International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

Economic and Environmental Assessment of Ammonia as a Sustainable Fuel for Tugboat Operations at the Port of Texas

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International Journal of Science and Research Archive, 2024, 13(02), 748–756

Publication history: Received on 25 September 2024; revised on 05 November 2024; accepted on 07 November 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.2.2138

Abstract

This study assesses the feasibility of ammonia as a sustainable alternative fuel for tugboat operations in the Port of Texas, a major U.S. maritime, oil and gas hub. Tugboats, while critical to port logistics, contribute significantly to localized air pollution and greenhouse gas emissions, impacting both environmental quality and public health in surrounding communities. Given the International Maritime Organization's (IMO) goals to reduce carbon emissions by 40% by 2030 and 70% by 2050, exploring alternative fuels has become imperative.

Ammonia, a carbon-free fuel, presents both opportunities and challenges. While ammonia combustion produces no direct CO_2 emissions, making it attractive from a decarbonization standpoint, its lower energy density results in higher fuel volumes and increased operational costs compared to marine fuel oil (MFO). This paper presents a comparative analysis based on real-world data, mathematical modeling, and emission trade-offs, examining the economic implications, environmental impact, and safety concerns of adopting ammonia as a tugboat fuel. Results indicate that while ammonia could enable significant CO_2 reductions, challenges related to fuel storage, cost, and infrastructure must be addressed. The findings suggest that with appropriate policy support and investment in handling infrastructure, ammonia can become a viable fuel option for sustainable maritime operations.

Keywords: Ammonia as Marine fuel; Maritime Decarbonization; Tugboat Emissions; Sustainable Shipping; Port of Texas; Low-Carbon fuels

1. Introduction

The global maritime industry, responsible for approximately 3% of worldwide greenhouse gas (GHG) emissions, is under increasing regulatory and societal pressure to transition toward sustainable energy sources. The sector's emissions are projected to grow, making decarbonization a pressing issue, especially for high-traffic port operations like those at the Port of Texas. This port handles substantial cargo volumes, including crude oil and chemicals, positioning it as a critical contributor to the region's economy but also as a significant source of pollution. Tugboats, which play a vital role in maneuvering larger vessels, are particularly high emitters of CO_2, NO_x, and other pollutants, given their frequent use and high fuel consumption.

To align with IMO targets and local environmental standards, ports are exploring low-carbon alternatives to conventional marine fuels like Marine Fuel Oil (MFO). Ammonia has emerged as a promising candidate in the maritime industry's fuel transition. It is a hydrogen-derived fuel that, when produced through renewable methods, offers a

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carbon-free combustion process. This could significantly reduce CO_2 emissions from maritime activities, aligning with global decarbonization goals. However, ammonia's lower energy density compared to MFO means that vessels require larger fuel storage capacities, leading to increased operational costs and logistical challenges in fuel supply and bunkering infrastructure.

Table 1 Typical characteristics of Marine Fuels (Aatola et al., 2009; DNV, 2019; Herdzik, 2021; Speight, 2011; Valera-Medina et al., 2018; Haynes, 2016; MAN, 2019)

Fuel Properties	MGO	Diesel	LPG	LNG	Methanol	HVO	Liquid hydrogen	Ammonia
Flash point (°C)	60–75	52	−104	−188	11–12	>61	Not defined	132
Auto-ignition temperature (°C)	250	210	410–580	537	470	204	500	630
LHV (MJ/kg)	42.7	43.4	46	48.6	19.9	37.8	120	18.6
HHV (MJ/kg)	45.9	46	49.3	55.2	22.7	40.2	141.8	22.5
Flammability range (% volume in air, LFL-UFL)	0.4–8	0.6–7.5	1.8–10.1	4–15	6.7–36	0.6–7.5	4–74.2	15–28
Density (t/m^3)	0.835	0.832	0.49	0.49	0.79	0.78	0.071	0.68
Energy density (GJ/m^3)	35.7	38.6	25.3	22.2	15.6	34.3	8.5	11.4
Volume per unit energy (m^3/GJ)	Standard(1)	0.92	1.41	1.61	2.29	1.04	4.18	3.14
Toxicity	No	No	No	No	Low acute toxicity	No	No	High

The objective of this study is to evaluate the economic and environmental feasibility of adopting ammonia as a tugboat fuel at the Port of Texas. By comparing fuel consumption rates, cost structures, and emissions, this research aims to provide valuable insights into ammonia's potential as a sustainable maritime fuel. The findings will inform stakeholders about the economic viability, environmental benefits, and necessary infrastructure investments associated with adopting ammonia in port operations.

2. Material and methods

This study uses a comparative fuel analysis, real-world operational data from similar environments such as Bonny Nigeria and Port of Antwerp Brugges Belgium, including mathematical modeling to assess the feasibility of using ammonia versus MFO for tugboat operations at the Port of Texas.

2.1. Data Collection and Analysis

Table 2 Tugboat Data sourced from Machinery Manual of the Manufacturer

	Tugboat 1	Tugboat 2	Tugboat 3	Tugboat 4
Length Overall (LOA)m	34.4	27.59	27.56	27.59
Breath Overall (BOA)m	12.0	12.93	12.93	12.93
Draught (m)	5.7	5	5.95	5.95
Gross Tonnage	350	381	350	380
Bullard Pull	81	81	80	80
Main Engine Power	3500/1200rpm	6722/1800rpm	6722/1800rpm	6722/1800rpm
Engine Maker	Cat 3516C	Cat 3516C TA HD/D.	Cat 3516C TA HD/D	Cat 3516C TA HD/D
Propulsion System			Rotor Tug Tier 3	Azimuth stern drive

Fuel consumption data for four different tugboats operating with MFO were gathered as a baseline.

Ammonia consumption was modeled using mathematical methods based on its energy density, allowing comparison with MFO in terms of required fuel volume and cost. The cost of ammonia, particularly "green" ammonia, was assessed to reflect current market prices, with comparisons to MFO for operational expense analysis.

2.2. Environmental Impact Assessment

The emissions profile of ammonia versus MFO was calculated, focusing on CO_2 and NO_x emissions. Given ammonia's potential to emit NO_x, additional mitigation technologies, such as Selective Catalytic Reduction (SCR) systems, were considered necessary for compliance with emission regulations.

2.3. Assumptions

Key assumptions included stable fuel prices, unchanging energy densities, and no additional retrofitting costs for infrastructure beyond those required to handle ammonia.

3. Results

3.1. Fuel Consumption

Ammonia's lower energy density (13-19 MJ/kg) compared to MFO (43 MJ/kg) requires approximately 2.69 times the fuel volume to produce the same energy output, significantly impacting storage requirements on tugboats and more frequent refueling, which may impact the operational efficiency of tugboats in high-traffic environments such as the Port of Texas.

The specific fuel consumption (SFC) is calculated, as below, based on the energy density of the fuel and the total system efficiency.

$$SFC_K(i) = \frac{1}{\partial(k) \times n} \text{ [g/kWh]}$$

Where

- i = the load factor of the Main Engine
- δ = the energy density of the fuel used [kWh/g].
- k = the fuel type (MDO, NH_3).
- η = the total system efficiency

For his study, the total system efficiency *(η)* and load factor (i) are assumed based on references (Kyunghwa Kim, et al 2020) and these might be different from manufacturer specifications. (K. Machaj el al 2022).

The Total Fuel Consumption (TFC) is the sum of the fuel demand for propulsion load (P_p) and ship service load (P_s), as below, while using the SFC′, the total fuel consumption for one month (F) is calculated by adding the fuel used at each operating running time.

$$F_{total} = \sum_i \{P_p(i) \times T(i) \times SFC_k^{!}(i)\} + \sum_i \{P_s(i) \times T(i) \times SFC_k^{!}(i)\}$$

Where

- i = the load factor of the Main Engine,
- k = the fuel type (MDO, NH3).
- P (i) = the power demand for the load factor (i) [kW].
- T (i) = the time spent for the load factor (i) [hours]

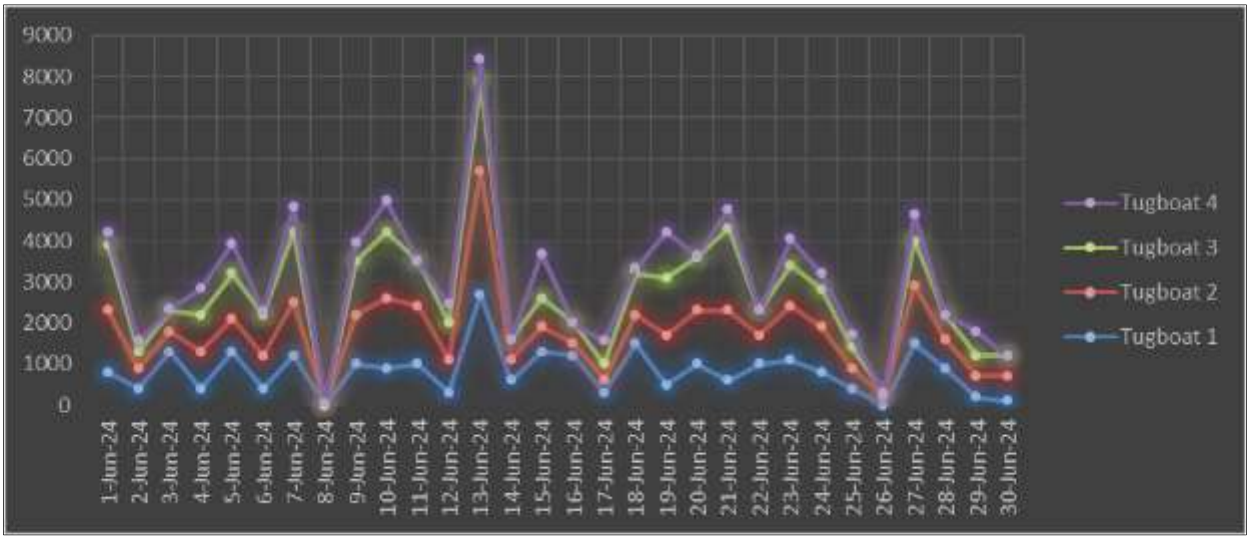

Figure 1 MDO Consumption Trend for Tugboat (Bonny Nigeria and Port of Antwerp – Bruges, Belgium)

3.2. Cost Analysis

The cost of ammonia depends on the method of production. Green ammonia, produced using renewable energy, remains more expensive ($400–$1,200 per tonne) compared to MFO ($500–$700 per tonne). Despite ammonia's lower price per unit, the increased volume required raises overall operational costs. For the tugboats studied, ammonia use increased fuel costs by approximately 12.4%, compared to MFO.

Total Fuel Cost – This is calculated based on the amount of fuel consumed and the unit price of the fuel. (Yunfan et al., 2023)

$$TFC_F = FC_F \times P_F$$

Where

- FC_F = Total amount of Fuel (l)
- P_F = Unit price of fuel

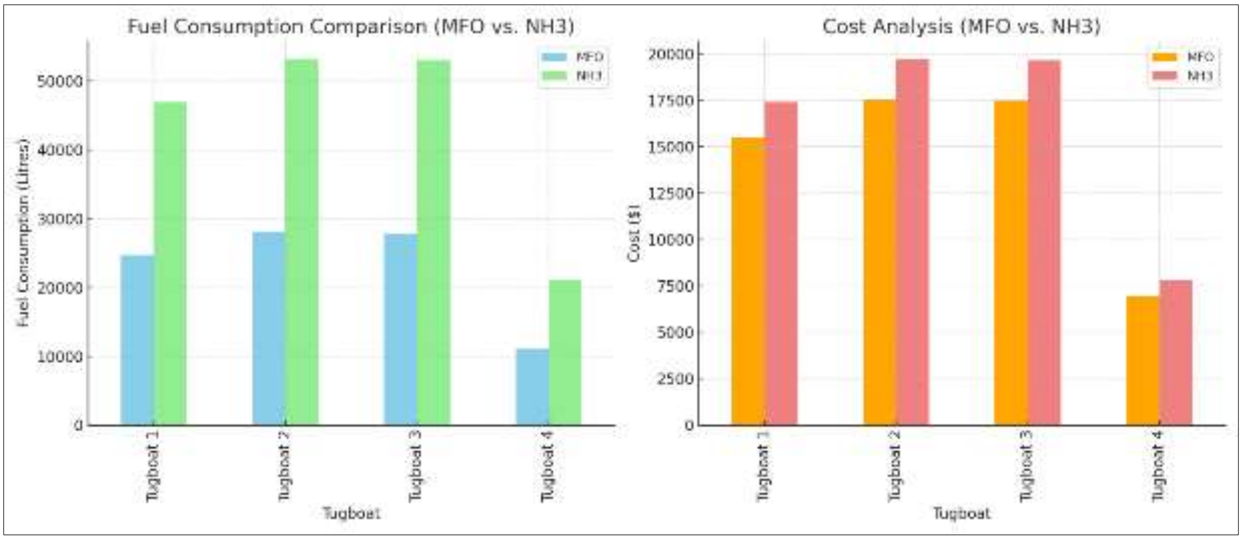

Figure 2 Chart comparing Fuel consumption and Costs analysis for MFO and NH3 across the four tugboats

3.3. Environmental Impact

Ammonia combustion produces no direct CO_2 emissions, positioning it as a key solution for reducing GHGs. However, ammonia does produce NO_x emissions, necessitating emission control measures. Safety risks associated with ammonia toxicity were also considered, highlighting the need for robust handling protocols and infrastructure updates.

The emission profile is calculated based on the amount of fuel consumed with respect to the emission factor of the individual fuel and the specific pollutant (Zhang et al., 2016)

$$Emissions = Fuel\ Consumption\ (FC) \times Emmision\ Factor(EF)$$

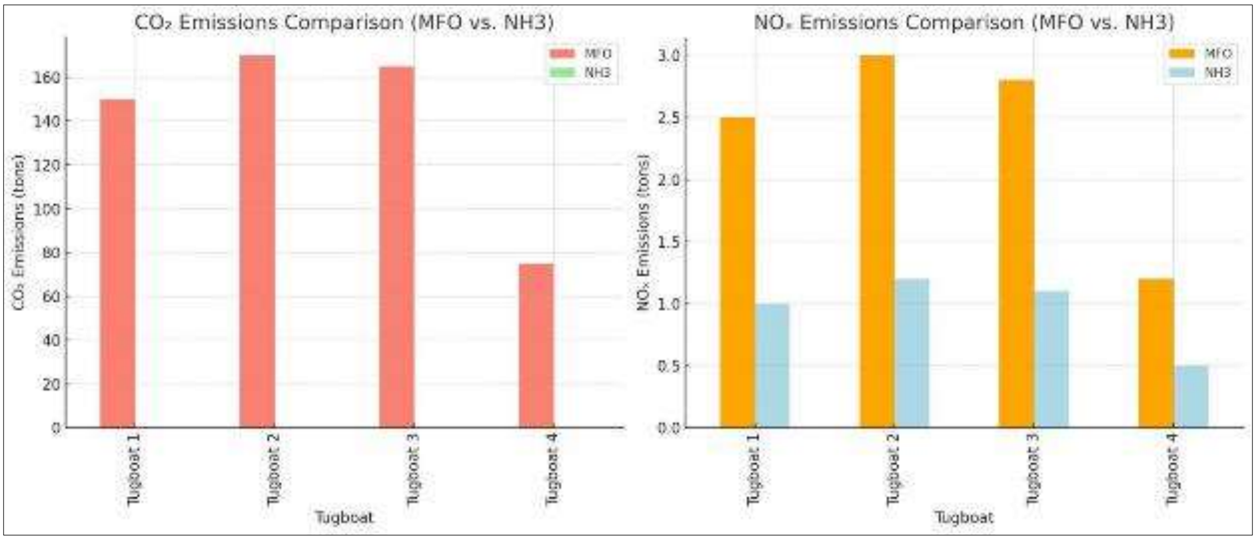

Figure 3 Chart comparing Fuel Emission for MFO and NH3 across the four tugboats

4. Discussion

The results of this study highlight ammonia's potential as a zero-carbon fuel capable of supporting the maritime industry's decarbonization goals. Compared to MFO, ammonia offers significant environmental advantages, primarily due to its zero direct CO_2 emissions. Given the increasing regulatory pressures on maritime operators to reduce their carbon footprint, ammonia could be a key player in transitioning tugboats and other high-emission port vessels toward sustainability. However, this transition is not without challenges. Ammonia's lower energy density (approximately 13-19 MJ/kg compared to 43 MJ/kg for MFO) results in higher fuel volumes, which translates to increased fuel storage requirements and more frequent refueling. This could affect tugboat operational efficiency, particularly in ports with limited refueling infrastructure.

Economically, the adoption of ammonia poses substantial initial and ongoing costs. While green ammonia, produced from renewable energy sources, aligns with sustainability goals, it remains costly to produce, and its market price is higher than that of MFO. This study's cost analysis suggests an approximate 12.4% increase in operational costs when switching to ammonia, primarily due to the higher fuel consumption rates. However, this cost disparity could be mitigated over time through policy interventions, technological advancements, and economies of scale as ammonia production processes improve. Government incentives, such as those provided under the U.S. Inflation Reduction Act, which subsidizes green hydrogen and ammonia production, could significantly offset these costs and make ammonia more economically competitive.

Safety and infrastructure considerations also pose challenges. Ammonia is highly toxic, necessitating stringent handling and storage protocols to protect both crew and the surrounding environment. In the event of a leak or spill, ammonia's toxicity could pose severe risks to human health and marine ecosystems, underscoring the need for advanced safety systems and crew training. Additionally, ports would need to invest in ammonia-specific bunkering infrastructure, including storage tanks, transfer systems, and handling equipment. Ports such as Antwerp have begun adopting ammonia bunkering facilities, providing a useful benchmark for implementing similar systems at the Port of Texas.

Table 3 Effects on humans for different exposure durations and concentrations

Risk level	Exposure duration (in min)			Effect on humans
	10	**20**	**30**	
AEGL-1	30 ppm	30 ppm	30 ppm	Discomfort, irritation, or asymptomatic numb effect
AEGL-2	220 ppm	220 ppm	160 ppm	Irreversible or other serious and long-lasting adverse health effects or impaired ability to escape
AEGL-3	2700 ppm	1600 ppm	1100 ppm	Life-threatening health effects or death

Despite these challenges, ammonia holds substantial promise as a long-term solution for decarbonizing the maritime industry. It aligns with the industry's move toward low-carbon operations and has the potential to become a competitive alternative to conventional fuels if production costs decrease and infrastructure investments are made. Future research should focus on advancing NO_x reduction technologies, such as selective catalytic reduction (SCR) systems, to address ammonia's NO_x emissions during combustion. Additionally, lifecycle analysis of green ammonia, particularly comparing its production emissions to those of traditional MFO, will be essential for validating its environmental benefits fully.

Table 4 Comparative Table of Ammonia and MDO

Factor	Ammonia	MDO
Fuel Cost	Potential for lower long term fuel cost. $400 - $1200 depending on the production method	Lower upfront cost due to existing infrastructure. Higher long term fuel cost due to increasing regulation and demands. $500 - $700 /Tonne depending on market fluctuation
Taxation	Maybe eligible for incentives or exemption to promote adoption.	Subject to standard taxation and fines
Fuel Energy Density	Lower 13 – 19MJ/kg	Higher 43MJ/kg
Infrastructure	Benefits from existing infrastructure due to usage in fertilizer, reducing new capital	Has an existing fully established infrastructure globally.
Safety	Higher safety risk due to toxic nature. Requires stringent safety measures and training	Lower safety risk compared to ammonia.
Environmental Impact	Considerably lower greenhouse gas (GHG) emission compared to MDO	Higher greenhouse gas (GHG) emission compared to ammonia.

In summary, while ammonia presents economic and operational hurdles, its environmental benefits make it a compelling choice for the maritime industry's decarbonization pathway. A coordinated effort among port authorities, regulatory bodies, and industry stakeholders will be essential to overcome these barriers and unlock ammonia's full potential as a sustainable marine fuel.

5. Conclusion

Ammonia represents a viable long-term alternative to MFO for decarbonizing the maritime industry, particularly in port operations where emissions are heavily scrutinized. While ammonia offers clear environmental advantages, including zero CO_2 emissions, its adoption faces hurdles related to operational costs, infrastructure, and safety.

Future efforts should focus on reducing ammonia's cost through technological advancements and scaling up green ammonia production. Policy interventions, including subsidies for green hydrogen production and carbon pricing, will be essential to making ammonia a competitive option for the maritime industry

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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