ENABLING LOW CARBON TRANSITIONS IN THE MARITIME SECTOR- INTEGRATING GREEN AMMONIA

AALBORG UNIVERSITY

MASTER'S THESIS

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Master's Thesis:

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Abstract

The European Union has set ambitious goals to reach carbon neutrality by 2050 to reduce the impact on the climate crisis. Sectors like the power and heat sector can be directly electrified through the integration of renewable energy sources to shift away from the use of fossil fuels. The transport sector and its sub-sectors like international shipping heavily rely on fossil fuel feedstocks to generate the necessary fuels to function. This implies that new strategies are required to remove the phenomenon called the techno-institutional carbon lock-in from international shipping to achieve the EU's goal of carbon neutrality.

With the aim of finding the solutions to this predicament, it is necessary to *enable a low carbon transition in the shipping sector by integrating green ammonia in the sector.* This means that the transition is a multi-faceted challenges with one dimension dealing with the decarbonization of the ammonia production chain and the other with finding strategies to introduce the transition in shipping through the integration of green ammonia.

First, technological pathways for green ammonia are designed based on a preliminary ammonia demand. Important factors that affect the production of green ammonia such as levelized cost of energy (LCOE) and levelized cost of hydrogen (LCOH) are determined leading to the identification of the most viable technological pathway for green ammonia for the shipping sector. The socio-economic analysis shows that having an LCOE of 27 Euro/MWh from onshore wind and an LCOH of 5 Euro/kg through an alkaline electrolysis cell (AEC), results in an LCOA of 344 ton/NH_3, giving the most socio-economically viable pathway for green ammonia production.

The next part focuses on understanding the complexities of a low carbon transition in the shipping sector and the factors that affect this transition in addition to the economic analysis. It is noted that several challenges exist for a transition to green ammonia, among which energy density plays an important part. Due to the differences in the energy densities of traditional maritime fuels and green fuels like ammonia, it is seen that there is considerable difference in the unit costs, causing a certain level delay in the low carbon transition in the shipping sector. This implies that strategies that include market-based measures like strong carbon prices and subsidies are necessary to enable the low carbon transition in shipping. In addition to the carbon ETS mandated by the EU, additional incentives are required to adopt green ammonia as a fuel and get rid of the carbon lock-in.

Preface

This thesis report is part of the Master Program in Sustainable Cities at Aalborg University, Copenhagen. As part of my master's program, I have come across a whole new dimension of knowledge and for that, I am grateful to Aalborg University.

I would like to thank the following experts who shared their immense knowledge and insights with me as part of my thesis. Without their help, it would be difficult to learn about the shipping sector:

- Rob Stevens, Topsoe
- Jesse Fahnestock, Global Maritime Forum
- Navid Ostadian-Binai, Maersk Tankers
- Conor Furstenberg, Furstenberg Maritime Advisory

I also want to express my gratitude to my supervisor who has been incredibly supportive of my journey through this thesis and also for his guidance when needed. His patience during the thesis is extremely appreciated.

I would like to take a moment to thank my father who has been incredibly helpful in proofreading my thesis and my mother for her immense support. And I'd also like to extend this gratitude to my friends who always had my back during my thesis and gave me constant support to complete it.

Reading Guide

The referencing style in the report is in the form of Harvard style and they are listed alphabetically at the end of the report. The references from books and articles researched will appear with the last name of the author and the year it was published in the form of (Author, Year). Figures and tables are numbered in the order that they appear and hence continue across the report. Explanatory text appears at the top for tables and at the bottom for figures.

There is one addendum attached in this study, the end of the report as a reference to the interviews held for this study.

- Appendix A- Interviews

Nomenclature

AEC	Alkaline Electrolysis Cells
ASU	Air Separation Unit
CO_2	Carbon
EU	European Union
ETS	Emissions Trading Scheme
GHG	Greenhouse Gases
H_2	Hydrogen
IMO	International Maritime Organization
HFOs	Heavy Fuel Oils
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
LCOA	Levelized cost of Ammonia
LNG	Liquified Natural Gas
N_2	Nitrogen
NH_3	Ammonia
NOx	Nitrogen Oxides
PEM	Polymer Electrolyte Membrane Cells
PtX	Power-to-X
SOEC	Solid Oxide Electrolysis Cells
SOx	Sulphur Oxides
VLSFOs	Very Low Sulphur Fuel Oils

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Chapter 1: Problem Analysis

The European Union (EU) has ambitions plans to combat climate change and aims to reach carbon neutrality till 2050. To achieve this target, the EU has decided to focus on hydrogen and its derivatives like methanol and hydrogen carriers like ammonia as cleaner fuels compared to fossil-fuel based energy sources. Yet, in its current form, hydrogen and its derivatives represent only a small amount in the energy mix for transport despite having the potential to reduce carbon by 70% and are still produced from fossil fuels (Marta Yugo and Alba Soler, 2019). The Paris agreement serves as a critical framework for member states, to drive their efforts to control emissions and recognize the need to find technological innovations to reduce the increasing threat of climate change. It is the first step of establishing parameters for subsequent policies outlined by the EU such that they align with its ambitious climate objectives. Furthermore, it lays down important guidelines to incorporate hydrogen and its derivatives in the current energy mix by diversifying its use across various sectors.

Recent breakthroughs in the power and heat sector have fundamentally altered the energy system by integrating intermittent energy sources in the overall energy mix. However, the share of renewables in long haul transport including it sub-sectors like shipping have been slow to materialise due to deep rooted reliance on fossil fuels such as oil and diesel and built up of current infrastructure based on it. Harnessing renewable energy to produce green fuels presents an opportunity for the transport sector and its sub-sectors to reduce their reliance on fossil fuels significantly. Power-to-X (PtX) represents using renewable energy to synthesize a final product 'X' to further enable decarbonization as Power-to-X presents an innovative solution to bridge the gap for fossil fuels in the transport sector. This encompasses various fuel derivatives of hydrogen, providing sustainable solutions as an interim measure until mature technologies for complete decarbonisation of the transport sector are available (European Commission, 2018).

To facilitate the green transition, the European Commission has outlined a comprehensive framework known as REpowerEU. This strategy is devised to reduce EU's dependence on the Russian natural gas by establishing a hydrogen infrastructure and by diversifying the energy portfolio. It includes various initiatives to increase the contribution of clean energy, promote cleaner fuels derived from hydrogen and expand renewable hydrogen capacity

(European Commission, 2022). If the EU needs to make substantial progress to achieve the objective of carbon neutrality by 2050, the transport sector is a focal point.

1.1. Maritime Transport

The transportation sector, including subsectors like aviation and shipping are significant consumers of fuels and clean energy sources contribute very minutely to their energy demand. Within the EU the transport sector alone emits 32% of CO_2 and over the years, emissions from the transportation sector have been on the rise considering factors such as increase in economic growth as well as an increase in private vehicles. These emissions are a result of high use of fossil fuels and therefore it is imperative to explore alternative fuels that are tailored to meet the demand of different modes of transport. A fundamental shift in the value chain of the sector is essential to achieve a low carbon future as per the EU's goal. A low carbon transition entails achieving a state of net-zero or low-carbon alternatives. The transition hinges on synergies with other sectors emitting low emissions to achieve changes in the socio-economic state of society.

Maritime transport plays a significant role in the EU's economy, but in turn contributes to a substantial portion of carbon emissions, accounting for about 2.9% emissions globally (European Commission, n.d.) and 4% within the EU (European Commission, 2013). If the shipping industry continues with a business-as-usual approach, without recalibrating its path to reduce global emissions, it will be challenging to meet the goals of the Paris agreement.

To address this issue, the EU is creating a policy framework aimed at reducing market and technical barriers to facilitate a transition toward sustainability in the shipping sector. The International Maritime Organization (IMO), responsible for setting standards, has indicated that international shipping must align with EU's goal of carbon neutrality by 2050. These guidelines also include incorporation of alternative fuels by 2030 and enhance efficiency of ships because the current technological infrastructure of ships is based on an internal combustion engine which uses fossil oils to operate. Furthermore, the shipping sector has been incorporated in the EU Emissions Trading System (ETS), a carbon pricing mechanism, where sectors can acquire permits for their carbon emissions through actions based on market prices for carbon (CO_2). The ETS incentivises emissions reductions through innovation and investment in sustainable technologies. Other measures are aimed at increasing the monitoring and reporting of CO_2 emissions of shipping companies, ensuring that they are required to pay for each tonne of CO_2 emitted (European Commission, 2013). These policies are paving the way forward to decarbonise sectors like maritime transport.

However, in the long-term scenario, the case of low carbon fuels needs to be investigated to reduce the emissions as the current fuel structure revolves around fossil feedstocks. As the maritime sector is dependent on fuels for global trade, it becomes necessary to explore fuels that emit less greenhouse gases. Thus, exploring energy efficient fuels is imperative for maritime transport and developing technological pathways that effectively address this gap can facilitate this transition.

1.2. Research Question

The European Union's goal to be carbon neutral by 2050 can only be achieved if the entire spectrum of the transport sector actively participates in this transition. Among the transportation sectors, the shipping industry has unique challenges to navigate, due to the unattainability of direct electrification. This is why it is imperative for the shipping sector to find alternatives which mitigate GHG emissions from the sector.

In this context, the research endeavours to address these challenges through the following question:

"What strategies can be employed to integrate ammonia in the shipping sector to align with EU's climate objectives".

1. What are viable technological pathways available for the shipping industry in its pursuit for using ammonia as a fuel?
2. Are there solutions available that are economically feasible for emission reduction within the shipping sector?
3. What are the critical factors that are needed for policy decisions aimed at facilitating a low carbon transition in the shipping sector?

Low carbon transition in the maritime sector is a multifaceted challenge. One such dimension deals with changes in fuel mentioned in the sub-question, which will be studied in the following chapters.

The next chapter, Chapter 2 will delve into the theoretical framework that will guide the next few sections. Chapter 3 explains the methodology of research. Afterwards, Chapter 4 and 5 answer the sub questions 1,2 and 3. The discussion is elaborated in Chapter 6 and the research is concluded in Chapter 7.

Chapter 2: Theoretical Research framework

This chapter will delve into the theoretical framework used for the research, that will underpin the subsequent analyses. It will serve as a foundation for analysing and understanding the necessary solutions required to accelerate the low carbon transition in the maritime sector.

2.1. Pathway Theory- Traversing Low Carbon Transitions

Innovation and advancements in the transportation sector in terms of available technologies and knowledge has enabled vast opportunities for the green transition within the transport sector. However, this has had unintended consequences for policy makers as it is difficult to synthesize the information into distinct policy decisions. Instead of assimilating this wealth of knowledge, it has overwhelmed their capacity to seamlessly integrate this knowledge into a framework of policies and standards for the maritime sector, thereby creating a bottleneck in the progress of a low carbon transition.

Daniel Sperling is of the opinion that when policymakers take decisions regarding technological transformation in shipping, they often do so as part of planning process where the future is viewed in fixed outcomes, which he terms *"end of state thinking", e.g., relying entirely on economic analysis*. The process of technological change is not given due credit because policymakers are more concerned with the final outcome, which results in short-sightedness. Sperling highlights the lack of attention to address the intricate process of technology-driven systems (Sperling, 1984).

2.1.1. The problem of 'End of State Scenarios'

Sperling explains that technological change and development is often portrayed as a single breakthrough rather than a gradual accumulation of small advancements which assist development (Sperling, 1984). He presents certain issues associated to this romanticised approach to planning for technological change which inadvertently fosters an "end of state thinking". Firstly, societal goals are not rigidly defined and evolve over time, introducing an element of uncertainty about the future. There could be additional external factors which cannot be predicted, which makes conventional economic analysis a less effective tool to determine the value of technology development.

Human cognition is limited (Sperling, 1984); the concept of *"end of state"* thinking restricts policymakers and economic analysts to comprehend the process of change and hence does not allow for incorporation of larger societal goals.

Sperling also acknowledges the drawbacks of relying solely on economic analysis for technology development. While economic paradigms are effective for understanding valuable individual technologies, development cannot be compartmentalised and needs to be synergised. There is a need to incorporate variables which include long-term thinking for the maritime sector that align with wider societal goals. To address this, Sperling introduces the 'Pathway application' which advocates for a thorough analysis of 'critical factors' (Sperling, 1984).

2.1.2. The Solution- Facets of the Pathway Theory

The "Pathway theory" says that abundant opportunities are available for transformation in the transport sector, and this can be achieved in a systematic manner through identification of major constraints and open-ended thinking of 'what could be'(Sperling, 1984). This is the most robust point of the pathway theory as opposed to conventional end state thinking and rational planning practices.

1. **Consistent values and beliefs:**

   The pathways theory gives rise to identifying solid values and beliefs for technological development and innovation. These principles encompass values relate to environmental quality, pricing and provisions, efficiency of market systems and control. Recognizing that values are attached to technological transformation can serve as the driving force behind ensuring that the analysis is not simply based on technical and economic analysis. It also allows for the inclusion of human cognition and error, thereby increasing the creativity of the technology subsets.

2. **Critical factors are identified:**

   Technological change is influenced greatly by critical factors, including but not limited to cost considerations, technology performance metrics, and advantages of economies of scale. Critical factors also extend to institutional capacities such as skillsets and adaptability to change. Sperling also emphasizes the influence of exogenous forces such as regulation which is also reflected in the work of (Geels et. al., 2017) who highlight exogenous factors as an integral component of technological change through the framework of the 'multi-level perspective'. Both concepts advocate the importance of external forces and human interactions as the key for the incorporation of radical changes in technological development.

Therefore, when analysing technological pathways for an ammonia-based economy for the maritime sector, there is a need to not only scrutinise these pathways through the lens of conventional economics but also a need to include critical factors related to the regulation of the European Union for the specific sector. Identification of critical factors within regulation and institutional opinions will facilitate the creation of a roadmap for the establishment of an ammonia-based economy for the maritime sector.

3. **Critical factors in a representative and temporal setting**

   When assessing critical factors, it is equally crucial to understand the context of the path being analysed. Given that application of pathway theory seeks to answer the question of 'what could be', maintaining flexibility in the analysis of technological change could be paramount. This allows for an exploration of diverse directions that technological change may potentially embark upon.

Having introduced the concept of pathway theory, it can now be implemented through the chosen research methodology. It is important to acknowledge that energy planning is context dependant (International Renewable Energy Agency, 2021) and could be subject to various challenges based on the temporal setting. The identification of critical factors to navigate technological change cannot simply rely on rational-comprehensive planning. (Sperling, 1984) highlights the need to depart from the normative rational planning and urges instead to focus on analysing sequences of change along the way rather than end state scenarios.

In his work, (Sperling, 1984) also explicitly emphasizes the application of pathway theory, highlighting its capacity to scrutinize determinants that enable technological change in the context of policy analysis. While critical factors play an important role in addressing the question of "what could be", sound path attributes increase the accuracy of answering this question. Hence, developing technological pathways of ammonia-based solutions will assist more accurately in answering the question of whether this can indeed be a reality for the maritime sector. These pathways should be perceived to be dynamic choices through which the future of the maritime sector can evolve to align with societal goals.

Furthermore, it is crucial to note the core issue at hand, which revolves around human-induced production and consumption patterns. These patterns often result in a systemic lock-in of technologies and institutional practices.

2.2. The Carbon Lock-in:

2.2.1. An Incapacitating Dependence

Current events and research show that anthropogenic emissions are exerting a noticeable impact on the climate (Unruh, 2000). The maritime sector significantly contributes to these emissions by relying on heavy fuel oils derived from remnants of oil refineries. This persistent emission is a pattern emerging from governments globally to take action, a phenomenon termed by Unruh as the carbon lock-in.

The concept of carbon lock-in as described by '(Unruh, 2000), refers to as "systemic forces which perpetuate the infrastructures that depend on fossil fuels despite the known environmental damages of fossils". To understand what a lock-in entails and how they are perpetuated, it is essential to first understand its scope and origin.

As mentioned, a carbon lock is a systemic problem, that not only impacts institutions and organisations but creates a lack of vision for incorporation of new technology. In this context, technological infrastructures are defined as individual components that are sub-sets of a larger system which provide services to end users. Along with technological infrastructures, institutions and organisations collaboratively emerge together to generate knowledge to establish the technology as the dominant design. The convergence of public and private institutions governing the dominant technological systems gives rise to a phenomenon called the techno-institutional complex. Since it is a systemic loop, they are created by incentive structures, personal vested interests and thus control the system's stability.

These vested interests give rise to policy inaction and a reluctance to embracing alternative more environment friendly solutions. Consequently, these factors in turn create barriers to phasing out fossil fuels, collectively termed as the 'Techno institutional complex'(TIC). Progress within the system essentially means generation of new knowledge on emerging technologies which could threaten the 'dominant' design and 'dominant' standards. A TIC is established since the economics of the existing technology has been validated and accepted upon by the market particularly in terms of the returns it provides to the organisations and the industries supporting its production. Within the maritime sector, this phenomenon is evident in the use of heavy fuel oils, driven by their low cost to power long-haul shipping operations. Regarding policy action aimed at achieving carbon neutral energy production, a TIC can present barriers to the adoption of innovative technologies that could liberate the industry from the carbon lock-in. A carbon-based TIC will only delay the action required to mitigate the effects of climate change by encouraging the use of carbon-based technologies. The impact of not mitigating emissions from the maritime sector could be high and pose challenges to achieving EU's goals for carbon neutrality.

Overcoming a carbon-based TIC is a disruptive but required process. Once a TIC if entrenched, it shapes societal preferences and practices. Policy action which will override this TIC are needed to reduce anthropogenic emissions. (Unruh, 2000) suggests that addressing climate change requires integrated policy action that consider the larger picture and an interplay of various factors. A TIC can have multiple sources and (Unruh, 2002a) identifies them as:

- Technology based which are caused by the dominant design in the market and standard technological designs
- Organisational TICs which are based in regular routines within the organisation, their entrenched practices and how the organisational staff is trained.
- Industrial based TICs which deal with standards built alongside the dominant design and play a role in contributing to the lock-in
- Societal TICs which are based in user behaviours and preferences due to adoption of the dominant design
- Institutional TICs which are based in government intervention in ensuring the market economics are based in the carbon lock-in technologies

However, TICs are not resistant to changes and low carbon transitions in the maritime sector can be achieved. These changes can be fostered by shifts in societal, institutional and organisational structures to allow for diffusion of newer technologies.

2.2.2. The Carbon Lock-In: Escaping it

While TICs introduce a level of stability to the existing system, it crucial to know that this is not a permanent condition. As per (Arthur, 1988), external forces and pressures are required to trigger a change within a techno-institutional complex. This is reinforced by (Cowan and Hulten, 1996), who explain that to overcome the existing lock-in, six events are required;

- A crisis involved with the existing technology
- Changes in the regulation
- An alternative technological breakthrough
- Changes in societal preferences

- Niche markets which challenge the dominant design
- Scientific results which back the new alternative

As mentioned earlier, a techno-institutional complex represents a loop of systemic forces wherein institutions are so deeply entrenched in the existing practices, they often cannot consider alternatives. Consequently, the onus to usher in new change rests on exogenous forces.

Public and private institutions often find themselves locked in TIC which impedes on their ability to commit to policy actions. To overcome TICs and shift to low carbon transitions, it becomes imperative to upgrade both the technological and social dimensions of the lock-in. Overcoming TICs is a multifaceted challenge and hence multiple variables need to be addressed which are part of a complex institutional structure. Therefore, policymakers play a crucial role in ensuring technological innovations become a part of the fight action against climate change. This entails creating opportunities for integration of larger renewable technologies, alternative fuels, energy efficiency measures in the shipping sector which has been reliant on conventional technologies so far.

Now that the theoretical framework has been presented, the research will transition to the methodology which will explore how this framework translates into a practical approach for data collection and then analysis.

2.3. Boundary of Research

2.3.1. Alternative fuels

The technological pathways and its economic analysis are limited to studying ammonia's suitability as a maritime fuel. Thus, the proposed technological pathways explore the prospective technologies available to produce ammonia from renewable energy sources and refrain from exploring fuels like methanol and LNG that have still have the potential to emit greenhouse gases.

2.3.2. Topographical setting

It is important to note that output for renewable energy is completely dependent on the geographical location and the resources based on the topography. All member states of the EU will not have rich renewable resources and thus the capacity factors and costs are based in a Danish setting. This limits the research in finding the most appropriate regional setting for green ammonia. This means that green ammonia plants need to be strategically built at locations where renewable energy is readily available to fulfil the power consumption requirement for green hydrogen and the plant itself.

2.3.3. Public Regulation Study

This research is concerned with exploring technological pathways for production of green ammonia. As explained by (Hvelplund and Lund, 1998), a public regulation study entails the *implementation* of technological pathways while a feasibility study entails the *exploration* of various technological pathways. Hence, the research will focus on exploring potential technological pathways that can be made more feasible and how these scenarios will affect the maritime sector in the future in light of EU's goal of carbon neutrality.

Chapter 3: Research Design and Methodology

The methodology will unveil the blueprint for the rest of the research. The methodology proves instrumental in establishing a structure on how the research is analysed. It presents a path to navigate the intricate landscape of ammonia technology, drawing upon insights through literature review. Furthermore, economic analysis of technological pathways will reveal the complexities of alternative technologies like ammonia fuel for the maritime sector as opposed to conventional fuels, and a stakeholder analysis to understand the myriad perspectives at play in the maritime sector.

The thesis investigates the challenges associated with alternative fuels like ammonia for the maritime sector. The core research question revolves around identifying gaps in technological development and potential pathways which could underpin the future of ammonia in the maritime sector. This involves thorough investigating of technological pathways based on various renewable energy sources. Currently, there is an emphasis on exploring technological pathways for ammonia production to drive decarbonisation of the maritime sector and consequently, it becomes imperative to study these pathways to assess their feasibility. Furthermore, the research also aims to identify the paths that will support a low carbon transition in the maritime sector. This is done by conducting a stakeholder analysis to gain insights into various perspectives on how a low carbon transition can be brought forward in the sector. Thus, the methodology can be visually represented as follows:

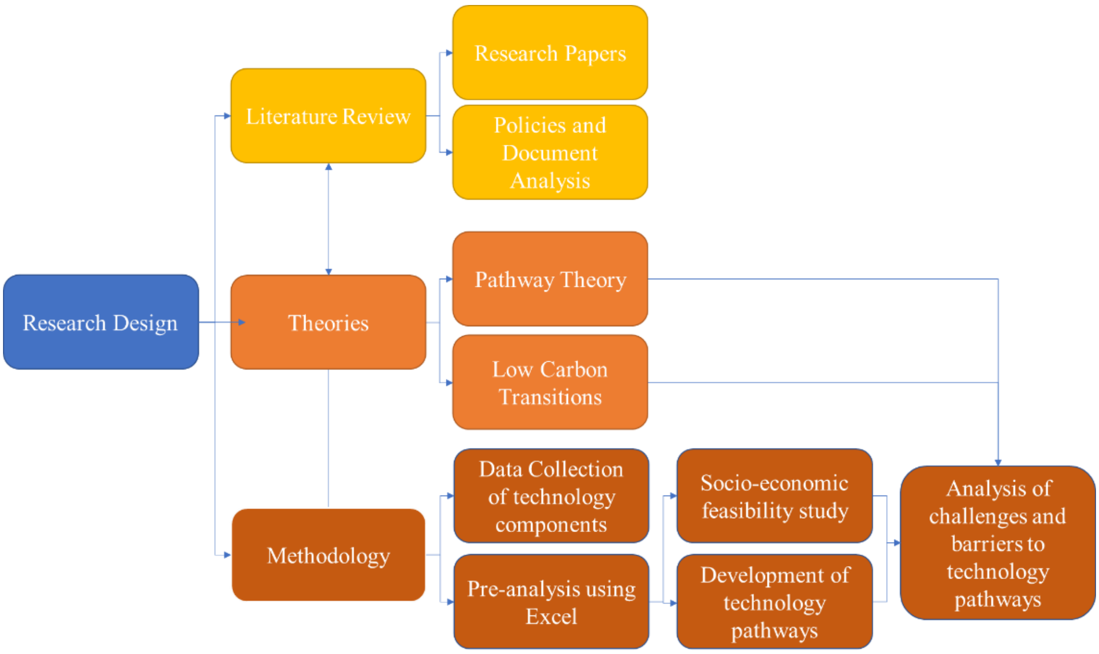

Figure 1: Research Design. Source: Self-made figure

3.1. Literature review

The process of Literature review for research is a continuous process and should follow a methodology rather than being an ad hoc task. It serves as a systematic means of gathering information on a specific topic and is said to build the foundation upon which theories are constructed. It allows the author to draw their own conclusions after studying diverse perspectives and address the research question, thus creating a unique answer (Snyder, 2019). A literature review is necessary at the commencement of a project to identify potential research gap within the chosen field and topic. This initial step helps to formulate a precise problem statement and delve further into exploring the topic.

A literature review encompasses both primary and secondary sources. Primary literature is described as addition to literature by the author's own investigation and empirical findings. Secondary literature on the other hand, entails the analysis of primary literature by drawing insights from scientific papers, books and journals (UMass Boston, 2023). In this report, much of the analysis is synthesised using secondary literature.

3.2. Data Collection and Review

3.2.1. Socio Economic Feasibility Study

'End-of-pipe' solutions as termed by (Hvelplund and Lund, 1998), refer to changing certain technological components, primarily focused on increasing system efficiencies. However, simply optimising efficiencies is insufficient to complete climate goals set out by the EU.

Developments in the value chain require sound capital decisions given that the technology components are specific to that particular system. This presents a challenge in introducing new technologies considering the substantial amount of capital investment required to replace components of the system. Additionally, political interests also play a part in the adoption of new technologies.

Thus, feasibility studies can be done in two ways:

As a socio-economic feasibility study which simply *explores* various technical scenarios and alternatives and focuses on finding the best type of solution for achieving climate goals.

Or as a public regulation study which focuses on *the implementation* of these alternative scenarios and forming a strategy around how a market share can be established.

This research will focus on the role of ammonia in driving the significant transformation in the maritime sector to align with EU's goals of achieving a zero-carbon economy by 2050 and will take its point of departure by analysing various technical scenarios for ammonia technologies and the implementation of these technologies will not be a part of the scope of the thesis.

3.2.2. Technological pathways:

A socio-economic feasibility study (SEFS) as elaborated by (Geels et. al., 2017) is carried out at a broader scale, or to create a change in the socio-technical landscape of the energy system. In the context of this research, SEFS play a vital role in bridging the gap between short- and long-term optimisation of the energy system landscape. The primary function is to form a base for long term strategies, to help accelerate a transition to greener fuels in the maritime sector.

Within the realm of socio-economic analysis, a substantial portion of the assessment revolves around doing a cost-benefit analysis. This method evaluates the proposed technological pathways for ammonia based on how they can benefit the maritime sector and the broader advantages of decarbonisation. A further important difference is that an economic evaluation juxtaposes the “with project” scenario against the “without project”, concentrating only on the differences. Conversely, in a financial analysis, only the return on investment of the ‘with’ project is considered (The World Bank and Public-Private Infrastructure Advisory Facility (PPIAF), 2009). The research will focus on the advantages of the technological pathway through an economic perspective and suggest what pathway should be adopted for maximum benefits for the maritime sector.

The adoption of renewable energy is gaining momentum across various sectors and the maritime sector can also benefit from fuels derived from clean energy sources. However, as (Hvelplund and Lund, 1998) rightly highlight, it is imperative to conduct an in-depth investigation when making energy investments, given the technical lifetime of such technology spans 27- 35 years. As mentioned previously, many of these investments are asset specific and hasty decisions in this regard could lead to unknown risks. To develop a green ammonia value chain which is meant to supply the entire maritime sector in the future, developing technical scenarios becomes an important task.

Therefore, it becomes essential to develop scenarios that explore different methods of ammonia production as a pre-analytical tool to understand the interdependencies between the energy system and the rest of the ammonia value chain. The variables are input into MS excel and generating scenarios that offer insights about technologies having efficient ammonia yields, ensuring sound investments. These scenarios are quantitative models and can be established with the right economic incentives. This approach aligns with the Pathway theory by (Sperling, 1984) which underscores the high uncertainty of the future and the limited utility of ‘end of state thinking’ in such contexts. The pathway theory helps to identify and mitigate potential barriers, ultimately helping to create well-defined pathways that visualise the socio-economic benefits and provide a roadmap to a low carbon transition.

As emphasized by (Hvelplund and Lund, 1998), “A feasibility study must relate to the main external socioeconomic and environmental impacts”. In this context, it becomes imperative to analyse the impact of how the market’s transition to new technologies will affect the environment and evaluate its implications on sustainability at a local and global level.

3.2.3. Stakeholder Mapping And Analysis

Stakeholders are also defined as the main actors within the public or private sphere in a specific sector with vested interests toward promoting policy action within the sector. Stakeholders can be from governmental organisations, NGOs or multinational corporations with a knowledge of the current infrastructure and policies of the sector and work toward contributing their knowledge toward long term goals of decarbonisation.

The maritime sector is under scrutiny due to the high amount of emissions and its impact on the local environment and global climate and is undergoing changes to overcome these challenges. There are multiple elements at play when it comes to technological development since technological change is not a linear process. This directly impacts the stakeholders involved in the maritime sector and unless they actively participate to make a change, it will have catastrophic effects in the future. The maritime sector poses challenges in achieving decarbonisation and requires large efforts to make a substantial impact for the future.

Stakeholders need better collaboration to improve the sustainability of the maritime sector, and this can be done with the help of stakeholder mapping and analysis. Ensuring the sustainability of the sector is an important aspect but it is equally important to understand the interests of the various stakeholders and incorporate them while making policy decisions and to capture resources in the long run. While it is vital to involve various stakeholders to distribute resources equally, stakeholder participation is important for co-creation of synergies with other sectors (Yuen et al., 2020).

Traditionally, the stakeholder theory suggests a capitalist view of stakeholder management, stressing on the interconnected relationships of a business with its partners and also within an organisation. It describes the values that are created to the stakeholders through these relationships. In the case of creating value for a sustainable future for the maritime sector, this thought process needs to be elevated by analyzing additional synergies that can be created with stakeholders in different sectors and that do not hold a purely business mindset. This connects with the concept of socio-economic feasibility of the project as it is associated with the social and environmental impacts of the project which in the case of the maritime sector are significant.

Stakeholder mapping and analysis is the visual mapping of the various stakeholders which will have a substantial influence on policy decisions for decarbonization of the sector. The diagrammatic representation of stakeholders will help to identify the main stakeholders in the sector and then a qualitative analysis of the interviews will be done. The goal of stakeholder analysis is to understand their perspectives through semi-structured interviews. This is done to gather their insights on the current and future outlook on the maritime sector and identify the major themes which will guide the low carbon transition in the maritime sector. (Sarah Gibbons, 2022).

Stakeholder mapping and analysis is also important to plot new concepts that might prove useful for the future of the sector. In this case, the cognitive map approach to stakeholder analysis is taken to analyze the similarities and differences in the ideas presented by the various stakeholders (Ahmad and Xu, 2021). The cognitive map approach of stakeholder analysis highlights the visualizations of constructs which are presented by the stakeholders interviewed. (Eden, 1988), expresses that there is always meaning in action and man finds meaning in these actions through contrasts and similarities and placing these ideas and actions hierarchically. By cognitively mapping stakeholder interviews, the question of "so what?" can be answered. This is done through the following methodology:

1. Stakeholder identification:
    - The stakeholders are chosen to provide a wide variety of perspectives on the current setup of the maritime sector and are part of NGOs and the private sphere but are involved with forming key strategies for a transition in the maritime sector. The stakeholders are selected to be from various organizations to pool in different types of datasets and to create detailed stakeholder maps. The following stakeholders were identified and interviewed to understand vital technologies available for alternative fuels for the maritime sector, to identify market

challenges to the uptake of the fuels and gain knowledge to bridge the gap between technological prowess and governance aspects within the sector.

   i. Rob Stevens, Topsoe

      Rob Stevens is the Sector Lead for Green Fuels and Power-to-X at Topsoe and has immense experience with the ammonia energy and fuel value chain.

   ii. Jesse Fahnestock, Global Maritime Forum

      Jesse Fahnestock is the Head of Research and Analysis at Global Maritime Forum and works extensively with research on zero-emission fuels.

   iii. Navid Ostadian-Binai, Maersk Tankers

      Navid Ostadian-Binai is the Head of Green vessels and Fuels at Maersk Tankers and has experience with promoting green shipping.

   iv. Conor Furstenberg, Furstenberg Maritime Advisory

      Conor Furstenberg is a partner at his firm Furstenberg Maritime Advisory and works extensively with the maritime and offshore sectors.

2. Stakeholder interviews
   - The interviews are semi-structured to gain the insights of the various experts regarding the concept of green fuels for the maritime sector. This is also done to gauge where the sector currently stands with respect to alternative fuels. Semi-structured interviews help to not only gain valuable knowledge from industry experts but also learn about professional perspective on the topic. The stakeholder interviews were conducted online.
3. Pooling of data, development and analysis of stakeholder maps
   - Once the interviews have been conducted, the data is studied, and the qualitative information is put together in the form of a map to better visualize the main themes (Ahmad and Xu, 2021).

Chapter 4: Economic Analysis of Green Ammonia Production Chain

Fuel is a vital energy source for smooth functioning and operation of the ship and thereby it is also the major contributor to the greenhouse gas (GHG) emissions its adverse impact on the environment. Hence, there are compelling reasons for the shipping industry to shift towards green fuels to support the climate objectives, foremost among these being the reduction of GHG emissions and the subsequent socio-economic impacts on the surrounding environment.

As highlighted previously, the shipping sector emits 2.9% emissions globally (European Commission, 2013). The fuel usage in the shipping sector is dominated by heavy fuels oils or marine diesel which are residual oils from the crude oil refining process. Combustion of these fuels releases high concentrations of carbon dioxide (CO_2), sulphur oxides (SOx) and nitrogen oxides (NOx) which have detrimental effects on the environment. Hence it is imperative to delve into the type of fuels under consideration within the shipping sector and explore how a low carbon transition can be brought about through more sustainable choices.

4.1. Alternative Fuels-An Ongoing Debate

There is an increasing concern on the use of fossil fuels due to its destructive and adverse impact on the environment and global climate change. This has prompted the search for alternative fuels, having efficiencies similar to those conventional fuels, those are sustainable to support net-zero and climate goals, and can be produced through viable technologies.

This research focuses on economic analysis of the use of ammonia as a green alternative fuel for the shipping industry after a brief evaluation of LNG and methanol.

4.1.1. LNG-Potentials for Shipping

Liquified Natural Gas (LNG) is being hailed as an appealing and cleaner option to replace heavy fuel oil for ships. The LNG infrastructure is more straightforward in locations where natural gas has been previously used as an energy source, allowing for better utilization of its energy density. The use of LNG as maritime fuels offers the diversification of natural gas and a shift away from marine fuel oil which emits 3.15 tonnes of CO_2 per tonne of fuel oil (Marine Benchmark, 2020) consumed in contrast to LNG which mainly consists of methane, resulting in reduction of carbon emissions up to 25% (Pavlenko et al., 2020).

The production process of LNG starts off with the feedstock as natural gas, which is then liquified at extremely low temperatures (minus 150 Deg. C), after effectively removing heavier hydrocarbons as well as impurities such as carbon, sulphur and nitrogen, retaining the main component methane. Use of LNG as fuel reduces pollutants such as NOx and SOx emissions that are pressing concerns for the maritime industry. SOx emissions cause health concerns for the populations living close to the ports and coasts, while NOx emissions cause adverse effects to human life and aquatic ecosystems.

A major concern for LNG is the potential of methane slip. Methane slip occurs when unburned methane escapes into the atmosphere during the combustion of LNG in engines. This is extremely dangerous due to the high global warming potential of unburned methane, which is 30 times that of CO_2 (Oliver Sachgau, 2022). The methane slip poses a much larger conundrum than CO_2emissions and while engines optimization can reduce methane slip, the risk of its release can never be eliminated. Even though methane's atmospheric lifetime is smaller than CO_2, its environmental impact is higher, creating irreparable damage (Schmidt and Heidt, 2014).

Furthermore, LNG is extracted from natural gas, eventually perpetuating the fossil fuel dilemma, creating embedded practices of the carbon lock-in within the shipping sector. This problem arises from choosing the path of least resistance- using LNG as a 'cleaner' alternative, despite having consequences which only exacerbate climate change.

Notably, the IMO lacks specific regulations for methane slip, which diminishes accountability in cases where it occurs during the combustion process. Thus, the disadvantages associated with LNG outweigh its advantages. It can be concluded that while LNG has a good energy density, is not a suitable alternative that the shipping sector should be investing in.

4.1.2. Methanol-Potentials for Shipping

Another intriguing fuel option under consideration is methanol. Similar to LNG, the main feedstock for methanol is natural gas or coal and is produced through catalytic conversion of syngas to methanol. While methanol has generally been associated with the chemical industry, it is being viewed as a prospective fuel for the maritime sector.

A remarkable advantage of methanol is it doesn't emit sulphur which aligns with the IMO's goal of reducing sulphur from the atmosphere. This is particularly significant to the shipping sector, as it reduces emissions right from the outset of the production chain. However, the energy density of methanol presents a challenge in terms of its role in the low carbon transition of the shipping sector. Additionally, methanol has a low flash point and is corrosive which could pose safety concerns due to the explosive nature of alcohol fuels (Lloyd's

Register, n.d.). This demands development of new infrastructure should methanol be incorporated in the fuel mix for shipping.

To facilitate low carbon transitions, the industry must rethink its fuel production methods, requiring elimination of feedstock like natural gas and coal if the fuel needs to be considered 'sustainable'. The conventional production of methanol involves methane to produce the intermediate product syngas, which is then reacted with steam (H_2O) to produce methanol. Alternatively, methanol can be produced from biomass which gives methane (bio-methanol) or biogenic CO_2 reacted with renewable hydrogen (green methanol) (Technology Data for Renewable Fuels, 2023; "Technological data," n.d.). The main component in green methanol is tied to biomass which is an immense challenge to navigate.

Additionally, methanol combustion results in the release of CO_2 which contradicts the purpose of producing green fuels, especially when considering the long-term goal of carbon neutrality. In conclusion, although methanol seems like a much better alternative than LNG and heavy fuel oils (HFOs), it does not address the issue of CO_2 emissions. Additionally, it poses problems onto food systems to provide much needed feedstock for its production.

4.1.3. Green Ammonia-Potentials for Shipping

Ammonia is increasingly gaining popularity as a potential alternative fuel for the shipping sector that is greener and sustainable. Ammonia has already been a primary feed for making fertilizers and is widely synthesized through the Haber-Bosch synthesis process, which relies on feedstock like natural gas, liquid hydrocarbons (e.g., naphtha) or coal (through gasification) for its production (K. Rouwenhorst et al., 2022). This method of producing ammonia heavily emits CO_2 and other pollutants and is not sustainable in view of the net zero carbon and climate objectives. In the current environmental context, there is a growing focus on production of green ammonia that is produced through renewable energy sources. The reason for green ammonia gaining wider popularity is because, unlike other alternative fuels like LNG and Methanol, green ammonia stands out as the option which could help the shipping sector achieve carbon neutrality and align with the IMO and the EU's climate targets.

Green ammonia doesn't emit SOx and NOx particles thus aligning with the IMO's goal for reduction of these pollutants. Consequently, the adoption of ammonia as a maritime fuel can lead to reduced investments in engine scrubbing technologies. The ammonia molecule consists of the H_2 and N_2 molecules which are easily and abundantly available respectively in the water and in the air. Furthermore, there is no risk of methane slip occurring during the combustion of ammonia, making it an obvious and advantageous addition to the fuel mix. The production of green ammonia requires straightforward technologies such as electrolysers and cryogenic air separation units which are readily available in the market.

Although ammonia has far more advantages than methanol and LNG as an alternative fuel, there are still certain challenges that need to be addressed. Ammonia is a toxic gas and requires refrigeration to be safely stored, but due to its gaseous nature at ambient temperatures and pungent smell, it can be easily detected in the air at concentrations of 5-50 ppm (Alfa Laval et al., 2020). This implies that as ammonia emerged as a fuel for the maritime sector, specialized safety and handling standards need to be developed for use.

In light of EU's goal to be carbon neutral by 2050, ammonia stands out as the optimal choice to decarbonize the maritime sector. Although the green ammonia market is still a niche one, developing it is an important solution for facilitating a low carbon transition in the maritime sector. While investments are needed for all fuels like green LNG, methanol or ammonia, it might be counterproductive to produce fuels that emit greenhouse gases upon combustion when stiving for low carbon futures.

Considering the comparisons among alternative fuels and recognizing the advantage of green ammonia over the rest, it is crucial to develop pathways which will test the feasibility of green ammonia production. The next section will explore how the existing process of ammonia through conventional feedstocks can be transformed into a more sustainable one, *enabling a low carbon transition within the maritime sector.*

4.2. Developing Technological Pathways for Green Ammonia

Developing technological pathways is a way to create a roadmap to a low carbon future for maritime transport as envisioned by the European Union. The following section will dive into the description of the components required to produce a green value chain. Additionally, the following chapter will answer the following sub-research questions:

"*What are the technological pathways available for the shipping industry?";* and

"Are there solutions available that are economically feasible for emission reduction within the shipping sector?"

To develop these technological pathways, it is important to study the components and processes that make up the system for green fuels for the maritime transport. The system can be broken down into the following categories (Ince et al., 2021)

- **The Energy Source**- the source point of where the power is generated for rest of the system components. The generation of power from renewable sources such as solar power and wind power are relevant here to study the technological pathways for green ammonia.
- **The Feedstock-** in the context of green ammonia, key chemical components of ammonia are nitrogen (N_2) and hydrogen (H_2) that are synthesized to produce ammonia. For the production of green ammonia, the hydrogen is to be produced through green technology e.g., water hydrolysis and by using renewable energy source. Nitrogen is available in abundance in the air, and it is required to be separated from air to produce pure nitrogen. For the production of green ammonia, the nitrogen is produced through Air Separation Unit (ASU) by using renewable energy source.
- **Ammonia Synthesis Processes**- The feedstocks as produced above are synthesized through high-pressure Haber-Bosch process in presence of iron-based catalyst to produce ammonia. Use of renewable energy is vital to qualify such-produced ammonia to be green ammonia. Ammonia is separated from unconverted feedstocks and other impurities, is liquefied through refrigeration, and is stored under refrigerated conditions. Below diagram depicts a high-level production lifecycle of green ammonia.

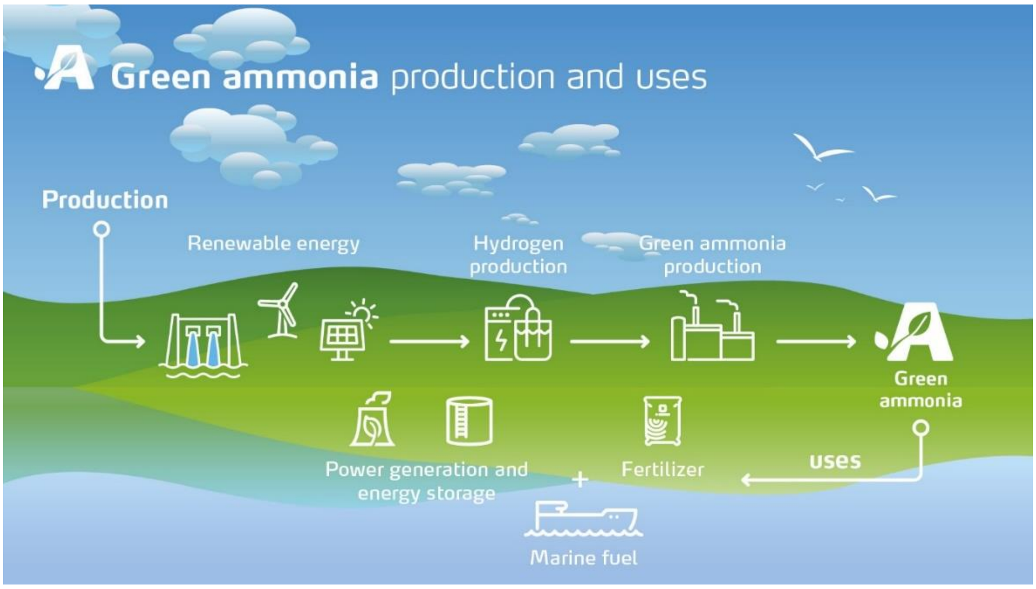

Figure 2: Image Source: Can green ammonia stop our addiction to fossil fuels? | World Economic Forum

The next section describes the above components in detail.

4.2.1. The Energy Source

To achieve the EU's objective of carbon neutrality, it is imperative to optimize the energy systems to accommodate fluctuating energy sources. In this analysis, renewable energy is the primary focus, with no consideration for fossil fuel-based technologies. The central objective is to explore the potential long-term benefits arising from the synergies of fluctuating renewable energy sources with the rest of the ammonia value chain.

A segment of the analysis focuses on increasing the capacity of renewable energy sources and the impact of that on the energy system. The first cog in the system involves energy production which can be obtained from renewable sources such as wind and solar photovoltaic (PV) modules. Renewable energy can be assessed through the capacity factor which is a ratio that compares the actual electricity production over a specific period to the maximum output it can produce over that given period of time.

The capacity factor gives valuable insights into the number of hours a technology is available to produce electricity (Jorge Morales Pedraza, 2019). This is a crucial metric to evaluate whether the given technology will be able to produce the required output if integrated into the energy system and whether investments in its expansion are justified. It also serves as a key economic indicator as technologies with a higher capacity factor gives higher energy outputs.

4.2.2. The Feedstock – Hydrogen and Nitrogen Production

Hydrogen Production

The initial phase for any PtX project is the production of hydrogen via the process of electrolysis. Hydrogen fuels is an attractive option because of its high energy density (120 kJ/g) as compared any other hydrocarbon fuels e.g., gasoline (Møller et al., 2017) and it is absolutely environment friendly since it emits only water vapours. However, hydrogen production demands substantial energy input due to its low energy content per volume which is based on fossil feedstocks and fuels.

There are various methods to produce hydrogen including chemical processes such as reformers, gasifiers and thermochemical cycles fed by fossil fuels or biomass. Alternatively, this process can also be done through electrolysis by splitting water into its primary elements, hydrogen and oxygen Hydrogen production through water electrolysis technology has gained momentum in recent times after the 2010s, which is further driven by the reduction in the cost of electricity through renewable sources such as solar PV and wind energy (Ince et al., 2021).

Hydrogen is a valuable feedstock not only for ammonia, but it can be converted to other fuels such as methanol, jet fuel etc. to reduce the consumption of fossil fuels in heavy transport, shipping, and aviation (European Environment Agency, 2021). It is important to understand the chemistry of hydrogen production through electrolysis. The main principle of an electrolyser is using electricity to split the water molecule into their constituents:

$$2H_2O \rightarrow 2H_2 + O_2$$

Presently, three types of electrolysers are available, Alkaline electrolysis cells (AECs), Polymer electrolyte membrane electrolysis cells (PEMECs), and Solid oxide electrolysis cells (SOECs). Electrolysers serve as the main component in the production of hydrogen. Their feasibility when combined with different renewable energy sources will be evaluated to learn about the best feasible option.

Hydrogen is colour sorted based on its origin and based on the method of production. There are several categories of hydrogen namely, white, grey, blue, turquoise, and green. White hydrogen is a naturally occurring version that can occasionally be found underground, but there are not many viable methods of extracting this. So, hydrogen consuming industries generate it from feedstocks such as hydrocarbons or water.

1. **Conventional Hydrogen (Grey Hydrogen):**
   This is the most prevalent and widely used technology to produce hydrogen from natural gas, methane or other hydrocarbons that are processed via steam reforming to produce grey hydrogen. Grey hydrogen relies on carbon-intensive fossil fuels and emits significant amount of methane and CO_2 emissions during the production (National Grid, n.d.).

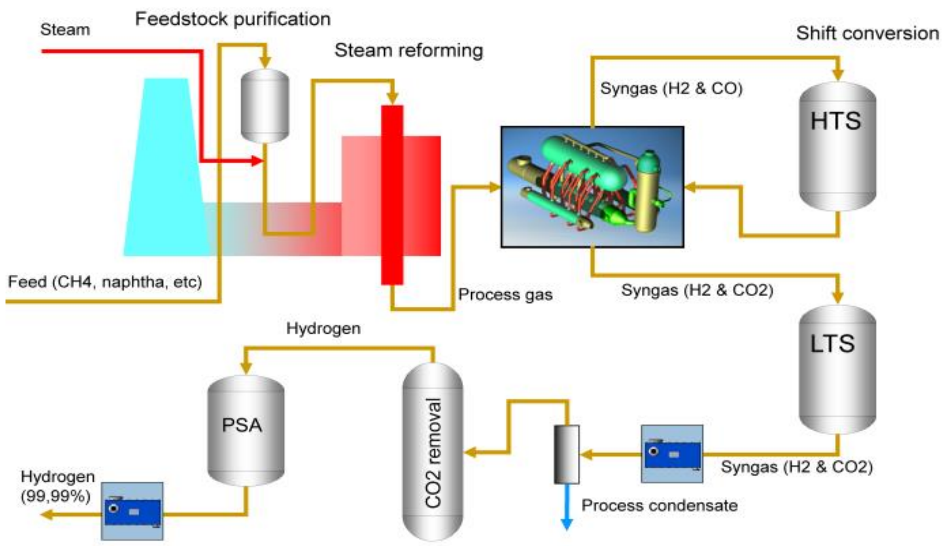

Figure 3: Conventional Hydrogen production method. Source: Enggbook Website

2. Blue Hydrogen

When the hydrogen that is produced via the conventional process as stated above but it is further enhanced to capture the CO_2 emissions through carbon capture and sequestration technologies, such hydrogen is categorized as Blue Hydrogen. This type of hydrogen is often described as 'low-carbon hydrogen' because though the emissions are an inherent part of the process, but they are captured in the integrated technology thus reducing CO_2 emissions (National Grid, n.d.).

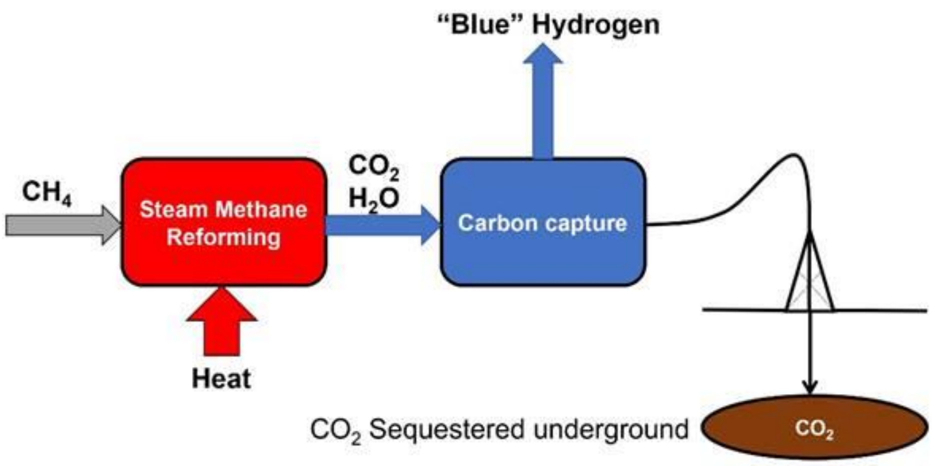

Figure 4: Blue Hydrogen Production Process. Source: SLB Website

3. **Turquoise Hydrogen**

Turquoise hydrogen is produced through pyrolysis of methane to convert that into hydrogen and solid carbon. This emerging technology allows hydrogen production while avoiding CO2 emissions. Carbon is stored in a solid form (ENGIE Research & Innovation.) Using fossil natural gas, turquoise hydrogen performs significantly better than both grey and blue hydrogen, but less than green hydrogen based on water electrolysis which is having almost negligible production emissions.

4. **Pink hydrogen**

This type of hydrogen is produced from energy that comes from nuclear power. However, potential of hydrogen through this process is unexplored due to the limited number of nuclear power plants (Fraunhofer (IEE), 2020).

5. **Green hydrogen**

Hydrogen that is produced from electrolysis, which is powered through renewable electricity resulting in a process that is emissions free. This type of hydrogen production is the only one that can be termed as truly sustainable. In the following section, the pathways will be centred around green hydrogen as the feedstock, aligning with the objective of assessing the feasibility of a green ammonia production chain.

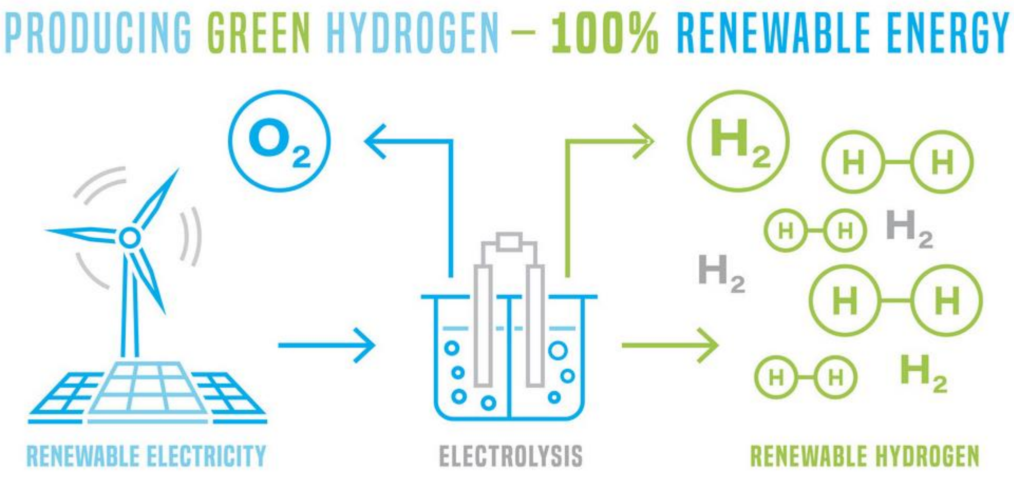

Figure 5: Green Hydrogen Production Process. Source: Washington State University Website

Nitrogen Production

Typically, nitrogen required for ammonia production is produced in a cryogenic air separation system, in which atmospheric air feed is compressed and cooled to remove water vapor, carbon dioxide, and hydrocarbons before it enters the Air Separation Unit (ASU), where a distillation column separates the air into nitrogen gas and an oxygen-enriched waste stream. The nitrogen gas then flows into the supply line to downstream applications, in this case for ammonia production.

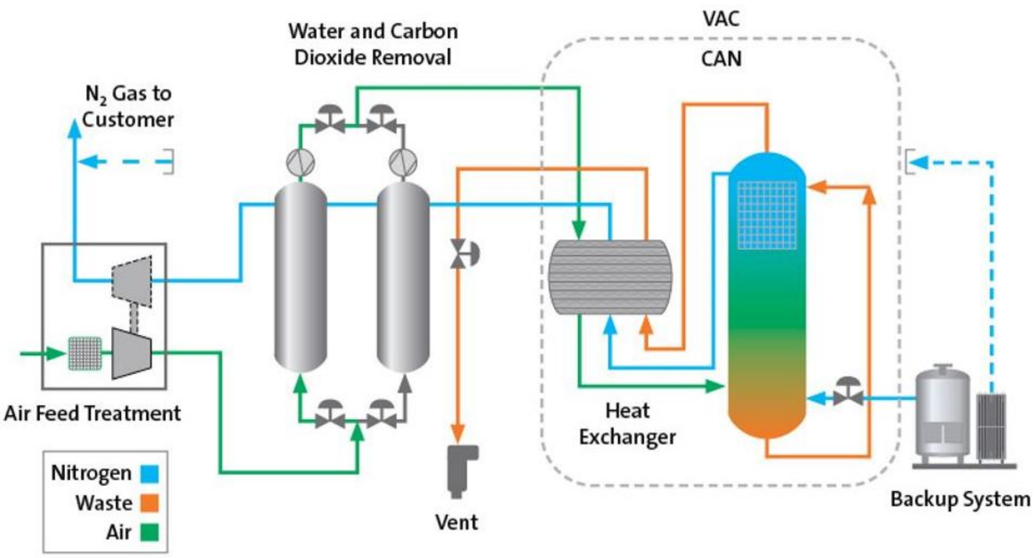

Figure 6: Nitrogen Production Process. Source: Air Products Website

4.2.3. Ammonia Synthesis Processes

Conventional ammonia is synthesized through the Haber-Bosch process with hydrogen sourced from fossil fuels such as coal, naptha and methane. Blue ammonia follows the same process to brown ammonia, but hydrogen production is paired with carbon capture to reduce the carbon footprint (Rouwenhorst et al., 2020). Below diagram depicts the ammonia synthesis process.

Green ammonia is produced from the same synthesis process as above however, the only difference is that hydrogen, nitrogen, and ammonia synthesis technologies rely fully on renewable energy and green hydrogen produced through water hydrolysis, without the use of fossil feedstocks like methane, is used as the feedstock.

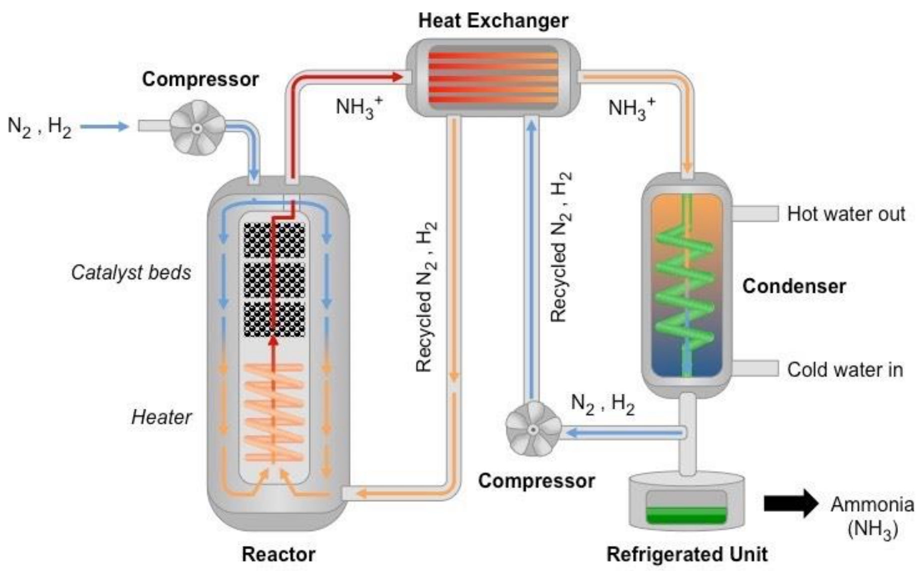

Figure 7: Ammonia Synthesis Process diagram. Source: Bio Ninja Website

In a conventional steam-methane reformer (SMR) process-based ammonia plants, the process commences with de-sulphurisation of methane which is then fed into primary and secondary steam methane reformers to produce synthesis gas which comprises primarily of Hydrogen (H2) and Carbon dioxide (CO_2). After the removal of CO_2, the synthesis gas is purified to produce grey or blue hydrogen depending on whether the process uses CO_2 capture step. The hydrogen thus produced is mixed with nitrogen from ASU and in the final step this mixture of hydrogen and nitrogen is sent to ammonia synthesis loop in a Haber-Bosch synthesis reactor to produce ammonia (Efig, n.d.). Ammonia formed is liquefied by using refrigeration and is sent to storage for further usage.

The key component that is required for green ammonia is green hydrogen which is obtained through electrolysis. The next component is nitrogen which is directly sourced from air through a cryogenic air separation unit, which efficiently separates oxygen to give pure N_2. Finally, H_2 and N_2 are compressed and fed into the Haber-Bosch reactor that can operated either at a low or high pressure resulting in production of green ammonia (Technology data for Renewable fuels, 2023). Substitution of steam reforming process with electrolysis will directly reduce emissions from the production chain.

4.2.4. Ammonia as a Green Alternative for Shipping

Ammonia is a gas which is highly used in the agricultural sector and the industrial sector with significant emissions resulting in 450Mt of CO_2 annually. China is the biggest producer of

Ammonia, taking up 32% of the production (Simonelli et al., n.d.). In the EU, ammonia is produced with natural gas (NG) as the main feedstock, given the prevalence of NG in energy generation in the EU.

The reason to choose ammonia as a fuel for the shipping industry is attributed to its versatility as opposed to hydrogen. Ammonia has a higher volumetric energy density than hydrogen by 30% and is easier to store than liquid hydrogen. The stable nature and low storage pressure of ammonia make it an ideal fuel for maritime transport due to long travel distances (Muhammad Aziz et al., 2020).

This research is primarily concerned with the production of green ammonia and involves a comparative cost analysis with conventional ammonia derived from natural gas. Developing scenarios involves understanding the role of each technological component within the entire system. Once the system functions have been identified, the next step is to develop a combination of different technologies to learn which can be integrated to form a value chain with the most socio-economic benefit. The next section will elaborate further the system and the assumptions are made to form a green ammonia value chain.

4.3. Preliminary Analysis

Now that the components of the system are elaborated upon, and alternative options have been evaluated, the pathways can be developed. The aim is to compare various production pathways for green ammonia to learn which is the most feasible. The analysis is based on the premise that the energy source is harnessed from renewable sources like onshore and offshore wind energy and solar PV energy. The analysis also takes into consideration that the hydrogen feedstock is produced from an electrolyser and the nitrogen is obtained from a cryogenic air separation unit (ASU).

4.3.1. State-Of-the-Art

Adopting a bottom-up approach to understand the production of green ammonia, the calculation of the required energy for ammonia production is imperative to calculate the capacity of renewable energy required for the system. This calculation is further used to calculate the renewable energy generation capacity required for the green ammonia production. Once the energy demand and the generation capacities are established, a comparison of the renewable energy sources reveals the most efficient and cost-effective way to produce the energy for the whole process of green ammonia production. Following description provides the state of art for green ammonia production process.

1. Electrolyser- AEC/PEM/SOEC

   As stated earlier, to produce green ammonia it requires the green hydrogen feedstock that is generated based on water hydrolysis method and by using renewable energy sources. The water electrolyser is an energy intensive component in green hydrogen production, utilising about **94.4%** of energy in the entire process (Technology Data for Renewable Fuels, 2023). Water electrolysers serve as the main component in the production of green hydrogen. Presently, there are three types of water electrolysers available, namely:

   1. Alkaline Electrolysis Cells (AEC),
   2. Polymer Electrolyte Membrane Electrolysis Cells (PEMEC), and
   3. Solid Oxide Electrolysis Cells (SOEC).

   Three types of electrolysers stated above are available in the market today with varying hydrogen production efficiencies and distinct advantages. The AEC and PEMEC have similar efficiencies, but AEC is more mature and have higher densities, making them more efficient and capable of a higher rate of H_2 production (Technology Data for Renewable Fuels, 2023).

   As electrolysis for H_2 production is the largest energy consumer in the process of NH_3 production, the energy demand is **1.69 TWh/y** to power the electrolyser.

2. Air Separation Unit

   Nitrogen is produced from the cryogenic ASU, and it utilises **2.2%** of the total energy required for entire green ammonia production process. (Technology Data for Renewable Fuels, 2023). Using the same energy efficiency quotient as that of hydrogen, the ASU will require **0.04 TWh/y** of energy.

3. The Haber-Bosch (HB) process

   Ammonia is produced industrially through thermochemical synthesis of hydrogen and nitrogen feedstocks by the Haber-Bosch (HB) process. As the research is concerned with green ammonia, the ammonia synthesis process is integrated with the water electrolyser and an air separation unit to get hydrogen and nitrogen feedstocks. Supplementary units and additional components are required to compress feedstocks to required pressure for HB synthesis, and refrigeration facility to liquefy and separate ammonia. The hydrogen and nitrogen are first compressed within the make-up compressor and then entered into the synthesis loop on an iron catalyst bed producing ammonia. The ammonia is condensed while the rest of the uncreated reactants are separated and then fed into the loop once again.

The efficiency of Haber-Bosch process where hydrogen is obtained from electrolysis is 56% (Trevor Brown, 2019). The energy efficiency of a system is the pivotal aspect of system output and hence the more efficient a system will be, the lower energy it will consume and the higher the output (European Environment Agency, 2023). Based on this description, the energy required to produce green ammonia of **1.0 TWh/y** sums up to be **1.79 TWh/y**.

The supplementary units account for **3.3%** of the overall energy consumption (Technology Data for Renewable Fuels, 2023). The compressor consumes **2.9%** of the energy input within the loop and the condensation unit consumes **0.3%.** Based on these quotients, the compressor will require **0.05 TWh/y** and the condenser will require **0.01 TWh/y** of energy

Now that the state of the art has been presented, the various pathways can be compared. It is important present a base scenario which shows the current methodology of ammonia synthesis.

Table 1: Technology pathway for conventional ammonia

Conventional Ammonia Production							
Pathway	**Demand**	**Energy Source**	**Hydrogen Source**	**Nitrogen Source**	**Feedstocks**	**Ammonia Synthesis**	**Final Product**
P1	Variable	Natural Gas	Steam Methane Reformer (SMR)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Haber-Bosch Process	Grey Ammonia

Table 2: Technology pathways for thermochemical synthesis of green ammonia

Green Ammonia Production via Thermochemical Synthesis							
Pathway	**Demand**	**Energy Source**	**Hydrogen Source**	**Nitrogen Source**	**Feedstocks**	**Ammonia Synthesis**	**Final Product**
P2	Variable	Onshore Wind	Electrolysis (AEC/PEM/SOEC)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Thermochemical Haber-Bosch Process	Green Ammonia
P3	Variable	Offshore Wind	Electrolysis (AEC/PEM/SOEC)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Thermochemical Haber-Bosch Process	Green Ammonia
P4	Variable	Solar PV	Electrolysis (AEC/PEM/SOEC)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Thermochemical Haber-Bosch Process	Green Ammonia

Table 3: Technology pathways for electrochemical synthesis of green ammonia

Green Ammonia Production via Electrochemical Synthesis							
Pathway	**Demand**	**Energy Source**	**Hydrogen Source**	**Nitrogen Source**	**Feedstocks**	**Ammonia Synthesis**	**Final Product**
P5	Variable	Onshore Wind	Electrolysis (AEC/PEM/SOEC)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Electrochemical Synthesis of NH_3	Green Ammonia
P6	Variable	Offshore Wind	Electrolysis (AEC/PEM/SOEC)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Electrochemical Synthesis of NH_3	Green Ammonia
P7	Variable	Solar PV	Electrolysis (AEC/PEM/SOEC)	Air Separation Unit (ASU)	Hydrogen & Nitrogen	Electrochemical Synthesis of NH_3	Green Ammonia

4.3.2. Preliminary Ammonia Demand

The initial energy demand for the production of 523 Tons per Day (TPD) green ammonia is assumed to be 1.0 Terra Watt Hours per Year (TWh/y). Based on the demand of ammonia, the values for the feedstock and the corresponding data are sourced from the Danish Energy Agency's catalogues. (Technology Data for Renewable Fuels, 2023).

Based on the mass energy balance of H_2 and N_2 provided by the (Technology Data for Renewable Fuels, 2023), feedstock required for 523 tons of NH_3 can be obtained. The more important aspect of developing the pathways deals with the power consumption for green ammonia production.

Table 4: Initial Ammonia Demand

	Unit	**Value**
Green ammonia production demand	TWh/y	1.00
Efficiency of Haber-Bosch process	%	56%
Energy demand required	TWh/y	**1.79**

Table 5: Power Consumption for green ammonia

1. Overall Power Consumption		
Process Components	**Energy Contribution**	**Energy Consumption**
Electrolyser	94.4%	192.43
ASU	2.2%	4.48
Syngas & makeup compressor	2.9%	5.91
Ammonia refrigeration	0.5%	1.02
Total	**MW/y**	**203.85**
	TWh/y	**1.79**

4.4. Pathways-Developing the Future for The Maritime Sector.

4.4.1. Pathway 1- Conventional Natural Gas-Based Production

Conventional ammonia production utilises the Steam methane reforming (SMR) to produce hydrogen where the energy source is natural gas. This pathway produces a large amount of CO_2 in the production, emphasizing the need for technological intervention to mitigate the emissions. This highlights the necessity to shift to more renewable based production pathways which will enable the ammonia production chain to become carbon neutral in line with EU's goals for 2050.

4.4.2. Pathway- Green Ammonia based on Thermochemical Synthesis

Pathway 2: Onshore Wind

The conventional pathway as outlined in *Pathway 1- Conventional Natural Gas-Based Production* highlights the need of transitioning to renewable energy sources. This pathway is designed to produce ammonia through the thermochemical process of Haber Bosch process with feedstocks produced from renewable energy as opposed to the base scenario. Onshore wind is selected to supply the electricity to the electrolyser and the air separation unit for H_2 and N_2 as well as ammonia synthesis.

Table 6: Energy requirements for Onshore Wind

Parameter	Unit	Value
Total energy required (demand)	TWh/y	1.79
Wind farm capacity required	MW/y	525
Generating capacity of one turbine	MW/y	4.20
Number of onshore wind turbines required	Turbines	125
Energy Output	MW/y	525

Having conducted the preliminary analysis of the energy requirements of all system components within the ammonia plant, the onshore wind capacity can be designed. Onshore wind energy has the capacity factor of 39%, having full load hours of 3400 hours. A single turbine can produce 4.2 MW of power and hence to produce 1.79 TWh/y of energy, a wind farm of 525 MW producing 1.79 TWh/y of energy would be required based on its capacity factor.

Pathway 3: Offshore Wind

Similar to earlier pathway, this pathway is designed in a similar manner and offshore wind is taken as the source of renewable energy.

Table 7: Energy Requirements for Offshore Wind

Parameter	Unit	Value
Total energy required (demand)	TWh/y	1.79
Wind farm capacity required	MW/y	420
Generating capacity of one turbine	MW/y	8.40
Number of offshore wind turbines required	Turbines	50
Energy Output	MW/y	420

In comparison to onshore wind, offshore wind exhibits a higher capacity factor, coming up to 50%. This means that offshore wind energy production is higher than land-based turbines. The individual power production of the turbine is also higher, resulting in a reduced number of turbines required to generate an equivalent amount of energy. Based on the parameters, an offshore wind plant with a capacity of 420 MW will produce the energy required to supplement all the units for an ammonia plant of 1TWh/y. While this is advantageous, the investment in offshore wind plants is double that of onshore wind plants.

Pathway 4: Solar PV

In this pathway, energy is derived from utility scale PV modules which produce a DC current. Similar to previous pathways, the ammonia is synthesised through Haber Bosch synthesis and the energy required for the feedstocks is provided through solar energy.

Table 8: Energy Requirements for Solar PV

Parameter	Unit	Value
Electricity required	TWh	1.79
Solar Modules required	MW	76,218
Generating capacity of one module	MW	0.01

The table indicates that to supply energy of 1.79 TWh which is equivalent to an ammonia plant of 523 TPD, a solar plant of 1330 MW is required. Solar energy has a capacity factor of 15% which is significantly less than onshore and offshore wind. Thus, it is necessary to gauge whether investments in solar plants will be enough for a green ammonia plant.

4.4.3. Pathway- Green Ammonia based on Electrochemical Synthesis

There are many advantages of producing green ammonia through electrolysis of hydrogen, but it also means that additional technological components are added in the production chain, thus increasing capital costs in the process because the technologies are not mature yet. In the conventional production of ammonia from the Haber Bosch process requires technologies which first generate H_2 and N_2 as the feedstock, which are then required to be compressed through auxiliary units and then converted to NH_3. In Electrochemical synthesis, ammonia is synthesised within one cell, which would mean that the compact design would reduce investment costs and increase the energy efficiency of the process (Lazouski et al., n.d.).

Parameters for Electrochemical Synthesis

The system components related to the electrochemical synthesis vary with respect to the conventional method of ammonia production. The main characteristic of electrochemical synthesis is the reduction of dinitrogen due to its high activation barrier (Rouwenhorst et al., 2020) and this mainly depends on the catalyst, electrolyte and opening conditions of the reaction. Additionally, the temperature and the pressure at which ammonia is synthesised are deciding factors in the efficiency of ammonia yield.

Electrochemical synthesis can be done through either low temperature or high temperature path. In the low temperature path, an aqueous cell is used which can also serve as a source for H_2. Although the low temperature aqueous cell yields very low ammonia. In the high temperature path, a non-aqueous cell is used, where H_2 would have to be produced separately, but this path doesn't have good efficiency (Technology Data for Renewable Fuels, 2023). The advantage for electrochemical synthesis of NH_3 is the ease of production for smaller demand.

Production process

The electrochemical synthesis of ammonia is of interest as it reduces nitrogen electrochemically with hydrogen in a single cell. H_2 as a feedstock can be obtained either from water or through electrolysis where the constituents are spilt and then fed onto the anode where they oxidise (Lazouski et al., n.d.). Nitrogen can be obtained directly from the air and reduced at the cathode. This pathway essentially reacts H_2 and N_2 in one cell (Rouwenhorst et al., 2020).

As mentioned earlier, both the aqueous and non-aqueous pathways suffer from low yields, but the high temperature pathway showcases better yields, although suffers from low energy efficiency due to separate production of H_2 from the electrolyser, and high cell potentials (Rezaie et al., 2023). Thus, for this pathway, it is assumed that H_2 is obtained through the electrolyser and nitrogen is obtained through the air separation unit as it reduces the introduction of other elements such as oxygen and argon and provides pure nitrogen for the analysis to ensure the catalysts in the electrochemical reactor are not damaged (Lazouski et al., n.d.).

Based on the parameters described, the economic analysis for electrochemical synthesis of ammonia can be done. The highest efficiency obtained through the Lithium mediated ENRR was 25.66% in a non-aqueous media and hence this metric is assumed for this analysis due to higher production rate (Rezaie et al., 2023). Although the energy efficiency is lower, the TRL for this method of ammonia synthesis is higher, coming upto 4 (Rezaie et al., 2023).

The energy consumed by all components is assumed to be obtained from onshore or offshore wind, or solar PV. The capacities for the renewable energy set-up will depend on the energy required by the components of the electrochemical synthesis.

4.4.4. Pathway- Hybrid Ammonia

A hybrid ammonia plant is an interesting configuration. It is a grey ammonia plant having components such as the primary reformer or steam methane reformer for production of hydrogen and steam and the secondary reformer which adds N_2 into the mix. H_2 and then N_2 are then added to the Haber Bosch synthesis loop for NH_3 production (Technology Data for Renewable Fuels, 2023). But a hybrid plant retrofits units like the steam methane reformer to an electrolyser to introduce a "green" component in the mix.

In this scenario, the units in conventional ammonia production remain the same and an additional electrolyser is added to produce green ammonia. Taking inspiration from (Haldar topsoe, 2020), 10% of green ammonia is produced through green hydrogen as a feedstock and the rest is through the conventional process.

As ammonia production will rise, it will mean new ammonia plants will have to be constructed which adhere to green ammonia production principles. A hybrid ammonia plant runs on the principle that the existing plant can be retrofitted by replacing units which have high CO_2 emissions such as the primary reformer to green technological components like the electrolyser.

Table 9: Power Consumption for "green ammonia"

Overall Power consumption		
Process Components	**Energy Contribution**	**Energy Consumption**
Electrolyser	94.4%	31.25
ASU	2.2%	0.73
Syngas & make-up compressor	2.9%	0.96
Ammonia refrigeration	0.5%	0.17
Total	**MW/y**	**33.11**
	TWh/y	**0.29**

Table 10: Power Consumption for "gray ammonia"

Overall Power consumption		
Process Components	**Energy Contribution**	**Energy Consumption**
Electrolyser	94.4%	93.75
ASU	2.2%	2.18
Syngas & make-up compressor	2.9%	2.88
Ammonia refrigeration	0.5%	0.50
Total	**MW/y**	**33.11**
	TWh/y	**0.29**

Similar to the Pathway- Green Ammonia, the hybrid ammonia is assumed to be connected to a renewable energy source like onshore or offshore wind, or a solar PV plant. The feedstock on an existing ammonia plant will have a primary and secondary reformer for H_2 and N_2.

Additionally, a small electrolyser needs to be connected to the plant to increase efforts to reduce CO_2 emissions.

4.5. Cost comparisons and economic feasibility assessment

The economic analysis for various ammonia production pathways provides an overview of the investment required to produce green ammonia. These costs encompass the establishment of the entire green ammonia chain starting with the energy sources such as onshore, offshore wind and solar PV. They also involve costs associated with the feedstock, comprising of green hydrogen produced through different electrolysers, as well as nitrogen produced through cryogenic distillation. Finally, it includes the cost of setting up of the NH_3 plant where the synthesis is done through the Haber-Bosch process, electrochemical synthesis or through a hybrid mixing of conventional and green technologies.

Based on the analysis the following costs are obtained:

Table 11: Total Investment Costs required.

		Energy Source-Investment	Total Costs		
			RE+AEC+ASU+PLANT	RE+PEM+ASU+PLANT	RE+SOEC+ASU+PLANT
Thermochemical Sythesis	Pathway-2	500 M€	2.15 Bn €	2.35 Bn €	4.67 Bn €
	Pathway-3	1 Bn€	4.32 Bn €	4.40 Bn €	5.09 Bn €
	Pathway-4	1 Bn€	2.85 Bn €	2.34 Bn €	5.31 Bn €
Electrochemical Synthesis	Pathway-5	500 M€	3.02 Bn €	3.43 Bn€	9.13 Bn €
	Pathway-6	1 Bn€	6.10 Bn €	6.30 Bn €	7.75 Bn €
	Pathway-7	1 Bn€	3.06 Bn €	3.38 Bn €	9.36 Bn €

The above table presents the costs associated with producing ammonia through green thermochemical and electrochemical pathways. The costs are impacted by different ammonia yields due to the energy efficiencies of both processes, influencing capacities of the energy source and the feedstock.

The cost associated with a hybrid ammonia plant is 800 million Euros, considerably lower than investment required for a fully green ammonia plant. In the hybrid ammonia pathways, only 10% of hydrogen is produced through electrolysis, resulting in sustainable reductions in the investment. This means that for a green transition for an ammonia economy, costs associated with hydrogen production play a crucial role.

Since hybrid ammonia majorly includes conventional technologies, the unit cost of NH_3 will remain the lowest out of all the pathways, coming up to 133 ton/ NH_3. However, it is important to emphasize that a hybrid ammonia plant doesn't provide the required solution of emission reduction in the long term as the feedstock is still derived from fossil fuels. To reach to the EU's goal of carbon neutrality, hybrid plants will ultimately need to be converted to fully green ammonia plants.

In the electrochemical pathway the costs of green ammonia are observed to be the highest. This can be attributed to the low efficiency of electrochemical synthesis, which in turn necessitates the design of a higher electrolyser capacity to achieve the desired ammonia output. This implies that electrochemical synthesis is not a feasible alternative based on technologies currently available in the market. The ammonia yields obtained from this process are incredibly low due to factors like faradaic efficiency and overall energy efficiency. This process should not be considered as economically feasible to produce ammonia unless the ammonia yields are substantially increased in the coming decades. A significant observation is that the energy efficiency of the pathway is extremely low, and hence results in twice the amount of energy required to produce a very low ammonia yield. Thus, this pathway needs much more improvement in terms of achieving faradaic efficiency and energy efficiency of the whole process to be considered commercially viable.

4.6. Looking toward a low carbon transition

Now that the preliminary calculations have determined the energy and feedstock requirement for 1TWh/y of ammonia demand, it can be extrapolated to the year 2050 to align with EU's goal of carbon neutrality. Until now, the ammonia industry has primarily served the agricultural industry and industrial applications. However, if the maritime sector is also set to adopt ammonia as a fuel, the demand for ammonia will increase.

The production of ammonia aligns with the maritime sector's goal to achieve net-zero or close to net zero emissions by 2050 as also set out by the IMO's revised strategy in 2023. Global shipping emitted 1076 million tons of CO_2 equivalent GHG in 2018. The sector accounted 1056 million tons of CO_2, and this is projected to rise around 130% by 2050 reaching 1279 million tons of CO_2 of 2008 emissions (International Maritime Organization, 2021). To reduce these emissions, efforts need to be made to incorporate green fuels such as ammonia which have a zero-carbon footprint when the entire production chain becomes completely free of emissions.

The current global production of ammonia is 180 million tons and to support the maritime sector in its pursuit of a low carbon transition, additional 150 million tons of ammonia is required (Alfa Laval et al., 2020). To meet this capacity of 150 million tons of ammonia or 775 TWh/y, renewable energy capacity will also have to simultaneously increase as observed in the previous section. Renewable energy production is entirely dependent on full load hours available in a year. This aspect, while unpredictable, affects the shipping sector directly and affects societal progress indirectly but is crucial to take into account when forming strategies for green ammonia production.

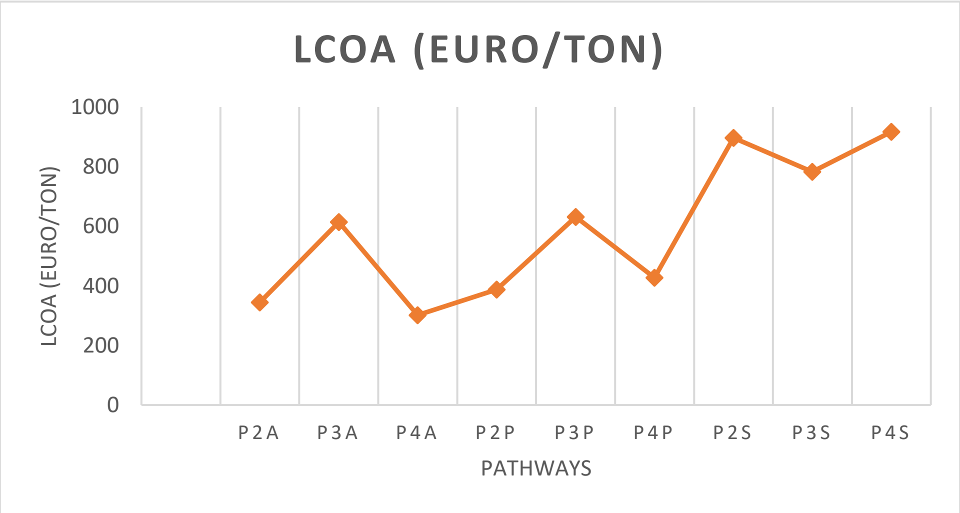

Figure 8: Levelized Cost of Thermochemical Green ammonia. Source: Self-made figure

Based on the projected 2050 ammonia demand of 775 TWh/y, to obtain the lowest LCOA to ensure feasibility of green ammonia production, involves combining onshore or solar energy with AEC or PEM as represented in *Figure 8: Levelized Cost of Thermochemical Green ammonia*. In contract, the SOEC pathways show the highest LCOA and incurs the highest costs for green ammonia production. The pathway P4A, that combines AEC or PEM with solar PV, exhibits the lowest LCOA of 302 Euro/ton NH_3. Onshore wind combined with AEC or PEM is equally competitive with an LCOA of 344 Euro/ton NH_3.

The analysis reveals that to ensure green ammonia is made feasible, renewable capacity needs to grow concurrently alongside the production and retrofitting of existing ammonia plants. The competitiveness of green ammonia can be amplified through economies of scale. When taking into account the total costs for green ammonia plant, the optimum pathway which is also competitive with the base scenario is one where the energy is obtained from an onshore wind farm at the rate of 27 Euro/MWh and hydrogen is produced at 5 Euro/kg through an AEC electrolyser. This results in the least cost for a green ammonia plant.

It is observed that a mere change of +1Euro/MWh changes the LCOA by 6 Euro/ton of NH_3, which highlights the significance of LCOE in determining the levelized cost of ammonia as well.

Based on the analysis, the most feasible alternative as it stands is hybrid ammonia where a certain percentage of hydrogen (10%) is produced through electrolysis. A smaller electrolyser capacity leads to lower costs overall costs for NH_3 production. This presents an interesting option for a short-term solution for the shipping sector where the ammonia plants can be fitted with a small-scale electrolyser which can eventually be scaled up for higher NH_3 demands for the future. Hybrid ammonia is a straightforward option that doesn't demand stringent changes in the current ammonia production infrastructure. However, there is a trade-off between the investment cost and the emissions which have to be rectified through strong market-based measures.

In comparison to the green Haber-Bosch process, the differences in costs are vast. The green HB pathway represents the future of ammonia production for the maritime sector. This will require changes in the current methods of production for ammonia where each segment of the production chain will require substantial scaling up until 2050 to reach the goal of carbon neutrality. The Haber-Bosch synthesis with green hydrogen production is pivotal to a achieve a low carbon transition in the maritime sector.

Chapter 5: Enhancing the Path to Low Carbon Transitions in Shipping

5.1. The Problem

The shipping sector plays an important role in the global economy by providing cost-effective logistics, fostering international economic relations and prosperity through global exports and imports (International Chamber of Shipping, n.d.). The shipping sector is instrumental for the development of global trade, nonetheless, it grapples with sustainability challenges.

Maritime transport is integral to the European commission's internal and external trade and serves as a crucial link between various islands and maritime regions worldwide. This comes with an environmental cost, contributing to large amount of greenhouse gases, amounting to 3-4% of the EU's total CO_2 emissions (European Commission, n.d.). Globally, the maritime sector alone is responsible for 2.9% of GHG emissions, which accounts for *1056 million tonnes of* CO_2 (International Maritime Organization, 2020). The EU's long-term ambitions may face setbacks unless efforts are taken to reduce emissions. Furthermore, there is also a lack of strong policies that can guide decarbonisation in this sector.

Becoming aware of the current challenges is the initial step to technological development and transformation. The International Maritime Organisation, a United Nations agency has developed a strategy focused on setting efficiency standards and promoting fossil free alternatives for fuels for the maritime industry. The initial IMO strategy encompasses policy actions designed to reduce the sector's emissions by at *least 50% until 2050*. The strategy was amended in 2023 to urge more ambitious actions in shipping with the goal of achieving *carbon neutrality or close to carbon neutrality in shipping*(International Maritime Organization, 2023) . While the strategy outlines long term goals, the question remains, *how is this to be done?*

The shipping sector faces several technological barriers in its endeavour to achieve low carbon transition, and a large portion is attributed to the scarcity of sustainable fuels. This scarcity is driven by the fact that fuel costs account for major ship operation costs. Ships carry commodities across international borders and these voyages are frequently powered by inexpensive leftover heavy fuel oils from refineries. It goes without saying that as fuel costs rise, so do the operating costs of the ship. As shipping is classified as long-haul transport, this issue is particularly pronounced, where the use of efficient fuels is crucial in keeping operating costs at the minimum.

The IMO strategy encompasses short term, medium term and long-term measures aimed at reducing GHG emissions from the shipping sector. The strategy explains the importance of exploring alternative low-carbon fuels (International Maritime Organization, 2018). The most notable aspect of the strategy is to encourage energy efficiency of ships and also promote the use of low carbon fuels for the shipping sector, however, does not specify the type of fuel that needs to be prioritized.

Furthermore, aside from transitioning to low carbon fuels, the maritime industry will also have to find solutions associated with the fuel value chain. In particular, production of hydrogen and its derivatives like ammonia necessitate a shift toward renewable energy to also mitigate emissions from the production side. This requires robust standards and sustainability criteria to guide the investment flows into low carbon fuels.

Another significant aspect of the IMO's strategy pertains to the reduction of SOx emissions as they are detrimental to the air quality. To mitigate this, the IMO has taken the pivotal step to limit the sulphur emissions to 0.5% m/m down from the previous threshold of 3.5%.

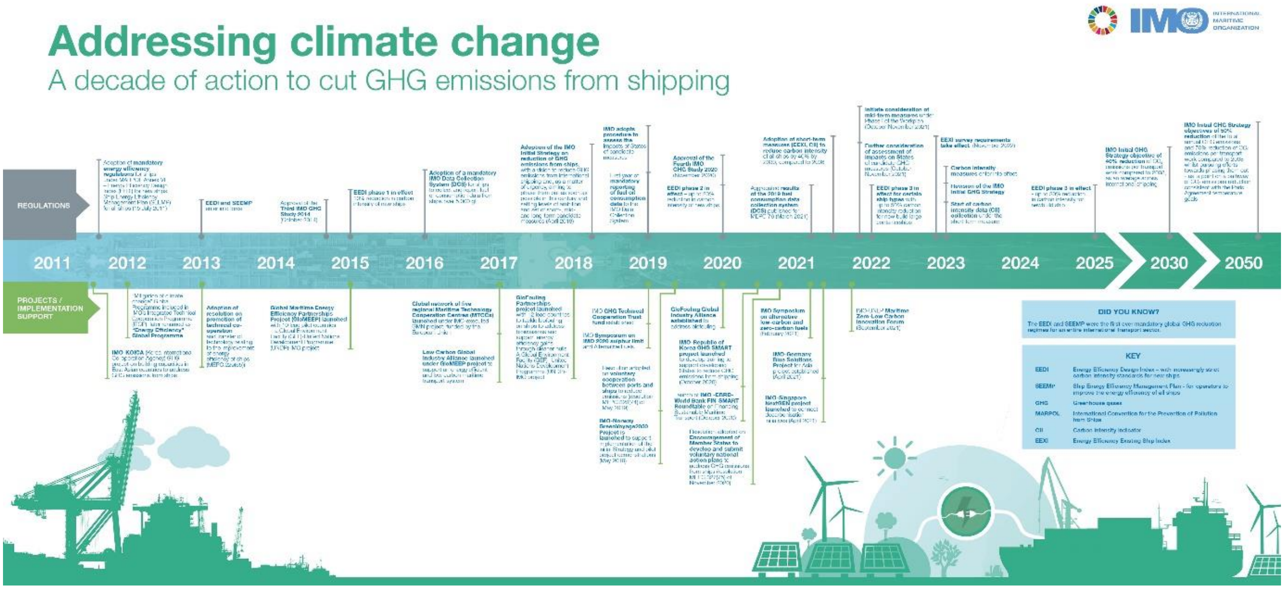

Figure 9: IMO's Work to cut GHG emissions from ships. Source: (International Maritime Organization, n.d.)

As illustrated in the figure above, the IMO has established a comprehensive timeline which reflects the organizations vision to reduce the GHG emissions from international shipping. To supplement these efforts, the Energy Efficiency Existing Ship Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) have been developed. Their primary objective is to measure the emissions generated by various ships by optimising their design to achieve

40% reduction in the carbon intensity of international shipping by 2030 compared to 2008 levels (International Maritime Organization, n.d.). The measures target ships of various tonnage and aim to enhance technical features to reduce emissions. The SEEMP plays a crucial role in establishing energy efficient plans to boost overall ship efficiency, enabling shipping companies and charterers to find cost effective solutions for operational sustainability. These measures represent innovative strategies to reduce emissions in a setting where fuel consumption still relies on HFOs and very low sulphur fuel oils (VLFOs). However, bridging the gap between these energy efficiency measures and incorporation of low carbon fuels in the shipping sector remains a challenge due to distinct chemical properties of alternative fuels.

As previously mentioned in *Section 1.1 Maritime Transport*, the maritime sector is now included in the EU ETS. The extension of the ETS to the shipping sector is compelling the industry to reconsider their operational approaches and stimulating the development of innovative solutions for low carbon fuels and ship design.

The shipping sector is currently navigating numerous challenges and strategies need to be developed to guide a low carbon transition. To pave the way for a sustainable transition, it is imperative to address key challenges that extend to low carbon fuels and supporting infrastructure. To facilitate a transition to clean fuels, it is vital to introduce incentives for hydrogen based synthetic fuels, making them competitive to fossil fuels. The feasibility of this change ultimately depends on the ability to accrue investments that yield long term benefits including mitigation of greenhouse gases and addressing climate change.

5.2. Pathway Toward a Low Carbon Maritime Industry- Pathway Theory and Critical Factors that Affect this Transition.

The future of a green transition is often perceived in terms of 'final outcomes' without presenting a real pathway to achieve this outcome. The way toward this final outcome is of equal importance if a green transition is to be achieved. (Sperling, 1984) asks a similar question regarding how technological change should be steered. His answer emphasizes the importance of trying to understand what determines this change can be applied to the maritime sector. By trying to understand what factors determine technological change, strategies to transform an industry can be devised. End-of-state prevails due to the urgent need for strong policy decisions. Consumerism is anticipated to increase in the coming decades and coupled with shipping role as the preferred method of transportation, point to a surge in emissions unless mitigative efforts are developed. While it becomes important to examine the end scenarios to make critical investment decisions, it is equally important to examine factors that will steer the diffusion of new technologies within the maritime sector.

The first step then is to identify these conditions under which technological change can be studied to perform a cumulative breakthrough for future policy decisions. Currently, the maritime sector has limited options when it comes to low carbon fuels like LNG, Methanol and Ammonia. Among these, ammonia stands out to bring about a low carbon transition in the sector.

It is worth noting that Sperling approach to analysing pathways to technological change raises an open-ended question like "what could be" and this can be interpreted as context dependant planning for the future of the maritime sector. At the EU level, the context for technological change is driven by the need to reduce anthropogenic emissions from this sector. in this context, the critical factors are vital to the technological transformation as they play an indirect but significant role in societal progress.

Critical factors could be attributed to a variety of features for a green ammonia production chain. To truly understand and build a green pathway tailored to the shipping sector, (Sperling, 1984) mentions that various non-market factors are also critical. These perspectives are identified through stakeholder analysis and are part of a consistent set of values that are critical to the maritime sector and its journey toward decarbonisation. The stakeholder analysis reveals various challenges in the production of green ammonia and offers insights into potential strategies for a transition.

The organization of the stakeholder analysis into visual cognitive maps, makes the identification of other critical factors easier. The cognitive maps are reflective tools that highlight the critical factors required for a low carbon transition in the shipping sector. The map highlights various *constructs (critical factors)* which are connected with '*linkages' or arrows*. An arrow into a construct shows an explanation and an arrow out of a construct shows a consequence. Taking the example of the first map, it can be seen that '*Collaborative action*' is the result of '*Community minded politics'*. *'Community minded politics'* also gives meaning to the construct *'Strong ambition to commit to carbon neutrality'.* Thus, one construct gives meaning to the one before it in the hierarchy.

5.2.1. Cognitive Maps

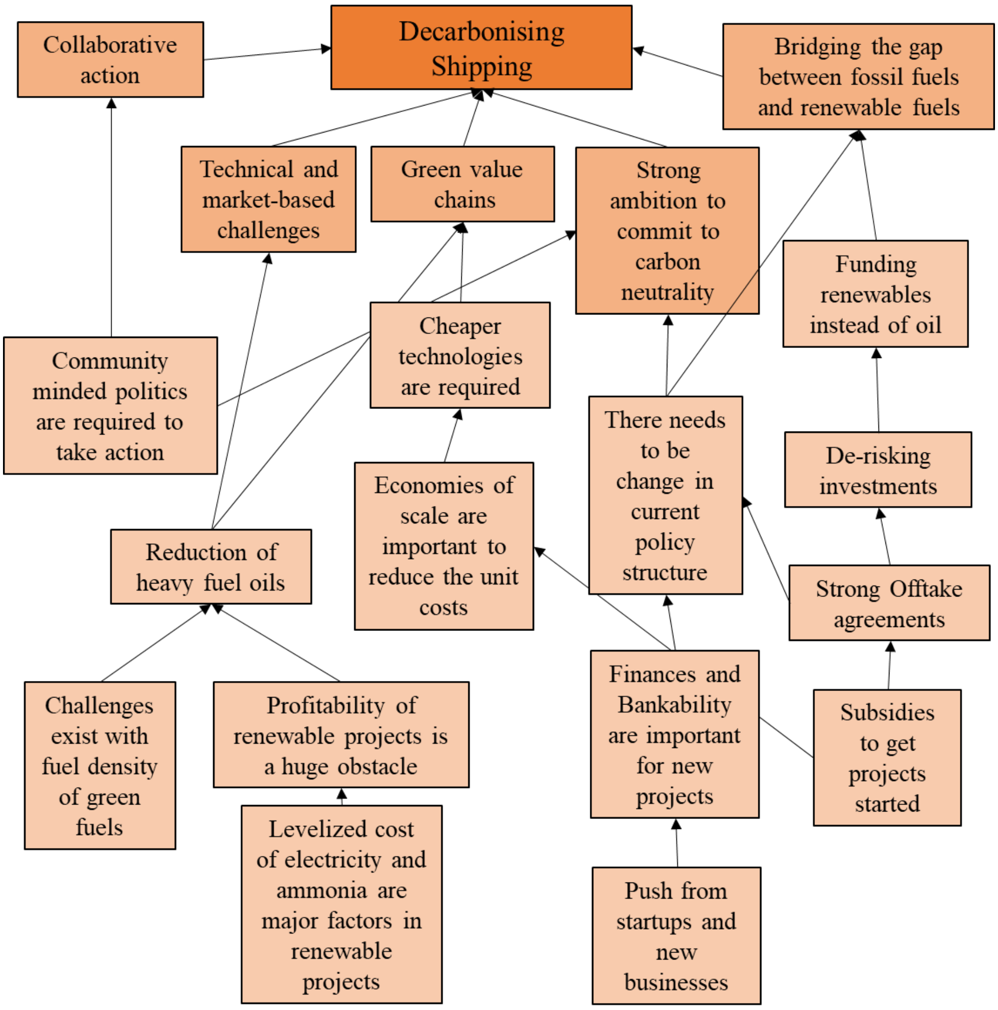

Figure 10: Cognitive Map 1. Source: Self-made figure inspired by Eden's cognitive map

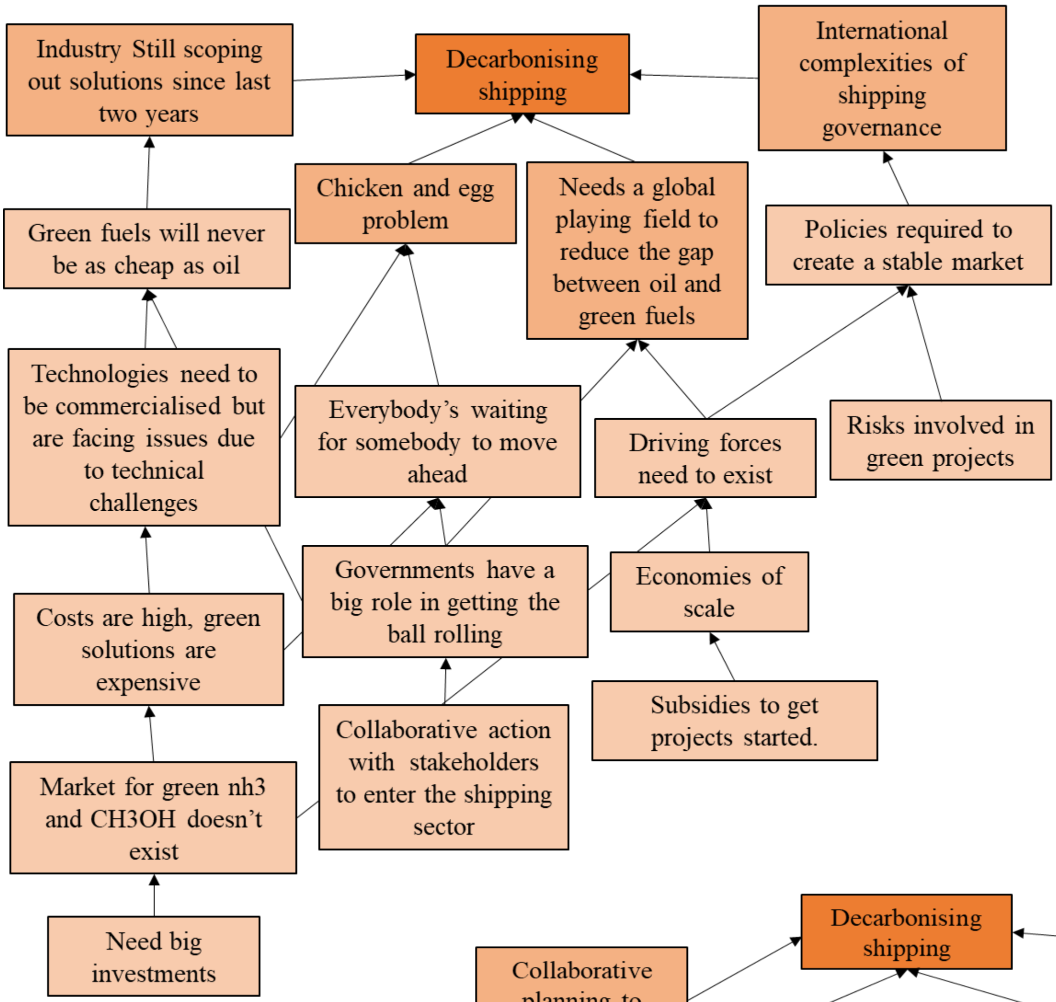

Figure 12: Cognitive Map 2. Source: Self-made figure inspired by Eden's cognitive map

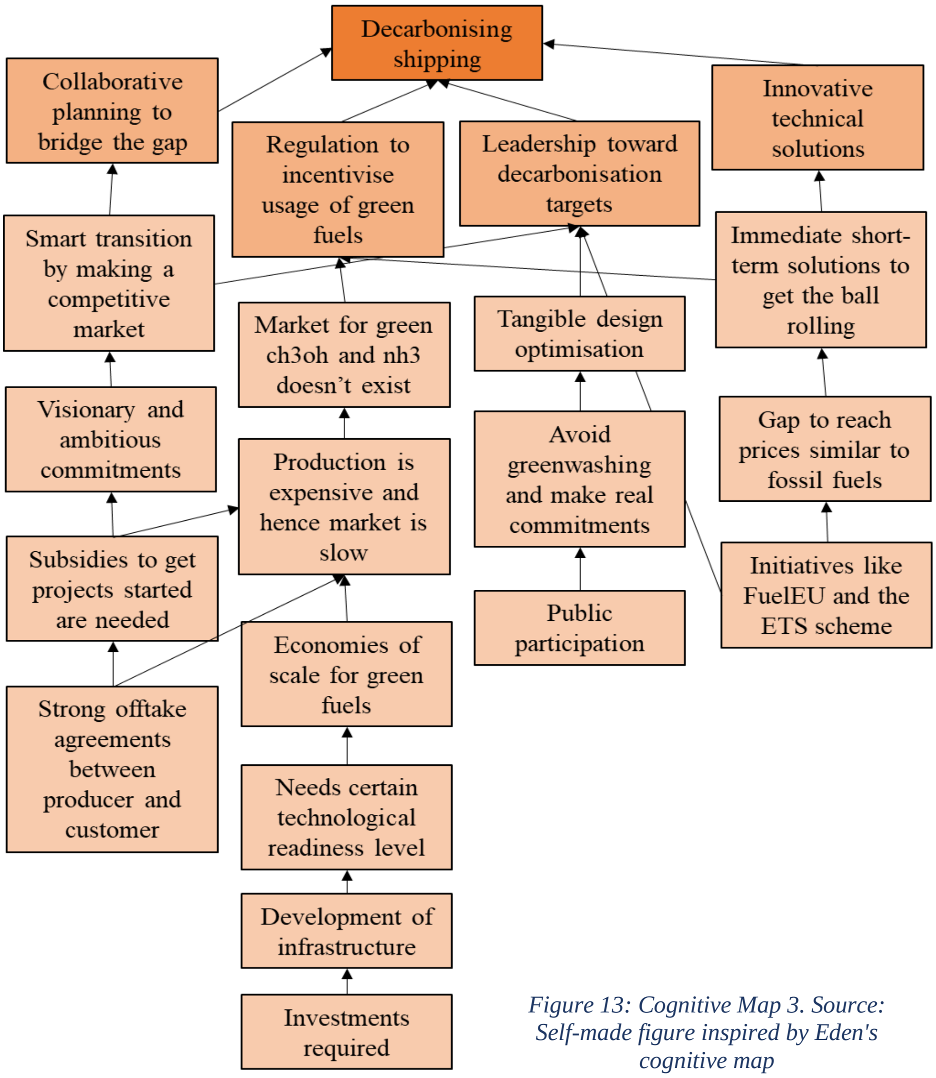

Figure 13: Cognitive Map 3. Source: Self-made figure inspired by Eden's cognitive map

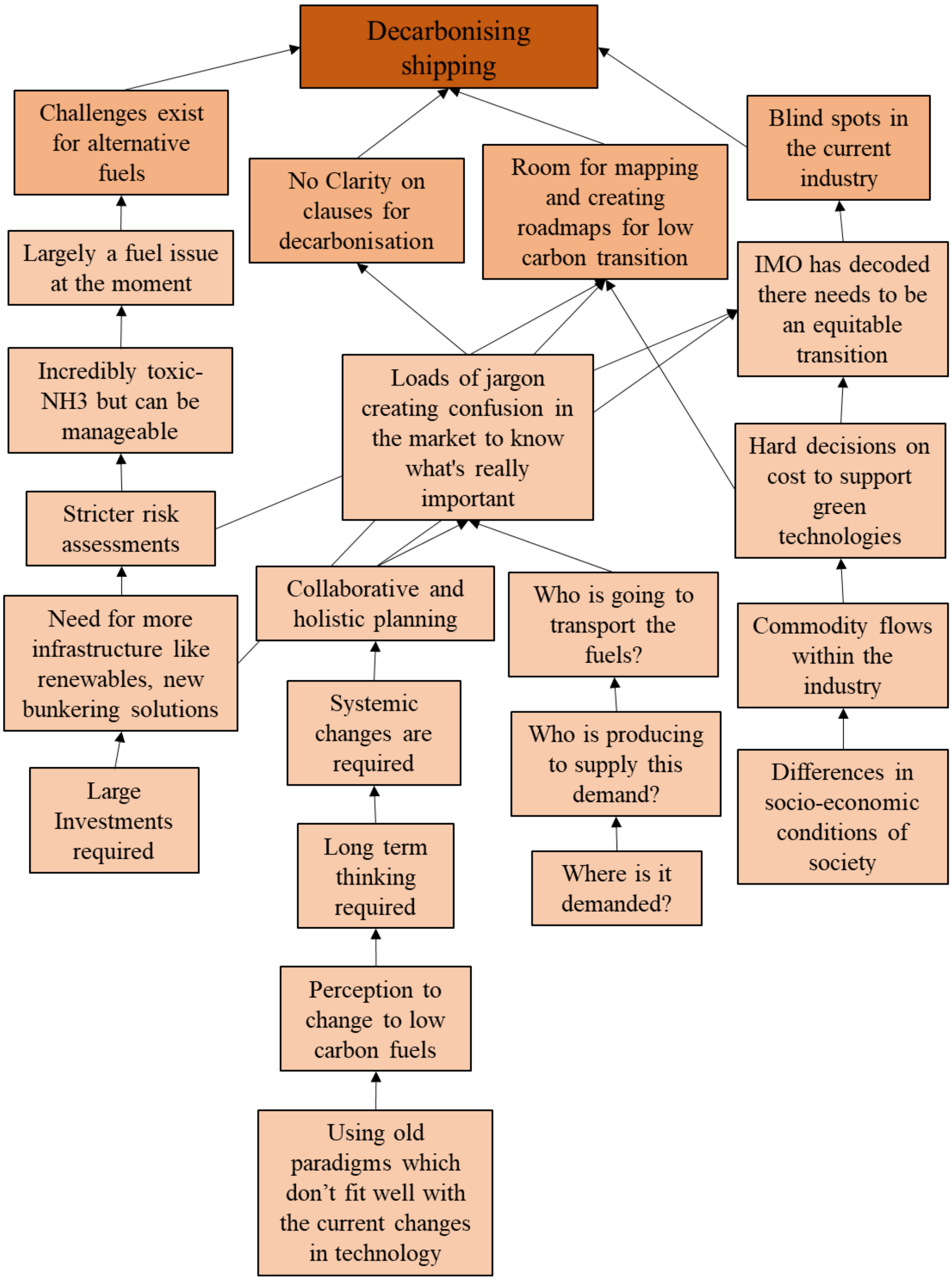

Figure 14: Cognitive map 4. Source: Self-made figure inspired by Eden's cognitive map

The pathway approach advocates to introduce a dimension of human cognition to achieve technological development, therefore, the knowledge provided by various stakeholders plays a crucial role in analysing low-carbon transition within the shipping sector. The insights provided are divided into distinct sections to better understand the pathway to achieving this transition. Additionally, the critical factors derived from the economic analysis will also serve as guiding elements in the following analysis of low carbon transitions.

5.2.2. Consistent set of values and beliefs

The low carbon journey for shipping is one which needs integrated solutions such that they develop simultaneously to create a uniform regulation surrounding shipping. Additionally, to reach the Paris target and EU's commitment to carbon neutrality by 2050, shipping has major challenges to overcome.

Firstly, shipping is a hard sector to decarbonise because of complexities involving energy density of fuels, technological efficiencies of vessels as well as the vessel voyages illustrated in *Fig. 13 and 14.* Shipping is one of the swiftest ways to transport commodities which means that fuel prices and investment in technical and operational optimization affect the sector to a large extent. In pursuit of a low carbon transition in the sector, pathways designed in Chapter 4, have been set around consistent values. These values are centered on identifying economically viable solutions for establishing a green ammonia value chain through different production methods like thermochemical or electrochemical synthesis. This is tied to addressing the second sub-question *"Are there solutions available that are economically feasible for emission reduction within the shipping sector?"*.

The analysis in Chapter 4 provides knowledge regarding the socio-economic value of green ammonia for shipping and how this change can be brought about from a systemic perspective. It shows that to completely change the narrative and shift to production of green ammonia, a large amount of renewable energy is required, which makes it a critical factor in achieving the green transition. This indicates that the shipping sector needs to synergise with other sectors to bring a transformation.

Chapter 4 highlights the pivotal role of renewable energy costs in determining the operating costs for hydrogen and subsequently green ammonia. Consequently, the levelized cost of energy (LCOE) is a critical factor which influences the overall cost of establishing an ammonia plant. The LCOE is observed to be affected by the capacity factor of the renewable plant and the technologies individual power production. Differences in the efficiency, as illustrated in the LCOE, have a direct bearing to the overall cost of ammonia production.

The LCOE has a substantial influence on the OPEX of various ammonia pathways, where it is fluctuations in the LCOE affect the LCOH. This is because the electrolyser is recognized as the largest energy consuming component in the production of green ammonia (*Technology Data for Renewable Fuels*, 2023), it follows that increased energy costs, translate into higher overall costs for the value chain. Thus, regulation of LCOE is vital to make green ammonia more economically feasible, increasing the chances for integration as a maritime fuel.

Stakeholders consulted as part of the research consistently emphasize the importance of increase in renewables technologies and achieving economies of scale within the ammonia value chain. This strategic approach serves to reduce the unit cost associated with production green ammonia while simultaneously diminishing the reliance on fossil fuels. This is also a concept that (Unruh, 2002b) highlights, which emphasizes preference for innovative solutions such as renewable energy to fight climate. This signifies a shift away from dominant fossil fuel-based market encouraging policymakers to reconsider existing policy structures.

Within the context of shipping which traditionally leans toward HFOs and VLSFOs, the innovation in green fuels through subsidies, much like the power sector, could catalyse the creation of a robust market. This approach aims to create a level-playing field for energy producers and provide tangible value to the maritime sector through the provision of economically viable energy for green ammonia production. It becomes evident that for the entire green ammonia production chain to remain cost-effective, the availability of green energy is necessary.

When developing strategies for the shipping sector, it is crucial not to fixate on end-state scenarios but build it through common values which will enable the economic analysis and help to narrow down a solution for a low carbon transition.

5.2.3. Critical factors placed in a temporal setting to achieve the required technological change

(Sperling, 1984) highlights that to assist technological change, the changes need to be put in systemic context and the major constraints need to be explored. The stakeholder analysis and the economic analysis reveals incredibly important critical factors which positively and negatively affect the low carbon transition in the shipping sector. However, these critical factors need to be contexualized within a temporal setting, to achieve the necessary breakthrough. This implies that strategies need to be formulated within a timeline otherwise, the transition can be delayed.

It is observed that electricity obtained from renewable energy sources is competitive and this directly affects the cost of production for green ammonia. These critical factors are integral to the sequence which is required to analyse technological change empirically within the shipping sector. Furthermore, the LCOE can be significantly reduced through optimisation of technologies and reduction in CAPEX, thereby creating a competitive market comprising mainly of renewable energy. The alignment of increase in RES capacity and the uptake of green fuels in the maritime sector is a coordinated effort. Additionally, increased support from the EU in the form of strategic plans and policies aimed at bolstering renewable capacity further drives the market.

To backtrack, in the pursuit of low carbon transitions, it is imperative that the ammonia production chain undergoes a strategic recourse. Green hydrogen thus plays a vital role, and the production of green ammonia cannot be achieved without an efficient H_2 production unit. The efficiency not only extends to the cost but also to the volume of hydrogen produced per MWh, where the higher the output, the lower the LCOH. Based on the existing market benchmarks for electrolysers, the most efficient and cost-effective pathway for green ammonia production is AEC coupled with onshore or solar PV followed by PEM and SOEC technologies. Hence, constraints related to green hydrogen must be addressed before production for green ammonia can start.

The maritime sector faces several challenges beyond the integration of intermittent renewable energy sources and technological limitations of H_2 production. Specifically, regarding fuels like green ammonia, there are several critical challenges. Firstly, they are not competitive with conventional fuels, and this lack of competitiveness is likely to persist due to differences in the energy densities of conventional fuels like HFOs and ammonia. This means that a larger volume of ammonia is required to complete the voyage which means that shipping companies have to spend more to stay afloat as a business. And since there is also a niche market for green ammonia, it is an expensive choice for companies to opt for.

Additionally, the existing fossil fuel subsides create barriers for the uptake of green fuels due to fundamental cost differences. The stakeholder analysis revealed that the preceding factors contribute to a less competitive market for green fuels like ammonia. Thus, a major hurdle in the competitiveness between green fuels and conventional fuels pertains to high costs associated with each facet of the ammonia value chain.

The stakeholder analysis also highlights one of the biggest hurdles in maritime sector closely linked to financial aspects of green projects and the ability to attract investments. The core issue identified here is that green projects are associated with high risks and bank loans are dependent on the expected returns from the project. This implies that green projects struggle with financial challenges due to high up-front costs but may not guarantee the same level of profitability (Tran et al., 2020). Furthermore, green technologies witness ongoing innovations and hence the market is niche and is perceived as an unreliable investment. Stakeholders consulted for the research corroborate these concerns, emphasizing that banks tend to be risk-averse, resulting in low bankability, thus diminishing the chances for establishment.

When viewed in a systemic context, the shipping sector must confront challenges with the integration of green fuels in the fuel mix and simultaneously address infrastructure modifications of existing and new ships. This entails a comprehensive overhaul of the entire fuel structure and ship infrastructure capable of accommodating such changes by 2050. It is projected that emissions from shipping are set to rise by 2050 the most straightforward means to mitigate carbon emissions involves investing in green fuels like ammonia.

5.2.4. Paradigm shift for low carbon transitions

The maritime sector is facing a gap in trying to overcome the techno-institutional complex and contributing to the carbon lock-in. Within the shipping industry, a "chicken and egg problem" exists. This essentially refers to confusion in the industry surrounding the type of fuels to focus on due to lack of strong regulations, which then contributes to lack in actions from the industry. This dilemma further embeds the techno-institutional carbon lock in, creating a sort of deadlock.

When forming regulations for a transition in the shipping sector, the primary goal should be to plan for the long-term and limit immediate short-term solutions that are focused on profitability. The challenges related to fuel density, low penetration of renewable energy in the transport sector and high risks associated with green projects, have only added to the "chicken and egg problem".

As seen in the cognitive maps, this issue is further complicated by the fact that the current market for fuels like e-methanol and green ammonia is niche primarily because technical prowess for a completely green production chain is still under development. This problem also causes an incapacitation of reaching policy decisions regarding the shipping sector as there is a lack of consensus regarding which fuel is more suitable to achieve net zero GHG emissions. This also goes back to the problem of trying to achieve cost parity between conventional and green fuels due to disparities in their energy densities.

Furthermore, stakeholder analysis highlighted the absence of subsidies for green fuels, as seen in the power sector. This discourages potential investors from exploring into green fuels and further exacerbates the issue of the carbon lock-in. Subsidies from the government play an important role in achieving economies of scale for renewable technologies by lowering the initial cost for production (Grantham Research Institute on Climate Change and the Environment, 2018). This offers an illustrative approach to changing the paradigm toward green fuels for the shipping sector.

This transformation involves comprehensive risk assessments for green fuels and providing subsidies will ensure a level playing field and ease the low carbon transition for the shipping sector.

5.2.5. Escaping the carbon-lock in through cumulative strategies

(Unruh, 2002b) explains that to escape the lock-in, cumulative efforts must be taken that include development of regulation, technological breakthroughs and developing niche markets. Corroborating this perspective with (Sperling, 1984), the transition to a low carbon maritime sector involves simultaneous efforts, rather than silo solutions. The carbon lock-in is an unsustainable entrenchment for the long-term future, demanding effective carbon emission mitigation.

The carbon lock-in in shipping exists due to its historical reliance fossil fuels since all technical and operational features of ships depend on fuels to function. This means that to the reach EU’s goal the only way for shipping to achieve this target is a full substitution of its fuel (UMAS and Global Maritime Forum, n.d.). Other factors contributing to the techno-institutional carbon lock in in shipping include higher initial costs of green fuels, limited technological readiness of electrolysers, limited integration of renewable energy in the maritime sector, differences in energy densities of conventional fuels and green ammonia. Escaping the carbon-lock-in within the maritime sector is a multifaceted challenge. One dimension extends to incorporation of green fuels and the complete decarbonization of their production processes. Parallelly, another dimension includes the development of regulations to facilitate the transition and the diffusion of green technologies to produce green ammonia.

Ammonia presents a viable solution to reduce carbon emissions from the shipping sector. Notably, liquified ammonia is already transported via ships and pipelines for use in the fertilizer industry (International Energy Agency, 2021). This highlights the existing level of expertise for ammonia handling. Thus, regulations for ammonia as a fuel can be developed for the maritime industry to increase its uptake.

Furthermore, subsidies also currently exist for fossil fuels. Consequently, fuel producers who supply to the shipping sector will always favour fossil fuels over renewable energy sources for fuel production. To kickstart the adoption of green ammonia, it is necessary to devise incentives and subsides to shift the support toward its production.

Escaping the carbon lock-in requires a paradigm shift in both institutional and technological dimensions and external driving forces play a pivotal role in facilitating this transformation. Consequently, global leaders in the shipping sector should strive toward establishing a level-playing field to empower a low carbon transition in the shipping sector. This would imply the formation of phased regulations to create an environment to minimize industry-wide confusion, thus making it easier to adopt specific technologies like electrolysers.

Chapter 6: Discussion

With the help of the economic analysis of technological pathways and insights provided by the stakeholder analysis, critical factors were identified for understanding and analyzing how the process of technological change can be initiated in the shipping sector. Achieving low carbon transitions requires a holistic, systemic overhaul from all actors within the industry. Delaying the transition will escalate the costs required for decarbonization because the options will be limited, and immediate solutions will need to be taken. The discussion provides key strategies for the shipping sector to successfully navigate the path toward achieving a low-carbon transition.

Niche Markets- Escaping it

Section 4.5: Cost comparisons and economic feasibility assessment, highlights the amount of investment that will be required to turnaround the current shipping fuel market if ammonia is to be incorporated in the mix. Renewable energy plants will need to be increased manifold. This is a relatively simple task considering the learning rates for onshore and offshore turbines and increasing efficiencies for solar modules. The need for decarbonisation and additional support provided by EU policies like the European green Deal and initiatives like REPowerEU have increased the RE capacity. Additionally, the learning curve due to innovation and optimization in technologies helps to reduce 23-30% of the cost due to economies of scale which describes the reduction in cost per unit with the increase in production scale (Bertelè and Chiesa, 2001). Due to this, renewable energy costs continue to reduce. The economic analysis in Chapter 4 is an indication of the principle of economies of scale for renewable energy technologies, where the LCOE of different renewable energy technologies can be reduced by increasing production scale due to reduction in CAPEX and increase in individual power output i.e improvements in full load hours and efficiency of the technology.

The green ammonia market is currently niche and exogenous forces are needed to escape it. Following the same principle for the production of green ammonia, LCOA can be decreased if the improvements in the components for ammonia production are optimized. Thus, the economic aspect of the low carbon transition can only be achieved if economies of scale are materialised for green fuels. This end-of-state scenario is achievable through the maturity of technologies required to produce green ammonia. This implies that the end-of state scenario can be achieved through cumulative increase in technologies and economics of scale, thus reducing costs.

Paradigm Shift for Green fuels

Chapter 5, Section 5.2.4 highlights the need for a paradigm shift in the current operation of the shipping sector. Feasibility of the technology is also defined by the critical factors and its interaction with larger systems, political and temporal settings (Sperling, 1984). The important aspect here is the need to check the feasibility of ammonia as a green fuel for the shipping sector within a band of attributes. By identifying the critical factors, the necessity of ammonia has been established, and also the gap to reach this goal is also highlighted.

Policy action by the IMO has already regulated that by 2025, marine fuels should be decided upon, and measures should be set to reduce their GHG intensity in phases. Additionally, a pricing mechanism should be agreed upon based on the GHG emissions (International Maritime Organization, 2023). Now that the IMO strategy has been tightened regarding its goals, it also increases the pressures on shipping industry to co-ordinate and come to a consensus regarding maritime fuels. This should not be an easy pass for the industry to take the straightforward choice and adopt the least expensive solution while ignoring the long-term implications of the easy solution. Additionally, it is interesting to note that as the maritime sector starts to think of innovative solutions to solve its fuel problem and has been debating about the drafting of safety regulations for fuels like LNG, methanol and ammonia, the chemical industry has been working with such chemicals for decades and has rigorous safety and handling procedures.

Presently, companies are focusing on Methanol as a starter fuel to accelerate the low carbon transition in the shipping sector. Expert stakeholders consulted as part of the research shared similar sentiments regarding the differences in methanol and ammonia as maritime fuels. Stakeholder analysis revealed that "It was just get started with the best solution at hand" in response to why methanol was being considered as part of the fuel mix for shipping. The stakeholder also stated that "It does not stop them from looking for other solutions that are even better" and that "Bio-methanol is currently seen as a short-term solution before you can shift to green ammonia for shipping". Thus, since bio-methanol can be deployed at an easier rate than green ammonia, it is seen more relevant at the current stage in the transition for shipping.

Development for special bunkering facilities and engines with methanol in mind are also being designed. Maersk has ordered 24 vessels which will have a dual-fuel technology running on methanol and conventional fuels (Johannes Birkebaek, 2023). While it is a great first step toward decarbonisation, methanol has its own set of safety hazards and feedstock challenges that create challenges for the future of methanol as maritime fuel. The handling and safety for methanol also pose an equally high problem, because methanol has a low flash point since it is an alcohol-based derivative it has explosive properties. By OSHA standards, methanol is considered hazardous (Acros Organics, 2016). Thus, strict regulations for its handling have to be developed for methanol as a fuel when incorporating it into the shipping sector.

Additionally, bio-methanol and green methanol each require a source of biomass or biogenic CO_2 for it to be sustainably produced. This means that the cost for acquiring biomass and biogenic CO_2 is also a part of the methanol value chain which increases the cost for methanol substantially. In a world where the CO_2 emissions need to be decreased and various sectors rise to the challenge, carbon sources will be less available for the future. Methanol's production requires CO_2, which will be increasingly hard to find for the future. With respect to the supply of bioenergy for shipping, there are major constraints because biomass is also sought out by other sectors. The growing demand for biomass from all sectors may cause a challenge for the supply to the maritime sector (Sustainable Shipping Initiative, 2019). Thus, presently bio-methanol costs are 310-720 Euro/ton, while e-methanol costs 750-1500 Euro/ton.

The incorporation of biomass-based fuels like bio-methanol and methanol fuel blends is a good starting point for the shipping sector. This is because production of biofuels like methanol closely resembles the current technology and therefore few changes need to be made to the ship engines to incorporate completely new fuels which have different chemical compositions such as ammonia (Sustainable Shipping Initiative, 2019). Therefore, as a starting point, minimal investments are required and can be accumulated in phases as the IMO's 2023 strategy suggests. But these measures are only suitable as short- or medium-term measures. Green methanol costs are in a similar range to green ammonia but have the additional constraint of biomass or biogenic $CO_{2.}$ This means that methanol is not exactly carbon neutral and will continue needing an extra source of bioenergy for its production. To achieve EU's goal for carbon neutrality, methanol seems a less attractive option as a marine fuel than ammonia which can be produced through completely renewable sources, making it truly carbon neutral. Since the costs for methanol and ammonia are in the same range, it is more sensible to pick the option which can completely mitigate emissions from the entire value chain.

The low carbon transition in shipping in not only restricted to the type of fuels that the ships will need. It also extends to the infrastructure where the industry has to develop new bunkering and storage solutions to assist the uptake and deployment of alternate fuels. This is because the energy density of methanol and ammonia is half that of heavy fuel oil (Alfa Laval et al., 2020), which means that ships will need to refuel more often. Changes to the ship design, storage of fuel on ships and safety regulations need to be re-drafted for ammonia based on its chemistry. Thus, the IGF regulation for ships will need to be updated to ensure the risks are minimized when using methanol and ammonia as fuels in the future.

Strategies required to overturn the current fuel landscape

The shipping industry is trying to navigate how a low carbon transition can be brought about and is still scoping out solutions regarding the safety and handling of alternate fuels, and developing new infrastructure that are compatible with green fuels like ammonia and methanol. All of the above require strong regulations and substantial investments.

Need for Strong Regulation!

The first step to do this involves ensuring that the regulations acknowledge the strong attributes of green fuels and the socio-economic benefits they have for long term decarbonisation and fulfilling the Paris agreement. First and foremost, the IGF code needs to be developed which handles material safety. Other regulations can be developed in phases as more knowledge is shared amongst the stakeholders and as the market advances. The IGF code for low flashpoint fuels is necessary for shipbuilders and designers to understand the implications of green fuels. Currently the code only covers natural gas and has no provision for methanol and ammonia and hence if this code is updated, the shipping industry will be forced to consider alternate fuels.

Starting with the production of green fuels, it is important to design green ammonia plants to ensure the present production chain based in fossil fuels transitions to a green production chain. This can be achieved in phases where the plants can be retrofitted to be converted to blue ammonia plants before, they are converted to completely green ammonia plants. While hybrid ammonia plants seem like an attractive option, it doesn't solve the problem of emission reduction in the long term. This is because in a hybrid plant, only a certain percentage of H_2 (10%, 20% or 50%) is produced through electrolysis. This implies that the electrolyser must either be designed according to the required capacity or a larger capacity, which may remain unutilized unless there is provision for H_2 storage.

Furthermore, the inclusion of ammonia as a maritime fuel will not only put pressure on the existing ammonia production, but also on the energy sector as the renewable energy will be required to produce ammonia. As stated earlier, this would entail that the energy sector and the shipping sector will need to collaborate closely to ensure that the supply and demand are balanced.

Financial Backing

As mentioned earlier, incorporation and establishment of green ammonia can only be realized if finances are available. Utilisation of market-based measures until technologies like electrolysers mature for fuels like green ammonia are a surefire way to reduce CO_2 from the shipping sector. One way to achieve this is by introducing a carbon price on fuels that are not sustainable. This should be done to build incentive to not only reduce their CO_2 emissions but also build a financial backbone for future investment in green fuels. The Carbon ETS applied to the shipping sector is a start to ensure that companies are made responsible for their emissions while also rewarding the engagement in accelerating the transition. The carbon price is a broader mechanism which simply puts a price on per tonne of $CO_{2,}$ while the ETS helps to cap the emissions.

The ETS, which is a cap-and-trade system imposes a limit on the number of GHG emissions that various sectors can emit. Furthermore, a certain number of allowances are made available to companies, and these can be traded through an auctioning system. Each allowance grants a company to emit a tonne of CO_2 or a GHG equivalent, which means that possessing more allowances, permits them to emit more. Approximately, 57% of the allowances are auctioned while 43% are given away for free (European Commission, n.d.). The addition of the shipping sector to the ETS, enables companies to lower their carbon emissions and encourages the adoption of green technologies, reducing the necessity to purchase additional allowances.

The ETS also serves as a way to develop a fund specifically for investment in green fuels like green ammonia. The EU ETS allowances already help to finance the Innovation fund, and a similar approach could be enforced for the shipping sector (European Commission, n.d.). Presently, the focus is on creating more accessible funds for hydrogen for heavy duty transport and industrial applications. It is equally important to redirect this focus toward the shipping sector as hydrogen plays a critical role in the production of ammonia, which is indirectly vital for the shipping sector.

Further market-based measures like carbon prices and subsidies for green technologies can also facilitate the low carbon transition within the shipping sector. Implementing higher and more stringent carbon prices could generate revenue and establish a fund aimed at reducing the gap between conventional maritime fuels and green fuels. Stronger carbon prices, ideally ranging between 150-200 euros per ton of CO_2 as recommended by the industry would allow to bridge the gap between use of HFOs and green fuels, (UMAS and Global Maritime Forum, n.d.).

Carbon offsets also represent an interesting market-based approach that can complement the carbon reduction process within the shipping sector. Solely relying on this mechanism will only incentivize companies to offset their emissions by purchasing credits to invest in carbon mitigation projects such as carbon sequestration or carbon capture without fundamentally changing their practices. This approach will not bring a change in their institutional practices, and will continue to perpetuate the carbon lock-in.

This implies that for a successful transition, market-based measures should be combined together. By creating a hybrid policy structure that integrates measures like carbon pricing and the ETS, a more stable and competitive environment for the adoption of green fuels can be established.

As seen in *Figure 14: Cognitive map 4. Source: Self-made figure inspired by Eden's cognitive map*, a low carbon transition entails holistic planning, highlighting the interdependence of technological advancement and governance within the shipping sector. while businesses understandably focus on maximizing profit, it is short sighted to approach a low carbon transition solely from a profit centric perspective. Delaying a low carbon transition will create more socio-economic unrest in the future in the form of increased global warming and climate risks causing more money to be spent in rectifying the impacts (Mekala Krishnan et al., n.d.).

Socio-Economic Feasibility

Failure to address the increasing CO_2 emissions from the shipping sector could lead to dire consequences. Given that the current ammonia industry is based in fossil fuels, it is already contributing to CO_2 emissions. When incorporating ammonia in the shipping sector, the use of grey ammonia is not a viable option as that will only exacerbate the issue of CO_2 emissions. Instead, ammonia fuel blends with a larger green ammonia component need to be introduced, paving the way for economies of scale of green ammonia. This will reduce the carbon intensity of the heavy fuel oils used in shipping and also help as a pilot test for ammonia-based engines on ships.

The integration of green ammonia in the shipping sector is incredibly important because as a fuel it not only has the ability to reduce emissions from the shipping sector, but also has the ability to create synergies with the power sector as an energy carrier. This dual role holds the potential for energy storage in the form of a hydrogen carrier when green energy needs to be exported. This also offers various solutions for the transportation sector, making investments in green ammonia a valuable step toward mitigating the effects of climate change.

Chapter 7: Conclusion

The low carbon transition in the shipping sector is essential as anthropogenic emissions from shipping will only exacerbate climate change. Additionally, the European Union has set ambitions goals to mitigate emissions to ensure the global temperature doesn't rise past 1.5^0C. The EU's commitment to carbon neutrality by 2050 places an onus on the shipping sector to align with these goals.

The shipping sector is faced with major technical and operational challenges when it comes to finding solutions for carbon mitigation. This implies the existence of a techno-institutional carbon lock-in which means that institutions involved within the shipping sector heavily depend on fossil fuels, making it difficult to leave these embedded practices behind. Addressing this issue requires development of strategies which will help introduce a low carbon transition in the shipping sector. As European union strives to move toward carbon neutrality, there will be a shortage of heavy fuel oils available for shipping, prompting the sector to look for innovative solutions for fuel substitution like green ammonia. This entails examining factors that will enable the integration of green ammonia in the sector.

Green ammonia offers an innovative solution for the shipping sector as it presents a carbon free path to reduce emissions from the sector. This can be achieved if the production of ammonia can be integrated with renewable energy sources and green technologies, particularly for the key feedstocks namely, H_2 and N_2. The incorporation of ammonia in the shipping sector will essentially increase the demand of ammonia by millions by 2050. This implies that the renewable energy capacity will need to increase to meet the demand for ammonia.

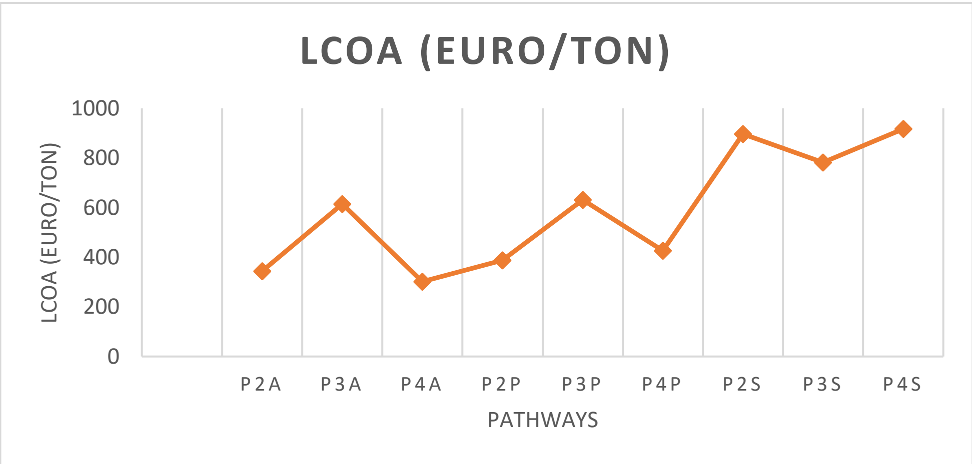

Figure 15: Levelized cost of thermochemical ammonia.

The economic analysis of green ammonia reveals that the production of green ammonia depends on critical factors like the LCOE and LCOH. Consequently, the LCOE is influenced by the CAPEX, capacity factor and power production output of the energy source. Notably, onshore wind energy is the most competitive technology in terms of renewable energy. Conversely, the LCOH is dependent on the type of electrolysers available, and AEC is the most competitive one available. Based on the technological pathways analyzed, the pathway with solar PV and AEC is the most feasible pathway for green ammonia.

Other pathways like the electrochemical synthesis currently lack the technology readiness level to be considered as a feasible option. Thus, unless the ammonia yields through this pathway can be optimized, it should not be included as a pathway for green ammonia for the shipping sector. Furthermore, hybrid ammonia presents as a viable pathway feasible based on current market standards as the cost for green ammonia is extremely high. This is because it contains both gray and green ammonia, with the former having a larger component in the synthesis, thus reducing the cost for a large electrolyser. Although hybrid ammonia offers an easy short-term solution, it is important to note that hybrid ammonia plants will ultimately need to transition to green ammonia production to reduce emissions arising from the gray ammonia production.

Based on these factors, the current Levelized cost of ammonia of ammonia from natural gas stands at 188 Euros/ton NH_3 (Bunro Shiozawa, 2020), while the LCOA of green ammonia ranges from 300-900 Euros/ton NH_3, showing a huge disparity between conventional and green fuels. This disparity can be rectified through market-based measures.

Economic analysis plays an important role in assessing the investments required for green ammonia production, while also addressing the infrastructure required to integrate it as a maritime fuel. The stakeholder analysis revealed several critical factors that address the challenges with the adoption of ammonia as a fuel and the necessary measures to integrate it in the maritime sector.

Besides the economic viability of ammonia, there are other factors that influence its adoption in the maritime sector. One such challenge pertains to its toxicity and corrosive nature, which raises concerns for crew safety. In comparison to methanol and LNG, which have an explosive nature, ammonia can be detected easily at 3 ppm, enabling prompt implementation of safety measures in case of any leaks. Notably, ammonia has been transported worldwide via tankers and there is existing experience with ammonia handling. This would entail well designed pressurised tankers to hold ammonia such that the risk of leaks is minimised on board. This implies that infrastructure would need to be developed to accommodate for ammonia's chemical composition which is different than HFOs.

Such vast changes in infrastructure entail huge investments in innovative technologies to ensure that ammonia will pose no harm on board. Therefore, it is necessary to mitigate risks associated with such investments before they can be initiated. The process of accumulating investments can be facilitated through the use of market-based measures such as the Emissions Trading system (ETS).

The cap-and-trade system, where companies can trade emissions based on market established carbon prices through an auction system, is an important measure. The ETS helps to not only reduce emissions, but also enables the establishment of a specialised fund for the maritime sector. The allowances accrued as part of the ETS can be reinvested into the sector to optimise niche technologies and create a stable market for innovate green fuels like ammonia. However, the ETS needs to be combined with additional market-based measures like a strong carbon price mechanism. This will help to reduce the gap between green fuels and conventional maritime fuels in the initial phase of deployment.

Additionally, green ammonia can be made economically viable with the help of subsidies. Green projects require large investments due to a niche market and to build up economies of scale, it is necessary to incentivize such projects through the increase of subsidies. In the case of green ammonia, where a significant part of the investment pertains to the electrolyser, introducing subsidies will encourage hydrogen producers to ramp up production, which will build economies of scale for hydrogen, driving down production costs. Furthermore, this also means that subsidies for fossil fuels need to be phased out and subsidies for renewable energy need to be bolstered to ensure the entire ammonia chain will remain green. This transition is equally beneficial for potential fuels like methanol where part of the investment is subsidized.

The low carbon transition in the maritime sector is socio-economically feasible through holistic efforts from stakeholders in the maritime sector. Moreover, it requires cross-sector synergies, as the transition in the maritime sector presents a multifaceted challenge. This encompasses transitions within the energy sector, fuel production processes, and the design of vessels to accommodate the new fuels.

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Appendix

Interviews

A.2. Rob Stevens- Topsoe

Rob Stevens is presently at Topsoe and has experience with green fuels and Power-to-X. As he is an expert in green fuels, the focus of the interview was first to learn about various technologies to produce green ammonia and existing challenges with respect to the market dynamics of green ammonia production. The interview with Rob highlighted the need for strong financial commitments and driving forces from new entrants for a transition in shipping. Additionally, the interview highlighted the importance of key policies and regulations to make an impact in the shipping industry and how financial instruments and strong off-take agreements for green fuels are necessary for a transition in the shipping sector. Additionally, the complexity of transitions in industries was discussed and the need for long term policies to navigate the complexities of a low carbon transition were also discussed.

A.1. Jesse Fahnestock-Global Maritime Forum

Jesse Fahnestock is part of the Global Maritime Forum, which is a non-profit organisation that works with stakeholders in the shipping sector to provide individually tailored solutions to help decarbonize the sector. The conversation with Jesse revealed many key challenges associated with the decarbonization of the maritime industry, which were related to absence of commercialized technologies, and lack of available solutions like direct electrification. Additionally, cost of scaling up clean technologies was also identified as a major hinderance. Factors like fuel density are also a concern as ammonia doesn't provide energy density like HFOs. Additionally, there is also the need for driving forces to overcome the gap with conventional fuels and driving forces from the industry are needed to lead the transition. As the focus of the research is on green ammonia, the potential of ammonia in decarbonizing the shipping sector was discussed.

Key solutions to introduce a low carbon transition in the sector such as ammonia fuel blends, and the need for proper governance in the sector were discussed. And the need for collaboration and agreements between countries to facilitate adoption of new technologies.

Furthermore, the socio-economic consequences of not decarbonizing the shipping sector highlight the inequalities in global economic trade in the future as cleaner fuels are more expensive. Additionally, major environmental causes could lead to higher risks associated with climate change.

A.3. Navid Ostadian Binai- Maersk Tankers

Navid Ostadian Binai is the head of biofuels at Maersk Tankers and hence the interview was focused on learning perspectives about the steps that global companies in shipping are taking to introduce the low carbon transition. The discussion was also steered toward learning about challenges and strategies that the industry is facing toward adoption of green fuels like ammonia and methanol, which highlighted the differences between the two fuels and infrastructural challenges associated with their adoption. Additionally, the importance of subsidies and regulatory measures are seen as promoting causes for the industry to align with the EU's goal for carbon neutrality that can lead to the widespread adoption of fuels. Interesting perspectives such as public participation and innovative solutions for the industry are also important for the adoption of green fuels.

The conversation highlighted the complexities of finding new solutions and the importance of collaboration between nations to create a substantial change within the shipping sector.

Additionally, the conversation also highlighted a business perspective and how both are important motivations for companies to find solutions. This conversation highlighted the solutions that the industry is currently looking forward to implementing such as the co-exitance of fuels like methanol and ammonia and the suitability of both fuels in the short- and long-term transition in the shipping sector.

A.4. Conor Furstenberg

Conor Furstenberg is a partner at Furstenberg Maritime Advisory and works closely with the Ammonia Energy Association. This interview highlighted various aspects of green ammonia as an alternative for the shipping industry and how it can be brought forward. Safety concerns, and infrastructure challenges associated with green ammonia were discussed and how it will impact the transition in the shipping sector. Additionally, challenges related to ammonia were discussed which highlighted that a paradigm shift needs to be brought about to change the perception of ammonia in the industry as it is viewed as an unsafe fuel. Additionally, the need for global collaboration is highlighted to develop strategies for the shipping sector and its transition.

Other challenges associated with green ammonia were discussed highlighting the niche technological scale for green fuels.

Furthermore, solutions to introduce a transition like financial support and market-based measures to ease in the transition were discussed.

Additionally, socio-economic concerns related to the industry were discussed which highlighted factors such as challenges in making policy decisions, the introduction of a just and equitable transition and what it entails, and the impacts of silo planning.