Decarbonizing Maritime Shipping in the EU: A PESTLE and MICMAC Factor Analysis of Green Ammonia (e-NH3) Adoption Using Rogers' Innovation-Decision Process

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Abstract

This thesis analyzes the PESTLE factors influencing the adoption of green ammonia (e-NH_3) as an alternative fuel for the EU's maritime fleet, focusing on the persuasion stage of Rogers' innovation-decision process. A comprehensive literature review established the dominance of traditional fuels and the maritime sector's high emissions, underscoring the need for sustainable alternatives. This study then presents the potential of e-NH_3, which has no CO_2 emissions throughout its supply chain and combustion, to significantly improve the maritime sector's environmental impact.

Content analysis of grey and academic literature on the Scopus database, supplemented by interviews with 11 experts, identified 26 PESTLE factors impacting e-NH_3 adoption. These factors were categorized using LIPSOR's MICMAC software into three categories: independent (high influence, low dependence), moderate (equal influence and dependence) and dependent (low influence, high dependence). Key independent factors included ammonia-specific legislation, health & safety, CO_2 emissions reduction potential, and infrastructure needs. Moderate factors included energy autonomy, stakeholder support, and the EU's maritime regulations like the FuelEU Maritime Initiative and ETS. Dependent factors included green shipping corridors, e-NH_3 fuel performance, and marine impact.

This study outlines the steps for the EU to advance from the persuasion stage to the decision, implementation, and confirmation stages of Rogers innovation-decision process, using the MICMAC categorization of identified influencing factors. The EU's commitment to e-NH_3 adoption in the decision stage is crucial, as it will pave the way for financial support and stakeholder engagement. Implementation should focus on regulatory development, social acceptance, and pilot projects. The confirmation stage requires ongoing R&D, performance evaluation, environmental impact assessments, and international collaboration.

Integrating a PESTLE into the innovation-decision process enhances the e-NH_3 adoption analysis by providing complementary perspectives. This synergistic approach offers holistic insights into EU maritime policy and industry decisions, proving to be the primary academic contribution of this study. Future research could combine PESTLE with models like TAM or TPB to study alternative fuel adoption across various sectors.

Despite limitations, including the limited number of expert interviews and focus on MICMAC's direct influences, this study provides strategic recommendations for the EU to facilitate e-NH_3 adoption. Addressing independent factors first, moderate factors second and dependent factors third can align the adoption process with climate goals, economic resilience, and energy security, making e-NH_3 a fuel for a sustainable maritime sector.

Acknowledgement

I express my deepest gratitude to Dr. Steven McGreevy for his continued feedback and guidance throughout this study. His advice and encouragement have been crucial in shaping my academic path and enhancing the quality of my work.

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Abbreviations

DNV - Det Norske Veritas
EMSA – European Maritime Safety Agency
EU - European Union
ETS- Emissions Trading Scheme
GHG - Greenhouse Gas
HFO - Heavy Fuel Oil
IEA - International Energy Agency
IMO - International Maritime Organization
LR - Lloyd's Register
LFO - Low-Fuel Oil
LSFO - Low-Sulfur Fuel Oil
MDI – Matrix of Direct Influences
MGO - Marine Gas Oil
MICMAC - Matrice d'Impacts Croisés Multiplication Appliquée à un Classement
MRV - Monitoring, Reporting, and Verification
PESTLE - Political, Economic, Social, Technological, Legal, Environmental

1. Introduction

1.1. Background

Maritime shipping is the epicentre of global trade as it facilitates the transport of 80% of the world's cargo (Balci et al., 2024; EU, 2023; Tsvetkova et al., 2024). According to the most recent studies, over 100,000 ships with a gross tonnage of 100 and more were operating worldwide in 2023 (Balci et al., 2024; UNCTAD, 2023). Compared to other cargo transportation methods like roads, railways, or air, maritime shipping is the cleaner choice in terms of GHG/ton-km (Balci et al., 2024; EU, 2023). But, despite its efficiency in transporting large volumes of goods, most ships still use high-emission fuels like heavy fuel oil (HFO), light fuel oil (LFO), marine gas oil (MGO), liquified petroleum gas (LPG), liquified natural gas (LNG) and methanol (Aakko-Saksa et al., 2023; Balci et al., 2024; Christodoulou & Cullinane, 2022). As a result, the maritime sector is estimated to be responsible for 3% of global anthropogenic CO2 emissions (EU, 2023; T&E, 2022). Figure 1. depicts the increase in CO2 emissions from the international shipping sector, using the most recent data from the International Energy Agency (IEA) (IEA, 2023).

The maritime sector is under increasing pressure to cut CO2 emissions in alignment with the Paris Agreement, which aims to reduce global warming to below 2℃, preferably to 1.5℃ compared to pre-industrial levels (Balci et al., 2024; Christodoulou & Cullinane, 2022). The urgency of decarbonizing shipping was highlighted at COP26 which emphasized the sector's role in global efforts to mitigate CO2 emissions (Christodoulou & Cullinane, 2022). In response, the International Maritime Organization (IMO), the UN's specialized agency for regulating international shipping, adopted an initial strategy that targets achieving net-zero CO2 emissions from the sector by 2050 (Christodoulou & Cullinane, 2022). In 2023, the IMO revised this initial strategy to include four essential steps for decarbonizing the shipping sector. Among these, the second goal states the importance of increasing the adoption of alternative fuels (Christodoulou & Cullinane, 2022).

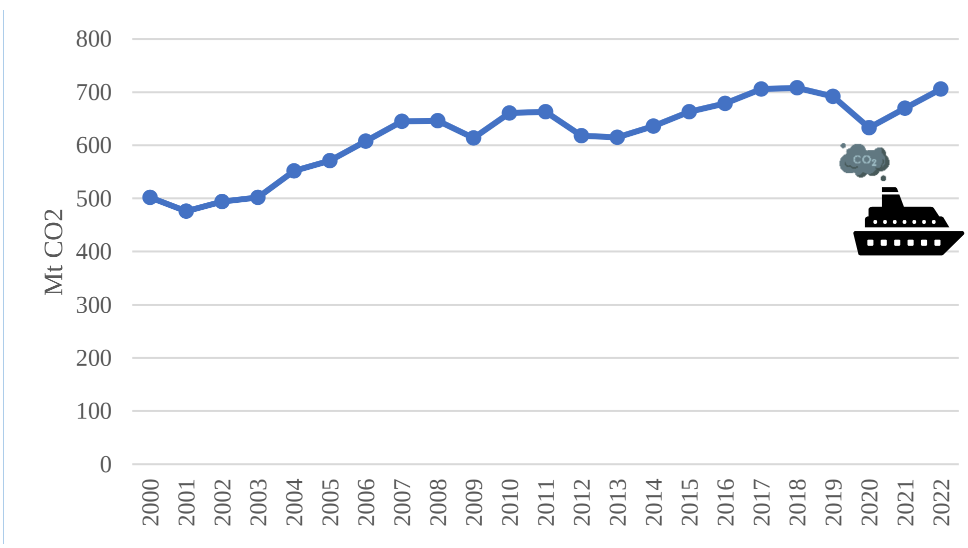


Figure 1. Estimated CO2 emissions in Mt CO2 from the international shipping sector. Data was adopted from the most recent IEA report on global shipping emissions and graphed using Excel (IEA, 2023).

1.2. Maritime Shipping in the European Union (EU)

In the EU, maritime shipping has been a primary driver of economic growth and prosperity by connecting all member states through trade and exchange (EU, 2024). Maritime shipping secures the energy, food, and goods supply and exports products to the rest of the world (EU, 2024). With its significant share of the global maritime fleet, the EU, which owns 16% of the world's vessels, substantially influences the maritime sector (EMSA, 2024). Moreover, the number of ships operating in the EU is expected to rise to meet growing trade demands (EU, 2024). Consequently, the fleet has a considerable environmental impact due to the continual use of traditional bunker fuels, which account for about 4% of total CO2 emissions from the EU (EU, 2023). Figure 2. illustrates the rising trend of CO2 emissions from the shipping sector, indicating that the estimated emissions have surpassed pre-pandemic levels (T&E, 2024).

To align with global efforts to reduce CO2 emissions from shipping, the EU has adopted legislation under the 'Fit for 55' package in the form of the FuelEU Maritime Initiative, set to commence in 2025 (Chen et al., 2021; Christodoulou & Cullinane, 2022; Von Malmborg, 2023). This initiative establishes decreasing GHG intensity limits for ships operating within the European Economic Area (EEA). It aims to reduce the GHG intensity of energy use by 80% in 2050 compared to 2020 (Christodoulou & Cullinane, 2022). The initiative mandates that ships adopt alternative fuels or energy sources to comply with proposed GHG intensity limits (Christodoulou & Cullinane, 2022).

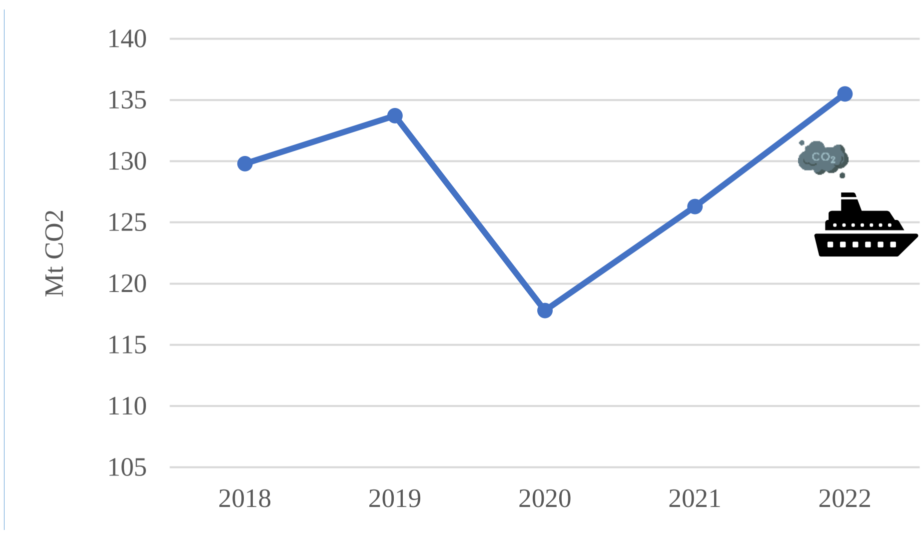


Figure 2. Estimated CO2 emissions in Mt CO2 of the EU's maritime shipping sector. Data was adopted from the most recent report on shipping emissions from the European Federation for Transport and Environment and was graphed using Excel (T&E, 2024).

1.3. e-NH3 as an Alternative Fuel for the EU

In the pursuit of decarbonizing shipping, the IMO and the European Maritime Safety Agency (EMSA), responsible for reducing marine pollution from ships in the EU, together with academia, have identified various alternative fuels and technologies (EU, 2024; EMSA, 2023). These include wind-assisted technologies, hydrogen, biofuels, and one that stands out as a potential long-term fuel, ammonia (Balci et al., 2024; EMSA, 2023; EU; Rony et al., 2023;

Tsvetkova et al., 2024). Particular attention has been paid to green ammonia (e-NH3), a carbon-free molecule produced from renewable energy, thus carbon neutral throughout its life cycle (Rony et al., 2023). Many studies emphasize that ammonia possesses a greater volumetric energy density than hydrogen, making it apt for both long and short maritime voyages, indicating superior onboard storage (Balci et al., 2024; EMSA, 2023; Marrero & Martinez-Lopez, 2023). Furthermore, ammonia attains a liquid form under 0.8 MPa at 20 °C, simplifying its transportation (Balci et al., 2024). Ammonia can be utilized in combustion engines and fuel cells, making it suitable for widespread maritime application (Balci et al., 2024). More importantly, ammonia combustion does not produce CO2. Hence, e-NH3 is recognized as a sustainable fuel that could aid the decarbonization of the EU's maritime fleet.

1.4. Rogers' Innovation-Decision Process

Rogers' Diffusion of Innovation theory's 'innovation-decision process' is a theoretical framework that outlines the stages that organizations or individuals go through when adopting new technologies (Ayanwale & Ndlovu, 2024; Rogers 2003). Developed by Everet Rogers in 1962, it is one of the most used frameworks to analyze the process of communicating innovations through a system (Menzli et al., 2022; Rogers 2003). It has been utilized in over a thousand studies dealing with innovations at individual and organizational levels (Menzli., et al., 2022).

1.5. MICMAC Analysis

Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) analysis is a strategic planning tool and software which enables the quantification and fuzzing of the relationship intensity between factors or variables (Balci et al., 2024; Tsvetkova et al., 2024). The MICMAC software and analysis method was created by LIPSOR (Laboratoire dʹInvestigation en Prospective, Strat´egie et Organisation) and has been utilized in many studies to identify and display the relationships between key variables or drivers influencing a specific outcome (Balci et al., 2024; Tsvetkova et al., 2024).

1.6. Problem Statement

Decarbonizing the EU's maritime fleet is a complex journey that involves balancing the need for decarbonization with the practicalities of adopting new fuels or technologies. This is particularly challenging as the sector has remained unchanged for a significant period (Chiong et al., 2021). Traditional bunker fuels such as HFO, MGO, and LFO have long dominated the shipping fuel market, with alternative fuels primarily overlooked until recently (Balci et al., 2024; Chiong et al., 2021). Nevertheless, the utilization of alternative fuels has been minimal on an industrial scale, but the maritime sector is now prioritizing the shift towards broader adoption of alternative fuel sources (Chiong et al., 2021). While various cleaner technologies like wind-assisted, solar energy, and battery-based propulsion are being assessed for maritime shipping, alternative fuels are often viewed as a long-term decarbonization solution for short- and deep-sea shipping (Rony et al., 2023; Tsvetkova et al., 2024).

While the adoption of e-NH3 is recognized to have the potential to aid the decarbonization of the EU's shipping sector, most existing literature focuses on the cost and engineering aspects (Balci et al., 2024). Consequently, little attention has been given to the various factors that influence its adoption, including political, social, technical, legal, and environmental (PESTLE) aspects collectively. Some research has analyzed these factors for clean propulsion technologies in general, but a specific analysis for e-NH3 in the EU's maritime fleet has been relatively neglected (Tsvetkova et al., 2024). Focusing solely on the cost and engineering aspects neglects other crucial factors; overlooking these broader considerations can result in the failure of adoption. Moreover, there is limited research that applies theoretical frameworks to this context. Additionally, while EU agencies mention e-NH3, no specific policies and regulations focus on its adoption. Although policies aimed at decarbonizing the shipping sector, such as the FuelEU Initiative, often emphasize alternative fuels collectively, it is crucial to acknowledge that each fuel or technology has unique characteristics and challenges. Understanding these factors individually is essential for facilitating widespread adoption.

Therefore, addressing this research gap by integrating a PESTLE alongside a theoretical model to understand the multifaceted factors influencing e-NH3 adoption contributes to academic literature and advances the theoretical understanding of sustainable fuel diffusion into the EU's maritime fleet. Examining the PESTLE domains can also assist the European Commission and member nations better comprehend the influencing factors to address them accordingly to facilitate the diffusion of e-NH3 or similar net-zero fuels.

1.7. Research Objective

The objective of this study is first to provide an overview of the EU's maritime fleet, focusing on fleet size, bunker fuel types used, and CO2 emissions to underscore the need for decarbonization through a comprehensive literature review of Scopus and relevant grey literature. Subsequently, it presents e-NH3 as an alternative fuel and a critical analysis of the multifaceted factors influencing its adoption by integrating a PESTLE analysis into the persuasion stage of Rogers' innovation-decision process. The persuasion stage is when an industry, sector, or society forms an opinion or belief over a specific technology or innovation, in this case, e-NH3. This is to validate if it's a viable path to follow by analyzing the factors that must be considered before adoption. More specifically, each PESTLE factor influencing e-NH3 adoption will be analyzed based on the 'relevant advantage,' 'compatibility,' 'complexity,' 'trialability,' and 'observability' characteristics as specified by Rogers.

The study then identifies the key PESTLE factors through a content analysis of literature and consultation with experts. Subsequently, the identified factors are entered into a MICMAC analysis to understand and describe their influence. The MICMAC software program provides a structured approach to understanding the influence of identified factors or variables and is a valuable tool for decision-making and strategic planning. The key factors identified in this study are then presented along with some implications and recommendations for the EU, following the subsequent stages of the innovation-decision process (decision, implementation, and confirmation stage). The outcomes of this research aim to foster the widespread adoption of e-NH3 and advance the EU's transition towards a sustainable maritime sector. Furthermore, this study contributes to academic literature by addressing the existing research gap in utilizing the PESTLE framework with Rogers' innovation-decision process followed by a critique of this methodology. Therefore, advancing the theoretical understanding of e-NH3 diffusion in the maritime context and including a broader and guided analysis within Rogers' theory.

1.8. Research Questions

What are the key PESTLE factors, and how do they influence the adoption of green ammonia (e-NH3) as an alternative fuel for the EU's maritime fleet using Rogers' innovation-decision process and LIPSOR's MICMAC Analysis?

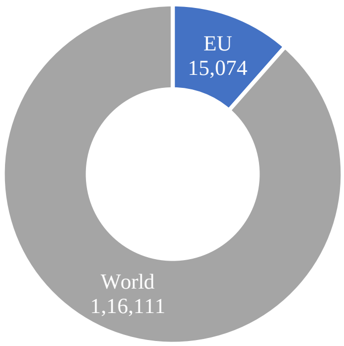
1. What PESTLE factors influencing the adoption of e-NH3 have been identified in grey and academic literature?
2. What PESTLE factors influencing the adoption of e-NH3 are identified by experts in the field?
3. How do the identified PESTLE factors influence the adoption of e-NH3, as determined through a MICMAC analysis?
4. How do the PESTLE framework and Rogers' innovation-decision process enhance the analysis of the adoption of e-NH3 as a fuel?
5. What are some implications and recommendations for the European Commission and EU member nations considering the identified PESTLE factors for adopting e-NH3?

2. Literature Review

The first step of this research was a comprehensive literature review of academic and grey literature to understand and provide the pivotal context of the current status of the EU's maritime fleet. This was followed by an analysis of the information present on the current fuel types used, their emissions, and the steps the EU is currently taking to decarbonize. Information on the various alternative fuels and a brief background on e-NH3 are also presented here. The literature review was the backbone of this study, as it identified the knowledge gap, the data collection and analysis methods. Finally, it provides the essential context for the subsequent PESTLE analysis.

2.1. The EU's Maritime Fleet

In the EU, maritime shipping is crucial in global trade facilitation. Consequently, the union boasts a significant maritime presence in terms of absolute numbers, gross tonnage (the internal volume of a ship), and dead weight (the weight a ship can carry) (EMSA, 2024). According to the latest data from the EMSA, in 2023, approximately 16% of the world's active fleet was under an EU flag. Notably, around two-thirds of the ships belong to private owners or companies (EMSA, 2024). Figure 3 illustrates the fleet size and gross tonnage in 2023 compared to the rest of the world.



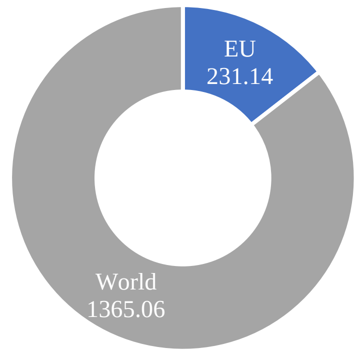


Figure 3. Doughnut chart on the left depicts the fleet size in absolute numbers and the doughnut chart on the right illustrates the gross tonnage (million). Data collated from the EMSA and graphed manually using Excel (EMSA, 2024).

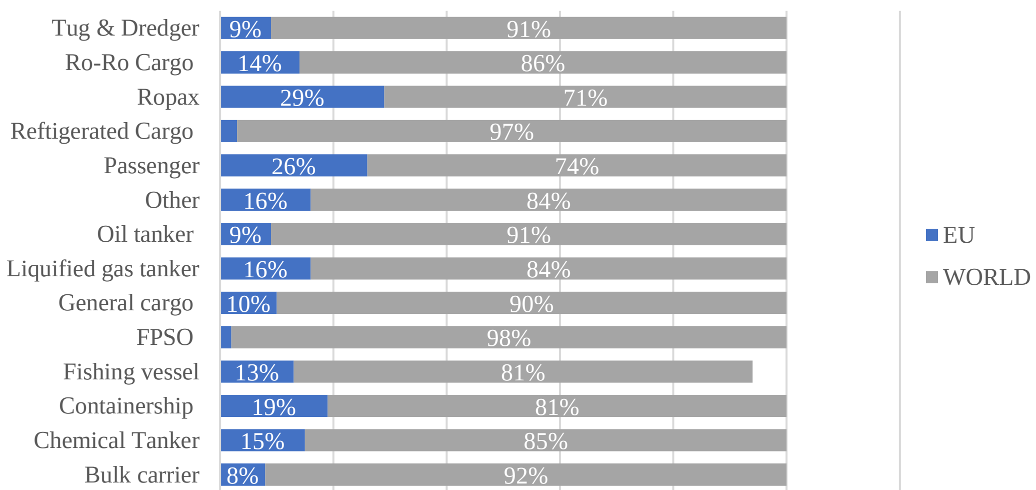


Figure 4. EU's maritime fleet portfolio, compared to the rest of the world. Data collated from the EMSA and graphed manually using Excel (EMSA, 2024).

In terms of composition, a diverse portfolio of ship types form the fleet. Some notable types include ropax (ships for freight vehicle transport along with passengers), passenger ships, and container ships. Among the total number in the world, the EU accounts for 29%, 26%, and 19% respectively (EMSA, 2024). Figure 4 presents a summary snapshot of the EU's diverse and active maritime fleet by ship type. Data suggest that there are more ships in the EU now than before, and this number is expected to increase in the coming years to meet the growing trade and exchange demands (T&E, 2023).

2.2. Current Fuel Types Used & CO_2 Emissions

Both academic and grey literature suggest that, like the rest of the world, the EU's maritime fleet still heavily relies on traditional fossil fuels (Aakko-Saksa et al., 2023; Balci et al., 2024; Christodoulou & Cullinane, 2022). These conventional fuels dominate the sector because of their competitive price and existing port infrastructure that make them the more practical choice for the industry at present. Consequently, the EU reports that 99% of maritime fuels are currently derived from fossil fuels (European Commission, 2024).

Despite their high energy density and cost-effectiveness, conventional bunker fuels are a significant source of CO_2 emissions, accounting for about 4% of the EU's emissions (EU, 2023). HFO is one of the primary fuels utilized in the sector due to its economic viability and high energy content. At the same time, LFO and LSFO have gained traction in recent years due to their lesser sulphur content (Christodoulou & Cullinane, 2022). Data suggests that there has been a slight increase in the use of LNG by some vessels due to its lower emissions profile when compared to HFO and MGO (EU, 2023). Although not as commonly used, LPG is utilized by some specialized carriers as well. There has also been some use of batteries, H_2, and methanol for ship propulsion, but not enough to cause any significant CO_2 reduction (EU, 2023).

The use of these traditional fuels, while still crucial for the EU's maritime sector, has come under scrutiny in recent years due to their environmental impact, specifically regarding their high CO_2 emissions, sulphur oxide release, and nitrogen oxide emissions during combustion (Chen et al., 2021; Christodoulou & Cullinane, 2022; Von Malmborg, 2023). Figure 5 depicts the current fuel types used by the EU's maritime fleet by ship type. It is evident here that HFO and LFO dominate across ship types, and MGO is a close third.

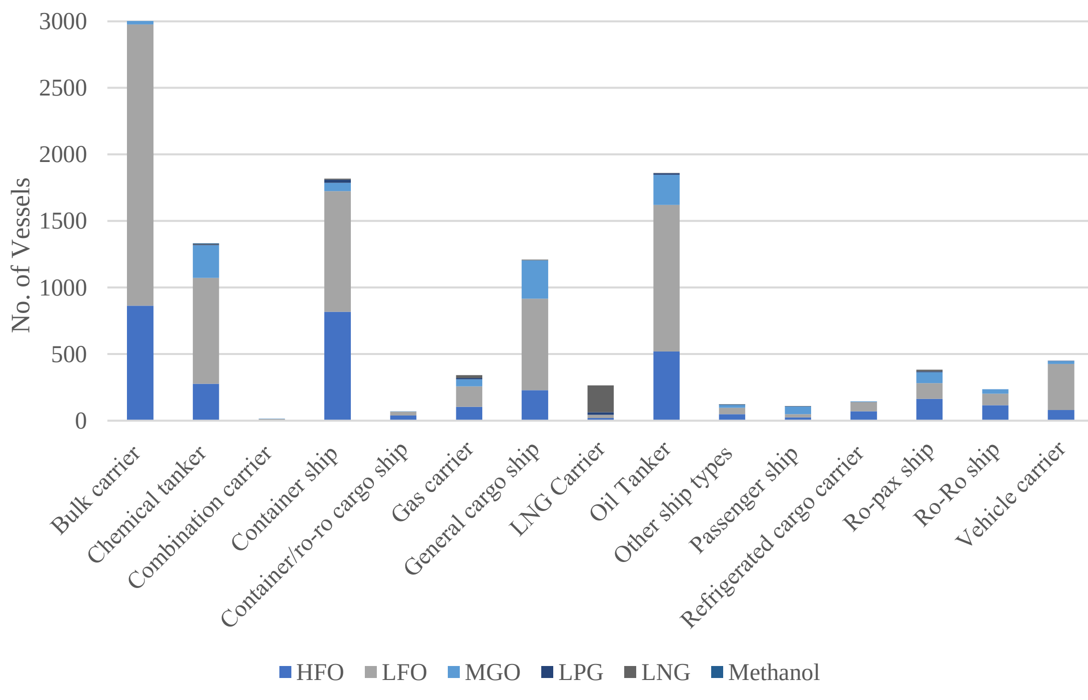


Figure 5. The different fuel types used by the EU's maritime fleet ship types. Data adapted from Christodoulou & Cullinane (2022) and graphed manually using Excel.

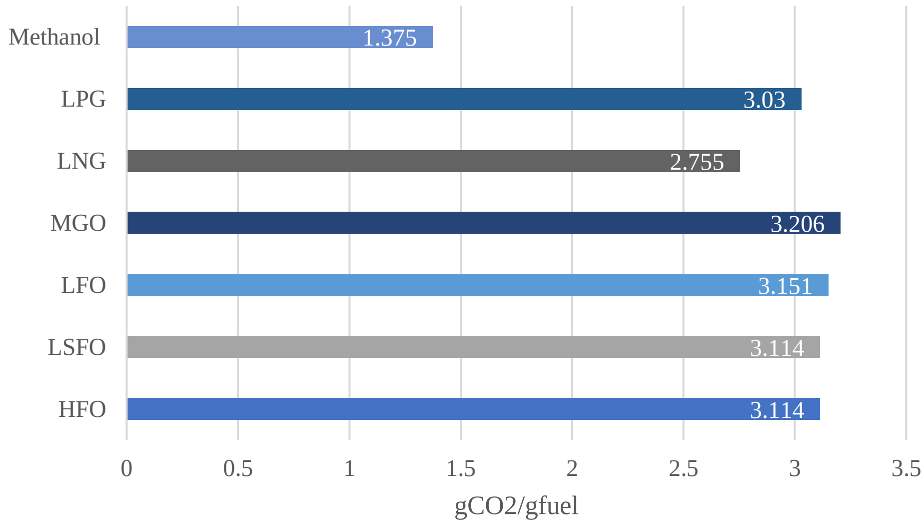


Figure 6. CO2 emission factor of traditional maritime fuels (gCO2/gfuel) (Christodoulou & Cullinane, 2022; European Commission, 2024).

Traditional fuels are notorious for their high CO2 emissions per unit of energy used (gCO2/gfuel). This is echoed by findings in literature, as diagrammatically represented in Figure 6, which shows the relatively higher gCO2/gfuel for HFOs, LFOs, LSFOs, and MGOs when compared to newer net-zero fuels, which have a 0 gCO2/gfuel value (such as H2 for example) (Christodoulou & Cullinane, 2022). The EU fleet's reliance on traditional fuels underscores the challenges of transitioning to a more sustainable, low-carbon maritime sector. The existing infrastructure, economic considerations, and regulatory frameworks are still heavily oriented towards these fuels, making the shift to lower emissions complex. Moreover, the fleet's dependence on these fuels, coupled with almost negligible use of alternative or net-zero fuel pathways, is critical to highlight. It emphasizes that the sector is unlikely to meet any of the EU, national, or international climate agreements if the current situation continues for the foreseeable future. Consequently, it also underscores the urgent need for the European Commission to initiate more dialogue on using alternative net-zero fuels or greener propulsion shipping technologies to become more widespread. Finally, it highlights the need for continual innovation and investment in cleaner energy solutions for the sector. This context is essential to provide and forms the backdrop for this thesis.

2.3. FuelEU Maritime Initiative

From a policy standpoint, literature reveals that in response to global efforts to decarbonize maritime shipping, the EU has implemented the FuelEU Maritime Initiative. This initiative is a crucial component of the ambitious 'Fit for 55' package (Chen et al., 2021; Christodoulou & Cullinane, 2022; Von Malmborg, 2023). The initiative focuses explicitly on the maritime industry by setting progressive limits on GHG intensity (the number of emissions per unit of energy used by ships) (Chen et al., 2021; Christodoulou & Cullinane, 2022; Von Malmborg, 2023). Starting in 2025, ships over 5000 gross tonnages will be required to transition to alternative fuels or energy sources to comply with these limits, which will become increasingly stringent, aiming for an 80% reduction by 2050 compared to 2020 (European Commission, 2023). The specific GHG limits per year are outlined in Table 1. Moreover, the initiative covers energy used by ships while docked at EU ports, all energy used on trips between EU ports and about half the energy used on trips to or from non-EU ports as well (Chen et al., 2021; Christodoulou & Cullinane, 2022). However, certain vessels are excluded from this, such as warships and fishing boats (Christodoulou & Cullinane, 2022). As a regulation, the FuelEU Maritime initiative is legally binding and directly applicable in all member states without requiring national governments to adopt it into their legislation. Hence, if ships or companies operating under an EU flag do not comply with the regulation and ensuing GHG limits, they are subjected to the FuelEU penalty (European Commission, 2024). Only after the payment will the FuelEU Certificate of Compliance be issued (European Commission, 2024).

Table 1. Increasing GHG intensity limits placed by the FuelEU Maritime Initiative (European Commission, 2024)

GHG intensity limit	Year (Starting January 1)
-2%	2025
-6%	2030
-14.5	2035
-31%	2040
-62%	2045
-80%	2050

The GHG intensity limits are based on reference values calculated from the average energy intensity of ships in 2020, using data from the EU's Monitoring, Reporting, Verification database (Christodoulou & Cullinane, 2022). This system tracks the energy efficiency of vessels every year, providing a benchmark for future reductions required by the initiative. With these limits, the initiative aims to increase the adoption of net-zero technologies. The initiative also introduces a special incentive to support the uptake of renewable fuels of nonbiological origin (RNFBO), referred to as e-fuels (European Commission, 2024). However, it is evident that from a policy standpoint, existing literature caters more toward potential fuel pathways as a whole with a lack of singular focus on e-NH3.

2.4. Alternative Fuels & Green Ammonia (e-NH3)

Several alternative fuels and technologies that have the potential to aid the decarbonization of the EU's fleet are identified in academia and grey literature. These include wind-assisted technologies, hydrogen, battery-assisted technologies, and, of course, alternative fuels (Balci et al., 2024; EMSA, 2023; EU; Rony et al., 2023; Tsvetkova et al., 2024). However, literature identifies that shifting to alternative fuels is more preferable (Balci et al., 2024). Of the many identified, one that has gained significant traction in recent years is green ammonia (e-NH3). The IEA, EMSA, IMO and the European Commission highlight the specific potential of e-NH3 as a long-term maritime fuel (EMSA, 2024; IEA, 2024; IMO, 2024). The IEA estimates explicitly that 44% of the marine fuel mix by 2050 will be e-NH3 (IEA, 2024). Although other types of ammonia are available, such as grey and blue, producing these alternatives requires fossil fuels and thus is not favourable for decarbonization (Rony et al., 2023). Table 2 depicts the various traditional fuels and their higher gCO2/gfuel values compared to the lower values of RFNBOs, especially that of e-NH3's 0 gCO2/gfuel value (highlighted in green).

Table 2. Depicting CO2 emissions per unit of energy used for traditional fuels and RFNBOs (gCO2/gfuel) (Christodoulou & Cullinane, 2022; European Commission, 2024).

Source	Type	gCO2/gfuel
Fossil Fuels	HFO	3.114
	LSFO	3.114
	LFO	3.151
	MGO	3.206
	LNG	2.755
	LPG	3.03
	Methanol	1.375
RFNBO	e-diesel	3.206
	e-methanol	1.375
	e-LNG	2.755
	e-H2	0
	e-NH3	0

e-NH3 refers to ammonia entirely produced from renewable energy and carbon-free sources (Balci et al., 2024). The process begins with harnessing renewable energy, which is then used to power two main steps. First, to produce hydrogen, the process of electrolysis is used to split water into hydrogen and oxygen (DNV, 2023). Then, e-NH3 is synthesized by using the hydrogen produced, combined with nitrogen from the air, through the method known as the Haber-Bosch process (Balci et al., 2024; DNV, 2024). The process is effectively outlined in Figure 7 (DNV, 2023).

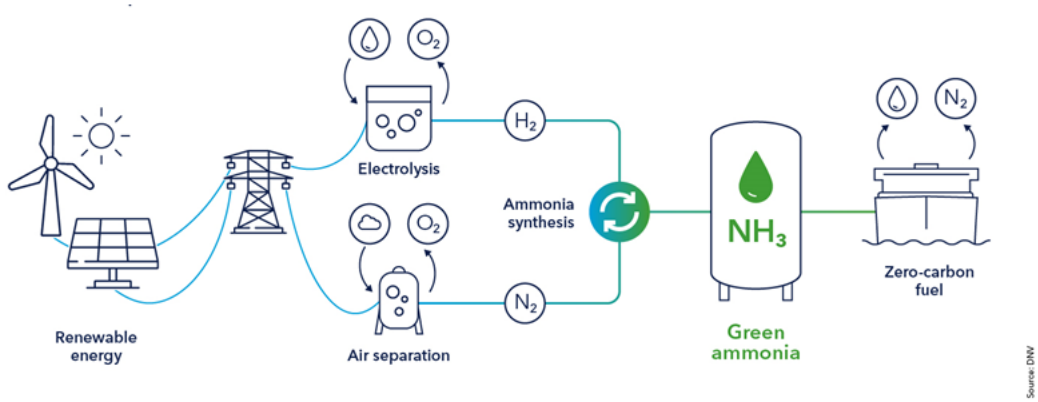


Figure 7. The production process of e-NH3 showing no CO2 release at any stage of the process (DNV, 2023).

According to literature, e-NH3 is recognized as a leading alternative maritime fuel for short and long-shipping practices (EMSA, 2023; Marrero & Martinez-Lopez, 2023). Several characteristics of the fuel are essential to highlight, such as it boasts a marginally higher energy density per volume than methanol and significantly more than hydrogen (Balci et al., 2024;

EMSA, 2023; Marrero & Martinez-Lopez, 2023). In addition, it can be stored as a liquid under pressure of 0.8 MPa at 20°C and or at atmospheric pressure at -33°C, which makes transportation and storage an advantage (Balci et al., 2024). e-NH3 can also be used in internal combustion engines (ICEs) and fuel cells, making retrofitting of ships possible (EMSA, 2024). Although, like methanol in terms of characteristics, e-NH3 appears to be the more viable and preferred option due to its significantly higher H2 content (40% more than methanol) (Marrero & Martinez-Lopez, 2023). Another essential point is that ammonia production is not necessarily a new phenomenon (Balci et al., 2024). Due to its historical use in the fertilizer and agricultural industries, it benefits from an already established infrastructure that caters to its production processes, transportation, and storage (EMSA, 2023; Marrero & Martinez-Lopez, 2023). However, some retrofitting and adjustments are required for the fuel, specifically in the maritime context.

One crucial factor that literature has revealed is that the combustion of e-NH3 does not produce CO2 emissions, owing to its lack of carbon molecules coupled with its renewably sourced energy for production (Balci et al., 2024; EMSA, 2023; Marrero & Martinez-Lopez, 2023). Studies that have conducted life cycle assessments for various alternative bunker fuels also indicate that e-NH3 provides a sustainable and efficient combustion performance (Balci et al., 2024). Though favourably identified, e-NH3 does come with some complications. Information from grey literature, academic literature, and leading shipping companies adduce that e-NH3, in comparison with diesel oils, has a slower rate of flame propagation, which means that it burns much slower when compared to traditional fuels (DNV, 2024). This suggests that maintaining combustion once initiated is more challenging. Another consideration is that although e-NH3 can mitigate CO2 emissions, it is rich in nitrogen and hence results in the emission of nitrogen oxide (NOX) and nitrous oxide (N2O) (DNV, 2024). However, retrofitting ships can easily be a solution for NOX. The greater challenge lies in nitrous oxide (commonly referred to as laughing gas) emissions, which is a potent GHG (DNV, 2024). Moreover, continuous human exposure to ammonia can also have detrimental health effects and may even lead to death (DNV, 2024).

2.5. Research Gap

The potential of e-NH3 to assist in decarbonizing the EU’s shipping sector is widely acknowledged in literature. However, most studies primarily focus on the cost and engineering dimensions. As a result, there is a lack of comprehensive analysis of the multiple other factors that can impact the integration of e-NH3. These factors collectively encompass political, social, technical, legal, and economic considerations. Focusing solely on the cost and engineering aspects neglects other crucial factors influencing adoption; overlooking these broader considerations can result in the failure of adoption. Therefore, conducting a comprehensive PESTLE analysis to understand the factors influencing e-NH3 integration into the EU’s maritime fleet is crucial for academia and for the EU. Addressing this research gap will provide a detailed overview of e-NH3, pinpointing key influencing factors while also enabling strategic interventions to promote successful integration into the fleet.

The literature review revealed that while some research has explored these aspects of clean propulsion technologies, a targeted analysis specifically for using e-NH3 within the EU’s maritime fleet has not been given much attention, setting the premise of this study. In their publication, Balci et al. (2024) analyze a roadmap for decarbonizing shipping, focusing on e-NH3 by examining its cost, safety, and infrastructure success factors. Hence, with a specific concentration on the economic and technical aspects. This publication commences with a comprehensive literature review on ammonia for the shipping sector from a global perspective (Balci et al., 2024). This approach was adopted in this thesis but with a focus on identifying factors in the context of e-NH3 adoption into the EU's maritime fleet. Additionally, following Balci et al.'s (2024) focus on e-NH3, this study incorporates a PESTLE factor analysis, thereby offering a broader inclusion of factors coupled with a narrowed-down focus on the EU. Therefore, allowing for a more detailed analysis in a more specific context. This was exploited in Tsvetkova et al.'s (2024) study, which examines the role of PESTLE drivers for 'clean propulsion' shipping in the EU without focusing on a specific alternative fuel (Tsvetkova et al., 2024). While Tsvetkova et al. (2024) offer a PESTLE analysis for clean propulsion shipping in the EU, Balci et al. (2024) focus on the economic and technical aspects of e-NH3. Hence, this study leverages the insights from these two cornerstone papers to conduct a PESTLE factor analysis on e-NH3 for the EU's maritime fleet. Both papers utilize the MICMAC analysis to illustrate how factors either collectively or individually influence a desired outcome regarding clean shipping and/or e-NH3 and is, therefore, employed in this study as well. Furthermore, the review also revealed a scarcity of studies applying theoretical models to analyze the diffusion of alternative fuels in the EU's maritime fleet. Therefore, this thesis also addresses this research gap by utilizing Rogers' innovation-decision process model to provide a deeper understanding of theoretical diffusion which provides academia and the EU with better insights to address the influencing factors for e-NH3 adoption in practise.

3. Theoretical Framework

This research draws inspiration from two frameworks. Firstly, Rogers' Diffusion of Innovation theory's 'innovation-decision process' guides the analysis of factors that must be considered before adopting a new technology or innovation into a sector, business, or society (Ayanwale & Ndlovu, 2024; Rogers 2003). Developed by Everet Rogers in 1962, it is one of the most used frameworks to analyze the process of communicating innovations through a system (Menzli et al., 2022; Rogers 2003). It has been utilized in over a thousand studies dealing with innovations at individual and organizational levels (Menzli., et al., 2022). The choice of this framework over others is not arbitrary. While some other models and theories could be applied like MLP, TIS, SNM or TAM, Rogers' theory was selected for its systematic approach to understanding the diffusion of innovations. It provides a step-by-step process that allows for a thorough analysis of the various stages, from initial knowledge of the innovation to its final confirmation, thereby formulating the adopter's perception (Menzli et al., 2022). Rogers' model also allows for a longitudinal view of the adoption system of new technologies by recognizing that the process is dynamic and iterative which is crucial for studying novel fuels like e-NH3 that need ongoing adjustments for successful integration (Ayanwale & Ndlovu; Menzli et al., 2022). In addition, the step-by-step approach that the model provides is advantageous in anticipating the next steps, offering the ability to be proactive in adopting new technologies (Ayanwale & Ndlovu, 2024). This makes it particularly suitable for theoretically analyzing the adoption of e-NH3, a new and complex fuel for the maritime sector, while also anticipating the following stages of the adoption process, allowing for a proactive approach to promote adoption.

Secondly, the PESTLE framework offered a broader understanding of e-NH3 adoption, as most studies concentrated on the cost and engineering aspects. The PESTLE framework is a widely employed strategic management tool to assess macro-environmental influences over a particular decision or outcome. It has been utilized by many firms around the world and in studies focusing on energy transition (Amega et al., 2024; Münter, 2024; Tsvetkova et al., 2024). Although not scientifically backed, the PESTLE allows for a holistic identification and organization of external factors influencing a particular decision. It provides insights into factors influencing a system from different angles and classifies them into political (P), economic (E), social (S), technical (T), legal (S) and environmental (E) (Amega et al., 2024; Münter, 2024).

3.1. Diffusion of Innovation Theory & The Innovation-Decision Process

Rogers' Diffusion of Innovation Theory suggests that social systems adopt and spread novel ideas or technologies over time by following the innovation-decision process (Ayanwale & Ndlovu, 2024; Rogers 2003; Zhou et al., 2024). He emphasizes that this occurs in five main stages: knowledge, persuasion, decision, implementation and finally, confirmation, as represented in Figure 8 (Rogers 2003; Zhou et al., 2024).

The knowledge stage is when an industry, sector or society is aware of an innovation (Rogers 2003). Many studies and pieces of gray literature identify e-NH3 as a potential alternative fuel, indicating that the knowledge stage has already been reached, represented by the tick on stage 1 (Figure 8). The second stage of the innovation-decision process is the persuasion stage, which calls for analyzing various factors that make a specific innovation a viable path to follow (Rogers 2003; Zhou et al., 2024). In the persuasion stage, groups form attitudes over a specific innovation by analyzing the various factors that make it advantageous or disadvantageous over others (Menzli et al., 2022; Rogers 2003; Zhou et al., 2024). In the context of e-NH3, this includes analyzing the factors based on the characteristics of **'compatibility'** (Is it compatible to be used in the EU's maritime fleet?) and **'trialability'** (Is it being tested as an alternate fuel? Is it being produced sustainably?), **'relative advantage'** (Is it better than other fuels that can also assist with decarbonization? Is it environmentally and economically viable?) and **'simplicity or complexity'** (Is it hard to acquire, adopt, and are there various technical factors that come to play that need to be considered, what are the social factors?) (Ayanwale & Ndlovu, 2024; Rogers 2003).

Therefore, in line with this framework, this research concentrates on the persuasion stage, which forms the foundation and objective of this study, represented by the red question mark (Figure 8). Based on the findings, recommendations and implications for the European Commission and EU member nations will be proposed for the subsequent stages, should the EU decide to widely adopt (third stage), implement (fourth stage) and confirm (fifth stage) e-NH3 as an alternative fuel (Figure 8).

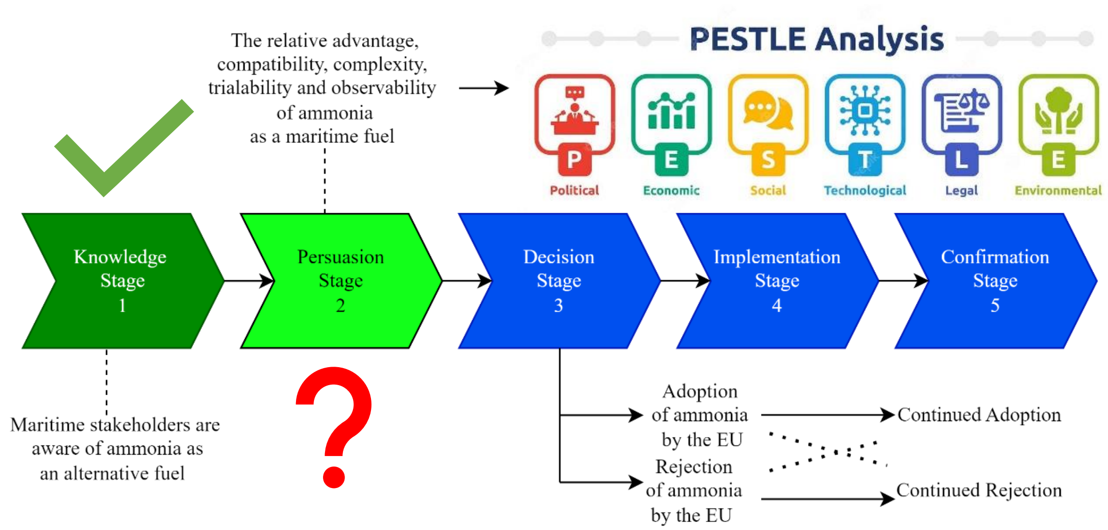


Figure 8. Roger's innovation-decision process applied to e-NH3 as a maritime fuel in the EU, adopted visually using draw.io.

Limitations of the theory include its assumption of a structured approach to understanding innovation diffusion through a system, which may differ in reality, as deduced in a study conducted by Menzli et al. 2022. Adopting innovations can be more complex and unpredictable, as many external factors always influence a particular innovation, and there may be new ones every day (Menzli et al., 2022). Moreover, a system may also move backwards in reference to the stages if a certain innovation fails to be adopted or may even be rejected and then return to being adopted later (Ayanwale & Ndlovu, 2024; Zhou et al., 2024) (Figure 8). Additionally, some systems could skip stages or spend more time on a particular stage. Therefore, although the innovation-decision process offers a structured approach, in theory, the practicalities may differ (Menzli et al., 2022). Thus, it is crucial to remember that this research utilizes the framework to guide a theoretical analysis rather than a confirmed projection for e-NH3.

3.2. PESTLE Framework

Although Rogers identifies the key characteristics necessary for comparing innovations, the theory needs guidance on which factors to consider; thus, the PESTLE analysis fills this gap by providing this guidance. Developed by Francis Aguilar in 1967, the PESTLE framework organizes and comprehensively analyzes the broad spectrum of factors influencing a particular decision (Tsvetkova et al., 2024). As most studies on e-NH3 focus on the cost and engineering aspects, integrating the PESTLE into the persuasion stage of the innovation-decision process enables not only a more comprehensive examination of influencing factors but also makes a more persuasive argument for the adoption of e-NH3 (Figure 8). A study conducted by Amega et al. 2024 concluded that a PESTLE allows stakeholders to better understand the external challenges and opportunities influencing a certain decision in the context of an energy transition such as the focus of this study. Moreover, this enables the development of proactive actions to address the identified factors to facilitate successful adoption. Taking inspiration from Tsvetkova et al. (2024), this study employs the framework to classify the factors as per the categories and description outlined below (Figure 9):

Political Factors: The current political environment that could sway the adoption of e-NH3.
Economic Factors: The economic feasibility of e-NH3, including capital, fuel and retrofitting costs.
Social Factors: The social considerations, such as safety and health associated with e-NH3 usage.
Technical Factors: The readiness level of e-NH3, suitability to be incorporated into the EU's fleet, operational factors, efficiency, onboard ship storage and the current state of production.
Legal Factors: The legal factors in the EU that could influence the widespread adoption of e-NH3 like policies that cater to alternative fuels.
Environmental Factors: The environmental performance of e-NH3 in terms of CO2 emissions reduction capability, its impact on the environment, and the lifecycle of e-NH3 production and use.

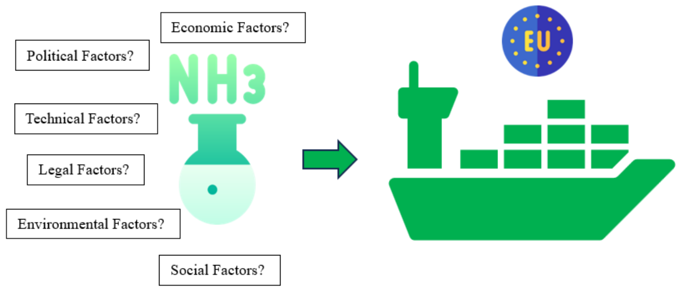


Figure 9. Diagrammatic representation of the PESTLE factors influencing the adoption of NH3 into EU's maritime fleet, created using drawio.

Although the PESTLE is a commonly used analysis tool, the categorization above was devised for individual analysis of factors based on their respective categories for this study following Tsvetkova et al., 2024 (Figure 9). However, it is important to note that many factors could simultaneously have political, legal, economic, technical, or economic implications (Münter, 2024). Moreover, one limitation of the PESTLE is its subjectivity, as the interpretation of factors can vary depending on the analyst's perspective (Amega et al., 2024). Another limitation is the complexity of analyzing factors across six domains at a specific point in time, which may not account for future changes, especially in volatile sectors.

4. Research Methodology

The methodology for this report was developed from an exhaustive reading of similar studies found on the Scopus database. The approach begins with identifying and analyzing the various PESTLE factors from a content analysis and expert consultation. It then proceeds to conduct a MICMAC analysis of the identified factors to categorize them based on their influence. Finally, considering this categorization, this thesis offers recommendations for the EU to facilitate the successful adoption of e-NH3 and critiques the theoretical framework utilized (Figure 10).

4.1. Methodological Approach

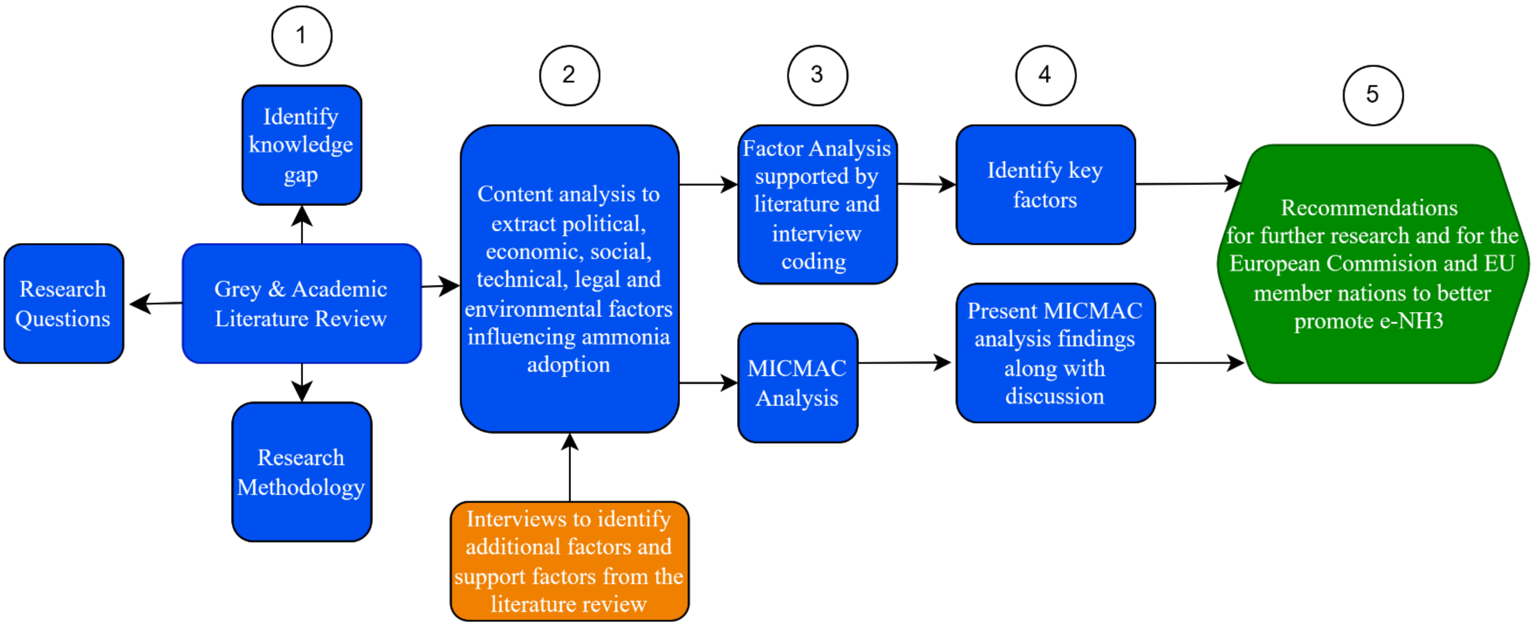


Figure 10. The methodological approach devised for this thesis was adopted from similar studies and visualized manually using draw.io (Balci et al., 2024; Tsvetkova et al., 2024).

This study leverages insights from two cornerstone papers to conduct a PESTLE factor analysis on e-NH3 for the EU's maritime fleet (Balci et al., 2024; Tsvetkova et al., 2024). The methodological approach diagrammatically represented in Figure 10 is outlined below:

1. Conduct a literature review of both grey literature and Scopus articles on alternative fuels, ammonia and decarbonization of shipping. This review identified the methodological approach, knowledge gaps, theoretical framework, problem statement, data analysis method and research question.
2. Data collection through content analysis of Scopus and grey literature to identify and extract PESTLE factors influencing e-NH3 adoption. This is supplemented with qualitative data collection by interviewing maritime and e-NH3 experts.
3. Identify key PESTLE factors and then analyze using literature and coded excerpts from experts. Organize, label, and enter factors into the MICMAC software.
4. Display the MICMAC analysis cluster diagram and describe the results. Discuss how the findings relate to the research questions.
5. Based on the findings, propose recommendations and further academic research, following the innovation-decision process for the European Commission and EU member states to enhance or improve the adoption of e-NH3. Discuss the academic contribution and critique the theoretical methodology utilized.

4.2. Literature Review

The initial step of this study involved a comprehensive literature review on the Scopus database, focusing on publications discussing the use of ammonia and other alternative fuels in shipping. The initial Scopus search string is presented in Table 3. The literature review was conducted between February and July 2024, following the inclusion criteria below:

1. The year range was from 2020-2024 to provide the most recent analysis.
2. The search excluded irrelevant subject areas like Medicine, Pharmacology, Immunology etc.
3. The search was refined to only include Article title, Abstract and Keywords to ensure publications most relevant to the topic were shown.
4. The articles were published in English.
5. The source document type was restricted to "Journal."
6. The document type was confined to "Article."
7. The articles were open-access, allowing for unrestricted study.

Table 3. Initial Scopus search string utilized in this study.

Search String	Publications
"Alternative fuel" (Article title, Abstract, Keywords) AND "Shipping" (Article title, Abstract, Keywords)	206
"Ammonia" (Article title, Abstract, Keywords) AND "Shipping" (Article title, Abstract, Keywords)	91
"Ammonia" (Article title, Abstract, Keywords) AND "Decarbonization" (Article title, Abstract, Keywords) "Shipping" (Article title, Abstract, Keywords)	22

Following an initial review of the abstracts, the selection was refined to include only those articles that specifically discussed either alternative fuels or technologies in shipping, ammonia in shipping or the decarbonization of shipping. Articles that were deemed less relevant were excluded from this study. A snowball method was utilized to broaden the scope of the literature review, which involved examining the references cited in the selected publications. This approach ensured a comprehensive and focused literature review pertinent to the study's objectives. Furthermore, this allowed for discovering additional publications that might not have been identified in the initial search, thereby providing in-depth research.

The most relevant grey literature was examined alongside academic literature, specifically focusing on documents from the UNCTAD, EMSA, IEA, IMO, LR and the EU. The comprehensive review of academic and grey literature forms the backbone of this study. It facilitates the identification of key factors through content analysis, which are then individually assessed in the subsequent MICMAC analysis.

4.3. Data Collection

Data was sourced via two methods. First, a detailed analysis of identified grey and academic literature was conducted to extract the PESTLE factors. Second, interviews with maritime experts were conducted to validate and supplement factors identified from the content analysis. The data collection matrix of how each research sub-questions was answered is presented in Table 4.

4.3.1. Content analysis

The articles identified in the literature review underwent a detailed analysis to identify the PESTLE factors individually. The individually identified factors also served as the predetermined codes for the ensuing codebook. Alongside the scholarly articles, grey literature was analyzed, specifically focusing on the PESTLE framework's political and legal aspects. The objective was to supplement the factors initially identified in the academic content analysis and to discover additional factors.

Table 4. Data Collection Matrix

Sub-Research Question	Information and Data needed	Sources	Access Method
1. What PESTLE factors influencing the adoption of e-NH3 have been identified in grey and academic literature?	Extract PESTLE factors influencing the adoption of e-NH3 based on the criteria provided by Tsvetkova et al., 2024.	**Secondary Sources:** Scopus articles (Academic literature), IEA, IMO, EMSA, EU, EU, MRV (Grey literature)	Content analysis of academic literature Content analysis of grey literature
2. What PESTLE factors influencing the adoption of e-NH3 are identified by experts in the field?	Support or contrast factors identified from the content analysis coupled with identifying any additional factors for the adoption of e-NH3.	**Primary Sources:** e-NH3 and maritime experts.	Interviews
3. How do the identified PESTLE factors influence the adoption of e-NH3, as determined through a MICMAC analysis?	Understand the PESTLE drivers and barriers influencing the adoption of e-NH3 into the EU's maritime fleet via the MICMAC and expert consultation.	**Secondary Sources:** Scopus articles (Academic literature), IEA, IMO, EMSA, EU, EU MRV, DNV, LR (Grey literature)	Content analysis of academic literature Content analysis of grey literature
		Primary sources: e-NH3 and maritime experts. MIMAC	Interviews
4. How do the PESTLE framework and Rogers' Innovation Decision Process enhance the analysis of the adoption of e-NH3 as a fuel?	Assess the effectiveness of integrating a PESTLE with Rogers' innovation-decision process.	**Secondary Sources:** Scopus articles (Academic literature)	Content analysis of academic literature Results from this study
5. What are some implications and recommendations for the European Commission and EU member nations	Policy and strategies that can be made to better promote the diffusion of e-NH3 in the EU's maritime fleet for the European	**Secondary Sources:** Scopus articles (Academic literature), IEA, IMO, EMSA, EU, EU MRV, DNV, LR (Grey literature)	Content analysis of academic literature Content analysis of grey literature

considering the identified PESTLE factors for adopting e-NH3?	Commission and EU member states.	**Primary sources:** e-NH3 and maritime experts.	Interviews

4.3.2. Interviews with e-NH3 and Maritime Experts

Studies investigating the analysis of alternative fuels in the maritime sector highlight the importance of understanding the factors identified by experts (Balci et al., 2024; Tsvetkova et al., 2024). Hence, to deepen the understanding of e-NH3 adoption in the EU's maritime sector and to identify the PESTLE factors, semi-structured interviews were carried out with 11 experts in the field. These experts were selected from shipping companies, ports, maritime consultancies, and leading energy providers. The selection criteria included identifying individuals with specialized knowledge of e-NH3 within the EU's maritime sector or those actively involved in e-NH3-related projects found through an initial search of "Green Ammonia Projects" on Google. Participation was limited to individuals willing to participate in the study and were in the EU.

The interviews, which followed the questionnaire found in Appendix A, lasted approximately 30 minutes. They began with a brief introduction of the topic and of the interviewee's themselves to gauge their experience with e-NH3. This was followed by specific questions relating to each PESTLE domain and questions on what the experts believed the EU could do to facilitate adoption, and these insights were used to formulate recommendations in the discussion section.

Although there was a questionnaire, the interviews led with the notion of organically identifying PESTLE factors. Outreach for the interviews was conducted via email and LinkedIn, following the initial search outlined above. This method ensured a targeted and effective approach to gathering firsthand insights from experts. Table 5 represents a summary of the experts' anonymized tags, their expertise, and the date of the interview.

Table 5. Summary of experts consulted, showing their experience with e-NH3, interview date and anonymized tag.

Anonymized Tag	Expertise	Date of Interview
e-NH3 expert 1	Worked on e-NH3 projects and researched potential roadmaps for widespread adoption in the European context.	02.05.2024
e-NH3 expert 2	Works at a company that designs innovative ammonia-to-hydrogen and ammonia-to-heat process solutions and related equipment for the energy sector.	01.05.2024
e-NH3 expert 3	Expert in clean ammonia production and works as a manager and engineer at a clean energy production company.	05.05.024
e-NH3 expert 4	Works as a strategy and business advisor focusing on the energy transition. Significance expertise in ammonia.	27.05.2024
e-NH3 expert 5	Works with developing ammonia-based vessels and engines for maritime applications.	06.06.2024
Maritime expert 1	Works as a project engineer at a leading European maritime consultancy and research institute.	08.05.2024

Maritime expert 2	Expert in policy and GHG emissions reduction, specifically in the context of the EU's maritime sector.	08.05.2024
Maritime expert 3	Works as a project engineer specializing in port development at a major EU port, preparing for e-NH3 bunkering.	22.05.2024
Maritime expert 4	Expert in ammonia and renewables at a leading energy company in Europe. Experience with various ammonia projects in the context of the maritime industry.	27.05.2024
Maritime expert 5	Expertise in maritime fuels' technicalities, both traditional and new e-fuels, including knowledge of environmental aspects.	31.05.2024
Maritime expert 6	Alternative fuels expert at a leading maritime consultancy in the EU. Specific expertise with e-NH3 adoption in the maritime context.	05.06.2024

4.4. Data Analysis

Two data analysis methods were used in this study. First, a codebook with deductive coding was created to analyze the interviews. Finally, once all the factors were finalized by compiling those identified in the content analysis and from the codebook, they were labelled and entered into a MICMAC analysis to understand their influence.

4.4.1. Interview Analysis

A deductive coding analysis was conducted on the interviews with e-NH3 and maritime experts through developing a codebook. The initial step involved creating predetermined codes, guided by the overarching theme of identifying the PESTLE factors related to e-NH3 adoption. The codebook was then constructed by performing a content analysis on grey and academic literature to identify relevant PESTLE factors, subsequently established as the predetermined codes. This approach ensured that the coding process was grounded in existing knowledge and theoretical frameworks from prior research, providing a structured method for analyzing data and systematically examining each PESTLE factor.

It was assumed that the factors identified in the content analysis would overlap with those identified by experts in the field. Moreover, the questionnaire was designed to extract the PESTLE factors (Appendix A). Table 7 summarizes the identified PESTLE factors (used as codes). The description of what was considered a PESTLE factor is outlined in 3.2.

The interviews were then transcribed, and the excerpts that aligned with the predetermined codes (or identified PESTLE factors) were coded accordingly. A snapshot of the codebook is found in Appendix B. This analysis aimed to pinpoint the PESTLE factors specifically identified by the experts that supported those found in the content analysis. Additionally, it aimed to uncover any new factors not initially revealed, in which case, a new code was inductively added. Additionally, radar charts are presented for each PESTLE group to illustrate how many experts supported the identified factors. A predetermined code, 'Recommendations,' was also created to guide recommendations in the discussion section. This code categorized expert excerpts on what the EU could do to promote e-NH3 diffusion.

4.4.2. MICMAC Analysis of Factors

This study employs the Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) analysis tool, which enables the quantification and fuzzing of the relationship intensity between two factors (Balci et al., 2024; Tsvetkova et al., 2024). The MICMAC software and analysis method was created by LIPSOR (Laboratoire d′Investigation en Prospective, Strat´egie et Organisation) and has been utilized in many studies to identify and display the relationships between key variables or drivers influencing a specific outcome (Balci et al., 2024; Tsvetkova et al., 2024). Firstly, the key factors identified from the content analysis of literature, along with those from the interviews with experts, were categorized according to the PESTLE Framework. Then, each factor under a certain category was given a label. For example, political factor 1 was POL1, political factor 2 was POL2, and so on. This allowed for each factor under each category to be expressed and included for individual analysis.

Table 6. Criteria table for assorting power of influence for identified PESTLE factors for e-NH3 adoption. Inspired by a similar methodology conducted by Balci et al., 2024; Tsvetkova et al., 2024.

Power of Influence	Criteria	Meaning
1 (Low)	Identified in either grey or academic literature and/or by 1-2 of the experts consulted in this study.	Low influence on the adoption of the e-NH3 system.
2 (Medium)	Identified in grey and academic literature and/or by 3-4 experts consulted in this study.	Medium influence on the adoption of the e-NH3 system.
3 (Strong)	Identified in grey and academic literature and/or by 5 or more experts consulted in this study.	High influence on the adoption of the e-NH3 system.

The identified factors were then subjected to a structural analysis to examine their influence on e-NH3 adoption. Firstly, a matrix of direct influences (MDI) was created by assessing the intensity of their influence on a scale of 0-3: (0) for no influence (only applicable for a factor on itself), (1) for low influence, (2) for medium influence, and (3) for high influence, based on the criteria in Table 6 (Tsvetkova et al., 2024). For simplicity of analysis, the influence of each factor was kept consistent over all other factors. For example, if the influence of "CO2 Emissions Reduction Potential" (ENV 1) on e-NH3 adoption was determined to be a value of 3, this was applied uniformly to its influence on all other factors. This served to simplify the complexity of analyzing multiple interdependent factors by maintaining consistent influence values across the matrix. In addition, it creates a clear visual representation and categorization of the factors, which allows for easier interpretation in the resulting cluster graph.

The completed MDI generated a cluster graph via the MICMAC software. The results consider the influence and dependence of each factor on the others and is represented by a graph where the x-axis signifies the dependence, and the y-axis denotes the influence (Figure 11). Consequently, the factors (individually) are grouped based on their power of influence or dependence, namely *independent factors* (high influence & low dependence) meaning that these factors have a high influence on e-NH3 adoption without being influenced by other factors (top left cluster, Figure 11). *Linkage factors* (high influence & high dependence) meaning that these factors are not only highly influential but also highly dependent on other factors to facilitate e-NH3 adoption (top right cluster, Figure 11). *Autonomous factors* (low influence & low dependence), these factors are those that exhibit both a low influence and low dependence on other factors to facilitate e-NH3 adoption (bottom left cluster, Figure 11). *Dependent factors* (high dependence & low influence), factors segregated in this cluster are those that are highly dependent on other factors to facilitate e-NH3 adoption, while having a low influence themselves (bottom right cluster, Figure 11). Finally, *moderate factors* (equal influence & dependence) are those that exhibit an equal level of dependence on other factors and influence on e-NH3 adoption (middle cluster, Figure 11). The segregation of the factors according to the five possible MICMAC clusters allows for an understanding how each identified factor individually or collectively influences the adoption of e-NH3 and how they are interdependent. The resulting clusters are subsequently utilized to formulate recommendations for the EU through making strategic interventions based on their categorizations.

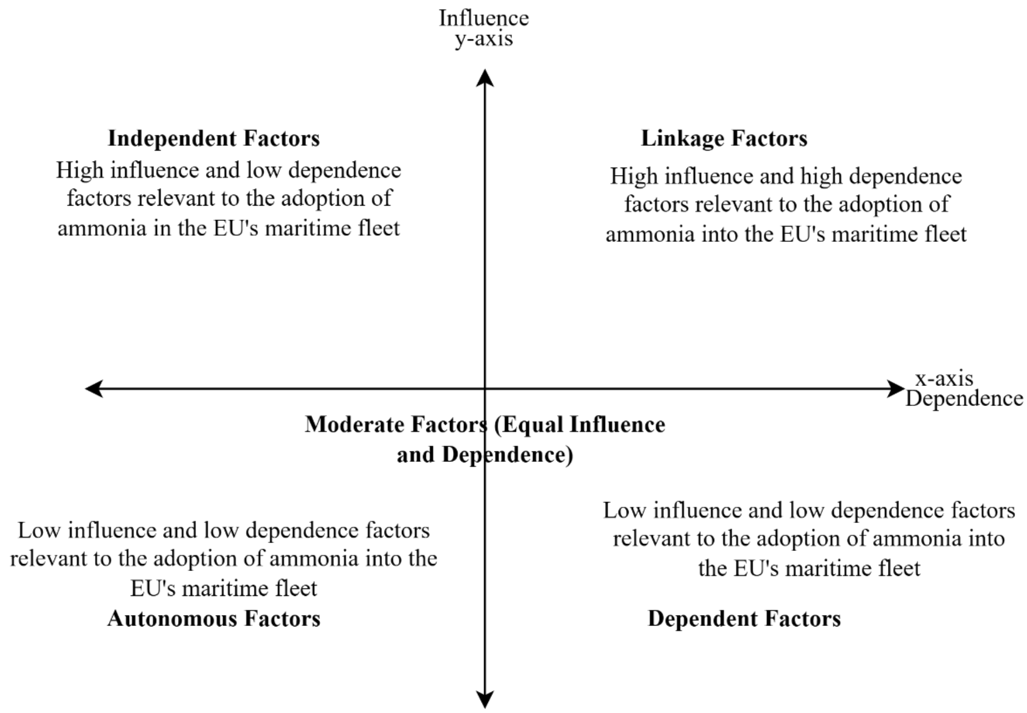


Figure 11. MICMAC analysis Cluster Diagram for e-NH3 adoption.

4.5. Ethics

All interview procedures have followed the University of Twente's ethical guidelines. Before the interview, a consent form was presented and agreed to by the interviewees, along with verbal consent before recording (Appendix C). Given that the interviews were semi-structured with open-ended questions, the General Data Protection Regulation (GDPR) was applied. The faculty of Behavioural Management and Social Sciences (BMS) obliges students conducting interviews for their thesis to submit a proposal for ethical assessment. Only once the faculty approved the study did it commence. Furthermore, interviewees were kept anonymous, in which case they were referred to by an anonymous title (Table 5). All names and affiliations mentioned in the interviews were removed from the transcriptions, and no private questions or sensitive information was asked. (Appendix B).

5. Findings

This section reveals the key 26 PESTLE factors extracted from grey and academic literature compiled and supported by the excerpts from the 11 experts consulted. It then presents the findings from the MICMAC analysis, displays the final MICMAC cluster, and describes the results. Overall, this section focuses on answering sub-questions 1 and 2.

5.1. Political Factors

The key political factors extracted from literature (same as their deductive codes) are the labels in Figure 12. This chart shows that energy autonomy, dependence on nations with high renewable energy, green shipping corridors and EU national-level volatility were the factors identified. The shaded area represents how many experts of the 11 consulted referred to these factors in their interviews. Following this, each identified political factor was analyzed using their corresponding coded excerpts supported by relevant literature.

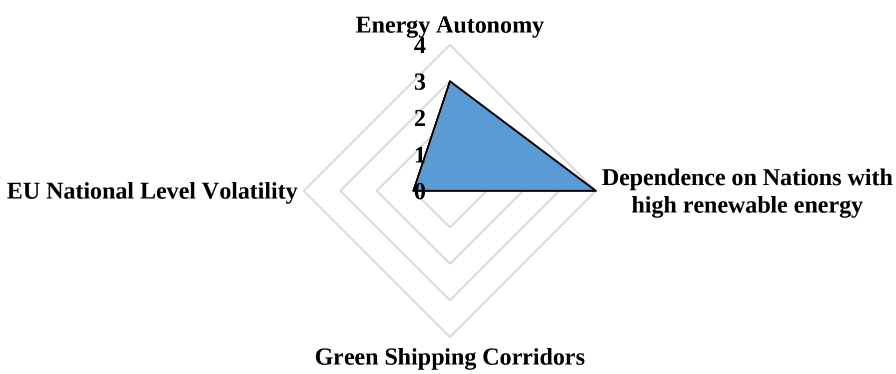


Figure 12. Radar chart illustrating the identified political factors, the labels are the factors extracted from literature. The shaded area represents the number of experts who identified each respective factor.

5.1.1. Energy Autonomy (POL1)

One political factor influencing the adoption of e-NH3 is the EU's stance on increasing energy autonomy. (Balci et al., 2024). Studies suggest the EU has pursued energy autonomy as part of its energy and policy objectives. (Christodoulou & Cullinane, 2022; Malmborg, 2023). This includes reducing reliance on imported fossil fuels from oil states that are subject to geopolitical turmoil and price volatility (Chiong et al., 2021; Tsvetkova et al., 2024). Tsvetkova et al. (2024) identify this factor, particularly about the Russia-Ukraine conflict in 2022, which destabilized fossil fuel supply within the EU. The resulting instability had a significant impact on global fossil fuel prices and spurred the EU's drive to reduce dependence on oil states and, more broadly, to enhance its energy security (Tsvetkova et al., 2024).

The adoption of e-NH3 aligns with the EU's goal of diversifying its energy sources and achieving a higher energy independence (Juntunen & Martiskainen, 2021). e-NH3 offers the ability to be produced domestically or in allied countries via renewable energy, thus reducing the dependence on imported fossil fuels for maritime transportation (Machaj et al., 2022). By investing in domestic or allied production of e-NH3, the EU can strengthen its energy security and reduce vulnerability to disruptions in the global oil market (López et al., 2024). This initiative also stimulates job creation and boosts the EU's green economy (Tsvetkova et al., 2024). However, reducing dependency on imports for maritime fuel does not mean complete autonomy but refers to diversifying energy sources and minimizing over-reliance on oil-producing states (López et al., 2024).

Three experts consulted in this study referenced energy autonomy as a key factor (Figure 12). *e-NH3 expert* 1 highlighted that a move away from depending on oil states is important and establishing a supply chain within the EU or with close allies can ensure a secure supply with more "stable countries" he says. Having a supply chain for e-NH3 production within the EU or with allied countries can put the EU in a "better bargaining position" which results in "a cheaper supply of ammonia" he states.

In line with the innovation-decision process, the energy autonomy that e-NH3 provides is a 'relevant advantage' over traditional bunker fuels, hence influencing its adoption. This political factor is, therefore, labelled **POL1** for the ensuing MICMAC analysis.

5.1.2. Dependence on Nations with High Renewable Energy (POL2)

While the EU's pursuit of energy autonomy is a significant contributing factor, it introduces a new dynamic- reliance on nations with abundant renewable energy resources (Al-Aboosi et al., 2021; Galimova et al., 2023). e-NH3, a sustainable alternative to traditional fuels, can only be produced using renewable energy, meaning that the production is directly tied to renewable energy availability (Galimova et al., 2023). As the EU moves towards widespread adoption, it becomes increasingly dependent on nations that have a high capacity for renewable energy production (Al-Aboosi et al., 2021). These include nations with high solar, wind or even hydroelectric power resources (Galimova et al., 2023). Consequently, this reliance could extend beyond just energy trade, potentially influencing diplomatic relations and international policy as well (Juntunen & Martiskainen, 2021). This could impact the EU's energy security strategy. Therefore, the EU needs to balance these dependencies while ensuring a steady supply of e-NH3, making this an influencing factor for adoption.

Four experts consulted in this study referred to this factor during their interviews (Figure 12). *e-NH3 expert* 1 reports "Ammonia is going to be produced in Senegal, Algeria, Spain, places with high solar and wind energy" he further goes on to say that "It's a safe bet in the sense that you are not depending on oil states". This narrative was supported by *e-NH3 expert 4* who says, "You can only sustainably produce e-NH3 in areas with a lot of renewable energy like Chile and Brazil or it's not even a viable option". *e-NH3 expert 4* hints that this dependence may not be a bad thing as "It's not a problem because countries will play off each other" hinting at a mutual benefit, where countries with abundant renewable energy can monetize their resources. At the same time, the EU secures a stable supply. Finally, *Maritime expert 3* highlights this as one of the main advantages of e-NH3 as it "can be produced anywhere in the world where there is enough sun or wind power".

Although there is an increased dependence on nations with renewable energy, the transition to e-NH3 aligns with the EU's commitment to sustainable development and climate change mitigation (López et al., 2024). It not only lessens the dependency on oil states but also aids in global CO2 mitigation efforts.

Therefore, the EU can view the increased reliance on nations with high renewable energy as a 'relevant advantage' in the persuasion stage of the innovation-decision process, as it signals a shift towards a more sustainable, secure, and mutually beneficial energy future. This factor is, therefore, labelled **POL2** for the MICMAC analysis.

5.1.3. EU National Level Volatility (POL3)

The EU's commitment to increasing renewable energy is an important stance in its various climate policies (López et al., 2024). However, these initiatives may be subject to volatility at the national level within the member states. Changes in governance can cause shifts in national priorities and policies that may not always align with the EU's overarching renewable energy and climate goals. If a new government takes power in a member state that does not prioritize green energy, it may deviate from the EU's unified approach. An example of this volatility can be seen with the Polish right-wing party's priority over coal. Such volatility can undermine efforts to scale up e-NH3 adoption which require investment and regulatory support from the member states (López et al., 2024). Tsvetkova et al. (2024) hint at this when mentioning that the political will to reduce GHG emissions from the maritime sector is an important driver for cleaner shipping.

One expert consulted in this study referred to this factor during their interview (Figure 12). *Maritime expert 4* quotes "On a national level you always have the volatility of an economic or political landscape. One administration might want to move in this direction, and nobody knows what the next administration would be doing".

In line with the persuasion stage of the innovation-decision process, this makes the widespread adoption of e-NH3 'complex' for the EU as its implementation nationally across all member states may prove difficult. Therefore, this factor is labelled **POL3**.

5.1.4. Green Shipping Corridors (POL4)

Green shipping corridors are maritime routes within the EU and internationally that focus on reducing GHG emissions by promoting the use of alternative fuels and technologies (Tsvetkova et al., 2024; H. Wang et al., 2023). There has been significant importance given to such initiatives as it promotes collaborative efforts between nations to initiate sustainable shipping solutions (Tsvetkova et al., 2024; H. Wang et al., 2023). Further supported by the Clydebank Declaration, an international initiative aimed at this specific cause at COP26, the declaration includes land-side infrastructure and vessels, hence applying to the usage and production of e-NH3 (Tsvetkova et al., 2024; H. Wang et al., 2023) .

Within the EU there has been collaboration on this effort between some of the most important pots such as the Port of Antwerp Bruges in Belgium, Port of Tallinn in Estonia, Port of

HaminaKotka in Finland and Klaipeda Port in Lithuania. This shows dedicated support for shipping corridors in the Baltic Sea (European Commission, 2024). Such initiatives create political unification within the EU to promote the adoption of e-NH3 and other such fuels, hence influencing adoption (Tsvetkova et al., 2024). Figure 13 schematically represents some of the green shipping corridors established in the EU (in the cut-out) and the rest of the world. (DNV, 2024).

Figure 13. Summary of announced green shipping corridors. Image from DNV.

Although not specifically referenced by experts in the interviews, Tsvetkova et al (2024) evoke the political importance of this factor in driving clean shipping. Hence, in line with the innovation-decision process, green shipping corridors provide an opportunity to 'trial' the use of e-NH3 and allows maritime stakeholders to gain insight into its feasibility as an energy solution. Furthermore, the outcomes of using e-NH3 as a maritime fuel in the corridors are visible to stakeholders making it 'observable' and hence, a compelling influencing factor for adoption. This factor is labelled **POL4**.

5.2. Economic Factors

The key economic factors extracted from literature (same as their codes) are the labels in the radar chart (Figure 14). The chart shows that capital expenditure, cost of e-NH3, R&D cost and retrofitting & new ship production cost were the factors identified. The shaded area represents how many of the 11 experts consulted referred to these factors in their interviews. Following this is an analysis of each identified economic factor using their accordingly coded excerpts supported by literature.

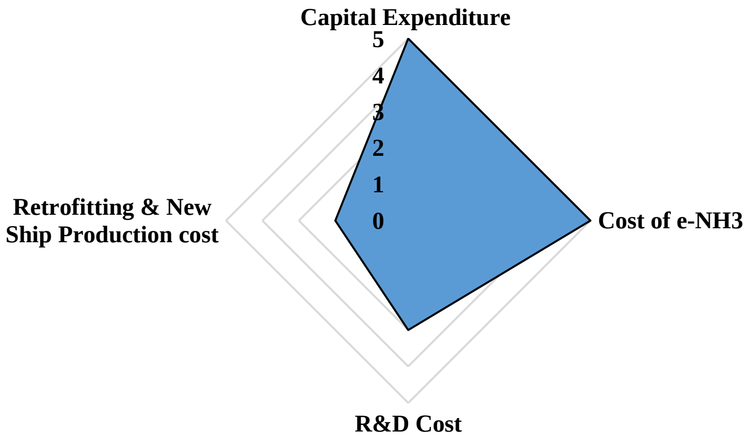


Figure 14. Radar chart illustrating the economic factors, the labels represent factors extracted from literature. The shaded area represents the number of experts who identified each respective factor.

5.2.1. Capital Expenditure (ECO1)

The adoption of e-NH3 is significantly influenced by the availability of capital expenditure. This consists of investments in infrastructure, upscaling production, storage tanks and creating an established supply chain from the site of production to the site of bunkering or usage (Al-Aboosi et al., 2021; Balci et al., 2024; Galimova et al., 2023; Marrero & Martínez-López, 2023; H. Wang et al., 2023). In addition, this requires significant investment to upscale renewable energy production, posing a huge economic challenge (Galimova et al., 2023). The question of cost allocation also arises, involving potential stakeholders like the EU, national governments, shipping companies and ammonia producers. Although governments can play a vital role in providing capital for reducing the cost of e-NH3 production; shipping companies as end users will need heavy capital to hire specialized employees. This is to assist with new e-NH3 operating vessels or retrofit existing ones to use e-NH3 (Balci et al., 2024; Tsvetkova et al., 2024). Ammonia producers on the other hand will need to upgrade their production facilities to produce e-NH3 as the majority of the production still comes from fossil fuels (Al-Aboosi et al., 2021; Galimova et al., 2023). Moreover, solely switching ammonia production for the maritime industry is not a viable solution. It is imperative for a sizable portion of ammonia that is currently produced for agricultural purposes, also to transition as they have the same environmental and economic drivers further exacerbating the capital required (Galimova et al., 2023). Therefore, the capital to transition the entire ammonia value chain is crucial for making the adoption of e-NH3 feasible (Galimova et al., 2023).

Five experts consulted in this study evoked the importance of the capital required (Figure 14). *e-NH3 expert 1* places specific importance on capital expenditure when quoting that "CapEx? That's the hard part. You need big money in the start for the shipping industry". He further adduces that "Infrastructure will be one of the highest amounts" and "if you want ammonia for maritime infrastructure, you need 80% of the value chain for every use of ammonia and it's going to cost a heap". *Maritime expert 4*, also refers to the heavy capital required to transition the ammonia supply chain, stating that "One of the main things that are overlooked with regards to cost, is not only the expansion of the supply chain or the expansion of manufacturing capacities. It's also that the current primary user of ammonia is the agricultural industry which has the same drivers as shipping to go green. Currently, with the majority of ammonia being methane-based, they will also need to go into e-NH3, which means you don't even have to scale up the ammonia supply chain to meet shipping demand into green. But also, the original demand that was already there must diverge to green." He further emphasizes that "the upscaling of the manufacturing capabilities is at such a high scale that the cost is humongous" and the only way to do that is "if you have a lot of capital."

In the persuasion stage of the innovation-decision process, the high capital expenditure required makes the adoption of e-NH3 'complex' and thereby, a 'relevant disadvantage' for its success as a maritime fuel. This economic factor was labelled **ECO1.**

5.2.2. Cost of e-NH3 (ECO2)

The cost of e-NH3 is a key economic factor influencing its adoption. The production of the fuel involves the electrolysis of water to produce hydrogen, which is then combined with nitrogen to produce e-NH3 (Balci et al., 2024; Galimova et al., 2023). This process requires substantial energy that needs to be renewably sourced (Al-Aboosi et al., 2021). Hence, the prohibitive cost of renewable energy significantly contributes to the cost of e-NH3 in addition to the transportation cost from the site of production to the site of bunkering/usage (Balci et al., 2024; Galimova et al., 2023). For e-NH3 to be widely adopted, it needs to be cost-competitive with traditional maritime fuels like HFO, MGO and other green alternatives (Balci et al., 2024). Consequently, the higher costs of e-NH3 compared to other fuels hinder its widespread adoption as it becomes an economically less desired choice (Balci et al., 2024; Christodoulou & Cullinane, 2022; Machaj et al., 2022). In addition, higher fuel costs result in higher operational costs for shipping companies, encouraging them to continue the use of traditional fuels or explore cheaper alternatives (Rony et al., 2023; Malmborg, 2023). Presently, renewably sourced fuels like e-NH3 are more expensive than those of fossil fuel origin, thereby slowing the uptake of greener fuels. Currently, the cost of e-NH3 is about €700 - €1400 per ton, which is significantly higher than the cost of fossil fuels and hence not viable (Govindan, 2024). According to Hellstrom et al., 2024, e-NH3 is presently one of the least economically feasible fuels. As illustrated in Figure 15 which shows ammonia as the furthest away from other fuels.

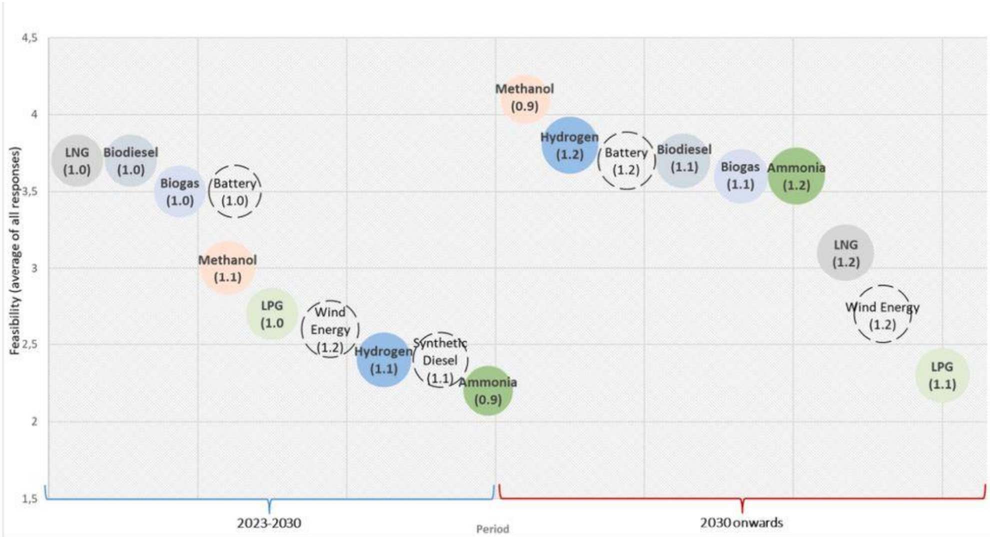


Figure 15. Economic feasibility of various alternative fuels, showing a comparison of now vs the future. Closer to the left means more feasible while closer to the right means less feasible (Hellstrom et al., 2024).

Five experts referenced the cost of e-NH3 (Figure 14). When asked about the economic factors, *e-NH3 expert 3* states “e-fuels are much more expensive than fossil fuels” and that “The production cost of e-fuels, in general, is much higher”. *e-NH3 expert 4* states that “The cost per ton of ammonia is too high”. Overall, the experts consulted in this study echo the stance in literature that the high cost of e-NH3 is currently a significant influencing factor for the adoption of e-NH3.

In reference to the persuasion stage of the innovation-decision process, the current cost of e-NH3 is a ‘relevant-disadvantage’ and the many inputs required to reduce this cost render it ‘complex’ for adoption. This factor is therefore labelled **ECO2.**

5.2.3. R&D Cost (ECO3)

e-NH3 as a maritime fuel is still in its infancy, its viability depends substantially on R&D investments. These investments are essential to ensure safe and efficient ammonia engines, fuel cells, retrofitting of traditional internal combustion engines (ICEs) as well for creating storage systems on board to handle its unique physical properties (Al-Aboosi et al., 2021; Galimova et al., 2023; Machaj et al., 2022). These costs are a necessity to give e-NH3 a competitive advantage in comparison to the well-established traditional maritime fuels and over other green alternatives (Christodoulou & Cullinane, 2022; Tsvetkova et al., 2024). Additionally, R&D costs are required to ensure that effective large-scale production of e-NH3 is available for the projected increased usage, not only for the maritime sector but also for its agricultural uses (Galimova et al., 2023; Kim et al., 2024). Furthermore, efficient R&D needs to be conducted to warrant safe bunkering methods at ports in the EU (Balci et al., 2024; Chiong et al., 2021; Machaj et al., 2022). R&D cost for trials and pilot projects will also be substantial (Kim et al., 2024). Therefore, the high R&D cost that e-NH3 entails deviates the sector from investments, thus continuing the use of traditional fuels or other established green fuels.

Three experts consulted in this study highlighted R&D cost (Figure 14). Firstly, *e-NH3 expert 1* states “It will cost a lot to get the optimal design and we still do not know if it is more efficient to use fuel cells or an engine". *Maritime expert 4* corroborates this when saying that "There needs to be R&D for creating ammonia at no cost".

In line with the innovation-decision process, the R&D cost to make e-NH3 a competitive alternative maritime fuel is a relevant 'disadvantage' to widespread adoption. This can also make shipping companies deviate from assessing the 'trialability' of e-NH3. This factor was labelled **ECO3.**

5.2.4. Retrofitting & New Ship Production Cost (ECO4)

As the literature review section revealed, the EU possesses a wide array of ships, the majority of which still use traditional fuels. To run on e-NH3, the ships will need to be retrofitted, which is a complex and cost-heavy process (Balci et al., 2024; Chiong et al., 2021; Wang et al., 2024). Retrofitting includes not only the structure and functionality of the ship, but also that of the engine, storage, and handling systems (Al-Aboosi et al., 2021; Wang et al., 2023). Many of the ships vary in size, age, and condition, therefore requiring specific modifications rather than general retrofitting (Melideo & Desideri, 2024). Consequently, shipping companies will primarily have to bear these costs if they intend to use e-NH3, slowing adoption. In addition to retrofitting, producing new ships that run entirely on e-NH3 is also a significant cost burden. Not only do the new ships have to be produced, but they must be tested for a significant period to ensure maritime safety is up to EU and international standards (Al-Aboosi et al., 2021). According to the EMSA, the expected cost for retrofitting a ship can range from €10-€16 million (EMSA, 2022). The EU's maritime sector may see this as an unnecessary burden and hence, continue to use fossil fuels or green fuels that are more easily retrofitted (Liu et al., 2024; Sánchez et al., 2023; Smith & Mastorakos, 2023).

Two experts consulted reference this factor (Figure 14), e-*NH3 expert 1* emphasized the importance of R&D costs when quoting that "It will be a huge cost to retrofit and build a new fleet entirely" supporting the narrative found in literature.

Referring to the innovation-decision process, retrofitting cost can be seen as a 'relevant-disadvantage' to the adoption of e-NH3 and that e-NH3 is currently 'incompatible' with the EU's maritime fleet unless much retrofitting is conducted. This factor is thus labelled **ECO4.**

5.3. Social Factors

The key social factors extracted from literature (same as their codes) are the labels in the radar chart below. This chart shows that expertise & training, health & safety, market/stakeholder support and social acceptance were the factors identified. The shaded area shows how many of the 11 experts consulted brought up these factors in their interviews. Following this is an analysis of each identified social factor along with their coded excerpts.

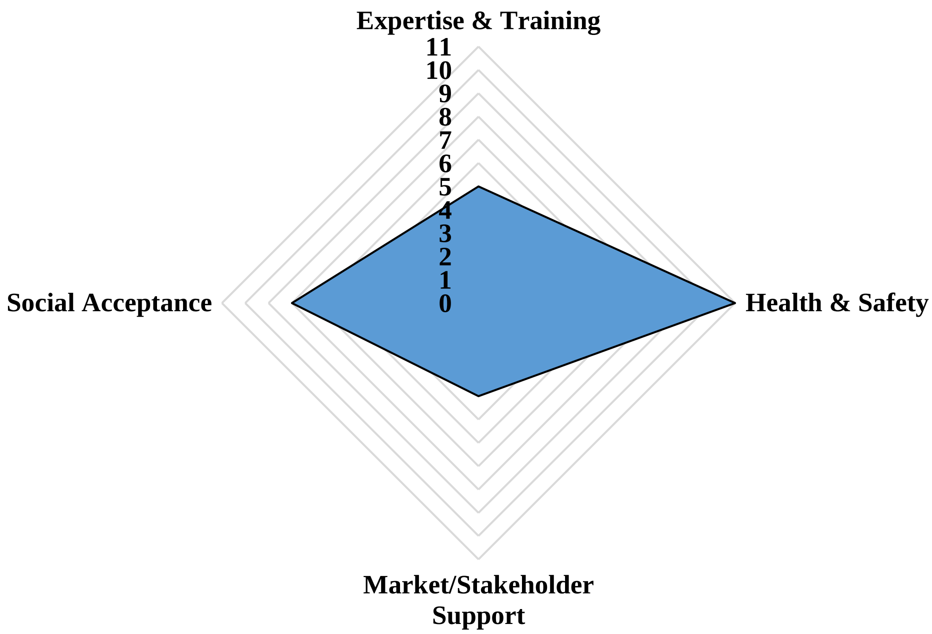


Figure 16. Radar chart for the social factors, the labels are the factors extracted from literature. The shaded area represents the number of experts who identified each respective factor.

5.3.1. Expertise & Training (SOC1)

The adoption of e-NH3 is strongly influenced by the presence of expertise and trained personnel. As e-NH3 emerges as a key pathway toward decarbonizing shipping, the demand for specialized knowledge for production, handling, transportation, and safety becomes increasingly important (Abraham et al., 2024; Egerer et al., 2023; Karvounis et al., 2024; Louvros et al., 2023; Machaj et al., 2022; Melideo & Desideri, 2024; Zincir, 2022). This expertise is required not only on-board vessels but also on the landside, including the entire supply chain (Balci et al., 2024; Kim et al., 2024; van Leeuwen & Monios, 2022). In addition, expertise is required for innovation, technological advancements, infrastructure, and equipment design (Melideo & Desideri, 2024; Ye et al., 2022).

The presence of expertise will not only minimize safety and environmental risks but also support a smoother adoption of the fuel. e-NH3 is a completely different fuel to what the maritime industry is used to, thus warranting specialized personnel (Balci et al., 2024; Kim et al., 2024; Louvros et al., 2023; Sánchez et al., 2023; H. Wang et al., 2023; Ye et al., 2022). In addition, the availability of highly trained professionals enhances the diffusion of the fuel within the maritime sector as increased trust in the fuel arises from knowing that more e-NH3-trained personnel are present. (Tsvetkova et al., 2024). While there is some level of knowledge in the handling process due to ammonia’s use in the fertilizer industry, increased usage will undoubtedly increase this requirement (Machaj et al., 2022). Hence, ports around the EU which are knowledgeable in handling ammonia will also require more trained personnel when scaling up their capabilities (Galimova et al., 2023; Z. Wang et al., 2024).

Five experts consulted in this study critically highlight the importance of trained personnel (Figure 16). *e-NH3 expert 1* quotes “We need highly qualified personnel. But that's, with any substance that's going to be used as a fuel”. This is further supported by *e-NH3 expert 2* who highlights the need for experts and training when quoting “The skill set required onboard is still not there yet”. Further echoed by *Maritime expert 2* who said, “You will need extra training for the crew”. In addition, *Maritime expert 3* evokes the need for trained personnel when saying that “There always was some import of ammonia, but that ammonia is used for the fertilizer industry and that's a relatively low amount compared to what we expect in the future and there is only some experience present in the industry”. *Maritime expert 4* also states that the e-NH3 “Supply chain is highly specialized. People are highly trained. Like with LNG, like with chemical cargoes, or like currently with ammonia or the LPG trade. It's a small pool of highly educated people. If you would adopt it as a general view on an X number of ships, you need a higher level of expertise”.

In reference to the persuasion stage of the innovation-decision process, the need for expertise & training affects the ‘trialability’ and ‘complexity’ aspects as it makes it hard to trial e-NH3 and complex in terms of its adoption. Hence, this factor was labelled **SOC1.**

5.3.2. Health & Safety (SOC2)

Just like any other fuel, the health & safety aspects associated with the usage of e-NH3 is a compelling adoption factor. Ammonia itself is a toxic and corrosive compound, any leakage can have serious health implications for the crew on board or the handling crew during bunkering processes onshore or offshore (Balci et al., 2024; Galimova et al., 2023; Machaj et al., 2022). Therefore, ammonia in general poses severe health risks if inhaled, ingested, or if in contact with skin (LR, 2024). Studies have found that ammonia vapor can cause a range of health problems such as respiratory irritation, cough and even throat burns (LR, 2024). In addition, exposure to high concentrations can lead to respiratory issues, permanent lung damage and even death (LR, 2024). For crew members, the confined spaces of a ship can further increase the risk of exposure, making even minor leaks significantly more dangerous regardless of whether the leak is gaseous or liquid (Al-Aboosi et al., 2021; Galimova et al., 2023). The corrosive nature of ammonia can threaten the structural characteristics of the ships as well, causing equipment malfunction and structural harm (Al-Aboosi et al., 2021; Galimova et al., 2023; Kim et al., 2024). Hence, these characteristics of ammonia as a compound could hinder its adoption (Al-Aboosi et al., 2021; Balci et al., 2024; Galimova et al., 2023; Machaj et al., 2022).

This was perhaps the most important social factor identified in literature also supported by all 11 experts consulted in this study (Figure 16). When asked about the health & safety concerns regarding ammonia, *e-NH3 expert 2* says "As a mobility fuel, there is a significantly higher risk" due to it being “Flammable”. He also goes on to compare an ammonia leak with that of a traditional fuel by saying “A little bit of traditional fuel leak is okay, but a little bit of ammonia leak can be dangerous for engineers on board”. *Maritime expert 1* supports the dangerous narrative of e-NH3 usage when saying “It is dangerous, and the acceptable levels are really low”. As ammonia is mostly stored either pressurized or at low temperatures, *e-NH3 expert 4* quotes that “The most dominant risk is toxicity, but it's also cryogenic, so people working around ammonia are also at risk of getting freezing injuries”. *e-NH3 expert 4* states that “the lowest level where you're going to be exposed to ammonia is the toxicity. That's around a few hundred PPMs, that's at a level where explosion will not happen. For explosion, you need 17% ammonia compared to air, and to translate that, that's 170,000 PPM and hence, it’s easier to have toxicity” which suggests that toxicity is more of a concern than flammability.

Although toxic, experts noted that ammonia is easily detectable at low concentrations which could be potentially advantageous from a safety perspective. *e-NH3 expert 1* says “We are more aware now than ever about the social impacts of a leak. So, we are more prudent than we were. Ammonia has such a strong smell that before you can even get hurt, you're just going to abandon ship or take safety regulations". This was corroborated by *e-NH3 expert 3* who says that "Ammonia is highly toxic but can be detected at unharmful concentrations of 1-5 PPM". Therefore, while ammonia's toxicity raises concerns, its detectability at low concentrations could serve as a safety feature, potentially promoting its adoption.

In reference to the innovation-decision process, the health and safety aspects of ammonia usage presents a 'relevant disadvantage', potentially leading maritime stakeholders to utilize alternative fuels. This factor was labelled **SOC2.**

5.3.3. Market/Stakeholder Support (SOC3)

Support from the maritime market and stakeholders significantly drives the adoption of e-NH3 by fostering investment in necessary infrastructure and technology (Al-Aboosi et al., 2021; Galimova et al., 2023; Inal et al., 2022; H. Wang et al., 2023). When major shipping companies and port operators demonstrate commitment to e-NH3 by investing in retrofitting ships, new ships and bunkering infrastructure, this signals confidence in e-NH3's viability as a fuel (Balci et al., 2024; S. Chen et al., 2023; Z. Wang et al., 2024). This, in turn, encourages further investments and innovation, reducing costs and improving the safety and efficiency of e-NH3 technologies (Malmborg, 2023; Tsvetkova et al., 2024). Widespread industry support can create a secure supply chain, making the fuel a more accessible and practical option (Aakko-Saksa et al., 2023; Melideo & Desideri, 2024).

Literature hints that industry leaders are generally enthusiastic about e-NH3, seeing it as a viable solution to meet maritime fuel demands (Karvounis et al., 2024; McKinlay et al., 2021; Melideo & Desideri, 2024; Tsvetkova et al., 2024; Zincir, 2022). Many stakeholders have invested heavily and shown some sort of activity in terms of ammonia usage as a maritime fuel. There has been interest from governmental and intergovernmental organizations as well (Balci et al., 2024; S. Chen et al., 2023; Z. Wang et al., 2024).

Four experts consulted referred to the importance of market/stakeholder support (Figure 16). *e-NH3 expert 1* says "Ask anyone in the industry and they'll say the same, we love ammonia, and we're going to use it". *Maritime expert 2* contributes to this standpoint by saying that "there are a lot of areas in the world where it is seen as a potential good development. A lot of areas, developing areas in the world, are viewing ammonia as a potential new energy situation for them and a way to capitalize on that". This shows regardless of the motive, there is growing support for e-NH3.

However, complexities and risks do arise. Some shipping companies like "CMA CGM and Maersk" have shown signs of hesitancy, pulling back on orders for ammonia-powered vessels due to concerns over "Stranded asset risk" as quoted by *Maritime expert 4*. He further says that "A stranded asset risk is if you bet on a certain market, and then invest in that, and then the market doesn't take off", He further emphasizes that "You end up with ships that can only sail on a fuel that's not readily available. Or if you're betting on providing the fuel but end up with no market for it." *Maritime expert 2* also places exclusive importance on the support of stakeholders and the market when saying, "I think this is up to the market, in the end, to decide which fuel to use".

Referring to the innovation-decision process, market/stakeholder support presents a 'relevant advantage'. However, changing narratives within the market and amongst stakeholders can contribute to the 'complexity' of adopting e-NH3. Thus, this factor was labelled **SOC3.**

5.3.4. Social Acceptance (SOC4)

The social acceptance of e-NH3 plays a pivotal role in influencing its adoption. The inherent risks associated with ammonia, particularly its toxicity and corrosive nature can generate apprehension from the public (Balci et al., 2024; Galimova et al., 2023; Inal et al., 2022; Karvounis et al., 2024). Similarly, negative perceptions over the safety, handling and storing of ammonia may lead to resistance from local communities, port workers and crew members (Balci et al., 2024; Egerer et al., 2023; Galimova et al., 2023; Karvounis et al., 2024; Sánchez et al., 2023). Consequently, incidents or accidents involving leaks may further exacerbate these concerns, leading to more social opposition (Galimova et al., 2023). Therefore, many studies suggest that it is only when alternative fuels like e-NH3 or ammonia as a compound itself are perceived in a positive light by the public, policymakers, and stakeholders that diffusion will occur (Balci et al., 2024).

The compound ammonia is often negatively perceived due to its historical use as a fertilizer and associated adverse effects (Balci et al., 2024). Its strong odour and potential health risks, as noted in the health & safety section, further contribute to its negative image (Galimova et al., 2023). Studies suggest that this negative perception could be attributed to a lack of understanding of its efficacy as a fuel and its potential environmental benefits (Balci et al., 2024; Galimova et al., 2023; Tsvetkova et al., 2024). Therefore, it is crucial to highlight that employing ammonia as a fuel involves different considerations than its application as a fertilizer (Galimova et al., 2023; Kim et al., 2024; Louvros et al., 2023; Machaj et al., 2022; H. Wang et al., 2023; Ye et al., 2022). Moreover, with proper safety measures and continuous technological advancements, the risks associated with ammonia can be effectively managed (Balci et al., 2024). While the negative perceptions from ammonia's past uses pose a challenge, they do not rule out its potential as a viable maritime fuel (Balci et al., 2024).

Six of the experts consulted identified social acceptance as a crucial factor (Figure 16). *Maritime expert 4* corroborates what is referred to in literature when saying "Ammonia already has a different name. It's something that people know as a reactive agent, as a fertilizer." *e-NH3 expert 1* when asked about the importance of social acceptance says "people think it's very toxic, even more toxic than it is. There are misconceptions about the dangers of a leakage. So, I think the societal part may be pivotal in the eventual success of ammonia in the maritime sector". *e-NH3 expert 3* resonates this perspective when saying "The perception of ammonia as dangerous, and as toxic can cause NIMBY reactions. This narrative was fostered over the past 20 years, so it is difficult to change the narrative fast." *Maritime expert 3* also places significant importance on social acceptance when saying that "We all want it and you'll see that it's needed to go to a sustainable future. But if you don't have the public with you, or you don't the support of public parties, representing the public. That may be an issue".

Therefore, in reference to the persuasion stage of the innovation-decision process, social acceptance contributes to the 'complexity' as it is harder to utilize it as a fuel without widespread acceptability as social concerns and resistance may hinder its 'trialability'. This factor was hence labelled **SOC4.**

5.4. Technical Factors

The key technical factors extracted from literature (same as their codes in the codebook) are the labels in the radar chart below. This chart shows that transportation (handling & storage), port & bunkering infrastructure, production & supply chain infrastructure, ship & engine compatibility and fuel performance were the factors identified. The shaded area represents how many of the 11 experts consulted brought up these factors in their interviews. Following this is an analysis of each identified technical factor using their accordingly coded excerpts.

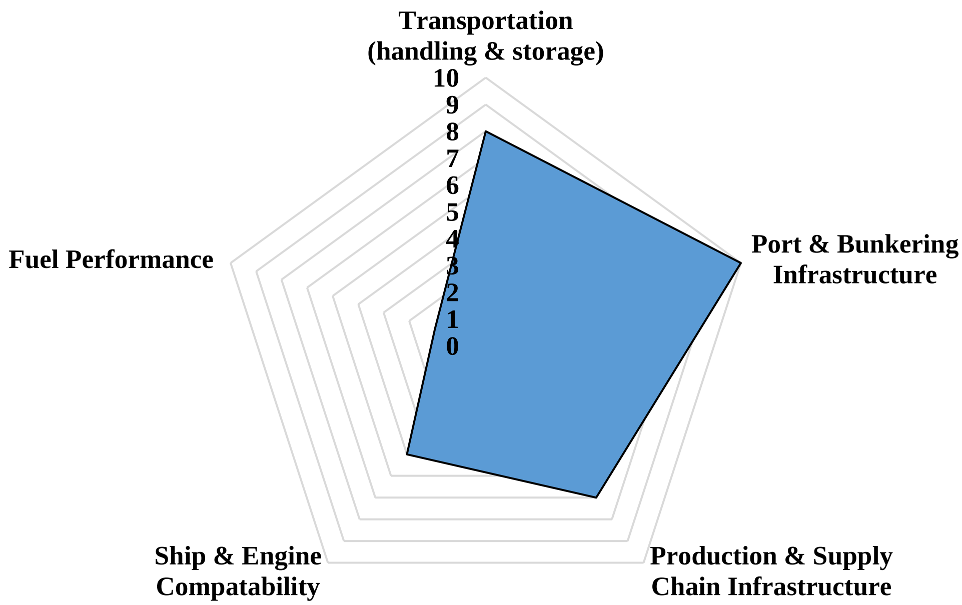


Figure 17. Radar chart for the technical factors, the labels are the factors extracted from literature while the shaded area represents the number of experts of the 11 consulted that identified each respective factor.

5.4.1. Transportation (Handling & Storage) (TEC1)

Transportation is a crucial influencing factor for the widespread adoption of e-NH_3. Unlike other traditional fuels such as MGO, HFO etc., ammonia as a compound requires specialized handling and storage solutions on board (Balci et al., 2024; Louvros et al., 2023; H. Wang et al., 2023). It must be stored in double-walled tanks with appropriate insulation and or pressure/temperature controls to prevent leaks (Balci et al., 2024). These safety measures while essential, occupy valuable space on board ships (Inal et al., 2022; Kim et al., 2024; Louvros et al., 2023; McKinlay et al., 2021; Sánchez et al., 2023; Ye et al., 2022). The need for additional and more complex storage modifications means that cargo space may have to be sacrificed, potentially reducing the overall cargo capacity of vessels utilizing e-NH_3 (Inal et al., 2022; Smith & Mastorakos, 2023). This is especially a consideration for retrofitted ships that are not originally designed for ammonia storage (Balci et al., 2024). The reduction in cargo capacity can affect the economic viability of retrofitting ships for e-NH_3 as shipping companies may face decreased revenue from reduced cargo loads (Egerer et al., 2023; Karvounis et al., 2024; Kim et al., 2024; Zincir, 2022).

Eight experts referred to the transportation and handling aspects of e-NH_3 (Figure 17). *Maritime expert 1* emphasizes giving up cargo space to carry more ammonia weight when stating "With traditional fuel, you can just put in in any shape as long as it is not leaking, but with ammonia you need more space and flexibility, the freedom of shaping is much lower". *e-NH3 expert 4* also brought up the extra weight and potential cargo loss when saying "Because of ammonia's physical and chemical properties, you will have to ship a lot more weight. So that's a drawback".

However, the maritime sector does have a foundational advantage due to its extensive experience in transporting and handling ammonia as a commodity (Galimova et al., 2023) . This also comes with some established protocols for safely handling and storing ammonia that can be adapted for its use as a fuel (Kim et al., 2024; Liu et al., 2024). *Maritime expert 2* says "On the other hand, ammonia is shipped, of course, at the moment all over the world. I think it's possible to be handled at a larger scale". *Maritime expert 3* places singular importance that ammonia-related tanks and pipes must be "double-walled" and "if that's the case, then it won't be that big an issue" further showing that with established protocols, the transportation, handling, and storage of ammonia is achievable.

Therefore, in reference to the persuasion stage of the innovation-decision process, transportation contributes to the 'complexity' of using e-NH3 on board a ship and making it 'incompatible' if retrofitting an existing vessel. This factor was hence labelled **TEC1.**

5.4.2. Port & Bunkering Infrastructure (TEC2)

To be a viable alternative to traditional fuels, ports in the EU will need to be equipped with specialized facilities to bunker e-NH3 safely and efficiently (Balci et al., 2024; Galimova et al., 2023). This includes the construction of bunkering stations with double-walled tanks and advanced leak detection systems (Balci et al., 2024). Most ports are busy, thus having reliable equipment and infrastructure is pivotal (Sánchez et al., 2023; H. Wang et al., 2023; Ye et al., 2022). Without such infrastructure, ships running on e-NH3 face significant operational challenges, limiting the attractiveness and practicality of its adoption (Al-Aboosi et al., 2021; Louvros et al., 2023; Machaj et al., 2022; McKinlay et al., 2021).

Several studies suggest that the availability of port infrastructure directly affects the feasibility of refuelling ships with e-NH3 (Abraham et al., 2024; Sánchez et al., 2023; Smith & Mastorakos, 2023; van Leeuwen & Monios, 2022). Ports that invest in and develop the needed facilities can become strategic bunkering hubs, supporting a network of e-NH3-powered vessels (Tsvetkova et al., 2024). While a lack of port and bunkering infrastructure discourages maritime stakeholders from investing in e-NH3 vessels due to refuelling uncertainty (Abraham et al., 2024; Sánchez et al., 2023; Smith & Mastorakos, 2023; van Leeuwen & Monios, 2022). Therefore, the enhancement of port infrastructure is vital to ensuring a smoother integration of e-NH3 into the EU's maritime fleet (Balci et al., 2024).

Ten experts consulted in this study placed substantial importance on the necessity of port infrastructure and bunkering equipment. *e-NH3 expert 1* emphasizes that "You need a place to bunker, and you need good bunkering equipment, you need storage tanks, which are going to be significantly larger than what we currently have". *Maritime expert 2* explains that "for fueling large seagoing vessels with ammonia, you need bunkering equipment, so smaller ships loading the ammonia to the larger ships and that equipment needs to be developed, and you also run into all kinds of safety and design issues". Further highlighting the need for specialized equipment and the complexity of ensuring safe operations when bunkering at a port.

Therefore, in reference to the persuasion stage of the innovation-decision process, the lack of port & bunkering infrastructure contributes to the 'complexity' of using e-NH3 and makes it hard to 'trial' as fuel. This factor was hence labelled **TEC2.**

5.4.3. Production & Supply Chain Infrastructure (TEC3)

The adoption of e-NH3 heavily depends on the development of production and supply chain infrastructure. This includes the creation of large-scale Haber-Bosch and electrolysis plants, which are crucial for sustainable production (Balci et al., 2024; Egerer et al., 2023; Kim et al., 2024; H. Wang et al., 2023). Additionally, to meet the demand for maritime fuel, the entire supply chain must be scaled up, from production to distribution (Galimova et al., 2023). The necessary renewable energy infrastructure and efficient transport of the e-NH3 from the production site or country to the end users is also required (Balci et al., 2024; Galimova et al., 2023; Z. Wang et al., 2024). Moreover, the supply chain needs to serve industries beyond maritime applications, necessitating extensive logistical coordination and investment in infrastructure capable of handling ammonia's unique properties. Without this broader approach, focusing only on the maritime sector would render the infrastructure financially and technically unfeasible (Balci et al., 2024; Kim et al., 2024).

Seven experts highlighted the importance of production & supply chain infrastructure (Figure 17), *e-NH3 expert 1* noted "We haven't even started talking about the large production infrastructure required". *e-NH3 expert 4* remarked "If you look at the entire supply chain and infrastructure required for just using e-NH3 for maritime use, it is already that big, imagine if we need to get other sectors on board". This underscores the significant challenge in establishing a secure e-NH3 supply chain.

In connection to the persuasion stage of the innovation-decision process, the lack of proper production & supply chain hinders the 'trial' e-NH3 and therefore, 'complex' to adopt as a fuel for the EU's maritime sector. This factor was labelled **TEC3.**

5.4.4. Ship & Engine Compatibility (TEC4)

Integrating e-NH3 into the EU's maritime fleet requires significant modifications to existing vessels and the development of new engine technologies (Balci et al., 2024; Kim et al., 2024; Louvros et al., 2023; H. Wang et al., 2023; Z. Wang et al., 2024). This is a huge task across the industry, considering the EU has a significantly diverse fleet as displayed in the literature review. Furthermore, these engines must efficiently and safely utilize ammonia, posing unique challenges compared to their fossil fuel counterparts (Hellström et al., 2024; Louvros et al., 2023; Sánchez et al., 2023). One advantage that e-NH3 offers is its ability to be used in traditional internal combustion engines (if retrofitted) and via fuel cells to power clean shipping propulsion (Balci et al., 2024; Louvros et al., 2023). However, retrofitted engines require some sort of pilot fuel for ignition (Abraham et al., 2024; Al-Aboosi et al., 2021; Hellström et al., 2024; Kim et al., 2024; Liu et al., 2024; Sánchez et al., 2023; Tomos et al., 2024). Therefore, retrofitting ships with dual-fuel engines that run on e-NH3 adds an extra layer of complexity, driving the sector to use fuels more compatible with existing engine technology (Aakko-Saksa et al., 2023; Al-Aboosi et al., 2021; H. Wang et al., 2023).

Five experts highlighted ship & engine compatibility and its associated challenges (Figure 17). *e-NH3 expert 1* emphasized the need for engine and motor development, questioning whether they will resemble traditional engines (retrofitted) or utilize fuel cells when quoting "For the ship, you need adequate motors…Are those going to be like traditional motors where you fire ammonia? Or are they going to be stacks where we do the same with hydrogen? Or a mix of both?". This reflects the industry's uncertainty over which technology will prove the most efficient. Regarding retrofitting existing ships *Maritime expert 1* mentions "If you have an existing diesel engine, then quite likely it will be a dual fuel engine", he further points out that "Those still run a bit of diesel which acts as an ignition source for the ammonia. So, you will not run on 100% ammonia but a limited amount of diesel and ammonia". This hints that to fully reap the benefits of e-NH3, a complete change to the engine might be necessary to only burn e-NH3 without the need for a pilot fuel.

Connecting back to the persuasion stage of the innovation-decision process, the technical difficulties that e-NH3 poses in terms of the various ship & engine adjustments required, make it 'incompatible' to 'trial' easily as a maritime fuel of choice for the EU. This factor was hence labelled **TEC4.**

5.4.5. Fuel Performance (TEC5)

The performance of e-NH3 as fuel is an important influencing factor for adoption, this includes aspects such as energy density and combustion characteristics. Firstly, compared to traditional fossil fuels, ammonia has a lower energy density, as a result, ships will need a larger quantity of ammonia to produce the same energy output as a smaller amount of traditional fuel (Ayanwale & Ndlovu, 2024; S. Chen et al., 2023; Chiong et al., 2021; Christodoulou & Cullinane, 2022; Islam Rony et al., 2023; Machaj et al., 2022). This means that ships need larger fuel storage capacities or more frequent refuelling stops that directly impact operational efficiency (Chiong et al., 2021; Christodoulou & Cullinane, 2022). Additionally, ammonia as a compound itself does not burn well and hence, requires the need for a pilot fuel to be able to start the ignition process in a retrofitted ship. However, less so for ammonia-specific engines (Machaj et al., 2022).

Two experts consulted in this study referred to e-NH3's performance as a maritime fuel (Figure 17). Firstly, *Maritime expert 1* in reference to ammonia's low energy density, says "For maritime applications or on large ships, you will need to carry a substantial amount of ammonia". He also goes on to refer to ammonia as a compound that "does not like to burn" and that "technically, it's complex... you always need some promoter or some extra actions to have it burn properly" supporting the narrative found in literature. *Maritime expert 2* also refers to the lower energy density of ammonia saying "Energy density is much lower and hence, discussion is narrowing down to methanol and methane or e-diesel" clearly evoking the significance of its performance as a fuel over other e-fuels.

In the persuasion stage of the innovation-decision process, the fuel performance of e-NH3 is considered a 'relevant disadvantage' due to its lower energy density and low combustibility, thereby making its adoption more 'complex'. This factor was labelled **TEC5.**

5.5. Legal Factors

The key legal factors extracted from literature (same as their codes in the codebook) are the labels in the radar chart below. This chart shows that ETS, ammonia-specific legislation, IMO regulations, renewable energy directive and the FuelEU Maritime Initiative were the factors identified. The shaded area represents how many of the 11 experts consulted evoked these factors in their interviews. Following this is an analysis of each identified legal factor using their accordingly coded excerpts.

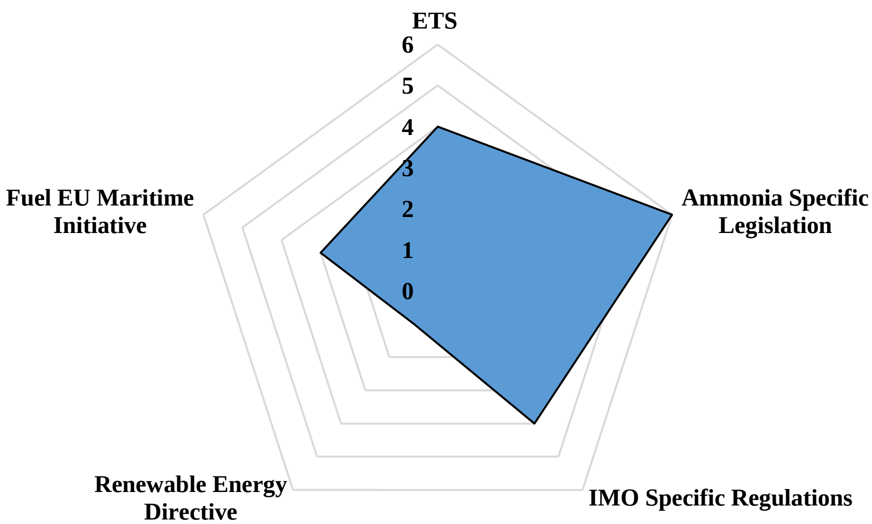


Figure 18. Radar chart for the legal factors, the labels are the factors extracted from literature while the shaded area represents the number of experts of the 11 consulted that identified each respective factor.

5.5.1. Emissions Trading Scheme (ETS) (LEG1)

The Emissions Trading Scheme (ETS) is an important legal mechanism for decarbonizing the EU's maritime fleet. It does so by setting a cap on the total GHG emissions and by permitting the trading of emission allowances (Christodoulou & Cullinane, 2022; Wu et al., 2024). This creates a financial burden on shipping companies exceeding their emissions limits, incentivizing the adoption of cleaner fuels and technologies like e-NH3 (Christodoulou & Cullinane, 2022; Machaj et al., 2022) . In the EU, the maritime sector has been specifically included in the ETS as of 2024 (Wu et al., 2024). As e-NH3 has gained market traction in recent times, the financial implications of ETS can influence its adoption. The ETS improves the economic feasibility of e-NH3 by increasing the cost of using traditional fuels through carbon allowances, therefore although currently more expensive than traditional fuels, using e-NH3 avoids the carbon cost posed by the ETS (Wu et al., 2024).

In addition, the ETS promotes a broader regulatory shift towards a sustainable maritime sector. As shipowners and operators face mounting top-down pressure to reduce their carbon emissions, the adoption of more sustainable fuels like e-NH3 becomes not just a compliance measure but also a strategic business decision (Wu et al., 2024). The ETS, combined with other EU policies creates a supportive environment for the transition towards a cleaner maritime sector (Christodoulou & Cullinane, 2022; Machaj et al., 2022; Malmborg, 2023).

Four experts consulted in this study referenced the role that ETS has in influencing e-NH3 adoption (Figure 18). A quote from *e-NH3 expert 3* says "Shipping becoming part of the ETS can bridge the cost gap, if CO2 prices reach 100+ EUR/t again" suggesting that if the price of carbon allowances in the ETS rises to 100+ Euro per ton of CO2, it would significantly increase the cost of emitting CO2. (Wu et al., 2024). Essentially, higher CO2 prices can bridge the cost gap between traditional fuels and greener alternatives, making the latter more financially viable over time (Wu et al., 2024). *Maritime expert 2*, identifies that "ETS for shipping is an important legal, goal-based measure". Finally, *Maritime expert 4* says "ETS schemes, where there is a cost to emitting CO2. If you don't emit CO2, you're not burdening the cost, which essentially is profit", further showing the economic incentive that ETS brings for shipping companies to adopt e-NH3.

In reference to the persuasion stage of the innovation-decision process, the ETS puts e-NH3 at a 'relevant advantage' over traditional fuels and hence makes it 'compatible' as a fuel for the EU's maritime fleet. This factor was labelled **LEG1.**

5.5.2. Ammonia Specific Legislation (LEG2)

Although there are general best practice guidelines for transporting ammonia as a commodity; the absence of ammonia-specific legislation, procedures, and guidelines for its use as a maritime fuel is a significant barrier for adoption (Balci et al., 2024; Galimova et al., 2023; Kim et al., 2024; H. Wang et al., 2023). Currently, there is a lack of regulatory frameworks that address the unique characteristics of ammonia for maritime applications, this regulatory gap creates uncertainty for shipping companies, fuel suppliers and other stakeholders to invest in ammonia fuel technologies and infrastructure (Balci et al., 2024; Christodoulou & Cullinane, 2022; Machaj et al., 2022).

Many reports relating to alternative fuels and ammonia, highlight a need for specific legislation in the maritime context. The development of ammonia-specific legislation and guidelines is crucial for ensuring safety, managing risks, and promoting best practices for e-NH3 usage (Christodoulou & Cullinane, 2022; Machaj et al., 2022). These regulations need to address a range of issues, from the design and construction of ammonia-fueled ships and fueling stations to operational procedures, crew training and emergency response plans (Christodoulou & Cullinane, 2022; Machaj et al., 2022). Without clear rules and standards, e-NH3 cannot become a widely adopted maritime fuel (Wu et al., 2024). Moreover, reports and studies also underline that the development of frameworks is required as soon as possible, for the maritime sector to avoid delays in future adoption (Balci et al., 2024; Galimova et al., 2023; Kim et al., 2024; H. Wang et al., 2023; Z. Wang et al., 2024).

Six experts consulted in this study specifically identify this factor (Figure 18). *e-NH3 expert 1* when asked about the legal influencing factors says "There's a lot of legislation, but nothing specifically catering to ammonia. The problem is, we don't know if ammonia is going to be the next big thing. The government doesn't want to into the market yet. So, there is no legislation that promotes the use of ammonia. Only since January, are we seeing some upward trend towards ammonia usage from legislators. But if we talk about barriers, then safety legislation is a barrier, but it's a necessary one. You will need to develop one specifically for ammonia, especially for the large volumes that we're going to transport it in". *e-NH3 expert 3* corroborates the need for maritime ammonia-specific legislation when saying "Definitely, some approvals for ammonia as a shipping fuel, and bunkering in ports are still pending. This is important for getting ammonia as a viable alternative to fossil fuel". *e-NH3 expert 4* also places importance on this factor saying that "Ships are outside the current legal area of expertise. There are best practices in those guidelines, which you can use, but it's not within those guidelines for maritime application".

In line with the persuasion stage of the innovation-decision process, the lack of ammonia-specific legislation for the EU's maritime sector makes it 'complex' to adopt. But also, 'complex' to 'trial' as a fuel. This factor is labelled **LEG2.**

5.5.3. IMO Regulations (LEG3)

The IMO plays a key role in shaping the adoption of e-NH3 as a maritime fuel through its various regulations and guidelines not just in the EU but internationally. It's 2023 Strategy aims for international shipping to reduce at least 50% of GHG emissions by 2050 and to eventually phase them out (Sánchez et al., 2023; H. Wang et al., 2023; Ye et al., 2022). Under this goal umbrella, the IMO has specific regulations and regulatory guidelines that apply to the adoption of e-NH3. The 2020 sulphur cap, enforced by MARPOL Annex VI, limits the sulphur content in maritime fuel oil used on ships to 0.50% m/m, aiming to drastically reduce sulphur oxide emissions (Louvros et al., 2023; Machaj et al., 2022; McKinlay et al., 2021; Smith & Mastorakos, 2023). e-NH3 which does not contain sulfur, presents a viable alternative to meet these requirements. Contrarily, grey literature identifies that the IGC code of the IMO currently recognizes ammonia as a toxic substance and forbids the use of toxic cargo as fuel (IMO, 2024). Moreover, the IGF code does not currently encompass the use of ammonia as a fuel (Balci et al., 2024; Inal et al., 2022). However, literature and information available from IMO documents suggest that the guidelines ensuring the safety of ships utilizing ammonia are presently in the works, which could positively influence e-NH3 adoption (Balci et al., 2024; Inal et al., 2022).

Overall, the IMO identifies e-NH3 as a fuel with a low-medium regulatory readiness level when compared to traditional fuels and other alternatives (IMO, 2024). This will need to be higher for e-NH3 to be a viable alternative for the maritime sector (IMO, 2024).

Four experts identified IMO regulations as an important influencing legal factor (Figure 18). *Maritime expert 2* refers to a new policy under development by the IMO saying, "There is a policy under development at the global level by the IMO who are creating a Global Fuel Standard, which would be very similar to FuelEU".

In line with the persuasion stage of the innovation-decision process, the presence and further development of IMO regulations makes e-NH3 adoption 'compatible' and 'observable' to 'trial' for the EU. This factor is labelled **LEG3.**

5.5.4. Renewable Energy Directive (RED II) (LEG4)

RED II sets targets for increasing the share of renewable energy in the EU's total energy consumption (Chiaramonti & Goumas, 2020). It specifically highlights the need for increasing the share of renewable energy from the transport sector, setting a target of 14% by 2030. This includes a sub-target for advancing the use of RFNBOs like e-NH3. The RED II also provides a regulatory framework that encourages the development of supply chains and infrastructure needed for the widespread adoption these fuels (Chiaramonti & Goumas, 2019).

One expert consulted identified the RED II (Figure 18) as an influencing factor, when stating "You have the renewable energy directive, there is a target of which a certain percentage of the fuel sold in the EU that must be renewable. There is also a specific target for transport. Because you must have a certain percentage of your sales to be from renewable fuels. This is incentive for maritime shipping to use the fuels".

In line with the persuasion stage of the innovation-decision process, the legal backing of the RED II gives e-NH3 a 'relevant advantage' over traditional fuels and incentive to develop infrastructure, making it 'trailable' as a maritime fuel. This factor was labelled **LEG4.**

5.5.5. FuelEU Maritime Initiative (LEG5)

The FuelEU Maritime Initiative is a key regulation that influences the adoption of e-NH3 (Christodoulou & Cullinane, 2022; Malmborg, 2023). As a regulation, it is legally binding and directly applicable to all member states without the need for national governments to adopt into their legislation (Balci et al., 2024; S. Chen et al., 2023; Christodoulou & Cullinane, 2022; Malmborg, 2023; Menzli et al., 2022) . The main goal of the initiative is to decarbonize maritime shipping by setting progressive limits on GHG intensity. Starting from 2025, ships over 5000 gross tonnages are required to switch to alternative fuels or energy sources to meet these limits, which aim for an 80% reduction by 2050 (Malmborg, 2023). The initiative applies to energy consumption both in EU ports and during voyages to and from the EU while non-compliance results in penalties (Christodoulou & Cullinane, 2022; Malmborg, 2023). Furthermore, the initiative provides a unique incentive for RNFBOs and specifically mentions ammonia in the policy document (Christodoulou & Cullinane, 2022; Machaj et al., 2022).

Three experts identified the initiative as an important influencing legal factor (Figure 18). *Maritime expert 2* emphasizes that "All ships, independent of their flag. Must comply with FuelEU". *Maritime expert 3* says the initiative "is a very strong measure that the EU has taken. It will really be an incentive to use different fuels. If there is no strict regulation such as this, nobody will ever buy or produce the fuels". This further evokes the importance that the initiative has on the diffusion of alternative fuels.

Therefore, in line with the persuasion stage of the innovation-decision process, the FuelEU Maritime Initiative allows for the 'trialability' and hence, the 'observability' of e-NH3 as a maritime fuel. This factor was labelled **LEG5.**

5.6. Environmental Factors

The key environmental factors extracted from literature (same as their codes in the codebook) are the labels in the radar chart below. This chart shows that the CO2 emissions reduction potential, NOx emissions, marine/ocean impact and other emissions were recognized to be the key factors. The shaded area shows how many of the 11 experts consulted brought up these factors in their interviews. Following this is an analysis of each identified environmental factor using their accordingly coded excerpts.

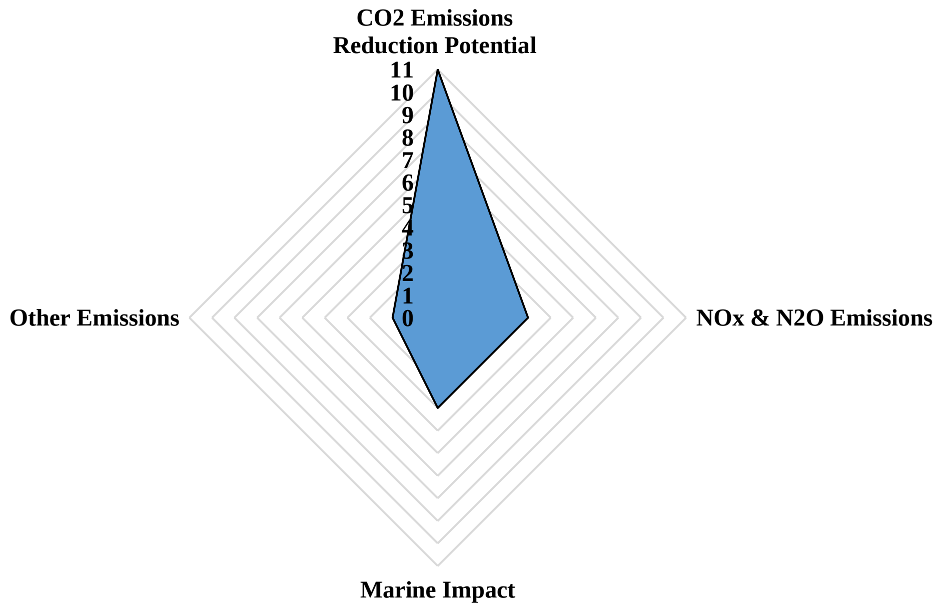


Figure 19. Radar chart illustrating the environmental factors, the labels represent factors extracted from literature. The shaded area represents the number of experts who identified each respective factor.

5.6.1. CO2 Emissions Reduction Potential (ENV1)

The CO2 reduction potential that e-NH3 offers is a compelling influencing factor for adoption. e-NH3 does not produce CO2 emissions during combustion as it does not contain any carbon atoms. (Kim et al., 2024; Machaj et al., 2022; Sánchez et al., 2023; H. Wang et al., 2023) This contrasts the traditional fuels currently used like HFO and MGOs that release a significant amount (Christodoulou & Cullinane, 2022; Louvros et al., 2023; Machaj et al., 2022; Z. Wang et al., 2024; Zincir, 2022). With the adoption of e-NH3, there is potential for the EU's maritime fleet to achieve a substantial reduction in its overall lifecycle emissions. Specifically, the production of e-NH3 uses renewable energy to generate hydrogen, which is then synthesized to produce e-NH3 (Christodoulou & Cullinane, 2022; Machaj et al., 2022). This process results in a fuel that is nearly carbon-neutral, well-to-wake (Christodoulou & Cullinane, 2022). The lifecycle reduction in CO2 and GHG emissions enhances e-NH3 as an attractive fuel by offering a viable pathway for the EU's maritime sector to achieve its long-term decarbonization goals (Aakko-Saksa et al., 2023; Malmborg, 2023; Marrero & Martínez-López, 2023; Tsvetkova et al., 2024). The importance of this factor cannot be overstated in the context of regulatory pressures and governmental push towards greening the maritime sector (Tsvetkova et al., 2024). As the maritime sector faces increasing scrutiny over its historically high emissions, the ability of e-NH3 to provide a viable zero-carbon alternative is a key solution to comply with current and future emissions targets (Hellström et al., 2024).

Perhaps the most influential factor, all experts consulted in this study reference this specific potential (Figure 19). Some important excerpts from the experts include *expert 1* who said "The biggest benefit for the environment is that there is no new CO2 emitted to the air, that's the primary reason why you want to move away from fossil fuels. If you look at ammonia versus other carriers, it's not a carbon carrier. So, if you if you burn ammonia, or if you use a stack for ammonia, it's not going to emit carbon". *e-NH3 expert 2* further echoes this stance quoting "No CO_2, therefore benefitting on the environmental aspect". *e-NH3 expert 3* quotes "Ammonia does not contain carbon and will thus not form CO_2 upon combustion". Overall, all experts corroborate the CO_2 reduction potential of e-NH3.

In the persuasion stage of the innovation-decision process, the CO_2 reduction potential of e-NH3 provides a 'relevant advantage' over traditional fuels and other alternatives. This factor was labelled **ENV1.**

5.6.2. NOx & N2O Emissions (ENV2)

Nitrogen monoxide (NO), nitrogen dioxide (NO_2) (collectively referenced as NOx), and nitrous oxide (N_2O) are potent gases that can slip from ammonia combustion (Kim et al., 2024; Sánchez et al., 2023; Smith & Mastorakos, 2023). NOx emissions pose significant environmental concern for the shipping industry due to their contribution towards air pollution and their role in the formation of ground-level ozone and particulate matter (Abraham et al., 2024; Smith & Mastorakos, 2023; Tomos et al., 2024; Zincir, 2022). N_2O on the other hand, is a potent GHG with higher global warming potential than CO_2 (Balci et al., 2024; Galimova et al., 2023; McKinlay et al., 2021; Z. Wang et al., 2024).

The persistence of NOx and N_2O emissions from using e-NH3 has been recorded in many studies (Egerer et al., 2023; Galimova et al., 2023; Karvounis et al., 2024; Z. Wang et al., 2024; Zincir, 2022). While e-NH3 combustion does produce NOx & and N_2O, there are ways that this can be tackled (Al-Aboosi et al., 2021; Inal et al., 2022; Smith & Mastorakos, 2023). According to literature, ammonia engines can be designed to run at lower temperatures resulting in a reduction of NOxs (Balci et al., 2024; Karvounis et al., 2024; McKinlay et al., 2021; Smith & Mastorakos, 2023). Furthermore, having a selective catalytic reduction (SCR) system can further mitigate this by converting NOx to nitrogen and water vapor (Balci et al., 2024; Karvounis et al., 2024). In addition, N_2O emissions can be curbed by ensuring complete combustion and a lower ammonia slip (Galimova et al., 2023; Machaj et al., 2022; Z. Wang et al., 2024).

Four experts consulted identified these emissions as a crucial factor (Figure 19). *e-NH3 expert 2* when asked about the influencing environmental concerns, stated "Nitrous or NOX emissions in high-pressure combustion on ships is a big problem". This recurring stance was expressed by *e-NH3 expert 3* who says "N_2O emissions must be kept in check for ammonia combustion". However, literature revealed that various mitigation techniques can curb these emissions, a point the consulted experts also supported. *Maritime expert 3* says "you need after treatment; you need to clean up your exhaust gases. You need to use SCR. It requires attention, it requires extra hardware, it requires control. Then, it is solvable.".

In reference to the persuasion stage of the innovation-decision process, NOx and N_2O emissions bring concerns for the adoption of e-NH3, if not addressed, makes the fuel 'incompatible' and hence, a 'relevant disadvantage' over other alternatives. This factor was labelled **ENV2.**

5.6.3. Marine Impact (ENV3)

With an increase in e-NH3 usage, it is safe to assume that there will be an increased likelihood of a leakage and hence a threat to the marine environment (M. Chen et al., 2024). Studies suggest that an ammonia leak in the marine environment can have significant impacts on biodiversity (M. Chen et al., 2024; Karvounis et al., 2024; Zincir, 2022). However, the impact of an ammonia leak is significantly less severe than a conventional fuel spill (EDF, 2022). One study suggests that, in the event of a large ammonia leak, the ecological effects can vary widely based on the location of the spill, the time of day, and temperature (EDF, 2022). Particularly, marine ecosystems like estuaries, wetlands and mangroves are more sensitive to ammonia spills than open sea or deeper waters (EDF, 2022).

Four experts explicitly express their concern over the marine environment (Figure 19). *Maritime expert 4* quotes "The environmental challenges sit in a potential release. If you look at a larger environment, ammonia is highly soluble in water, but has a low threshold for toxicity for aquatic life. If you have a major spill of ammonia, then there is a risk to the aquatic life". *Maritime expert 1* echoes this narrative when saying "When you have a leakage or spill, you will start with very high concentrations, which will probably kill sea life and also cause algal blooms". *e-NH3 expert 4* also addresses this environmental concern saying "It will have a negative impact on environmental waters, but it's very dependent on where it will happen. If you're near some wetlands, it will be disastrous. If you're above coral reef, it's also not great. But if you're in the middle of the Pacific Ocean, well, just dump it in there, it's very easily soluble in water. It's present in water normally. But too much is always a bad thing. So, if you have a very large body of water, no problem".

In the persuasion stage of the innovation-decision process, the potential marine impact of an ammonia leak can raise concerns over its adoption. If these concerns are not actively addressed, the fuel becomes 'incompatible' and therefore, a 'relevant disadvantage' compared to other alternatives. This factor was labelled **ENV3.**

5.6.4. Other emissions (ENV4)

e-NH3 does not consist of other contaminants which are usually contained by conventional fuels that result in emissions of sulfur dioxide, carbon monoxide, heavy metals, and polycyclic aromatic hydrocarbons (M. Chen et al., 2024; Karvounis et al., 2024; Zincir, 2022). This implies that adopting e-NH3 can bring significant reduction in soot and particulate matter, which are both harmful to humans and the environment (M. Chen et al., 2024; Karvounis et al., 2024; Zincir, 2022). Furthermore, e-NH3 does not cause methane slip, which refers to the unburned methane that escapes into the atmosphere which is a major concern posed by traditional fuel and some alternatives like LNG. (M. Chen et al., 2024; Karvounis et al., 2024; Zincir, 2022) This is particularly important as methane is a potent GHG, with a warming potential much higher than CO2 (M. Chen et al., 2024; Karvounis et al., 2024; Zincir, 2022).

Two experts consulted in this study paid specific attention to this factor during their interviews (Figure 19). Firstly, *e-NH3 expert 4* says "So with heavy fuel oils there, next to CO2, there's a lot of soot and other heavy metals emitted, environmentally speaking, ammonia is a lot cleaner". e-*NH3 expert 2* further corroborates this saying "No SOx emissions, particulate matter emissions, and no CO2 emissions, no CH4 slip".

In the persuasion stage of the innovation-decision process, the environmental benefits of e-NH3 when compared to other fuels serve as a compelling factor for adoption, making it 'compatible' and hence, a 'relevant advantage' over other alternatives. This factor was labelled **ENV4.**

5.7. MICMAC Analysis

The MICMAC software was used to understand and describe the influence of the factors by categorizing them based on their influence on the adoption of e-NH3. Each of the 26 identified key factors (Table 7) was assigned a value that represents their power of influence. A matrix was then created to illustrate the direct influence of each factor on the others, with the values in the matrix signifying the strength of these influences (MICMAC Matrix). These values were assigned based on the criteria in Table 6.

Table 7. Summary table of the 26 identified PESTLE factors and their corresponding labels for the MICMAC analysis.

PESTLE Factor	Label
Energy Autonomy	**POL1**
Dependence on High Renewable Energy Nations	**POL2**
EU National Level Volatility	**POL3**
Green Shipping Corridors	**POL4**
Capital Expenditure	**ECO1**
Cost of e-NH3	**ECO2**
R&D Cost	**ECO3**
Retrofitting & New Ship Production Cost	**ECO4**
Expertise & Training	**SOC1**
Health & Safety	**SOC2**
Market/Stakeholder Support	**SOC3**
Social Acceptance	**SOC4**
Transportation (Bunkering & Storage)	**TEC1**
Port & Bunkering Infrastructure	**TEC2**
Production & Supply Chain Infrastructure	**TEC3**
Ship & Engine Compatibility	**TEC4**
Fuel Performance	**TEC5**
Emissions Trading Scheme (ETS)	**LEG1**
Ammonia Specific Legislation	**LEG2**
IMO Regulations	**LEG3**
Renewable Energy Directive (RED II)	**LEG4**
FuelEU Maritime Initiative	**LEG5**
CO2 Emissions Reduction Potential	**ENV1**
NOx & N2O Emissions	**ENV2**
Marine Impact	**ENV3**
Other Emissions	**ENV4**

The resulting cluster graph categorized the factors into three groups: independent factors, moderate factors, and dependent factors (Figure 20). 12 of the identified factors were recognized as independent (depicted in the red cluster). This means that they have a high influence on the adoption of e-NH3 without being dependent on all other factors identified in this study (Balci et al., 2024; Tsvetkova et al., 2024). Dependence on nations with high renewable energy (POL 2) was the only independent political factor. While the cost of e-NH3 (ECO2) and capital expenditure (ECO1) were the independent economic factors. Expertise & training (SOC1), health & safety (SOC2) and social acceptance (SOC4) were the social independent factors. The technical independent factors identified were transportation (TEC1), port & bunkering infrastructure (TEC 2), production & supply chain infrastructure (TEC3) and ship compatibility (TEC 4). The only legal independent factor was ammonia-specific legislation (LEG2). Finally, the only environmental independent factor was CO2 emissions reduction potential (ENV1). These independent factors, exert substantial influence on the adoption of e-NH3, emphasizing their importance (Balci et al., 2024; Tsvetkova et al., 2024)

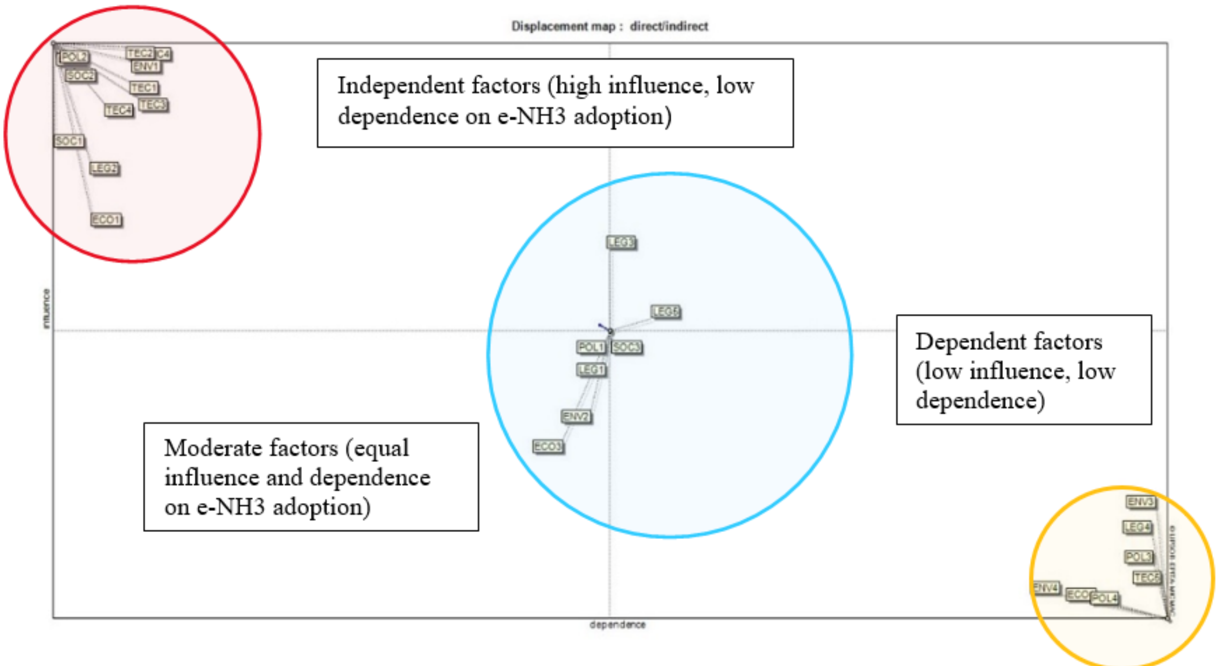


Figure 20. MICMAC cluster graph for the PESTLE influencing factors for e-NH3 adoption.

7 moderate factors were recognized that exhibit an equal level of influence and dependence on all other factors for the adoption of e-NH3, pictured in the blue cluster (Balci et al., 2024; Tsvetkova et al., 2024) (Figure 20). Energy autonomy (POL 1) was identified as the sole moderate political factor. While R&D cost (ECO3) was recognized as the only moderate economic factor. The only moderate social factor was market/stakeholder support (SOC3). In addition, the legal moderate factors included the ETS (LEG1), the FuelEU Maritime Initiative (LEG5) and the IMO-specific regulations (LEG 3). Finally, the only environmental factor was NOx and N2O Emissions (ENV2).

The 7 dependent factors as depicted by the yellow cluster are those that exhibit a low influence but are heavily dependent on all other factors for driving e-NH3 adoption (Balci et al., 2024; Tsvetkova et al., 2024) (Figure 20). Green shipping corridors (POL4) and EU national level volatility (POL3) emerged as the dependent political factors. The cost of retrofitting the ship (ECO4) emerged as the sole dependent economic factor. Fuel performance (TEC5) was the only technical factor while the renewable energy directive (LEG4) was the only legal factor. Finally, the environmental factors included marine impact (ENV3) and other emissions (ENV4).

6. Discussion

This section begins with a discussion of the MICMAC analysis results, coupled with connecting back to Rogers' innovation-decision process to offer some recommendations for the EU for the next stages of adoption. Then a discussion on how this study contributes to academic literature is presented followed by that of the limitations. Overall, this section focuses on answering sub-research questions 3, 4 and 5.

6.1. MICMAC Analysis

This study identified 26 key PESTLE factors from literature and consultation with experts that influence the adoption of e-NH3 into the EU's maritime fleet. The MICMAC software then categorized these factors into three main categories based on their determined influence. This categorization aids in identifying and prioritizing the factors, providing the European Commission and EU member states with a clear roadmap for a phased approach (Balci et al., 2024) (Figure 21). By prioritizing interventions or initiatives to address the identified factors based on their MICMAC clusters of independent first, moderate second, and dependent last, the EU can effectively allocate resources and efforts to address successful adoption.

Firstly, the 12 independent factors characterized by their high influence and autonomy serve as the base for adoption efforts (Hellström et al., 2024; Tsvetkova et al., 2024). Addressing these factors first lays a solid foundation for the widespread adoption of e-NH3 (Hellström et al., 2024; Tsvetkova et al., 2024). As the EU is aiming to reduce GHG emissions from maritime shipping, the most compelling factor for adoption is the CO2 emissions reduction potential (ENV1) that e-NH3 offers. Moreover, initiatives targeting independent factors such as enhancing port and supply chain infrastructure (TEC2, TEC3) is a crucial first step that allows for the sector to consider e-NH3 (Hellström et al., 2024). The EU and member states should improve on or create regulations or frameworks specific to the maritime application of e-NH3 (LEG2) and provide a baseline for health and safety (SOC2) on board (Sánchez et al., 2023; H. Wang et al., 2023). Furthermore, placing significant measures to reduce the cost of e-NH3 (ECO2) will also be crucial to make e-NH3 an economic fuel option (Kim et al., 2024). The EU and member states should assist with the capital (ECO1) required to do so by bearing some if not most of the cost to initiate an e-NH3 transition (Kim et al., 2024; Machaj et al., 2022). Moreover, the EU should ensure that personnel are trained (SOC1) to manage e-NH3 not just on board (TEC1) but also during bunkering at all key ports. This should be coupled with taking measures to improve the social acceptance of e-NH3 (SOC4). The new political climate that might develop with the EU's dependence on nations with high renewable energy (POL2) should be seen in a positive light that mutually benefits both parties and the environment as a whole.

Once, tackling the independent factors, the second category is the moderate factors. These 7 factors exhibit equal influence and dependence on all other factors identified in this study (Balci et al., 2024; Tsvetkova et al., 2024). They are neither the most influential nor the most influenced, they instead occupy an intermediate position. Moderate factors are crucial to consider for the adoption of e-NH3 as they often function as connectors or intermediates. These factors play a stabilizing role in helping balance the interaction between independent factors and dependent factors. Addressing the moderate factors is essential in this context as they provide insight into potential leverage points and areas where the EU can improve (Balci et al., 2024; Tsvetkova et al., 2024). The EU's stance on increasing its energy autonomy (POL1) is crucial for ensuring that the maritime fleet operates independently of fluctuating external energy supplies and hence, the EU must do so promptly to avoid a sudden switch to alternative fuels as this might evoke political turmoil (Tsvetkova et al., 2024). The continual need for R&D cost (ECO3) reflects the requirement of continual innovation and technological advancements necessary to make e-NH3 a technically successful alternative fuel, which is where the EU can step in (Balci et al., 2024). Market/stakeholder support (SOC3) is essential for gaining the necessary backing from industry players and the public to drive adoption forward. The legal moderate factors including the ETS (LEG1), the FuelEU Maritime Initiative (LEG5), and the IMO-specific regulations (LEG3), highlight the importance of international and regional regulatory alignment in facilitating e-NH3 adoption. Finally, the environmental consideration of NOx and N2O emissions (ENV2) indicates a need to manage the broader environmental impact of adopting e-NH3, beyond just a reduction in CO2 for the EU.

The 7 dependent factors are those that have a high level of dependence on other factors while having a relatively low influence. These factors reveal areas that require supportive measures and favorable conditions to facilitate e-NH3 adoption (Tsvetkova et al., 2024). Political factors such as green shipping corridors (POL4) and EU national level volatility (POL3) indicate the reliance of the EU on strategic maritime initiatives and stable political environments (Tsvetkova et al., 2024). The cost of retrofitting ships (ECO4) emphasizes the financial barriers that need to be addressed to retrofit existing vessels for e-NH3, which emerges as another area where the EU can assist. Fuel performance (TEC5) as a technical dependent factor highlights the necessity of ensuring that e-NH3 meets the performance standards required for maritime shipping. Finally, environmental factors like marine impact (ENV3) and other emissions (ENV4) show the necessity of managing the broader environmental impact of an increased usage of e-NH3.

6.2. Recommendations and Implications for the EU

Connecting back to Rogers' innovation-decision process, this study focuses on the persuasion stage, it is in this stage where groups from attitudes and beliefs by analyzing the numerous factors that make a certain innovation advantageous or disadvantageous over others. Hence, this study provides the EU and member states with this analysis by utilizing the PESTLE framework illustrated by the tick in Figure 21. The following are recommendations and implications for the EU, incorporating those found in literature and excerpts from the experts consulted in this study to address the identified key PESTLE factors for the next stages of the innovation-decision process, namely the decision (stage 3), implementation (stage 4) and confirmation (stage 5) based on their MICMAC categorization. A summarized roadmap is found in Figure 21.

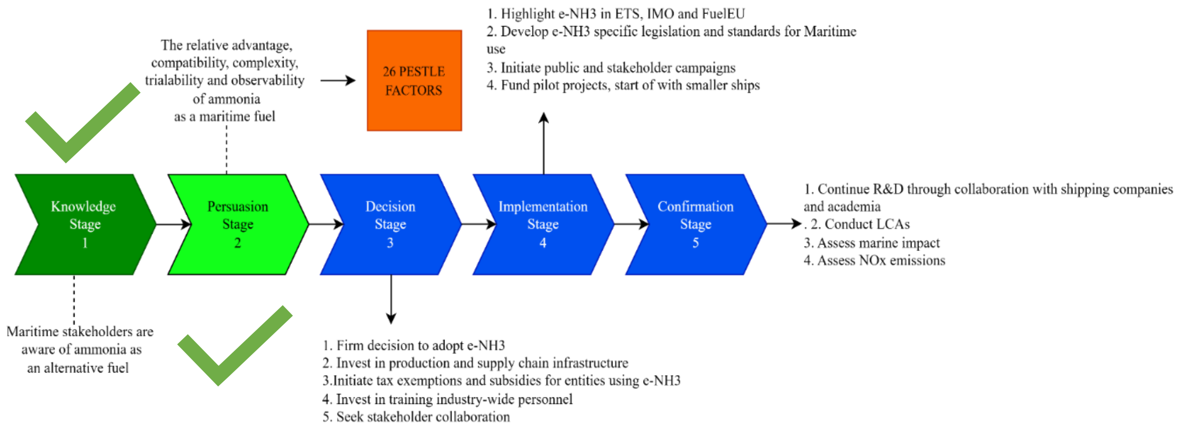


Figure 21. Recommendation roadmap for the subsequent stages of the innovation-decision process for the EU to facilitate widespread adoption of e-NH3.

Approaching the decision stage, the EU should make a firm decision to facilitate adoption. Firstly, providing financial support to overcome the huge economic barriers associated with the cost of e-NH3 (ECO2) via subsidies and tax exemption is essential. This was supported by *e-NH3 expert 1* who says, "We need fair trading deals on ammonia, which needs to be exempt from import taxes". The capital expenditure (ECO1) needed to establish the infrastructure should also be supported by the EU and member nations (POL3). This was noted by *e-NH3 expert 1*, who states, "Basic infrastructure should come from the government, who should cover 40% of this infrastructure cost". Furthermore, investing in industry-wide training programs to ensure personnel are trained (SOC1) to handle e-NH3 safely (SOC2) will be important at this stage. *Maritime expert 2* emphasizes this saying, "Industry-wide training is essential". Inputs from stakeholders must be taken into account to develop standardized training protocols and ammonia-specific certifications as supported by *Maritime expert 3* who states, "Set clear regulatory standards for ammonia". A summary of decision stage actions is found in Table 8.

Table 8. Summary of decision stage actions for the EU.

	EU Action	**Collaboration Partners**	**Expected Outcome**
Decision Stage	Provide financial support via subsidies and tax exemptions (ECO2)	EU member nations, financial institutions	Overcome economic barriers, reduce cost of e-NH3
	Support capital expenditure for infrastructure (ECO1, POL3)	EU member nations, infrastructure companies	Establish necessary infrastructure for e-NH3
	Support capital expenditure for infrastructure (ECO1, POL3)	EU member nations, infrastructure companies	Establish necessary infrastructure for e-NH3
	Invest in industry-wide training programs (SOC1, SOC2)	Training institutions, maritime industry	Ensure personnel are trained to handle e-NH3 safely
	Communicate decision with stakeholders and develop standardized training (SOC3)	Maritime industry, regulatory bodies	Identify e-NH3 as a fuel pathway, standardized training protocols and certifications

In the implementation stage, the EU's focus must shift to executing the adoption (Zhou et al., 2024). Firstly, specific importance must be given to e-NH3 under regulatory compliance with ETS, IMO regulations and FuelEU (LEG1, LEG3, LEG4, LEG5). Similarly, the EU must develop regulations and framework for e-NH3's usage as a fuel along with providing guidance and support to facilitate compliance for maritime stakeholders. *Maritime expert 3* supports this narrative when quoting "Make clear regulations on e-NH3's maritime use". In addition, the EU should implement a monitoring, reporting and evaluation system to assess the management of NOx and N2O emissions (ENV2, ENV4). This ensures that ships are taking the necessary technical measures to mitigate these emissions. *e-NH3 expert 4* supports this when stating "N2O emissions must be kept in check for ammonia combustion". At this stage, the EU could carry out public campaigns to promote the use of e-NH3 and reduce stigma (SOC4) associated with the fuel. The EU could also fund pilot projects for e-NH3 adoption, considering its lower energy density, a way forward could be to push for e-NH3 usage in smaller ships or ships that conduct shorter trips so that frequent refuelling is possible (TEC5). A summary of implementation stage actions is found in Table 9.

Table 9. Summary of Implementation actions for the EU.

	EU Action	**Collaboration Partners**	**Expected Outcome**
Implementation Stage	Develop specific regulations and framework for e-NH3 usage (LEG1, LEG3, LEG4, LEG5)	IMO, maritime regulatory bodies, industry stakeholders	Clear regulations and compliance framework for e-NH3 usage
	Implement monitoring, reporting, and evaluation system (ENV2, ENV4)	Environmental agencies, maritime industry	Assess and manage NOx and N2O emissions
	Conduct public campaigns to promote e-NH3 (SOC4)	Media, public relations firms	Reduce stigma associated with e-NH3, increase public acceptance
	Fund pilot projects for e-NH3 adoption, start with smaller ships or ships that can refuel easily (TEC5)	Maritime industry, research institutions	Practical demonstration and validation of e-NH3 as a maritime fuel

In the confirmation stage, it will be essential to continue R&D (ECO3) to ensure vessels using e-NH3 improve via collaboration between stakeholders including academia, technology-providing companies, shipping companies and governmental bodies (Menzli et al., 2022). This was corroborated by *e-NH3 expert 2* who quotes "We need to overcome technical hurdles with more research and collaboration". Furthermore, once a stable supply chain has been established it is essential to conduct a lifecycle assessment to ensure that e-NH3 production stays net-zero as stated by *e-NH3 expert 4* that an "LCA will need to be done" (ENV1). It will also be pivotal to assess marine impact with the increased use of e-NH3 to ensure that the marine environment (ENV3) is not being harmed. The EU must recognize that while e-NH3 offers a significant CO2 reduction potential for the maritime sector, the future will not rely on a single solution but rather an interdisciplinary approach. Ammonia should be treated as a distinct fuel pathway, but its widespread adoption will ultimately depend on market dynamics, as *Maritime expert 2* points out "The decision is up to the market". Finally, international collaboration is essential, all the EU's measures will remain aimless if international waters do not follow suit. Other countries should also focus on decarbonization and e-NH3 to ensure that refuelling bunkers are available in ports all over the world (POL1, POL2). A summary of confirmation stage actions is found in Table 10.

Table 10. Summary of Confirmation stage actions for the EU.

	EU Action	Collaboration Partners	Expected Outcome
Confirmation Stage	Continue R&D for technical improvements (ECO3)	Academia, technology companies, shipping companies, governmental bodies	Overcome technical hurdles, improve e-NH3 technology
	Conduct lifecycle assessment for net-zero production (ENV1)	Environmental scientists, production companies	Ensure e-NH3 production remains net-zero
	Assess marine impact of e-NH3 usage (ENV3)	Marine biologists, environmental agencies	Protect marine environment, ensure sustainable use of e-NH3

6.3. PESTLE & Rogers' Innovation-Decision Process

Building upon the two cornerstone papers of Balci et al. 2024 and Tsvetkova et al. 2024, the primary research gap identified from the literature review was the lack of comprehensive analysis of the influencing adoption factors for e-NH3, with existing research predominantly focusing on cost and engineering aspects. This thesis fills this gap by providing a more holistic analysis of the various influencing factors for e-NH3 using the PESTLE framework as utilized by Tsvetkova et al., 2024. By broadening the scope of analysis through the PESTLE in the narrowed down context of e-NH3 into the EU's fleet, this thesis provides valuable insights for the EU coupled with a more complete understanding of the factors driving adoption, forming the primary academic contribution of this thesis.

Furthermore, this study reveals that the PESTLE's integration into the persuasion stage of the innovation-decision process enhances the analysis of e-NH3 adoption by providing complementary perspectives and methodologies (Amega et al., 2024; Münter, 2024). While Rogers' model outlines the key innovation characteristics to which a factor must be compared, it does not guide which factors to consider (Menzli et al., 2022; Zhou et al., 2024). The PESTLE analysis steps in here by offering this guidance. Additionally, this integration enables a more synergistic methodology for understanding the diffusion of e-NH3 (Münter, 2024). Therefore, this study contributes a fresh theoretical perspective to study innovation adoption particularly for sustainable fuels like e-NH3, which are under-explored academically. By blending these frameworks, this research not only provides a strengthened theoretical foundation but also a more holistic insight to understand the implications for policymaking and industry decisions in the EU's maritime sector. Importantly, this approach can be applied to understand the diffusion of other alternative fuels or technologies which are not widely adopted.

However, limitations do arise with this methodology as the innovation-decision process assumes a structured approach that may not align with real-world complexity in innovation adoption, potential regression between stages can also occur (Ayanwale & Ndlovu, 2024). The PESTLE on the other hand is subjective and hard to analyze across six domains at once, making it difficult to predict future changes, especially in the maritime sector (Münter, 2024).

Further research could include the integration of the PESTLE with other theoretical frameworks such as the technology acceptance model (TAM) or the theory of planned behaviour

(TPB) to understand the widespread adoption of e-NH3 or other fuels not only in the maritime context, but for other sectors as well (Zhou et al., 2024). Moreover, research focusing on each of the six domains individually could also provide a more detailed analysis.

6.4. Limitations

Although this study provides a broad yet detailed analysis of the PESTLE factors, there are several limitations. One of the primary challenges was the limited time available for conducting interviews. Conducting a longer study to incorporate the perspectives of more experts in the field could result in the identification of more factors that were not identified in this study.

Another limitation is that this study only focused on understanding the influence of factors using their direct influences. Using the MICMAC to account for indirect influences could provide a more accurate representation of the e-NH3 adoption system. Although the influence power of each factor in the MICMAC was kept constant, to provide a better understanding of the PESTLE factors' influence, assessing the weightage of each factor's influence on others through expert consultation could yield a clearer and more representative MICMAC cluster graph. Furthermore, employing other social variable software like the mental modeller to run different scenarios could further enhance the theoretical understanding of how addressing specific factors could lead to the successful adoption of e-NH3. Moreover, the application of the MICMAC model in this study is based on individual usage and interpretation. Conducting a similar analysis with a broader group of experts could yield a more comprehensive model.

It is important to highlight that this study's use of the innovation-decision process is primarily theoretical and should be understood as such. While it offers a detailed analysis, the projections are hypothetical and may differ from practical outcomes due to real-world complexities and unforeseen factors. Lastly, it is important to note that the PESTLE factors in this study were segregated for simplicity and clarity of analysis. However, in real life, many of the factors have multiple implications.

7. Conclusion

This thesis aimed to analyze the PESTLE factors influencing the adoption of e-NH3 as an alternative fuel for the EU's maritime fleet, with a focus on the persuasion stage of Rogers' innovation-decision process. It began with a literature review to provide the essential context, offering an overview of the current status of the EU's maritime fleet. This review revealed that traditional fuels still dominate the sector and that emissions remain high, not aligning with international climate targets. e-NH3 was then introduced as a sustainable alternative fuel due to its lack of CO2 emissions throughout its supply chain and upon combustion.

Then, a content analysis was conducted on grey and academic literature on the Scopus database to extract the 26 PESTLE factors, supported by interviews with 11 experts, addressing sub-questions 1 and 2. To answer sub-question 3, which focuses on how the PESTLE factors influence e-NH3 adoption, a MICMAC analysis was used. This analysis created a matrix of influences, categorizing the factors into independent factors (high influence, low dependence), moderate factors (equal influence and dependence) and dependent factors (low influence, low dependence). This segregation showed the influence of each group and how the EU should prioritize addressing these factors for successful adoption.

Key independent factors included ammonia-specific legislation, health & safety, expertise, CO2 emissions reduction potential, and the need for infrastructure. Moderate factors included energy autonomy, market/stakeholder support, and the EU's various legal mechanisms, such as the FuelEU initiative and ETS. Dependent factors included green shipping corridors, fuel performance and marine impact. Addressing the independent factors first lays a solid foundation as these factors have a high influence; then, the moderate factors, which serve as connectors, and finally, the dependent factors, which rely on other factors in the system, should be addressed last.

To answer sub-question 4, integrating a PESTLE into the innovation-decision process enhances the e-NH3 adoption analysis by providing complementary perspectives. This synergistic approach offers holistic insights into EU maritime policy and industry decisions, proving to be the primary academic contribution of this study. Future research could combine PESTLE with models like TAM or TPB to study alternative fuel adoption across various sectors.

To answer sub-question 5, following Roger's innovation-decision process, this study outlines the necessary steps for the EU to move from the persuasion stage to the decision, implementation, and confirmation stages. In the decision stage, the EU needs to make a firm commitment to e-NH3 adoption, providing financial support, and ensuring industry-wide training and stakeholder engagement. During the implementation, the EU should focus on executing the adoption process, developing specific regulations, promoting social acceptance, and funding pilot projects. Finally, in the confirmation stage, continuous R&D, performance evaluation, and assessing environmental and marine impact coupled with seeking international collaboration will be essential to confirm and sustain the adoption of e-NH3. Overall answering the main research question.

Although this study provides a comprehensive analysis of the PESTLE factors and offers strategic recommendations some limitations do arise, these include the number of experts consulted and its focus on direct influences. Future studies could further explore indirect influences and individual PESTLE groups to enhance the understanding and practical application of these findings.

In conclusion, although in its infancy phase, the adoption of e-NH3 into the EU's maritime fleet offers enormous potential for decarbonization. By systematically addressing the identified independent, moderate, and dependent PESTLE factors, the EU can lay a solid foundation for the success of e-NH3. This adoption not only aligns with the EU's environmental objectives but also promotes economic resilience and energy security. Through continued R&D, regulatory support, and international collaboration, e-NH3 can become an important fuel for a sustainable maritime sector in the EU and pave the way for cleaner global maritime shipping.

References

Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J. P., Johnson, K., Jung, H., Ntziachristos, L., Gagné, S., Takahashi, C., Karjalainen, P., Rönkkö, T., & Timonen, H. (2023). Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options. *Progress in Energy and Combustion Science*, 94, 101055. https://doi.org/10.1016/J.PECS.2022.101055

Abraham, E. J., Linke, P., Al-Rawashdeh, M., Rousseau, J., Burton, G., & Al-Mohannadi, D. M. (2024). Large-scale shipping of low-carbon fuels and carbon dioxide towards decarbonized energy systems: Perspectives and challenges. *International Journal of Hydrogen Energy*, 63, 217–230. https://doi.org/10.1016/J.IJHYDENE.2024.03.140

Al-Aboosi, F. Y., El-Halwagi, M. M., Moore, M., & Nielsen, R. B. (2021). Renewable ammonia as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, 31, 100670. https://doi.org/10.1016/J.COCHE.2021.100670

Amega, K., Moumouni, Y., Laré, Y., Bhandari, R., Takouda, P., & Madougou, S. (2024). Power system transformation in emerging countries: A SWOT/PESTLE analysis approach towards resiliency and reliability. *Heliyon*, 10(12), e33018. https://doi.org/10.1016/J.HELIYON.2024.E33018

Ayanwale, M. A., & Ndlovu, M. (2024). Investigating factors of students' behavioral intentions to adopt chatbot technologies in Higher Education: Perspective from Expanded Diffusion Theory of Innovation. *Computers in Human Behavior Reports*, 14, 100396. https://doi.org/10.1016/j.chbr.2024.100396

Balci, G., Phan, T. T. N., Surucu-Balci, E., & Iris, Ç. (2024). A roadmap to alternative fuels for decarbonising shipping: The case of green ammonia. *Research in Transportation Business & Management*, 53, 101100. https://doi.org/10.1016/J.RTBM.2024.101100

Chen, M., Jiang, S., Han, A., Yang, M., Tkalich, P., & Liu, M. (2024). Bunkering for change: Knowledge preparedness on the environmental aspect of ammonia as a marine fuel. *Science of The Total Environment*, 907, 167677. https://doi.org/10.1016/J.SCITOTENV.2023.167677

Chen, S., Zheng, S., & Sys, C. (2023). Policies focusing on market-based measures towards shipping decarbonization: Designs, impacts and avenues for future research. *Transport Policy*, 137, 109–124. https://doi.org/10.1016/j.tranpol.2023.04.006

Chiaramonti, D., & Goumas, T. (2019). Impacts on industrial-scale market deployment of advanced biofuels and recycled carbon fuels from the EU Renewable Energy Directive II. *Applied Energy*, 251, 113351. https://doi.org/10.1016/J.APENERGY.2019.113351

Chiong, M. C., Kang, H. S., Shaharuddin, N. M. R., Mat, S., Quen, L. K., Ten, K. H., & Ong, M. C. (2021). Challenges and opportunities of marine propulsion with alternative fuels. *Renewable and Sustainable Energy Reviews*, 149, 111397. https://doi.org/10.1016/J.RSER.2021.111397

Christodoulou, A., & Cullinane, K. (2022). Potential alternative fuel pathways for compliance with the 'FuelEU Maritime Initiative.' *Transportation Research Part D: Transport and Environment*, 112, 103492. https://doi.org/10.1016/j.trd.2022.103492

DNV. (2024, March). Key considerations for establishing a green shipping corridor. Retrieved June 16, 2024, from https://www.dnv.com/expert-story/maritime-impact/key-considerations-for-establishing-a-green-shipping-corridor/

EDF. (2021, November). Alternative fuels for shipping. Environmental Defense Fund. Retrieved June 16, 2024, from https://www.edfeurope.org/alternative-fuels-shipping

Egerer, J., Grimm, V., Niazmand, K., & Runge, P. (2023). The economics of global green ammonia trade – "Shipping Australian wind and sunshine to Germany." *Applied Energy*, 334, 120662. https://doi.org/10.1016/J.APENERGY.2023.120662

EMSA. (2024). *The EU Maritime profile – the maritime cluster in the EU*. Retrieved March 31, 2024, from https://www.emsa.europa.eu/eumaritimeprofile/section-2-the-eu-maritime-cluster.html#:~:text=possible%20safety%20implications.-,Ownership%20and%20age,by%20EU%20nationals%20or%20companies

EMSA. (2023). *Potential of NH3 as a fuel in shipping*. Retrieved March 31, 2024, from https://emsa.europa.eu/newsroom/latest-news/item/4833-potential-of-NH3-as-fuel-in-shipping.html

EU. (2023). *Reducing emissions from the shipping sector*. climate.ec.europa.eu. Retrieved March 31, 2024, from https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en

EU. (2024). *Mobility and Transport*. transport.ec.europa.eu. Retrieved March 31, 2024, from https://transport.ec.europa.eu/transport-modes/maritime_en

European Maritime Safety Agency (2022), Update on potential of biofuels in shipping, EMSA, Lisbon

European Ports align for green Maritime Future | European Alternative Fuels Observatory. (2024, June 10). https://alternative-fuels-observatory.ec.europa.eu/general-information/news/european-ports-align-green-maritime-future

Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Feasibility of green ammonia trading via pipelines and shipping: Cases of Europe, North Africa, and South America. *Journal of Cleaner Production*, 427, 139212. https://doi.org/10.1016/J.JCLEPRO.2023.139212

Govindan, S. (2024, April 15). Green Ammonia – an alternative fuel - FutureBridge. FutureBridge. https://www.futurebridge.com/industry/perspectives-energy/green-ammonia-an-alternative-fuel/

Hellström, M., Rabetino, R., Schwartz, H., Tsvetkova, A., & Haq, S. H. U. (2024). GHG emission reduction measures and alternative fuels in different shipping segments and time horizons – A Delphi study. *Marine Policy*, 160, 105997. https://doi.org/10.1016/J.MARPOL.2023.105997

IEA. (2023). International Shipping - IEA. Retrieved March 31, 2024, from https://www.iea.org/energy-system/transport/international-shipping

IMO. (n.d.). GreenVoyage2050. https://www.imo.org/en/OurWork/PartnershipsProjects/Pages/GreenVoyage2050.aspx

Inal, O. B., Zincir, B., & Deniz, C. (2022). Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. *International Journal of Hydrogen Energy*, 47(45), 19888–19900. https://doi.org/10.1016/J.IJHYDENE.2022.01.189

Juntunen, J. K., & Martiskainen, M. (2021). Improving understanding of energy autonomy: A systematic review. *Renewable and Sustainable Energy Reviews*, 141, 110797. https://doi.org/10.1016/J.RSER.2021.110797

Karvounis, P., Theotokatos, G., & Boulougouris, E. (2024). Environmental-economic sustainability of hydrogen and ammonia fuels for short sea shipping operations. *International Journal of Hydrogen Energy*, 57, 1070–1080. https://doi.org/10.1016/J.IJHYDENE.2024.01.058

Kim, S., Park, J., Heo, S., & Lee, J. H. (2024). Green hydrogen vs green ammonia: A hierarchical optimization-based integrated temporal approach for comparative techno-economic analysis of international supply chains. *Journal of Cleaner Production*, 465, 142750. https://doi.org/10.1016/J.JCLEPRO.2024.142750

Liu, H., Yi, W., Jalkanen, J.-P., Luo, Z., Majamäki, E., Matthias, V., Moldanová, J., Shi, Z., & He, K. (2024). Atmospheric impacts and regulation framework of shipping emissions: achievements, challenges and frontiers. *Fundamental Research*. https://doi.org/10.1016/J.FMRE.2024.02.013

LLoyd's Register. (2024, March). Fuel for thought – Ammonia | LR. Retrieved June 16, 2024, from https://www.lr.org/en/knowledge/fuel-for-thought/ammonia/

López, I., Goitia-Zabaleta, N., Milo, A., Gómez-Cornejo, J., Aranzabal, I., Gaztañaga, H., & Fernandez, E. (2024). European energy communities: Characteristics, trends, business models and legal framework. *Renewable and Sustainable Energy Reviews*, 197, 114403. https://doi.org/10.1016/J.RSER.2024.114403

Louvros, P., Trivyza, N. L., Komianos, A., & Boulougouris, E. (2023). Fuel cell, ammonia powered container ship: A case study. *Transportation Research Procedia*, 72, 2245–2252. https://doi.org/10.1016/J.TRPRO.2023.11.713

Machaj, K., Kupecki, J., Malecha, Z., Morawski, A. W., Skrzypkiewicz, M., Stanclik, M., & Chorowski, M. (2022). Ammonia as a potential marine fuel: A review. *Energy Strategy Reviews*, 44, 100926. https://doi.org/10.1016/J.ESR.2022.100926

Malmborg, F. von. (2023). Advocacy coalitions and policy change for decarbonisation of international maritime transport: The case of FuelEU maritime. *Maritime Transport Research*, 4, 100091. https://doi.org/10.1016/J.MARTRA.2023.100091

Marrero, Á., & Martínez-López, A. (2023). Decarbonization of Short Sea Shipping in European Union: Impact of market and goal based measures. *Journal of Cleaner Production*, 421, 138481. https://doi.org/10.1016/J.JCLEPRO.2023.138481

McKinlay, C. J., Turnock, S. R., & Hudson, D. A. (2021). Route to zero emission shipping: Hydrogen, ammonia or methanol? *International Journal of Hydrogen Energy*, 46(55), 28282–28297. https://doi.org/10.1016/J.IJHYDENE.2021.06.066

Melideo, D., & Desideri, U. (2024). The use of hydrogen as alternative fuel for ship propulsion: A case study of full and partial retrofitting of roll-on/roll-off vessels for short distance routes. *International Journal of Hydrogen Energy*, 50, 1045–1055. https://doi.org/10.1016/J.IJHYDENE.2023.10.142

Menzli, L. J., Smirani, L. K., Boulahia, J. A., & Hadjouni, M. (2022). Investigation of open educational resources adoption in higher education using Rogers' diffusion of innovation theory. *Heliyon*, 8(7), e09885. https://doi.org/10.1016/J.HELIYON.2022.E09885

Münter, M. T. (2024). Pestle-Analysis. Reference Module in Social Sciences. https://doi.org/10.1016/B978-0-443-13701-3.00200-0

Rogers, E. M. (1962). *Diffusion of innovations*. Free Press.

Rony, Z. I., Mofijur, M., Hasan, M., Rasul, M., Jahirul, M., Ahmed, S. F., Kalam, M. A., Badruddin, I. A., Khan, T. M. Y., & Show, P. (2023). Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. *Fuel*, 338, 127220. https://doi.org/10.1016/j.fuel.2022.127220

Sánchez, A., Martín Rengel, M. A., & Martín, M. (2023). A zero CO2 emissions large ship fuelled by an ammonia-hydrogen blend: Reaching the decarbonisation goals. *Energy*

Conversion and Management, 293, 117497. https://doi.org/10.1016/J.ENCONMAN.2023.117497

Smith, J. R., & Mastorakos, E. (2023). A Systems-Level Study of Ammonia and Hydrogen for Maritime Transport. *Maritime Transport Research*, 5, 100099. https://doi.org/10.1016/J.MARTRA.2023.100099

T&E. (2022). FuelEU Maritime: T&E analysis and Recommendations. How to drive the uptake of sustainable fuels in shipping. In transportenvironment.org. Retrieved March 31, 2024, from https://www.transportenvironment.org/wp-content/uploads/2022/02/TE-Report-FuelEU-Maritime-1.pdf

T&E. (2024). *Shipping emissions: Latest data - Transport & Environment*. Transport & Environment. Retrieved March 31, 2024, from https://www.transportenvironment.org/challenges/ships/european-shipping-emissions-2022/

Tomos, B. A. D., Stamford, L., Welfle, A., & Larkin, A. (2024). Decarbonising international shipping – A life cycle perspective on alternative fuel options. *Energy Conversion and Management*, 299, 117848. https://doi.org/10.1016/J.ENCONMAN.2023.117848

Tsvetkova, A., Hellström, M., Schwartz, H. G., Rabetino, R., & Syed, H. H. (2024). A transition towards clean propulsion in shipping: The role of PESTLE drivers and implications for policy. *Marine Policy*, 161, 106002. https://doi.org/10.1016/j.marpol.2023.106002

UNCTAD. (2023). Review of Maritime Transport 2023. In unctad.org. Retrieved March 31, 2024, from https://unctad.org/publication/review-maritime-transport-2023

van Leeuwen, J., & Monios, J. (2022). Decarbonisation of the shipping sector – Time to ban fossil fuels? *Marine Policy*, 146, 105310. https://doi.org/10.1016/J.MARPOL.2022.105310

Von Malmborg, F. (2023). Advocacy coalitions and policy change for decarbonisation of international maritime transport: The case of FuelEU maritime. *Maritime Transport Research*, 4, 100091. https://doi.org/10.1016/j.martra.2023.100091

Wang, H., Daoutidis, P., & Zhang, Q. (2023). Ammonia-based green corridors for sustainable maritime transportation. *Digital Chemical Engineering*, 6, 100082. https://doi.org/10.1016/J.DCHE.2022.100082

Wang, Z., Dong, B., Yin, J., Li, M., Ji, Y., & Han, F. (2024). Towards a marine green power system architecture: Integrating hydrogen and ammonia as zero-carbon fuels for sustainable shipping. *International Journal of Hydrogen Energy*, 50, 1069–1087. https://doi.org/10.1016/J.IJHYDENE.2023.10.207

Wu, J., Liu, J., & Li, N. (2024). The evasion strategy options for competitive ocean carriers under the EU ETS. *Transportation Research Part E: Logistics and Transportation Review*, 183, 103439. https://doi.org/10.1016/J.TRE.2024.103439

Ye, M., Sharp, P., Brandon, N., & Kucernak, A. (2022). System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping. *International Journal of Hydrogen Energy*, 47(13), 8565–8584. https://doi.org/10.1016/J.IJHYDENE.2021.12.164

Zhou, F., Yuan, T., Li, Z., Mu, X., & Lv, Y. (2024). The evidence-based practice teaching competence of clinical preceptors at different stages of innovation-decision process: A cross-sectional survey in traditional Chinese medicine hospitals. *Nurse Education Today*, 132, 106027. https://doi.org/10.1016/J.NEDT.2023.106027

Zincir, B. (2022). Environmental and economic evaluation of ammonia as a fuel for short-sea shipping: A case study. *International Journal of Hydrogen Energy*, 47(41), 18148–18168. https://doi.org/10.1016/J.IJHYDENE.2022.03.281

MICMAC Matrix

	1 : POL1	2 : POL2	3 : POL3	4 : POL4	5 : ECO1	6 : ECO2	7 : ECO3	8 : ECO4	9 : SOC1	10 : SOC2	11 : SOC3	12 : SOC4	13 : TEC1	14 : TEC2	15 : TEC3	16 : TEC4	17 : TEC5	18 : LEG1	19 : LEG2	20 : LEG3	21 : LEG4	22 : LEG5	23 : ENV1	24 : ENV2	25 : ENV3	26 : ENV4
1 : POL1	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2 : POL2	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3 : POL3	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4 : POL4	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5 : ECO1	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6 : ECO2	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
7 : ECO3	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8 : ECO4	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9 : SOC1	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
10 : SOC2	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
11 : SOC3	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
12 : SOC4	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3
13 : TEC1	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3
14 : TEC2	3	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3
15 : TEC3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3	3
16 : TEC4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3	3	3	3
17 : TEC5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
18 : LEG1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2
19 : LEG2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3	3	3
20 : LEG3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2
21 : LEG4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
22 : LEG5	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2
23 : ENV1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3
24 : ENV2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2
25 : ENV3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
26 : ENV4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Appendix A

Interview Questionnaire

Political Factors:

1. Are there any political challenges or barriers that need to be addressed for widespread adoption?

Economic Factors:

2. What are the economic implications of switching to ammonia as a fuel for maritime vessels?
3. How do the costs of ammonia production and infrastructure development compare to traditional maritime fuels?
4. Are there potential economic benefits or incentives for companies to invest in ammonia adoption?

Social Factors:

5. How do societal attitudes and perceptions towards environmental sustainability impact the acceptance of ammonia as a maritime fuel?
6. What are the potential social benefits or concerns associated with the use of ammonia in maritime transportation?
7. Are there any social challenges related to workforce training or public acceptance that need to be considered?

Technological Factors:

8. What technological advancements are necessary to facilitate the widespread adoption of ammonia in the maritime fleet?
9. Are there any technical challenges or limitations that need to be addressed in terms of ammonia production, storage, or engine compatibility?

Legal Factors:

10. What legal frameworks or regulations govern the use of ammonia as a maritime fuel in the EU?
11. Are there any legal barriers or uncertainties that need to be resolved for successful adoption?

Environmental Factors:

12. What are the environmental benefits of using ammonia as a fuel in the maritime industry?
13. How does the adoption of ammonia contribute to reducing greenhouse gas emissions and improving air quality?
14. Are there any environmental challenges or risks associated with the production, transportation, or use of ammonia in maritime applications?

Appendix B

Snapshot of the codebook. All transcribed interviews can be found here.

Theme	Code	e-NH3 Expert 1
Environmental Factors	CO2 Emissions Reduction Potential	"the biggest benefit for nature for the environment is that there is no new CO2 emitted in the air, that's the primary reason why you would want to move away from fossil fuels that no additional CO2 enters the air. Then if you look at ammonia versus other carriers, I mean, ammonia, it's not a carbon carrier. So if you if you burn ammonia, or if you use a stack for ammonia, it's not gonna emit carbon into the air. "
	NOx Emissions	"It's only gonna emit Nitrogen, NOxs and water" "there were the main technical challenges or limitations you see of using ammonia on ships right now. e-NH3 expert 1: Emissions. So we don't know exactly how much at least I don't know, maybe someone else deals. How much ammonia how much NOx is are emitted when you burn ammonia, especially when you burn it like so it's more on NOx is that people are that your people are worried about now, because they haven't been using it long, long term" "It's the NOxs that we are worried about. So that's definitely one limitation does. How much does it emit? And liters? Yes, yes, because it's a really toxic, flammable, flammable or combustible but it's just shit. Yes. You don't want it? It probably smells really bad to expose to the environment"
	Ocean Impact	
	Other emissiosn and environmental impact (Sulfur)	"So then there's carbon in the molecule with atom LOHCS. You have a organic carrier, which if it leaks or if it spills or if something goes wrong, you have carbon in the air. And with ammonia, you can capture the NOxs or you can even dilute it. So it's, I think, for the environment, it's just better to move away from the crude oil use now. Basically, anything else? Yes, that I prefer. "
Technical Factors	Transporation, handling & Storage	
	Port & Bunkering Infrastructure	"Well, first you need infrastructure. You need a place to ship to bunker, you need good bunkering equipment, you need storage tanks, which are going to be significantly larger than we currently have"
	Production & Supply chain infrastructure	". And then when we didn't even start talking about the transportation of large quantities of ammonia from the production place. " ": So you're going to transport that from those places to the port of Rotterdam, which is the second largest bunkering place in the world? How is that gonna go out? How are we going to make sure that that's going to be safe? So you need transportation ships? Those ships are going to need to run on ammonia as well and can they be directly fed from their feeder tank or is that going to be some other system so that's, again, if you look at the entire supply chain of just using ammonia for maritime use, it's already that big. That if you want to add another part, say transported to Germany, this much more. So I'd say to have ammonia as a maritime fuel. You already need like 70% of the entire ammonia value chain, maybe 80. " ". So we need new infrastructure, which needs to go through safety with safety regulations set by a national and international
	Ship & Engine Compatability	"Yes. So that's only on the board side, but it's for the ship, you need adequate motors? Yeah. Are those going to be like traditional motors where you fire the ammonia? Or are they going to be stacks where we do the same with hydrogen? Like the cells? Yeah, like cells. So if you turn hydrogen back into energy, you basically do the reverse of electrolysis." "With that work, you do the reverse process. So you add oxygen, and it's a controlled burning process. And the thing you can do with ammonia probably? Is that going to be the solution? But then you need several megawatts of stacks, which will take space on the ship as well, I think. Exactly. So, you know, we don't know which technology is going to be more efficient. We have some assumptions. But I know that some organizations are working on this you CMBD tech. Check in there's also man energy, man energy as well. Yara, the Norwegian company, I did see them as well. Two ships running now. So I think we're at that point in evasion" "So I think we're at that stage where we don't know what the engine is going to be like, we just know that there's going to be a ammonia powered engine." "So no, I'm completely with you. And I believe they already do" "CMBD technology Antwerp" "So there's already so much that needs to happen, and storage in the ship as well. " "But it's not too long you can use in the normal combustion ICEs. Right. And the internal combustion semi semi makes it a bit but it's still
	Fuel Performance	
Social Factors	Expertise & training	"So in that way, it might be a good thing, in a way, in a way yeah, of course, it's a health hazard for anyone working with it. So we need highly, highly qualified personnel. But that's, again, with any, any substance that's going to be used as a fuel being used as fuel."
	Health & Safety	"That from ammonia, we know the effects because we already use it for 100 years. That's true" "I think it's over prudence. Okay. We are more aware now than ever about environmental impacts about social impacts of a leak, for example. So we are more prudent than we were, and risks that we're fine with natural gas or with, with the kerosene line going from Rotterdam to schedules. Now, we are more careful, and we have to consider everything. And there are a stakeholder groups for everything. I'm not saying that's a bad thing, it's a good thing that people aren't getting involved them and that we are considering environmental impact" "I'm paraphrasing right now, and I hope I've been doing it right, because I was telling you that day they said, ammonia has such a strong smell that before you can even get hurt. It's not so bad, you're just gonna abandon ship or take safety regulations" "So in that way, it might be a good thing, in a way, in a way yeah, of course, it's a health hazard for anyone working with it. So we need highly, highly qualified personnel. But that's, again, with any, any substance that's going to be used as a fuel being used as fuel."
	Market/Stakeholder Support	"No, industry wants it. Industry is fine with it. Basically, ask anyone in the industry and they'll say the same, we love ammonia, and we're gonna use it."
	Social Acceptance	"But if you ask anyone in the public, yeah, two or three years ago, people were scared of hydrogen, there was this flammable substance, and you know, we wouldn't go near it. Now, people are crying out loud, oh, I wanted hydrogen car, which is nuts. But you know, it shows the development of that hydrogen had to go through. And the same is with ammonia. Now, people think it's very toxic, even more toxic than it actually is. There are misconceptions about its use about the dangers of leakage now. So I think the societal part may be pivotal in the eventual success of Yes, ammonia in the maritime sector."
Economic Factors	Capital Expenditure	"capex? That's the shitty part. Yeah, you need to have the big money in the start for the shipping industry"
	Cost of e-NH3	"But if you look at the OPEX, if you have a good ammonia value chain, yeah, in which you you import very cheap ammonia from from again" "So if you have a more bigger, better bargaining position, you know, the supply of ammonia is also going to be cheaper. Yes. So in that sense, I think the OPEX of running ammonia is going to be lower. But that's only true when the cost of ammonia actually falls"
	Capital Expenditure	"It is going to cost a heap of money" The infrastructure will be one of the highest amount to spend" "Obviously, building big stuff cost big money. " "So like pipelines and like transport ship, stuff like that. Yeah. All of that. Exactly. But it's not. Like I said, if you want ammonia for maritime infrastructure, you're going to build about 80% of the of the needed value chain for every use of ammonia. So it's not just for the ships, you're saying need to go for everything. Exactly. Once you build it, it's not just going to be for the ships. It's going to be for Shell, for example, who are very interested in using ammonia and hydrogen carrier instead of natural gas. So they are also going to invest, so you're spreading costs already. German coal centers are going to use first coal fired and then I believe, solely fired ammonia plants." "Don't tie me down on that one. But we expect there's going to be about 7 million tonnes of ammonia going that way. Well, all of that is infrastructure which you also need for
	Cost of e-NH3	"Yes. So in that sense, I think the OPEX of running ammonia is going to be lower. But that's only true when the cost of ammonia actually falls" "Yes. So in that sense, I think the OPEX of running ammonia is going to be lower. But that's only true when the cost of ammonia actually falls" "(if you source it from a country with which you have better ties or keep it within the EU"
	R&D cost	"Will cost a lot to get the optimal design, we still don't know if it is more efficient to use stacks or engine"
	Retrofitting & New Ship Production cost	"It will cost to retrofit and for new fleet entirely" "Like, you're gonna have to retrofit a ship or you're gonna have to build a new Ship entirely. So for when you're renewing your fleet, when ships are obsolete, and you're going to build a new ship anyway, that's going to be a problem and existing ships, those are going to be a problem ""
Political	Energy Autonomy	"Algeria, Spain, I don't care. That's also the thing. It's, it's safe in a sense that you're not depending on oil states." "we can import ammonia from the UK, we can do the same from Canada, we can do the same from Spain. Those are way more stable countries than a Saudi Arabia. So if you have a more bigger, better bargaining position, you know, the supply of ammonia is also going to be cheaper. Yes. So in that sense, I think the OPEX of running ammonia is going to be lower. But that's only true when the cost of ammonia actually falls" "(if you source it from a country with which you have better ties or keep it within the EU"
	Dependence on Nations with high renewable energy	"where? Because the place where ammonia is probably going to be produced. That's gonna be Senegal, Nigeria. High solar energy places, right? HIGH WIND infrastructure. Yes."
	Green Shipping Corridors	
	EU National Level Volatility	
Legal	ETS	
	Ammonia Specific Legislation	"I know that the PGS 12 is being revised that's on storage and transfer of ammonia. So there is some there's not some legislation in place. There's a lot of legislation, but nothing specifically catering to ammonia. Correct. It's just general. There is there is the PGS as they are for dangerous materials. I think materials not even okay, but I guess like for example, like that would just be for general, all the dangerous " ": So there's a lot of when I think of legislation right now, because we're working on a safety project. It's only on safety. " "Which works a bit towards that. Yeah, the problem is, we don't know if ammonia is going to be the big thing because there's also methanol and the hello LOHCs. The government doesn't want to go on the market yet. So there is no legislation which is promoting the use of ammonia. Only since January, are we actually seeing some upward trend, positive trend towards the use of ammonia from legislators so we're still very much in government with them like a it's a great alternative. Please consider it don't just shut it down like you're doing right now. And that's why we started the platform because industry was calling out to the government we need ammonia. And the government said Alright, come with the facts and show us why." "But if we talk about barriers, that safety legislation is a barrier, but it's a necessary one. So you will need to develop one specifically for ammonia or Yeah,yeah, especially for the large volumes that we're going to transport it in. Now. Because we calculate it if you want to transport 7 million tonnes a year, which we think is going to happen in 2042. Germany, you're going to have to have 100 trains a day, with 47 quarts, or pulling ammonia"
	IMO Specific Regulations	
	Renewable Energy Directive	
Recommendations	Recommendations	"We need Fair Trading deals on the trade of ammonia, maybe ammonia needs to be exempt in import taxes, which is part of that economy part already. But also like, so. It's all it's all one really. " "And I'm gonna get very political, my eyes, the Dutch government has a responsibility to ensure that there's going to be economic activity in the Netherlands. So yeah, in my eyes, the Dutch government at least should cover 30% 40% of this infrastructure, because they are also going to be the ones responsible if something goes wrong" "It need to get on to the agenda in a positive away, it needs to get the factual attention that it gets without the worrying about the fear mongering going on by lobbying organizations. It is a slightly more dirty, but really more economic and efficient way to make steps with this energy transition. Yeah I think that's the issue. We need to take it more seriously and be more open to it instead of pushing it away. " ""They are going to be the ones benefiting from the tax revenues as well. So and it's to make the amendments, the more attractive lending position for organizations as well. So in my eyes, the government at least has to cover a big part of it. Then another part is going to come from a shell really like to have this infrastructure. They have the revenue to invest." "Kohler industries, going to invest in things like terminals. Need for transferring ammonia, private companies will invest in the things that come along, but the main infrastructure itself should come from governments. I think the government should support them with subsidies to nudge them into the right direction, but the basic infrastructure should come from the government""

Appendix C

Consent Form for Interview Participation

Title of Research Study: Exploring Factors Influencing the Adoption of Ammonia as a Maritime Fuel

Principal Investigator: Zamin Syed

I, [Interviewee's Name], have been invited to participate in a research study titled "Analyzing the PESTLE Factors influencing the adoption of green ammonia as an alternate fuel for the EU's maritime sector." The purpose of this study is to investigate the various factors influencing the adoption of ammonia as a sustainable fuel in the maritime industry.

Study Procedures: As a participant in this study, I understand that I will be interviewed about my perspectives, experiences, and opinions related to the adoption of ammonia as a maritime fuel. The interview may be conducted in person, over the phone, or via video conferencing, and it is expected to last approximately 15-20 minutes.

Confidentiality: I understand that all information collected during the interview will be kept strictly confidential. Any personal identifiers will be removed from transcripts, and my identity will remain anonymous in any reports or publications resulting from the study.

Voluntary Participation: My participation in this research study is entirely voluntary, and I have the right to withdraw at any time without penalty. I understand that my decision to participate or withdraw will not affect any relationships or services I have with the researcher or affiliated institutions.

Benefits and Risks: There are no direct benefits or risks associated with participating in this study. However, by sharing my insights and experiences, I may contribute to a better understanding of the factors influencing the adoption of ammonia as a maritime fuel, which could potentially inform future industry practices and policies and contribute to the theoretical understanding of the diffusion of ammonia in the EU's maritime fleet.

Contact Information:

If I have any questions or concerns about the research study, I may contact the principal investigator, Zamin Syed at z.syed@student.utwente.nl.

Consent: I have read and understood the information provided in this consent form, and I voluntarily consent to participate in the research study described above.

Participant's Signature: ________________________

Date: ________________________