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Decarbonizing Port Operations: A Case Study Mapping the Sustainability Impacts of Green Ammonia Production and Bunkering in Estonia

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The maritime transport sector is vital to the global economy, facilitating the movement of goods and resources through ports, which are key hubs in global supply chains. However, the sector's rapid growth poses environmental challenges, as maritime activities contribute up to 4% of global greenhouse gas (GHG) emissions. To address this, the International Maritime Organization (IMO) has set targets to reduce emissions by at least 50% by 2050 compared to 2008 levels. One proposed solution is green ammonia (GA), a carbon-neutral fuel derived from renewable energy sources. This study explores GA's potential to reduce maritime transport's environmental footprint and support the United Nations Sustainable Development Goals (SDGs). Focusing on existing port infrastructure, the research evaluates GA production and bunkering's impact on port sustainability (PS) through a literature review and a case study of Estonia. The findings provide opportunities and challenges for integrating GA into port infrastructure, creating a sustainability framework for zero-carbon operations that balance environmental, social, and economic goals.

Keywords: alternative marine fuels, green ammonia production, ammonia bunkering, port operations, sustainability, sustainable investment, Sustainable Development Goals, SDGs, ESG, TBL.

1. Introduction

As a fundamental component of the global economy, the maritime transport sector facilitates the cross-border exchange of goods, fuels, and other assets, thereby supporting interconnected trading systems. Ports function as strategic hubs in global supply chains, performing basic operations such as cargo handling, as well as providing specialized services such as freight forwarding and customs clearance which contribute to regional economic competitiveness (Finger and Prause, 2024). Shipping demand is projected to increase three to sevenfold by 2050, raising concerns about whether port capacity can keep it up. Some forecasts suggest that ports may also face capacity constraints as early as 2030, potentially creating challenges in meeting market demands and maintaining efficient operations (Housni et al., 2022).

This expected growth of maritime trade volumes intensifies anthropogenic pressures on both marine and coastal ecosystems. Currently, the sector accounts for approximately 4% of global greenhouse gas (GHG) emissions, a figure expected to rise with continued trade growth (Finger and Prause, 2024). To address this challenge, the International Maritime Organization (IMO) set ambitious targets to reduce emissions by 40% by 2030 and by at least 50% by 2050, compared to 2008 levels. In addition to GHG emissions, maritime operations, including land transport and port activities, are significant contributors to noise and water pollution, which threaten marine biodiversity and negatively impact nearby communities (Diniz et al., 2024).

These environmental challenges highlight the pressing need to move towards more sustainable practices in the maritime and port sectors (Housni et al., 2022). Implementing integrated sustainability frameworks such as the Triple Bottom Line (TBL) and Environmental, Social, and Governance (ESG) criteria is critical to addressing interrelated issues including marine biodiversity loss, atmospheric pollution, and socio-economic inequalities in surrounding communities (Alamoush et al., 2021). Achieving this balance requires innovative approaches that not only enhance the sustainability of port operations but also promote economic development and social cohesion. In order to address these challenges, port authorities must implement green initiatives and maintain continuous collaboration with stakeholders (Diniz et al., 2024).

Ports around the world initiated sustainability measures (hereinafter referred to as Port Sustainability, or PS) to reduce emissions, improve energy efficiency, and adopt cleaner technologies (Housni et al., 2022). These efforts are not only essential for mitigating environmental impacts but also for strengthening the resilience of port operations in the face of climate change. Global initiatives such as the United Nations 2030 Agenda for Sustainable Development, emphasize the importance of integrating sustainable practices across all sectors, including transport and logistics (Diniz et al., 2024). The urgent need for this transition prompted researchers and practitioners to evaluate investment strategies that would minimize the environmental footprint of port operations while ensuring the long-term economic efficiency and sustainability of the maritime industry. Such efforts are in line with the achievement of the Sustainable Development Goals (SDGs) (Alamoush et al., 2021).

A promising solution to these challenges is the adoption of alternative fuels, with green ammonia (GA) emerging as an economically feasible candidate (Hrenov et al., 2025). Produced using renewable energy and water electrolysis, GA offers the possibility of storing energy and producing carbon-free fuels, that could significantly reduce emissions from maritime operations (Olabi et al., 2023). Its high energy density, convenient storage, and versatility in powering both internal combustion engines and fuel cells make it an attractive option for reducing the carbon footprint of ships and port operations (Olabi et al., 2023).

Despite its potential, the large-scale implementation of GA in port and shipping operations remains largely unexplored. Key challenges include technological readiness, compatibility with existing infrastructure, and economic feasibility (Olabi et al., 2023; Diniz et al., 2024; Hrenov et al., 2025). This study addresses this gap by examining how the potential of GA production and bunkering can contribute to improving the sustainability of maritime transport and port operations as a mechanism for the practical implementation of the SDGs. Special attention is placed on evaluating the environmental, social, and economic impacts (Martins et al., 2024) of integrating GA into port operations.

This paper is structured as follows: Section 2 reviews relevant literature, Section 3 outlines the research methodology and data collection process, Section 4 presents the study's findings and discussion, and Section 5 concludes this study.

2. Literature review

2.1. *Green Ammonia as a Catalyst for Decarbonizing the Maritime Industry*

Ammonia (NH_3) attracted considerable attention as a potential fuel for marine decarbonization due to its dual functionality as a high-density hydrogen carrier and its integration into existing global supply chains for agricultural and chemical commodities (Prause et al., 2023). Its potential as a cleaner alternative to fossil fuels aligns with the maritime sector's push to meet international emissions reduction targets. Among these alternatives, GA produced using renewable energy sources, gained significant traction as a critical tool for advancing SDGs (Olabi et al., 2023).

Currently, global NH_3 production stands at approximately 150 million tonnes per year, primarily used in agriculture (e.g., fertilizers) and the chemical industry. This widespread demand and existing infrastructure underscore ammonia's role in the global economy. However, traditional production methods, such as methane reforming in the Haber-Bosch process, are significant contributors to GHG emissions, releasing approximately two tonnes of CO_2 for every tonne of NH_3 produced (Prause et al., 2023).

Continued reliance on fossil fuels fundamentally contradicts the Paris Agreement's 1.5°C pathway and undermines progress towards SDGs 13 (Climate Action) and 7 (Affordable and Clean Energy). Switching to GA synthesis using renewable electricity could significantly reduce GHG emissions, eliminate the need for fossil fuels, and take advantage of modern renewable energy technologies (Olabi et al., 2023). With NH_3 production expected to rise to 270 million tonnes annually by 2050 (Joseph Sekhar et al., 2024), the successful scaling of GA initiatives will require significant investment in renewable energy infrastructure and ongoing innovation in production technologies.

The integration of GA into maritime operations offers both environmental and practical benefits. Ammonia's ability to liquefy under moderate pressure, combined with its narrow flammability range, makes it safer to store and handle than more volatile alternatives like hydrogen (Olabi et al., 2023; Hrenov et al., 2023). These properties enhance its compatibility with existing marine technologies, enabling its use in internal combustion engines with minimal modifications. With an octane rating of 120 (Research Octane Number or RON), surpassing gasoline (86–93 RON) and methanol (108 RON), NH_3 exhibits anti-knock properties conducive to high-compression marine engines, reducing pre-ignition risks in heavy-fuel applications (Al-Aboosi et al., 2021).

2.2. *Multifaceted Concept of Port Sustainability*

Port Sustainability (PS) requires minimizing environmental impacts while fostering economic growth and addressing societal needs through the integration of TBL principles and ESG frameworks (Alamoush et al., 2021). While both emphasize sustainability, TBL focuses on measurable economic, environmental, and social outcomes, whereas ESG prioritizes governance mechanisms, including transparent decision-making protocols and compliance with international standards. While ports contribute significantly to economic growth, their operations often result in negative externalities such as pollution and habitat destruction (Joseph Sekhar et al., 2024), highlighting the need for strategies that balance economic progress with environmental sustainability and social responsibility (Housni et al., 2022).

TBL and ESG complement each other in guiding sustainable port operations. Together, these frameworks enable ports to improve their competitiveness while ensuring social equity and alignment with the SDGs. This holistic approach encourages ports to balance operational efficiency with global environmental responsibilities (see Figure 1). Moreover, PS encompasses both internal operations, such as cargo handling and energy consumption, and external activities like marine and land transport connections (Alamoush et al., 2021).

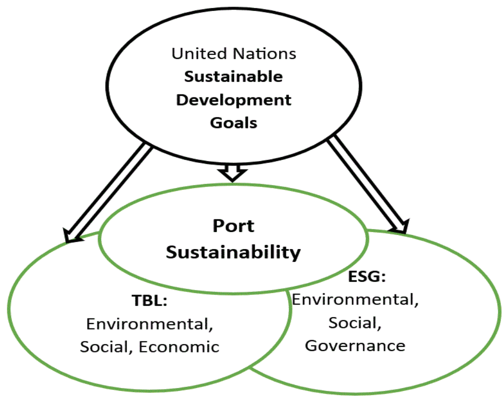

Fig. 1. Port sustainability framework

Environmental Dimension of PS: Ports have significant environmental impacts due to their role in cargo handling, maritime and land transport, and related operations. For example, port activities contribute to marine pollution, which threatens biodiversity and disrupts ecosystem services (Joseph Sekhar et al., 2024). To address these issues, ports are increasingly adopting sustainable practices to reduce their environmental footprint (Prause et al., 2023). These include electrification of cargo-handling machinery, deployment of renewable energy systems, and adoption of energy efficiency across all operations. Additionally, ports are advancing the use of low-emission bunkering fuels, such as liquefied natural gas (LNG) and GA, to lower shipping-related emissions (Alamoush et al., 2021).

Social Dimension of PS: Ports are closely connected to local communities, creating both opportunities and challenges that define their social impact (Aguilera et al., 2023). On the positive side, ports drive social development by generating employment, improving infrastructure, and fostering economic growth. However, these benefits can come with challenges. Port activities, such as cargo handling and increased traffic, often lead to noise pollution, congestion, and air quality issues, which can negatively impact nearby communities. Such disruptions may cause tensions between ports and local stakeholders (Aguilera et al., 2023). To address these challenges, ports are adopting socially responsible practices, prioritizing stakeholder engagement, and actively working to minimize adverse effects on communities (Alamoush et al., 2021).

Economic/Governance Dimension of PS: Effective governance is essential for ensuring that ports operate economically efficiently and responsibly. This involves clear accountability, compliance with regulations, and ethical decision-making. To stay competitive, ports must innovate by adopting energy-efficient practices, lowering operational costs, and improving service quality (Alamoush et al., 2021). The integration of green technologies, such as alternative fuels and renewable energy systems, can provide substantial long-term economic benefits by reducing dependence on fossil fuels and mitigating environmental risks. Investments in sustainable infrastructure and low-emission transport networks further bolster ports' economic competitiveness and resilience (Hrenov et al., 2025).

3. Material and Methods

This study employed a mixed-methods approach, integrating both qualitative (e.g., document analysis, interview content analysis, case study research) and quantitative techniques (e.g., operational data analysis, economic feasibility, and GHG calculations) to provide a comprehensive evaluation of GA in sustainable port operations. The research was designed to assess the environmental, social, and economic impacts of PS through case study analysis and sustainability assessment frameworks. The methodology consists of four components:

(i) A systematic review of peer-reviewed articles, industry reports, and regulatory documents (2020–2025) was conducted to examine current sustainability standards, policies, and best practices related to GA production and bunkering;

(ii) To gain practical insights, 12 semi-structured interviews were conducted with experts in ammonia production, maritime logistics, and port management. Participants were strategically selected to ensure a broad representation of expertise. The interviews focused on technological readiness, infrastructure challenges, regulatory barriers, and the economic feasibility of GA adoption. Additionally, data from six GA-related projects across Europe (2016–2024), incl. technical reports, investment plans, and environmental impact assessments, were analyzed to contextualize findings;

(iii) A detailed case study of the GA project in Paldiski, Estonia was conducted, drawing from project documentation, operational data, environmental impact assessments, and financial reports. This case study aimed to evaluate the feasibility, risks, and potential benefits of integrating GA into port infrastructure;

(iv) A custom impact-mapping framework, aligned with TBL and ESG criteria, was used to assess GA's sustainability outcomes in maritime and port operations. Quantitative indicators included GHG emission reduction rates, job creation metrics, operational efficiency, financial data, and economic performance indicators. Qualitative themes encompassed stakeholder perceptions, compliance with sustainability frameworks, perceived safety risks, regulatory gaps, governance challenges, and business risks.

4. Results and Discussion

4.1. *Case Study of Green Ammonia Project*

Estonia is actively working to decarbonize shipping operations in the Baltic Sea region through a combination of private sector initiatives and public funding. The main results of the case study show that GA project in Paldiski can reduce port-related CO_2 emissions by at least 77.5 $ktCO_2$ annually compared to the use of fossil fuels. This reduction comes from two main sources: avoided emissions from GA production (45.1 $ktCO_2$/year) and the replacement of heavy fuel oil (HFO) in maritime bunkering operations (32.3 $ktCO_2$/year).

At the center of this initiative is Derivaat NH3, a private company leading the development of a GA production facility in Paldiski, Estonia. The facility, with an expected annual capacity of

22.6 kt of GA, is set to commence operations in 2026. The project represents a €70.4 million investment, partially supported by a €16.97 million grant from the Estonian Environmental Investment Centre. Beyond its contribution to sustainable fuel production, the project serves as a potential model for scaling up green ammonia initiatives in maritime transport. A financial analysis using the Net Present Value (NPV) model indicates that the plant can achieve economic viability when the market price of GA is at least 1.2 times its operating costs, with an Internal Rate of Return (IRR) of 15% (Hrenov et al., 2025), demonstrating its long-term investment potential.

A risk assessment identified key hazards associated with the project, such as toxic ammonia leaks or spills during storage and bunkering, human errors, organizational shortcomings, and technical or equipment failures, which could endanger port personnel, ship crews or passengers and marine ecosystems. To mitigate these risks, the facility will implement automated leak detection systems, emergency water curtains, and protocols for refrigerated ammonia storage to reduce spill severity. Additionally, comprehensive worker training programs will aim to minimize operational risks and ensure compliance with industry safety standards (Hrenov et al., 2023).

The Paldiski facility will rely on local renewable energy sources, including wind and solar power, requiring approximately 168 GWh annually for hydrogen production via high-temperature Solid Oxide Electrolysis Cell (SOEC) technology. This accounts for about 2% of Estonia's total electricity consumption (7.5 TWh in 2023) and will necessitate the development of offshore wind farms in the Gulf of Riga. Hydrogen will be synthesized with nitrogen, extracted from the air, to produce GA. To optimize sustainability, treated wastewater from Paldiski's municipal sewage system will be used for electrolysis, supplemented by rainwater harvesting to minimize freshwater consumption (EIA, 2024). However, according to the interviews, the project faces challenges, including high energy costs in the Baltic states, limited availability of green energy, public concerns related to ammonia toxicity, and the need for capital-intensive infrastructure for ammonia storage and bunkering.

The GA production plant is part of a broader regional strategy to enhance maritime transport sustainability. A key element of this initiative is the hybrid rail ferry M/V SEARAIL, designed to improve freight connectivity between Finland and the Baltic countries. The planned completion of Rail Baltica in 2030 is expected to further enhance logistical efficiency and support the economic feasibility of GA production (EIA, 2024). The ferry will be equipped with hybrid engines capable of running on both GA and marine diesel, complemented by onboard solar panels and wind generators.

With an estimated annual consumption of 19 kt of GA as bunker fuel, the marine vessel will utilize 84% of the Paldiski plant's total production, while the remaining 16% will be allocated for decarbonized fertilizer production for regional agriculture. The inclusion of maritime emissions in the EU Emissions Trading System (ETS) from 2024 provides a regulatory incentive for GA adoption. By classifying GA as a zero-emission fuel, the Paldiski project is expected to generate approx. €2.6 million in annual EU ETS cost savings for shipping operators, assuming a carbon price at approx. €80/t and full exemption from well-to-wake emissions taxation. These savings could help offset around 40% of GA's current price premium over HFO (€340/t), significantly reducing the cost gap and increasing the viability of GA in the maritime sector.

4.2. *Mapping Green Ammonia (GA) Impacts on Port Sustainability (PS)*

To effectively map the impacts of GA production and bunkering, this case study considers key sustainability aspects across environmental, social, and economic/governance dimensions (Alamoush et al., 2021). Table 1 summarizes the interconnections between GA impacts and SDGs, followed by a discussion of the findings.

4.2.1. *Environmental Impact on PS*

GA production and bunkering (Table 1: E1–E5) significantly reduce emissions of CO_2, sulfur oxides, nitrogen oxides, and particulate matter, directly improving air quality and mitigating climate change. These improvements support

Table 1. Interconnections between the impact of green ammonia on port sustainability and SDGs

	SDG 1 No Poverty	SDG 2 Zero Hunger	SDG 3 Good Health	SDG 4 Quality Education	SDG 5 Gender Equality	SDG 6 Clean Water	SDG 7 Renewable Energy	SDG 8 Economic Growth	SDG 9 Innovation Infrastructure	SDG 10 Reduced Inequalities	SDG 11 Sustainable Cities	SDG 12 Responsible Consumption	SDG 13 Climate Action	SDG 14 Life Below Water	SDG 15 Life on Land	SDG 16 Peace and Justice	SDG 17 Partnership
E 1. Air Pollution Reduction			V						V		V		V	V	V		
E 2. Water Quality Improvement	V					V					V			V	V		
E 3. Energy Efficiency							V	V	V			V					
E 4. Noise Pollution Reduction			V								V			V			
E 5. Marine Ecosystem Protection	V					V								V	V		
S 1. Community Engagement	V			V				V		V	V						V
S 2. Improved Health and Quality of Life			V				V						V				
S 3. Labor Rights	V		V	V	V			V		V						V	V
S 4. Local Employment Opportunities	V							V	V		V	V					
S 5. Port and Marine Professionals			V	V						V						V	V
E/G 1. Economic Viability	V	V					V	V	V			V	V				V
E/G 2. Capital Growth and Investment Gains	V	V						V	V		V		V				V
E/G 3. Sustainable Economy and Technology				V		V	V	V	V	V		V	V	V	V	V	V
E/G 4. Supply Chain Optimization								V	V			V	V	V			V

SDG 3 (Good Health and Well-Being) by lowering respiratory and cardiovascular health risks and SDG 13 (Climate Action) by advancing carbon-neutral port operations. Additionally, GA minimizes the risk of water pollution by replacing conventional fuels, reducing oil spills, and cutting waterborne pollutant emissions. This aligns with SDGs 6 (Clean Water and Sanitation) and 14 (Life Below Water), focusing on protecting freshwater and marine ecosystems while ensuring communities have access to clean water.

Integrating renewable energy and energy recovery systems into GA production enhances efficiency and aligns with SDGs 7 (Affordable and Clean Energy) and 9 (Industry, Innovation, and Infrastructure). Moreover, quieter production technologies reduce noise pollution, improving the health and well-being of workers and nearby residents (SDG 3) while minimizing disturbances to marine life (SDG 14).

These findings echo Alamoush et al. (2021), who highlight the critical role of port environmental initiatives in achieving SDGs related to public health, climate action, water quality, and biodiversity conservation. Similarly, Martins et al. (2024) underline green hydrogen's potential in advancing climate action and achieving net-zero emissions. However, they caution that its production and use require careful management to address trade-offs involving water and land use, ecosystem health, and pollution, ensuring its benefits are realized without compromising biodiversity or human health.

4.2.2. *Social Impact on PS*

GA (see Table 1: S1-S5): fosters stronger community engagement through job creation, partnerships, and decision-making processes, addressing SDG 1 (No Poverty) by creating sustainable livelihoods and SDG 8 (Decent Work and Economic Growth) by boosting employment in clean energy sectors. Training programs and workforce development further support SDG 4 (Quality Education) by equipping workers with advanced skills. These initiatives, along with community-driven urban planning, align with SDGs 11 (Sustainable Cities and Communities) and 17 (Partnerships for the Goals). Reduced emissions from GA production improve air quality, which directly benefits public health (SDG 3) and promotes cleaner, more resilient ecosystems for future generations (SDG 13). GA projects also uphold fair labor practices, ensuring safe workplaces and equitable opportunities, which align with SDGs 5 (Gender Equality) and 10 (Reduced Inequality). By adhering to strict safety standards, GA operations mitigate workplace risks (SDG 3), while transparent governance practices reinforce SDG 16 (Peace, Justice, and Strong Institutions).

In terms of economic benefits, GA projects stimulate local economic activity, lifting local communities out of poverty (SDG 1) and fostering urban resilience (SDG 11). These initiatives support responsible resource use (SDG 12) while driving innovation in clean energy and technology (SDG 9). Partnerships between industry, education, and local governments facilitate progress (SDG 17), while green technology training equips workers with the skills needed to thrive in sustainable industries (SDG 4).

Alamoush et al. (2021) highlight ports' role in advancing SDGs through initiatives that focus on employee rights, workplace safety, community well-being, and the welfare of marine professionals. Similarly, Martins et al. (2024) explore the social dimension of green hydrogen, emphasizing its potential to reduce systemic inequalities and promote sustainable development. However, they stress that achieving this potential relies on addressing challenges related to social equity, workforce development, and education.

4.2.3. *Economic/Governance Impact on PS*

GA (see Table 1: E/G1-E/G4) plays a key role in driving sustainable economic growth while encouraging technological innovation and collaboration. By creating jobs and supporting clean energy solutions (SDG 7), GA contributes to reducing poverty (SDG 1) and boosting agricultural productivity (SDG 2). It fosters economic growth (SDG 8) by generating employment opportunities and strengthening industrial infrastructure (SDG 9) through the advancement of renewable energy technologies. Additionally, GA helps achieve SDG 13 (Climate Action) by facilitating the transition to carbon-neutral energy solutions and promoting sustainable practices across industries. Its role also aligns with SDG 17 (Partnerships for the Goals) by encouraging international cooperation and knowledge-sharing.

The capital growth and investment generated by GA support SDG 1 (No Poverty) by creating jobs and alleviating poverty, and they contribute to SDG 2 (Zero Hunger) by enhancing agricultural productivity with sustainable fertilizers. These economic benefits also stimulate industrial growth and infrastructure development (SDGs 8 and 9), fund sustainable urban initiatives (SDG 11), and support climate action projects (SDG 13). Furthermore, investments in GA encourage global partnerships (SDG 17), fostering collective progress toward achieving sustainability goals.

A GA-driven sustainable economy helps accelerate the adoption of renewable energy (SDG 7), promotes inclusive industrial development (SDG 8), and drives innovation and infrastructure growth (SDG 9). It also contributes to SDG 12 (Responsible Consumption and Production) by improving resource efficiency and promoting cleaner production, while supporting SDG 13 (Climate Action) by reducing greenhouse gas emissions. Moreover, GA encourages global collaboration under SDG 17, advancing knowledge-sharing and joint sustainability efforts.

Optimizing GA supply chains directly supports SDG 8 (Decent Work and Economic Growth) by improving logistical efficiency and promoting inclusive economic growth, while also advancing SDG 9 (Industry, Innovation, and Infrastructure) with investments in innovative technologies and infrastructure. Through better resource management, GA aligns with SDG 12 (Responsible Consumption and Production) by reducing waste and supporting sustainable consumption. It also contributes to SDG 13 (Climate Action) by lowering emissions. Additionally, optimized supply chains help protect aquatic ecosystems (SDG 14) and foster global partnerships (SDG 17), enabling joint efforts to meet sustainability targets.

Alamoush et al. (2021) emphasize the economic potential of GA use in ports, highlighting its role in economic growth as well as its contributions to trade, logistics, and digitalization initiatives. In the same vein, Martins et al. (2024) highlight the significant potential of green hydrogen to support sustainable development by integrating it into local economies and energy systems. However, they stress the need to address economic barriers such as infrastructure, costs, and policy frameworks to fully unlock its potential and ensure equitable benefits, particularly through enhanced global partnerships.

5. Conclusion

This study highlights the potential of GA production and bunkering to improve the sustainability of maritime transport and port operations. By addressing environmental, social, and economic considerations, GA presents a viable alternative to conventional marine fuels. However, its large-scale adoption depends on technological advancements, infrastructure readiness, and regulatory support. The case study of the Paldiski project in Estonia illustrates how integrating renewable energy into GA production can reduce environmental impact while contributing to regional economic development. These findings emphasize the need for further investment, policy alignment, and stakeholder collaboration to facilitate the transition toward sustainable maritime operations. The risks related to GA production, bunkering operations, and its use as marine fuel on ships also require further in-depth analysis.

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