerg e-ammonia plant and the e-ammonia storage tank (QGIS project, 2023). The size of the e-ammonia storage tank demonstrates its actual size by adjusting the diameter of the tank in point features.

Subsequently, transportation and distribution distances of e-ammonia are drawn and measured in length. In that regard, a vector line layer is created, whereafter, the feature *drawings* enable a designation and visualisation of estimated transportation and distribution routes (QGIS project, 2023). All routes are drawn based on the principle of following the shortest route by road or in the harbour. Shortest routes are only identified based on background layer information, which can imply a limitation to the results because private or closed roads can, in practice, lay hinder for road connections.

Quays used for bunkering in Port of Esbjerg are identified and pointed out based on the georeferenced layer, cf. Map 8. In the layer's attribute table, the quay number is mentioned to visualise it by adding *labels* in the layer feature (QGIS project, 2023).

Distances are measured by using the *measuring* tool that can estimate distances in requested units [m] by drawing a line on top of transportation and distribution routes (QGIS project, 2023). The length of distances is registered in the energy model (Appendix 2; "E-ammonia Storage" & "Bunkering Alternatives").

With all methods applied for the feasibility study in place, the sensitivity as the last method elaborates on.

7.11. Sensitivity study

A sensitivity study assesses the consequences of changing parameters for the feasibility study results by considering variable parameters and societal structures that might influence and add uncertainty to the techno-economic assessments given the long-term investment period (Hvelplund & Lund, 1998). The sensitivity study is conducted by following two approaches.

One is a *sensitivity analysis* that applies to understand the applied assumptions' impact on technical and economic specifications related to the e-ammonia bunkering infrastructure (CFI Team, 2023). Based on the feasibility study results, variable parameters and assumptions are designated for investigation due to their considered uncertainty and indicated an impact on the results. It accomplishes by following a systematic approach, where parameters are modified by respectively by the principle of:

- +10 % and -10 %: Less probable to change.
- +20 % and – 20 %: Probable to change.
- +40 % to – 40 %: Probable to change given the case.

It implies that techno-economic conditions consider for choice of changing parameters. Based on the analysis, those that assess with high uncertainty for the results will be modified with + 40 % and - 40 %.

Additionally, a *scenario analysis* that investigates anticipated changes in societal structures contemplates (CFI Team, 2023). It encompasses actual situations where societal structures are objections to significant shocks by changes in market conditions(CFI Team, 2023). Two scenarios are referred to that build on one historical and one future event that will influence cost differences between baseline and alternatives. These are:

- Electricity prices in 2022
- EU ETS

These scenarios are elaborated on in the sensitivity study, cf. Section **Feil! Fant ikke referansekilden.**. In association with an examination of sensitivity study results, discussion points are raised to add perspectives on societal conditions.

Overall, the sensitivity study aims to strengthen the decision-making on e-ammonia bunkering infrastructure for Port of Esbjerg by providing perspectives on uncertainties and limitations related to the feasibility study.

7.12. Summary of Methods

The methodological approach constitutes a feasibility study that builds on a critical case study analytical approach and the theoretical framework. The feasibility study approach belongs to a business economic approach where techno-economic parameters assess related to one baseline and two alternatives for e-ammonia bunkering infrastructure. Data are collected to enable compiling the feasibility study and following on a mixed-method simple design. The data comprise primary data in terms of qualitative interviews and secondary data encompassing quantitative and qualitative data. Quantitative data are processed in an energy model for simulating and calculating the techno-economic parameters of the baseline and alternatives. Furthermore, GIS is used to collect and process data with geographical measures. Lastly, a sensitivity study is structured to enable an investigation of the sensitivity related to the results of the feasibility study to assess their validity and reliability.

The results of the performed methods are presented with the analysis in the next chapter, which constitutes the investigation of the baseline and the feasibility of e-ammonia bunkering alternatives.

8. The Techno-economic Feasibility Study

This analysis constitutes the feasibility study where the techno-economic feasibility of implementing e-ammonia bunkering infrastructure in Port of Esbjerg with a departure in two alternatives is demonstrated and assessed compared with a baseline. The alternatives involve truck-to-ship and ship-to-ship bunkering.

The feasibility of the bunkering alternatives is assessed based on their fulfilment of two feasibility criteria: High bunkering performance and low cost of e-ammonia per tonne, cf. Textbox 3. The results on the cost of e-ammonia per tonne build on the techno-economic conditions measured of e-ammonia production, transportation and storage that are defined as part of the investigated e-ammonia bunkering infrastructure in Port of Esbjerg, cf. Figure 7.

Results are compiled and simulated in an energy model that can be found in Appendix 2. Reference to presented results is mentioned under each heading that refers to the energy model and separate spreadsheet. As emphasised in Figure 7, first step of the feasibility study is to examine the baseline.

8.1. The Baseline

The baseline represents the status quo of existing marine fossil fuel bunkering infrastructure in the Port of Esbjerg that anticipates applicable to the investment year 2028. The demanded bunkering supply capacity depends on ship activities of included ship segments. The first step is, therefore, to investigate the number of included ship segments that bunker in Port of Esbjerg.

8.1.1. Ship Activities

Please find Appendix 2; "Ship Data" and "Ship Data Processed" as reference to presented results in this section.

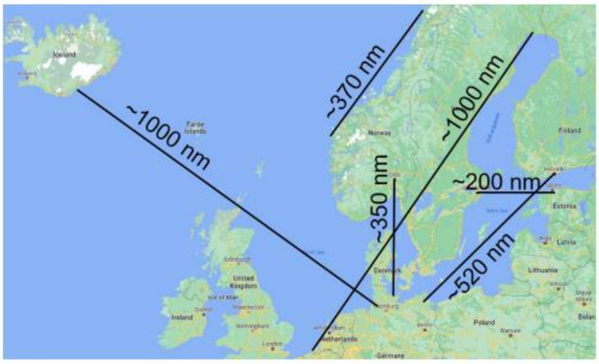
The first step is to identify ships with permitted weight. In 2022, the port received 5 411 ship calls that are assumed all have a bunkering demand. Ship types include domestic and regional work/service ships and tankers weighing above or equal to 5 000 GT. Simulating the *if statement* presented with *Equation 2* (Appendix 1) reveals that 1 060 ships have a weight equal to or above 5 000 GT. Work/service ships constitute 21 %, and less than 2 % are tankers. Comparably, cargo ships constitute 73 %, but since no pilot projects run on e-ammonia in the Nordic Region today, cf. Section 3.2.2, the uncertainty associated with having e-ammonia ship designed commercially viable in 2018 should be lowered for them to be included.

Ship segments with weight equal to or above 5 000 GT assigns a numeric value between 1 to 6 to distinguish them by type. Type categorisation follows the one contemplated by DNV for their AIS analysis (Rivedal & et.al., 2022). It involves a categorisation of type into six groups that comprise: *cargo vessel* [1], *wet and dry bulk carrier* [2], *passenger vessel (cruise)* [3], *passenger vessel* [4], *work/service vessel* [5], and *fishing vessels* [6], with the number assigned attached for this study (Rivedal & et.al., 2022). Consequently, work/service ships (vessels) refer to *5* and tankers *2* that belong to the ship type category *wet and dry bulk carrier* (Rivedal & et.al., 2022).

Distance is next parameter that decides average marine fossil fuel consumption. It relies on a modified categorisation of DNV's that comprise international, intra-Nordic, and domestic shipping

(Rivedal & et.al., 2022). Distances divide instead into three categories that are *international [1]*, *regional [2]*, and *domestic [3]*, which determines based on countries represented in respective port-to-port connections.

Map 6 presents distances [nautical miles] between ports/countries that considers *intra Nordic* (Rivedal & et.al., 2022). The conversion performs to reflect the critical case study. Due to the geographical location of the Port of Esbjerg in the Southern part of the Nordic Region, countries such as Great Britain, France, the Netherlands, and Germany can be reached within the same max. distance of ~ 1 000 nm. Consequently, the categorisation encompasses *regional* port-to-port connections instead of Nordic. Countries included for the *regional* categorisation are mentioned in conjunction with *Equation 3* in Appendix 1.



Map 6: Distances between ports categorised as Intra Nordic by DNV, which has prepared the map (Rivedal & et.al, 2022).

Table 3 presents the number of ships with a weight equal to or above 5 000 GT divided into the included category of ship types. Blue rows indicate ship segments included in the study. It highlights that 134 ships belong to domestic work/service ships, 89 ships to regional work/service ships, and 16 ships are regional tankers. No tankers perform domestic voyages according to the ship activity data. Hence, only regional tankers are registered.

Table 3: Number of ships with weight above or equal to 5 000 GT in Port of Esbjerg in 2022. Blue marked rows indicate ship segments included in the feasibility study. The table is structured based on if statements compiled in Appendix 2, "Ship Data".

Ship types >= 5 000 GT	No. of Ship Calls	Ship Type No.	Ship Type Description	No. of Included Ships
Barge	3	2	Wet and dry bulk ship	
Bulk carrier	11	2	Wet and dry bulk ship	
Container ship	22	1	Cargo ship	
General cargo ship	182	1	Cargo ship	
Offshore construction ship	54	5	Work/service ship	Domestic: 134
Offshore standby ship	5	5	Work/service ship	Regional: 89
Offshore supply ship	140	5	Work/service ship	
Oil drill rig	2	2	Wet and dry bulk ship	
Passenger (cruise)	2	4	Passenger ship (cruise)	
Passenger ship	27	3	Passenger ship	
Ro-Ro ship	475	1	Cargo ship	
Special cargo ship	55	1	Cargo ship	
Special non-cargo ship	10	1	Cargo ship	
Tanker	19	2	Wet and dry bulk ship	Regional:16
Tug	2	5	Work/service ship	
Vehicles carrier	27	1	Cargo ship	
Well stimulation ship	24	5	Work/service ship	
Sum	**1060**	-	-	-

With the number of included ships clarified, marine fossil fuel consumption and demand can be estimated.

8.1.2. Marine Fossil Fuel Consumption

Please find Appendix 2; "Ship Data" as reference to presented results in this section.

Equation 3 shows the if statement simulated for assigning estimated average marine fossil fuel consumption for the included ship segments according to their type and distance. In contrast, weight is accounted for in *Equation 2* (Appendix 1). Estimated marine fossil fuel consumption per ship calculates based on AIS data from 2019 that DNV processes historical ship consumption according to weight, type and overcome distance (Rivedal & et.al., 2022). The data referred to can be found in Appendix 2, "Ship Data", as Table 4-1. and Table 4-2. The consumption measures are assumed to reflect total consumption per roundtrip without energy loss during propulsion to be accounted for.

The AIS data presents total marine fossil fuel consumption per ship segment. Hence, the average consumption per ship is calculated by dividing total marine fossil fuel consumption by the number of ships in the category (Appendix 2; "Ship Data"). Total consumption is given in the unit, toe MGO eq., where toe indicates the amount of energy that can be extracted per tonne (Eurostat, 2018) and MGO eq. is an equivalent for marine gas oil(Brynolf & et.al., 2023). To receive the estimate in tonnes, the average marine fossil fuel consumption in toe MGO eq. multiplies by 0,99 that follows the conversion factor of diesel[1] (Eurostat, 2018).

It returns values on the estimated average marine fossil fuel consumption of the three ship segments. For domestic work/service ships, each ship estimates having a marine fossil fuel consumption of 7,4 tonnes. Regarding regional work/service ships, the consumption is slightly higher by 19,1 tonnes and turns out highest for regional tankers, with 33,3 tonnes of marine fossil fuels consumed per roundtrip. It indicates that regional tankers have the highest consumption rate of the included ship segments. A delimitation is, however, that the size within each ship segment deviates from ship to ship. Hence, in practice, some will have higher or lower marine fossil fuel demands than the average. Based on estimated marine fossil fuel consumption per ship, the total demand annual demand for bunker fuels in Port of Esbjerg is 3 225. In contrast, domestic work/service ships constitute the largest share at 53 %.

P The price of marine fossil fuel per tonne is not publicly available for the Port of Esbjerg, cf. Section 7.5. Instead, the bunker price of diesel in the Port of Aberdeen is referred to which is 3,23 British Pounds per tonne (Port of Aberdeen, 2023). The price converts to DKK by a conversion factor of 8,5 DKK/British Pound (Valuta ex, 2023). It results in a considered price of marine fossil fuel at 27,5 DKK/tonne. It leads to a conclusion of baseline results that are summarised into the following bullet points:

- Marine fossil fuel consumption per ship:
  - Domestic work/service ship: 7,4 tonnes.
  - Regional work/service ship: 19,1 tonnes.
  - Regional tanker: 33,3 tonnes.
- Total annual marine fossil fuel demand in the Port of Esbjerg: 3 225 tonnes.
- Considered price on marine fossil fuels: 27,5 DKK/tonne.

Baseline of bunkering infrastructure in the Port of Esbjerg is concretised which leads to studying the alternatives.

[1] 1 t diesel = 1,01 toe (Eurostat, 2018)

8.2. Alternatives

Two e-ammonia bunkering alternatives are formulated truck-to-ship and ship-to-ship. Those feasibility depends on techno-economic conditions of the supply side of the defined e-ammonia bunkering infrastructure that constitutes e-ammonia production, transportation, and storage. Hence, each part of the supply side is analysed ahead of the bunkering alternatives with a summary of preliminary results. Subsequently follows, a feasibility assessment of each alternative in chronological order results in a section where the results are compared, and the cost of e-ammonia per tonne is calculated based on a levelized cost of e-ammonia calculation.

The production, transportation, and storage capacity required to operate and implement depend on the demand for e-ammonia, which is first to be clarified.

8.2.1. E-ammonia Demand

Please find Appendix 2; "Ship Data" and "Ship Data Processed" as reference to presented results in this section.

The e-ammonia demand determines based on estimated marine fossil fuel consumption per ship from the baseline. E-ammonia has different technical specifications and chemical properties than diesel, resulting in higher demand for e-ammonia than diesel. Firstly, it contains lower energy density by a factor of 2,14, which is measured by dividing the energy density of MGO eq. of 40,4 MJ/kg (DNV, 2019) with the energy density of ammonia at 18,9 MJ/kg (Wolter & Jensen, 2021). Consequently, the e-ammonia demand per ship is estimated by multiplying the marine fossil fuel demand per ship by 2,14 (Appendix 2; "Ship Data").

Additionally, onboard energy losses related to e-ammonia ingestion occur depending on the energy efficiency of the respective e-ammonia engine, which must be accounted for to estimate the demand. The reference e-ammonia fuel cell, SOFC, has an energy efficiency of around 60 % (Brynolf & et.al., 2023), which results in further increased demand for e-ammonia per ship, calculated by multiplying the marine fossil fuel consumption by 1,6.

It results in approximately an average e-ammonia demand per round trip of included ship types:

- E-ammonia demand of a domestic work/service ship = 25 tonnes
- E-ammonia demand of a regional work/service ship = 65 tonnes
- E-ammonia demand of a regional tanker = 114 tonnes

Total annual e-ammonia demand adds up to 11 031 tonnes by summarising the e-ammonia demand for all ships. The monthly peak demand for e-ammonia occurs in August, and the lowest demand is in February, which underlines differences in the monthly demands of e-ammonia for bunkering. Figure 10 shows monthly deviations in the e-ammonia demand divided into the three ship segments and summarised. Overall, regional work/service ships constitute the highest share of the total e-ammonia demand, with 53 %, followed by domestic work/service ships (31 %) and regional tankers (17 %) (Appendix 2; "Ship data").

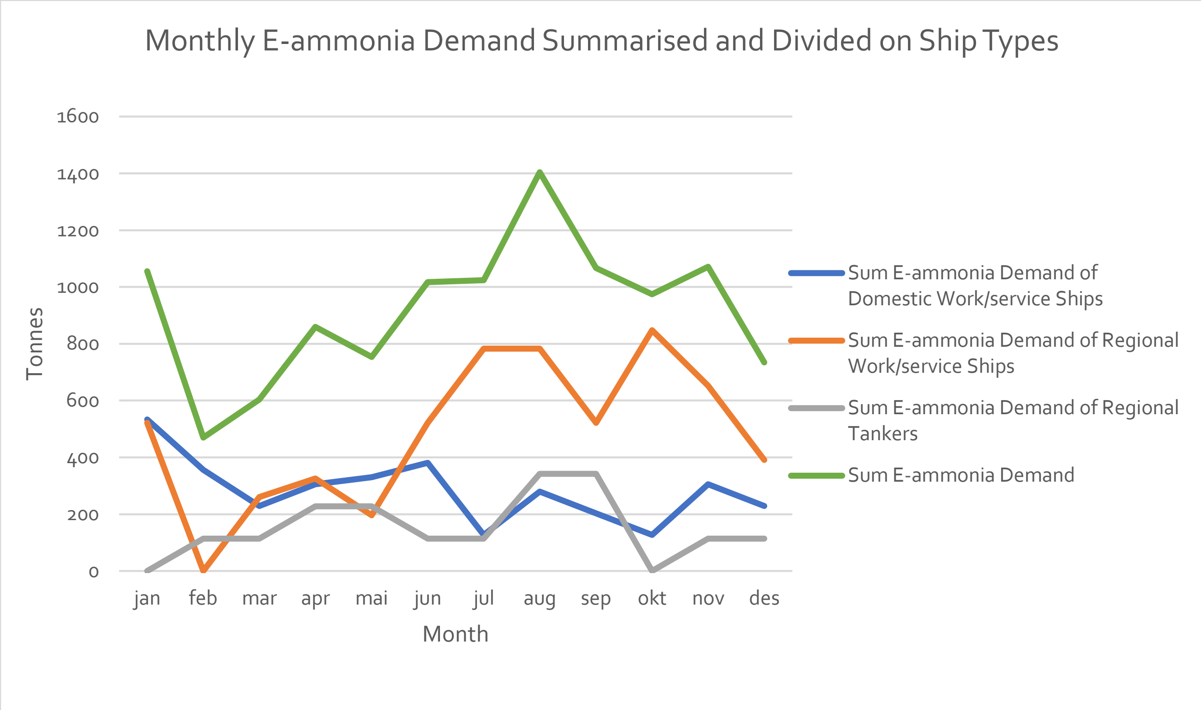


Figure 10: Monthly e-ammonia demand in Port of Esbjerg summarised and divided on ship segments. The figure is compiled in Appendix 2, "Ship Data Processed".

Total monthly and annual e-ammonia demand must be met for e-ammonia production to enable the security of supply. Production hours are decided and determined by electricity prices to enable the lowest cost on e-ammonia per tonne. Hence, it investigates in the next section how the balance is between demand and production at the Høst PtX Esbjerg e-ammonia plant according to production based on spot market electricity prices.

8.2.2. E-ammonia Production

Please find Appendix 2; "E-ammonia Production" as reference to presented results in this section.

E-ammonia assumes produced at the Høst PtX Esbjerg e-ammonia plant. It has a total annual e-ammonia production expected at 500 000 to 600 000 tonnes with an electrolyser capacity of 1 GW and connection to the power grid (Høst PtX Esbjerg, 2023). The e-ammonia demand of Port of Esbjerg constitutes a share of 1,8 % of the total annual e-ammonia production. Hence, it concludes that the demand can be met in 2028.

Based on the second feasibility criteria that requests a low price on e-ammonia, the e-ammonia production simulates hourly according to the lowest spot market electricity prices. It results in divergent monthly production and demand.

Ordinarily, an e-ammonia plant operates at 70 % to 100 % of its hourly production capacity (Wolter & Jensen, 2021). It anticipates that there is an incentive to produce at full load (100 %) during hours with low electricity prices to enable low production costs. With 1 GW electrolyser capacity, the hourly e-ammonia production capacity is estimated at approx. 558 MW. It calculates by multiplying the 1 GW capacity with the alkaline electrolyser efficiency of 68 % and 82 % being the energy efficiency of the Haber Bosch process (Appendix 2; "Technical Specifications"). All values refer to 2030 prices. (Danish Energy Agency, 2017).

The hourly production in tonnes is subsequently measured by dividing 558 MW by the energy density of e-ammonia at 5,2 kWh/kg (Wolter & Jensen, 2021). It results in 106,5 tonnes of e-ammonia output per hour (Appendix 2; "E-ammonia Production").

Further, 10 % is applied to the annual e-ammonia demand to provide supply security and account for potential energy loss during transportation, storage, and bunkering of e-ammonia since it is not emphasised. It is as well a limitation to the results. Therefore, annual e-ammonia production for the Port of Esbjerg demands 12 134 tonnes.

It requires 113 production hours to fulfil this demand, with the hourly production at 106,5 tonnes, which is estimated by the if statement presented in *Equation 6* (Appendix 1) Additionally, the if statement designates respective hours of production with an electricity spot market price below 26,26 DKK/MWh, which is the price in hour 114 that constitutes the limit. With an anticipated electricity consumption of 9 900 kWh per ton of e-ammonia (Danish Energy Agency, 2017), the e-ammonia production cost becomes -9,32 DKK/tonnes, only based on the spot market electricity price. The cost of procuring water and nitrogen for production is considered to be included in the variable operational cost of the Haber Bosch unit (Danish Energy Agency, 2017).

Applying the variable cost of variable operational costs to the price turns increases it to -9,17 DKK/tonnes. It estimates the variable operational price of e-ammonia production at 0,15 DKK/ton e-ammonia, which is the converted value of 0,02 EURO/ton e-ammonia by a conversion factor of 7,5 EURO/DKK (Danish Energy Agency, 2017).

Figure 11 visualises the balance of monthly e-ammonia demand and production during the year. There appears to be a significant deviation between demand and production under the criterion of producing e-ammonia during hours with the lowest electricity spot market prices. Meanwhile, the demand is relatively stable during the year, when e-ammonia is only produced in November and December. Therefore, it is a prerequisite to installing an e-ammonia storage tank in the Port of Esbjerg with a capacity adequate to meet the annual demand based on a monthly imbalance in demand and production.

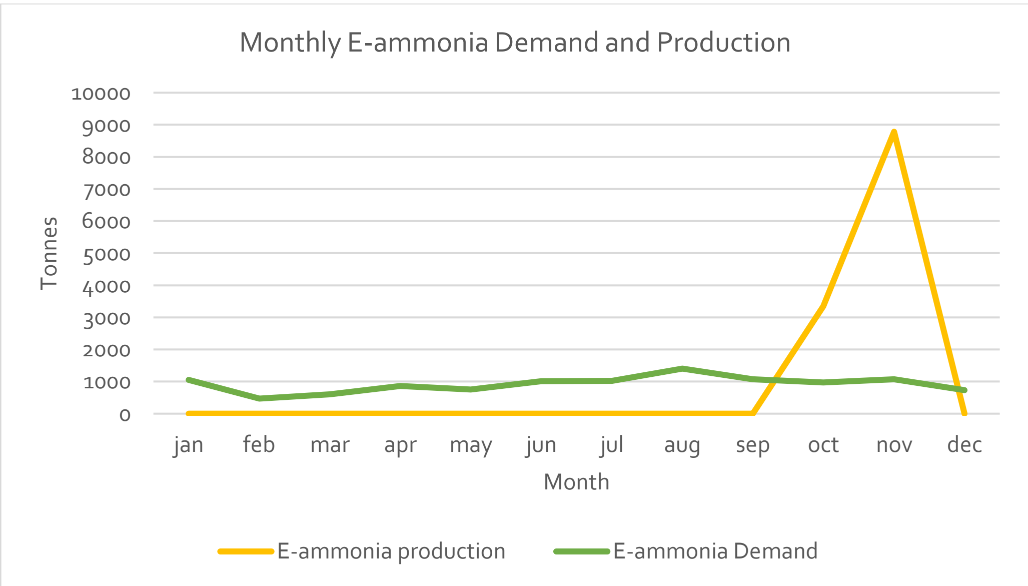


Figure 11: Monthly balance between e-ammonia demand and -production.
The figure is prepared in Appendix 2, "E-Ammonia Storage".

Therefore, the requested e-ammonia storage capacity and associated transportation costs to the storage site investigates.

8.2.3. E-ammonia Storage Tank and Transportation

Please find Appendix 2; "E-ammonia Storage" as reference to presented results in this section.

An onsite e-ammonia storage tank is considered installed in the Port of Esbjerg for storing the cheapest e-ammonia produced from the Høst PtX Esbjerg e-ammonia plant.

The e-ammonia storage tank capacity is estimated by simulating *Equation 7* in Appendix 1. *Equation 7* builds on a combined if statement. Firstly, if monthly production exceeds the demand, the storage tank must be filled with surplus production extracted from the monthly demand. If it is false, the storage will be discharged to meet deficient production. Should monthly production meet the demand, nothing happens to the storage content. A noticeable limitation is that storage loss and practical feasibility of storing the amount of e-ammonia during a year with frequency of charging and discharging the e-ammonia is not considered.

Required e-ammonia storage tank capacity is measured by simulating the formula with a variable storage capacity. A verification statement applies to turn out the value 1 for the respective month, where the storage tank capacity is inadequate for storing excess e-ammonia production. The verification statement presents *Equation 7* as well (Appendix 1). When the variable storage tank capacity assigns a value of 10 090 tonnes, it turns out adequate for meeting the monthly annual demands. It also equals the highest excess production per month that appears in November, according to Figure 11. September considers the month when the e-ammonia storage tank is installed to have it constructed before the first monthly production.

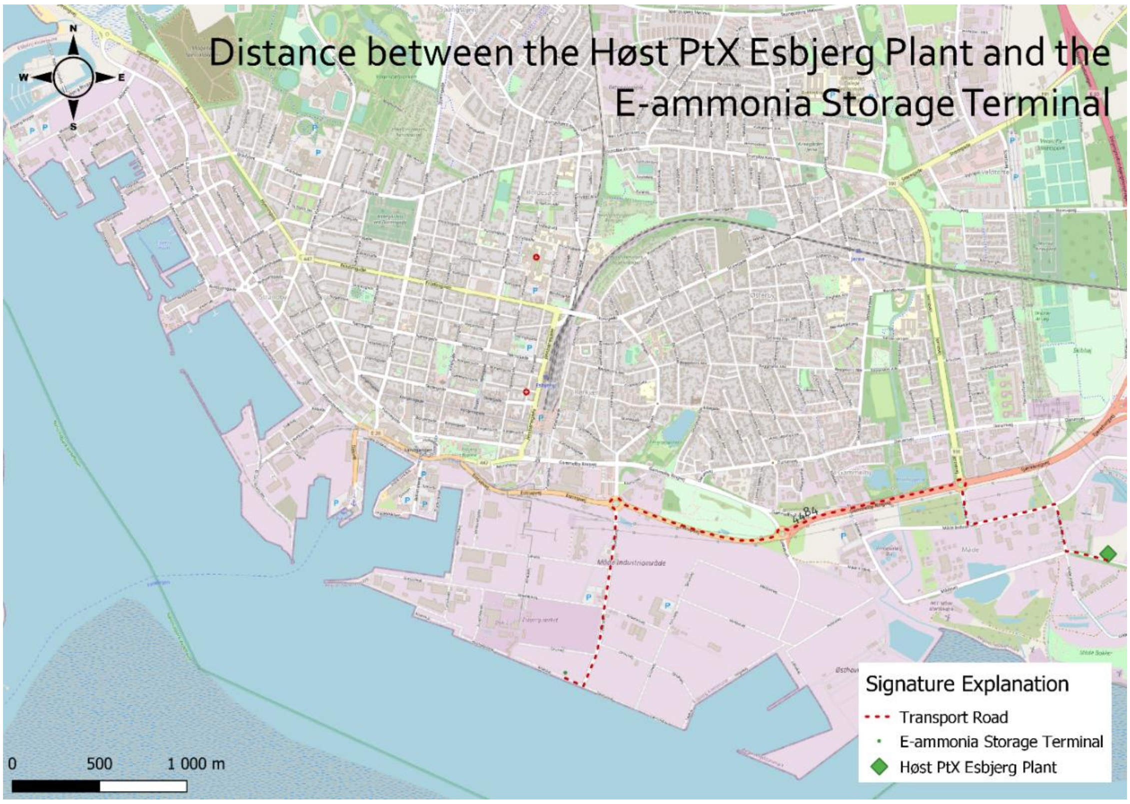
The requested space uptake for and site of the e-ammonia storage tank in the Port of Esbjerg is necessary to assess for clarifying transportation distance and available space for the storage. A double-walled refrigerated e-ammonia storage tank refers to due to higher safety related to a refrigerated ammonia storage tank compared with a pressurised one (Zakariyya et.al., 2021). Technical specifications are used to calculate the volume of the respective e-ammonia storage tank.

Refrigerated ammonia contains a specific energy density of 610 kg/m^3 (Lloyd's Register, 2020) By dividing the 610 kg/m3 with the requested size of 10 090 tonnes, the volume of the e-ammonia storage tank equals 16 541 m^3 (Appendix 2; "E-ammonia Storage"). The reference refrigerated ammonia storage tank also has an outer diameter of approximately 42 m, a height of 32 m and can contain 36 700 m3 of ammonia (Geldof, 2023). That is around twice as much as the e-ammonia storage tank in the Port of Esbjerg. By multiplying the diameter and height of the reference ammonia storage tank with the size difference (0,46), the diameter of the outer tank becomes 19 m and the height 14 m for the e-ammonia storage tank in the Port of Esbjerg.

It assumes that the Port of Esbjerg is responsible for the investment in the e-ammonia storage tank. Investment costs of an e-ammonia storage tank consider to be 0,81 USD/kg NH_3 (Nayak-Luke et.al., 2021), which equals 6,1 DKK/kg NH3 by a conversion factor of 6,8 DKK/USD (Valuta ex, 2023). The price of storage located decentral from the production site, such as to a port terminal, is 50 % higher than centrally located ones (Nayak-Luke et.al., 2021). Therefore, the estimated investment of the e-ammonia storage in the Port of Esbjerg anticipates 18,7 MDKK in 2028. Annual maintenance costs constitute 3 %, which results in an annual operational and maintenance cost of 0,6 MDKK (Nayak-Luke et.al., 2021). Divided by total e-ammonia production that is stored annually, it equals 46,2 DKK/tonne of e-ammonia. Variable costs such as insurance and employment expenditures are not included because price estimates from Nayak-Luke et.al. (2021) refer to the United States (Nayak-Luke et.al., 2021). It considers an invalid estimate for this feasibility study but indicates a limitation to the results. Operational and maintenance costs related to the e-ammonia storage tank are included for the e-ammonia price per tonne for the LCOA calculation, cf. Section 8.4.

The transportation of e-ammonia transportation between the Høst PtX Esbjerg e-ammonia plant and the e-ammonia storage tank is determined performed by trucks. A truck is chosen because it provides mobility according to flexible e-ammonia production profiles (Danish Energy Agency, 2017). Trucks carrying e-ammonia in refrigerated condition can have a capacity of 28 tonnes/50 m^3 e-ammonia (Danish Energy Agency, 2017). Annual costs related to transportation assume to be determined by fixed and variable operational costs that will be applied final cost of e-ammonia per tonne.

The transportation route, location of the Høst PtX Esbjerg e-ammonia plant site, and the e-ammonia storage tank are designated in GIS, cf. Section 7.10. The Høst PtX Esbjerg e-ammonia plant will be placed in the industrial area, Måde, close to the Port of Esbjerg (Høst PtX Esbjerg, 2023). Therefore, an anticipated available area identifies in GIS based on the Google street map background layer that can be allocated to the plant. A similar procedure follows for the e-ammonia storage tank. Criteria for site location are that the tank must be placed nearshore with a road connection in the Port of Esbjerg to accommodate ship-to-ship and truck-to-ship bunkering potentially. Designated sites and transportation route are visualised in Map 7.



Map 7: Site locations of the Høst PtX Esbjerg e-ammonia plant and the e-ammonia storage tank, as well as the designated transportation road between the two. The map is compiled in QGIS.

The distance between the e-ammonia storage tank and the Høst PtX Esbjerg e-ammonia plant is measured to be around 4 500 m in GIS, which gives a roundtrip of 9 000 m per carried 28 tonnes of e-ammonia. Consequently, it requires 434 roundtrips which equals a total annual distance of 3 900 km without accounting for any losses. Variable operational costs per roundtrip are given at 0,13

EURO/tonne e-ammonia timed the distance overcome in kilometres. In contrast, the fixed operational cost of the truck is 4,5 EURO per tonne of e-ammonia (Danish Energy Agency, 2017). It results in a variable cost of 8,8 DKK/tonne of e-ammonia and a fixed cost of 34 DKK/tonne.

Cost and technical conditions for the supply side of the e-ammonia bunkering infrastructure are now assessed. Hence, a preliminary summary provides to encapsulate results and findings.

8.2.4. Preliminary Results of Alternatives

The results of e-ammonia demand, production, transportation, and storage that determine and constitute the supply side of the e-ammonia bunkering infrastructure are summarised in Table 4. The numeric results distinguish into being technical or economical to reflect the techno-economic conditions that influence each other.

Table 4: Results of the e-ammonia supply infrastructure. Prices anticipate for investment year 2028. Production price per tonne e-ammonia only refers electricity spot market prices.

Parameter	Technical	Economical
E-ammonia demand	Annual demand: 11 031 tonnes	-
E-ammonia production	+ 10 % production demand: 12 134 tonnes Hourly production capacity: 558 MW or 106,5 tonnes Production hours: 113	E-ammonia production price (incl. variable OPEX): -9,17 DKK/tonnes
E-ammonia storage tank	Capacity: 10 090 tonnes or 16 541 m3 Outer tank diameter = 19 m Outer tank height = 14 m	CAPEX: 18,7 MDKK OPEX: 46,2 DKK/tonne
Transportation	Truck capacity: 28 tonnes or 50 m3 Roundtrip: 9 km Annual distance: 3 900 km	Variable OPEX: 8,8 DKK/tonne Fixed OPEX: 34,3 DKK/tonne
Summarised	CAPEX (e-ammonia storage tank)**:** 18,7 MDKK (2028) Total OPEX (production, transportation, and storage): 71 DKK/tonne e-ammonia (2028)	

The preliminary findings underline that the highest costs related to the e-ammonia supply side belong to the e-ammonia storage tank. With the investment cost of the tank considered for the levelized cost of e-ammonia, it becomes interesting to discover its share of the total cost that influences the feasibility of bunkering alternatives and the e-ammonia bunkering infrastructure as a whole. Fixed operational transportation costs constitute the following costliest parameter with a price of 34,3 DKK/tonne applied and depend on the carried amount of e-ammonia. Additionally, the price of electricity according to spot market prices in 2021 and variable operational costs of transportation of e-ammonia to the storage site have a limited impact on the total share of total operational costs by 2028.

The implantation of the bunkering alternatives will add further costs to e-ammonia per tonne, depending on their bunkering performance.

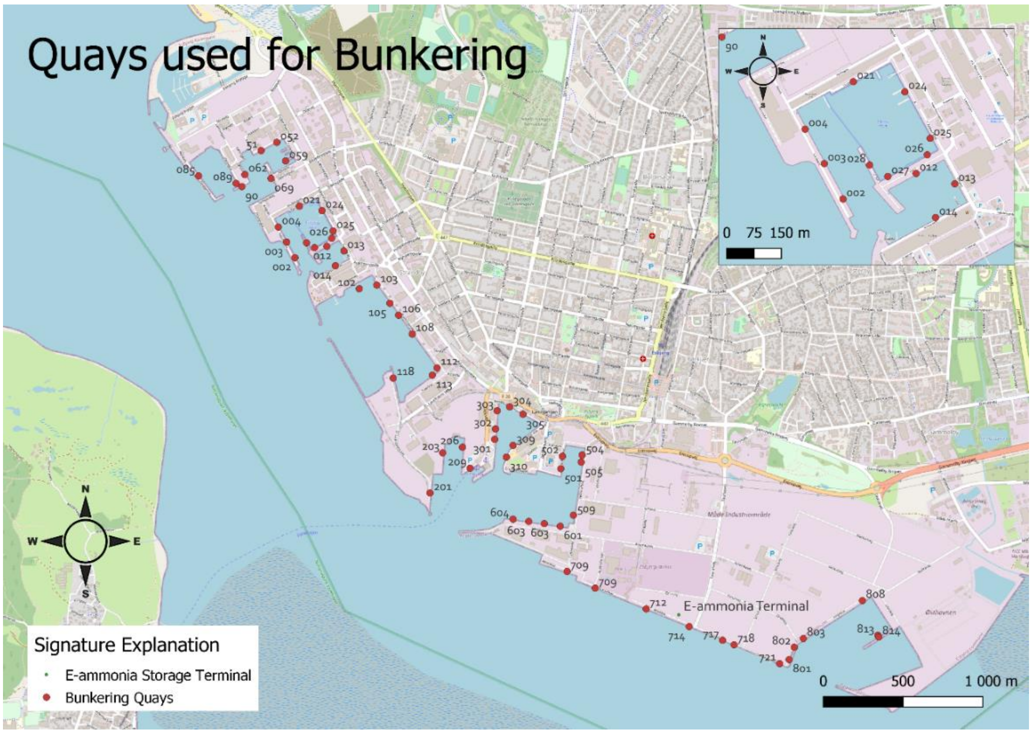
8.3. Bunkering Alternatives

Please find Appendix 2; "Bunkering Alternatives" and "Ship Data Processed" as reference to presented results in this section.

The purpose of the three e-ammonia bunkering alternatives is mutual: to distribute e-ammonia from the e-ammonia storage site to respective quays, which included ship segments bunker. Based on a pivot table analysis, 61 quays are identified for which bunkering appears. Map 8 provides an overview of the 61 quays in Port of Esbjerg with the attached numeration.

For ten of them, the lowest annual demand for e-ammonia bunker experiences at 25 tonnes, which constitutes the demand of one domestic offshore work/service ship. In quay 814, the highest annual e-ammonia demand occurs at 849 tonnes, dispersed over November and December. (Appendix 2; "Ship Data Processed")

The number of quays complicates an assessment of the two alternatives' bunkering performance according to annual demands within this scope. Therefore, the bunkering performance related to two events is investigated, representing two peak bunkering demands of ships.



Map 8: Quays used for e-ammonia bunkering with attached numeration. Small map frames Basin 1 and 2, cf. Map 4. The map is prepared in GIS based on provided map by Port of Esbjerg (Appendix 3) (Appendix 2; "Ship data").

Event 1 concerns the highest e-ammonia bunker demand for one ship with the fewest hour(s) allocated for bunkering. Based on a pivot table analysis, a regional tanker identifies as having the highest e-ammonia demand at 114 tonnes with the shortest time spent in port at around 7,5 hours on the 13th of July (Appendix 2; "Ship Data Processed"). Further specifications regarding event 1 are presented in Table 5.

Table 5: Specifications regarding event 2. The table is compiled in Appendix 2, "Bunkering Alternatives".

Event 1: Peak bunkering performance request of one ship								
Date	Arrival	Destination	Date	Departure	Destination	Quay	Ship type	E-ammonia [tonne]
13.07.2022	15:50:00	Antwerpen	13.07.2022	23:22:00	Göteborg	102	Tanker	114
Time in port:	7,50	Hours						

Event 2 represents the daily peak demand for e-ammonia. A similar procedure applies for identifying daily peak demand as for event 1. It occurs on the 26th of July with a total demand of approx. 196 tonnes of e-ammonia that bunkers in quay 112 and 113. The demands come from three regional work/service ships with a demand of 65 tonnes of e-ammonia each during overlapping time slots. Characteristics regarding event 2 are shown in Table 6.

Table 6: Specifications regarding event 2. The table is compiled in Appendix 2; "Bunkering Alternatives".

Event 2: Peak-load demand (daily)					Date	26.jul	Total Demand:	195,6
Date	Arrival	Destination	Date	Departure	Destination	Quay	Ship type	E-ammonia [tonne]
26.07.2022	08:30:00	NL - Offshore Installations	26.07.2022	15:50:00	NL - Offshore Installations	112	Offshore supply ship	65
Time in port:	6,50	hours						
26.07.2022	07:45:00	Offshore Installations - Germa	27.07.2022	19:10:00	Offshore Installations - Germa	112	Offshore supply ship	65
Time in port:	11,50	hours						
26.07.2022	14:45:00	Liverpool	27.07.2022	22:22:00	DK - Offshore Installations	113	Offshore supply ship	65
Time in port:	7,60	hours						

In the following sections, the feasibility of alternatives is assessed based on their bunkering performance and related e-ammonia costs per tonne for respectively event 1 and 2.

8.3.1. Truck-to-ship

The feasibility of truck-to-ship bunkering assessed for each event distinguished for respective feasibility criterion.

Event 1: Bunkering performance

Bunkering performance adequacy of the truck-to-ship alternative depends on the capacity, flow rate, and required reloading hours of the truck that constitutes technical specifications. Furthermore, the distance to quay 102 from the e-ammonia storage tank is a variable parameter that must be accounted for.

Technical specifications are considered similar to the transportation truck, cf. Section 8.2.3. Hence, the truck can carry 28 tonnes of e-ammonia per roundtrip and has estimated loading hours 2,5 hours (Danish Energy Agency, 2017). The flow rate is 50 m^3/hour, which equals 31 tonnes/hour, by dividing it by the specific energy density of ammonia at 610 kg/m^3 (Zakariyya et.al., 2021). It indicates that the truck can bunker the regional tanker with its carried amount per roundtrip within an hour.

In GIS, the distance between the e-ammonia storage tank and quay 102 measures 4 315 m, resulting in a roundtrip of approx. 8 630 m. The road can be identified on Map 8. It brings about a total overcome distance of 35 km for bunkering the regional tanker by dividing demanded e-ammonia with the truck's capacity.

With an assumed average truck speed of 60 km/h (Danish Energy Agency, 2017), it results in approx. 1,7 hours used on transportation. Lastly, the regional tanker demands 114 tonnes of e-ammonia within the 7,50 hours it is in port. Time spent on bunkering the ship equals around 3,7 hours, which is calculated by dividing the e-ammonia demand by the flow rate of 31 tonnes/hour. Lastly, with its capacity of 28 tonnes, the truck must be refuelled around 4 times during the bunkering process, which leads to taking around 10,2 hours.

Summarised, the total hours spent on bunkering the ship by one truck are 15,6, without accounting for potential loss of energy during refuelling processes by hose or occurred leakages. It is twice as much time than requested. Hence, one truck is infeasible to meet the first feasibility criterion. Instead, three trucks are required to fulfil the demand, but where the third truck only needs to operate 20 minutes.

Results on the bunkering performance relative to technical specifications are presented in Table 7.

Bunkering Performance: Event 1			
1 Truck	Bunkering hours	15,6	Hours
	Bunkering minutes	937	Minutes
2 Trucks	Bunkering hours	7,8	Hours
	Bunkering minutes	468	Minutes
3 Trucks	Bunkering hours	5,2	Hours
	Bunkering minutes	312	Minutes

Technical Specifications:		
Capacity	28	tonnes
Loading hours	2,5	Hours
Flow rate	50	m3/hour
Calculated Flow rate	31	tonnes/hour
Average speed	60	km/h
Round-trip distance	8 630	m
Driving speed	60	km/h

Table 7: Results regarding the bunkering performance of the truck-to-ship bunkering alternative for event 1 based on considered technical specifications. Tables can be found in Appendix 2, "Bunkering Alternatives".

It leads to examining associated costs related to the truck-to-ship bunkering alternative for event 1.

Event1: Costs of the truck-to-ship bunkering

As previously mentioned, economic specifications are similar to the costs of the transportation truck. Hence, the investment cost per truck is 7 350 KDKK with a fixed operational cost of 34 DKK/tonne of transported e-ammonia, cf. Section 8.2.3. Since three trucks are required to fulfil the bunkering demand, the total investment cost turns 22 050 KDKK for the investment year 2028. Estimated fixed and additionally variable operational costs do not change according to investment costs because they reflect the price per tonne of e-ammonia transported.

Consequently, variable operational costs add up to 965 DKK/refuel, around 34 DKK/tonne, and fixed operational costs turn 3 848 DKK annually, which is 34 DKK/tonne annually. Summarised operational costs are 68 DKK/tonne for the truck-to-ship bunkering alternative for event 1.

An essential assumption is that the fuel consumption price for the trucks is included in variable costs.

Event 2: Bunkering performance

For event 2, three work/service ships have an e-ammonia bunkering demand during overlapping time slots. These ships bunker in two quays, 112 and 113, which can be identified in Map 8. The distance of event 2 is measured to approx. 3 340 m gives a roundtrip at 8 780 m. It applies to both quays that are located close to each other. The total overcome distance adds up to around 60 km, with around 20 km to overcome for bunkering each ship. Surplus e-ammonia in the truck's tank is not considered utilised for the next ship bunkering; hence, after each bunkering process, the truck assumes driving back to the e-ammonia storage tank. It indicates a potential limitation in the results.

Based on the exact applied technical specifications for event 1, the bunkering performance of one truck measures 9,7 hours per ship, which is sufficient only for refuelling one of the ships that spend approx. 11,5 hours in the port. Hence, one truck is again inadequate for executing the required bunkering performance for event 2. The results can be identified in Table 8.

Table 8: Results regarding the bunkering performance of the truck-to-ship alternative for event 1. The table can be found in Appendix 2, "Bunkering Alternatives".

Bunkering Performance: Event 2			
1 Truck	Ship 1	6,5	Hours
	Bunkering hours:	9,7	Hours
	Ship 2	11,5	Hours
	Bunkering hours:	9,7	Hours
	Ship 3	7,6	Hours
	Bunkering hours:	9,7	Hours
2 Trucks	Ship 1	6,5	Hours
	Bunkering hours:	4,8	Hours
	Ship 2	11,5	Hours
	Bunkering hours:	4,8	Hours
	Ship 3	7,6	Hours
	Bunkering hours:	4,8	Hours
Sum	Bunkering ships	25,6	Hours
	1 truck	-3,4	Hours
	2 trucks	+11,1	Hours

On the other hand, the e-ammonia demand of bunkering ships enables two trucks to fulfil it. It takes 4,8 hours for them to bunker one ship, which results in a spare time of + 11,1 hours, providing an opportunity for flexible operations as well.

It leads to calculating costs related to the bunkering performance for event 2.

Event 2: Costs of truck-to-ship bunkering

The costs of bunkering performance operations are quite like those of event 1. Fixed operational cost is the same at 34 DKK/tonne e-ammonia, whereas the variable operational cost is 59 DKK/tonne due to increased overcome distance. On the other hand, less requires for the investment cost regarding event 2, because only two trucks are adequate to fulfil demanded bunkering performance. It results in an investment cost of 14 700 KDKK for trucks.

With both feasibility criteria assessed for event 1 and event 2 of the truck-to-ship alternative, the ship-to-ship bunkering alternative is analysed.

8.3.2. Ship-to-ship

Similar structure applies for the assessment of ship-to-ship bunkering as for truck-to-ship.

Event 1: Bunkering performance

A bunker supply vessel considers carrying e-ammonia in refrigerated condition. The capacity of a bunker supply ship is higher compared with the truck. It ranges from 7 000 to 21 000, according to Yang & Lam (2023). The lowest capacity of the bunker supply ship is adapted to follow the second feasibility criterion for enabling the lowest price on e-ammonia per tonne. However, Yang & Lam (2023) deal with a case study in the Port of Singapore, one of the world's largest ports, cf. Section 7.6. By weighting that, the bunker supply ship must be able to navigate in the quay areas of Port of Esbjerg; hence, 50 % of the 7 000 tonnes capacity applies as a practice measure. Additionally, Yang & Lam (2023) use a maximum filling limit of the supply ship at 98 %; hence, 3 430 tonnes of e-ammonia assume to be distributed per roundtrip by the bunker supply ship.

One roundtrip is only required for refuelling the regional tanker with the 114 tonnes of e-ammonia. Roundtrip distance measures around 3 850 m in GIS, giving a roundtrip of approx. 7 700 m from the loading arm at the quayside to quay 102. It performs at an assumed sailing speed of 28 km/h concerning a ship transporting CO2 because of a lack of data regarding a bunker supply ship (Danish Energy Agency, 2017).

The flow rate of bunkering e-ammonia applies to the lowest dealt with flow rate at 350 tonnes/hour by Yang & Lam (2028). However, following the previous decrease in capacity, the flow rate at 350 tonnes/hour deducts by 50 %. It results in a flow rate of 125 tonnes/hour. Consequently, it takes around 39 min for the bunker supply ship to bunker the regional tanker.

Time spent on refuelling the bunker supply ship depends on the flow rate of a loading arm that, by a process pipeline, is connected to the e-ammonia storage tank (Zakariyya et.al., 2021). The flow rate of the loading arm is, according to Zakariyya et.al. (2021), 200 m^3/hour, which gives a flow rate of 122 tonnes/hour by multiplying it by 610 kg/m3 as the specific energy density of ammonia. According to applied data, it results in 28 hours spent on refuelling, which is significantly higher than the truck. However, time spent on refuelling the ship is not necessary for event 1, since it can fulfil the demand by one tank.

Results on estimated bunkering performance of the ship-to-ship bunkering are presented in Table 9.

Table 9: Results regarding the bunkering performance of the ship-to-ship bunkering alternative for event 1 based on considered technical specifications. Tables can be found in Appendix 2, "Bunkering Alternatives".

Technical Specifications:		
Capacity of e-ammonia supply ship	3430	tonnes
Sailing speed	28	km/h
Flow rate of bunkering (e-ammonia)	175	tonnes/hour
Flow rate of loading arm	200	m3/h
Converted	122	tonnes/hour
Time spent per refuel	28	hours
Loading hours	5	hours
Maximum filling limit at port	98 %	

Bunkering Performance: Event 1			
1 Ship	Bunkering hours:	0,65	Hours
	Bunkering time:	39	Minutes

It concludes that the bunkering performance of the ship-to-ship bunkering alternative for event 1 is adequate for meeting the demand and, therefore, feasible according to the first feasibility criterion.

Event 1: Costs of ship-to-ship bunkering

Regarding costs of ship-to-ship bunkering, the investment cost is estimated at 1 750 EURO per carried weight of e-ammonia in tonnes (Danish Energy Agency, 2017). It gives an investment cost of 45 019 KDKK for one ship by a conversion factor of 7,5 EURO/DKK. One loading arm must also be installed to refuel the bunker supply ship. It has an estimated investment cost of 225 KDKK, based on a price of 30 0000 EURO converted into DKK by a conversion factor of 7,5 DKK/EURO (Danish Energy Agency, 2017). It results in a total investment cost of 45 244 KDKK in 2028 for the ship-to-ship bunkering alternative.

Fixed operational costs constitute 5 % of the investment cost as total annual costs (Danish Energy Agency, 2017). Hence, multiplying the investment costs by 5 % and subsequently dividing it by the carried amount of e-ammonia at 12 123 tonnes constitute considered annual carried amount, which turns 186 DKK/tonne. Costs of port services account for the 5 % estimate (Danish Energy Agency, 2017).

Additionally, variable operational costs are 0,13 EURO per overcome distance timed the carried weight of e-ammonia (Danish Energy Agency, 2017). Consequently, with a roundtrip at approx. 7 700 m, total variable operational cost becomes 856 DKK for this event 1 divided per tonne of the 3 430 tonnes, equals approx. 8 DKK/tonne e-ammonia. It gives a total operational cost of around 193 DKK/tonne of e-ammonia.

Event 2: Bunkering performance

Regarding the bunkering performance of event 2, it takes around 41 minutes to bunker each ship with a demand of 25 tonnes of e-ammonia. It is in response to almost having no distance between quay 112 and 113. It gives a total of approx. 2 hours. It underlines that bunkering by ship-to-ship provides flexibility to bunkering logistics because the time spent on refuelling ships is less than the time bunkering ships spend in port.

The sailing distance from the quayside at the loading arm to the two quays is around 4 400 m, with a roundtrip of approximately 8 800 m. Only one roundtrip is necessary to meet the fuel demand. Hence, the bunkering performance turns out convincingly high.

Table 10: Results regarding bunkering performance of the ship-to-ship bunkering alternative for event 2 based on considered technical specifications. The table can be found in Appendix 2, "Bunkering Alternatives".

Bunkering Performance: Event 2			
1 Ship	Ship 1	6,5	Hours
	Bunkering hours:	0,7	Hours
	Ship 2	11,5	Hours
	Bunkering hours:	0,7	Hours
	Ship 3	7,6	Hours
	Bunkering hours:	0,7	Hours
Sum	Bunkering ships	25,6	Hours
	1 bunker supply ship	23,5	Hours

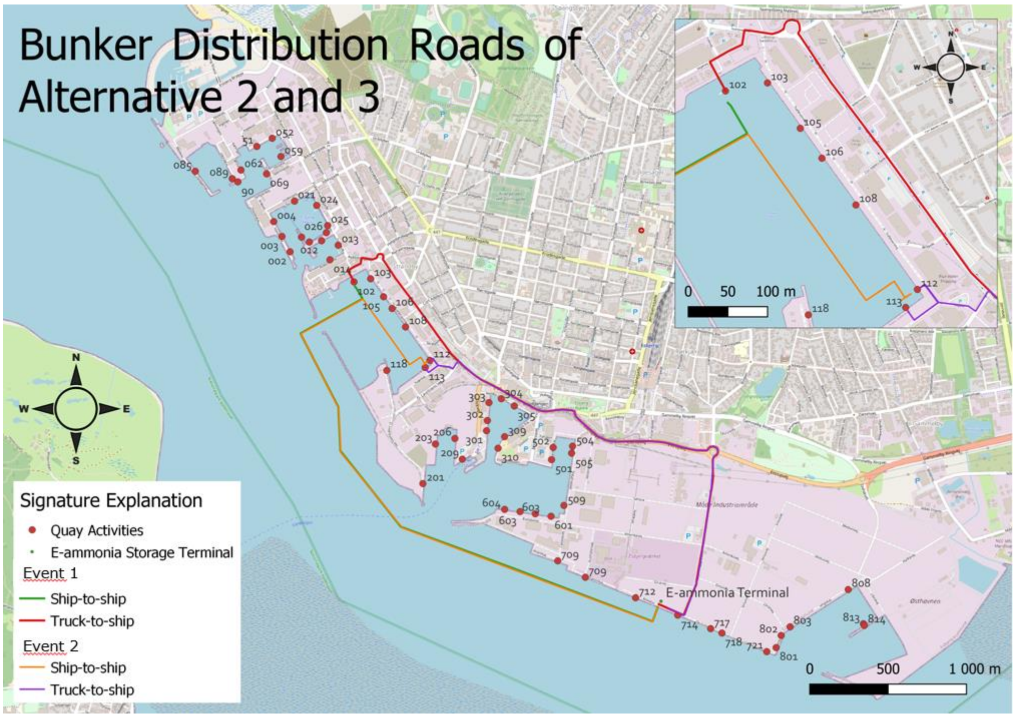
Based on the results, prices related to bunkering conditions of event 2 are examined for the forthcoming.

Event 2: Costs of ship-to-ship bunkering

Total investment cost does not differ from event 1, why it equals 45 019 KDKK in 2028. The same applies to fixed operational costs at 186 DKK/tonne.

Regarding variable operational costs, it is similar to event 1 because almost the same distance must be overcome between the loading arm at the quayside to quay 112 and 113 as for quay 102. Dividing variable operational cost per tonne of e-ammonia, the price becomes approx. 9 DKK/tonnes e-ammonia. It results in total operational cost related to ship-to-ship bunkering for event 2 at 194 DKK/tonne e-ammonia.

Map 9 shows designated routes that the e-ammonia bunkering alternatives overcome for individual events. Based on the results of each alternative, a comparison compiles with a calculation of the associated levelized cost of e-ammonia of each..



Map 9: Bunkering distribution roads for event 1 and event 2 for the two bunkering alternatives. The map is performed in GIS.

8.4. Comparison of Results and LCOA

Based on the feasibility assessment and demonstration of how the alternatives perform according to event 1 and 2, it can be concluded.

The ship-to-ship bunkering alternative can be assessed as most feasible for fulfilling the first feasibility criterion to provide high bunkering performance given current bunkering performance requirements. It is in response to its technically higher capacity and bunkering flow rate that enable reduced time for bunkering ships compared with the truck-to-ship bunkering alternative.

Summarised results regarding the second feasibility criteria are gathered in Table 11. These underline that the truck-to-ship bunkering alternative scores convincingly best on both investment and operational costs. Particularly fixed operational costs jump out for the ship-to-ship bunkering alternative because it refers to investment costs. Regarding the truck-to-ship alternative, it is primarily variable operational costs that constitute the highest share and, for which can be identified, is sensitive to the distance since the distance increase from event 1 to 2 leads to an inclined price of 25 DKK/tonne e-ammonia. The same sensitivity cannot be recognised for the ship-to-ship bunkering alternative because the distance is almost alike for the two events.

Table 11: Comparison of results regarding second feasibility criterion for the two bunkering alternatives. The compiled results can be found in Appendix 2; "Feasibility Study Results".

Comparison of operational costs			
	Truck-to-ship bunkering		
Event 1	Fixed OPEX	34	DKK/tonne
	Variable OPEX	34	DKK/tonne
Event 2	Fixed OPEX	34	DKK/tonne
	Variable OPEX	59	DKK/tonne
	Ship-to-ship bunkering		
Event 1	Fixed O&M	186	DKK/tonne
	Variable O&M	8	DKK/tonne
Event 2	Fixed O&M	186	DKK/tonne
	Variable O&M	9	DKK/tonne
Event 1	Sum Pipeline-to-ship	N/A	DKK/tonne
	Sum Truck-to-ship	68	DKK/tonne
	Sum Pipeline-to-ship	193	DKK/tonne
Event 2	Sum Pipeline-to-ship	N/A	DKK/tonne
	Sum Truck-to-ship	93	DKK/tonne
	Sum Pipeline-to-ship	194	DKK/tonne

Comparison of investment costs		
Truck-to-ship bunkering		
Event 1	22 050	KDDK
Event 2	14 700	KDDK
Ship-to-ship bunkering		
Event 1	45 244	KDDK
Event 2	45 244	KDDK

Considering the cost of e-ammonia per tonne for the investment period of 30 years which must be accounted for to reflect investment costs for the estimation of price per tonne. Included investment costs are those of Port of Esbjerg which embraces the e-ammonia storage tank and bunkering solutions. The following levelized cost of e-ammonia equation is used to calculate the costs of e-ammonia per tonne, cf. *Equation 1*:

$$LCOA = (\frac{\sum_{t=30}^{n}\left(\frac{OPEX_t}{(1+i)^t}\right)) - CAPEX_{t=0})}{Total\ e - a\ distribtion})$$

All operational costs for each alternative are processed as expenditures that must be financed by selling e-ammonia to ships. Incorporated are costs of e-ammonia production that involve prices on consumed electricity according to spot market electricity prices and additional, variable operations and maintenance costs related to e-ammonia production and transportation by truck to the storage, cf. Table 4. Total e-ammonia distributed for the bunkering infrastructure alternatives refers to the annual production and stored e-ammonia of 12 134 tonnes that is timed by the number investment lifetime of 30 years.

Results on the levelized cost of e-ammonia and, additionally, the NPV of the investments are presented Table 12 distinguished for each alternative and event to indicate potential changes according to fixed and variable operations costs. Values are discounted by a factor of 5 %.

Table 12: NPV and LCOA results for alternative 1 and 2 for respectively event 1 and event 2 with an applied discount rate of 5 % for the investment period of 30 years. Calculations can be found in Appendix 2, "Feasibility Study Results".

	Alternative 1 Event 1	Alternative 1 Event 2	Alternative 2 Event 1	Alternative 2 Event 2
NPV [MDKK]	-140	-136	-174	-174
LCOA [DKK/tonne]	-386	-373	-477	-477

The levelized cost of e-ammonia points that the e-ammonia selling price per tonne in Port of Esbjerg can be settled cheapest for the truck-to-ship bunkering alternative. It scores the lowest costs at respectively 386 DKK/tonne e-ammonia and 373 DKK/tonne e-ammonia for the two events that are respectively 91 DKK/tonne and 104 DKK/tonne cheaper compared with the ship-to-ship bunkering alternative. Consequently, the truck-to-ship score highest feasibility results in conjunction with the second feasibility criteria.

However, none of the alternatives provides a competitive price to the estimated marine fossil fuel price at 27 DKK/tonne. The lowest measured e-ammonia per tonne for the truck-to-ship alternative is still almost 14 times more costly than the marine fossil fuel price. Hence, the risks related to the innovative technology investment are high due to current *market preferences* that are primarily orientated, enabling the lowest cost of bunker fuels (Appendix 5).

It triggers a dilemma whether the price of e-ammonia should be settled lower than the estimated levelized cost of e-ammonia to provide a competitive price on e-ammonia compared with the baseline or kept with the reliance on societal structures changing during the investment period that can change the foundation for prices on bunker fuels. In connection with that, prospected changes are discussed on societal structures related to the critical case study context in connection with a sensitivity study that examines the sensitivity of applied technical and economic variables of the feasibility study to clarify the consequences of changing these variables that might do it for the next 30-years.

9. Sensitivity Study & Discussion

Please find Appendix 2; "Sensitivity Study" and "Sensitivity Study Results" as reference to presented results in this chapter.

The sensitivity study constitutes two elements. One element embraces an examination of the sensitivity of applied parameters and assumptions for the feasibility study results that follow the procedure of modifying numeric values by percentage deviations presented in Section 7.11. The other concerns discuss conditions and changes in societal structures that might influence the feasibility study results. The sensitivity study and discussion end with a reflection on how the results be used to support the development of Nordic green shipping corridors.

Due to uncertainties related to the investment period, the results of the baseline and alternatives are potentially sensitive to changes in applied parameters and assumptions. Hence, variable parameters and assumptions are modified to identify the consequences that respective change inflicts on the results. Variable parameters that are investigated concern:

- E-ammonia demand
- E-ammonia production demand and hours
- E-ammonia production prices according to electricity prices
- Bunkering performance:
  - Flow rate
  - Distances
- Economic factors:
  - Variable costs
  - Discount rate
- EU ETS

The parameters are designated because they expect having a noticeable impact on the feasibility study results based on the performed analysis. The first investigated parameter is the e-ammonia demand.

9.1.1. E-ammonia Demand

The e-ammonia demand anticipates significantly influencing feasibility study results when changed because it determines the required e-ammonia production level and distribution amount. Following the sensitivity study methodology, total e-ammonia demand modifies by respectively + 40 % and -40 % because uncertainty related to future e-ammonia bunker demand in Port of Esbjerg can be assessed as highly sensitive to developing e-ammonia compatible ship designs. Changing the e-ammonia demand by + 40 % entails a total demand of 16 988 tonnes of e-ammonia annually and 7 281 tonnes of e-ammonia annually with a -40 % decline. Both measures include the security of supply measure of 10 %. (Appendix 2; "Sensitivity Study")

Results of increasing and decreasing the demand monthly are presented in Figure 12 and compiled by following the same methodology as for the feasibility study, cf. *Equation 5* and *Equation 6* (Appendix 1).

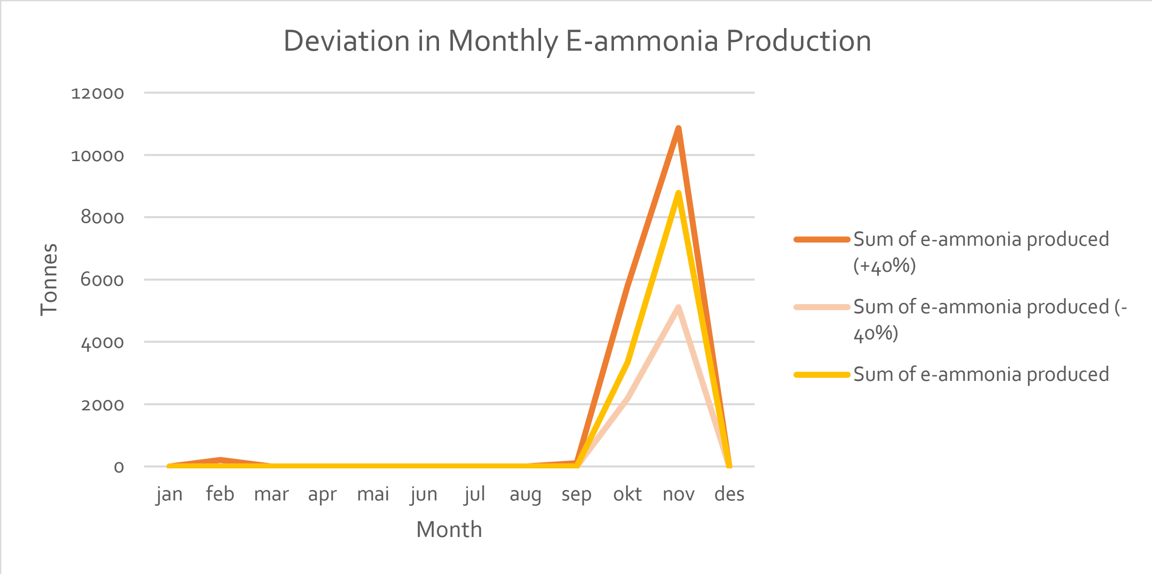


Figure 12: Consequences of changing e-ammonia production by +40% and -40% on monthly basis. The figure can be found in Appendix 2, "Sensitivity Study Results".

Increasing the e-ammonia demand by +40 % demonstrates that production of e-ammonia will occur in February and September, in conjunction with spot market electricity prices in 2021, which is not experienced for the feasibility study, cf. Figure 10. E-ammonia production also increases in November by 24 % more than for the feasibility study, which constitutes a peak production month already. Hence, according to the change, the e-ammonia storage tank must increase in size to meet annual demand since the production increases further in November and does not balance during the year. Excessive costs related to the e-ammonia storage tank, which constitutes 99 % of the total investment costs of the e-ammonia bunkering infrastructure, have costly consequences on the levelized cost of e-ammonia. Hence, lower production demand can foster decreased prices on e-ammonia for the alternatives following the principle of only procuring e-ammonia during hours with low electricity costs, at least for the case of this feasibility study.

9.1.2. Uncertainties related to Estimated E-ammonia Demand

Trends in expected e-ammonia demand per ship add further uncertainty to the validity of applied assumptions. Firstly, alternative fuel infrastructure, such as hydrogen and methanol, awaits implementation in Port of Esbjerg and potentially for bunkering purposes. According to Mr Pedersen, hydrogen will be supplied to the port by pipeline. Methanol is also distributed by pipeline but has yet to fulfil any bunkering purposes. (Appendix 5) Notably, the availability of methanol will impact estimations on the e-ammonia demand in Port of Esbjerg because of its high combability with the same ship types as e-ammonia, cf. Section 3.5. It places uncertainty on estimating the e-ammonia demand of included ship segments validly since a share of methanol operating ships might appear. It reflects competition from another *innovative technology* that might compete with e-ammonia to become the new *market and user preference* in society, adding complexity to measuring feasibility based on market competition.

On the other hand, it is inevitable that the Norwegian offshore supply shipping company, Eidesvik Offshore, bets on e-ammonia to transition its offshore vessel fleet (Eidesvik, 2023). However, the applied assumption that 100 % of all work/service ships that bunker in Port of Esbjerg will have a demand for e-ammonia in 2028 can be invalid in practice. According to Eidesvik Offshore's strategy, 60 % of their offshore work/service ships will consume ammonia (Eidesvik, 2023). Hence, the expected share of e-ammonia operating work/service ships in Port of Esbjerg might instead reflect the demand of – 40 % of the comprehended demand for the feasibility study in practice.

In contrast, the Finnish marine propulsion engine and energy market company, Wärtsilä, points out that dual-fuel solutions are a technological key enabler for decarbonising ships until 2050 (Hyvönen, 2023). It is a consequence of inadequate carbon-neutral fuel supplies and renewable energy adequacy globally that put pressure on the development of compatible ship engines for consuming different alternative fuels to enable security of supply (Hyvönen, 2023). This statement fosters a barrier and an opportunity to implement e-ammonia bunkering infrastructure in Port of Esbjerg. On one side, the demand becomes complex to predict because ships can consume different alternative fuels. It can lead to costly investment, e.g., in storage capacity that might be unnecessary due to other fuel demands. However, there will be a demand for e-ammonia, and the port can accommodate flexibility to provide low-price fuels according to supply adequacy, improving the feasibility. The development of dual-fuel engines can, consequently, be interpreted as a potential evolving technology in the *technological regime* that regulates the demand for e-ammonia bunkering infrastructure.

9.1.3. E-ammonia Production and Prices

Changes in e-ammonia demands impact prices since production hours regulates according to fluctuating spot market electricity prices. Prices per tonne of e-ammonia, in conjunction with the +40 % and – 40 % modification of production demand, are shown in Figure 13.

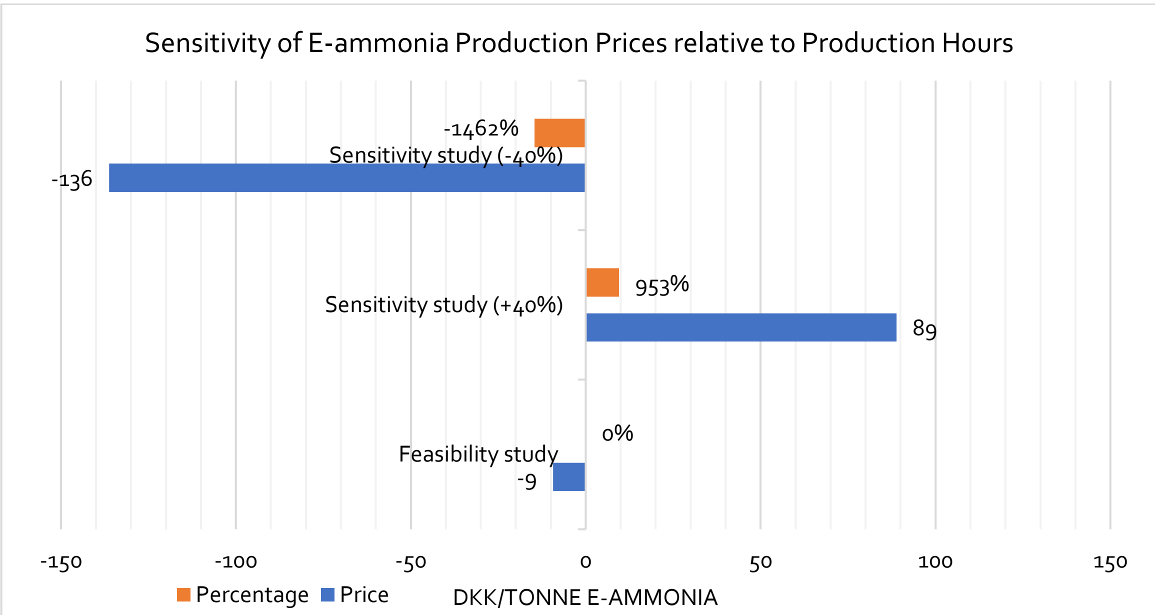


Figure 13: Deviation in e-ammonia prices per tonnes relative to increased (+ 40 %) and decreased (- 40 %) of the e-ammonia production. The figure can be found in Appendix 2, "Sensitivity Study Results".

Prices decrease by respectively -1 462 % for the -40 % decline and increase in comparison less with 953 % for the + 40 % incline. The condition of fluctuating electricity prices is conspicuous in the results since the percentage deviation in prices does not follow the +40 % and -40 % deviation in e-ammonia production. It underlines the complexity of adopting a required gap on electricity prices for e-ammonia production to provide low prices on e-ammonia for ships that bunker in the Port of Esbjerg because prices will differ unpredictably and non-linear to the production size. Adopting a fixed price requirement on spot market electricity prices can also challenge supply security.

9.1.4. Fixed Prices on E-ammonia relative Production

Therefore, fixed long-term price contracts should be considered since these can provide stable prices on e-ammonia. It emphasises by Mr Bergmann that fixed long-term contracts on e-ammonia, negotiated between e-ammonia suppliers and ship companies, is a fundamental enabler for investment in e-ammonia production. However, for ship companies, it makes it easier to predict bunker prices as for today's marine fossil fuel market. (Appendix 6) It reflects a techno-economic feasibility measure building on the common interest of consumers at the regime level and e-ammonia suppliers at the niche level for utilising the functionality of the innovative technology that can improve its feasibility but in contrast to the theoretical framework.

Additionally, determining prices of e-ammonia per tonne only based on production costs of the supplied amount to Port of Esbjerg only can be unreliable for the size of fixed prices that the e-ammonia supplier might settle based on total annual production. Therefore, it is calculated based on another production principle that concerns only utilising green electricity from the power grid, which can further be a grid stability measure (Appendix 6). It inspires by Elomatic's optimisation model of e-ammonia production at a planned e-ammonia plant in Naantali, Finland, which shows that production hours can reach 6 000 - 7 000 annually based on that principle (Appendix 6). If 7 000 production hours reach annually, it will encompass a productional profile of the Høst PtX Esbjerg e-ammonia plant, as visualised in Figure 12. For the simulation, hourly production capacity is limited to 70 % to attempt a reliable estimate and still follow production during hours with the lowest electricity prices that ordinarily characterises by high renewable electricity share (Energinet, 2022) (Appendix 2; "E-ammonia Production").

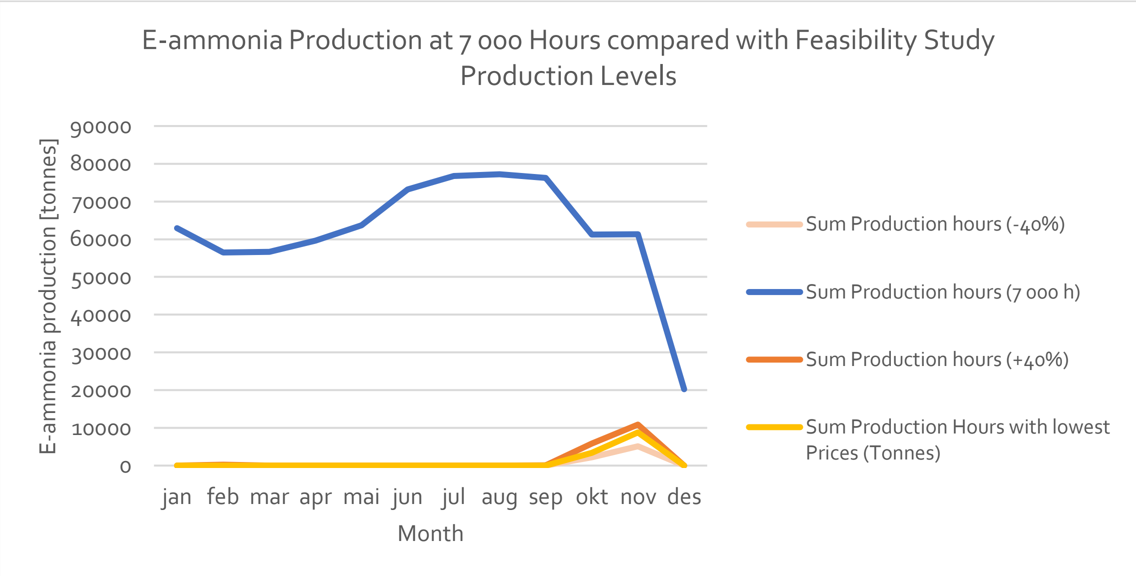


Figure 14: Difference between e-ammonia production level in case of having 7 000 operation hours for the e-ammonia production. The figure and simulations can be found in Appendix 2, "Sensitivity Study Results".

Figure 14 highlights that e-ammonia will be produced during the year continuously but with a recognisable decline in December for the respective year, 2021. Although e-ammonia produces during hours with higher prices than considered for the feasibility study, the price of e-ammonia per tonne turns 0,46 DKK/tonne e-ammonia, which is less than for the scenario with a +40 % increase in e-ammonia demand. Hence, considering total annual costs can provide fewer risks related to e-ammonia prices per tonne than based on smaller production capacities.

In 2022, an energy crisis emerged that fostered rapidly increasing energy prices (IEA, 2022). Considering price differences of a year with extreme prices can, nevertheless, indicate uncertainty to the adequacy of price levels of fixed long-term contracts. Figure 15 presents how production prices compared with the respective produced amount of e-ammonia deviate monthly. Results are based on the 7 000 hours production level and 2022 electricity prices from Energinet (Energinet, 2023).

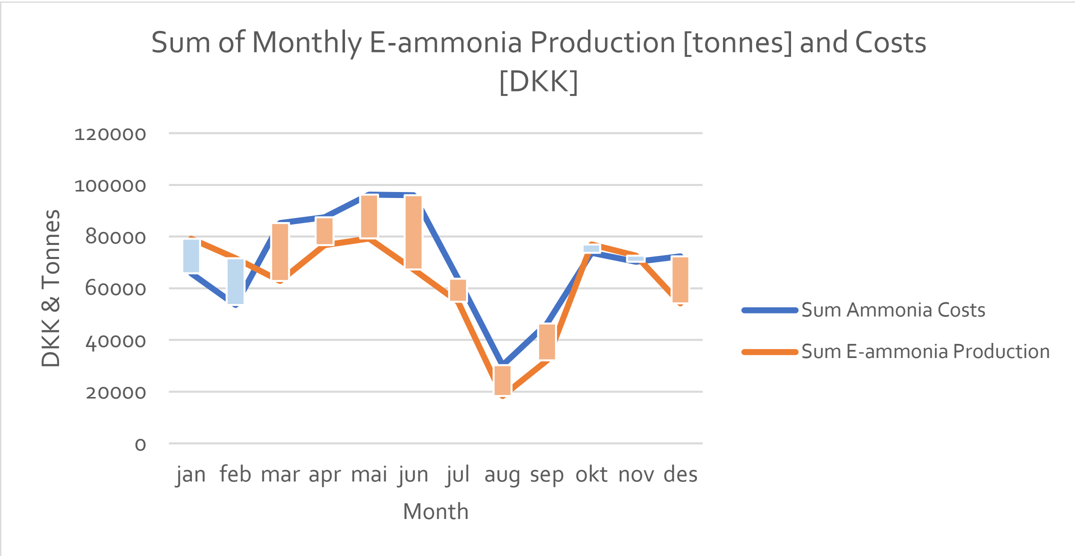


Figure 15: Monthly e-ammonia production and associated prices relative to 2022 electricity prices from Energinet (Energinet, 2023). The figure is compiled in Appendix 2, "Sensitivity Study".

The figure indicates that the cost of e-ammonia during most of the month is higher than the production in tonnes. It implies costs above 1 DKK/tonne with highest hourly production cost at 2 410 DKK/MWh. In case, fixed prices settle based on average costs, the price of e-ammonia production will be 1,2 DKK/tonne. (Appendix 2; "Sensitivity Study") Additionally, it points out that production costs during 2022 resulted in the average price per tonne of e-ammonia being three times higher compared with the 0,46 DKK/tonne for 2022. It would entail a levelized cost of e-ammonia for the e-ammonia bunkering infrastructure at -391 DKK/tonne e-ammonia for the truck-to-ship event 1 and -724 DKK/tonne e-ammonia for the ship-to-ship event 1 and 2.

One could consider changing the investment costs of the alternatives to identify related consequences. However, since the e-ammonia storage tank constitutes, as previously mentioned, 99 % of the total of the considered investment costs for alternatives 1 and 2, it underlines already that the levelized cost of e-ammonia is primarily sensitive to the price of e-ammonia storage tank under current conditions.

The sensitivity of results related to changes in the discount rate is, on the other hand, important to mention for considering the impact of the favoured interest rate of the investment. The Danish Ministry of Finance discount rate recommends applying an interest rate of 3,5 % for an investment with a lifetime between 0 and 35 years (Finansministeriet, 2021). Consequently, the sensitivity of regulating the discount rate to respectively 3,5 % and 8,5 % is examined with results presented in following Table 13.

Table 13: Results of changing the discount rate to respectively 3,5 % and 8,5 % for the investment of both alternative 1 and 3. Please notice that some of the applied data are discounted values (5 %) in respective studies, which adds sensitivity to the results (Nayak-Luke et.al., 2021). Associated calculations can be found in Appendix 2; "Feasibility Study".

	Alternative 1 Event 1	Alternative 1 Event 2	Alternative 2 Event 1	Alternative 2 Event 2
NPV [MDKK]	-140	-136	-174	-174
LCOA [DKK/tonne]	-386	-373	-477	-477
NPV [MDKK] (3,5 %)	-150	-144	-190	-190
LCOA [DKK/tonne] (3,5 %)	-412	-397	-522	-521
Difference [%]	94 %	94 %	92 %	92 %
NPV [MDKK] (8,5 %)	-126	-123	-149	-149
LCOA [DKK/tonne] (8,5%)	-346	-337	-410	-410
Difference [%]	112 %	111 %	117 %	116 %

Changing the discount rate shows recognisable changes in the net present value and the levelized cost of e-ammonia of the two alternatives. Changing the discount rate leads to the highest increase of LCOA for ship-to-ship bunkering that inclines by 16-17 % with a discount rate of 8,5 %, implying the sensitivity related to the discount rate for the ship-to-ship bunkering alternative. For an investor, it would be interpreted as an investment associated with high risks that can disincentivise the investment.Sensitivity related to the bunkering performance of the two alternatives is investigated besides economic parameters.

9.1.5. Bunkering Performance

Regarding bunkering performance, ship-to-ship bunkering has the highest bunkering performance compared to truck-to-ship. Consequently, a comparison of the sensitivity of technical parameters related to both alternatives is analysed. Nevertheless, the capacity is not emphasised for ship-to-ship bunkering because it can carry a higher capacity than peak demand for both events. However, it must be accounted for that the capacity size can be less, enabling lower investment costs and increasing total daily peak demand might show less feasibility of the technique since time spent on refuelling by the loading arm is estimated to take 28 hours, which is a recognisable sensitivity aspect (Appendix 2; "Bunkering Alternatives").

Instead, distance to quays modifies by respectively +40 % and -40 % for each alternative for event 1 to identify changes in variable operational costs of both alternatives. Results of changing distances by + 40 % and – 40 % are shown in Figure 16.

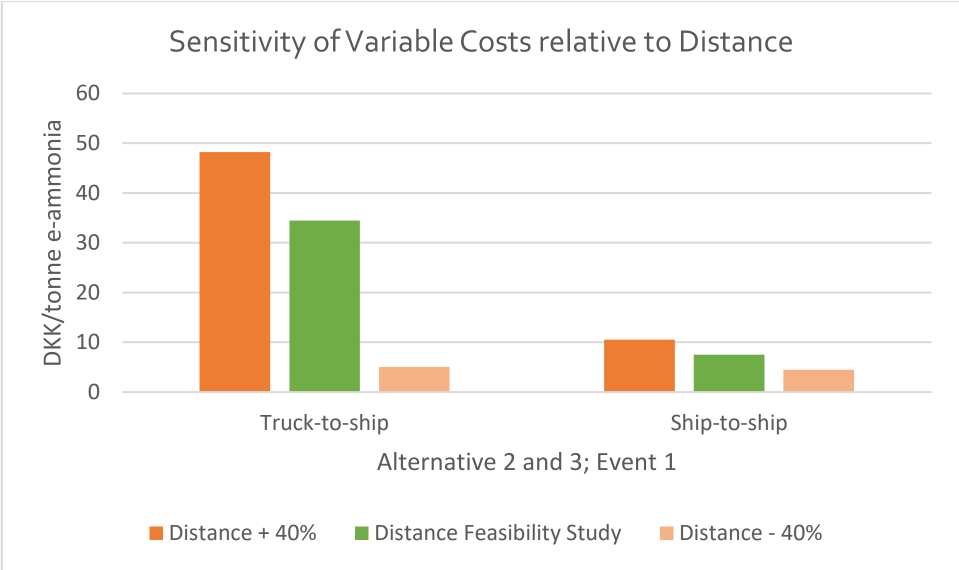


Figure 16: Sensitivity of variable costs relative to changing the distance per roundtrip by + 40 % and - 40 % for event 1. The figure can be found in Appendix 2, "Sensitivity Study Results".

The results indicate that, mainly, the truck-to-ship alternative is most sensitive to changes in distance. Decreasing the distance by – 40 % reduces the variable operational cost to 5 DKK/tonne e-ammonia compared with 34 DKK/tonne in the feasibility study. It underlines that truck-to-ship reaches the highest bunkering performance at the shortest distances, whereas variable costs of ship-to-ship bunkering do not change recognisably. Though, estimating the levelized cost of e-ammonia based on variable costs of one event might imply inadequacy or overestimation of average costs related to annual distribution networks.

Flow rate is another sensitive parameter of the two alternatives as it determines the time spent refuelling the ship with e-ammonia. The flow rate is only regulated to change by +20 % and -20 % because it is considered invalid that the truck's flow rate will increase by more, given its size. For ship-to-ship bunkering, however, the flow rate can increase by more than 20 % (Yang & Lam, 2023). Results are shown in Figure 17.

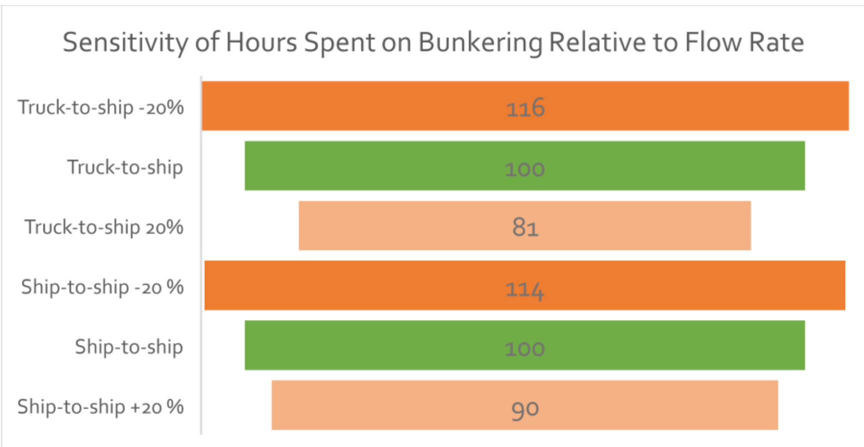


Figure 17: Sensitivity of hours spent on performing bunkering relative to flow rate by respectively +20 % and - 20% for alternative 1 and 2 for event 1. The figure can be found in Appendix 2, "Sensitivity Study Results".

Compared to previous parameters, some consistency in deviations can be identified for regulating the flow rate. It indicates that less time spends for all alternatives in case the flow rate increases as it is an index measure of time spent for the feasibility study. The truck-to-ship alternative once again proves more sensitive to changes in flow rate, which will result in only two trucks required for the investment in event 1 because time spent reaches 6,3 hours, which is more than an hour less than allocated for bunkering at 7,5 hours, cf. Section 8.3.1.

9.1.6. Other Port Bunkering Alternatives and Perspectives

Broadening the scope of the feasibility study can prove the feasibility of another alternative: pipeline-to-ship bunkering. As presented in Map 8, quay 712 and 714 are closely placed to the e-ammonia storage tank in Port of Esbjerg. Investigating the feasibility of implementing pipeline-to-ship bunkering could be feasible for short distances compared with ship-to-ship bunkering, which underlines another alternative technology that can be used in the critical case study context and competitive with clarified alternatives.

The mobile alternatives must also be accounted for, whether they can utilise road or water connections due to other traffic patterns. Particularly for the truck-to-ship alternative that currently points to using public road connections. It implies high sensitivity to not just bunkering performance results but also to potential safety risks that might influence the *user value* of the alternative.

Mainly, managing and handling transportation and distribution of ammonia with high safety measures are of concern in Port of Rotterdam. According to the director of regulation at the regional environmental protection agency, Mr Daan Molenaar, in the Netherlands, conducting feasibility studies that indicate sufficient safety conditions related to storing, transporting and utilising ammonia at large-scale in ports is incremental before use (Collins, 2023). High proximity to local cities can entail comprehensive environmental and health impacts on citizens and the environment (Collins, 2023). It underlines a potential discrepancy with standard regulations and measures on the regime-level that places a barrier to the implementation of studied e-ammonia bunkering infrastructure solutions.

Consequently, Mr Molenaar suggests transporting ammonia and hydrogen by pipelines instead trucks, inland boats or trains, which is the procedure today (Collins, 2023). It questions the decision to transport e-ammonia to the storage tank by truck from the Høst PtX Esbjerg e-ammonia plant, which might as well not fulfil current *safety regulations* because of the proximity to the public.

Nevertheless, ship-to-ship bunkering can entail limited risk related to the bunkering of e-ammonia. A study by DNV stipulates that bunker supply ships can be designed to prevent and reduce the risk of rupture or leakage during bunkering on third parties such as citizens, industries, and the environment (Zakariyya et.al., 2021). The statement about reduced safety risks is supported by respondent Mr Pedersen, who emphasises that ship-to-ship bunkering is safer to use compared with trucks because bunkering performs away from the quay, which mitigates risks related to mounting and dismounting the hose between the bunker vessel and receiving ship that constitutes high risk due to frequent performance (Appendix 5). Hence, ship-to-ship can also provide security measures.

9.1.7. Baseline and Societal Context

The baseline is the most economically feasible solution of the framed bunkering infrastructure options without considering potential reinvestment needs. However, the price of marine fossil fuels will increase starting in 2024, with the adoption of shipping for the EU ETS (DNV, 2023). By 2026, two years before the initial investment in 2028, prices are expected to double because of a 100 % increase in carbon-taxes for bunker consumption, which includes processed ship segments (DNV, 2023). If this scenario reinforces the assigned price level increase, the price of marine fossil fuels will turn out as in Table 14 compared to the levelized cost of e-ammonia of the feasibility study.

EU ETS Price + 100 %	Truck-to-ship (Event 1)	Ship-to-ship (Event 1)
LCOA [DKK/tonne]	386	477
Marine fossil fuels + 100 % [DKK/tonne]	55	55
Compared with LCOA	14 %	12 %

According to prices on e-ammonia estimated based on e-ammonia bunkering infrastructure alternatives in Port of Esbjerg, the marine fossil fuel prices will only constitute respectively 14 % and 8 % of the e-ammonia price related to event 1. It implies that other policy measures must be adopted or the price increased for enacting competitiveness of e-ammonia as bunker fuel by 2028 and abating the current structure of the *political* and *market regime* that continues to place a barrier on the niche development. Nevertheless, the adoption of ships in the EU ETS can be comprehended as enabling a window of opportunity for e-ammonia as bunker fuel to become adopted in current *consumer practices* in the regime.

However, the development of niches can be stimulated by more than demonstrating the techno-economic feasibility of innovative projects. It can be emphasised as contributing with knowledge on the complexity of implementing the infrastructure and how different parts of the infrastructure impact bunkering performance but in particular, the economic barrier that the project team of HOPE stresses most widespread for the introduction of e-ammonia and other alternative solutions, cf. Section 3.2.2. It underlines that the theory of regime-levels placing barriers for innovative technologies to reach maturity is applicable and that facilitating an implementation of techno-economic feasible e-ammonia is difficult to manage not just in Port of Esbjerg, but in other niche cases as well.

9.2. Summary

The sensitivity study proves sensitivity to several techno-economic parameters of the feasibility study. Primarily, the e-ammonia demand impact results as it is the determining factor for the capacity of the e-ammonia bunkering infrastructure. However, it is difficult to predict due to the technological development of new ship engines and other alternative fuels. The following principle for e-ammonia production according to the lowest spot market electricity prices might be a parameter not showing beneficial results on the techno-economic feasibility. Fixed long-term contracts for e-ammonia prices can enable investment and provide security of supply and predictable prices of fuels instead to benefit the concerned audience of the feasibility study. The sensitivity of the truck-to-truck bunkering alternative highlights that it is most sensitive to variable changes such as distances and regulated flow rates. On the other hand, ship-to-ship bunkering does provide a stable but costly alternative, which feasibility, however, must be further studied to account for the sensitive time required for refuelling. Alternatives. High costs related to the e-ammonia bunkering infrastructure are primarily a result of high investment costs that leads to uncompetitive prices of e-ammonia compared with marine fossil fuels. Additionally, the regulated future price of marine fossil fuels must be revised to improve the techno-economic feasibility. It highlights that the techno-economic feasibility is determined by current societal structures favouring existing bunkering infrastructure.

10. Conclusion

Implementing e-ammonia bunkering infrastructure techno-economic feasibly in Port of Esbjerg to support Nordic green shipping corridors concludes complex and challenged by the competitiveness of marine fossil fuels. This conclusion is based on a compiled feasibility study, where two e-ammonia bunkering alternatives are investigated: truck-to-ship and ship-to-ship. These two alternatives constitute parts of an investigated e-ammonia bunkering infrastructure that consists of production, transportation, storage, and bunkering.

The two alternatives are compared to each other and a baseline that comprises existing marine fossil fuel bunkering infrastructure and ship activities in the Port of Esbjerg. The baseline provides information on the functionality of existing bunkering infrastructure that must be fulfilled by e-ammonia bunkering infrastructure as an innovative technology to be assessed as feasible. Demanded functionality is summarised into two feasibility criteria: high bunkering performance and low cost of e-ammonia per tonne.

The bunkering performance of e-ammonia truck-to-ship and ship-to-ship prove convincing results under different conditions. Truck-to-ship bunkering can be assessed as suitable for performing bunkering of ships with limited demands and short distances between the e-ammonia storage tank and quays. It is because truck-to-ship bunkering is sensitive to variable costs with its limited capacity of e-ammonia per roundtrip. On the contrary, ship-to-ship bunkering has high bunkering performance due to its larger capacity and flow rate, making it less sensitive to variable costs. However, investment costs are higher compared with the truck-to-truck bunkering alternative, resulting in a higher price for using ship-to-ship bunkering of e-ammonia.

The competitiveness of e-ammonia bunkering infrastructure concludes unconvincing related to price. It is based on a comparison of estimated e-ammonia price per tonne and current considered price on marine fossil fuels at 27 DKK/tonne. The price on e-ammonia is estimated based on a modified levelized costs of e-ammonia calculation. Costs included in the calculation are results of simulated techno-economic parameters of the e-ammonia bunkering infrastructure in Port of Esbjerg in a prepared simulation energy model. With a considered investment year in 2028, lifetime of 30 years, and a discount rate of 5 %, the estimated prices e-ammonia by truck-to-ship bunkering is 373 – 386 DKK/tonne based on two events. For ship-to-ship bunkering, the price estimates at - 477 DKK/tonne, implying that none of them provide competitive prices to marine fossil fuels.

The bunkering performance of truck-to-ship and ship-to-ship bunkering for e-ammonia prove convincing results but with different characteristics. Truck-to-ship bunkering can be assessed suitable for bunkering purposes in ports with small bunker demands per ship and short distances between the e-ammonia storage tank and quays. It is because truck-to-ship bunkering is sensitive to variable costs with its small capacity. On the contrary, ship-to-ship bunkering has high bunkering performance due to its higher capacity and flow rate, making it less sensitive to variable costs. However, the investment cost is higher compared with the truck-to-truck alternative, resulting relative costlier price of using ship-to-ship bunkering of e-ammonia.

The competitiveness of e-ammonia bunkering infrastructure concludes unconvincing related to price. It is based on a comparison of estimated e-ammonia price per tonne and current considered price on marine fossil fuels at 27 DKK/tonne. The price on e-ammonia is estimated based on a modified levelized costs of e-ammonia calculation. Costs included in the calculation are results of simulating techno-economic parameters of the e-ammonia bunkering infrastructure in Port of Esbjerg in compiled an energy model. With a considered investment year in 2028, lifetime of 30 years, and a discount rate of 5 %, the estimations proves that the cost of e-ammonia by truck-to-ship bunkering is 373 – 386 DKK/tonne. For ship-to-ship bunkering, the price estimates at - 477 DKK/tonne, implying that none of them provide competitive prices to marine fossil fuel as bunker fuel.

With that emphasised, the results underline current research assessing that a primary barrier lies within societal structures, such as policy measures and regulations, for the innovative technology to be operated. Low prices on marine fossil fuels, costly and risky investments in e-ammonia bunkering infrastructure require political action to accelerate the implementation.

It complicates the execution of a techno-economic feasible implementation of e-ammonia bunkering infrastructure in Port of Esbjerg as a niche context. However, specific techno-economic parameters can be considered to facilitate improved feasibility. One important parameter is to optimise a local e-ammonia storage tank since it constitutes approx. 99 % of total investment costs, under the scope of this feasibility study. It applies to a refrigerated e-ammonia storage tank. Besides, fixed price contracts on produced e-ammonia according to full-production capacity and investment costs can enable a feasible investment for the e-ammonia supplier and offer predictable and stable prices for consumers. Optimising site location of the e-ammonia storage tank for shortening transport distances among quays used for bunkering or selecting bunkering solutions for the cases mentioned above also have an impact on the techno-economic feasibility.

Additionally, demonstrating the functionality of e-ammonia bunkering performance in ports that can be conceptualised as constituting niches in society can combined point to the necessity of solving common barriers for putting pressure on changing market conditions, user preferences, policy and regulations in society. It can also be accomplished by sharing knowledge of executed projects to inform about the functionality of e-ammonia bunkering alternatives.

However, the results might only be applicable to some ports, given the phenomena characterising Port of Esbjerg as a critical case study. Its future proximity to e-ammonia supplies, ship activities, designated potential energy hub of Nordic green shipping corridors, and as part of the TEN-T might support a feasible implementation, more than for other Nordic ports. However, the reality of society constituting different realities lays a general need for demonstrating feasible solutions for e-ammonia bunkering infrastructure in different contexts. Accomplishing it for Port of Esbjerg can still provide learnings and considerations helpful in accelerating the implementation of e-ammonia bunkering infrastructure in the Nordic Region to support the development of Nordic green shipping corridors.

11. Recommendations for Further Investigation

Based on the techno-economic feasibility study res-ults, conclusion, and limitations within the scope of the study, recommendations for further investigating the feasibility of e-ammonia bunkering infrastructure in Port of Esbjerg and other Nordic Ports are shared.

Firstly, it recommends investigating regulatory conditions concerning implementing the demonstrated e-ammonia bunkering infrastructure in Port of Esbjerg. In connection with this, an Environmental Impact Assessment suggest compiled where environmental consequences can be identified and evaluated regarding their impact on vulnerable actors or conflicts with existing spatial usages in Port of Esbjerg. It is mainly related to designated sites of the e-ammonia storage tank, transportation and bunkering routes in Port of Esbjerg that might be in discrepancy with spatial and safety regulations.

Other bunkering alternatives, such as pipeline-to-ship bunkering, recommend investigating the potential of in addition. It can also be included in an optimisation model where the synergy between the three existing bunkering solutions in ports to discover an optimal bunkering performance at the lowest costs with a combination of those. Transferring e-ammonia from the Høst PtX Esbjerg e-ammonia plant by truck-to-storage can, in that regard, be compared with pipeline-to-storage or ship-to-storage alternatives to clarify the one enabling the lowest costs of the e-ammonia bunkering infrastructure.

It leads to a recommendation to compile a study that considers logistics on bunkering performance concerning other traffic in Port of Esbjerg that might place a barrier on the bunkering performance of the mobile bunkering alternatives. With this, investigating quays with the potential to become junctions of e-ammonia bunkering can be completed to discover the consequence of price, logistics, safety, and bunkering performance of doing so.

The competitiveness of e-ammonia bunkering infrastructure and marine fossil fuel bunk-ering can also be identified by comparing bunkering performance differences and related port dues, service costs, etc., for ships. It also includes assessing costs related to qualifying employees for dealing with e-ammonia due to its chemical properties.

12. List of Reference

Arctic Council, 2021. *Navigating The Future of Artic Shipping.* [Online]
Available at: https://arctic-council.org/news/navigating-the-future-of-arctic-shipping/

Arizona State University, 2023. *What is the Difference Between Google Scholar and Google?.* [Online]
Available at: https://asu.secure.force.com/kb/articles/FAQ/What-is-the-difference-between-Google-Scholar-and-Google

Baresic, D. & Palmer, K., 2022. *CLIMATE ACTION IN SHIPPING - Progress towards Shipping's 2030 Breakthrough,* Report: UMAS, Getting to Zero Coalition, Race to Zero, Lloyd's Register.

Brinkmann, S. & Kvale, S., 2007. *Doing Interviews.* 2nd Edition: SAGE.

Brynolf, S. & et.al., 2023. *Life Cycle Assessment of Marine Fuels in the Nordic Region - Task 1C,* Gothenburg: Chalmers University of Technology and IVL Swedish Environmental Research Institute.

Byrne, D., 2023. *Data Collection.* [Online]
Available at: https://doi.org/10.4135/9781526408563

CFI Team, 2023. *What is a Sensitivity Analysis.* [Online]
Available at: https://corporatefinanceinstitute.com/resources/financial-modeling/what-is-sensitivity-analysis/

Collins, L., 2023. *Hydrogen 'nightmare' - Dutch agency expresses fears of toxic clouds and deaths from large-scale ammonia imports.* [Online]
Available at: https://www.hydrogeninsight.com/transport/hydrogen-nightmare-dutch-agency-expresses-fears-of-toxic-clouds-and-deaths-from-large-scale-ammonia-imports/2-1-1409047

Color Line, 2022. *Towards zero emission for fast passenger ferry.* [Online]
Available at: https://greenshippingprogramme.com/pilot/towards-zero-emission-for-fast-passenger-ferry/

CPMR, 2023. *The TEN-T review: a welcome but perfectible proposal.* [Online]
Available at: https://cpmr.org/trans-european-transport-network/#1643030839010-2c82cd38-cc9a

Danish Energy Agency, 2017. *Technology Data for Energy Transport,* Version number: 0004: Danish Energy Agency & Energinet.

Danish Energy Agency, 2017. *Technology Data for Renewable Fuels,* Version number: 0010: Danish Energy Agency and Energinet.

Danish Energy Agency, 2019. *Export cables, cable route survey report,* https://ens.dk/sites/ens.dk/files/Vindenergi/3308_scope_description_-_export_cables_cable_route_survey.pdf: Danish Energy Agency.

Danish Energy Agency, 2023. *Making a Difference Every Day.* [Online]
Available at: https://ens.dk/en

Davies, C., 2022. *A Quick Guide to Quantitative Research in the Social Sciences,* https://repository.uwtsd.ac.uk/id/eprint/2017/1/A%20quick%20guide%20to%20quantitative%20research%20in%20the%20social%20sciences.pdf: Wales Academy of Professional Practice and Applied Research, University of Wales Trinity Saint David.

Dawson, D. J., 2022. *Trends in Arctic and Antarctic Vessel Activity.* Polar Maritime Seminar by Nautical Institute, International Maritime Organization, and Environment, Society & Policy Group(London): https://wwwcdn.imo.org/localresources/en/About/Events/Documents/Polar%20Maritime%20Seminar%202022%20presentations/Day%201/01_Jackie%20Dawson-Trends%20in%20the%20Anctic%20and%20Antarctic%20Vessel%20Activity.pdf.

den Bosch, S. V., 2010. *Transition Experiments: Exploring societal changes towards sustainability.* Erasmus University Rotterdam: ISBN 978-90-8559-057-6.

DNV, 2019. *Comparison of Alternative Marine Fuels,* https://safety4sea.com/wp-content/uploads/2019/09/SEA-LNG-DNV-GL-Comparison-of-Alternative-Marine-Fuels-2019_09.pdf: DNV.

DNV, 2023. *EU ETS: Preliminary agreement to include shipping in the EU's Emission Trading System from 2024.* [Online]
Available at: https://www.dnv.com/news/eu-ets-preliminary-agreement-to-include-shipping-in-the-eu-s-emission-trading-system-from-2024-238068

DNV, 2023. *Pilots.* [Online]
Available at: https://greenshippingprogramme.com/pilots/

Döringer, S., 2020. *The problem-centred expert interview'. Combining qualitative interviewing approaches for investigating implicit expert knowledge,* Vienna, Austria: Routledge Taylor & Francis Group.

Edomah, N. & et.al., 2017. *Influences on energy supply infrastructure: A comparison of different theoritical perspectives,* http://dx.dori.org/10.1016/j.rser.2017.05.072: Elsevier Ltd..

Edquist, C., 1997. Systems of Innovation Approaches - Their Emergence and Characteristics. In: *Systems of Innovation: Technologies, Institutions, and Organisations.* Abingdon: A Cassell imprint, pp. pp. 1 -15.

Eidesvik, 2023. *Viking Energy with ammonia-driven fuel cell.* [Online]
Available at: https://eidesvik.no/viking-energy-with-ammonia-driven-fuel-cell/

Eidesvik, 2023. *Viking Energy with ammonia-driven fuel cell.* [Online]
Available at: https://eidesvik.no/viking-energy-with-ammonia-driven-fuel-cell/

ELOMATIC, n.d. *Visions of Tomorrow – Engineered Today.* [Online]
Available at: https://blog.elomatic.com/fi/?post_type=blogauthor&p=2541
[Accessed 01 06 2023].

Energinet, 2022. *Forventet udvikling i Energinets eltariffer,* Dok. 14/01334-105 : Energinet.

Energinet, 2023. *Elspot Prices.* [Online]
Available at: https://www.energidataservice.dk/tso-electricity/Elspotprices

Energinet, 2023. *Energy Data.* [Online]
Available at: https://en.energinet.dk/Electricity/Energy-data/

Equinor, 2022. *Ammonia powered tanker.* [Online]
Available at: https://greenshippingprogramme.com/pilot/ammonia-powered-tanker/

Esbjerg, P., 2023. *Prices.* [Online]
Available at: https://portesbjerg.dk/en/port-services/prices
[Accessed 01 06 2023].

espg.io, 2023. *EPSG:25832 - ETRS89/ UTM zone 32N.* [Online]
Available at: https://epsg.io/25832

European Commission, 2023. *Mobility and Transport.* [Online]
Available at: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t/ten-t-revision_en

European Commission, 2023. *Reducing emissions from the shipping sector.* [Online]
Available at: https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en

European Council, 2023. *FuelEU Maritime initiative: Provisional agreement to decarbonise the maritime sector.* [Online]
Available at: https://www.consilium.europa.eu/en/press/press-releases/2023/03/23/fueleu-maritime-initiative-provisional-agreement-to-decarbonise-the-maritime-sector/

Eurostat, 2018. *Glossary: Tonnes of oil equivalent (toe).* [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Tonnes_of_oil_equivalent_(toe)

Eurostat, 2022. *Glossary: Short sea shipping (SSS).* [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Short_sea_shipping_(SSS)

Eurostat, 2023. *Welcome to Eurostat - 70 years of high-quality statistics and data on Europe.* [Online]
Available at: https://ec.europa.eu/eurostat

Faber, J. & et.al., 2021. *Fourth IMO Greenhouse Gas Study 2020*,
https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf: International Maritime Organization.

Falbe-Hansen, T., 2023. *Denmark's Energy Islands.* [Online]
Available at: https://ens.dk/en/our-responsibilities/energy-islands/denmarks-energy-islands

Fernando, J., 2023. *Net Present Value (NPV): What It Means and Steps to Calculate It.* [Online]
Available at: https://www.investopedia.com/terms/n/npv.asp

Flyvbjerg, B., 2010. Fem misforståelser om casestudiet. In: *Kvalitative metoder.* Hans Reitzels forlag:
https://www.researchgate.net/publication/244485915_Fem_misforstaelser_om_casestudiet, pp. pp. 463-487.

Frithiof, N., 2023. *About the Project.* [Online]
Available at: https://futurefuelsnordic.com/about-us/

Frithiof, N., 2023. *Nordic Roadmap - Future Fuels for Shipping.* [Online]
Available at: https://futurefuelsnordic.com/about-us/

Gandhi, U., 23. *Georeferencing Topo Sheets and Scanned Maps.* [Online]
Available at: http://www.qgistutorials.com/en/docs/georeferencing_basics.html

Geels, F. W., 2004. Understanding system innovations: a critical literature review and a conceptual synthesis. In: *System Innovation and the Transition to Sustainability - Theory, Evidence and Policy.* Edward Elgar : ISBN 1 84376 683 3, pp. 19 - 47.

Geldof, 2023. *Cold ammonia storage tank.* [Online]
Available at: https://www.geldof.be/?portfolio=cold-ammonia-storage-tank

Genus, A. & Coles, A.-M., 2008. *Rethinking the multi-level perspective of technological transitions*, DOI: 10.1016/j.respol.2008.05.006: Elsevier.

Gibbens, S., 2019. *The Artic Ocean, explained.* [Online]
Available at: https://www.nationalgeographic.com/environment/article/arctic-ocean

Global Maritime Forum and Mckinsey & Company, 2022. *Green Corridors: Definitions and Approaches*,
https://www.globalmaritimeforum.org/content/2022/08/Discussion-paper_Green-Corridors-Definitions-and-Approaches.pdf: Global Maritime Forum.

Global Maritime Forum, 2023. *Getting to Zero Coalition.* [Online]
Available at: https://www.globalmaritimeforum.org/getting-to-zero-coalition

Google Scholar, 2023. *Stand on the shoulders of giants.* [Online]
Available at: https://scholar.google.com/intl/en/scholar/about.html

Grieg, 2022. *Green Ammonia Powered Bulk Carrier.* [Online]
Available at: https://greenshippingprogramme.com/pilot/ammonia-powered-by-bulk-carriers/

Gundersen, H., Chen, W., Bryan, T. L. & Moy, F. E., 2017. *Ecosystem Services In the Coastal Zone of the Nordic Countries,* DOI: 10.6027/TN2016-552: Nordic Council of Ministers.

Gunnarsson, B. & Moe, A., 2021. *Ten Years of International Shipping on the Northern Sea Route: Trends and Challenges,* https://arcticreview.no/index.php/arctic/article/view/2614/5113: Nord University & Fridtjof Nansen Institute.

Hammer, K., Sekkesæter, Ø., Slotvik, D. A. A. & Austefjord, J. W., 2023. *Executive summary and documentation: Measurement of Zero-Emission Shipping Mission KPIs,* Hørvik, Norway: DNV.

Hansson, J., 2023. *HOPE - Analyzing hydrogen fuel cells solutions in shipping.* [Online]
Available at: https://www.ivl.se/projektwebbar/hope.html

Hansson, J., 2023. *Hydrogen fuel cells solutions in shipping in relation to other low carbon options – a Nordic perspective (HOPE),* https://www.nordicenergy.org/project/hope/: IVL Swedish Environmental Research Institute & Nordic Energy Research.

Hansson, J. & Jiven, K., 2023. *The HOPE project.* The Nordic Maritime Transport and Energy Research Programme Conference(Malmö): IVL - Swedish Environmental Research Institute.

Herbst, A. & et.al., 2012. *Introduction to Energy Sytems Modelling,* Vol. 148 (2) 111–135: Swiss Society of Economics and Statistics.

Herning, L., 2018. *Official Nordic co-operation.* [Online]
Available at: https://www.norden.org/en/information/helsinki-treaty

Holländer, K. R., 2023. *Environmental Profile.* [Online]
Available at: https://portesbjerg.dk/en/about/environmental-profile

Holländer, K. R., 2023. *History.* [Online]
Available at: https://portesbjerg.dk/en/about/history

Humpert, M., 2011. *The Future of the Northern Sea Route - A "Golden Waterway" or a Niche Trade Route.* [Online]
Available at: https://www.thearcticinstitute.org/future-northern-sea-route-golden-waterway-niche/

Hvelplund, F. & et.al., 2007. Feasibility Studies and Technological Innovation. In: *Tools for Sustainable Development.* Aalborg: Aalborg Universitetsforlag, pp. pp. 595 - 618.

Hvelplund, F. & Lund, H., 1998. *Feasibility Studies and Public Regulation in a Market Economy.* Aalborg University : ISSN: 1397-3169.

Hyvönen, J., 2023. *Linking research and industry - ammonia and hydrogen-based solutions to marine engines.* Malmö(Nordic Maritime Transport and Energy Research Programme Conference): Wärtsila .

Høst PtX Esbjerg, 2023. *About the plant.* [Online]
Available at: https://hoestptxesbjerg.dk/about-ptx/

IEA, 2022. *The global energy crisis,* World Energy Outlook 2023 - Introduction: International Energy Agency.

IEA, 2022. *World Energy Outlook 2022,* Paris: IEA.

International Transport Forum, 2023. *Support bunkering infrastructure for alternative fuels.* [Online]
Available at: https://www.itf-oecd.org/node/26614

Jakobsen, E. & et.al., 2022. *TASK 2B - Infrastructure and Bunkering Challenges for Zero-Carbon Fuels,* s.l.: Menon Economics, Litehauz, IVL, DNV, and Chalmers.

Kemp, R. & et.al., 2007. *Transition Management as a Model for Managing Processes of Co-Evolution towards Sustainable Development,* ResearchGate: The International Journal of Sustainable Development and World Ecology.

Kronvall, A., 2023. *Facts about the Nordic countries.* [Online]
Available at: https://www.norden.org/en/information/facts-about-nordic-countries

Lerøy Havfisk, 2022. *Ammonia powered trawler.* [Online]
Available at: https://greenshippingprogramme.com/pilot/ammonia-powered-trawler/

Lloyd's Register, 2020. *Hydrogen and Ammonia Infrastructure - Safety and Risk Information and Guidance,* Kokstad, Norway: Lloyd's Register, Arena Ocean Hyqay Cluster, and Ocean Hyway Cluster.

Lund, H., 2014. Chapter 2 - Theory: Choice Awareness Theory. In: *Renewable Energy Systems (Second Edition). A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions..* s.l.:Academic Press, pp. pp. 15-34.

Lund, H. & Østergaard, P. A., 2010. *Fundamental Investment Theory,* Aalborg: Aalborg University.

Mallouppas, G., 2022. *A Review of the Latest Trends in the Use of Green Ammonia as an Energy Carrier in Maritime Industry,* https://www.mdpi.com/1996-1073/15/4/1453: Energies.

Maritime and Port Authority of Singapore, 2023. *About the Maritime and Port Authority of Singapore (MPA).* [Online]
Available at: https://www.mpa.gov.sg/who-we-are/about-mpa

Microsoft Teams, 2023. *Record a meeting in Teams.* [Online]
Available at: https://support.microsoft.com/en-au/office/record-a-meeting-in-teams-34dfbe7f-b07d-4a27-b4c6-de62f1348c24

Microsoft, 2023. *Create a PivotTable to analyze worksheet data.* [Online]
Available at: https://support.microsoft.com/en-us/office/create-a-pivottable-to-analyze-worksheet-data-a9a84538-bfe9-40a9-a8e9-f99134456576

Microsoft, 2023. *Excel help and learning.* [Online]
Available at: https://support.microsoft.com/en-us/excel

Microsoft, 2023. *IF function.* [Online]
Available at: https://support.microsoft.com/en-us/office/if-function-69aed7c9-4e8a-4755-a9bc-aa8bbff73be2

Mjøs, N. & Eide, M. S., 2023. *The world's most efficient and environmentally friendly shipping.* [Online]
Available at: https://greenshippingprogramme.com/about-green-shipping-programme/

Müller, J., 2011. *Making Ends Meet - Local socio-technological transformations in the South: based on case studies from Tanzania,* ISBN 978-87-91404-13-9: Department of Development and Planning, Aalborg University.

Mærsk Mc-Kinney Møller Center, 2021. *We show the world it is possible.* PowerPoint Slides: DNV.

Mæsrk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022. *Green Corridors: Feasibility phase blueprint,* Blueprint: Mæsrk Mc-Kinney Møller Center for Zero Carbon Shipping and McKinsey & Company.

Nayak-Luke et.al., R. M., 2021. Techno-Economic Aspects of Production, Storage and Distribution of Ammonia. In: *Techno-Economic Challenges of Green Ammonia as an Energy Vector.* Elsevier: https://doi.org/10.1016/B978-0-12-820560-0.00008-4, pp. pp. 191 - 207.

Nordic Energy Research, 2023. *About us.* [Online]
Available at: https://www.nordicenergy.org/about-us/

Nordic Energy Research, 2023. *Nordic Energy Research.* [Online]
Available at: https://www.nordicenergy.org/

Nordic Energy Research, 2023. *Nordic Maritime Transport and Energy Research Programme.* [Online]
Available at: https://www.nordicenergy.org/project/nordic-maritime-transport-and-energy-research-programme-2/

Nordpool, 2023. *Simple, Efficient, and Secure.* [Online]
Available at: https://www.nordpoolgroup.com/
[Accessed 01 06 2023].

North Sea Port, 2023. *Multimodal port.* [Online]
Available at: https://en.northseaport.com/multimodal-port

OECD, 2023. *Ocean shipping and shipbuilding.* [Online]
Available at: https://www.oecd.org/ocean/topics/ocean-shipping/

Pandey, A. & et.al., 2022. *How EU Contracts for Difference can support zero-emission fuels*, s.l.: Getting to Zero Coalition, Global Maritime Forum and World Economic Forum.

Pedersen, D. J., 2019. *Esbjerg Havn danner ny bæredygtighedsalliance sammen med ni nordiske havne.* [Online]
Available at: https://portesbjerg.dk/da/om-esbjerg-havn/nyheder/esbjerg-havn-danner-ny-b%C3%A6redygtighedsalliance-sammen-med-ni-nordiske-havne

Port Esbjerg, 2022. *Annual report 2021*, p. 5: Port Esbjerg.

Port Esbjerg, 2022. *Port Esbjerg Sustainable Strategy - Health, Safety, and the Environment*, Esbjerg: Port Esbjerg.

Port Esbjerg, 2023. *Bunker, fuel and lubricants – Nordic Marine Oil A/S.* [Online]
Available at: https://portal.portesbjerg.dk/rental-options/bunker-fuel-and-lubricants-nordic-marine-oil-a-s/

Port Esbjerg, 2023. *Maps.* [Online]
Available at: https://portesbjerg.dk/en/port-services/maps

Port Esbjerg, n.d. *Contact.* [Online]
Available at: https://portesbjerg.dk/en/contact
[Accessed 01 06 2023].

Port of Aberdeen, 2023. *Rates and Charges (including conditions)*, Aberdeen, Scotland: Aberdeen Harbour Board.

QGIS Documentation, 2023. *QGIS User Guide.* [Online]
Available at: https://docs.qgis.org/testing/en/docs/user_manual/index.html

QGIS project, 2023. *12. General Tools.* [Online]
Available at:
https://docs.qgis.org/3.28/en/docs/user_manual/introduction/general_tools.html?highlight=measure

QGIS project, 2023. *5.1. Lesson: Creating a New Vector Dataset.* [Online]
Available at: https://docs.qgis.org/3.28/en/docs/training_manual/create_vector_data/create_new_vector.html

QGIS, 2023. *QGIS - The Leading Open Source Desktop GIS.* [Online]
Available at: https://qgis.org/en/site/about/index.html

Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council (2021).

ResearchGate, 2023. *ResearchGate.* [Online]
Available at: https://www.researchgate.net/

Rivedal, N. H. & et.al., 2022. *AIS Analysis of Nordic Ship Traffic,* Nordic Roadmap Publication No. 2A/1/2022: DNV, Nordic Council of Ministers.

Rivedal, N. H. & et.al., 2022. *Nordic Roadmap for the introduction of sustainable zero-carbon fuels in shipping.* The Norwegian Ministry of Climate and Environment on behalf of the Nordic Council of Ministers(DNV): https://futurefuelsnordic.com/ais-analysis-of-the-nordic-ship-traffic-and-energy-use/.

Rivedal, N. H. & et.al, 2022. AIS Analysis of Nordic Ship Traffic. In: *Nordic Roadmap for the introduction of sustainable zero-carbon fuels in shipping.* Ministry for Climate and Environment Norway & the Nordic Council of Ministers: https://futurefuelsnordic.com/wp-content/uploads/2022/11/AIS-Analysis-of-Nordic-Ship-Traffic.pdf, p. Document No.: 10343861.

Rydin, Y., 2021. Theory in Planning Research. In: *Planning, Environment, Cities.* ISBN 978-981-33-6568-1: palgrave macmillan, pp. 1-19.

Sacred Heart University, 2023. *Organizing Academic Research Papers: Theoritical Framework.* [Online]
Available at: https://library.sacredheart.edu/c.php?g=29803&p=185919

Salmon, N., Bañares-Alcántara, R. & Nayak-Luke, R., 2021. *Optimization of green ammonia distribution systems for intercontinental energy transport,* Article: iScience.

Salmon, N. & et.al., 2021. *Optimization of green ammonia distribution systems for intercontinental energy transport,* https://www.cell.com/iscience/fulltext/S2589-0042(21)00871-3?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2589004221008713%3Fshowall%3Dtrue: iScience, volume 24, 102903.

Sandström, A.-M., 2018. *8 ways to determine the credibility of research reports.* [Online]
Available at: https://www.eaie.org/blog/8-ways-determine-credibility-research-reports.html

Saunders, M. & Tosey, P., 2013. *The Layers of Research Design,* s.l.: The accociation for NLP.

Schøyen, H. & Bråthen, S., 2011. *The Northern Sea Route versus the Suez Canal: cases from bulk shipping,* Elsevier Ltd.: Vestfold University College and Molde University College.

Scot, J. & Geels, F. W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. In: *Technology Analysis and Strategic Management.* Volume 20 (5)(Eindhoven University of Technology): Routledge Taylor & Francis Group, pp. pp. 537-554.

Snyder, H., 2019. *Literature review as a research methodology: An overview and guidelines,* BI-Norwegian School of Business, Oslo, Norway: Elsevier.

Sovacool, B. K. & et.al., 2018. Promoting novelty, rigor, and style in energy social science: Towards codes. In: *Energy Research & Social Science.* ScienceDirect: https://pure.au.dk/portal/files/179452495/Promoting_novelty_rigor_and_style_in_energy_social_science.pdf, pp. 12-42.

Suez Canal Authority, 2023. *Canal Characteristics.* [Online]
Available at: https://www.suezcanal.gov.eg/English/About/SuezCanal/Pages/CanalCharacteristics.aspx

Suez Canal Authority, 2023. *The Green Canal.* [Online]
Available at: https://www.suezcanal.gov.eg/English/About/SuezCanal/Pages/greencanal.aspx

Svendsen, J. B., 2023. *Green Corridors Pre-Feasibility Phase Blueprint.* [Online]
Available at: https://www.zerocarbonshipping.com/publications/green-corridors-pre-feasibility-phase-blueprint/

Takahiro, 2021. *History and Transition of Marine Fuel.* [Online]
Available at: https://www.mol-service.com/blog/transition-in-ships-fuel

Talalasova, E., 2022. *Annual Progress Report on Green Shipping Corridors,* https://cms.globalmaritimeforum.org/wp-content/uploads/2022/11/The-2022-Annual-Progress-Report-on-Green-Shipping-Corridors.pdf: Global Maritime Forum Getting to Zero Coalition.

The University of Edinburgh, 2022. *The characteristics of problem structuring methods: A literature.* [Online]
Available at: https://www.ed.ac.uk/institute-academic-development/study-hub/learning-resources/literature-review

Thome Group, 2022. *Retrofit of container ship to operate on green methanol.* [Online]
Available at: https://greenshippingprogramme.com/pilot/retrofit-of-existing-container-ship-to-operate-on-green-methanol/'

UK Government & United Nations Climate Change, 2021. *Clydebank Declaration for Green Shipping Corridors - COP26 Declaration.* [Online]
Available at: https://ukcop26.org/cop-26-clydebank-declaration-for-green-shipping-corridors/

Valuta ex, 2023. *GBP til DKK.* [Online]
Available at: https://valuta.exchange/da/gbp-to-dkk?amount=1

Van den Bosch, S., 2010. *Transition Experiments: Exploring societal changes towards sustainability.* Erasmus University Rotterdam: ISBN 978-90-8559-057-6.

Wang, H. & et.al., 2023. *Ammonia-based green corridors for sustainable maritime transportation,* https://www.sciencedirect.com/science/article/pii/S2772508122000734: Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN 55455, USA.

Wilson, V., 2014. Research Methods: Triangulation. *Evidence Based Library and Information Practice*, 11 02, pp. pp. 74-75.

Winje, E. & et.al., 2022. *Task 1A - Screening of Sustainable Zero-carbon Fuels,* Litehauz, IVL, DNV, and Chalmers: Menon Economics.

Wolter, C. & Jensen, A. K., 2021. 103 Green Ammonia. In: *Technology Data for Renewable Fuels.* Danish Energy Agency: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf, pp. pp. 272 - 298.

Wolter, C. & Jensen, A. K., 2021. 103 Green Ammonia. In: *Technology Data for Renewable Fuels.* s.l.:https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf, pp. pp. 272 - 298.

Yang, M. & Lam, J. S. L., 2023. *Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective,* https://www.sciencedirect.com/science/article/pii/S1361920923000639?via%3Dihub: Nanyang Technological University.

Yin, R. K., 2018. *Case Study Research and Applications - Design and Methods.* Los Angeles: SAGE Journals.

Zakariyya et.al., K., 2021. *Ammonia Bunkering of Passenger Vessel - Concept Quantitative Risk Assessment,* Hørvik: DNV.

Aagaard, N., 2019. *Our Vision 2030.* [Online]
Available at: https://www.norden.org/en/declaration/our-vision-2030

Aalborg University, 2023. *University Library.* [Online]
Available at: https://www.en.aub.aau.dk/

Appendix 1

Appendix 1 contains equations contemplated and applied for conducting the feasibility study. Each equation is denoted, *Equation X*, with title for identification purposes. All equations can be found in Appendix 2 that constitutes the energy model used for the feasibility study.

Equation 2: Ship weight

$$IF(\text{Weight} \geq 5\ 000; \text{Weight}; \text{""})$$

Logistical test: Apply weight in new column equal to weight of respective ship if it is *true* that the weight is equal to or above 5 000 GT. If it is *false*, leave a blank space [""].

Equation 3: Ship type and distance

$$Work/service: IF(Ship\ type = 5; IF(Distance = 1\ or\ 2; Demand_{tonnes\ e-a} * 10^6); \text{""}); \text{""})$$

$$Tanker: IF(Ship\ type = \text{Tanker}; IF(Distance = 2; Demand_{tonnes\ e-a} * 10^6); \text{""}); \text{""})$$

First logistical test: If ship type equals 5 (work/service ships) or tanker then,

Second logistical test: assign average e-ammonia demand value if distance belongs to categorisation 1 (domestic) or categorisation 2 (regional), if not in both cases leave a blank space [""].

Countries that belong to category 2: Norway [NO], Sweden [SE], Finland [FI], Iceland [IS], the Netherlands [NL], Belgium [BE], Germany [DE], Great Britain [GB], Polen [PL], Latvia [LV], Ireland [IE], and France [FR]. Countries affiliated in port-to-port connections with the Port of Esbjerg are identified in a pivot table analysis hence, countries are only mentioned if they are represented.

Equation 4: Annual e-ammonia demand

$$Annual\ Demand_{e-a} = \sum_{s=S}^{Annual\ S} e - a\ consumption_s * D_{e-a} * (1 + SOFC\ _e)$$

Annual Demand$_{e\text{-}a}$ [tonnes]

e-a: E-ammonia

s: One ship

S: Annual number of ships

$D_{e\text{-}a}$: Energy density of e-ammonia = *40,4 MJ/kg* (DNV, 2019)

$SOFC_e$: *Solid oxide fuel cell efficiency* = *60 %* (Brynolf & et.al., 2023)

Equation 5: Hourly e-ammonia production capacity [MWh]

$$Capacity = (C_e * E_e * E_{HB}) * 10^3$$

Capacity [MWh]

C_e: Capacity of electrolyser = 1 GW (Høst PtX Esbjerg, 2023)

E_e: Energy efficiency of alkaline electrolyser = 68 % (Danish Energy Agency, 2017)

E_{HB}: Energy efficiency of Haber-Bosch process = 82 % (Danish Energy Agency, 2017)

OBS. No data on an air separation unit hence, it is not applied (Danish Energy Agency, 2017).

Equation 6: E-ammonia production

$$IF\left(Price_e < Price_{rhp+1}; HP_{e-a}; IF\left(Price_e = Price_{rhp}; \frac{HP_{e-a}}{0{,}684}; \right)""\right)$$

$Price_e$: Hourly spot market electricity price [DKK/MWh]

$Price_{rhp}$: Hourly spot market electricity price for *requested hourly peak electricity price* (*rph)* + 1 [DKK/MWh]

HP_{e-a}: Hourly e-ammonia production [tonnes]

First logistical test: If the electricity price is lower than requested hourly peak electricity price, then return value equal to hourly e-ammonia production capacity (*true)*. If false, identify if the hourly price is equal to requested hourly peak electricity price, and if *true*, divide production with 0,684. If *false*, e-ammonia production is refused [""].

OBS. value 0,684 is measured by simulating and identifying needed e-ammonia production capacity during the hour with requested hourly peak electricity price for meeting the annual e-ammonia demand.

Equation 7: E-ammonia storage capacity

$$\begin{aligned}&IF(Production_{e-a} > Demand_{e-a};\\&Production_{e-a} + Storage\ Content_{e-a} - Demand_{e-a};\\&IF(Production_{e-a} < Demand_{e-a}; Storage\ Capacity_{e-a} - (Demand_{e-a} - Production_{e-a});))\end{aligned}$$

First logistical test: If monthly e-ammonia production exceeds monthly e-ammonia demand, then (re)fuel storage with excess production compared the demand. If it is *false*, implying that the production is lower than the demand, then tank e-ammonia from the storage to meet the monthly demand extracted the production.

E-ammonia storage capacity measures in [tonnes]. By a verification if statement stressing:

$$IF(S_c > C_v; 1; 0)$$

S_c: Storage capacity [tonnes]

C_v: Variable capacity [tonnes]

It emphasises that in case variable capacity that is simulated manually, is lower than required storage capacity, a numeric value [1] will return for respective month. It implies that for the respective month(s), the storage capacity in adequate to store annual demand on monthly basis. Hence, a higher storage capacity is simulated, though, following an optimisation principle, only to increase it to a sufficient size to limit storage costs.

Equation 8: Volumetric storage capacity

$$V_s = (S_c * 10^3)/Vd_{e-a}\ [kg/m^3]$$

V_s [m^3]

S_c: Storage capacity [tonnes]

Vd_{e-a}: Volumetric energy density of ammonia [kg/m^3] = 610 kg/m^3 (Lloyd's Register, 2020)