Life Cycle and Cost Assessment of Different Ammonia Fuels on a Case Ship

Buğra Arda Zincir[1,2*]
[1] Maritime Faculty, Istanbul Technical University, Tuzla 34940, Istanbul, Türkiye
[2] Maritime Vocational School, Galatasaray University, Besiktas 34349, Istanbul, Türkiye

Özcan Durukan[1,2]
[1] Maritime Faculty, Istanbul Technical University, Tuzla 34940, Istanbul, Türkiye
[2] Maritime Vocational School, Galatasaray University, Besiktas 34349, Istanbul, Türkiye

Yasin Arslanoğlu[1]
[1] Maritime Faculty, Istanbul Technical University, Tuzla 34940, Istanbul, Türkiye
[*] Corresponding author. E-mail: bazincir@gsu.edu.tr (B.A. Zincir)

Abstract

Amidst the rigorous regulations established by the International Maritime Organization (IMO) and the decarbonization goals outlined for 2050, the maritime sector is actively pursuing alternative approaches to achieve these targets. While alternative fuels hold promises due to their cleaner combustion, concerns persist regarding the harmful emissions generated during their production and transportation phases. Consequently, this study delves into the life cycle emissions and costs associated with conventional, blue, and green ammonia to mitigate GHG emissions. Additionally, the prevalent use of very low sulfur fuel oil (VLSFO) and marine diesel oil (MDO) warrants their consideration, enabling a comprehensive comparison of results. The assessment centers on a specific vessel, calculating the Global Warming Potential over 20 and 100 years according to the IMO guidelines introduced in July 2023. The findings reveal that green ammonia exhibits the highest potential for GWP reduction by 99.8%, followed by blue ammonia at 28.3-43.1%. From a cost perspective, blue ammonia holds an advantage over green ammonia by $3.21M for the reference vessel. Furthermore, the results indicate that conventional ammonia carries a higher environmental impact compared to VLSFO and MDO fuels, coupled with elevated costs, rendering it the least favorable option.

Keywords: *Ammonia, Decarbonization, Life cycle assessment, Life cycle cost assessment*

1. Introduction

Maritime transportation is responsible for the total cargo carried worldwide, with an 85% share, which represents 2.27 billion deadweight tons (dwt) [1]. To meet the energy demand for the transportation process, conventional marine fuels such as heavy fuel oil (HFO), marine diesel oil (MDO), and marine gas oil (MGO) are used. Moreover, after the revision of the sulfur cap on 1 January 2020, very low sulfur fuel oil (VLSFO) became an attractive choice. However, relying on fossil fuels causes harmful air pollutants, and to limit the emission of these emissions, recent regulations and strategies were introduced by the International Maritime Organization (IMO). A recent strategy was announced on 7 July 2023 about limiting GHG emissions by 20% by 2030 and 70% by 2040 regarding the 2008 levels while aiming at total decarbonization by 2050 [2]. Furthermore, at the same Marine Environmental Protection Committee (MEPC 80) meeting, a new set of guidelines was introduced for life cycle assessment (LCA). While currently in the monitoring stage, a new labeling scheme named Fuel Lifecycle Label (FLL) was introduced under the LCA guideline. Fuels will be categorized based on their feedstock, transportation, and combustion characteristics under the FLL scheme [3]. Besides, on 1 January 2024, the EU Emissions Trading System (ETS) entered into force. It is a mandatory regulation for ships above 5000 gross tonnages (GT) traversing in EU and European Free Trade Association (EFTA) ports [4]. Recently, it solely focused on CO_2 emissions, but after 2026, the whole GHG emissions will be included. In addition, FuelEU Maritime regulation will be effective after 1 January 2025, aiming to mitigate GHG emissions, which will also be compulsory for vessels above 5000 GT sailing in EU and EFTA ports [5].

The stricter regulations enforced by the authorities increased interest in alternative fuels, and many studies were conducted on them. However, concerning the decarbonization target of IMO, ammonia and hydrogen fuels became attractive solutions due to carbon freeness. Even though hydrogen provides benefits through decarbonization, alterations on ships are a major setback. Hence, this paper focused on ammonia fuel while considering different production pathways, including conventional, blue, and green ammonia. In this study, LCA and life cycle cost assessment (LCCA) for ammonia, MDO, and VLSFO are conducted on a case ship. Also, MDO and VLSFO fuels are added as the benchmark fuel choices, which enables a comparison opportunity. Despite LCA and LCCA studies being made on these fuels, for instance, Zincir and Arslanoglu, 2024 assessed 14 alternative marine fuels, including ammonia and MDO, in terms of LCA [6], Zou and Yang, 2023 evaluated HFO, ammonia, and other alternative fuels on various sized vessels [7], Zincir et al., 2022 delved into electro fuels for decarbonization target [8] and Bilgili, 2021 investigated alternative marine fuels for maritime transportation [9], it is believed that the paper will contribute to the literature by applying both LCA and LCCA for a case ship fueled by different fuels.

2. Methodology

MDO, VLSFO, conventional, blue, and green ammonia are the fuels included in this paper. MDO is a fossil fuel derived by mixing MGO and HFO. In this study, MDO consists of 52.2% HFO and 47.8% MGO. VLSFO is a residual part of the crude oil obtained after the desulphurization of HFO. Characteristics of VLSFO are the same as the HFO, except the sulfur content of it is less than 0.50%. Conventional ammonia is a carbon-free fuel that is produced from natural gas via

steam methane reforming [6]. Blue ammonia is also produced from natural gas, but part of the generated CO2 emissions, while providing sufficient energy for the process, is captured by a carbon capture system. Also, green ammonia is derived from natural gas, yet the electricity requirement is supplied from renewable energy, leading to lower harmful emissions.

In this study, a general cargo vessel with a capacity of 6177 GT is used to assess the impacts of fuel on the environment. To analyze, the fuel data of the reference ship is obtained from the management company. In Table 1 ship, specifications are presented, and in Table 2, the data are demonstrated. The vessel possesses a 2500 kW main engine and three auxiliary engines with 220 kW power output. According to the retrieved data, the case ship combusted 456.10 tons of MDO in 2022 and traveled 11,896.55 nm in a year. Moreover, the ship sailed with an average speed of 7.69 knots.

Table 1. Reference ship specifications.

Ship Specifications	
Ship Type	General Cargo
Ship Built Date	2004
Length Overall (m)	128
Beam (m)	18
Depth Moulded (m)	9.7
Draught (m)	7.6
Gross Tonnage (GT)	6177
Net Tonnage (NT)	3680
Deadweight Tonnage (mtons)	10,300
Main Engine	S.X.D. Daihatsu 8DKM-28 2500kW at 750 rpm
Auxiliary Engine	3x220 kW at 800 rpm
Ship Speed (knot)	12.3
Fuel Type	HFO/MDO
Fuel Tank Capacity (m^3)	363

Table 2. Data retrieved from the management company.

2022 Input Data	
Distance Travelled (nm)	11,896.55
Hours Underway	1546.25
Days at Open Sea	238
Days at Ports and Drydocks	127
Ship Speed (knots)	7.69
ME MDO Consumption (tons)	337.10
AUX MDO Consumption (tons)	119.00

2.1. LCA

LCA is a method to assess the environmental impact of a product or a system with a holistic approach covering its whole life cycle. According to ISO 14040, the LCA should consist of four parts, which are the definition of goal and scope, inventory analysis, environmental impact assessment (EIA), and interpretation of the results [10]. The goal and scope of the study are to analyze the environmental impact of VLSFO, MDO, and ammonia fuels. Consequently, the following assumptions are considered in the inventory analysis step:

- According to the voyage details, the reference ship sailed in the Black Sea and Mediterranean Sea. Hence, the bunkering station is determined in Aliaga (Türkiye).
- In Aliaga, refineries in that region cover 25% of the fuel production in Türkiye [11]. Thus, 25% of the VLSFO and MDO fuels are produced in that region, which requires 10 miles of transportation with pipelines to the port, while the other 75% are exported from Novorossiysk (Russia) by tankers, which is the primary crude oil exporter to Türkiye after Ukraine-Russia War [12]. The distance between the two ports is equal to 708 nm.
- In Türkiye, ammonia is not produced as fuel, therefore it must be imported. The closest facility to Türkiye that produces ammonia is Yara's facilities in the Netherlands and Norway [13]. Although the Netherlands is closer concurrently, conventional ammonia is produced there, while blue and green ammonia fuels are produced in Norway [14]. Consequently, conventional ammonia is imported from Sluiski (Netherlands), and other ammonia fuels are imported from Bergen (Norway). For both cases, ammonia is transported via ocean tankers, while the distance from Sluiski to Aliaga is 3023 nm, and from Bergen to Aliaga is 3534 nm.
- Fuel consumptions for VLSO and ammonia fuels are calculated according to the lower heating value (LHV) of fuels. LHV of MDO is 41.0 MJ/kg, while for VLSFO and ammonia, it is 39.5 MJ/kg and 18.6 MJ/kg, respectively [15].
- The lifespan of the ship is determined as 21 years, and every year, it is assumed that the same outcomes as presented in Table 2 apply.

In this study, LCA is conducted considering GWP_{20} and GWP_{100} results of the fuel choices. Regarding the assumptions, tank-to-wake (TTW) GWP_{20} and GWP_{100} emissions can be determined by using Equations 1 and 2, where $GWP_{CO2(20y)}$, $GWP_{CH4(20y)}$, and $GWP_{N2O(20y)}$ are the CO_2 equivalent of the emissions in 20 years, and for the 100y indices it is CO_2 equivalent in 100 years. For CH_4, the CO_2 equivalent in 20 years is 84, and for N_2O, it is 264, while it is 28 for the former and 265 for the latter [3].

$$GWP_{20} = GWP_{CO_2(20y)} \times gCO_2 + GWP_{CH_4(20y)} \times gCH_4 + GWP_{N_2O(20y)} \times gN_2O \quad (1)$$

$$GWP_{100} = GWP_{CO_2(100y)} \times gCO_2 + GWP_{CH_4(100y)} \times gCH_4 + GWP_{N_2O(100y)} \times gN_2O \quad (2)$$

Well-to-tank (WTT) is the other part of the emissions that are emitted, and it is determined by using GREET Model 2023 software. The default database for the production of the fuels is used while conducting the LCA, but transportation modes for the fuels are modeled considering the assumptions.

2.2. LCCA

In this paper, LCCA contains capital expenditure (CapEx) and operating expenditure (OpEx). CapEx considers equipment costs, including their installations, while OpEx consists of maintenance and fuel costs. LCCA is conducted for the reference general cargo vessel, and its 21-year lifespan is considered. Table 3 shows the input data while carrying out the LCCA analysis.

Table 3. LCCA inputs

Fuel	CapEx ($/kW)	Fuel Cost ($/ton)	Maintenance Cost ($/kW)	References
VLSO	272.5[a]	710	0.015[a]	[16-19]
MDO	272.5[a]	660	0.015[a]	[16-19]
Conventional Ammonia	577.7[a]	600	0.015[a]	[6, 18, 20, 21]
Green Ammonia	577.7[a]	800	0.015[a]	[6, 18, 20, 21]
Blue Ammonia	577.7[a]	640	0.015[a]	[6, 18, 20, 21]

[a]€/$ ratio is taken as 1.09

CapEx of the fuel systems is calculated by multiplying the main engine and auxiliary engine power with the CapEx cost in Table 3, while life cycle fuel cost is determined using Equation 3 [18].

$$LCFC_i = LM \times (FC_M \times FP_M + FC_D \times FP_D) \quad (3)$$

In the equation, $LCFC_i$ is the life cycle fuel cost for i type of fuel, LM is lifetime mileage, FC_M is the fuel consumption for the main fuel, FP_M is the price of the main fuel, FC_D is pilot fuel consumption, and FP_D is the price of the pilot fuel. Besides using Equation 4, the life cycle maintenance cost is determined [18].

$$LCMC_i = LM \times EC \times MC_i \quad (4)$$

In Equation 4, $LCMC_i$ represents the life cycle maintenance cost, EC stands for energy consumption, and MC_i is the maintenance cost for an i type of fuel system. EC is calculated by using Equation 5, where P_{MEavg} and P_{AUXavg} are the average power of the main and auxiliary engines.

$$EC = \frac{P_{MEavg} + P_{AUXavg}}{ShipSpeed_{avg}} \quad (5)$$

3. Results and Discussion

In Table 4, findings of the annual GWP calculations are presented for the case of a general cargo ship. Although ammonia is a carbon-free fuel in the combustion stage, during production, conventional ammonia emitted more than ten times higher CO_2 emissions compared to MDO and VLSFO. In addition, CH_4 emission is also higher considering MDO and VLSFO. Hence, conventional ammonia possesses the worst performance among the fuels. On the contrary, blue ammonia has higher GWP emissions in the WTT phase, except for conventional ammonia in TTW, which performed better than MDO and VLSFO. That makes it a competitive choice for maritime transportation. Furthermore, green ammonia has the lowest GWP among the choices, with a quiet margin both in the WTT and TTW phases.

Table 4. GWP results of the reference vessel

Fuel	Emission	WTT	TTW	WTW	GWP_{20}	GWP_{100}
VLSFO	CO_2	170.27	1474.2	1644.5	1644.5	1644.5
	CH_4	1.667	0.024	1.691	142.02	47.34
	N_2O	0.003	0.085	0.088	23.29	23.38
MDO	CO_2	163.80	1462.2	1626.1	1626.1	1626.1
	CH_4	1.647	0.023	1.670	140.26	46.75
	N_2O	0.003	0.082	0.085	22.47	22.55
Conventional Ammonia	CO_2	1781.8	-	1781.8	1781.8	1781.8
	CH_4	5.419	-	5.419	455.15	151.72
	N_2O	0.036	0.243	0.279	73.69	73.97
Green Ammonia	CO_2	-126.98	-	-126.98	-126.98	-126.98
	CH_4	-0.202	-	-0.202	-16.94	-5.65
	N_2O	-0.003	0.243	0.240	63.41	63.65
Blue Ammonia	CO_2	665.72	0	665.72	665.72	665.72
	CH_4	5.686	0	5.686	477.66	159.22
	N_2O	0.008	0.243	0.251	66.17	66.42

WTW: well-to-wake

Figure 1 shows the LCA results of the reference ship through its lifespan. Concerning the figure, green ammonia has the lowest GWP_{20} and GWP_{100} emissions, followed by blue ammonia. MDO and VLSFO fuels have similar outcomes with a slightly better performance with MDO, which is 1.16% for GWP_{20} and 1.15% for GWP_{100}. The least favorite fuel is conventional ammonia, which has 24.9% higher GWP_{20} and 18.5% higher GWP_{100} compared to MDO fuel. On the other hand, blue ammonia has 28.3% and 43.1% GWP_{20} and GWP_{100} reduction potential, respectively, compared to MDO. Additionally, compared to MDO, green ammonia mitigates GWP_{20} by 100.4% and GWP_{100} by 99.8%.

Figure 2 shows LCCA findings for the case ship throughout its 21-year lifespan. According to the results, maintenance cost has the lowest impact on the cost, followed by CapEx, while fuel price has the most. Even though ammonia fuel cost per ton is not that high compared to MDO and VLSFO, its lower LHV makes the fuel cost almost two times higher. Considering the total costs, MDO has the lowest with $7.850M, followed by VLSFO with $8.587M. For the ammonia fuels, conventional ammonia has the lowest with $14.843M, while blue ammonia is $15.646M, and green ammonia is $18.855M.

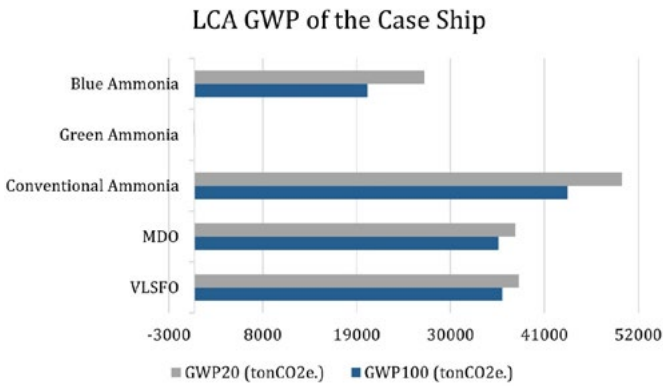
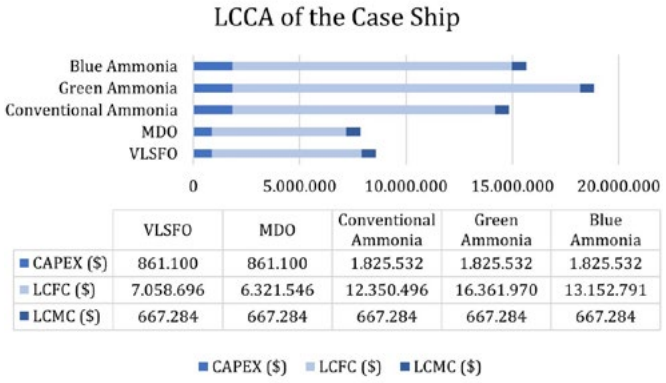


Figure 1. LCA results of the reference vessel through its lifetime



	VLSFO	MDO	Conventional Ammonia	Green Ammonia	Blue Ammonia
CAPEX ($)	861.100	861.100	1.825.532	1.825.532	1.825.532
LCFC ($)	7.058.696	6.321.546	12.350.496	16.361.970	13.152.791
LCMC ($)	667.284	667.284	667.284	667.284	667.284

Figure 2. LCCA results of the reference vessel through its lifespan

Lastly, a decision must be made regarding the LCA and LCCA analysis. The decision is evident among MDO, VLSFO, and conventional ammonia, as MDO demonstrates superior performance in both environmental and cost perspectives. However, for blue and green ammonia, several concerns arise. From an environmental standpoint, green ammonia can fulfill the IMO's 2050 decarbonization targets, while blue ammonia, at present, can only align with the 2030 strategies. On the other hand, recent targets solely focus on the combustion stage, and considering that ammonia is a carbon-free fuel, even conventional ammonia can meet this target. In July 2023, the LCA Guideline was introduced by IMO, indicating that not only the consumption of the fuels but also the production and transportation stages of the fuels will be included in the future years. Besides the environmental impact of blue and green ammonia, the costs of them play an important role. Green ammonia costs $3.21M higher compared to blue ammonia, which is the case for a 6177 GT general cargo vessel. The cost may vary depending on the ship type, size, route, and operations of the engine. Hence, in future studies, investigating those concerns plays an essential role in making a final decision.

4. Conclusion

With the stricter regulations introduced by the authorities in international shipping, alternative fuels emerged as one of the attractive solutions. The paper investigates different ammonia fuel pathways regarding LCA and LCCA. Besides, MDO and VLSFO are included to enable comparison of the fuel choices. The study reveals that green ammonia has the highest positive environmental impact with more than 99.8% GWP reduction, followed by blue ammonia with 28.3-43.1%, while conventional ammonia is the least favorite, performing worse than the current alternatives. Furthermore, in terms of cost, blue ammonia emerges as a promising option compared to green ammonia. However, further revisions to the LCA Guideline will ultimately determine the final decision. In addition, scarcity of green ammonia is still an issue as fossil-fueled electricity is more widely available instead of renewable energy. Consequently, the utilization of both blue and green ammonia may resolve the issues related to the availability of the fuels.

Acknowledgement

The author extends gratitude to Seahorse Shipping and Engineering Co. Ltd. and DD Shipping Ltd. for providing their ship data and voyage information for this study.

Nomenclature

CapEx	Capital Expenditure
dwt	deadweight tons
EFTA	European Free Trade Association
EIA	Environmental Impact Assessment
ETS	Emission Trading System
FLL	fuel lifecycle label
GT	gross tonnages
GWP	global warming potential
HFO	heavy fuel oil
IMO	International Maritime Organization
LCA	life cycle assessment
LCCA	life cycle cost assessment
LHV	lower heating value
MDO	marine diesel oil
MEPC	Marine Environmental Protection Committee
MGO	marine gas oil
NT	net tonnage
OpEx	Operation Expenditure
TTW	tank-to-wake
VLSFO	very low sulfur fuel oil
WTT	well-to-tank
WTW	well-to-wake

References

[1] United Nations Conference on Trade and Development (UNCTAD): "Review of Maritime Transport," *United Nations Conference on Trade and Development*, 2023. [Online]. Available: https://unctad.org/system/files/official-document/rmt2023_en.pdf [Accessed 27 November 2023].

[2] International Maritime Organization (IMO): "Resolution MEPC.377(80) – 2023 IMO strategy on reduction of GHG emissions from ships," *International Maritime Organization,* 2023. [Online]. Available: https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Clean%20version%20of%20Annex%201.pdf [Accessed 11 July 2023].

[3] International Maritime Organization (IMO): Resolution MEPC.376(80) – "Guidelines on life cycle GHG intensity of marine fuels (LCA guidelines)," *International Maritime Organization*, 2023. [Online]. Available: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2014.pdf [Accessed 11 July 2023].

[4] European Maritime Safety Agency (EMSA): "Fuel EU Maritime Regulation," *European Maritime Safety Agency,* 2023. [Online]. Available: https://www.emsa.europa.eu/reducing-emissions/fuel-eu-maritime-regulation.html [Accessed 10 November 2023].

[5] European Commission (EC): "Reducing emissions from the shipping sector," *European Commission*, 2023. [Online]. Available: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en accessed [Accessed 11 November 2023].

[6] B. A. Zincir, and Y. Arslanoglu, "Comparative Life Cycle Assessment of Alternative Marine Fuels," *Fuel*, vol. 358, 129995 February 2024.

[7] J. Zou, and B. Yang, "Evaluation of alternative marine fuels from dual perspectives considering multiple vessel sizes," *Transportation Research Part D: Transport and Environment*, vol. 115, 103583. February 2023.

[8] B. A. Zincir, B. Zincir, H. B. Usluer, and Y. Arslanoglu, "Using an E-fuel Method to Meet the 2030 Decarbonization Target: A Case Study," *in International Symposium on Energy Management and Sustainability, ISEMAS 2022, Tuzla, Istanbul, Türkiye, April 4-6, 2022*, M. Z. Sogut, T. H. Karakoc, O. Secgin, A. Dalkiran, Eds. Switzerland: Springer Proceedings in Energy. Springer, 2023. Cham, pp. 483-490.

[9] L. Bilgili, "Comparative assessment of alternative marine fuels in life cycle perspective," *Renewable and Sustainable Energy Reviews*, vol. 144, 110985. July 2021.

[10] International Organization for Standardization (ISO), "ISO14040 Environmental management - Life cycle assessment - Principles and framework," 2006; Geneva, Switzerland.

[11] International Trade Administration (ITA), "Oil and Gas Equipment – LNG and LNG Terminals, Upstream, Downstream and Midstream," January 2024. [Online]. Available: https://www.trade.gov/knowledge-product/turkey-oil-and-gas-equipment-lng-and-lng-terminals-upstream-downstream. [Accessed 22 February 2024].

[12] Bruegel, "Russian crude oil tracker" February 2024. [Online] Available: https://www.bruegel.org/dataset/russian-crude-oil-tracker. [Accessed 22 February 2024].

[13] Ammonia Energy Association (AEA), "Renewable Fertilizers in Europe," September 2022. [Online]. Available: https://www.ammoniaenergy.org/articles/renewable-fertilizers-in-europe/#:~:text=Yara%20is%20Europe's%20largest%20ammonia,around%20the%20globe%20each%20year. [Accessed 22 February 2024].

[14] Ammonia Energy Association (AEA), "Yara commits to Northern Lights for CCS ammonia production," December 2023. [Online]. Available: https://www.ammoniaenergy.org/articles/yara-commits-to-northern-lights-for-ccs-ammonia-production/. [Accessed 22 February 2024].

[15] Argonne National Laboratory (ANL): "GREET model," *Argonne National Laboratory*, 2016. [Online]. Available: http://greet.es.anl.gov;2016 (Accessed 10 August 2022).

[16] Ship & Bunker (S&B), "Istanbul Bunker Prices," February 2024. [Online]. Available: https://shipandbunker.com/prices/emea/medabs/tr-ist-istanbul. [Accessed 22 February 2024].

[17] T. Iannaccone, G. Landucci, A. Tugnoli, E. Salzano, and V. Cozzani, "Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies," *Journal of Cleaner Production*, vol. 260, 121069. July 2020.

[18] M. Perčić, I. Ančić, and N. Vladimir, "Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector," *Renewable and Sustainable Energy Reviews*, vol. 131, 110028. https://doi.org/10.1016/j.rser.2020.110028. October 2020.

[19] N. L. Trivyza, A. Rentizelas, and G. Theotokatos, "A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability," *Energy Conversion and Management,* vol.168, pp.128-149. July 2018.

[20] S&P Global Commodity Insights, Interactive, "Platts Ammonia price chart," February 2024. [Online]. Available: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/051023-interactive-ammonia-price-chart-natural-gas-feedstock-europe-usgc-black-sea. [Accessed 23 February 2024].

[21] International Transport Forum (ITF), "Decarbonising Maritime Transport Pathways to zero-carbon shipping by 2035," *International Transport Forum*, 2018. [Online]. Available: https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf [Accessed 7 March 2023].