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The feasibility of utilizing hydrogen fuel cells in livestock ships to mitigate greenhouse gas emissions

Mohamed SHOUMAN [1], Mamdouh ELMALLAH *[1,2], Ernesto MADARIAGA-DOMÍNGUEZ [2], José Agustín GONZÁLEZ-ALMEIDA [3]

[1] Department of Marine Engineering Technology, College of Maritime Transport & Technology, Arab Academy for Science, Technology, and Maritime Transport, Egypt.
[2] Department of Sciences and Techniques of Navigation and shipbuilding, School of Maritime Engineering, University of Cantabria, Spain.
[3] Department of Civil, Nautical and Maritime Engineering, Higher Polytechnic School of Engineering, Universidad de La Laguna, Spain.
*Email: mamdouhelmallah@aast.edu

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ABSTRACT: Global warming and air pollution are undoubtedly the major issues of our time. As livestock is considered the main source of protein and dairy products and one of the main food sources for humanity, in some regions of the world, livestock vessels serve as the main logistical means of transportation. Reducing emissions from vessels is vital to ensure animal welfare and livestock health. The vessel MV Ganado Express was chosen to evaluate the overall emissions resulting from the main engine during a 24-hour navigation period under full engine load. This study aims to develop an approach to reduce greenhouse gas emissions using hydrogen proton exchange membrane fuel cells as an alternative to the conventional fossil fuel-powered main engine. The study indicates that replacing the ship's conventional main engine with hydrogen proton exchange membrane fuel cells can mitigate CO_2 emissions by 10,200 kg, NOx by 1,637 kg, and SOX by 66 kg during a 24-hour sailing period under an engine load of 6,090 kW. During the same sailing conditions, the fuel consumption reduction when using hydrogen proton exchange membrane fuel cells is 62% lower than the fuel consumption when using a conventional diesel engine.
Keywords: climate change; International Maritime Organization; zero emissions livestock ships.

Viabilidade da utilização de células de combustível de hidrogênio em navios de transporte de gado para mitigar as emissões de gases de efeito estufa

RESUMO: O aquecimento global e a poluição do ar são, sem dúvida, os grandes problemas atuais. Como o gado é considerado a principal fonte de proteína e laticínios e uma das principais fontes de alimento da humanidade, em alguns regioes do mundo, os navios de gado servem como os principais meios logisticos de transporte. Reduzir as emissões dos navios é vital para garantir o bem-estar animal e a saúde do gado. O navio MV Ganado Express foi escolhido para avaliar as emissões gerais resultantes do motor principal durante um período de navegação de 24 horas sob carga total do motor. Este estudo visa desenvolver uma abordagem para reduzir as emissões de gases de efeito estufa utilizando células de combustível de membrana de troca de prótons de hidrogênio como uma alternativa ao motor principal convencional movido a combustível fóssil. O estudo indica que a substituição do motor principal convencional do navio por células de combustível de membrana de troca de prótons de hidrogênio pode mitigar as emissões de CO_2 em 10.200 kg, de NOx em 1.637 kg e de SOX em 66 kg durante o período de navegação de 24 horas sob uma carga de motor de 6.090 kW. Durante as mesmas condições de navegação, a redução do consumo de combustível durante o uso de células de combustível de membrana de troca de prótons de hidrogênio é 62% menor do que o consumo de combustível durante o uso do motor diesel convencional.
Palavras-chave: mudanças climáticas; Organização Marítima Internacional; navios de gado com emissão zero.

1. INTRODUCTION

Climate change and global warming have emerged as serious issues in the world, requiring the attention of governments, international organizations, and researchers (ELMALLAH et al., 2023; 2024a). The primary source of most environmental issues is the utilization of fossil fuels for energy production. The combustion of fossil fuels is the primary cause of greenhouse gas emissions (GHG), which contribute to global warming and other extremely serious environmental challenges (ELMALLAH et al., 2024a,b,c). Most recent studies and research are concerned with developing legislation and innovations in technology to minimize the use of fossil fuels and implement clean technological means to generate energy, as the global temperature is anticipated to rise by 1.5 degrees Celsius by

2050. Renewable energy is one of the most extensively researched clean technologies for reducing greenhouse gas emissions (Elmallah, 2025a,b,c,d,e); however, it should be noted that hydrogen can be a terrific substitute for fossil fuels in terms of efficiency and environmental protection (ELMALLAH, 2025f,g). More than 90% of all exports are transported by sea, rendering maritime transport the backbone of international trade. Studies have found that ships use 6.8% of the fuel used globally, producing hazardous pollutants that represent 1,076 million tons of carbon dioxide equivalent (CO-eq) greenhouse gas in 2018 (BILGILI, 2022). The maritime transport sector accounts for 3% of worldwide polluting GHG emissions the maritime transport sector accounted for around 932 million tons of CO_2 (ÖZKAYA et al., 2024).

The maritime industry's share of global emissions is as follows: It accounts for 15% of worldwide NOx emissions, 11% of worldwide SOx emissions, and 1% of worldwide CO emissions (EUROPEAN ENVIRONMENT AGENCY, 2021). Neglecting to implement proactive measures to lower these emissions will substantially increase their impact by at least 50% by 2050 (BILGILI, 2022).

Reducing ship emissions is critical to combating climate change and meeting emissions targets. To tackle the environmental repercussions of these airborne pollutants, the IMO has enforced laws and agreements and recommended technological alternatives. Adopting techniques, including maximizing energy efficiency, reducing ship speed, using alternative fuels, and introducing market-based instruments, will help reduce GHG emissions and enhance the shipping industry's environmental performance.

The IMO is making significant efforts to achieve its environmental plan, which aims to reduce CO2 emissions by 40% in 2030 and 70% in 2050 compared to 2008 CO2 emissions. There are numerous techniques to reduce emissions in the maritime industry; some emphasize the use of alternative energy, while others focus on other decarbonization strategies (XING et al., 2020; AL-ENAZI et al., 2021). In order to reduce greenhouse gas (GHG) emissions, the IMO started enacting mandatory measures such as the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP), the Energy Efficiency Operational Indicator (EEOI), and the Energy Efficiency Existing Ship Index (EEXI). The key approaches utilized to achieve the aims include improving energy efficiency and lowering the carbon intensity (CI) of new ships (FAZLOLLAHI et al., 2012; FAZLOLLAHI; MARÉCHAL, 2013; HWANGBO et al., 2017; REHMATULLA et al., 2017; HUAN et al., 2019; SANGAIAH et al., 2019; JOUNG et al., 2020).

Three methodologies are used to calculate ship fuel consumption and associated emissions. The bottom-up method depends on the ship specifications, the bottom-up method depends on ship activities, and the top-down method depends on fuel statistics. Using the combined bottom-up and top-down method, this study focuses on the emissions of the conventional fuel-powered main engine of MV Ganado Express during the 24-hour sailing period under full engine load. The study shows the mitigation amount of GHG emissions during replacing the conventional main engine with proton exchange membrane fuel cells (PEMFCs) that use hydrogen as an alternative fuel.

2. MATERIAL AND METHODS

MV Ganado Express was chosen to study the main engine's CO_2, SOX, and NOX emissions during a 24-hour sailing period under full engine load. The GHG emissions are calculated theoretically by the combination of the bottom-up and top-down methods and emission factors. The GHG emissions mitigation amount is calculated theoretically by assuming the replacement of the conventional main engine with PEMFCs for the MV Ganado Express. The maximum engine power for the case ship is 6090 kW. The PEMFCs used in this study are the Marine 200 PEMFC unit of Power Cell Group (Gothenburg, Sweden), with an amount of 30 units to equivalate the main engine's full power. This marine-type fuel cell unit has a maximum net power output of 200 kW and is appropriate for the case ship. Ganado Express is the second livestock carrier built by Cosco Guangdong Shipyard, based in China, for its Netherlands customer Vroon Offshore Services, who contracted in 2011 to build six livestock vessels at an anticipated cost of $28.25 million apiece. The first two vessels, Galloway Express and Ganado Express, were launched in April and May 2013.

The livestock carrier is intended to transport a range of animals for Landmark Global Exports for a medium-term charter, including cattle, sheep, horses, pigs, and goats. The vessel is 134.8 meters in overall length, 19.6 meters in molded beam, 125.25 meters in length between perpendiculars, and 14.8 meters in depth to the main deck. Its gross and net tonnage capacities are 10,421 and 3,126 tons, respectively. At its maximum draft of 6.8 meters, the vessel's dead weight is 5224.8 tons. The bow of the ship is built to use less fuel when traveling quickly without compromising the comfort of the livestock. It also complies with strict international standards and regulations for animal transportation and is equipped to guarantee the utmost comfort for both the crew and the animals being transported. With five decks and a total net pen area of around 4,500 m², the vessel can accommodate about 4,000 cattle at a weight of 350 kg each. There is roughly 495 m² of deck space available to hold up to 1,200 m³ of fodder. The Wärtsilä X35 engines that power the ship produce 6,090 kW (Table 1).

Table 1. Characteristics of the Ganado Express ship.
Tabela 1. Características do navio Ganado Express.

GENERAL	
Year built	2013
Builder	Cosco Guangdong, China
Flag	Portugal
IMO	9621209
PRINCIPAL DIMENSIONS	
Length Overall (LOA)	134.80 m
Beam Moulded	19.60 m
Depth	14.80 m
Summer Draft	6.80 m
MACHINERY & PROPULSION	
Main Engine	6090 kW Wartsila W7X35
Service speed Auxiliary Engines	16.75 knots
Auxiliary Engines	3x1100 kW
Shaft Generator	1050 kW
Bow Thruster	750 kW
TONNAGES	
Dead Weight Tonnage (DWT)	5225 t
Scantling Draft	6.8 m
Design Draft	5.8 m
Gross Tonnage	10421 t
Net Tonnage	3126 t

CARGO CAPACITIES & EQUIPMENT	
Total Gross Pem Area	4511 m²
Number of Decks	5
Deck Space Fodder	495 m²
Fodder (Silo)	1200 m³

Table 2 represents the main engine specifications. The engine's power output ranges from 3,475 to 6,960 kW, with a cylinder arrangement of 5-8 cylinders. Its specific fuel consumption (SFC) is 170 g/kWh.

Table 2. Main engine specifications.
Tabela 2. Especificações do motor principal.

Wärtsilä X35	
Cylinder bore	350 mm
Piston stroke	1550 mm
Speed	142–167 rpm
Mean effective pressure	21.0 bar
Stroke/bore	4.43
Number of cylinders	7
Rated power	6090 kW at 167 rpm
Weight in tonnes	95

It is crucial to determine the emission factors of the main engine to calculate its CO_2, NOx, and SOx emissions (GOLDSWORTHY; GOLDSWORTHY, 2014; BUBER et al., 2020; PARKER et al., 2018; LIU et al., 2017; ÖZKAYA et al., 2024). Table three shows the emission factors of the main engine.

Table 3. Emission factors of the main engine.
Tabela 3. Fatores de emissão do motor principal.

Emission factors	
CO_2	697 g/kWh
NOx	11.2 g/kWh
SOx	1.00 g/kWh

The equivalent number of PEMFC units that can replace the Wärtsilä X35 engine that powers the Ganado express livestock ships is 30 Marine System 200 PEMFC unit of Power Cell Group. Table three represents the specifications of the Hydrogen Fuel Cell unit.

Table 4. Specifications of the Hydrogen Fuel Cell Unit.
Tabela 4. Especificações da unidade de célula de combustível de hidrogênio.

Marine System 200 PEMFC	
Max. net power [kW]	200
Dimensions [m]	0.7 × 0.9 × 2.0
Volume [L]	1260
Weight [kg]	700
Gross output (rated power) [V/A]	600/380
Voltage output [VDC]	500–1000
Current output [A]	0–450
Fuel quality	Hydrogen ISO 14687:2019
Fuel consumption [kg/h]	13 at 200 kW
System efficiency at 200 kW	46

The following equations calculate the GHG emissions of the Wärtsilä X35 engine under full load and the ship's full capacity during a 24-hour sailing period. Equation (1) determines the amount of fuel consumption according to the trip traveled time in hours.

$$F_{trip} = SFC_{ME}.P_{ME}.t \quad (01)$$

where: F_{trip} is the fuel consumption of the trip, SFC_{ME} is the specific fuel consumption of the main engine (g/kWh), P_{ME} is the power of the main engine in kW, and t is the trip duration in hours.

Equations 2 and 3 show the total CO_2 emissions (ELKAFAS et al., 2021).

$$E_{CO2} = F_{trip}.C_F \quad (02)$$
$$E_{CO2} = \{\sum_{nME} P_{ME}.C_F.SFC_{ME}.t\} \quad (03)$$

where: E_{CO2} is the amount of CO_2 emission, C_F is the fuel carbon content, and nME is the number of main engines.

Equation 4 shows the total CO_2 emissions using the CO_2 emission factor in (g/kWh) (AMMAR; SEDDIEK, 2020).

$$E_{CO2} = P_{ME}.L_F.F_{CO2}.t \quad (04)$$

where: L_F is the engine load factor and F_{CO2} is the emission factor that is used concerning the engine power.

Equation 5 shows the total NOx emissions using the NOx emission factor in (g/kWh).

$$E_{NOx} = P_{ME}.L_F.F_{NOx}.t \quad (05)$$

where: E_{NOx} is the total NOx emissions and F_{NOx} is the NOx emission factor in (g/kWh).

Equation (6) shows the total SOx emissions using the SOx emission factor and SOx emission formula.

$$E_{SOx} = SFC_{ME}.P_{ME}.t.2.f_s.0.97753 \quad (06)$$

where: E_{SOx} is the total amount of Sox emissions. The molecular weight of SO_2 to sulfur is represented as 2, the conversion factor of fuel sulfur to SOX is 0.97753, the sulfur fraction is fs, which is 0.1% for LSMDO, and the fuel type coefficient for MDO is 0.23.

3. RESULTS

These results show the CO_2, NOx, and Sox emissions of the main conventional engine onboard MV Ganado Express during a 24-hour sailing period under full engine load. These GHG emissions are eliminated by replacing the conventional main engine with PEMFCs under the same sailing conditions. Figure one shows the CO_2 emissions of the conventional engine. The main engine's CO_2 emissions are 67000 kg under the minimum engine load power and 10200 kg under the maximum engine load power.

Figure 2 shows the NOx emissions of the conventional main engine. The NOx emissions are 1075 kg during 4000 kW of engine power and 1636.9 during 6090 kW of engine power. Figure 3 shows the conventional main engine's SOx emissions. They are 43 kg during 4000 kW of engine power and 65 kg during 6090 kW of engine power. Figure 4 shows the total CO_2, NOX, and SOX emissions under full engine load during a 24-hour sailing period. Figure 5 shows the total fuel consumption of the diesel main engine and the PEMFCs during a 24-hour sailing period under full engine load.

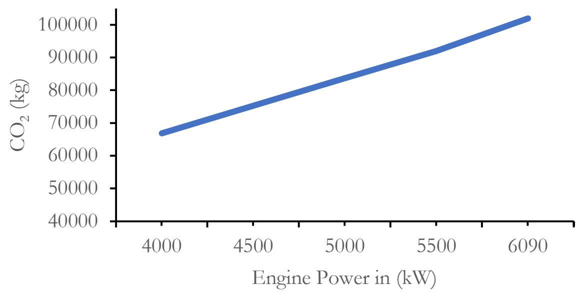


Figure 1. CO_2 emissions of the conventional engine.
Figura 1. Emissões de CO_2 do motor convencional.

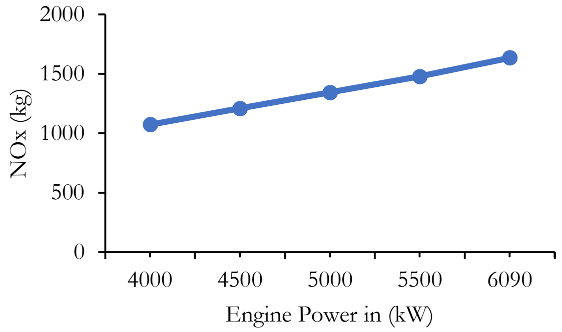


Figure 2. NOx emissions of the conventional main engine.
Figura 2. Emissões de NOx do motor principal convencional.

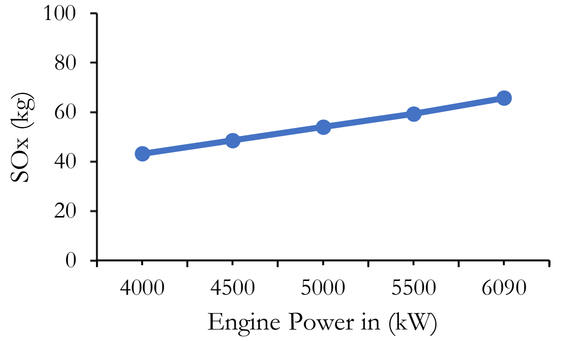
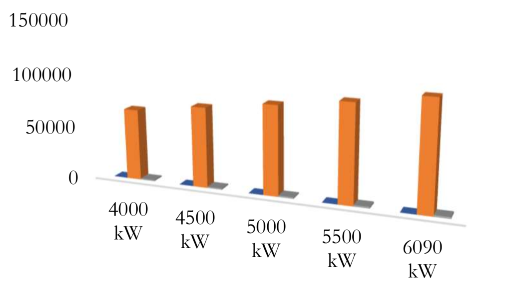


Figure 3. Sox emissions of the conventional main engine.
Figura 3. Emissões Sox do motor principal convencional.



	4000 kW	4500 kW	5000 kW	5500 kW	6090 kW
SOx emissions in (kg)	43	48	53	59	65
CO2 emissions in (kg)	66912	75276	83640	92004	102000
NOx emissions in (kg)	1075	1209	1344	1478	1636,9

SOx emissions in (kg) CO2 emissions in (kg)
NOx emissions in (kg)

Figure 4. Total CO_2, NOX, and SOX emissions.
Figura 4. Emissões totais de CO2, NOX e SOX.

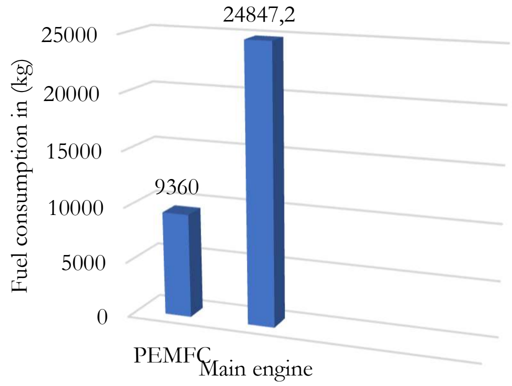


Figure 5. Total fuel consumption of the diesel main engine and the PEMFCs during a 24-hour sailing period under engine full load.
Figura 5. Consumo total de combustível do motor principal a diesel e dos PEMFCs durante um período de navegação de 24 horas com carga máxima do motor.

4. DISCUSSÃO

90% of global trade demand is transported by sea. Growing global trade demand increases the demand for maritime transport in the upcoming years; therefore, mitigating GHG emissions has become crucial (PAPADOPOULOS et al., 2022).

It is crucial to decrease the CO_2 emissions from maritime transportation, which is a major contributor to global warming and climate change. Using fossil fuels onboard ships is a great source of CO_2 emissions, which cause severe health problems for the environment, crew, and transported livestock.

This paper proves the feasibility of using hydrogen fuel cells as an alternative propulsion system onboard a ship. Using hydrogen fuel cells instead of conventional diesel engines has the potential to reduce GHG emissions while still delivering the required power for sailing. The usage of PEMFC tends to conserve space because they take up less space on board the ship and eliminate most of the auxiliary equipment that serves the conventional diesel engine. It is worth mentioning that minimizing the area utilized for the ship's engine lessens the ship's weight, lowering the required energy and providing a surplus of weight that may be used later to boost the cargo load. Hydrogen fuel cells also reduce fuel consumption by around 63%, enabling the saving of space in fuel tanks. Certainly, reducing weight assists in conserving energy, increasing efficiency when sailing, and providing a surplus that may be used to haul cargo.

The results show that the conventional diesel engine has huge GHG emissions during the 24-hour sailing period under engine load 6090 kW. The CO_2, NOx, and SOx emissions are 10200 kg, 1637 kg, and 66 kg, respectively. Replacing conventional diesel engines with hydrogen fuel cells will mitigate these emissions and eliminate them. Ship exhaust emissions pose risks to human health, generate acid rain, and contribute to global warming. The IMO held substantial discussions on controlling NOx and SOx emissions before and during the Air Pollution Conference (FITZGERALD et al., 2011). This case study shows that PEMFCs mitigate NOx emissions by 1637 kg and SOx emissions by 66 kg. Commercial ships must adhere to environmental standards requiring companies to reduce carbon dioxide emissions (MERSIN et al., 2019).

Thus, this study assessed the carbon dioxide emissions from the conventional engine and determined how significantly carbon dioxide was reduced after using hydrogen fuel cells. The PEMFCs decrease the CO_2 emissions by 10200 kg during the 24-hour sailing period while guaranteeing the same power the conventional diesel engine provides.

5. CONCLUSIONS

Maritime transportation is the most prevalent means of transporting products, particularly livestock. The ship's GHG emissions significantly contribute to climate change and environmental pollution. GHG emissions from livestock ships also endanger the health of operational crews and transported livestock. This research offers a novel way to reduce hazardous emissions aboard ships by using hydrogen fuel cells as an energy source for ship propulsion.

Bottom-up and top-down methodologies were used to calculate ship emissions onboard the MV Ganado Express Livestock. During the 24-hour sailing period under an engine load of 6090 kW, the results showed that PEMFCs eliminated CO_2, NOx, and SOx emissions by 10200, 1637, and 66 kg, respectively. PEMFCs reduce fuel consumption by 62% compared to the fuel consumption of the conventional diesel engine. This study revealed a feasible approach for reducing GHG emissions from livestock ships, enabling them to comply with the IMO objective to reduce ship emissions and achieve their future goal of zero carbon emissions.

6. REFERENCES

AL-ENAZI, A.; OKONKWO, E. C.; BIÇER, Y.; AL-ANSARI, T. A review of cleaner alternative fuels for maritime transportation. **Energy Reports**, v. 7, p. 1962-1985, 2021. https://doi.org/10.1016/j.egyr.2021.03.036

AMMAR, N. R.; SEDDIEK, I. S. Enhancing energy efficiency for new generations of containerized shipping. **Ocean Engineering**, v. 215, e107887, 2020. https://doi.org/10.1016/j.oceaneng.2020.107887

BILGILI, L. An assessment of the impacts of the Emission Control Area Declaration and alternative marine fuel utilization on shipping emissions in the Turkish Straits. **Journal of ETA Maritime Science**, v. 10, n. 3, p. 202-209, 2022. https://doi.org/10.4274/jems.2022.53315

BUBER, M.; TOZ, A. C.; SAKAR, C.; KOSEOGLU, B. Mapping the spatial distribution of emissions from domestic shipping in Izmir Bay. **Ocean Engineering**, v. 210, e107576, 2020. https://doi.org/10.1016/j.oceaneng.2020.107576

ELKAFAS, A. G.; ELGOHARY, M. M.; SHOUMAN, M. R. Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ships. **Environmental Science and Pollution Research**, v. 28, p. 15210-15222, 2021. https://doi.org/10.1007/s11356-020-11639-6

ELMALLAH, M.; ELGOHARY, M. M.; SHOUMAN, M. R. The effect of air chamber geometrical design for enhancing the output power of oscillating water column wave energy converter. **Marine Technology Society Journal**, v. 57, n. 1, p. 122-129, 2023. https://doi.org/10.4031/mtsj.57.1.14

ELMALLAH, M. The impact of livestock emissions on the maritime sector. **Journal of Maritime Research**, v. 21, n. 3, e374, 2024a.

ELMALLAH, M.; SHOUMAN, M.; ELGOHARY, M. Numerical study on enhancing the performance of air turbines in oscillating water column wave energy converters. **Journal of Maritime Research**, v. 21, n. 2, p. 428-435, 2024b.

ELMALLAH, M.; SHOUMAN, M.; ELGOHARY, M. Reduction of the methane emissions on livestock ships to mitigate greenhouse gas emissions and promote future maritime transport sustainability. **Nativa**, v. 12, n. 3, p. 551-558, 2024c. https://doi.org/10.31413/nat.v12i3.18180

ELMALLAH, M.; SHOUMAN, M.; ELGOHARY, M. M. Reducing methane emissions on livestock ships in order to mitigate greenhouse gas emissions and promote future maritime sustainability. **TransNav - The International Journal on Marine Navigation and Safety of Sea Transportation**, v. 18, n. 4, p. 797-804, 2024d. https://doi.org/10.12716/1001.18.04.05

ELMALLAH, M. Contributions to decrease noxious emissions and develop environmental sustainability in seafaring. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 246-252, 2025a. https://doi.org/10.30574/ijsra.2025.14.3.0671

ELMALLAH, M. Experimental study to investigate the effect of using a conical air chamber design in OWC wave energy converters. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 214-221, 2025b. https://doi.org/10.30574/ijsra.2025.14.3.0667

ELMALLAH, M. Experimental study to investigate the effect of using a cylindrical air chamber design in OWC wave energy converter. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 206-213, 2025c. https://doi.org/10.30574/ijsra.2025.14.3.0666

ELMALLAH, M. Experimental study to optimize the efficiency of the Oscillating Water Column wave energy converter by enhancing the air chamber design. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 196-205, 2025d. https://doi.org/10.30574/ijsra.2025.14.3.0665

ELMALLAH, M. Numerical study to investigate the effect of using a conical air chamber design in OWC wave energy converter. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 238-245, 2025e. https://doi.org/10.30574/ijsra.2025.14.3.0670

ELMALLAH, M. Numerical study to optimize the efficiency of the OWC wave energy converter. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 222-229, 2025f. https://doi.org/10.30574/ijsra.2025.14.3.0668

ELMALLAH, M. Fuel management systems and its applications on green energy. **International Journal of Science and Research Archive**, v. 14, n. 3, p. 230-237, 2025g. https://doi.org/10.30574/ijsra.2025.14.3.0669

European Environment Agency. **Emissions of air pollutants from transport**. 2021. Available on: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-8

FAZLOLLAHI, S.; MARÉCHAL, F. Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP). **Applied Thermal Engineering**, v. 50, n. 2, p. 1504-1513, 2013. https://doi.org/10.1016/j.applthermaleng.2011.11.035

FAZLOLLAHI, S.; MANDEL, P.; BECKER, G.; MARÉCHAL, F. Methods for multi-objective investment and operating optimization of complex energy systems. **Energy**, v. 45, n. 1, p. 12-22, 2012. https://doi.org/10.1016/j.energy.2012.02.046

FITZGERALD, W. B.; HOWITT, O. J.; SMITH, I. J. Greenhouse gas emissions from the international maritime transport of New Zealand's imports and exports. **Energy Policy**, v. 39, n. 3, p. 1521-1531, 2011. https://doi.org/10.1016/j.enpol.2010.12.026

GOLDSWORTHY, L.; GOLDSWORTHY, B. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data - An Australian case study. **Environmental Modelling & Software**, v. 63, p. 45-60, 2014. https://doi.org/10.1016/j.envsoft.2014.09.009

HUAN, T.; FAN, H.; LEI, W.; GUO-QIANG, Z. Options and evaluations on propulsion systems of LNG carriers. In: SERPI, A.; PORRU, M. (Eds). **Propulsion Systems**, IntechOpen eBooks, 2019. https://doi.org/10.5772/intechopen.82154

HWANGBO, S.; LEE, I.; HAN, J. Mathematical model to optimize design of integrated utility supply network and future global hydrogen supply network under demand uncertainty. **Applied Energy**, v. 195, p. 257-267, 2017. https://doi.org/10.1016/j.apenergy.2017.03.041

JOUNG, T.; KANG, S.; LEE, J.; AHN, J. The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. **Journal of International Maritime Safety, Environmental Affairs, and Shipping**, v. 4, n. 1, p. 1-7, 2020. https://doi.org/10.1080/25725084.2019.1707938

LIU, Y.; GE, Y.; TAN, J.; FU, M.; SHAH, A. N.; LI, L.; JI, Z.; DING, Y. Emission characteristics of offshore fishing ships in the Yellow Bo Sea, China. **Journal of Environmental Sciences**, v. 65, p. 83-91, 2017. https://doi.org/10.1016/j.jes.2017.02.020

MERSIN, K.; BAYIRHAN, İ.; GAZIOGLU, C. Review of CO_2 emission and reducing methods in maritime transportation. **Thermal Science**, v. 23, suppl. 6, p. 2073-2079, 2019. https://doi.org/10.2298/tsci190722372m

ÖZKAYA, E.; KAYA, A. Y.; TONOĞLU, F.; UĞURLU, Ö.; WANG, J. Effect of exhaust emissions produced by fishing vessels on air pollution: a case study of Purse Seine vessels operating in the Black Sea. **Journal of ETA Maritime Science**, v. 12, n. 2, p. 156-168, 2024. https://doi.org/10.4274/jems.2024.61214

PAPADOPOULOS, C.; KOURTELESIS, M.; MOSCHOVI, A. M.; SAKKAS, K. M.; YAKOUMIS, I. Selected techniques for cutting SOX emissions in maritime industry. **Technologies**, v. 10, n. 5, e99, 2022. https://doi.org/10.3390/technologies10050099

PARKER, R. W. R.; BLANCHARD, J. L.; GARDNER, C.; GREEN, B. S.; HARTMANN, K.; TYEDMERS, P. H.; WATSON, R. A. Fuel use and greenhouse gas emissions of world fisheries. **Nature Climate Change**, v. 8, n. 4, p. 333-337, 2018. https://doi.org/10.1038/s41558-018-0117

POWER CELL GROUP. **Marine System 200**. Available on: https://powercellgroup.com/segments/marine/

REHMATULLA, N.; CALLEYA, J.; SMITH, T. The implementation of technical energy efficiency and CO_2 emission reduction measures in shipping. **Ocean Engineering**, v. 139, p. 184-197, 2017. https://doi.org/10.1016/j.oceaneng.2017.04.029

SANGAIAH, A. K.; TIRKOLAEE, E. B.; GOLI, A.; DEHNAVI-ARANI, S. Robust optimization and mixed-integer linear programming model for LNG supply chain planning problem. **Soft Computing**, v. 24, n. 11, p. 7885-7905, 2019. https://doi.org/10.1007/s00500-019-04010-6

XING, H.; SPENCE, S.; CHEN, H. A comprehensive review on countermeasures for CO_2 emissions from ships. **Renewable & Sustainable Energy Reviews**, v. 134, e110222, 2020. https://doi.org/10.1016/j.rser.2020.110222

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