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ALTERNATIVE MARINE FUELS FOR CLEANER MARITIME TRANSPORT

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ABSTRACT

To reduce greenhouse gas (GHG) emissions, according to the vision of the International Maritime Organization (IMO), a good decision-making process is needed for the classification of alternative marine fuels considered a solution for the decarbonization of maritime transport. The paper aims to classify two alternative fuels (Liquefied natural gas (LNG) and green hydrogen obtained by electrolysis of water, in relation to four criteria (economic, technical, environmental, and social) using the specialized literature. The evaluation of the two fuels in relation to the selected criteria was carried out from a multicriteria perspective using the Analytical Hierarchy Process (AHP) method. The obtained results have shown that LNG is the best option, currently, for maritime transport, considering the operational cost, the available infrastructure, the impact on the climate, and operational safety.

Keywords: alternative fuels, AHP, electrolytic hydrogen, LNG, renewable resources

1. INTRODUCTION

Maritime transport represents over 80% of the volume of world trade and is dominated by the use of fossil fuels, such as heavy fuel oil (HFO) and marine diesel, which contribute approximately 1 million tons of fossil CO_2 annually [1], [34]. As a result of the related emissions of greenhouse gases (GHG), nitrogen oxides (NOx), sulfur oxides (SOx), and suspended particles (PM), it is necessary to reduce the climate impact of maritime transport in both the short and long term [6], [7], [32]. For this, in 2018, the International Maritime Organization (IMO) adopted a strategy proposing a reduction of total annual GHG emissions (the main driver of climate change) from international transport by at least 50 % by 2050 compared to 2008 [19]. In this sense, between 2018 and 2023, the IMO developed a series of measures regarding energy efficiency and fuel evaluation, aiming to implement low-carbon and zero-carbon fuels by 2030 [9], [26]. Also, targets were set to reduce CO2 emissions by 40% by 2030 and by 70% by 2050, compared to the same reference year, because every emitted ton of CO_2 contributes to global warming, and reducing emissions will help slow down the process. To reduce these CO_2 emissions, in addition to implementing energy efficiency measures, it is necessary to introduce alternative marine fuels with lower CO_2 emissions than conventional fuels [21], [22]. The introduction of alternative marine fuels can also lead to reductions in NOx, SOx [20].

Through the adoption of a regulation by the EU Council on the so-called FuelEU initiative in the maritime sector, the increased use of these low-carbon fuels will reduce the carbon footprint of the maritime industry [31].

There are several alternative marine fuels such as liquefied natural gas (LNG), liquefied biogas (LBG), methanol, hydrogen, ethanol, etc. The technical performance of these fuels, as well as other characteristics, namely the impact on the environment, availability, cost, and infrastructure, vary, which influences their potential in terms of propulsion power in the marine environment [2]. Therefore, the shipping industry and policymakers must select marine fuels by evaluating several factors [16].

In this study, alternative marine fuels refer to combustibles other than conventional marine fuels (such as heavy fuel oil and marine diesel), these being LNG and hydrogen obtained by electrolysis of water (green H_2).

LNG is a mixture of hydrocarbons, primarily composed of methane, and is produced from natural gas. It is created when natural gas is cooled to – 162 ° C and has the advantage of occupying a smaller volume compared to ordinary natural gas. This simplifies storage and transport and costs much less than diesel. LNG has the potential to reduce sulfur dioxide (SO_2) and PM_{10} emissions by over 90%, NOx emissions by 80%, and CO_2 emissions by 20% [4], [33].

Hydrogen, obtained by electrolysis of water (green H_2), is produced by splitting water into O_2 gas and H_2 gas. Hydrogen produced this way would avoid energy losses related to hydrogen transport and would allow a renewable and carbon-neutral marine fuel [17].

The two alternative fuels in this study were selected:
- based on the comparative data existing literature regarding certain criteria (economic, technical, environmental, and social), and
- the fact that, on the one hand, LNG is considered by the European Union as the most suitable alternative fuel for maritime transport, while wind-based electrolytic hydrogen is a renewable alternative to hydrogen.

The general purpose of this study is to evaluate the prospects of hydrogen obtained from renewable sources for the maritime transport sector, by applying a multicriteria analysis method.

The specific objectives of the study are: what is the relative importance of the criteria considered in the selection of alternative marine fuels? Which alternative marine fuel, among those analyzed, is the best ranked considering the selected criteria?

The work includes the following sections: Section 2 - Literature review, Section 3 - Applied Methodology, Section 4 - Case Study, and Conclusions.

2. LITERATURE REVIEW

A series of studies [4], [14], [18], [30] compare the economic and environmental performance of selected marine fuels and propulsion technologies. However, to better understand the potential of these fuels, assessments that cover a wide range of factors are needed. Among recent studies evaluating different alternative marine fuel options, taking into account different factors, as well as different attention given by stakeholders and experts are: [28], who found nuclear energy to be the most sustainable alternative energy source for maritime transport, followed by LNG; [10], who compared four marine fuels (fossil methanol, fossil ethanol, LNG, and hydrogen), by applying multi-criteria decision analysis (MCDA), taking into account eleven environmental and economic criteria, and who has concluded that LNG is the most suitable alternative fuel, followed by hydrogen (which can replace LNG), while the other two fuels chosen have been considered less suitable for the maritime transport sector; [27] classified LNG, hydrogen, and fossil methanol, applying MCDA for eleven criteria, considering that the first two fuels are the most sustainable marine fuels.

Another study carried out by [5] has observed that there is a tendency for the maritime fleet to be fueled with LNG, which has led, in recent years, to the construction of ships powered by this type of fuel for those of small size and for short distances.
[27] combined the fuzzy logarithmic least squares method with fuzzy TOPSIS to classify three alternative marine fuels, LNG, hydrogen, and methanol. The authors have found hydrogen to be the most sustainable option, followed by LNG and methanol.

Another study carried out in 2018 by a group of researchers has concluded that the use of any alternative fuel should lead to the reduction of GHG emissions and other pollutants throughout the life cycle, but at the same time comply with the regulations from the field. The performed analysis has demonstrated that there is no such fuel that is widely available and meets the two criteria [14].

Andersson et al. (2020) have analyzed the most important evaluation criteria of alternative marine fuels based on which they are compared from the perspective of significant GHG reduction.
[15] checked the profitability of four fuels (LNG, methanol, green hydrogen, and green ammonia), used in ships that frequently dock in Irish ports. The authors have noted that green hydrogen is the best option for decarbonization, provided that its current price is reduced.

All the results obtained in these studies depend on the included fuels, on their performance, and on the assumptions made regarding the production paths of the fuels.

To obtain additional information, other studies included a wider range of fuel options, especially biofuels, where they could more clearly assess the impact of the preferences of various stakeholders on the ranking of marine fuels [1], [10], [13], [16], [24], [25], [27], [28], [35], [36].

3. APPLIED METHODOLOGY

A tool used very often when looking to make decisions about a complex problem, which takes into account several criteria, is the Multi-Criteria Analysis (MCA). This method can be implemented through various techniques, the most used being the AHP method. The optimal solution is identified based on the judgment of the interested parties in the studied field [24]. I have used this technique because it is encountered quite often in transport problems, and because it allows the use of several independent criteria, taking into account the points of view of those involved in solving the problem [25], [35].
Figure 1 shows the steps used in the analyzed fuel classification process based on the considered criteria, according to [29].

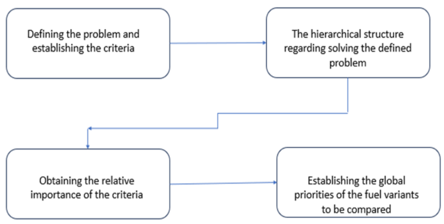

Figure 1 Steps in the AHP method

After obtaining the model, which is then broken down by levels from top to bottom (objective, criteria, competing variants that are compared), the analyzed fuel variants can be compared to be ranked (Figure 2). The ranking of these options is based on (i) the relative performance of one option compared to the other, for the established criteria and (ii) the relative importance of the criteria in achieving the objective of the decision [29].

First, it is necessary to establish the relative importance of the selected criteria, by using Saaty's numerical scale.

The criteria selected for the comparison of the two alternative fuels taken into analysis refer to the following aspects:
- technical (the available infrastructure, which includes the supply chain, the distribution and storage method, and the compatibility of the

fuel used with the existing infrastructure). Current trends regarding the available infrastructure for alternative fuels resulted from various sources (scientific articles, interest organizations, etc.) [5];

- economic (the operational cost of the fuel, which includes all the costs regarding the fuel price (which represents 30-50% of the operational cost, depending on the type of ship), crew costs, insurance costs, and maintenance costs). These operating costs for the two alternative fuels in this study were collected from [15] to be able to make comparisons;

-environmental (the impact of the used fuels on climate and environment, covering all CH_4, CO_2, and N_2O [23].

-social (safety in the exploitation of fuel on board the ship, which refers to risks regarding explosions, fires, toxicity, flammability range, but also the handling of these fuels). This information on the safety of using these fuels was collected from the reports/studies belonging to the European Maritime Safety Agency [12].

The total number of criteria used in this study is 4, selected based on the studies identified in the literature on alternative marine fuels.

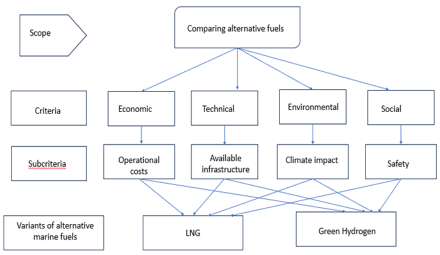

Figure 2 Hierarchical structure for ranking the established alternatives

The Saaty scale allowed the comparison of the analyzed criteria/variants of fuels, depending on the intensity of their importance, as follows: 1- when criteria i and j that are compared have the same importance; 3-when criterion i is slightly more important than criterion j; 5-when criterion i is much more important than criterion j; 7- when criterion i is strongly more important than criterion j; 9- when criterion i is absolutely more important than criterion j and 2, 4, 6- for intermediate judgments [29], [35].

By then dividing each entry in this matrix by the sum in the respective column, the normalized matrix is obtained and allows the determination of the column vector Wj (n-dimensional, where n is the number of compared criteria), which contains the weights of each criterion, calculated as the average of the entries on each row.

Taking into account the fact that the obtained values are based on subjective perceptions in the evaluation process, it is necessary to calculate the CR consistency ratio, which provides information on the consistency of these evaluations. This is possible using the consistency index for a randomly created matrix (RI) (Table 1), in which the entered judgments are very inconsistent, compared to the consistency index (CI) obtained for the judgment made in the analyzed case. CI is calculated with the formula:

$$CI = (\lambda max - n)/(n - 1) \qquad (1)$$

where: λmax is the largest eigenvalue, and n are the criteria compared in pairs

The ratio CR= CI/RI determined in this way establishes the continuation of the AHP analysis if its value is less than or equal to 0.1. Above this value, it is necessary to review the judgments.

Table 1 Randomly generated consistency indices [29]

n	3	4	5	6
RI	0.58	0.9	1.12	1.24

To calculate the λmax value start from the values obtained in the decision matrix, which are multiplied by the weight of the criterion in the corresponding column, and then the summation of the obtained values on each line leads to the so-called weighted sum. The value of λmax represents the average of the values obtained by dividing the weighted sums by the weight of each criterion.

For the derivation of local priorities for the two marine fuel variants chosen, they are compared in pairs in relation to the selected criteria, through reasoning similar to the criteria, resulting in n order matrices (mxm), where m is the number of the compared variants. To compare the two selected variants, in relation to each criterion, the same numerical scale of Saaty is used. If we note the score vectors of the two variants, in relation to the criteria chosen with s(i), i=1,2..n, the score matrix is of type mxn, and is of the form S= [s(i). ...s(N)].

The derivation of the global priorities (scores) of the two variants is achieved by weighting their local priorities with the weight of each criterion, which leads to obtaining the vector of global scores (V=S x W), based on which takes place the selection of the best variant of fuels.

Starting from the hypothesis that the factors involved in maritime transport give different priorities to these fuels, it is expected to obtain different rankings of the alternative marine fuel options. LNG is likely to be ranked first by decision-makers in the shipping industry due to its price and supply advantages [16]. For renewable options, however, it is less obvious, as each option has advantages and disadvantages, hydrogen being interesting from an environmental point of view.

The study uses the AHP method to be able to enter both quantitative and qualitative data, starting from the opinions of the interested parties involved in such studies.

4. CASE STUDY

The case study was carried out for the two marine fuels (LNG and green hydrogen). The results were obtained by applying the presented methodology, with the aim to compare the two fuels from the point of view of the four selected criteria, based on the literature (operational cost, available infrastructure, climate impact, operational safety), to select the best options, from the perspective of cleaner shipping.

The decision matrix was designed using Saaty's scale (considering that the operational cost is less important compared to the available infrastructure, the impact on the climate and operational safety are equal in importance and much more important than the operational cost (Table 2).

Table 2 Decision matrix

Criteria	Operational criteria	Availability infrastructure	Impact on the climate	Operational safety
Operational cost	1	0.333	0.2	0.2
Availability infrastructure	3	1	0.2	0.2
Impact on the climate	5	5	1	1
Operational safety	5	5	1	1
SUM	14.000	11.333	2.400	2.400

The normalized matrix is presented in Table 3.

Table 3 Normalized matrix

Criteria	Operational cost	Availability infrastructure	Impact on the climate	Operational safety	Criteria weights
Operational cost	0.071	0.029	0.083	0.083	0.067
Availability infrastructure	0.214	0.088	0.083	0.083	0.117
Impact on the climate	0.357	0.441	0.417	0.417	0.408
Operational safety	0.357	0.441	0.417	0.417	0.408

The order of importance of the criteria was established considering the results obtained by a series of studies [1], [10], [15], [16], [24], [25], [27], [28], [35], who evaluated quite clearly the point of view of the various interested parties in the field, on the ranking of marine fuels. In this way, starting from this database, the priorities of each criterion were calculated. The eigenvalue (λmax) was then calculated, which allowed the CR and CI indices to be calculated to check the consistency of the data obtained (Table 4).

Table 4 Eigenvalue

Criteria	weighted sum	weighted sum/priority
Operational cost	0.269	4.024
Availability infrastructure	0.481	4.101
Impact on the climate	1.737	4.258
Operational safety	1.737	4.258
	Total	16.641
	ʎmax	4.160

CI=(ʎmax-n)/(n-1)=(4.16-4)/3=0.053;
CR= CI/RI=0.053/0.9=0,059<0.1.

Based on the value obtained for CR, the consistency of the judgment is demonstrated, which means that the AHP process can be continued.

Using similar reasoning as in the case of the considered criteria, the global scores were obtained for the two types of analyzed fuels (Table 5). For this, within the pairwise comparisons of the two types of fuels, in relation to each of the four criteria, the following reasoning was considered:

-in terms of operational cost, LNG is much more important than green hydrogen, considering that studies such as [13], [36] have shown that green hydrogen is not competitive in terms of price compared to LNG;

-in terms of available infrastructure, LNG is more important than green hydrogen because, as stated in the studies [14], [15], [16], [17], [18], financial support is needed for the development of hydrogen from renewable sources, as well as politically to ensure the necessary infrastructure, while the number of LNG stations in Europe has increased in recent years;

-in terms of the impact on the climate, green hydrogen is more important than LNG, considering studies such as [23], [24], [26], [36], which show that clean hydrogen obtained by electrolysis of water is a fuel renewable marine, carbon neutral and thus becoming an alternative source of energy for the decarbonisation of maritime transport, while LNG has a lower potential in terms of reducing GHG emissions;

-in terms of operational safety, LNG is more important than green hydrogen gas, taking into account the studies [3], [8], [11], which have shown that ships using green hydrogen require high safety standards, compared to the LNG production process.

Table 5 Local priorities for the two variants of analyzed marine fuels

	Operational cost	Available infrastructure	Climate impact	Operational Safety
Criteria weight	0.067	0.117	0.408	0.408
LNG	0.833	0.75	0.250	0.75
Green H_2	0.167	0.25	0.750	0.25

Table 6 Overall priorities of the two variants of analyzed marine fuels

	Operational cost	Available infrastructure	Climate impact	Operational Safety	Overall priority
Criteria weight	0.067	0.117	0.408	0.408	
LNG	0.056	0.088	0.102	0.306	0.552
Green H_2	0.011	0.029	0.306	0.102	0.448

Based on these values obtained in Table 6 for overall priorities, in the case of the two alternatives (LNG and Green hydrogen), it appears that the LNG option (0.552) is better in relation to the selected criteria.

To see if the decision taken initially is robust, a sensitivity analysis is necessary. For this, the following scenarios are considered: a) the operational safety criterion has a weight of 50% and b) the climate impact criterion has a weight of 0.75.

Table 7 Scenario a)

	Operational cost	Available infrastructure	Climate impact	Operational Safety	Overall priority
Criteria weight	0.166	0.166	0.166	0.5	
LNG	0.138	0.125	0.042	0.375	0.679
Green H_2	0.028	0.042	0.125	0.125	0.319

Table 8 Scenario b)

	Operational cost	Available infrastructure	Climate impact	Operational Safety	Overall priority
Criteria weight	0.75	0.083	0.083	0.083	
LNG	0.069	0.062	0.188	0.062	0.381
Green H_2	0.125	0.021	0.062	0.021	0.229

The sensitivity analysis (Table 7 and Table 8) shows that, regardless of the weight of the criteria, the best variant of alternative marine fuel is LNG, which is the best decision for the selected criteria, currently.

5. CONCLUSIONS

The evaluation of the two variants of alternative marine fuels represents a synthesis of them. The information used in the study is obtained from reports, studies, and previous scientific works regarding these alternative fuels, used in maritime transport. To carry out the pairwise comparisons of the four selected subcriteria, but also of the two types of fuels analyzed in relation to these criteria, comparative data from previous research were necessary, with different cases being used, depending on the collected available data and taking into account, at the same time, the IMO requirements regarding these fuels.

LNG is considered a viable fuel used in maritime transport for about 20 years, seen as the fuel that makes the transition to zero-carbon fuels.

Compared to LNG, hydrogen, but especially hydrogen obtained from renewable sources, is seen today as an essential solution for the decarbonization of transport, the hydrogen-based fuel being burned with zero carbon emissions, water being the only secondary product. However, the use of this hydrogen-based fuel requires the training of the crew on board the ship, as it is a flammable gas, and the ship is obliged to implement a rather expensive infrastructure that allows the storage of hydrogen by pressurization.

On the other hand, the concern related to the safety in the exploitation of this fuel, as well as the operational costs and those related to the implementation of a dedicated infrastructure, which is very high, led to the result of this study, LNG being the more feasible option from an economic point of view, technological, operational safety, and the impact on the climate. Moreover, the transition to zero-carbon fuels (like green hydrogen) in the shipping industry requires, first of all, an increase in renewable energy generation sources.

REFERENCES

[1] Andersson, K., Brynolf, S., Hansson, J. and Grahn, M. "Criteria and Decision Support for A Sustainable Choice of Alternative Marine Fuels". *Sustainability,* Vol. 12, no.9, 3623, April. 2020; https://doi.org/10.3390/su12093623

[2] Andersson, K., Salazar, C.M. "Methanol as a Marine Fuel Report, FCBI Energy", 2015. Accessed: Nov. 23, 2023. [Online]. Available: https://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf

[3] Blanc, P., M. Zafar, F. Di Martino, A. Fargere, J. Carton and B. Kolodziejczyk. "New Hydrogen Economy - Hope or Hype?": *Innovation Insights Brief,* 2019.

[4] Brynolf, S., Fridell, E., Andersson, K. "Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol", *J. Clean. Prod. Vol.* 74, pp. 86–95, 2014.

[5] Calderón, M., Illing, D., Veiga, J. "Facilities for bunkering of liquefied natural gas in ports", *Transportation Research Procedia* Vol. 14, pp. 2431–2440, 2016.

[6] Chen, J.H., Fei, Y.J., Wan, Z. "The relationship between the development of global maritime fleets and GHG emission from shipping". *J. Environ. Manag*, Vol. 242, pp. 31–39, 2019.

[7] Cheng, Y.L., Wang, S.S., Zhu, J., Gou, Y.L., Zhang, R.F., Liu, Y.M., Zhang, Y., Yu, Q., Ma, W.C., Zhou, B.. "Surveillance of SO2 and NO2 from ship emissions by MAX-DOAS measurements and the implications regarding fuel sulfur content compliance". *Atmos. Chem. Phys*., Vol. 19, no. 21, pp. 13611–13626, 2019 https://doi.org/10.5194/acp-19-13611-2019

[8] Chi, J., and H. Yu. "Water Electrolysis Based on Renewable Energy for Hydrogen Production". *Chinese Journal of Catalysis*, Vol. 39, no. 3, pp. 390–94, 2018.

[9] Chryssakis, C., Brinks, H.W., Brunelli, A.C., Fuglseth, T. P., Lande, M., Laugen, L. "LOW CARBON SHIPPING TOWARDS 2050". Høvik, DNV GL, Norway, 2017. Accessed: Nov. 26, 2023. [Online]. Available: https://mcst-rmiusp.org/index.php/reference-library-main?task=download.send&id=106&catid=12&m

[10] Deniz, C., Zincir, B. "Environmental and economical assessment of alternative marine fuels". J. Clean. Prod., Vol. 113, pp. 438–449, 2016.

[11] Domínguez, R., Calderón, E. and Bustos, J. "Process Safety in Electrolytic Green Hydrogen Production". *Production Management and Process Control*, Vol. 36, pp. 185–195, 2022.

[12]European Maritime Safety Agency. "Mapping safety risks for hydrogen-fuelled ships", EMSA, Lisbon, 2024. Accessed: Nov. 25, 2023. [Online]. Avilable:https://www.emsa.europa.eu/tags/144-alternative-fuels.html

[13] Farhana, K., Mahamude, A. S. F. Kumaran Kadirgama, K. "Comparing hydrogen fuel cost of production from various sources - a competitive analysis". *Energy Conversion and Management,* Vol. 302, 2024, https://doi.org/10.1016/j.enconman.2024.118088

[14] Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A. "Assessment of full life-cycle air emissions of alternative shipping fuels", *J. Clean.*, Vol. 172, pp. 855–866, 2018, https://doi.org/10.1016/j.jclepro.2017.10.165

[15] Gore, K., Rigot-Müller, P., Coughlan, J. 2022. "Cost assessment of alternative fuels for maritime transportation in Ireland". *Transportation Research Part D: Transport and Environment*, Vol. 110, pp. 1-20, 2022, https://doi.org/10.1016/j.trd.2022.103416

[16] Hansson, J., Månsson, S., Brynolf, S., Grahn, M. "Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders", *Biomass and Bioenergy*, Vol. 126, pp. 159-173, 2019, https://doi.org/10.1016/j.biombioe.2019.05.008

[17] Hosseini, S. E. şi Wahid, M. A. "Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development". *Renewable and Sustainable Energy Reviews*, Vol. 57, pp. 850–866, 2016, https://doi.org/10.1016/j.rser.2015.12.112

[18] Horvath, S., Fasihi, M., Breyer, C. "Techno-economic analysis of a decarbonized shipping sector: technology suggestions for a fleet in 2030 and 2040", *Energy Convers. Manag,* Vol. 164, pp. 230–241, 2018, DOI: 10.1016/j.enconman.2018.02.098

[19] IMO. "Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG emissions in the shipping sector", International Maritime Organization, 2018. Accessed: Nov. 26, 2023. [Online]. Available: https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf.

[20] IMO. "Sulphur, Oxides (SOx) and particulate matter (PM)", Regulation 14, 2018. Accessed: Nov. 27, 2023. [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx.

[21] IMO. "Fourth IMO GHG Study 2020 – Final Report". International Maritime Organization, 2020. Accessed: Nov. 27, 2023. [Online]. Available: https://www.maritimecyprus.com/wp-

content/uploads/2021/03/4th-IMO-GHG-Study-2020.pdf.

[22] IMO. "Greenhouse gas emissions from shipping: waiting for concrete progress at IMO level", 2020. Accessed: Nov. 27, 2023. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/652754/IPOL_BRI(2020)652754_EN.pdf.

[23] Jones, M.W., Peters, G.P., Gasser, T., Andrew, R.M., Schwingshack, C., Gütschow, J., Houghton, R. A., Friedlingstein, P., Pongratz, J., LeQuéré, C. "National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850". *Sci Data*, Vol. 10, 155, 2023, DOI: 10.1038/s41597-023-02041-1

[24] Lanjewar Pramod B., Rao, R. V., Kale, A.V. "Assessment of alternative fuels for transportation using a hybrid graph theory and analytic hierarchy process method", *Fuel*, Vol.154, pp. 9–16, 2015.

[25] Osorio-Tejada, J.L., Llera-Sastresa, E., Scarpellini, S. "A multi-criteria sustainability assessment for biodiesel and liquefied natural gas as alternative fuels in transport systems", *J. Nat. Gas Sci. Eng.* Vol. 42, pp. 169–186, 2017.

[26] Oftedal, S. "The IMO GHG Strategy—Implications for Regulations and Alternative Fuels". *In Proceedings of the DNV GL Alternative Fuels online Conference*, 25 September, 2019.

[27] Ren, J., Liang, H. "Measuring the sustainability of marine fuels: a fuzzy group multicriteria decision-making approach", *Transp Res D Trans Environ*, Vol. 54, pp. 12–29, 2017.

[28] Ren, J. and Lützen, M. "Selection of sustainable alternative energy source for shipping: multi-criteria decision making under incomplete information". *Renew. Sustain. Energy Rev*, Vol. 74, pp. 1003–1019, 2017.

[29] Saaty, T. L. "Decision-making with the analytic hierarchy process", *Int. J. Serv. Sci.* 1, no. 1, pp. 83–98, 2008.

[30] Taljegard, M. Brynolf, S., Grahn, M., Andersson, K. Johnson, H. "Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model", *Environ. Sci. Technol.*, 48, no. 21, pp. 12986–12993, 2014.

[31]Transport & Environment. "Modelling The Impact Of FuelEU Maritime On EU Shipping", 2023. Accessed: Jan. 28, 2024. [Online]. Available: https://www.transportenvironment.org/uploads/files/FuelEU-Maritime-Impact-Assessment.pdf

[32] Traut, M. Larkin, A., Anderson, K. McGlade, C., Sharmina, M., Smith, T. "CO2 abatement goals for international shipping", *Clim. Policy*, 18, no.8, pp. 1066-1075, 2018.

[33] Turcanu, A. L. (Marcu), Gasparotti, C., Rusu, E. "Green fuels — A new challenge for marine industry". *Energy Reports*, Volume 7, Supplement 3, pp. 127-132, 2021.

[34] UNCTAD. "Developments in international seaborne trade". Review of Maritime Transport, 2018. Accessed: Dec. 20, 2023. [Online]. Available: https://unctad.org/system/files/official-document/rmt2018ch1_en.pdf

[35] Ziolkowska, J.R. "Evaluating the sustainability of biofuels feedstocks: a multi-objective framework for supporting decision-making", *Biomass Bioenergy,* 59, pp. 425–440, 2013.

[36] Wang, Y. and Wright, L.A. "A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation". *World*, 2, no. 4, pp. 456–481, 2021, DOI: 10.3390/world2040029

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