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Fueling the future: A techno-economic evaluation of e-ammonia production for marine applications

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It is noted that the authors bear sole responsibility for any errors, omissions, opinions, and interpretations presented herein.

Abstract

This paper examines the viability of green ammonia (NH3) as a marine fuel in the transition to decarbonized shipping. While there is no singular solution for achieving decarbonization, there is increasing recognition on the pivotal role of green ammonia in decarbonizing the shipping sector. The research employs a comprehensive model to estimate production, storage, and distribution costs for 2030 and 2050, focusing on regions with competitive photovoltaic and wind power generation. Key findings indicate that while the Levelized Cost of Electricity (LCOE) is a crucial factor, the high costs associated with green ammonia are likely to persist, even with anticipated cost reductions by 2030. Factors such as technological innovations and economies of scale may contribute to cost declines, yet significant reductions are contingent on supportive government policies. By 2050, costs are expected to remain elevated, emphasizing the necessity of policy support for economic feasibility. Ultimately, enhancing the economic viability of green ammonia requires a multifaceted approach, including financial incentives, regulatory frameworks, and technological advancements. The paper underscores that a diverse array of alternative fuels, including green ammonia, is essential to meet the energy demands of the maritime industry, advocating for a flexible, multi-fuel strategy to address the challenges of decarbonization of the shipping sector.

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Introduction

As a key component of global trade, maritime shipping transports more than 80% of the world's goods, making it indispensable for economic and trade activity, but also a significant emitter of CO2 and other harmful pollutants responsible for around 2-3% of global greenhouse gas (GHG) emissions (Armijo and Philibert 2020; Castellanos, Sloan, and Roesch 2021; Pape 2020). Notably, the global maritime fleet, which consisted of 92,251 vessels in 2018, has been growing at an average annual rate of 2.49% (StartUs Insights 2024; Castellanos, Sloan, and Roesch 2021). This fleet includes various types of ships such as large ships and very large ships, such as tankers, bulk carriers, and container ships, being particularly significant in terms of cargo transport and fuel consumption. These large vessels, although they make up only about 20% of the fleet, are responsible for approximately 85% of GHG emissions from international shipping (Castellanos, Sloan, and Roesch 2021).

As of 2023, the dominant fuels in the shipping industry included heavy fuel oil (HFO), marine gas oil (MGO), and very low-sulfur fuel oil (VLSFO). Together, HFO and MGO comprised 63.1% and 36.9% of the global shipping fuel supply, respectively (Placek 2023). While HFO has traditionally been the fuel of choice, its high sulfur content (3.5%) rendered it non-compliant with the International Maritime Organization's (IMO) global sulfur cap implemented in 2020. This regulation, which mandates stricter limits on sulfur oxide (SOx) emissions, has forced ship owners to seek alternative fuels or use HSFO and install scrubbers (Castellanos, Sloan, and Roesch 2021; Pape 2020; Alfa Laval et al. 2020). Also, recent international policies, mainly the IMO's 2018 strategy to cut shipping emissions by at least 50% by 2050 compared to 2008 levels, reflect the urgency of adopting low-carbon solutions (IMO 2018).

Green ammonia emerges as a potential fuel in this landscape. Produced from renewable energy through the electrolysis of water to generate green hydrogen, which is then combined with nitrogen, green ammonia could offer a low carbon pathway for decarbonizing maritime transportation (Castellanos, Sloan, and Roesch 2021; Pape 2020). Importantly, green ammonia benefits from an existing global distribution network, as ammonia is one of the widely produced chemicals (Castellanos, Sloan, and Roesch 2021). This infrastructure advantage, combined with its potential use as a direct fuel in internal combustion engines or fuel cells, makes it an option for the shipping industry (Castellanos, Sloan, and Roesch 2021). As the use of green ammonia grows in sectors such as shipping and fertilizer production expands, technological advancements and accumulated experience are expected to drive cost reductions, particularly in green hydrogen production (Cesaro et al. 2020).

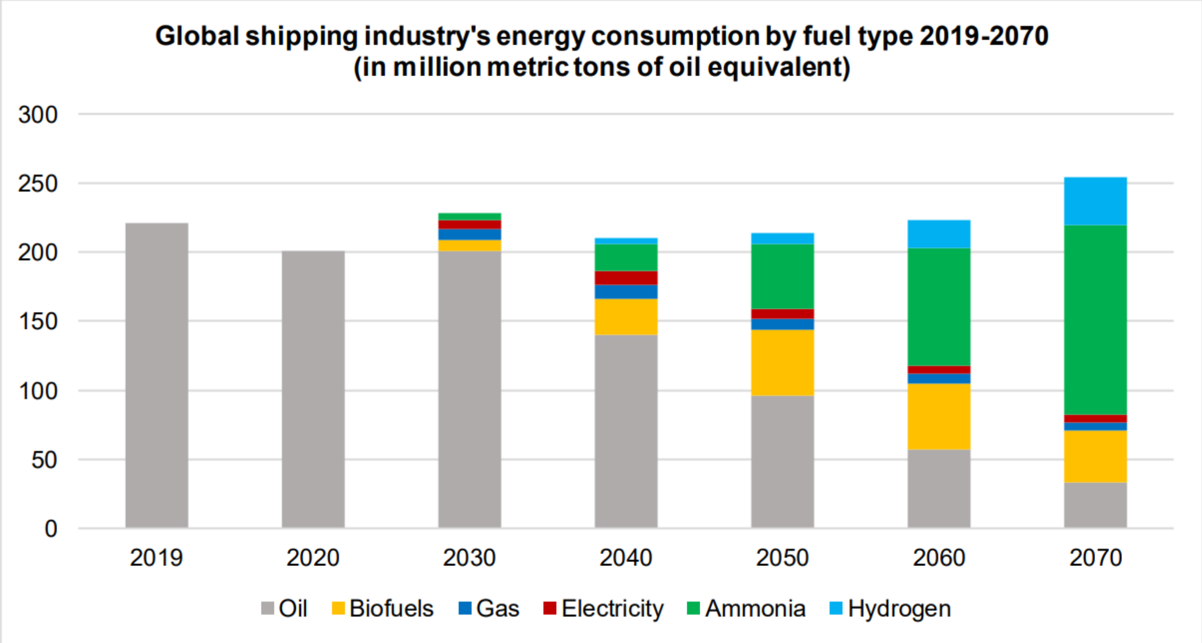
Despite its benefits, the widespread adoption of green ammonia faces significant challenges, including high production costs and the need for supportive policy frameworks. This raises crucial questions: How feasible is the implementation of green ammonia for decarbonizing the shipping sector? Under what conditions can it compete effectively with traditional maritime fuels?

This paper seeks to explore these critical factors in-depth, analyzing the feasibility, sustainability, and economic competitiveness of green ammonia in the maritime sector, with particular attention to the role of location, hydrogen production costs, and the importance of robust policy support. This paper offers a distinct contribution by not only by analyzing and providing a model-based assessment of green ammonia production costs across various regions, considering both photovoltaic (PV) and wind technologies, but also by incorporating potential technological advancements. Furthermore, it projects costs through to 2050 and evaluates multiple scenarios to present a more realistic analysis of green ammonia production. In addition, the paper includes a sensitivity analysis that highlights the role of policy and examines how it can influence ammonia production costs.

1. Potential alternative fuels for the shipping industry

The choice of fuel for shipping depends on factors such as supply availability, engine technology, environmental performance, and economic viability (Pape 2020; Castellanos, Sloan, and Roesch 2021). It also involves optimizing the use of key geographical locations that can support the transition to low-carbon fuels. This includes major trading ports and fuel supply points, as well as important navigation routes and choke points. Bunkering, the storage and resupply of fuel to ships, is a crucial aspect of port infrastructure[1]. Stakeholders in these areas are crucial in monitoring compliance with energy efficiency mandates and enabling access to renewable bunkering fuels. Investing in these strategic locations will be essential in the coming years (Castellanos, Sloan, and Roesch 2021; Alfa Laval et al. 2020; Pape 2020).

Figure 1: Global shipping industry's energy consumption by fuel type for the years 2019 and 2020, with projections extending through 2070 in million metric tons of oil equivalent.



Source: Scenario (Statista 2023), Author's own illustration.

Moreover, production costs and the availability of renewable fuels, as well as the technological readiness and availability of machinery capable of utilizing these fuels will likely be critical in shaping the future of fuel and propulsion technologies (Castellanos, Sloan, and Roesch 2021; Pape 2020). To comply with IMO regulations, shipowners are exploring alternative fuels such as low-sulfur fuels, biofuels, and hydrogen-based fuels. Figure 1 illustrates the global shipping industry's energy consumption by fuel type for 2019 and 2020, along with projections extending through 2070, measured in million metric tons of oil equivalent. According to Statista (2023), it is projected that oil derived fuels will remain dominant in the shipping industry until 2050. However, the energy mix is expected to diversify significantly, with alternative fuels comprising approximately half of the industry's total energy consumption. By 2070, ammonia is anticipated to become the primary energy source for powering ships.

Each fuel comes with its own challenges, such as lower energy content per volume (compared to traditional oil-based fuels) which requires larger fuel tanks and specific safety measures for onboard storage and use (Pape 2020; Castellanos, Sloan, and Roesch 2021; Armijo and Philibert 2020). This section will explore these alternative fuels, assessing their advantages, disadvantages, and overall feasibility for the shipping industry.

(a) Low-sulfur fuels

To comply with low sulfur limits, ships can either continue using high-sulfur heavy fuel oil (HFO) with the addition of exhaust gas cleaning systems such as scrubbers, or switch to low-sulfur fuels, which tend to be more costly (Pape 2020). The adoption of scrubbers gained significant traction as a cost-effective

[1] The ports with the highest bunkering capacity globally are Singapore, Fujairah (United Arab Emirates), and Rotterdam (Netherlands), with Rotterdam being the largest bunkering port in Europe (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021).

solution to comply with the IMO 2020 sulfur regulations. However, both methods lead to increased well-to-wake CO2 emissions, with scrubbers generally resulting in a smaller increase (Pape 2020).

Liquefied natural gas (LNG) has garnered significant interest in recent years as a potential alternative fuel for shipping. However, opinions on its efficacy are divided between industry stakeholders and environmental organizations (Pape 2020). Environmental groups argue that LNG's benefits are limited, potentially reducing GHG by only 6-10% (Pape 2020, Alfa Laval et al. 2020). The International Council on Clean Transportation (ICCT) suggests that LNG offers no substantial climate advantages regardless of the engine technology used (Pape 2020). On the other hand, industry advocates view LNG as the cleanest available fossil fuel, supported by existing infrastructure. While it may not drastically cut shipping's carbon footprint, it can enhance air quality in ports and reduce shipping's environmental and health impacts[2] (Pape 2020; Castellanos, Sloan, and Roesch 2021). According to this view, gas engines and LNG distribution systems could be used at a later stage with other alternative fuels having similar material properties as LNG such as both LBG (Bio-LNG) and liquefied synthetic methane (from Power-To-Gas process) (Ryste 2019; Pape 2020).

LNG bunkering facilities have significantly increased, with nearly 200 ports worldwide now equipped, especially in Europe and Asia. These regions have the highest concentration of such infrastructure. However, further expansion poses challenges due to the need to store LNG at cryogenic temperatures, which requires extensive modifications to existing infrastructure (Castellanos, Sloan, and Roesch 2021; Mandra 2023). Additionally, LNG engines currently experience a methane slip of 2% to 5%, which has a global warming potential (GWP[3]) 56 times higher than CO2 over a 20-year period (Castellanos, Sloan, and Roesch 2021; Swanson et al. 2020; NABU 2016). Economically, LNG is highly susceptible to market price fluctuations, as evidenced by the recent surge in natural gas prices affecting many countries, particularly in Europe (Pape 2020).

Another option is liquefied petroleum gas (LPG), which has a relatively low energy cost similar to LNG and low capital costs, making it economically attractive. However, its adoption is limited by a lack of operational experience and insufficient bunkering infrastructure. Additionally, LPG's environmental performance is poor when produced from fossil sources (Ryste 2019). Table 1 in Appendix I.1 provides an overview of low-sulfur fuels.

(b) Biofuels

Biofuels present a potential option for decarbonizing the shipping industry. Advanced biofuels can be integrated into the existing fuel supply chain, with current regulations allowing for blends of up to 20% without requiring engine modifications, and tests have shown that blends up to 30% are feasible (Castellanos, Sloan, and Roesch 2021). The production costs of advanced biofuels are comparable to other alternatives, ranging from $72 to $238 per MWh (Castellanos, Sloan, and Roesch 2021).

Two approaches can be taken with liquid biofuels: blending first-generation biofuels with existing fossil fuels or using second-generation biofuels as a replacement. First-generation biofuels[4] can cause sustainability issues (Castellanos, Sloan, and Roesch 2021; Nayak et al. 2010). Second-generation biofuels[5], on the other hand, offer significant GHG reductions, ranging from 70% to 100% compared to marine gas oil (MGO). The most viable second-generation biofuels include FAME (Fatty Acid Methyl Ester) biodiesel, HVO (Hydrotreated Vegetable Oil), Fischer-Tropsch (FT) diesel, dimethyl ether (DME), and bio-methanol (Castellanos, Sloan, and Roesch 2021; Nayak et al. 2010). Although other production methods using different feedstocks are possible, they are not yet mature. The shipping sector also faces

[2] Health impact of using conventional bunker fuels include premature mortality and cardiovascular and respiratory hospital admissions, from long-term exposure to shipping emissions (Castellanos, Sloan, and Roesch 2021)

[3] GWP: The Global Warming Potential (GWP) is a metric designed to compare the global warming impacts of different gases. It quantifies how much energy the emissions of 1 ton of a particular gas will absorb over a specified time period. relative to the absorption by 1 ton of carbon dioxide (CO2) (Castellanos, Sloan, and Roesch 2021)

[4] First generation (1G) biofuels are primarily produced from foods crops such as grains, sugar cane and vegetable oils

[5] Second-generation (2G) biofuels are derived from cellulosic energy crops like miscanthus and short rotation coppice (SRC) willow, as well as agricultural and forestry residues or co-products, including wheat straw and woody biomass.

competition for these feedstocks from other industries, including road transport and aviation (Castellanos, Sloan, and Roesch 2021; European Union 2023).

From a technological readiness standpoint, FAME biodiesel can be used in blends up to 20% without engine modifications, although additives are needed to prevent bacterial growth. HVO can also be used as a drop-in marine fuel or in blends without any modifications to the engine or fuel system (Castellanos, Sloan, and Roesch 2021). FT diesel, made from lignocellulosic biomass, and DME, produced through gasification or biomethane reforming, are also promising, though they require more development before widespread use (Castellanos, Sloan, and Roesch 2021).

Biomethane, produced through anaerobic digestion, is another potential biofuel. It has high technological maturity and can serve as a substitute for LNG. However, its scalability and logistical challenges limit its role in shipping. The production costs of biomethane vary widely, depending on feedstock availability and market prices, ranging from $25 to $176 per MWh (Castellanos, Sloan, and Roesch 2021).

In summary, scaling up production and ensuring the sustainability of feedstocks remain critical challenges that need to be addressed to realize the full potential of biofuels in decarbonizing shipping (Castellanos, Sloan, and Roesch 2021; Foretich et al. 2021; Hughes 2021). Table 2 in Appendix I.2. provides a comparative overview of these fuels.

(c) Hydrogen-based fuels

Hydrogen-based fuels are increasingly being recognized as a viable option for decarbonizing the maritime sector. These electrofuels, which include hydrogen, e-ammonia, e-methanol, e-methane, and Fischer–Tropsch liquid fuels such as e-diesel, hold potential for sectors that are challenging to decarbonize, such as shipping (Pape 2020; Castellanos, Sloan, and Roesch 2021).

The direct use of green hydrogen (H2) via fuel cells (FCs) and internal combustion engines (ICEs) could be suitable for short sailings and domestic navigation, which benefit from frequent port calls and stringent environmental regulations (Castellanos, Sloan, and Roesch 2021; Pape 2020; Alfa Laval et al. 2020). For instance, Norway is making strides by electrifying its ferry sector and developing hydrogen-powered ferries and cruise ships (Castellanos, Sloan, and Roesch 2021; Ryste 2019). Despite expected future competitive costs, using hydrogen as a fuel would necessitate a complete retrofit of ship fuel and engine systems, making its use as a drop-in fuel unfeasible. Nonetheless, some researchers anticipate that hydrogen will play a significant role in the maritime sector, primarily through indirect use, which facilitates the development of renewable fuels from green hydrogen.

One potential hydrogen derivative is e-methanol. Methanol has a low carbon content and high hydrogen content compared to other fuels, and it can significantly reduce emissions of sulfur oxides (SOx) and nitrogen oxides (NOx) by up to 60% and particulate matter by 95% compared to heavy fuel oil (HFO) (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021; Pape 2020). However, conventional methanol manufacturing processes, which includes steam reforming from natural gas, are not conducive to e-methanol production. The industry's dependence on this method, fueled by burning additional natural gas, presents a hurdle in transitioning to more sustainable production methods. The entire infrastructure, encompassing production, storage, and distribution, must be therefore established to facilitate the widespread use of synthetic methanol in shipping (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021; Pape 2020).

Synthetic methane, or e-methane, is another potential renewable fuel for shipping, benefiting from established processes and standards due to its similarity to LNG (Castellanos, Sloan, and Roesch 2021). However, its widespread adoption is challenged by the need for rapid construction of large-scale methane plants and the expansion of port infrastructure. Additionally, unburned methane is a potent GHG, necessitating meticulous measures to prevent accidental releases (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021; Pape 2020).

Liquid e-fuels, such as e-diesel and e-kerosene, also offer potential for the shipping sector. These fuels are compatible with existing combustion engines and infrastructure, providing lower infrastructure costs and enhanced scalability compared to other e-fuels (Castellanos, Sloan, and Roesch 2021; Pape 2020). However, they face challenges related to the high demand for renewable electricity for hydrogen production and lower energy efficiency due to the additional step of combining hydrogen with carbon (Castellanos, Sloan, and Roesch 2021; Pape 2020).[6]

E-ammonia has been extensively studied due to its carbon-free synthesis, which is beneficial given the limited availability of biogenic carbon sources and the high costs of extracting carbon from the air (Campion et al. 2023). Ammonia requires less cryogenic storage compared to hydrogen and is more energy-dense in liquid form. However, engines running on renewable ammonia still require small amounts of pilot fuel for combustion, which must also be carbon-neutral (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021; Pape 2020). Moreover, the incomplete combustion of e-ammonia is likely to result in NOx emissions which should be avoided (Ariemma et al. 2022).

In conclusion, hydrogen and its derivatives, such as e-ammonia, offer potential pathways for decarbonizing the maritime sector. Developing these fuels, along with the necessary infrastructure and safety measures, is crucial for achieving a sustainable and zero-emission shipping industry by 2050. Table 3 in Appendix I.3. provides a comparative overview of hydrogen-based fuels as well as fully electric ship options.

(d) Other alternatives

Fully electric propulsion systems offer the benefit of zero emissions when using electricity from renewable sources. However, due to their low energy density and significant storage costs, fully electric systems are currently feasible only for a limited number of vessel types and sizes with short sailing distances (Castellanos, Sloan, and Roesch 2021).

In addition to adopting alternative fuels or electricity as a source of energy for fuels, shipping companies are employing various strategies to reduce fuel consumption and emissions, targeting both ship design and operational practices. Improving ship design plays a crucial role in enhancing energy efficiency, with key modifications including engine enhancements, more efficient hull shapes, optimized propeller and rudder designs, and advanced exhaust cleaning systems. These improvements collectively reduce fuel consumption and emissions, making ships more environmentally friendly (Castellanos, Sloan, and Roesch 2021; Pape 2020). Operational measures are equally important in reducing fuel consumption. The most common strategies include speed reduction and optimization, which involves adjusting speed based on tide and current conditions to lower propulsion demand and fuel consumption. Applying specialized coatings to hulls deters the buildup of marine organisms, reducing water resistance and improving fuel efficiency. Additionally, utilizing digital tools to optimize routes, port calls, and cargo loading and distribution helps minimize fuel usage and enhance overall operational efficiency (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021; Pape 2020).

2. Exploring e-ammonia as a decarbonization fuel for shipping

Having examined various potential decarbonization fuels for the shipping industry—along with their advantages, disadvantages, and feasibility— the future of maritime energy will most likely be increasingly diverse. Among these emerging alternatives, green ammonia (or e-ammonia) stands out for its attributes as a sustainable fuel (Castellanos, Sloan, and Roesch 2021; Cames, Wissner, and Sutter 2021).

As a carbon-free fuel, it has the potential to significantly reduce both GHG emissions and other air pollutants (Castellanos, Sloan, and Roesch 2021). Additionally, the shipping industry has existing expertise in handling ammonia as a cargo. Experience from related industries, such as fertilizers, also contribute valuable knowledge; ammonia has been produced, transported, and utilized safely for decades, leading to a comprehensive understanding of its logistics (Castellanos, Sloan, and Roesch 2021; Cames, Wissner, and Sutter 2021). Furthermore, while ammonia production technologies are sufficiently mature to facilitate its synthesis, further advancements and scaling are necessary in green

[6] A comprehensive analysis of the potential of liquid e-fuels, particularly e-diesel, to decarbonize the shipping sector was provided in a previous paper by the author (Souissi 2024).

hydrogen production, which is essential for green ammonia synthesis (Castellanos, Sloan, and Roesch 2021; Cames, Wissner, and Sutter 2021).

2.1 Technical analysis

In IRENA's Renewable Energy Roadmap, green ammonia is projected to be the foundation of a decarbonized international shipping sector (Hansson, Fridell, and Brynolf 2020). By 2050, the shipping industry is expected to require a total of 46 million tons of green hydrogen. Of this total, 73% will be needed to produce e-ammonia, 17% for e-methanol, and 10% will be used directly as liquid hydrogen through fuel cells or combusted through internal combustion engines (Hansson, Fridell, and Brynolf 2020). Renewable ammonia is anticipated to be the cornerstone of the sector's decarbonization efforts, potentially accounting for as much as 43% of the energy mix by 2050, which translates to approximately 183 Mt of renewable ammonia for international shipping alone (Hansson, Fridell, and Brynolf 2020).

Currently, ammonia is the second most produced synthetic chemical globally, after sulfuric acid. In 2017, its production reached 166 Mt, with about 80% utilized in the production of nitrogen fertilizers (Armijo and Philibert 2020; Bañares-Alcántara and Salmon 2022). It also represents the second largest demand for pure hydrogen, following oil refining, consuming about 32 Mt (44%) in 2018 (Bañares-Alcántara and Salmon 2022; Armijo and Philibert 2020). Greening today's ammonia production already presents a significant opportunity for decarbonization. However, it is essential to first examine its technical feasibility. This section will explore the characteristics and properties of e-ammonia, its production processes, sustainability assessment, and suitability for use in the shipping industry.

(a) Characteristics and properties of e-ammonia

As an alternative to fossil marine fuels, green ammonia holds appeal due to its carbon-free composition and high energy density (Bañares-Alcántara and Salmon 2022; Mayer et al. 2023; Armijo and Philibert 2020). With a volumetric energy density of 12.7 MJ/L, ammonia offers significant energy storage capabilities, surpassing the volumetric density of compressed hydrogen and lithium-based batteries. This high energy density enhances the feasibility of green ammonia for long-range maritime applications (Bañares-Alcántara and Salmon 2022; Mayer et al. 2023; Armijo and Philibert 2020).

Ammonia has a relatively low boiling point of -33°C at atmospheric pressure allows for easier storage and transportation compared to liquid hydrogen, which requires cooling to -253°C. This characteristic significantly reduces the logistical challenges and costs associated with its use in the maritime industry. Moreover, green ammonia can be stored and transported, which could simplify its integration into current maritime fuel supply chains (Mayer et al. 2023; Ghavam et al. 2021).

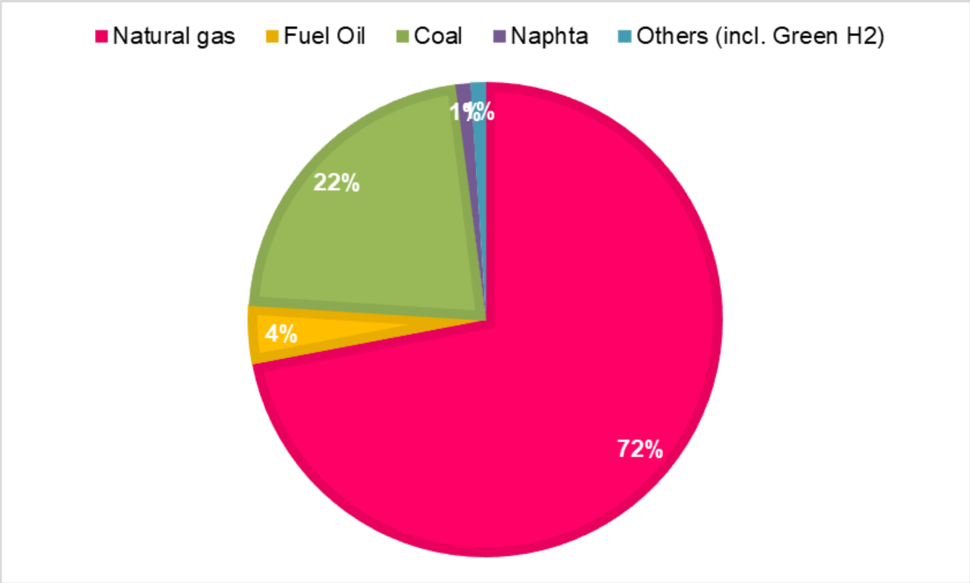
Its ability to be liquefied and stored, combined with its high energy density, positions green ammonia as a potential fuel for the shipping industry (Ghavam et al. 2021; Alfa Laval et al. 2020). Also, green ammonia closely resembles traditional ammonia in its chemical properties, boasting compatibility with existing ammonia infrastructure and engine systems (Mayer et al. 2023; Alfa Laval et al. 2020). In fact, although green and conventional ammonia exhibit significantly different carbon dioxide footprints, their physical properties remain identical. From an operational perspective, ammonia can be utilized as a marine fuel in either its conventional or green form, or as a blend of both. This interchangeability minimizes the investment risk associated with deploying ammonia-fueled ships, given that conventional ammonia is available as a commercially traded commodity though various sectors can compete for demand. Shipowners can initially adopt conventional ammonia and progressively increase the proportion of green ammonia in response to economic factors, regulatory requirements, and the imperative to support sustainable and carbon-neutral maritime operations (Mayer et al. 2023; Alfa Laval et al. 2020).

While the use of green ammonia in the shipping sector opens various opportunities, its widespread adoption is accompanied by significant challenges. In fact, the current availability of green ammonia remains limited, with only a few companies investing in its production (Siemens 2024). For instance, several pilot projects and small-scale production facilities are being developed globally, but large-scale production capacity is still in the early stages. Companies like Yara International in Norway and Siemens in Germany are among the pioneers in green ammonia production (Holsether 2024; Ammonia Energy association 2024), with plans to expand capacity in the future. Increased investment and technological advancements are essential to scale up production and meet the growing demand for sustainable marine fuels and from other sectors.

(b) Production of e-ammonia

The predominant method for producing ammonia is the Haber-Bosch process, which accounts for over 96% of global ammonia synthesis (Adeniyi et al. 2023; GIZ 2024). In this process, nitrogen is sourced from the air, and hydrogen is primarily derived from fossil fuels, with natural gas, coal and fuel oil contributing 72%, 22%, and 4% respectively (GIZ 2024, Dincer et al. 2023).

Figure 2: Current hydrogen sources for ammonia production



Source: (Dincer et al. 2023), Author's own illustration.

A typical Haber-Bosch ammonia plant synthesizes anhydrous liquid ammonia from hydrogen (H2) and nitrogen (N2) (see Figure 3). Electrolysis is regarded as one of the cleanest methods for hydrogen production, requiring approximately 50 kWh of electricity to produce one kilogram of green hydrogen by splitting water into H2 and O2 (Souissi 2024). Four key technologies in this domain are Alkaline Electrolysis (AE), Proton Exchange Membrane Electrolysis (PEM), Anion Exchange Membrane Electrolysis (AEM) and Solid Oxide Electrolysis Cells (SOEC).

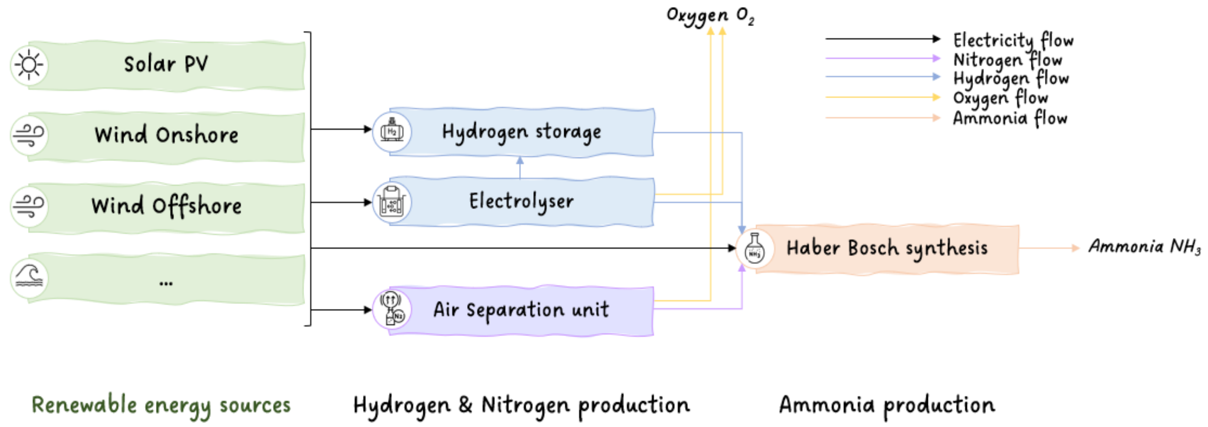
- Alkaline Electrolysis, a mature technology, is being scaled up, with the largest operational plant being a 25 MW facility in Malaysia (GIZ 2024). The energy efficiency of Alkaline Electrolysis systems is about 63% at full load and is projected to exceed 65% in the future, with long-term estimates suggesting efficiencies over 70% (GIZ 2024).

- PEM electrolysis, though more expensive due to precious metal content, is competitive in energy efficiency and excels in handling rapid electrical load changes (GIZ 2024).

- AEM electrolysis combines several advantages from both alkaline and polymer electrolyte membrane technologies, including the use of low-cost catalysts similar to alkaline systems, along with the compactness and high-pressure operation characteristic of PEM (Pozio et al. 2021, Liu et al. 2024 However, as a relatively new technology, AEM electrolysis still faces challenges that must be resolved for broader adoption, particularly in terms of long-term stability and achieving high current densities (Liu et al. 2024). Enapter & Co are actively working on these issues and were the first to commercialize this technology. However, it's important to note that their current maximum capacity is still quite small, at up to 1 MW (Enapter & Co 2024).

- SOEC is expected to achieve similar costs to alkaline electrolysis, with potential energy efficiencies up to 90% when integrated with ammonia synthesis, suggesting it may become the preferred long-term technology. However, this technology exhibits the lowest Technology Readiness Level (TRL) among the four primary electrolysis methods. Its commercialization is hindered by durability issues, posing significant challenges for long-term implementation (GIZ 2024).

Figure 3: Ammonia production process (simplified Haber-Bosch process)



Source: Author's own illustration.

Once hydrogen is produced, it undergoes the Haber-Bosch process, combining with nitrogen from an air separation unit (ASU) to form ammonia (GIZ 2024; Olli and Voovere 2021; Fasihi et al. 2021). Cryogenic distillation, the dominant technology for large-scale air separation, uses low temperatures to separate air components based on their boiling points (GIZ 2024; Olli and Voovere 2021). This method benefits from economies of scale, with a tenfold capacity increase in nitrogen purification resulting in only a threefold increase in capital expenditure. The Linde Ammonia Concept already utilizes cryogenic distillation for nitrogen feedstock (GIZ 2024).

In an NH3 plant, the Haber-Bosch synthesis occurs in a reactor within a synthesis loop, involving a catalytic reaction under pressures of 100–250 bar and temperatures of 350–550°C, using an iron catalyst (GIZ 2024; Olli and Voovere 2021). Despite being over 100 years old, the basic configuration of the Haber-Bosch process remains unchanged, although improvements in catalysts, reaction processes, and separation methods have optimized its energy efficiency to 60-70% when using natural gas (GIZ 2024).

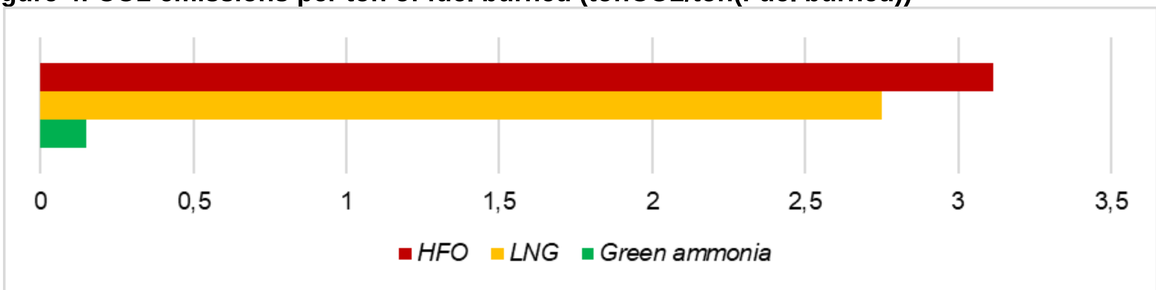
The Haber-Bosch process is expected to remain the leading technology for ammonia synthesis in the foreseeable future (IRENA 2022; Humphreys, Lan, and Tao 2020). Enhancements to the existing process are seen as the most feasible near-term solution for sustainable ammonia synthesis. Transitioning to green ammonia is possible but hinges on cost and significant changes to the current configuration, such as decoupling methane reforming and utilizing renewable energy for electric compressors (GIZ 2024; Torrente-Murciano, Hill, and Smith 2020). A major challenge is aligning the continuous Haber-Bosch process with intermittent renewable energy, as the reactor requires stable operating conditions, and cycling pressures and temperatures can induce failures and catalyst damage (GIZ 2024; Torrente-Murciano, Hill, and Smith 2020). Large-scale plant cold start-up times are 1-2 days, making shutdowns feasible only for prolonged electricity supply interruptions (GIZ 2024; Torrente-Murciano, Hill, and Smith 2020).

2.2 Sustainability assessment of e-ammonia

In April 2018, the Marine Environment Protection Committee (MEPC) adopted the Initial International Maritime Organization (IMO) Strategy on the reduction of GHG emissions from international shipping (IMO 2024). The key targets include a decline in the carbon intensity of ships through the implementation of further phases of the Energy Efficiency Design Index (EEDI) for new ships, a reduction in carbon intensity by at least 40% by 2030, with efforts towards a 70% reduction by 2050, compared to 2008 levels as well as a reduction in total annual GHG emissions by at least 50% by 2050 compared to 2008 (IMO 2024).

In alignment with the IMO's GHG emission reduction targets, ammonia emerges as a potential carbon-free fuel. Its use as a fuel offers substantial environmental benefits, including almost zero CO2 emissions when burned in an internal combustion engine (IMO 2024). Chisalita, Petrescu, and Cormos (2020) conducted a cradle-to-gate life cycle assessment of European ammonia production from various hydrogen sources. Their study, set in Germany, identified the scenario with the lowest GWP-based climate change impacts through sensitivity analysis. The results showed that the lowest climate change impacts were achieved with electrolysis-based hydrogen from renewable sources, yielding 0.15-ton CO_2-eq/ton NH_3 (Chisalita, Petrescu, and Cormos 2020) (see Figure 4 below). In contrast, using Heavy Fuel Oil (HFO) in the maritime sector results in approximately 3.114 tons of CO_2 emissions per ton of HFO burned, due to its carbon content (about 86-87% carbon) (Marine Benchmark Gothenburg AB, 2020; Green voyage 2050, 2024). Emissions from Liquefied Natural Gas (LNG) are lower, with around 2.75 tons of CO_2 emitted per ton of LNG burned, varying with engine efficiency and LNG composition (Green voyage 2050 2024; Marine Benchmark Gothenburg AB 2020). Another notable advantage of ammonia as a fuel is its sulfur-free nature, eliminating the need for SOx removal systems in the exhaust. Additionally, NOx emissions generated during ammonia combustion can be effectively managed using selective catalytic reduction (SCR) technology (Alfa Laval et al. 2020).

Figure 4: CO2 emissions per ton of fuel burned (tonCO2/ton(Fuel burned))



Source: Author's own illustration.

While ammonia is not a greenhouse gas, its emissions during normal operations and emergency scenarios must be controlled. Anhydrous ammonia gas, being lighter than air, disperses readily in dry air but reacts with atmospheric humidity, potentially limiting its dispersion close to the ground. Furthermore, future vessel engines operating on renewable ammonia still require a small amount of pilot fuel, which must also be low carbon (Castellanos, Sloan, and Roesch 2021).

2.3 Suitability of e-ammonia for maritime applications

(a) Production, storage and distribution challenges

Widely utilized across various industries and in agriculture, ammonia has been managed in substantial quantities for many decades (Castellanos, Sloan, and Roesch 2021). Consequently, the industry's methods for producing, storing, and distributing ammonia are highly developed. Presently, between 25-30 million tons of ammonia are transported annually via road, rail, ships, or pipelines, with 18-20 million tons transported by ship (Castellanos, Sloan, and Roesch 2021).

However, the production of e-ammonia for maritime applications involves significant challenges, primarily due to the high energy requirements and the need for sustainable energy sources. Current electrolysis and synthesis technologies require approximately 10.3 MWh of electricity to produce one ton of ammonia (Hansson, Fridell, and Brynolf 2020). Accordingly, meeting the 2050 demand for green ammonia production in the international shipping sector[7] will require approximately 140% of the total global renewable electricity generated in 2023 across all sectors. This demand also represents about 65.4% of the total global electricity production in 2023 (Hansson, Fridell, and Brynolf 2020; IEA 2024). Achieving this power production could be accomplished by installing 244 GW of wind power with a capacity factor of 0.6, alongside 244 GW of solar photovoltaics (PV) with a capacity factor of 0.3 (author´s own calculation). This installation would represent 27.13% of the actual installed wind

[7] According to IRENA's Renewable Energy Roadmap, the shipping industry is projected to demand 46 million tons of green hydrogen by 2050, with 73% of this amount required for the production of e-ammonia.

capacity (899.4 GW) and 15.71% of the installed solar PV capacity (1552.3 GW) worldwide in 2023 (IEA 2024).

A practical example of these energy demands can be observed through the case of The Yara Eyde, the world's first ammonia-powered container ship, expected to begin operations between Germany and Norway in 2026 (Yara-International 2023). The Yara Eyde is projected to consume about 10,000 tons of ammonia annually (Yara-International 2023). Producing this ammonia would require approximately 95,000 MWh of electricity (De la Hera et al. 2024), equivalent to 31.67% of the average annual output of a typical 50-turbine wind farm (UTI 2024). In comparison, this energy represents 1.76% of the total capacity of Norway's Hordavind Wind Farm, which is set to become the country's largest onshore wind farm by 2027 (Power technology 2023). Additionally, this energy demand is comparable to the annual electricity consumption of approximately 5,278 households in Norwaz (Power technology 2023). [8]

From a cost standpoint, producing 10,000 tons of ammonia annually for the Yara Eyde would range from $4.07 million to $12.39 million, based on the model developed in the study (see Section 3 for more detail). By contrast, the equivalent amount of low-sulfur fuel oil (roughly 4,653 tons) (ING 2023) presents a much lower financial burden, costing around $1.62 million for high-sulfur fuel oil (HSFO), $1.91 million for very low-sulfur fuel oil (VLSFO), and $2.48 million for marine gas oil (MGO), not accounting for carbon taxes or other regulatory costs (IEA(b) 2024). Despite the significantly higher costs of green ammonia, particularly in the worst-case scenario, it offers substantial environmental benefits. The Yara Eyde alone is expected to reduce carbon dioxide emissions by approximately 11,000 tons annually (Yara-International 2023).

As to storage, storing ammonia in a liquefied state at pressures of approximately 17 bar (or -33°C) offers a significant advantage over other gaseous fuels such as LNG, as it enables the use of cheaper carbon manganese or low nickel steels. The IGC code requirements (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO 2024), issued in 1986, provide an established marine reference for ammonia storage in tanks made from these steels (IMO 2024). The IGC Code specifically prohibits the use of nickel steels containing more than 5% nickel (IMO 2024). An advantage of ammonia storage is that the IGC Code allows ammonia to be carried in gas carriers designed for LPG transport. Currently, there are approximately 2,228 gas carriers in service, with 701 being LNG carriers and 1,527 being LPG carriers (IMO 2024). Of the LPG carriers, 856 have capacities at or below 10,000 m³, making them suitable for use as bunkering ships. About 167 LPG carriers can carry anhydrous ammonia, making them suitable for an ammonia-bunkering fleet. This suggests that existing LPG storage infrastructure could be repurposed for ammonia if its use as a marine fuel increases (IMO 2024).

E-ammonia can then be transported to consumption locations by ship, pipeline, rail, or truck (Castellanos, Sloan, and Roesch 2021). It is typically shipped in LPG carriers in a liquid state at -33°C and ambient pressure (Alfa Laval et al. 2020). The levelized cost of shipping ammonia depends on the annual volume transported, the shipping distance, and the speed of the vessel. For instance, transporting ammonia over a long international route, such as the 13,500 km from Patagonia to the Netherlands, incurs shipping costs of approximately 46-63 $/tNH3, depending on the fuel price, which ranges from 21.2 $/MWh(th) for low-cost diesel to 84.8 €/MWh(th) for e-ammonia as a shipping fuel in 2020 (Alfa L et al. 2020). Currently, 170 ships are capable of carrying ammonia as cargo, with 40 of these ships in continuous operation. General safety measures for liquid gas carriers include actions against leakage, firefighting procedures, cargo transfer protocols, gas freeing, ballasting, cargo cleaning, maintaining minimum allowable cargo tank steel temperature, and training personnel for emergency procedures (Alfa Laval et al. 2020).

[8] It is however essential to highlight that energy consumption in green ammonia production can be significantly reduced through advancements in electrolysis efficiency (New Atlas 2023). Hysata, an Australian company, claims to offer the lowest-cost hydrogen production globally with a capillary-fed electrolyzer that achieves 95% efficiency, approximately 20% higher than conventional electrolyzers (New Atlas 2023). This technology uses only 41.5 kWh of energy to produce one kilogram of hydrogen, significantly lowering the OPEX and CAPEX due to its cost-effective installation and operational requirements (New Atlas 2023).

Large quantities of ammonia are also be transported via pipelines, notably in the USA and Russia/Ukraine (Alfa Laval et al. 2020). Most of these pipelines are located near public roads or populated areas. In the USA, which has the largest liquid ammonia pipeline infrastructure, there have been nine reported incidents, none of which were fatal. Safety measures for pipelines include proper marking of dangerous goods, regular maintenance, guidelines for loading and unloading, protective clothing for handlers, and comprehensive emergency response plans.

In Europe, approximately 1.5 million tons of ammonia are transported annually by rail, equating to around 30,000 rail tank cars (Alfa Laval et al. 2020). Over the past 30 years, only a few accidents have occurred, with no casualties or injuries resulting from ammonia releases. Rail transport of ammonia requires adherence to stringent safety protocols to prevent accidents and ensure safe handling. Ammonia transported by road is classified as dangerous goods and must comply with existing legislation (Alfa Laval et al. 2020). This classification necessitates proper marking and handling of ammonia as a toxic gas. Safety measures include driver training, valid transport certificates, and industry-specific training programs for individuals involved in ammonia transportation.

Proximity to ports or pipeline grid connections is crucial for the efficient and cost-effective transport and distribution of ammonia. This strategic consideration ensures feasible and rapid distribution, reducing transportation costs and mitigating risks associated with distribution security. Maintaining continuous production and secure distribution channels is vital for the sustainable utilization of e-ammonia in the maritime industry. By leveraging existing infrastructure, such as LPG carriers and established pipeline networks, the maritime sector can facilitate the transition to e-ammonia as a sustainable marine fuel, ensuring safety and efficiency in its transport and distribution (Alfa Laval et al. 2020).

(b) Bunkering, handling, and utilization considerations

Globally, there are specialized ammonia terminals in 38 ports that export ammonia and 88 ports that import it, with six ports engaging in both activities (Alfa Laval et al. 2020). Many of these terminals are part of ammonia or fertilizer plants situated along coasts or riverbanks, equipped for the transshipment of fertilizers and ammonia (Alfa Laval et al. 2020). Other terminals operate independently, featuring dedicated ammonia storage facilities or integrated within larger port complexes. Ship-to-ship bunkering, where ammonia is transferred from a delivery vessel moored alongside the receiving vessel, offers a flexible solution for expanding ammonia availability (Alfa Laval et al. 2020). This method, already in use for LNG, minimizes the need for extensive facility investments and allows for flexible fuel supply. Bunkering ammonia parallel to cargo operations is theoretically feasible but requires port authority authorization to avoid additional port time and costs (Cames, Wissner, and Sutter 2021).

Introducing ammonia as a marine fuel involves deploying new systems onboard ships, each with specific requirements and risks. However, the use of ammonia on ships is not entirely novel, as existing technologies, materials, and procedures can be adapted for this purpose, leveraging industry experience with alternative fuels like LNG and methanol (Cames, Wissner, and Sutter 2021; Alfa Laval et al. 2020). For ships already carrying ammonia as cargo, these vessels are likely to be the first adopters, following the example of LNG, methanol, and LPG carriers. Ship adaptations will primarily involve installing a dedicated NH3 fuel supply system (LFSS) and upgrading the engine. Careful design of the LFSS is crucial to prevent pollution of the cargo by engine emissions (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021).

The development of ammonia-fueled engines is progressing, with Wärtsilä Gas Solutions, a division of the Wärtsilä technology group, introducing an innovative Ammonia Fuel Supply System (AFSS) for ships capable of running on ammonia fuel (Wartsila corporation 2024). The system is designed for use with both liquid and gaseous ammonia. In addition, manufacturers such as MAN Energy Solutions plan to have a commercially available two-stroke ammonia engine by 2024, followed by a retrofit package for the gradual conversion of existing maritime vessels by 2025. The LGI[9] engine family, with proven performance on alternative fuels, is a strong candidate for conversion to ammonia (MAN Energy

[9] LGI: The MAN B&W ME-LGI engine is the dual-fuel solution for methanol and LPG injected on liquid form into the engine

Solutions 2024). The LGIP[10] engine offers dual-fuel operation, allowing a mix of gas and liquid fuels to optimize CO2 reduction, cost, and fuel availability. Existing ME C-type engines can also be converted to ammonia fuel technology. The estimated additional investment for ammonia-fueled engines, excluding storage tanks and LFSS, is approximately 30% higher than for compliant fuel engines (Alfa Laval et al. 2020).

Several critical factors must align to ensure market readiness of ammonia powered ships. These include advancements in engine technology, the development of appropriate storage and safety systems, and the establishment of a reliable supply chain for green ammonia. Additionally, extensive testing and validation of the engine's performance and emissions are necessary to ensure compliance with environmental standards and operational efficiency (Alfa Laval et al. 2020). As an example, ammonia has a lower energy density than marine diesel, necessitating larger tanks to store an equivalent amount of energy. This design requirement means ships need to be redesigned to accommodate the larger tanks without significantly reducing cargo capacity. For instance, currently a 15,000 TEU container vessel would require about 20,000 cubic meters of ammonia storage, compared to 8,000 cubic meters for traditional fuel oil, potentially reducing container capacity by up to 1,100 containers (Alfa Laval et al. 2020; Castellanos, Sloan, and Roesch 2021).

The use of ammonia as a marine fuel, similar to other existing and alternative low-emission fuels, presents specific challenges to ensure the safety of crew members on board. Essential safety measures in these sectors include regular inspection and maintenance of equipment, personnel training, use of protective clothing, clear warning signs, and established emergency procedures to mitigate potential leakage incidents (Cames, Wissner, and Sutter 2021; Alfa Laval et al. 2020).

2.4 Risk assessment of e-ammonia usage in marine vessels

While ammonia possesses attractive characteristics as a carbon-free and almost zero-GWP energy vector, its usage presents certain safety risks due to its corrosiveness and toxicity (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). The primary safety risk of ammonia is associated with pressurized storage, where leaks can lead to dangerous air concentrations. Ammonia’s characteristic odor allows for easy detection, enabling workers to respond promptly to leaks (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). Ammonia is detectable at 5-50 ppm, and exposure to 700 ppm for less than one hour does not cause major injuries, which has been its major safety advantage.

Although repeated exposure to ammonia does not produce chronic effects, even small concentrations in the air can be extremely irritating to the eyes, throat, and respiratory system (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). Moreover, reliance on human detection is not enough and automated ammonia gas detection systems at ppm levels and automated responses such as alarms, increased ventilation, and line shutdowns should be implemented (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). Furthermore, material compatibility is crucial when handling ammonia. In the presence of moisture, ammonia reacts with and corrodes copper, zinc, and many alloys. Only iron, steel, and specific non-ferrous alloys resistant to ammonia should be used for tanks, fittings, and piping. For gaskets and sealing, only compatible rubbers and polymers, should be used (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). Nickel content in alloys should be kept below 6% to avoid nickel crystalline corrosion. Additionally, oxygen levels above a few ppm in liquid ammonia can promote stress corrosion cracking in steels, which progresses rapidly at high temperatures (Alfa Laval et al. 2020).

Historically, fatal accidents involving ammonia leakage have occurred, underscoring the importance of thoroughly addressing safety aspects when considering ammonia as a marine fuel. The shipping industry can benefit from examining safety practices in other sectors where large amounts of anhydrous liquid ammonia are handled, incorporating these measures into the early design phases of ammonia-fueled ships (Cames, Wissner, and Sutter 2021). Moreover, ammonia is not new to shipping; it is commonly transported as cargo and used as a refrigerant onboard. Established practices for safe ammonia handling are well-known and accepted in the marine industry, including operational and safety

[10] LGIP: Th only dual-fuel engine on the market that lets you switch between HFO. MGO and LPG fuels without any loss of power or efficiency.

procedures. International rules and regulations, such as the International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk (IGC Code), provide guidelines for protecting personnel operating onboard ammonia carriers (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). These include respiratory and eye protection devices for emergency escape purposes for every person onboard, gas-tight protective clothing as well as one or more suitably marked decontamination showers available on deck, operable under all ambient conditions (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021). The existing solutions, devices, and procedures for safe ammonia handling, combined with the experience of using LNG as a fuel, provide a solid foundation for developing specific guidelines for ammonia as a ship fuel (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021).

Currently, the IMO International Gas Carrier Code (IGC) prohibits the use of toxic cargoes as fuel, and the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) does not cover ammonia (Alfa Laval et al. 2020). Therefore, revisions of these codes are necessary to facilitate the use of ammonia as a fuel. Preliminary activities and risk assessments have been undertaken, focusing on addressing the specific issues related to ammonia, such as its lower flammability compared to LNG and higher toxicity. The industry's extensive experience with ammonia should enable the implementation of the required revisions (Alfa Laval et al. 2020; Cames, Wissner, and Sutter 2021).

In summary, ammonia presents several challenges for safety systems due to its potential hazards to human health and its corrosive effects on various standard materials. However, decades of experience with ammonia in the chemical industry have made these challenges manageable in professional and regulated settings.

3. Economic analysis of e-ammonia utilization in shipping

Various studies have examined the potential of green ammonia as a sustainable alternative fuel for the maritime sector. These studies focus on several key factors that influence the competitiveness of green ammonia, including production costs, feedstock sources, energy efficiency, and technology used for production.

Across the literature, it is noted that production costs for green ammonia show considerable variability depending on the region, technology, and time frame. Cesaro et al suggests that the cost of producing green ammonia is expected to fall from €634 per ton in 2025 to approximately €380 per ton by 2040 due to advancements in technology and increased production capacity (Cesaro et al. 2020). Current uncertainties in green ammonia production costs, mainly due to electrolyzer costs and limited deployment experience, are expected to decrease with large-scale projects. The competitiveness of green ammonia also depends on grid-specific factors, such as regional renewable energy supply, energy storage potential, and policy decisions (Cesaro et al. 2020).

Salmon and Bañares-Alcántara suggest that production costs for green ammonia can vary widely, from $400 to $1,200 per ton, depending on the technologies used and the availability of renewable energy (Bañares-Alcántara and Salmon 2022). Their research introduces the first global heat map for ammonia production, incorporating factors such as ocean-based production, land constraints, and transportation to key demand centers. Despite the elevated costs of floating wind turbines, there is still potential of offshore ammonia production. It could offer key benefits, including mid-journey refueling for large vessels and enhanced energy independence for countries with limited land but abundant marine wind resources, such as the UK (Bañares-Alcántara and Salmon 2022). Additionally, offshore ammonia production presents a lower environmental impact on land ecosystems compared to land-based renewable energy projects. Despite the challenges posed by high offshore infrastructure costs, the study suggests that this technology could be economically viable in a decarbonized future, positioning offshore ammonia production as a critical component in meeting global demand sustainably and affordably (Bañares-Alcántara and Salmon 2022).

Several studies highlight the importance of renewable energy inputs such as solar PV, wind, and hydroelectric power (Alfa Laval et al. 2020; Wang, Zhang, and Daoutidis 2023; Rivarolo et al. 2019). In particular, the use of solar PV combined with battery storage is seen as a promising solution for maintaining stable ammonia production (Cesaro et al. 2020), while offshore wind is identified as a critical factor in reducing production costs in areas with high wind potential (Bañares-Alcántara and Salmon

2022). Hydroelectric power is also noted for its capacity to provide low-cost electricity, particularly in regions like Paraguay and Brazil, where such resources are abundant (Rivarolo et al. 2019).

The technology used in green ammonia production, specifically electrolysis for hydrogen production, significantly affects both efficiency and cost. Reported efficiency rates for electrolysis vary across studies, with some citing a range of 54.3% (Wang, Zhang, and Daoutidis 2023) to 75% (Rivarolo et al. 2019). The choice of electrolyzer technology, such as alkaline electrolyzers is critical, as these are more mature and cost-effective options currently available for large-scale hydrogen production (Alfa Laval et al. 2020). The use of such efficient technologies, combined with access to cheap renewable energy, is crucial for driving down the cost of green ammonia (Alfa Laval et al. 2020; Campion et al. 2023).

Geographical location is another important consideration. Certain regions, particularly those with abundant renewable resources, are seen as ideal for green ammonia production. Studies point to areas like Australia, North America, and Northern Europe as having strong potential due to their high solar and wind capacity (Wang, Zhang, and Daoutidis 2023). Additionally, regions with extensive hydroelectric power, such as parts of South America, offer an advantageous environment for green ammonia production, helping to reduce electricity costs and, consequently, the overall cost of ammonia (Wang, Zhang, and Daoutidis 2023).

Looking ahead, the cost of green ammonia is expected to decline as technological advancements, improved efficiency, and economies of scale reduce production costs (Alfa Laval et al. 2020; (Ikäheimo et al. 2018; Alfa Laval et al. 2020). By 2050, some studies predict that green ammonia could become cost-competitive with conventional fuels if supported by governmental subsidies and carbon pricing policies (Ikäheimo et al. 2018; Alfa Laval et al. 2020). A summary of the reviewed papers is available in Table 1 below.

Table 1: Literature review

Production costs in $/ton	Feedstock costs	Efficiency electrolysis	Technology used	Energy source	LCOE in $/MWh	Scale of Production	Geographical Location	Time frame	Assumptions	WACC	Reference
771 (2020) - 494 (2030) -426 (2035) - 380 (2040)	Not specified	74%	Electrolysis, water desalination and air separation unit, Haber-Bosch process for ammonia synthesis.	Solar PV with battery storage	reduced from 28.5 in 2020 to 16.8 in 2040	10 t/hr	General global analysis, not specific to one location.	2020 - 2040	Technological developments. cost reductions in electrolyzers. and renewable energy costs	7.50%	Cesaro et al. 2020
400 - 1,200	Not specified	Not specified	Offshore wind turbines, electrolysis, and the Haber-Bosch process	Offshore wind, with floating solar panels	Not specified	Industrial scale	Global analysis with a focus on high-wind offshore locations,	Not specified	Technological advancements in floating wind and solar, cost reductions in electrolysis, and stable renewable energy prices	Not specified	Bañares-Alcántara and Salmon 2022
Minimum cost of 341	Not specified	54.3%	Electrolysis for hydrogen production, air separation for nitrogen, Haber-Bosch synthesis for ammonia	Solar and wind-based electricity	17 - 33 for solar PV and 17 - 48 for onshore wind	Industrial scale, global supply chain optimization	Global, with focus on some regions	2050	Technological advancements, renewable energy cost stability, and implementation of green shipping corridors	Not specified	Wang, Zhang, and Daoutidis 2023
388	Not specified	75%	Alkaline electrolyzers for hydrogen production, air separation unit for nitrogen, Haber-Bosch process for ammonia synthesis.	hydroelectric power plant	$7.42/MWh for spilled energy and $31.80/MWh for grid-purchased energy.	Industrial scale, with plant sizes ranging from 200 to 1500 tons/day of NH3.	Itaipu, located on the border between Paraguay and Brazil	Present	Large availability of low-cost electrical energy, plant size optimization, and potential oxygen sale	Not specified	Rivarolo et al. 2019

400-850 in 2025-2030, 275-450 in 2040-2050	Dependent on renewable costs	63-65 % for AEL, 90% for SOEC	Alkaline, PEM and SOEC, air separation, Haber-Bosch process	Solar, wind.	31.80 in 2025-2030, and 21.20 in 2040-2050.	Industrial scale with focus on scaling up to meet 30% of future marine fuel demand.	Global, with strategic emphasis on regions with high renewable energy potential.	2025-2050	Technological advancements, stable and reduced costs of renewable energy, and increased production capacities.	Not specified	Mayer et al. 2023
Cheapest off-grid configuration: $891/ton NH3	Dependent on renewable costs	AEC: 70% and SOEC 90%	Water electrolysis (AEC, SOEC), Haber-Bosch process, integration with renewable power sources.	Solar, wind, grid electricity.	Fixed-axis PV: $29.30/MWh 1-axis tracking PV: $26.61/MWh)	Industrial scale, 430,000 tons/year	Northern Chile (solar+), Denmark (wind+), South Australia (wind/solar).	(2020-2025)	Technological advancements, renewable energy cost stability, site-specific optimizations.	Not specified	Campion et al. 2023
487-580 $/ton (Chile) and 521-710 (Argentina)	LCOH (USD/kg) 1.94-2.12 (Chile) and 2.16-2.33 (Argentina)	68%	Water electrolysis (alkaline), Haber-Bosch process, integration with renewable power sources.	Solar, wind, hybrid systems.	26.7-49.9 (Argentina) 26.8-51.8 (Chile) wind (USD/MWh) 28-35.8(Argentina) 33.8-44.1 (Chile)	35 000 t/yr	Chile (Atacama desert, Patagonia), Argentina (Patagonia).	Present to near future (2020).	Technological advancements, renewable energy cost stability, hybrid system optimization.	Argentina 10%, Chile 7%	Bellini 2021
456.86 - 559.68 USD/ton	dependent on renewable power costs	70%	Proton-exchange membrane (PEM) electrolysis, Cryogenic distillation of air, Intermediate hydrogen storage an HaberBosch process	Solar, Wind and hydropower	Not specified directly, inferred from marginal cost competitivenes	large scale	North Europe: Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland, Sweden	2050	Fully renewable power and heat sectors, large-scale electrification of road transport, simultaneous optimization of capacity investments and dispatch scheduling	7%	Ikäheimo et al. 2018

3.1 Model overview

In all these studies, cost is one of the fundamental drivers of the adoption of clean ammonia and a key obstacle to overcome (Ryste 2019; Deloitte 2023). Currently, the production cost of green ammonia is up to four times higher than that of ammonia derived from fossil fuels (Burgess 2024). Furthermore, as discussed in the previous section, existing literature indicates significant uncertainty in the evolution of projected costs. The period leading up to 2035 is expected to be crucial for research and development, pilot projects, regulatory development, product innovation, and early commercialization efforts (Ryste 2019; Deloitte 2023). This section aims to estimate the intervals within which the costs of producing green ammonia lie and to examine how these costs can be influenced by external and internal factors.

The economic efficiency assessment provides an overview of the model, including the types of technologies used and the countries considered. Its primary aim is to analyze and interpret the results. A detailed description of the assumptions, the model, and the main data used can be found in the Appendix III.1.

The model comprises the fuel production system, including a desalination plant, an electrolyser, and an ammonia plant including an air separation unit and a Haber–Bosch loop. Importantly, the primary challenge in designing green ammonia plants is the limited flexibility of the Haber-Bosch synthesis loop, which cannot adequately adapt to the incoming variable renewable energy profile, that's why a hydrogen storage unit is added to the model which can help alleviate the flexibility requirements of the Haber-Bosch process (Bañares-Alcántara and Salmon 2022). However, advancements in new Haber-Bosch technologies are expected to offer greater flexibility, reducing the reliance on hydrogen storage and subsequently lowering costs (Bañares-Alcántara and Salmon 2022).

This paper specifically considers the alkaline type of electrolyser, which is the most mature technology for green hydrogen production and has the lowest capital expenditure compared to PEM and SOEC technologies (Alfa Laval et al. 2020; Campion et al. 2023; Christensen 2020). The system is designed to produce up to 825,000 tonnes of ammonia and up to 150,000 tonnes of green hydrogen annually. For comparison, Copenhagen Infrastructure Partners aims to build Europe's largest ammonia plant (HØST) in Esbjerg, Denmark. This plant will utilize electrolysis technology powered solely by renewable electricity and is expected to produce approx. 600,000 tons of green ammonia per year and to be completed by 2026 (HØST 2022).

This paper focuses solely on production costs, excluding storage and transportation costs for green ammonia. This exclusion is justified as green ammonia can be stored and transported at a relatively low cost, especially when compared to hydrogen. Indeed, transport and storage collectively account for approximately 5% of total cost, with storage cost being particularly marginal (Wang 2022; Nayak-Luke 2021). As previously mentioned, ammonia is liquid under relatively mild conditions compared to hydrogen (at atmospheric pressure, ammonia boils at -33°C), allowing it to be stored inexpensively for extended periods (Bañares-Alcántara and Salmon 2022). Additionally, there is substantial infrastructure for ammonia transport via both ships and pipelines globally. Due to its similar properties to LPG, existing gas carriers can be used to scale up ammonia transport. These favorable properties enable ammonia to be produced in isolated locations and transported to demand sites without significant increases in total costs (Bañares-Alcántara and Salmon 2022).

Ammonia production is expected to take place in regions with abundant and relatively low-cost energy sources. This paper considers several countries with favorable conditions: Chile (Atacama with photovoltaic (PV) and Patagonia with onshore wind energy), the United States and Canada (with onshore wind[11]), Australia, and the United Arab Emirates (with PV) (see Figure 5). These regions benefit from very low electricity costs (IRENA 2022); for instance, Chile has the world's strongest solar

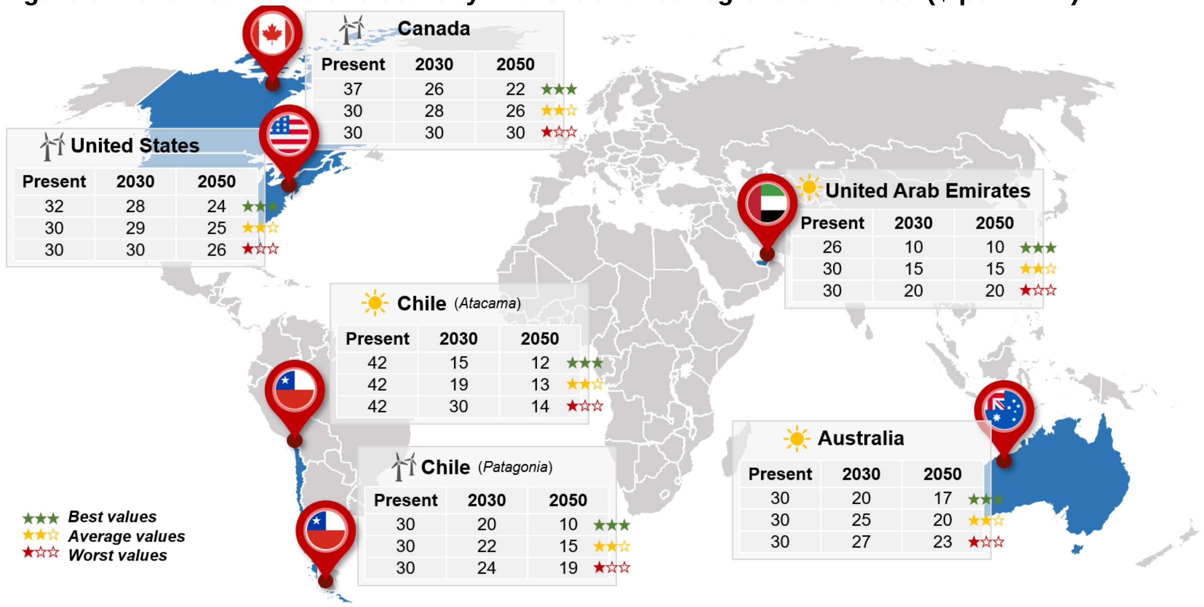
[11] Only onshore wind energy is considered in this study, as the costs of offshore wind turbines are more than double those of onshore turbines, making the best ocean sites non-competitive with the best land sites ((IRENA 2022; Armijo and Philibert 2020). However, it is important to note that economic conditions could shift, making offshore ammonia production viable, especially given the larger area of oceans compared to land and reduced competition for space (Wang, Zhang, and Daoutidis 2023).

resources and excellent wind conditions both in the north and far south, offering promising possibilities for solar, wind, or hybrid energy systems (Armijo and Philibert 2020). By 2050, the levelized production costs of green hydrogen in Chile could fall below US$1/kgH2 (Deloitte 2023). Additionally, the selected countries typically host ports that are connected to major trade routes with substantial fuel demands (Wang, Zhang, and Daoutidis 2023). For example, ammonia is transported long distances from Australia to New Zealand ports (Wang, Zhang, and Daoutidis 2023).

A recent study by LUT University in Finland further highlights the significance of these regions, evaluating the feasibility of transporting ammonia from distant locations like Chile to high-demand regions in Europe, including Germany, Finland, and Spain (Galimova et al. 2023). The study demonstrates that, despite the long distances involved, importing green ammonia from regions rich in renewable energy remains economically viable (Galimova et al. 2023). For example, the sea route between the Port of Antofagasta (Chile) and the Port of Hamburg (Germany) spans approximately 13,000 km. By 2030, the shipping cost of e-ammonia from Chile to Germany is projected to range between 9.2 and 12.7 €/MWh ($48.76 to $67.31 per ton) (Galimova et al. 2023). In contrast, the cost of pipeline transport from nearby regions, such as Morocco to Germany, is expected to be significantly higher, ranging from 33 to 47 €/MWh ($175 to $250 per ton) (Galimova et al. 2023).

Although Europe has a dense trade network and high fuel demands, renewable electricity costs remain relatively high. Given that transportation costs are lower relative to production costs, the optimal strategy is to produce ammonia in low-cost energy regions and transport it to major European ports[12] (Wang, Zhang, and Daoutidis 2023).

Figure 5: Levelized costs of electricity in the identified regions until 2050 ($ per MWh)



Source: Author's own illustration.

The paper thoroughly investigates the selected regions across three scenarios: best, average, and worst scenarios (see Figure 5 above). The best scenario prioritizes the most favorable values/conditions, while the worst scenario incorporates the least favorable ones. The average scenario averages values from all available sources. Various LCOE are analyzed for the years 2024, 2030, and 2050, providing a comparative overview of the six regions. An overview of the most pertinent data for each country is presented in Table 1 below. The average (region-independent) techno-economic characteristics of the

[12] Other locations with higher potential for ammonia production may yield better financial results but are not included in this study. Instead, the focus is on areas with publicly available data on electricity spot prices. Since the study aims to compare different renewable profiles rather than conduct a detailed case study, practical limitations such as available space, regulations, or existing infrastructure are not considered.

ammonia synthesis plant and electrolyzes, as well as the process simulation, are summarized in Appendix III.2.

Table 2: Relevant costs data

			Chile (Atacama)			Chile (Patagonia)			Australia			United States			Canada			Middle East		
			PV			Wind Onshore			PV			Wind Onshore			Wind Onshore			PV		
	Scenario	Unit	Present	2030	2050	Present	2030	2050	Present	2030	2050	Present	2030	2050	Present	2030	2050	Present	2030	2050
Water desalination costs	Optimistic	$/t	0.57	0.42	0.34	0.52	0.44	0.34	0.55	0.42	0.35	0.51	0.46	0.38	0.55	0.47	0.39	0.57	0.46	0.39
	Reference	$/t	0.57	0.43	0.35	0.52	0.45	0.36	0.55	0.44	0.36	0.51	0.46	0.38	0.55	0.48	0.40	0.57	0.48	0.41
	Pessimistic	$/t	0.57	0.48	0.35	0.52	0.46	0.38	0.55	0.45	0.38	0.51	0.46	0.39	0.55	0.49	0.42	0.57	0.50	0.43
Nitrogen production costs per ton	Optimistic	$/t	18.98	16.06	15.73	17.68	16.6	15.51	18.87	16.6	16.26	17.9	17.46	17.03	18.39	17.25	16.81	17.25	15.51	15.51
	Reference	$/t	18.98	16.46	15.87	17.68	16.81	16	18.87	17.11	16.59	17.9	17.54	17.14	18.39	17.46	17.24	17.25	16.1	16.12
	Pessimistic	$/t	18.98	17.68	15.95	17.68	17.03	16.49	18.87	17.36	16.92	17.9	17.68	17.25	18.39	17.68	17.68	17.25	16.6	16.6
Hydrogen production costs per kg	Optimistic	$/kg	2.23	0.86	0.59	1.65	1.1	0.51	2.19	1.1	0.79	1.8	1.52	1.11	1.97	1.38	1	1.5	0.66	0.53
	Reference	$/kg	3.42	1.68	1	2.81	1.84	1.04	3.37	1.98	1.28	3.19	2.34	1.6	3.15	2.13	1.54	2.81	1.65	1.17
	Pessimistic	$/kg	6.7	3.79	1.95	6.08	3.48	2.17	6.66	3.65	2.36	6.82	4.2	2.79	6.44	3.69	2.67	6.33	3.58	2.44

It is important to note that cost is not the only criterion to consider when evaluating such substantial projects. Other factors, including economic and political stability, as well as land availability, must also be taken into account (Nhan Le et al. 2023; Aisen and Jose Veiga 2010).

3.2 Estimated costs of e-ammonia

This section examines the projected production costs of green ammonia across three specific timeframes: the current year (2024), 2030, and 2050. Considering the maturity level of green ammonia engines, the further primary focus of the results will be from 2030 to 2050. This period is critical for assessing the long-term viability and cost-efficiency of green ammonia as a sustainable marine fuel, considering technological advancements and scaling production capabilities. However, it should be highlighted that potential delays in technology improvements, such as the development of more efficient electrolyzes or ammonia synthesis methods, may hinder the expected cost reductions. Additionally, market adoption could be slower than anticipated due to regulatory hurdles, infrastructure challenges, or competition from alternative fuels.

As an example, by 2050, projections suggest that more than 70% of global hydrogen production will originate from green electrolysis, representing a substantial increase from less than 1% today. This shift will necessitate a tripling of renewable energy generation, rising from the current 290 GW annually to over 1 TW by the mid-2030s (Bahador 2023). At the same time, the installed capacity of electrolyzes must expand dramatically, from 700 MW in 2021 to between 4 and 5 TW by 2050. Realizing this ambitious goal will require approximately US$4 trillion in investment by 2050, in contrast to the over US$330 billion currently allocated by governments and corporations pursuing hydrogen strategies (Bahador 2023).

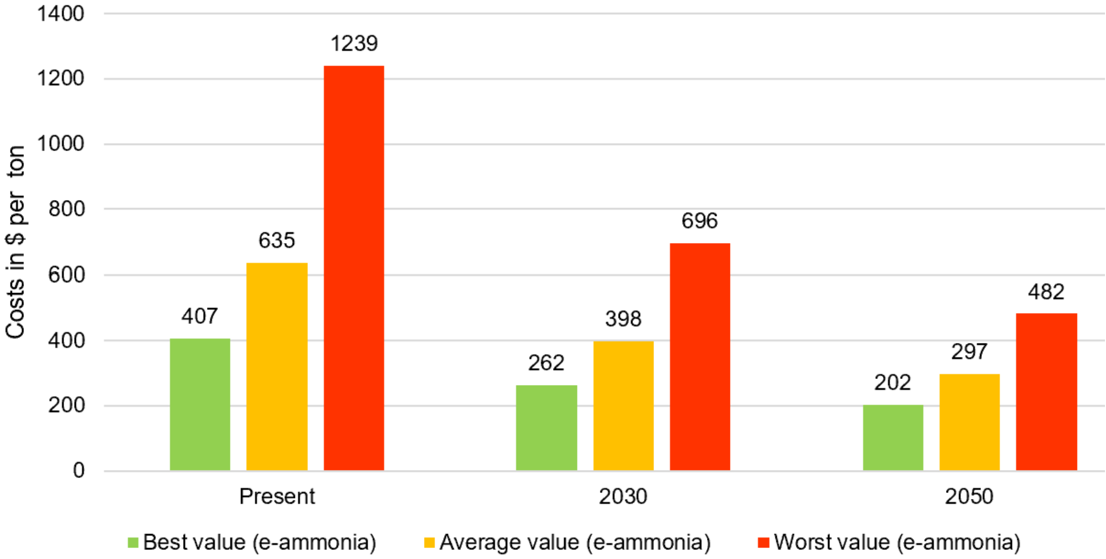
Several significant challenges persist. These include the need for greater renewable energy generation capacity, high costs throughout the value chain, limitations in infrastructure for distribution and storage, and insufficient commercial viability for many applications in the near to medium term (Bahador 2023). The enthusiasm surrounding green ammonia is now confronting the realities of the market, with increasing acknowledgment that the investment landscape, especially for early-stage projects, is complex. The green ammonia market and its associated value chains are still developing, with most ongoing initiatives remaining at pilot or pre-commercial stages (Bahador 2023).

The analysis centers on the utilization of photovoltaic (PV) and onshore wind technologies as primary sources of electricity. Figure 6 presents the variations in average production costs of green ammonia for all regions included in the study.

The projections of green ammonia production costs are categorized into three scenarios: best case, average case, and worst case. These scenarios reflect varying degrees of technological advancement and economic conditions that may impact production costs. In the graph, "Best" values indicate scenarios with the lowest production costs, characterized by maximum efficiencies, minimal Levelized Cost of Energy (LCOE), and other optimal conditions. Conversely, "Worst" values depict scenarios with the highest production costs, marked by minimal efficiencies, maximal LCOE, and less favorable conditions.

As observed from Figure 6, there is a notable decreasing trend in the production costs across all scenarios, which reflects projected improvements in efficiencies and technological advancements. According to Figure 6, in 2024, the average production costs for green ammonia vary between $407 and $1,239 per ton. These cost variations are primarily attributed to differences in the electricity costs, variations in plant efficiencies, as well as different investment and operational cost estimates. Additionally, installed capacities mainly for hydrogen and ammonia plants and the Weighted Average Cost of Capital (WACC) significantly influence the investment costs associated with technologies such as hydrogen production and air separation units.

Figure 6: Projected production costs of e-ammonia in $/ton (2024-2050)

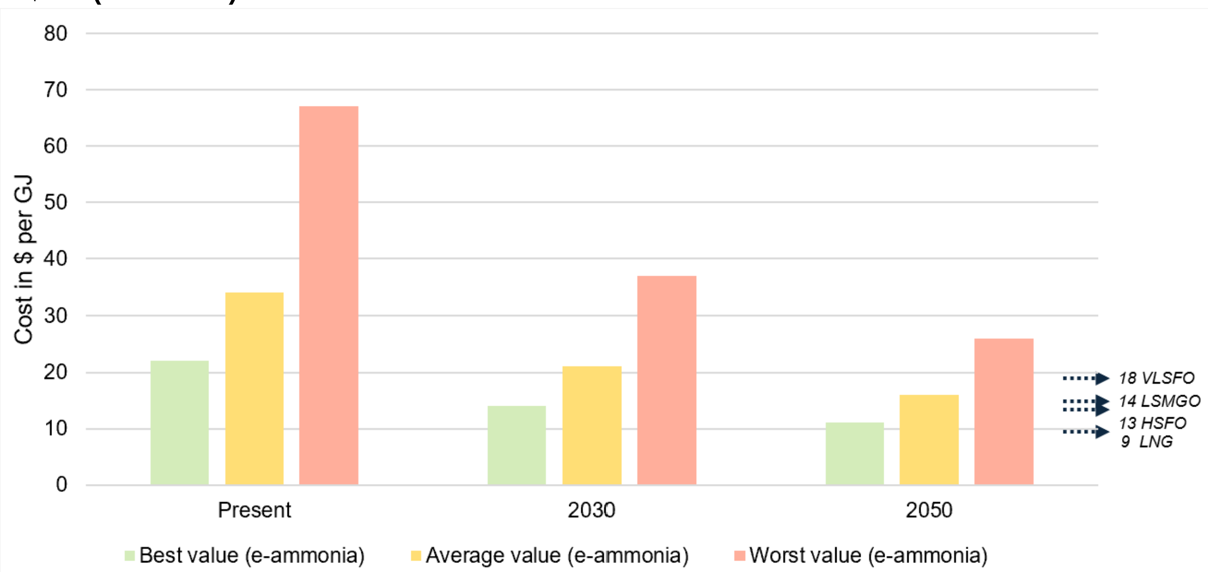


Source: Authors' own calculations.

By 2030, the production costs for green ammonia are projected to decrease significantly. The average cost across all regions falls to between $262 (for best case) and $696 per ton (for worst case), representing a substantial reduction of approximately 36% to 44%.

In 2050, the production costs for green ammonia are projected to continue to decline, with costs ranging between $202 and $482 per ton. Achieving these cost reductions depends on scaling up production to benefit from higher efficiency and learning effects. Also, this would depend on potential advancements in technology and efficiencies, including a significant incorporation of renewable energy sources and enhancements in electrolysis techniques, which are critical to the production of green ammonia. Moreover, increasing global emphasis on reducing carbon emissions will drive policy support and investment into research and development of more sustainable and economically viable production methods. Despite these promising projections, the substantial variance between the best and worst-case scenarios underscores the uncertainties inherent in such forecasts.

Figure 7: Projected production costs of green ammonia compared to conventional marine fuels in $/GJ (2024-2050)



Source: Authors' own calculations.

Figure 7 provides a comprehensive view of the projected costs of green ammonia compared to conventional marine fuels over the years 2024, 2030, and 2050 measured in dollars per gigajoule (GJ). It illustrates the cost dynamics of green ammonia across three scenarios—best, average, and worst case—against the backdrop of current marine fuel prices including Very Low Sulfur Fuel Oil (VLSFO), Low Sulfur Marine Gas Oil (LSMGO), High Sulfur Fuel Oil (HSFO), and Liquefied Natural Gas (LNG). Green ammonia, with a relatively low energy density of 18.6 MJ/ton is less energy-dense compared to conventional fuels such as LNG (55 MJ/kg) (UNITROVE 2024)), VLSFO (41.6 MJ/kg (Marsch and Shamray 2019), LSMGO (42.8 MJ/kg (Marsch and Shamray 2019), and HSFO (40.4 MJ/kg (Marsch and Shamray 2019)). This lower energy density implies that, despite a lower cost per GJ by 2050, green ammonia might still represent a more expensive option in practical terms as more of it would be required to produce the same energy output as its fossil fuel counterparts.

Currently, green ammonia's cost per gigajoule is substantially higher across all scenarios compared to conventional fuels. The best-case scenario for green ammonia is $22 per GJ, which is still more expensive than even the most costly conventional fuel, LSMGO, priced at $14 per GJ. HSFO and LNG are notably cheaper, at $13 and less than $9 per GJ, respectively, underscoring the initial economic challenge for green ammonia adoption. By 2030, green ammonia's costs are projected to decrease significantly. In the best-case scenario, green ammonia becomes as cost-effective as LSMGO currently, at $14 per GJ, indicating a shift towards competitiveness with conventional fuels. However, it still lags behind LNG, which remains the cheapest option. By 2050, the graph indicates a more dramatic shift. Green ammonia's cost in the best-case scenario is forecasted to drop to $11 per GJ, potentially making it cheaper than all current conventional fuels except LNG, assuming their prices remain constant.

3.3 Comparative assessment of the results

This section undertakes a comparative analysis of the prospective roles of green ammonia, focusing on its cost competitiveness and strategic position relative to both conventional and renewable fuel alternatives. Three principal evaluations are conducted to elucidate these aspects.

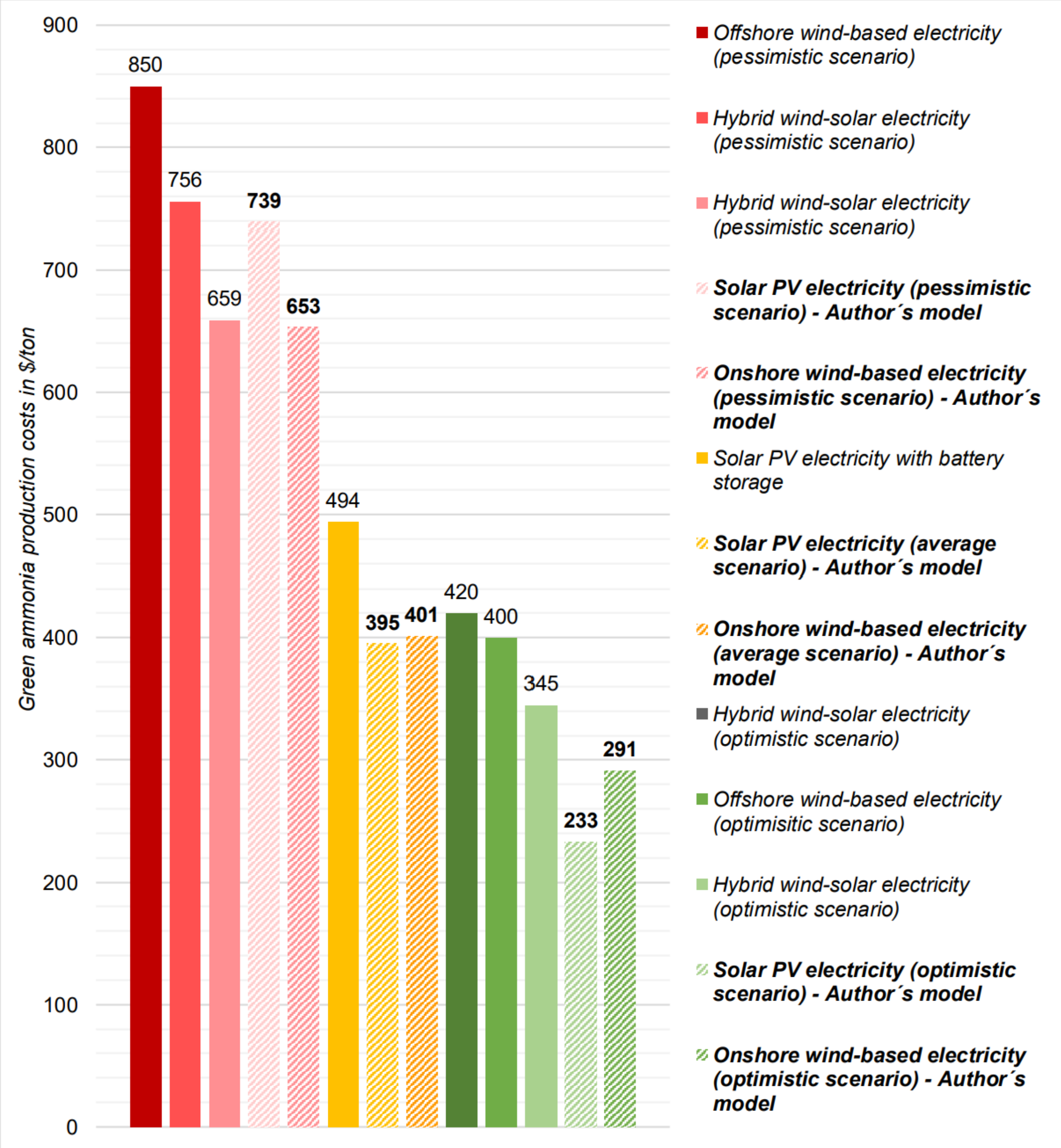
3.3.1. Different technologies

Firstly, as depicted in Figure 8, the analysis involves correlating the author's model forecasts for 2030 and 2050 with data from existing studies on green ammonia. This correlation serves as a crucial test to validate the reliability and robustness of the model's predictions by examining their consistency with established research findings in the field. The assessment reveals considerable variability in the anticipated costs, influenced by factors such as the source of renewable energy used and the operational efficiencies of the plants. This variability underscores the complexity of accurately predicting green ammonia costs and highlights the critical influence of external economic and technological factors on these projections.

Figure 8 below delineates the projected costs of green ammonia production for 2030, leveraging various energy sources across multiple scenarios—optimistic, average, and pessimistic. Each scenario reflects possible advancements and efficiencies, revealing how different energy strategies might impact the economics of green ammonia production. Green ammonia production costs utilizing offshore wind-based electricity are among the highest within the various scenarios. The pessimistic scenario indicates a cost of $850 per ton, and even under more favorable conditions, costs remain elevated at $756 per ton. These costs highlight the potential challenges associated with offshore wind, including high infrastructure and maintenance costs, which may undermine its cost-effectiveness for green ammonia production (Campion et al. 2023). In contrast, hybrid wind-solar electricity systems demonstrate considerably lower production costs. Under pessimistic assumptions, costs are estimated at $420 per ton, while optimistic projections suggest a more economical $345 per ton (Bellini 2021). This significant cost reduction reflects the advantages of combining wind and solar power, which not only mitigates the intermittency associated with each energy source but also leverages their synergistic potentials to boost economic efficiency. This strategic integration suggests that hybrid systems could offer a more sustainable and cost-effective approach to green ammonia production. The integration of solar PV electricity with battery storage shows a cost of $494 per ton. While the addition of battery storage involves higher upfront costs, it enables a more consistent energy supply, which is crucial for continuous ammonia production processes.

Among the scenarios modeled by the author, solar PV electricity offers the lowest costs, particularly under the optimistic scenario at $223 per ton, underscoring solar energy potential as a cost-effective solution for green ammonia production. The analysis also includes a scenario using onshore wind-based electricity, priced at only $291 per ton in an optimistic setting suggesting that onshore wind could serve as a more cost-effective and viable middle-ground option.

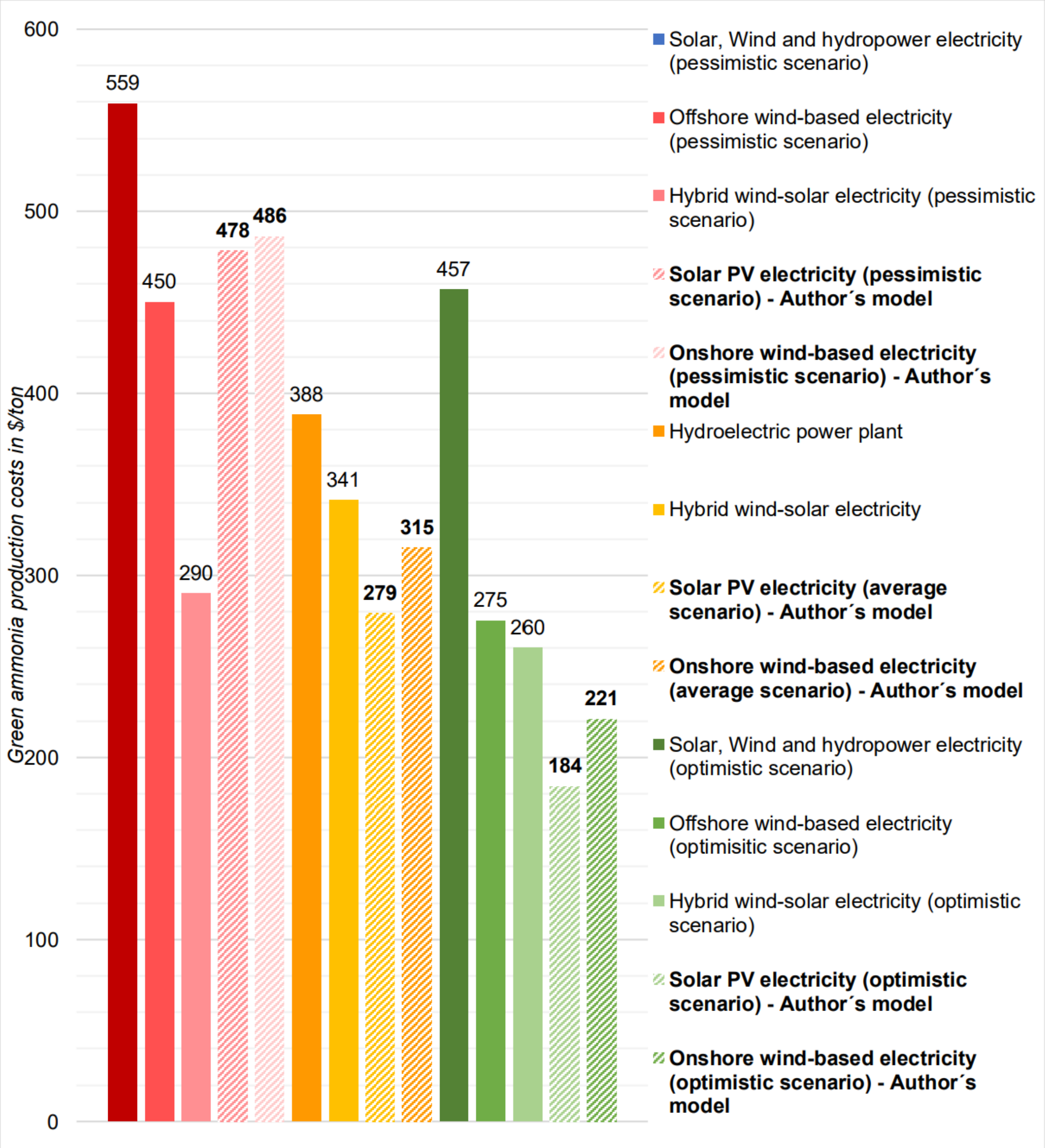
Figure 8: Benchmarking estimates: Projected costs of green ammonia production in 2030: A comparative analysis of renewable energy scenarios



Source: Authors' own illustration.

Figure 9 offers a comprehensive projection of the potential costs associated with green ammonia production in 2050 utilizing a variety of renewable energy sources across several scenarios from pessimistic to optimistic. Offshore wind-based electricity, a major contributor to green ammonia production, is anticipated to see its costs substantially reduced to approximately 275 $/ton in the optimistic scenario. Even under less favorable conditions, the projected cost does not surpass 500 $/ton, indicating potential advancements in offshore wind technology or decreases in associated costs over the coming decades. Hybrid systems combining wind and solar power also show promising projections, with costs aligning in the mid-range spectrum. This suggests that the synergy between wind and solar could yield a consistent and reliable energy output, beneficial for continuous industrial processes like ammonia production (Bellini 2021; Wang, Zhang, and Daoutidis 2023). Hydroelectric power emerges as one of the most cost-effective solutions, with projections around 388 $/ton. The efficiency and low operational costs of hydroelectric power could make it a cornerstone in the energy mix for green ammonia production (Rivarolo et al. 2019).

Figure 9: Benchmarking estimates: Projected costs of green ammonia production in 2050: A comparative analysis of renewable energy scenarios



Source: Authors' own illustration.

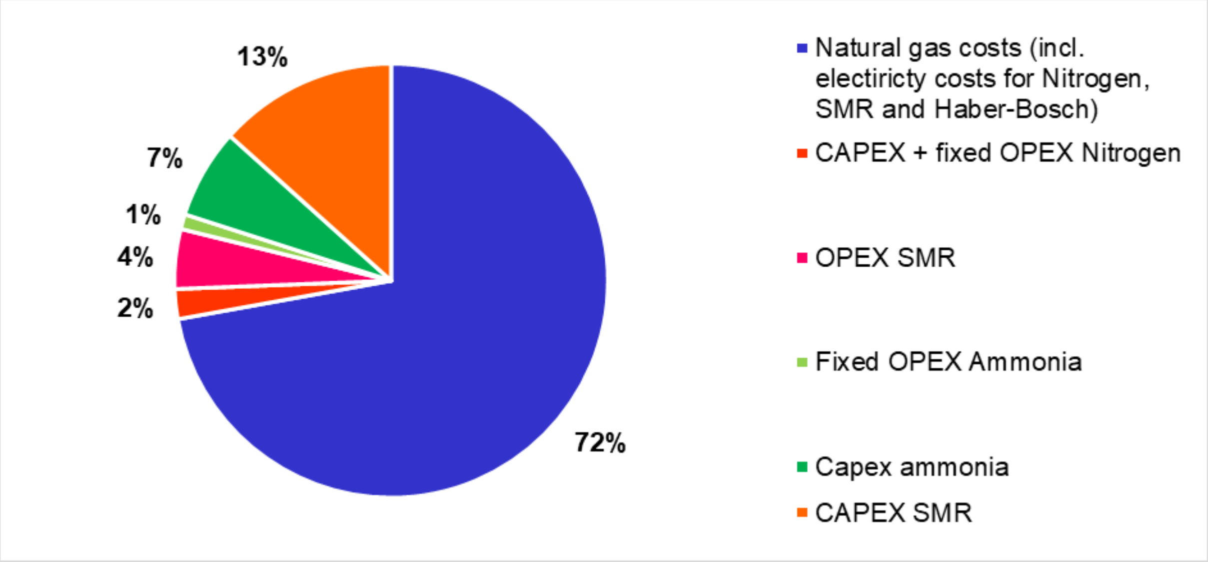
The solar PV electricity scenarios outlined in the author's model show an optimistic cost of about 183 $/ton, suggesting solar PV's potential to become an extremely economical choice due to advances in technology or reductions in component costs. Even under average and pessimistic conditions, the costs remain competitive, underpinning the robustness of solar PV as a key player in future energy strategies. Onshore wind-based electricity remains also cost-effective at about 221 $/ton in the optimistic scenario.

3.3.2. Comparison with conventional ammonia

The second comparison involves juxtaposing the model results with the anticipated conventional ammonia prices for 2030 and 2050.

Conventional ammonia production primarily relies on natural gas as its essential raw material. The production of one ton of ammonia requires approximately 33 million British thermal units (mm Btu) of natural gas. The cost of natural gas constitutes 72% to 85% of the total ammonia production cost with variations depending on the size of the production plant and the prevailing market price of ammonia (Huang 2007) (see Figure 10 below). These percentages have been employed to project ammonia production costs through to the year 2050. Future natural gas prices are sourced from Statista's forecasts for the years 2030 and 2050 (Statista 2023). Figure 11 illustrates the estimated production costs derived from the provided model, alongside the projected costs for conventional and green ammonia based on anticipated natural gas prices. It is important to note that these estimates do not account for environmental costs, such as carbon taxes or sustainability penalties.

Figure 10: Projected cost composition for conventional ammonia



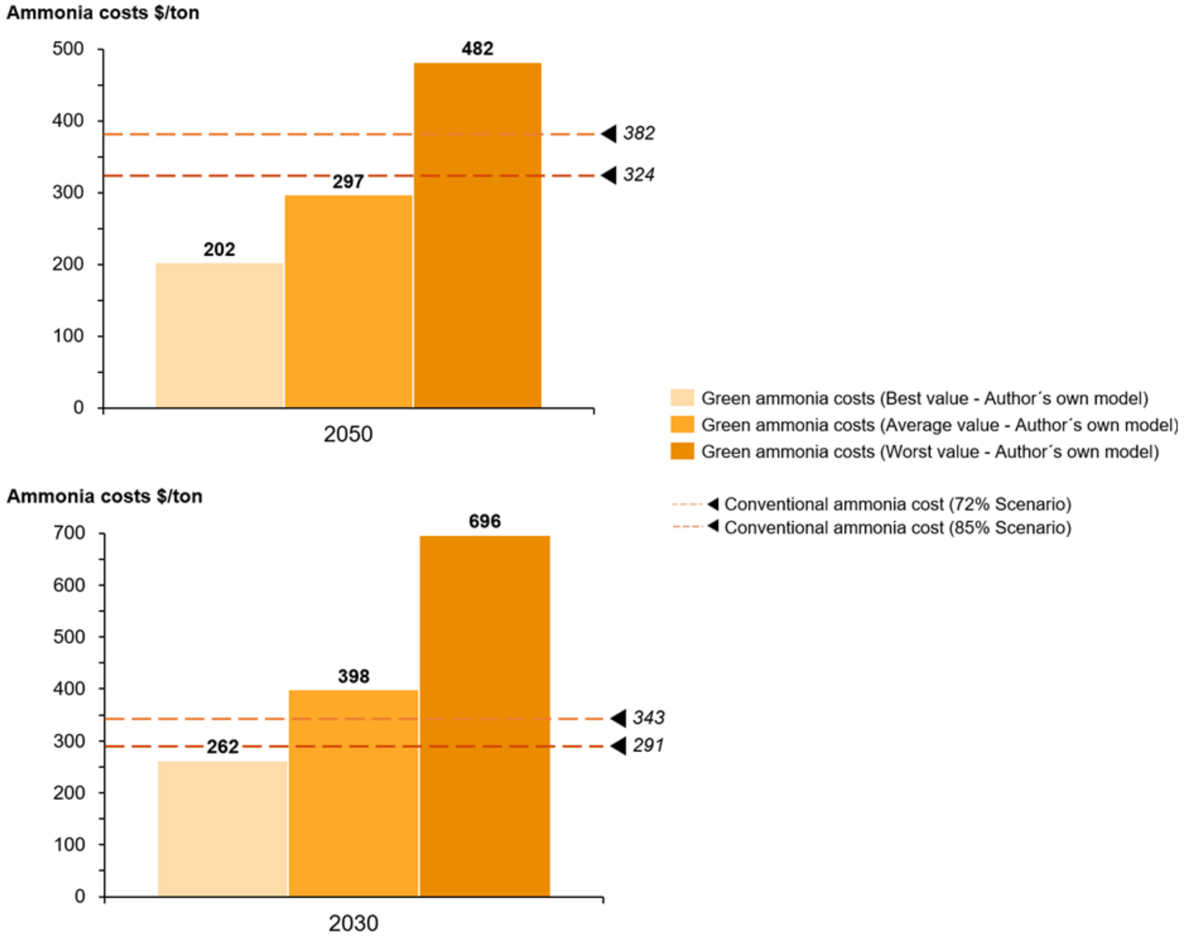
Source: (Saygin et al. 2023), Authors' own illustration.

In 2030, conventional ammonia costs are estimated to be $291 per ton in scenarios where natural gas makes up 85% of the production costs, and $344 per ton where natural gas accounts for 72% of the costs. In these estimations, the most favorable scenario for green ammonia production shows greater cost efficiency at $262 per ton; however, both the average and worst-case scenarios for green ammonia production are higher, with the worst-case scenario being more than twice as expensive as conventional ammonia.

By 2050, the cost of conventional ammonia is projected to increase to $324 and $382 per ton, respectively. This upward trend reflects the expected rise in natural gas prices, highlighting the susceptibility of conventional ammonia production to volatility in gas markets. The best-case production costs for green ammonia are projected to be approximately 47% lower than the conventional costs under the 72% natural gas scenario. Although the average costs of green ammonia are more economical, the worst-case scenario shows green ammonia being only $100 more per ton than the 85% scenario for conventional ammonia.

The diminishing cost disparity between conventional and green ammonia in both 2030 and 2050 reflects massive improvements in technology and efficiency. This emphasizes the need for strategic investments in green ammonia technologies and supportive policy frameworks that facilitate the transition from fossil fuel dependency.

Figure 11: Comparative cost analysis of conventional and green ammonia production in 2030 and 2050



Source: Authors' own illustration.

It is also important to mention that environmental costs associated with conventional ammonia production are not considered in the previous comparison. For example, approximately 1.6 tons of CO2 are emitted per ton of grey ammonia (Royal Society 2020). Factoring in a carbon price of $62.5 per ton, the net cost differential would decrease by $100, further enhancing the competitiveness of green ammonia, even under worst-case scenarios by 2050. A carbon price of $221 per ton would be sufficient to render green ammonia more economically viable than conventional ammonia by 2030.

3.3.3 Alternative fuels

Green ammonia represents just one of several potential replacements for conventional ammonia, particularly within the maritime sector. Current discourse also explores alternatives such as low sulfur fuels and green methanol. In this paper, a comprehensive comparative assessment has been conducted, where green ammonia is evaluated against these alternatives in terms of costs, energy density, CO2 emissions, and commercial readiness. Specific focus has been given to low sulfur fuels—predominantly LNG (Liquefied Natural Gas) and HFO (Heavy Fuel Oil) with scrubbers—as well as bio- and green methanol. This multifaceted evaluation aims to delineate the most practical and environmentally beneficial options available for modern shipping practices.

Table 3: Evaluating alternative fuels for the maritime sector: costs. energy density. emissions. and readiness

	Green ammonia	HFO + scrubbles	LNG	Bio-methanol	Green methanol
Costs	**$143/MWh** to **$219/MWh** By 2050. expected to be between **$67/MWh** and **$114/MWh**	Around **$41/MWh**	**$27.30** to **$34.12/MWh**	**$57.89/MWh** to **$139.30/MWh**	**$144.72/MWh** to **$289.45/MWh** + expected to fall progressively, eventually achieving a 2050 cost of between **$107/MWh** and **$145/MWh**
Energy density	18.6 MJ/kg	39-42 MJ/kg	50-55 MJ/kg	15.6 MJ/kg	19.5 MJ/kg
CO2 emissions	**Carbon-neutral if produced from renewable sources** *NOTE: vessel engines operating on green ammonia still require small amounts of a pilot fuel to combust. so it is important that the pilot fuel also be carbon zero*	**Roughly 3.15 tonnes CO2 per ton of HFO burned** *Note: Reduced emissions by 80-90% for SOx and up to 70% for particulate matter with scrubbers*	**Roughly 2.76 tonnes CO2 per ton of LNG burned** *Note: Reduced SOX emissions by 99%. NOx by 60%. particulates by 95%*	**Carbon-neutral if produced from renewable sources**	**Carbon-neutral if produced from renewable sources**
Commercial readiness	Emerging, with some pilot projects in shipping TRL=4	Widely used, but facing regulatory pressure due to emissions TRL=9	Growing, with increasing adoption and infrastructure development TRL=8-9	Growing interest and adoption, but infrastructure development ongoing TRL=6	Still in early stages of commercialization, with infrastructure development ongoing TRL=5-6

Table 3 above is derived from the IRENA study, which provides a comprehensive overview of potential pathways to decarbonize the maritime sector by 2050, with green ammonia highlighted as a potentially transformative fuel given its favorable environmental and economic trajectories. Currently priced between $143/MWh and $219/MWh, green ammonia is projected to decrease in cost to between $67/MWh and $114/MWh by 2050. In contrast, HFO with scrubbers and LNG, priced around $41/MWh and ranging from \$27.30 to \$34.12/MWh respectively, offer more cost-effective solutions at present. However, these fuels impose significant environmental burdens. For example, HFO with scrubbers emits approximately 3.15 tons of CO2 per ton of fuel burned, despite reductions in sulfur and particulate emissions by up to 80-90% and 70%, respectively, due to modern scrubbing technologies. LNG emits about 2.76 tons of CO2 per ton of HFO equivalent burned and, while offering a higher energy density of 50-55 MJ/kg compared to green ammonia's 18.6 MJ/kg, faces challenges related to methane slip and infrastructure requirements.

Bio-methanol and green methanol present viable mid-range options, both in terms of cost and emissions. Bio-methanol is priced between \$57.89/MWh and \$139.30/MWh, while green methanol ranges from \$144.72/MWh to \$289.45/MWh, with prices anticipated to decrease to between \$107/MWh and \$145/MWh by 2050. Both types of methanol are carbon-neutral when produced from renewable sources and feature energy densities comparable to LNG. The primary challenge with green methanol involves sourcing carbon dioxide from carbon capture technologies, which are not only costly but also still developing. Moreover, bio-methanol's feasibility as a long-term alternative is questionable due to extensive land use requirements for feedstock production and potential limitations in scaling up gasification technologies.

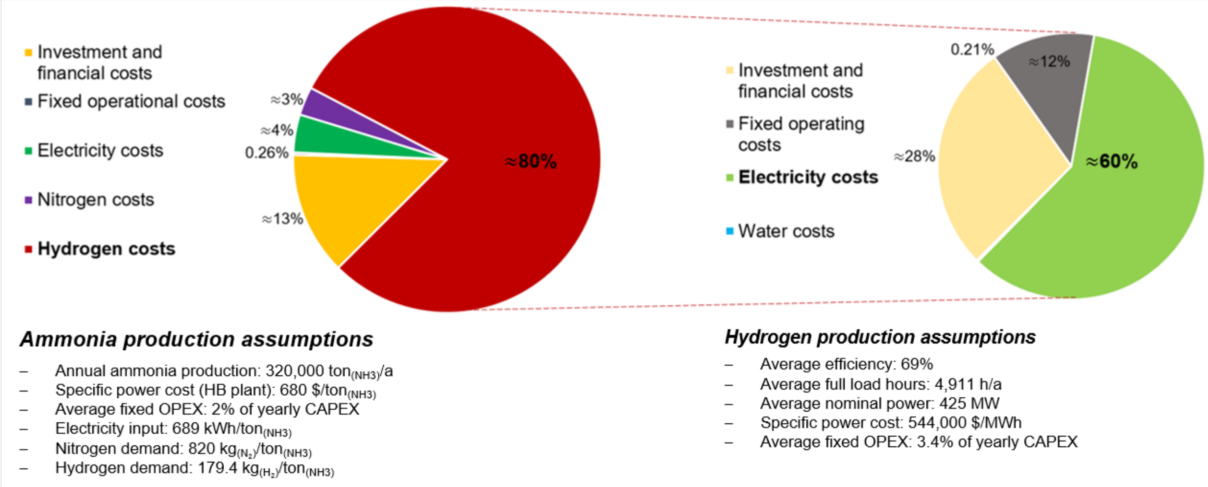
Green ammonia, though still in the early stages of commercial deployment with several pilot projects in shipping, is emerging as a notable alternative. It is carbon-neutral if produced from renewable sources and does not contribute to CO2 emissions during use. Although initial usage requires small quantities of pilot fuel for combustion in vessel engines, ongoing advancements in technology are expected to improve its standalone utility.

3.4 Costs composition for e-ammonia

According to the 1.5°C scenario outlined by the International Renewable Energy Agency (IRENA), green ammonia is projected to account for approximately 35.7% of the total energy demand in the shipping sector by 2050 (Atchison 2021). This target can´t be achieved without significant cost reductions by then. To understand the potential decrease in costs, the cost compositions for the average-costs results in 2030 are presented in Figure 12. It provides a comparative analysis of the projected cost compositions for green ammonia and green hydrogen production projected for 2030, highlighting distinct economic challenges and focal points for each.

Starting with green ammonia, the pie chart illustrates that the majority of the production cost—approximately 80%—is attributed to hydrogen costs. This significant proportion underscores the dependency of green ammonia production costs on the efficiency and affordability of hydrogen production techniques. Such high dependency suggests that any technological advancements or reductions in hydrogen production costs could dramatically influence the overall economic viability of green ammonia. Nitrogen costs, which are necessary for the synthesis of ammonia, make up about 4% of the total costs. This relatively low percentage indicates that, while essential, nitrogen is not a major financial burden in the production process. Investment and financial costs also represent a significant portion, amounting to 18% of the total. This indicates a considerable capital requirement for the infrastructure and technologies needed to produce green ammonia, underscoring the importance of capital investment in the overall economic feasibility of the production process. Electricity costs account for 3% of the total costs, and fixed operational costs are minimal, making up only 0.36% of the total. This small percentage reflects efficient operational management and potentially high automation levels in the production facilities, minimizing the costs associated with regular operations.

Figure 12: Projected cost composition for green ammonia and green hydrogen production in 2030



Source: Authors' own calculation.

This cost distribution underscores the need for innovations in hydrogen production technologies and strategies to manage investment costs effectively to enhance the overall economic viability of green ammonia as a sustainable alternative fuel. Turning to the cost composition for green hydrogen, electricity costs dominate, accounting for about 60% of the total costs. This reflects the energy-intensive nature of the electrolysis process. Investment and financial costs follow at approximately 28%, indicating a need for significant capital investment. Fixed operating costs contribute around 12%, and water costs are minimal, around 0.21%, indicating their minor role in the broader cost structure but still essential for the electrolysis process.

This detailed cost analysis highlights the need for targeted technological innovations and strategic management of investment costs to enhance the economic feasibility of these sustainable energy technologies. For green ammonia, reducing hydrogen production costs is critical, whereas for green hydrogen, decreasing electricity consumption and managing operational efficiencies are paramount. This comparative understanding is essential for stakeholders in the energy sector to develop effective strategies for the adoption and scaling of green ammonia and green hydrogen as viable alternative fuels.

4. Policy analysis

Building on the detailed cost analysis provided, this section transitions into a sensitivity analysis focused on the impact of policy support and regulatory changes on conventional marine fuels and green ammonia. This analysis explores how enhanced policy mechanisms could elevate the competitiveness of green ammonia, aligning it more closely with traditional fuel options and influencing its adoption rate within the shipping industry. By examining the potential effects of policy interventions, a better understanding of the dynamics that may drive broader acceptance and economic viability of green ammonia as a sustainable alternative can be achieved.

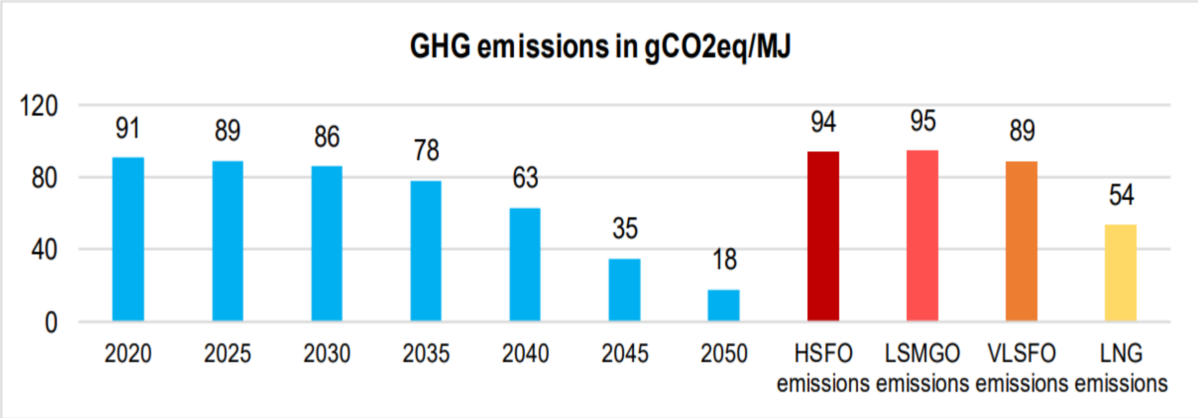
4.1 GHG penalties on conventional marine fuels

In 2023, the European Union adopted the FuelEU Maritime regulation, which mandates the use of renewable and low-carbon fuels in maritime transport to promote sustainable practices within the industry (European Council 2023). This regulation, set to become mandatory across all EU Member States by 2025, aims to reduce the greenhouse gas (GHG) intensity of energy utilized on board ships. It introduces a compulsory adoption of onshore power supply or zero-emission technologies at ports, significantly impacting maritime operations throughout the EU (European Council 2023).

The regulation applies to all maritime vessels operating within the EU with a gross tonnage exceeding 5,000, encompassing both commercial passenger and cargo ships, irrespective of their flag (European Council 2023). It specifies a progressive reduction in GHG emissions for all energy consumed during voyages within the EU, and for 50% of the energy used on voyages that enter or exit the EU (European

Council 2023). Exceptions are provided for vessels serving small islands, public service obligations. outermost regions, transshipment ports, and ice-class ships navigating icy waters. To enforce these environmental standards, the regulation establishes precise limits on GHG emission intensity per unit of energy consumed by ships, targeting an 80% reduction by 2050 from a baseline set in 2020 (European Council 2023). This trajectory is detailed in Figure 13, which illustrates the gradually lowering permissible emission levels per megajoule of marine fuel used as well as the lifecycle GHG intensity of marine fuels (Comer and Osipova 2021; SEA-LNG 2024). Should a vessel fail to meet these stringent requirements, the regulation stipulates financial penalties based on the extent of the non-compliance (European Council 2023).

Figure 13: Projected GHG emission intensity limits for maritime fuels according to ReFuel Maritime (2020-2050) and current emissions of conventional marine fuels



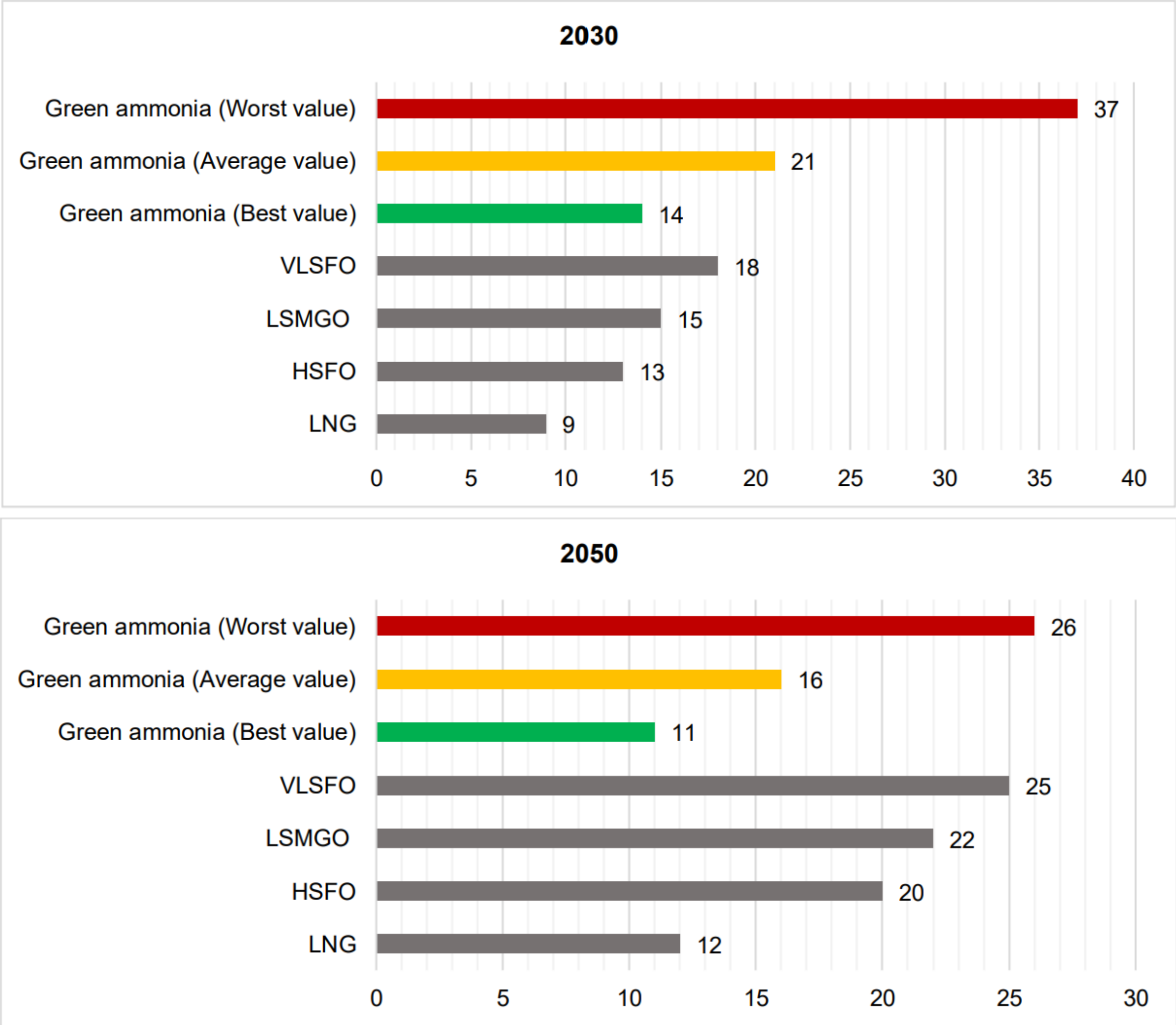
Source: Authors' own illustration.

This initial sensitivity analysis evaluates the effects of a new policy on traditional marine fuels and examines its potential to boost the competitiveness of green ammonia compared to these conventional fuels. The emission limits are derived from the ReFuel Maritime directive, while the penalties for non-compliance are based on the European Union's Emissions Trading System (EU ETS). According to the EU ETS, penalties include a fee of €100 per tonne of CO2 equivalent for each tonne of GHG emissions not accounted for. It is stipulated that the names of companies failing to meet these requirements will be publicly disclosed (argus 2023). Additionally, if a shipping company repeatedly fails to fulfill its surrendering obligations for two or more years, the EU member state where the port of entry is located may deny access to the vessels of the offending company until they comply with their ETS obligations (argus 2023).

Figure 14 below presents a comparative analysis of the projected costs associated with various marine fuels under ReFuel Maritime GHG limitations and the EU ETS penalties for the years 2030 and 2050. In the projected analysis for 2030, the cost of LNG is estimated at $9/GJ, with a moderate increase to $12/GJ by 2050, reflecting its relatively lower carbon intensity. HSFO, which is more carbon-intensive, is expected to experience a substantial cost increase from $13/GJ in 2030 to $20/GJ in 2050, highlighting the significant financial impact of GHG penalties on traditional high-emission fuels. Similarly, LSMGO and VLSFO are projected to see their costs rise substantially—from $15/GJ to $22/GJ for LSMGO, and from $18/GJ to $25/GJ for VLSFO—as emission regulations continue to tighten. This significant cost escalation underscores the increasing financial burden associated with using high-emission fuels under the EU Emissions Trading System (ETS), even with a penalty of $100/ton CO2 equivalent. It is important to note that if the penalty were to increase to $300/ton CO2 equivalent in 2050, the costs could rise even more dramatically, with VLSFO potentially reaching $39/GJ, LSMGO $29/GJ, HSFO $28/GJ, and LNG $20/GJ. These trends vividly illustrate the escalating costs of conventional marine fuels as stricter environmental policies are implemented.

In contrast, green ammonia presents a markedly different cost trajectory under these conditions. In the best-case scenario, the cost of green ammonia is projected at $14/GJ in 2030, decreasing to $11/GJ by 2050, positioning it as an increasingly competitive alternative to conventional fuels. When compared to the projected 2030 costs of conventional fuels, green ammonia's best-case scenario is only about 56% higher than LNG, 7% higher than HSFO, and is already less expensive than VLSFO. By 2050, green ammonia could be cheaper than all conventional fuels, with its best-case scenario cost being approximately 45% lower than VLSFO. Even under average conditions, where costs decrease from $21/GJ in 2030 to $16/GJ in 2050, green ammonia becomes more economically viable compared to traditional fuels, especially considering the potential rise in emission penalties. The worst-case scenario for green ammonia, while initially higher, shows a cost reduction from $37/GJ in 2030 to $26/GJ in 2050, which suggests that green ammonia could still improve in competitiveness over time, particularly as production efficiency increases and market conditions evolve.

Figure 14: Projected 2030-2050 costs of marine fuels under GHG emission penalties according to the EU ETS: Evaluating the competitiveness of green ammonia $/GJ



Source: Authors' own calculation.

This analysis reveals that while traditional marine fuels may initially appear more cost-effective, the long-term financial landscape, shaped by stricter emission regulations and higher penalties, increasingly favors green ammonia. The rising costs associated with conventional fuels, driven by regulatory measures, position green ammonia as a viable and potentially more economical alternative in the maritime industry.

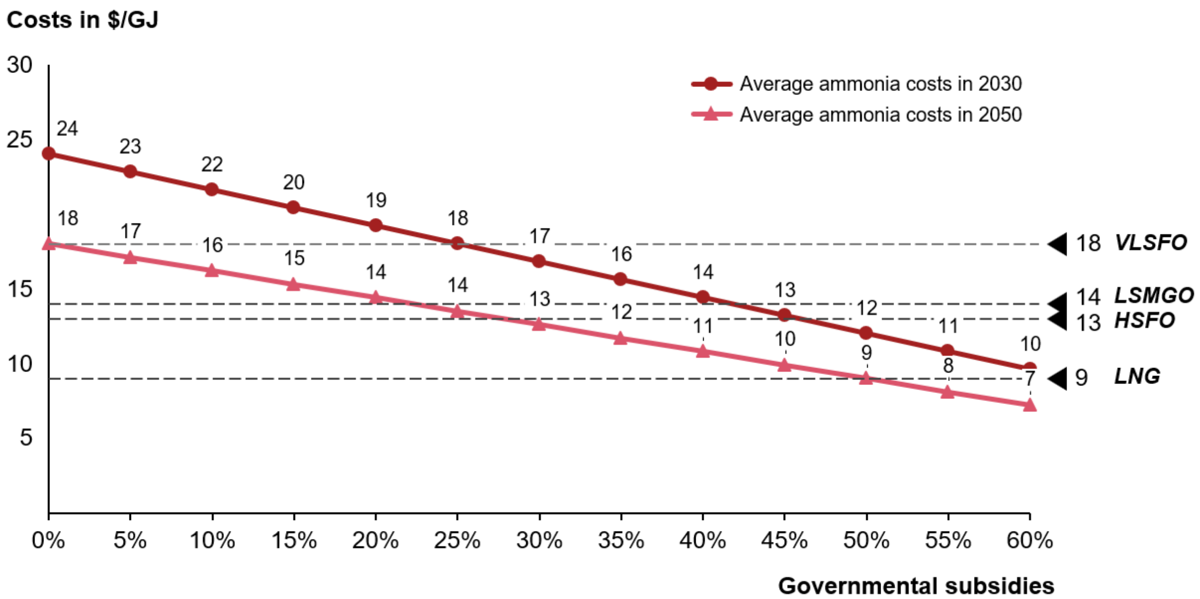
4.2 Subsidies and support for green ammonia

To support the development and widespread adoption of green ammonia, governments can implement a variety of policies that combine financial incentives, regulatory frameworks, and infrastructure development. These policies play a critical role in making green ammonia a competitive alternative to conventional fuels (Eisenhuth, Hubert, and Betina 2022). One of the most effective ways governments can support green ammonia is through the introduction of production subsidies (Eisenhuth, Hubert, and

Betina 2022; Korchunov and Beyer 2024). These subsidies reduce the cost differential between green ammonia and conventional fuels, encouraging large-scale production. Similar to mechanisms used for renewable electricity and green hydrogen, production subsidies can help bridge the financial gap by covering part of the production costs (Eisenhuth, Hubert, and Betina 2022; Korchunov and Beyer 2024). Additionally, tax credits and exemptions could be applied to capital investments in green ammonia production facilities, lowering operational costs and providing more financial certainty for investors (Eisenhuth, Hubert, and Betina 2022; Korchunov and Beyer 2024).

The following sensitivity analysis explores a gradual increase in governmental support for green ammonia production over time. In this scenario, subsidies start at 0% and rise to 60%, calculated relative to the average production costs between 2030 and 2050. The objective is to identify the break-even point at which green ammonia becomes equally competitive with conventional marine fuels and LNG. This analysis aims to determine the level of governmental intervention required for green ammonia to achieve cost parity with traditional fuels, considering that higher subsidies will lower the effective production costs and potentially make green ammonia a more attractive alternative in the maritime sector. The figure below presents a detailed cost analysis of green ammonia in relation to conventional marine fuels, including VLSFO, LSMGO, HSFO, and LNG, under different levels of governmental subsidies. The two lines represent the average cost of green ammonia in 2030 and 2050, illustrating how costs are expected to change over time and how subsidies could make green ammonia competitive with conventional fuels.

Figure 15: Projected cost competitiveness of green ammonia with conventional marine fuels (2030-2050) under various government subsidy levels



Source: Authors' own calculation.

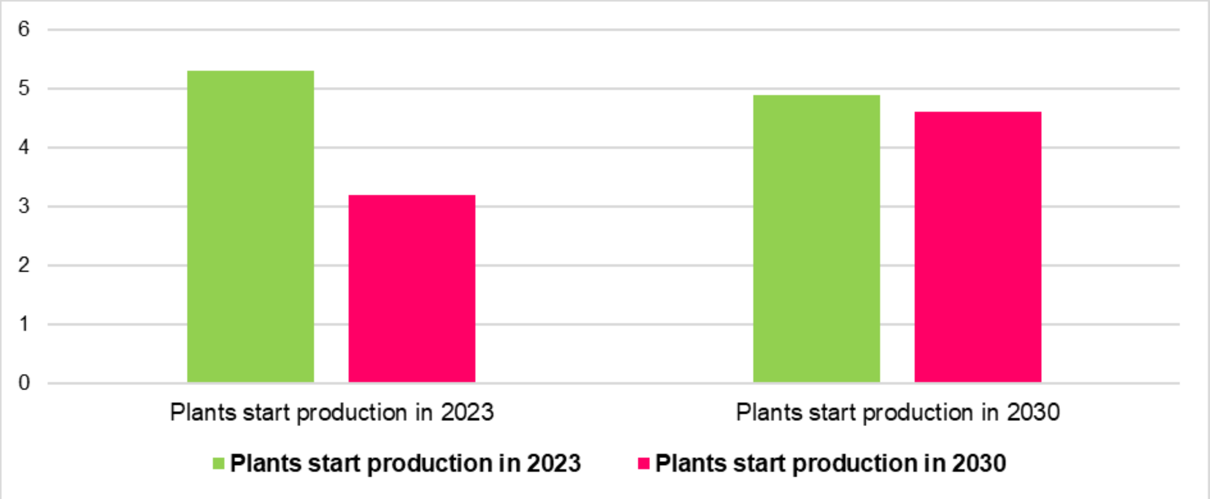
As shown in Figure 15, by 2030, subsidies of more than 60% would be necessary for green ammonia to compete with LNG. Lower subsidies are required for other fuels, with approximately 45% and 40% sufficient to make green ammonia competitive with HSFO and LSMGO, respectively. To reach price parity with VLSFO, a subsidy of only 25% would be required. The situation improves significantly by 2050, as less financial support is needed. For green ammonia to compete with LNG in 2050, a 50% subsidy remains essential, but for HSFO, less than 30% will be sufficient, and for LSMGO, a subsidy of less than 5% would make green ammonia equally priced. For VLSFO, no subsidies are necessary by 2050, as the projected average costs of green ammonia are already on par with VLSFO costs.

These percentages do not account for potential fluctuations in natural gas prices, which could affect the costs of conventional fuels, thereby impacting green ammonia's competitiveness without additional subsidies. Additionally, the analysis does not factor in penalties for carbon emissions, as was done in the earlier sensitivity analysis. A combination of carbon penalties on conventional fuels and targeted subsidies for green ammonia could substantially increase investments in green ammonia from 2030 onwards, ensuring that it becomes a more attractive and economically viable alternative in the maritime sector.

In the US, the Inflation Reduction Act (IRA) is the most significant piece of legislation in U.S. history to address clean energy and climate change, expanding tax credits for renewable electricity and introducing new incentives for clean hydrogen production (Chyong et al. 2023). Under the IRA, renewable electricity projects starting in 2023 are eligible for a production tax credit of 2.6 cents per kWh, while clean hydrogen plants can receive up to $3 per kg of hydrogen for the first 10 years of operation, though their typical lifespan extends up to 30 years. However, these tax incentives only run through 2032, meaning projects beginning in 2023 will benefit from the full 10-year credit, while those starting later will receive progressively reduced credits. Figure 16 below illustrates the estimated hydrogen production costs with and without the IRA, which will significantly affect the green ammonia production costs (Zhou 2023).

According to (Zhou 2023), for plants commencing production in 2023, the cost without tax credits is $5.3 per kg, while the inclusion of IRA tax credits significantly reduces the cost to $3.2 per kg, representing a 40% reduction. This highlights the considerable financial impact of the IRA on early-stage projects. In contrast, for plants starting production in 2030, the cost without tax credits decreases to $4.9 per kg, reflecting modest advancements in technology and scaling. With IRA tax credits, the cost further reduces to $4.6 per kg; however, the impact of the tax credits is less pronounced, resulting in only a 6% cost reduction compared to the non-tax credit scenario. Overall, the IRA tax credits play a crucial role in lowering production costs, particularly for projects initiated in the early years. As a result, green ammonia, which depends on hydrogen as a key input, will be significantly affected.

Figure 16: Modeled production cost of green hydrogen for a new project built in 2023 or 2030, with and without IRA tax credits



Source: (Zhou 2023).

Overall, these trends indicate that as technology matures and costs decline, green ammonia production will become increasingly viable. The presence of incentives like the IRA could accelerate this trend, leading to broader adoption in various applications, such as shipping and energy storage. Ultimately, as hydrogen production costs decrease, so too will the costs of green ammonia, making it a more attractive option in the transition to a low-carbon economy.

Conclusions

The maritime industry is confronting significant challenges, primarily fueled by the escalation of stringent air emissions and climate regulations. The selection of fuel for decarbonizing shipping is shaped by a multitude of factors, including availability, engine compatibility, environmental impact, and economic viability. Although traditional oil-derived fuels are projected to remain dominant until 2050, alternative fuels—such as low-sulfur fuels, biofuels, and hydrogen-based options—are coming into focus. Each of these alternatives presents distinct challenges, particularly concerning cost, energy density, and the necessary infrastructure for implementation.

Among these alternatives, green ammonia has emerged as a potential sustainable fuel for the shipping industry. As a carbon-free alternative, it holds significant potential for reducing greenhouse gas emissions and air pollutants. The paper identifies several advantages of green ammonia over other fuel options. Unlike carbon-based fuels that necessitate CO2 capture, green ammonia is inherently carbon-free, thereby eliminating the need for costly carbon management processes. Furthermore, the existing global infrastructure for ammonia production and distribution could enhance its competitive position.

Despite these advantages, challenges persist, including limited current production capacity and the need for substantial investment in green ammonia facilities. The predominant production method, the Haber-Bosch process, currently relies on hydrogen sourced primarily from fossil fuels. Ongoing innovations in hydrogen production—particularly various electrolysis methods—are being explored to enhance the sustainability of ammonia production. This research provides critical insights into the viability of green ammonia as a decarbonization fuel for the maritime sector, evaluating its sustainability, technological readiness, and economic competitiveness. It underscores the importance of location in determining the feasibility and cost-effectiveness of green ammonia production.

The developed model shows that cost continues to be a substantial barrier to the widespread adoption of green ammonia, with current production expenses being up to four times higher than those of fossil fuel-derived ammonia. Future costs remain uncertain, especially as we approach 2035—a pivotal period for technological and regulatory developments. This paper projects production costs for 2024, 2030, and 2050, highlighting the potential of renewable energy sources such as solar and wind. Regions rich in low-cost renewable energy, such as Chile and the UAE, could see production costs decrease to between $202 and $482 per ton by 2050. While green ammonia currently faces economic hurdles, it has the potential to reach cost parity with certain traditional marine fuels by 2030 as production scales and technologies advance and as policy support strengthens.

Robust policy support is essential for the successful adoption of green ammonia. Financial mechanisms, including subsidies, carbon taxes, and regulatory frameworks—such as greenhouse gas penalties—are critical to closing the cost gap with conventional fuels. The EU's FuelEU Maritime regulation serves as a prime example, mandating the use of renewable fuels and imposing stringent GHG emission limits, which could substantially elevate costs for traditional marine fuels. By 2030, as GHG penalties increase, green ammonia is expected to become economically competitive, with costs projected to decline from $14/GJ to $11/GJ by 2050. Additionally, scenario analyses indicate that substantial subsidies—up to 60%—will be necessary by 2030 for green ammonia to compete with LNG, while significantly lower subsidies will suffice for parity with traditional fuels by 2050. The U.S. Inflation Reduction Act provides incentives that could significantly reduce hydrogen production costs, further benefiting green ammonia.

In conclusion, enhancing the economic viability of green ammonia requires a combination of financial incentives, regulatory measures, and technological advancements. These strategies will facilitate its adoption in reducing greenhouse gas emissions within the shipping sector. However, it is important to stress that no single fuel solution will fully decarbonize the maritime industry. Instead, a diverse portfolio of alternative fuels, including green ammonia, and other low-carbon options, will be necessary to meet the industry's energy demands and operational requirements. This highlights the need for a flexible, multi-fuel strategy to address the complex challenges of decarbonizing maritime transportation.

Appendix

Appendix I.1

Table I.1: Low sulphur fuels overview

	HFO + scrubber	liquefied natural gas (LNG)	Methanol	Liquefied Petroleum Gas (LPG)
Energy density	39-42 MJ/kg	50-55 MJ/kg	19.9 MJ/kg	25.3 MJ/kg
Technological maturity	Mature. facing regulatory pressure	Well-established with ongoing advancements	Mature for production and use in internal combustion engines	Mature. widely used in various applications
Local emissions	Reduced Sox emissions by 80-90% and up to 70% for particulate matter with scrubbers	Almost zero Sox emissions. up to 90% reduction of NOx and particulate matter compared to HFO	Lower emissions of SOx. NOx. and particulate matter compared to HFO	Lower emissions of SOx. NOx. and particulate matter compared to HFO
Carbon footprint	Roughly 2.66 kg CO2 per liter of HFO burned	Only 26% lower CO2 emissions than fuel oil on an energy basis	Reduced CO_2 by 25%. thus complying with the latest ECA regulations on its Baltic Sea route	Lower CO2 emissions compared to traditional fuels
Bunkering availability	Widely available	Global bunkering infrastructure continues to expand (188 ports with a further 82 bunkering locations decided (2023)	Limited availability. with several bunkering facilities under development	Limited. but growing interest
Commercial readiness	Widely used. but facing regulatory pressure due to emissions (TRL=9)	Growing. with increasing adoption and infrastructure development (TRL=8-9)	Growing interest and adoption. but still developing infrastructure (TRL=7-8)	Relatively mature. but infrastructure development ongoing (TRL=7-8)
Costs	Around \$41 per MWh	\$27.30 - \$34.12 per MWh	\$54.36 - \$72.36 per MWh	\$42.48 - \$84.60 per MWh
Production process	Refined from crude oil	Liquefaction of natural gas. involving cooling to approximately -162°C.	Many sources. including natural gas. from catalytic hydrogenation of a waste CO2 stream or from biomass	Extracted during natural gas processing or petroleum refining
Advantages	Widely available and compatible with existing infrastructure	-Well-established supply infrastructure -High energy density	-Can be implemented in shipping with relative ease	-Widespread availability - Can be used in existing engine technology

			- Compatible with existing engine technology	
Disadvantages	High emissions of pollutants	-Methane release ('slip') needs control -Requires insulated tanks. taking 3-4 times the volume of fuel oil for the same energy	-Lower energy density. requiring more storage space - Infrastructure development needed for broad adoption	-Lower energy density than HFO and limited bunkering infrastructure - Safety concerns due to heavier-than-air LPG vapors. requiring leak detectors and ventilation
	Prone to high market price volatility			
State of the art /Use	Commonly used. particularly in large marine vessels.	Used since the early 2000s. there are 400 LNG-powered ships today. with a further 144 vessels to be converted (2023)	-There are 24 methanol fuelled ships - Increasingly used in maritime sector. particularly in dual-fuel engines	-34 LPG-powered ships - Increasingly used in marine applications. particularly in dual-fuel engines

Appendix I.2

Table I.2: Biofuels overview

	Hydrogenated vegetable oil (HVO)	Dimethyl Ether (DME)	Biomethane	Bio-diesel	Biomethanol
Energy density	34 MJ/kg	28 MJ/kg	50-55 MJ/kg	FAME: 37.16 MJ/kg FT Diesel: 40.24 MJ/kg	15.6 MJ/kg
Technological maturity	Well-established and widely used	Established. but not as widely used as other biofuels	Well-established and widely used	Well-established and widely used	Established. but not as widely used as other biofuels
Local emissions *emissions*	Low emissions of SOx. NOx. and particulate matter	Low emissions of SOx. NOx. and particulate matter	Low emissions of SOx. NOx. and particulate matter	Low emissions of SOx. NOx. and particulate matter	Low emissions of SOx. NOx. and particulate matter
Carbon footprint	Varied GHG emission reductions (19 %-88 %).	Can be carbon-neutral if produced from renewable sources	Can be carbon-neutral if produced from renewable sources	Up to 80% reduction in CO2 emissions compared to fossil diesel	Can be carbon-neutral if produced from renewable sources
Bunkering availability	Limited availability compared to traditional fuels	Limited availability. with some pilot projects	Limited availability. but growing interest	Limited availability. with some ports offering bunkering	Limited availability. with some ports exploring bunkering
Commercial readiness	Commercially available (TRL=7)	In early stages of commercialization (TRL=5-6)	Increasing adoption in maritime applications (TRL=7)	At a lower level of technological readiness (TRL =7)	Growing interest and adoption (TRL=6)
Costs	\$86.40/MWh - \$140.40/MWh	\$50.40/MWh - \$75.60/MWh.	\$68.18/MWh - \$176.36/MWh	FT: \$86.5/MWh - \$237.6/MWh FAME: \$72/MWh - 126/MWh	\$57.89/MWh - \$139.30/MWh
Production process	Produced through hydrotreating of vegetable oils or animal fats	Produced by gasifying solid biomass or reforming biomethane to syngas. followed by gas cleaning and catalytic synthesis	Produced through anaerobic digestion or gasification of organic waste or biomass.	FAME: Made from recycled fats. oils. and greases from various sources FT-Diesel: Produced via the Fischer-Tropsch process	Produced using biomass gasification and reformation

Advantages	-Easy integration into current engines	-Existing LPG infrastructure is suitable for DME	-High technological maturity. making it a strong LNG alternative	-Up to 20% fuel blends don't need engine modifications	-Little to no engine modification needed
	-Drop-in fuel with no engine modifications needed	-Can be made from various feedstocks. including biomass	-Produced from various renewable sources. including organic waste	-FT fuel is promising as it uses widely available. non-consumable feedstock.	-Utilizes existing transport and storage infrastructure
		-Can be stored and handled at low pressure	-Compatible with existing natural gas infrastructure	-Can use existing HFO bunkering infrastructure. reducing transition costs	-Compatible with both four-stroke and two-stroke engines. with well-developed technology
Disadvantages	- Biofuels involve trade-offs with resources like food and water - Their global potential is limited by competition for crops and land needed for food. as well as constraints on water and fertilizers - Air pollution concerns and challenges in achieving carbon neutrality because of deforestation				
State of the art /Use	2020: global HVO production stood at between 6 and 7 million tons	Currently. no commercially available examples of DME being used as a marine fuel because the technology is still under development (2022)	Increasingly used	To date. only trials have been completed using FAME blends. with a maximum of 30% being used by a vessel funded by the Mediterranean Shipping Company	Increasingly used

Appendix I.3

Table I.3: Hydrogen-based fuels and fully electric option overview

	E-Methanol	E-Ammonia	Hydrogen	Fully electric
Energy density	19.5 MJ/kg	18.6 MJ/kg	120 MJ/kg (for liquid hydrogen)	Depends on the battery technology used
Technological maturity	Mature technology for production and use in engines	Emerging. with large two-stroke engines expected by 2025	Emerging. with some pilot projects in shipping	Established for various applications. including transportation
Local emissions	Lower emissions of SOx. NOx. and particulate matter	Very low emissions of pollutants	Zero emissions	Zero emissions at point of use
Carbon footprint	Can be carbon-neutral if produced from renewable hydrogen and captured CO2	Reductions of GHG emission between 83.71 and 92.1%	Zero emissions if produced from renewable sources	Can be carbon-neutral if from renewable sources
Bunkering availability	Limited	Limited	Very limited	Not applicable
Commercial readiness	Still in early stages of commercialization. with infrastructure development ongoing (TRL=5-6)	Emerging. with some pilot projects in shipping (TRL=4)	Emerging. with high costs and technical challenges (TRL=5)	In operation. primarily for short-sea shipping and ferry services. (TRL=7-8)
Costs	\$144.72/MWh - \$289.45/MWh (TRL=7)	\$67/MWh - \$114/MWh	\$66/MWh - \$154/MWh	Higher upfront costs compared to traditional engines. with lower operational costs
Production process	Produced from sourcing H2 from electrolysis and renewably sourced CO2	Synthesized from renewable hydrogen and nitrogen	Electrolysis of water using renewable electricity	Stored electricity in batteries and used to power electric motors
Advantages	Compatibility with existing infrastructure and engine technology.	- Existing production and transport infrastructure - Higher efficiency compared to other fuels - Easier storage and transport than H2 - Established terminals in	- Multiple applications across sectors can boost research - Silent electric motors	- Zero emissions at point of use - Lower maintenance costs compared to traditional propulsion systems

		Japan. the US. Europe. and major maritime routes - Production cost not dependent on carbon capture technology like e-methanol		
Disadvantages	- Need for an external carbon source - Fire detection systems are required	- Corrosive and hazardous if inhaled in high concentrations - Needs 1.6 to 2.3 times the fuel volume compared to conventional HFO ships	- Costly production and storage - Low energy density by volume - Needed complete refit of ship fuel and engine systems	- Limited range and endurance compared to fossil fuel-powered vessels - Dependence on charging infrastructure and grid capacity
	Prone to electricity market price volatility			
State of the art /Use	Still in research and development stages. with limited commercial use	Great interest in Ammonia ships potential as an alternative fuel. with large investments from South Korea totaling $870 million	3 H2 fueled ships exist and bunkering infrastructure is not available.	About 450 battery-powered ships in operation or on order. mostly ferries and offshore ships

Appendix II.1: Critical material content of electrolysis technologies

Technology	Mineral	Content (kg/MW)
Alkaline	Nickel	800 to 1.000
	Zirconium	100
PEM	Platinum	0.3
	Iridium	0.7
Solid oxide electrolysis cells (SOEC)	Nickel	150-200
	Zirconium	40
	Lanthanum	20
	Yttrium	<5

Appendix III.1: Model and formula

The total costs for the production of green ammonia are estimated using the annuity method. The annuity factor is calculated using formula (1):

$$A = \frac{1 - (\frac{1}{(1 + WACC)^{a}})}{WACC} \tag{1}$$

With:

a = number of periods

WACC = Weighted Average Cost of Capital. For each technology, the total investment costs should be divided by the annuity factor to obtain the investment costs per year. The technology is assessed by analyzing the cost per kilogram of e-diesel produced.

i. Water desalination costs

The costs linked to seawater desalination plants are determined in dollars per kilowatt-hour (kWh) of hydrogen produced. The formulation (1)for these costs is expressed as follows:

$$\dot{C}^{D}_{Water,el(H2)} = C\dot{APEX}^{D}_{el(H2)} + OP\dot{E}X^{D}_{el(H2)} + \dot{C}^{D}_{Electricity,\,D(H2)} \tag{2}$$

The total annual costs comprise the summation of annual Capital Expenditure ($C\dot{APEX}^{D}_{el(H2)}$), annual fixed operating Expenditure ($OP\dot{E}X^{D}_{el(H2)}$) and variable Operating Expenditure which encompasses electricity costs ($\dot{C}^{D}_{Electricity,\,D(H2)}$). The fixed operating costs ($OP\dot{E}X^{D}_{el(H2)}$) are presumed to constitute a fixed percentage p_{OPEX} of the annual investment costs.

$$OP\dot{E}X^{D}_{el(H2)} = C\dot{APEX}^{D}_{el(H2)} \cdot p_{OPEX} \tag{3}$$

The electricity costs ($\dot{C}^{D}_{Electricity,\,D(H2)}$) of the plants, are determined by multiplying the annual electricity demand ($\dot{E}$ $\left[\frac{kWh}{m^3}\right]$) by the Levelized Cost of Electricity ($LCOE$ $[\frac{\$}{kWh_{el}}]$). The annual electricity demand ($\dot{E}$) is calculated by multiplying the electricity demand per cubic meter of water (E_W $\left[\frac{kWh}{m^3}\right]$) and the annual water consumption (W $\left[\frac{m^3}{y}\right]$) in cubic meters per year. The annual water consumption ($\dot{W}$ $\left[\frac{m^3}{y}\right]$) is equivalent to the desalinated water amount per output unit ($B_{Water}[\frac{m^3}{kWh_{H2(el)}}]$) multiplied by the annual production of hydrogen in kilowatt-hours per year ($\dot{Q}$ $[\frac{kWh_{H2(el)}}{y}]$).

$$\dot{C}_{Electricity,D} = \dot{E} \cdot LCOE \tag{4}$$

$$\dot{E} = E_W \cdot \dot{W} \tag{5}$$

$$W = B_{Water} \cdot \dot{Q} \tag{6}$$

ii. Hydrogen costs

The calculation of the cost of one kilowatt-hour (kWh) of hydrogen (k_{H2}) involves dividing the total annual production costs of hydrogen ($\dot{C}^{H2}[\$.y^{-1}]$) by the quantity of hydrogen produced in kilograms per year

($\dot{Q}^{H2}[\frac{kg}{y}]$). This result is then multiplied by the caloric value of hydrogen ($\Delta_{H2}[\frac{kWh}{kg}]$), set at 33.33 $kWh.kg^{-1}$:

$$k_{H2} = \frac{\dot{C}^{H2}}{\dot{Q}^{H2}} \cdot \Delta_{H2} \quad (7)$$

The formula for the annual hydrogen production equals the summation of investment costs ($C\dot{APEX}^{H2}, [\frac{\$}{y}]$), fixed operating costs ($OP\dot{E}X_{f.H2}, [\frac{\$}{y}]$), electricity costs ($\dot{C}^{H2}_{Electricity}, [\frac{\$}{y}]$) and water costs ($\dot{C}^{H2}_{Water}, [\frac{\$}{y}]$). It is expressed as follows:

$$\dot{C}^{H2} = CAP\dot{E}X^{H2} + OP\dot{E}X_{f.H2} + \dot{C}^{H2}_{Electricity} + \dot{C}^{H2}_{Water} \quad (8)$$

The annual CAPEX ($CAP\dot{E}X^{H2}$) are calculated by multiplying the nominal capacity power of the plant ($P_N, [MW]$) by the specific power costs ($c_p, [\frac{\$}{MWh}]$), and subsequently utilizing the annuity method.

$$CAP\dot{E}X^{H2} = P_N \cdot c_p \cdot \frac{WACC}{1-(1+WACC)^{-a}} \quad (9)$$

The fixed operating costs ($OP\dot{E}X_{f.H2}$) are assumed to represent a fixed percentage p_{OPEX} of the annual investment costs, with a variable rate depending on the scenario ranging from 2% to 9% with a relevant decrease over time.

$$OP\dot{E}X_{f.H2} = p_{OPEX} \cdot CAP\dot{E}X^{H2} \quad (10)$$

The calculation of the electricity costs ($C^{H2}_{Electricity}$) involves multiplying the full load hours ($T, [h]$) by the nominal power ($P_N, [MW]$) and by the LCOE expressed in $\frac{\$}{MWh}$:

$$\dot{C}^{H2}_{Electricity} = T \cdot P_n \cdot LCOE \quad (11)$$

The water costs ($\dot{C}^{H2}_{Water}$) are derived straightforwardly from the desalinated water costs per kilowatt-hour of hydrogen output, multiplied by the quantity of hydrogen produced per year ($\dot{Q}^{H2}, [\frac{kWh}{y}]$):

$$\dot{C}^{H2}_{Water} = C^{D}_{Water,el(H2)} \cdot \dot{Q}^{H2} \quad (12)$$

The annual quantity of hydrogen produced ($\dot{Q}^{H2}$) is contingent upon the efficiency of the plant ($\eta, [\%]$), the full load hours ($T, [h]$), the nominal power of the plant ($P_n, [MW]$) and the number of electrolyzers in operation (n).

$$\dot{Q}^{H2} = \eta \cdot T \cdot P_n \cdot n \cdot 1000 \quad (13)$$

The efficiency of the plant ($\eta, [\%]$), the full load hours ($T, [h]$) as well as the nominal power of the plant ($P_n, [MW]$) are scenario-dependent, exhibiting notable advancements over time and contributing to the reduction of costs.

iii. Green ammonia production costs

The costs per kg green ammonia produced ($c^{eD}. \left[\frac{\$}{kg_{eA}}\right]$) are determined by dividing the total yearly costs ($\dot{C}^{eD}. [\frac{\$}{kg_{eA}}]$) by the total quantity of green ammonia produced per year ($\dot{M}_{eA}. [\frac{kg}{y}]$). and can be expressed as follows:

$$c^{eD} = \frac{\dot{C}^{eA}}{\dot{M}_{eA}} \quad (14)$$

The overall output of the fuel synthesis ($\dot{M}^{eA}$) fixed in tons per year and depends on the scenario; better scenarios produce more green ammonia annually.

The total yearly costs ($\dot{C}^{eD}.\left[\frac{\$}{y}\right]$) are the sum of the total CAPEX ($CA\dot{P}EX_{HB.f}.[\frac{\$}{y}]$). the annual fixed operating costs ($O\dot{P}EX_{HB.f}.[\frac{\$}{y}]$). the annual electricity costs ($\dot{C}_{El.HB.v}.[\frac{\$}{y}]$). the annual hydrogen costs ($\dot{C}_{H2}.[\frac{\$}{y}]$). the annual nitrogen costs ($\dot{C}_{N2}.[\frac{\$}{y}]$) and the annual hydrogen storage costs ($\dot{C}_{H2.S}.[\frac{\$}{y}]$):

$$\dot{C}^{eD} = CA\dot{P}EX_{HB.f} + O\dot{P}EX_{HB.f} + \dot{C}_{El.HB.v} + \dot{C}_{H2} + \dot{C}_{N2} + \dot{C}_{H2.S} \quad (15)$$

$$O\dot{P}EX_{HB.f} = p_{OPEX.HB} \cdot CA\dot{P}EX_{HB.f} \quad (16)$$

The electricity costs ($\dot{C}_{el.FT.v}$) are calculated by multiplying the annual electricity demand ($\dot{E}_{HB}.[\frac{kWh}{y}]$). derived from the required amount of electricity per ton of Fischer-Tropsch (FT) output and assumed to be constant as per literature. with the $LCOE$.

$$\dot{C}_{el.HB.v} = \dot{E}_{HB} \cdot LCOE \quad (17)$$

The annual hydrogen costs ($\dot{C}_{H2}$) depend on the hydrogen production costs ($c_{H2}.[\frac{\$}{kg_{H2}}]$) and the quantity of hydrogen required per kg of output ($\dot{M}_{e_A}.[\frac{kg}{y}]$). This is therefore influenced by the efficiency ($\eta_{HB}.[\%]$) of the FT plant.

$$\dot{C}_{H2} = \frac{c_{H2} \cdot \dot{M}_{e_A}}{\eta_{HB}} \quad (18)$$

The annual nitrogen costs ($\dot{C}_{CO2}$) are determined by multiplying the total output of Haber-Bosch synthesis ($\dot{M}_{e_A}.[\frac{kg}{y}]$) with the nitrogen demand per kilogram of output produced ($B_{N2}.[\frac{kg_{N2}}{kg_{eA}}]$). and the nitrogen costs per kilogram of nitrogen ($c_{N2}.[\frac{\$}{kg_{N2}}]$).

$$\dot{C}_{N2} = \dot{M}_{eA} \cdot B_{N2} \cdot c_{N2} \quad (19)$$

The annual stored quantity of hydrogen is calculated as the difference between the quantity of hydrogen produced ($\dot{Q}.[kg_{H2}.y^{-1}]$) and the amount required for the HB process with considering the remaining quantity of stored hydrogen from the previous years ($I^{H2}.[kg]$).

$$\dot{C}_{H2.S} = \; = (I^{H2} + \dot{Q} - \frac{\dot{M}_{eA}}{\eta_{HB}}) \cdot c_S \quad (20)$$

With:

c_S = costs for storing one kg of hydrogen.

Appendix III.2. Model assumptions

Table III.1.a: Water desalination costs

		Present			2030			2050		
		Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic
Amount of desalinated water (per output H2el)	*m³/kWh*	0,0002103	0,0002919	0,0004206	0,0002103	0,0002919	0,0004206	0,0002103	0,0002919	0,0004206
Investment cost	*$/m³day*	1232	1232	1232	1108	1108	1108	912	912	912
Lifetime	*years*	25	25	25	25	25	25	25	25	25
Operating cost per year	*%*	4	4	4	4	4	4	4	4	4
Energy Consumption	*kWh(el)/m³*	4,1	4,1	4,1	4,1	4,1	4,1	4,1	4,1	4,1

Table III.1.b: Hydrogen costs

		Present			2030			2050		
		Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic
Efficiency	*%*	69	66	65	71	69	66	82	78	75
Full load hours	*h*	8000	4433	2300	8000	4433	2300	8000	4433	2300
Nominal capacity	*MW*	220	140	100	750	425	100	750	425	100
Specific power cost	*$/MWh*	338000	949000	1145000	289000	623000	750000	212000	431000	636000
Lifetime	*year*	25	22	20	30	23	20	30	23	20
Operating cost per year	*%*	2	3.666666667	9	2	3.2	5	2	2	2
Electricity demand	*MWh. y*	1760000	620620	230000	6000000	1884025	230000	6000000	1884025	230000

Table III.1.d: Green ammonia costs

		Present			2030			2050		
		Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic
Ammonia produced per year	*tons, y*	206036	69003	24941	713087	217605	25410	823566	245988	28875
Specific power cost	*$/(tNH3·a)*	680	680	680	680	680	680	680	680	680
Lifetime	*year*	30	29	25	30	30	30	30	30	30
Operating cost per year	*%*	2,00	2,75	5,00	2,00	2,00	2,00	2,00	2,00	2,00
Electricity input	*KWh/t(NH3)*	640	676	740,00	640	689	738,00	238	439	640
N2 demand per ton NH3	*kg(N2)/t(NH3)*	820	824.57	830.7	820	820	820	820	820	820
H2 demand per ton NH3	*kg/t*	177	178.8	180	179.4	179.4	179.4	179.4	179.4	179.4
Storing costs per kg H2	*$/kg*	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35

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