CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	A perspective on the role of multi-criteria decision-making in assessing the sustainability of alternative shipping fuels
Authors	Sorkhab, Mohammadali Babanejadi;Gray, Nathan;Wall, David;Murphy, Jerry D.;O'Shea, Richard
Publication date	2026-07-08
Original Citation	Sorkhab, M B, Gray, N, Wall, D, Murphy, J D & O'Shea, R 2026, 'A perspective on the role of multi-criteria decision-making in assessing the sustainability of alternative shipping fuels', Journal of Cleaner Production, vol. 571, 148658, pp. 1-25. https://doi.org/10.1016/j.jclepro.2026.148658
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://www.scopus.com/pages/publications/105042455434 - 10.1016/j.jclepro.2026.148658
Rights	© 2026, authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/) - https://creativecommons.org/licenses/by/4.0/
Download date	2026-11-11 13:01:56
Item downloaded from	https://hdl.handle.net/10468/19584



UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Journal of Cleaner Production 571 (2026) 148658

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A perspective on the role of multi-criteria decision-making in assessing the sustainability of alternative shipping fuels

Mohammadali Babanejadi Sorkhab [a], Nathan Gray [a,b], David Wall [a,b], Jerry D. Murphy [a,b], Richard O'Shea [a,b,*]

[a] MaREI Centre for Energy, Climate and Marine, Sustainability Institute, University College Cork, Ireland
[b] Civil, Structural and Environmental Engineering, School of Engineering and Architecture, University College Cork, Ireland

HIGHLIGHTS

- No prior literature assessed considered refuelling infrastructure.
- The social pillar is the least considered in prior assessments.
- The use of LCA and process simulation to obtain performance data is rare.
- Subjective weighting methods are more common than objective methods.
- A framework for future work is proposed to improve transparency and comparability.

ARTICLE INFO

Keywords:
Shipping fuel
Alternative fuels
Sustainability assessment
Multi-criteria decision making

ABSTRACT

The shipping sector was responsible for 2.9% of global greenhouse gas emissions in 2018. Alternative low/zero-carbon fuels could reduce these emissions. Of issue is high financial investment, long development times, and difficulties in selecting the most sustainable fuel. Multi-Criteria Decision Making (MCDM) methods can aid decision-makers in comparing alternative shipping fuels from technical and sustainability perspectives. MCDM provides methodologies to deal with multiple, often conflicting, criteria with varying degrees of importance or allowable trade-off. This paper provides a perspective on the use of the MCDM methods for comparing alternative shipping fuels. The work indicates that: 1) future research should use Life Cycle Assessment for a more holistic approach to assessing the environmental impact of each fuel; 2) process simulation software can be used to develop the data required for comparing different fuel production pathways; 3) objective weighting methods can be used more in future research; 4) input from port stakeholders should be considered in future research; and 5) to generate a robust comparison, infrastructural requirements should be considered. To enhance the methodological robustness of the results, compensatory aggregation methods should be used with weights that represent a trade-off among criteria rather than their relative importance. When applying such aggregation methods, researchers must clarify whether poor performance in one criterion can be compensated by strong performance in another one.

1. Introduction

1.1. Current state of the shipping sector from an emissions perspective

In 2021, the volume of goods transported by maritime shipping reached 11 billion metric tonnes, 3.2% higher than in 2020 (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2023), which indicates the importance of shipping in global trade. The share of the maritime sector in terms of global anthropogenic emissions grew to 2.9% in 2018 from 2.8% in 2012 (International Maritime Organisation (IMO) 2020). Without any mitigation action or efficiency improvements, greenhouse gas (GHG) emissions from this sector will increase by between 90% and 130% by 2050 as compared to 2008, based on anticipated energy scenarios and economic growth (International Maritime Organisation (IMO) 2020). The International Maritime Organization (IMO) plans to decrease total annual GHG emissions due to

* Corresponding author. MaREI Centre for Energy, Climate and Marine, Sustainability Institute, University College Cork, Ireland
E-mail address: richard.oshea@ucc.ie (R. O'Shea).

https://doi.org/10.1016/j.jclepro.2026.148658
Received 8 December 2025; Received in revised form 10 February 2026; Accepted 31 May 2026
Available online 19 June 2026
0959-6526/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

international shipping activities by at least 20% by 2030 and at least 70% by 2040, as compared to 2008 (International Maritime Organization, 2023). In addition to GHGs, the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI set strict rules regarding NO_x, SO_x, and particulate matter (PM) emissions from shipping (Čampara et al., 2018). The shipping industry is not only responsible for GHG emissions, but it is also affected by climate change. Climate impacts such as tropical storms, sea level rise, extreme heat events, inland flooding, and drought may cost the shipping sector an extra 25 billion US dollars annually by 2100 (Van Houtven et al., 2022).

The IMO obligates ships with a gross tonnage above 400 engaged in international voyages to adopt an on-board Ship Energy Efficiency Management Plan (SEEMP). This plan consists of three parts. In the first part, the energy efficiency of ships should be monitored and improved. The second part obligates ships above 5000 gross tonnage to record and report their fuel oil consumption. The third part obligates ships covered in the second part to report the calculation and improvement of a Carbon Intensity Indicator (CII) (International Maritime Organization, 2022). To achieve the IMO's target of reducing the carbon emission intensity of ships, existing ships above 400 gross tonnage engaged in international shipping should calculate their Energy Efficiency Existing Ship Index (EEXI) (International Maritime Organization (IMO), 2021).

The FuelEU Maritime regulation (Council of the EU, 2023) sets targets to reduce the well-to-wake GHG intensity (gCO_2eq/MJ) of the fuels used by ships above 5000 gross tonnage visiting European ports by 2% by 2025, and by 80% by 2050, both relative to 91.16 gCO2eq/MJ as the baseline fossil fuel comparator. This can be achieved by using alternative fuels such as e-methanol, e-ammonia, and e-LNG. Besides voyages, passenger and container ships berthing at port must use either an onshore electrical power supply or fuel cells, onboard electrical energy storage, or onboard wind or solar power generation from 1st January 2030. This regulation, by considering stakeholders (shipowners, ship operators, and port operators), provides flexibility and time to achieve mitigation targets. The flexibility and time frame are crucial due to the challenges and decision-making complexity of using alternative fuels. Since 2024, the maritime sector has been included in the European Union Emission Trading System (EU ETS), which limits the allowable annual GHG emissions from ships entering European ports (European Union, 2024) while promoting energy efficiency improvements and the reduction of the fuel price difference between conventional and alternative shipping fuels. This policy has impacts on the economy (capital costs, operational costs, fuel costs, carbon costs), environment (GHGs, black carbon, and air pollutant emissions), and society (employment in the shipping sector and related sectors, vulnerable households), which should be considered and monitored before and after implementation (European Union, 2021). In addition, the proposed IMO net zero framework, which is under review at the time of writing this paper, may have substantial impact on the development of alternative fuels projects.

1.2. The challenge of emissions mitigation in shipping

There are many options to reduce GHG emissions in the shipping sector. Motlagh et al. (Soltani Motlagh et al., 2023) compared 12 different technological and operational solutions for meeting the IMO GHG reduction target in container shipping, including: main and auxiliary machinery efficiency optimization; lighter material used in containers; ship trim optimization; speed optimization; and route and schedule optimization. According to their findings, operational solutions are more favorable than technological ones. Also, the emissions reduction potential differs among different solutions. For example, slow steaming (an operational solution) can reduce GHG emissions by 40% (Farkas et al., 2022), while improvement in ship hull coating (a technical solution) can reduce carbon emissions by at most 5% (Sames and Köpke, 2012).

Inal et al. (2022) categorized possible energy sources in the shipping industry into four groups, including diesel engines; batteries; renewable energy; and fuel cells. The study outlined available fuels for fuel cells and diesel engines, along with ways of producing renewable energy on ships. They also categorized each fuel or power generation system from the perspective of GHG emissions and possible range, into three groups: Carbon Content & Long Distance; Zero Carbon & Short Distance; and Zero Carbon & Long Distance. For example, ammonia used in a fuel cell is marked as Zero Carbon & Long Distance; solar energy is marked as Zero Carbon & Short Distance; and diesel used in a diesel engine is marked as Carbon Content & Long Distance. Implementing decarbonization strategies depends on the type of ship and its application. For example, passenger ferries may focus on electrification, while cruise ships are investing in developing shore-to-ship power technologies (U.S. Department of Transportation, 2023).

Due to the unique needs and characteristics of shipping, common solutions for decarbonization in other sectors of transportation are not necessarily applicable in this sector. For instance, due to the long distances travelled in shipping and high power requirements, the use of batteries in this industry seems unlikely without a major improvement in battery manufacturing technology (Fulton et al., 2015). Moreover, operational and technical decarbonization pathways are not solely sufficient to meet the global targets (Balcombe et al., 2019). As an example, the Energy Efficiency Design Index (EEDI) sets a minimum carbon efficiency for newly manufactured ships; however, all vessels are not expected to comply with EEDI until 2040 (Gray et al., 2021). As a result, alternative low or zero-carbon fuels will play a major role in reducing both GHG emissions and air pollutants. The IMO's goal for 2030 is that at least 5% of the energy consumption in the international shipping sector should be provided by zero or near-zero carbon fuels or energy sources (International Maritime Organization, 2023).

Beyond the ship itself, the shipping industry must consider logistical and infrastructural elements such as trucks, lighting, and port activities (such as using cranes for cargo handling and the emissions by berthed vessels), which are further sources of GHG emissions and air pollutants. In this regard, ports can implement strategies to reduce their environmental impacts. For example, ships can be forced to turn off their diesel engines and use renewable electricity provided by ports during their stay (U.S. Department of Transportation, 2023). Another possible action is the electrification of port activities while generating renewable energy with the help of solar panels or wind turbines.

With regards to SO_x reduction, ship owners can use low-sulphur fuels such as very low sulphur fuel oil (VLSFO) or marine gas oil (MGO), liquefied natural gas (LNG), methanol, liquefied petroleum gas (LPG), hydrogen, or biofuels which emit very small amounts of SO_x, or they can use exhaust gas treatment equipment like scrubbers to reduce SO_x emission from the combustion of high-sulphur fuels (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2023).

Overall, decarbonizing and reducing air pollutant emissions from the shipping industry should be implemented on both vessels and ports.

1.3. Sustainability indicators

Different countries and shipping companies choose different criteria to assess their progress towards sustainability. For example, the IMO acts in line with the Sustainable Development Goals. In this regard, the IMO has announced the rules for reducing GHG emissions and air pollutants in MARPOL VI (International Maritime Organization, 2024). As another example, Maersk divided its strategies toward sustainable development into three areas: environment; society; and governance (Møller – Mærsk A/S, 2023). The environment section includes three subcategories: climate change; environment and ecosystems; and responsible ship recycling.

Regarding climate change, Maersk has committed to aligning with 1.5-degree pathways by 2030 and reaching net zero by 2040. Concerning the environment and ecosystem, they have commitments to decrease pollution and waste in the air, land, and water. In this regard,

they monitor their air pollutant emissions (NO_X, SO_X, non-methane volatile organic compounds (NMVOCs), PM10, PM2.5, and black carbon), oil spills, containers lost, material consumption, and water consumption. The Mediterranean Shipping Company (MSC) announced that its goal is to use net-zero emission vessels by 2030 and to achieve net-zero goals by 2050. This target will be achieved by improving energy efficiency, vessel performance and route optimization, and decarbonizing ports (Mediterranean Shipping Company, 2022).

Singapore, a major country with respect to the shipping industry, has set targets regarding climate change for its maritime operations. In terms of ports, Singapore will reduce GHG emissions by 60 % by 2030 (compared with the 2005 level) and reach net zero by 2050. Concerning the fleet, Singapore plans to reduce the emissions from the domestic harbour craft fleet by 15 % by 2030 (compared with 2021) by using low-carbon energy sources (MARITIME SINGAPORE, 2022).

Choosing the most sustainable fuel for shipping is a challenging process that needs a comprehensive view of the whole supply chain. Utilizing alternative fuels in the shipping industry should be assessed while considering technical viability and sustainability. In this regard, all three pillars of sustainability (economy, environment, and society) need to be considered. In many cases, these pillars can act in opposite directions, meaning that improving one could worsen the other; therefore, finding an alternative fuel that performs best across all three pillars is challenging. A technical assessment is also crucial to avoid proposing impractical or infeasible fuels. Some technical aspects need to be studied for alternative fuels, such as: fuel delivery to seaports; fuelling infrastructure and regulations; onboard storage facilities; engine performance and changes in the type and quantity of emissions; workforce training; and safety (International Energy Agency (IEA), 2024).

The aim of this paper is to provide a comprehensive overview of the current state of the art on the use and implementation of multi-criteria decision making (MCDM) to compare alternative shipping fuels, highlighting common trends and knowledge gaps. A key focus of this paper is the identification of knowledge gaps regarding the implementation of MCDM methods, specifically the different steps within MCDM methods, stakeholder engagement, and sensitivity analysis, based on current literature. Subsequently, a perspective is offered to address these knowledge gaps by proposing the need to use more robust and less common MCDM methods. Finally, a key contribution of this paper is the development of a systematic and comprehensive framework to improve future studies that use MCDM to compare alternative shipping fuels based on the aforementioned perspective.

1.4. Multi-criteria decision-making and sustainability assessments

Multi-criteria decision-making (MCDM), also known as Multi-Criteria Decision Analysis, Multi-Attribute Decision Making, and Multi-objective Decision Making, is a common approach that helps decision-makers to compare different alternatives according to their performance under some defined criteria. It can be completed by one decision-maker or a group of decision-makers. With regards to the decision-making context and the objective of the analysis, MCDM may be used to rank, sort, or select alternatives, whilst considering multiple performance criteria. This method, through the engagement of decision makers, enables them to systematically apply their opinions on the importance of or allowable trade-off between criteria and the performance of alternatives. In this way, the possibility of ignoring a criterion or alternative is reduced, and the decision-making process becomes clear and, most of the time, repeatable.

The use of MCDM methods to rank alternative shipping fuels is therefore an appropriate application which can aid in the holistic comparison of these alternative shipping fuels. In addition, if there is no consensus among decision makers, or if they are unsure about their opinions, MCDM may be used to rapidly generate differing scenarios in terms of the importance of or allowable trade-off between criteria by altering the criteria weights. This scenario development may be used to aid decision makers in reaching a consensus on the criteria weights by presenting how the ranking of alternative shipping fuels alters with different criteria weights. To undertake MCDM, firstly, the goal of the study should be clarified. Secondly, all criteria (such as GHG emissions, production costs, and job creation) and their relative importance or allowable trade-off should be defined. Thirdly, all alternatives (such as alternative fuels in the form of ammonia or hydrogen) and their performance concerning each criterion should be gathered (for example, GHG emissions from ammonia utilization). Finally, the alternatives are compared using mathematical methods.

In an MCDM study with m alternatives and n criteria, a decision matrix can be formed, along with a weight vector as per Equations (1) and (2), respectively.

$$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} w_1 & \ldots & w_n \end{bmatrix} \tag{2}$$

Where a_{ij} is the performance data of i^{th} $(1 \le i \le m)$ alternative with respect to the j^{th} $(1 \le j \le n)$ criterion. w_j is the weight (importance or allowable trade-off) of the j^{th} criterion. Note that the sum of all weights is equal to 1. Using the weights and performance matrix, it is possible to rank alternatives from the best to the worst by using several MCDM methods.

MCDM methods are widely used in different fields for different purposes. For example Wu et al. (2018) and Streimikiene et al. (2012) used MCDM in the energy context for the assessment of power generation systems. MCDM methods are also used in the field of bioenergy, fuel synthesis, and material production. Abdel-Basset et al. (2021) identified the most sustainable bioenergy production technology, Haase et al. (2020) selected the most sustainable renewable fuel production pathways, and Ren et al. (2020) chose the most sustainable technology for hydrogen production, all using MCDM methods. These methods are used in combination with life cycle assessment (LCA) in the paper by Nagy et al. (2023) to compare processes for nitrogen recovery from rejected water with minimal environmental impacts. Another example of the application of MCDM methods is ranking residential heating options in the paper by Martín-Gamboa et al. (2019). Table 1 summarizes the cited examples and the MCDM methods used.

There are several aspects that need to be considered when conducting an MCDM study to find the most sustainable shipping fuel for a specific port, country, or region, which differentiates it from other fields of study. These include geographical characteristics, available energy and material resources, type and number of ships visiting ports, national and international regulations and policies, and available or planned infrastructure for energy systems (particularly at ports). In addition, if a port or country does not provide refueling for ships at present, it will be challenging to calculate the accurate demand for fuels in the future because ships often refuel once and visit multiple ports during a voyage.

In terms of review papers, many articles tried to synthesize how and where MCDM methods are used. Guzmán et al. (Campos-Guzmán et al., 2019) reviewed 154 papers published from 2007 to 2017 related to the use of life cycle assessment and MCDM to choose the most sustainable renewable energy technologies. They concluded that the combination of Life Cycle Assessment and Analytic Hierarchy Process is the most used method by researchers. MCDM methods considered were Data Envelopment Analysis (DEA), Analytical Network Process (ANP), PROMETHEE, ELECTRE, VIKOR, AHP, and TOPSIS. They categorized the criteria into four groups: economic, environmental, social, and technical. In each group, they determined how many times each sub-criterion was used. Siksnelyte et al. (2018) reviewed 105 articles on the use of MCDM methods and sustainable energy development problems published from 2004 to 2017 by exploring the Web of Science Core Collection database. Articles were divided into 9 application categories

Table 1
– Examples of using MCDM in different fields of study.

Reference number	Field of study	MCDM method used	Description
Wu et al. (2018)	Power generation	Areal Grey Relational Analysis, Fuzzy Rough Set, Entropy, AHP[a]	Sustainability assessment of existing Chinese coal-fired power generation units.
Abdel-Basset et al. (2021)	Bio-energy production	DEMATEL[b],EDAS[c]	Selecting the most sustainable bioenergy production method.
Nagy et al. (2023)	Waste water treatment	TOPSIS[d]	Selecting the process with minimal environmental impacts for nitrogen recovery from rejected water by combining LCA[i] and MCDM.
Haase et al. (2020)	Renewable fuel production	TOPSIS	Selecting the most sustainable renewable fuel production pathways from 2nd generation biomass, considering economic, social, and environmental indicators.
Streimikiene et al. (2012)	Power generation	MULTIMOORA[e], TOPSIS	Selecting the most sustainable power generation technologies.
Ren et al. (2020)	Chemicals production	Fuzzy BWM[f], TOPSIS	Choosing the most sustainable technology for hydrogen production.
Martín-Gamboa et al. (2019)	Residential heating	WSM, TOPSIS, ELECTRE[g], PROMETHEE[h]	Choosing the most sustainable residential heating system.

[a] Analytical Hierarch Process
[b] Decision-Making Trial and Evaluation Laboratory
[c] Evaluation based on Distance from Average Solution
[d] Technique of Order Preference by Similarity to the Ideal Solution
[e] Multiple Objective Optimization on the basis of Ratio Analysis plus Full Multiplicative Form
[f] Best-Worst Method
[g] ÉLimination Et Choix Traduisant la REalité
[h] Preference Ranking Organization Method for Enrichment Evaluation
[i] Life Cycle Assessment

(Energy policy/project selection, impact analysis, evaluation of power generation technologies, regional planning, place selection, national planning, review, methods selection, and others) and 10 MCDM methods categories including AHP/ANP, Fuzzy Sets, TOPSIS, Weighted Aggregated Sum Product Assessment (WASPAS), PROMETHEE, VIKOR, ELECTRE, Analysis and Synthesis of Parameters under Information Deficiency (ASPID), MULTIMOORA, and other. It was found that AHP, TOPSIS, PROMETHEE, and Fuzzy Sets are the most used MCDM methods in reviewed papers.

Wang et al. (2009) reviewed available articles that used MCDM methods in the sustainable energy field. The study categorized weighting and ranking methods and divided criteria into four groups: economic; social; technical; and environmental. Weighting methods were classified into three groups of subjective (Simple Multi-Attribute Rating Technique (SMART), SWING, SIMOS, pairwise comparison, and AHP), objective (Entropy, Vertical and horizontal method), and combined weighting methods. For the MCDM method, they recorded papers that used the Weighted Sum Method (WSM), AHP, Grey Relational Analysis, PROMETHEE, ELECTRE, Novel Approach to Imprecise Assessment and Decision Environments (NAIADE), Measuring Attractiveness through a Categorical-Based Evaluation Technique (MACBETH), and Preference Assessment by Imprecise Ratio Statements (PAIRS). It was found that investment costs and CO_2 emissions are the criteria considered most often and equal criteria weighting is the most used weighting method, followed by subjective weights from the AHP method. Jamwal et al. (2021) completed a systematic review of papers published from 2000 to 2020 to find how MCDM approaches are used in sustainable manufacturing. MCDM methods were categorized into three groups - outranking (ELECTRE, PROMETHEE), utility based (Multi Attribute Utility Theory (MAUT), AHP, WSM), and miscellaneous models (Stochastic Multicriteria Acceptability Analysis (SMAA)). It was found that AHP was the most used method, and that social aspects and sensitivity analysis were neglected in most of the reviewed papers.

A review paper by Alam et al. (2021) considered the use of MCDM and alternative shipping fuels. The study assessed papers available on the Scopus database published from 2000 to 2021. Firstly, papers related to MCDM and alternative fuels were analysed regardless of the end use sector. The assessment was then limited to papers related to alternative shipping fuel. In the study, the MCDM approach as a whole was analysed for the reviewed papers but the different steps (data collection and normalization, weight elicitation, and weighting method) of MCDM were not included in their assessment. They also conducted a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis for the different MCDM methods.

As mentioned, MCDM methods are widely used in various fields, (and have been used in the selection of sustainable shipping fuel), due to their transparency and structured framework. These methods can compare several options by considering different criteria while considering the opinions of decision-makers and stakeholders, which is especially useful when the criteria conflict with each other. As stated previously, this study aims to determine the current state of the art on the use of MCDM to compare alternative shipping fuels, especially the identification of common trends and knowledge gaps. This work can be used as a guide for future research by providing an up-to-date database of prior studies that used MCDM to assess shipping fuels. The audience of this paper includes for academic researchers, industrial decision-makers, and policy makers in the shipping sector.

2. Current research on using MCDM to compare alternative shipping fuels

To offer a comprehensive perspective, this study first evaluates current research on the use of MCDM for comparing alternative shipping fuels. In total, 31 published papers were assessed. These papers were identified using a non-systematic search on Google Scholar with combinations of keywords such as “shipping fuel”, “multi-criteria decision making”, and “sustainability assessment”. Fig. 1 illustrates the different fields that this paper aims to cover.

In summary, the analysis of alternative fuels from fossil sources by assessed papers reflects the efforts of researchers to reduce tank-to-wake emissions. Therefore, a key gap remains in assessing the well-to-tank emissions (Fig. 2) through a life cycle approach. In previous studies, ship characteristics and the port facilities required for each alternative fuel were not widely considered. Investment costs and fuel prices have been well accounted for in prior works, however the social impacts of replacing conventional fuels with alternative shipping fuels have been less investigated. Furthermore, since environmental impacts in prior studies were limited to greenhouse gas emissions or NO_x/SO_x; the authors suggest a wider set of environmental impacts should be considered in future studies. Considering the opinions of ship builders, ship operators, and port operators in determining technical criteria is not widespread in prior studies, and their input can be helpful in future studies to ensure the relevance of criteria considered. Subjective methods for obtaining performance data and criteria weights have been used more

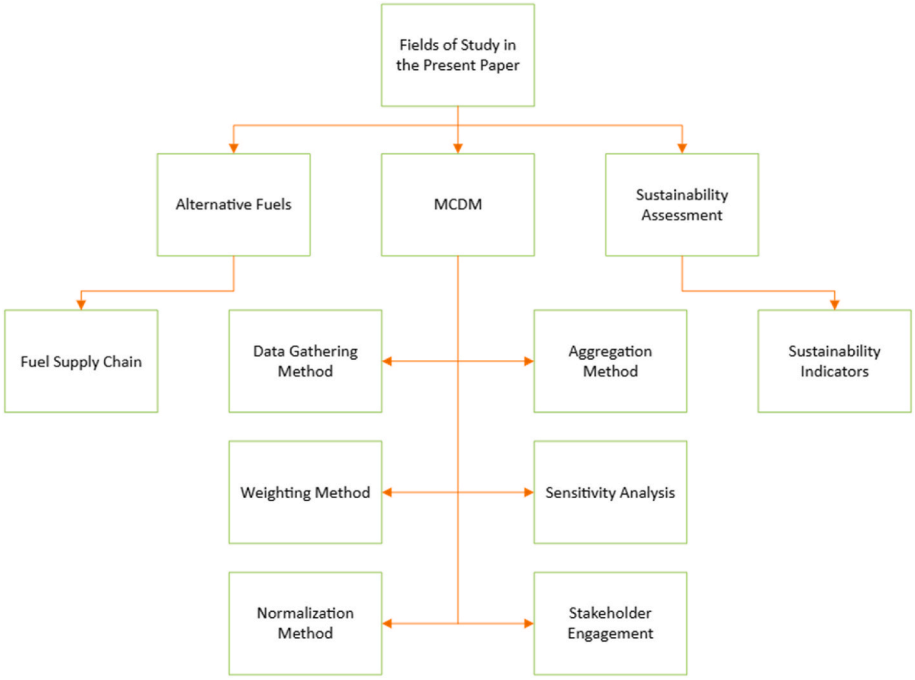


Fig. 1. Fields of study for the present study.

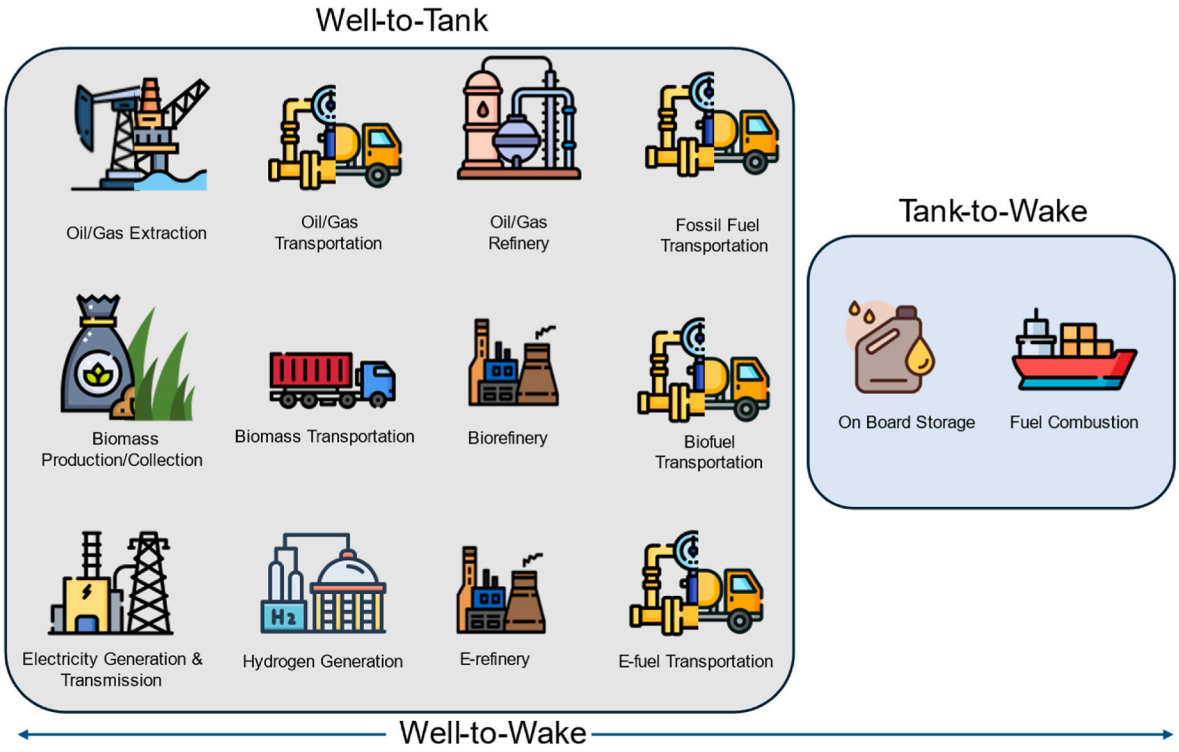


Fig. 2. System boundary and emission sources of Well-to-Tank and Tank-to-Wake emissions for shipping fuels.

than objective methods. This can reduce the repeatability of analyses and increase the uncertainty of the results obtained. Although objective methods do not require expert opinions, the results may differ from their expectations. The normalization method should be selected based on performance data, aggregation methods, and consultation with decision makers. Among the aggregation methods, the WSM was the most common one in the assessed papers due to its simplicity and understandability. Lastly, the implementation of sensitivity analyses by changing the weights of the criteria, performance data, and MCDM method is uncommon in prior studies; future implementation of this will enhance the reliability and robustness of studies.

2.1. Fuel supply chain components

To assess the sustainability of alternative shipping fuels, the whole fuel supply chain comprising of production, delivery, and end-use

should be considered and assessed. In this paper, fuel supply chains for shipping are divided into three subsections.

- Fuel: Includes the fuel itself (such as hydrogen, ammonia, LNG, Heavy Fuel Oil) and its production pathways as well as the power train on vessels (internal combustion engine, fuel cell, steam turbine).
- Infrastructure: Includes facilities that are needed for fuel delivery from production sites to seaports and the refuelling of ships. Examples include pipelines, trucks, and bunkering vessels infrastructure.
- Ship: Includes different types of ships (such as cruise ships or container ships).

Available alternative shipping fuels are categorized into three groups of fossil fuels, biofuels, and e-fuels. Fossil fuels are conventional fuels that are currently used for shipping, such as HFO, MDO, MGO, or fossil-derived alternative fuels such as hydrogen, ammonia, methanol, and LNG from natural gas. Biofuels are synthesized using biomass via thermochemical and/or biochemical processes. Examples are biomethane, biodiesel, and Hydrotreated Vegetable Oil (HVO). E-fuels are produced via power-to-X technologies using hydrogen from water electrolysis. Examples are e-hydrogen, e-methanol, e-ammonia, and e-LNG. Physiochemical properties (such as gravimetric energy density, cetane number, autoignition temperature, flammability limits, and tank-to-wake emission intensity) are compared in Fig. 3.

Concerning the fuel or power systems, 27 papers (out of a total of 31 reviewed papers) considered either alternative fuels (such as ammonia, hydrogen, methanol) or power systems (such as battery, fuel cell, wind turbine, solar cells) in their studies. The fuels studied in each paper are shown in Table 2. In this table, methanol, ammonia, and hydrogen are derived from fossil fuel sources, while the "e-fuels" group includes all alternative fuels produced from renewable sources like green hydrogen, green methanol, and green ammonia (Gray et al., 2024). Fourteen papers studied fossil-based methanol, ammonia, and hydrogen, indicating that these researchers are currently more focused on reducing direct tank-to-wake GHG and air pollutant emissions from shipping and are less focused on the overall well-to-wake life cycle emissions of these fuels. The number of papers that studied LNG as an alternative fuel is 20, which is the highest number among all studied fuels, highlighting its important role in the future of shipping.

In this paper, all types of liquid and gaseous biofuels, including hydrotreated vegetable oil (HVO), biomethane, and biodiesel, are categorized in the "Biofuels" group to make the comparison more convenient. In total, 9 papers considered biofuels in their studies (Table 2). Conventional shipping fuels like heavy fuel oil, marine gas oil and marine diesel oil are studied in 13 papers, and they are mainly used as a reference point to compare the emission reduction obtained by using alternative fuels. There are also some other fuel systems such as nuclear, wind (Ren and Lützen, 2017), batteries (Mandić et al., 2021), and LPG (Xuan et al., 2022) which are studied in 5 papers. Hybrid fuelling systems are also studied in 2 papers (Jeong et al., 2018), (Munim et al., 2023). For example, Munim et al. (2023) considered LNG-wind and HFO-wind hybrid systems for power generation.

Concerning ship type, 4 papers considered the type of vessel in their analysis, and one did not clearly describe the ship type they studied. Table 3 includes information related to these 4 papers. Ships and their characteristics, such as traveling distance, interval between refuelling, required engine modifications, and alternative fuel storage systems, have received less attention in the assessed papers.

No prior works had considered infrastructural requirements for the shipping sector. This is a knowledge gap in this field of research, considering infrastructure requirements may alter the final rankings of alternative fuels.

2.2. Assessment criteria

The comparison of alternatives from the perspective of sustainability should consider three basic pillars of sustainability: society; economy; and environment. In addition to sustainability, the use of alternative fuels for ships should also be assessed from a technical perspective. Technical considerations can include the possibility of ships using the alternative fuels, or it can be limited only to the technology readiness levels (TRL) of the alternative fuels. In some cases, researchers have considered other dimensions, such as safety or political support, as

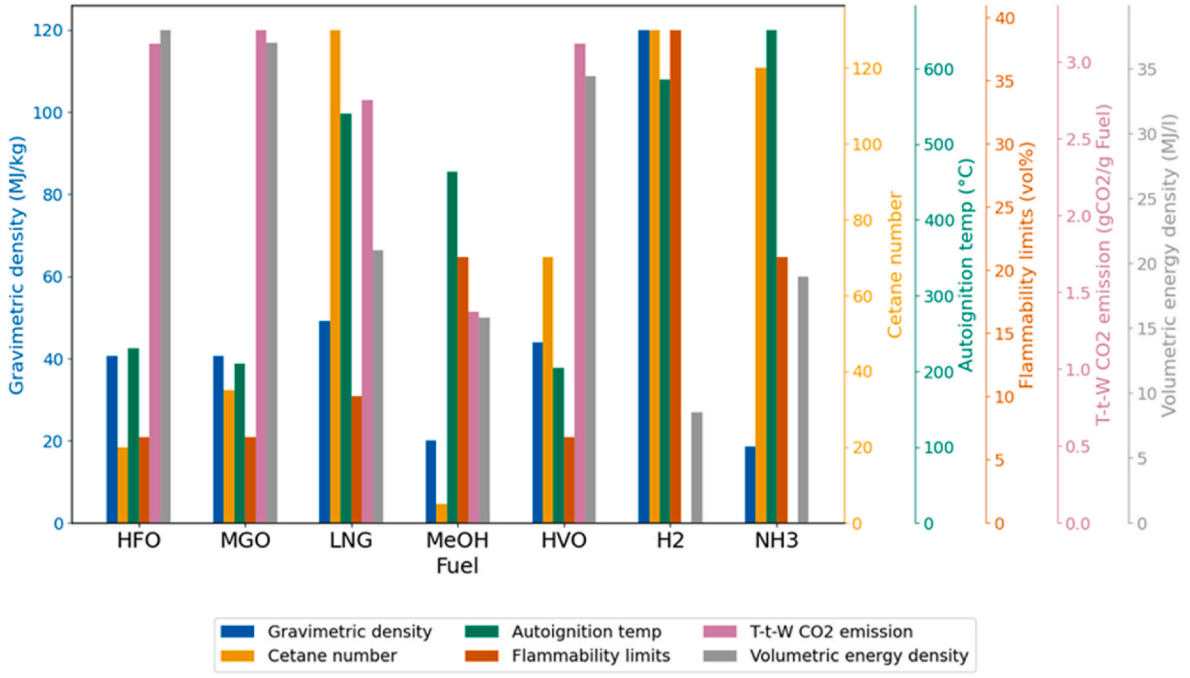


Fig. 3. Comparison of shipping fuel characteristics. T-t-W: tank to wake. Data from (Solakivi et al., 2022), (European Union, 2024), (Thepsithar et al., 2020). HFO: heavy fuel oil, MGO: marine gas oil, LNG: liquified natural gas, MeOH: methanol, HVO: hydrotreated vegetable oil, H2: hydrogen, NH3: ammonia.

Table 2
Fuels considered by each paper that used multicriteria decision making to find the most sustainable shipping fuels.

HFO[a]	MGO[b]	MDO[c]	LNG[d]	Methanol	Ammonia	Hydrogen	e-fuel	Biofuel	Other	Reference
✓	✓		✓	✓	✓	✓	✓	✓		Strantzali et al. (2023)
							✓	✓		Yang et al. (2023)
							✓	✓		Carvalho et al. (2021)
			✓			✓		✓	**Battery, LPG**	Mandić et al. (2021)
	✓		✓							Andra Luciana et al. (2021)
			✓	✓	✓	✓	✓	✓		Hansson et al. (2020)
✓			✓	✓		✓	✓	✓		Hansson et al. (2019)
			✓				✓		**Nuclear**	Ren and Lützen (2017)
			✓	✓		✓				Ren and Liang (2017)
			✓	✓		✓				Deniz and Zincir (2016)
			✓							Ren and Lützen (2015)
			✓					✓	**Battery**	Aspen and Sparrevik (2020)
			✓	✓		✓				Maceiras et al. (2024)
		✓	✓	✓	✓	✓				Rivarolo et al. (2023)
		✓	✓	✓	✓	✓				Rivarolo et al. (2021)
		✓							**Battery mode, hybrid mode**	Jeong et al. (2018)
	✓		✓							Iannaccone et al. (2020)
	✓		✓		✓	✓				Zanobetti et al. (2023)
✓			✓		✓	✓			**LNG-wind hybrid, HFO-wind hybrid**	Munim et al. (2023)
✓	✓	✓	✓	✓						Bui et al. (2021)
			✓	✓	✓	✓		✓	**Battery Powered, LPG**	Xuan et al. (2022)
					✓	✓	✓			Inal et al. (2022)
		✓	✓	✓	✓	✓				Montagna et al. (2022)
✓			✓							Lu et al. (2020)
✓					✓	✓	✓	✓		Xing et al. (2021)

[a] Heavy Fuel Oil.
[b] Marine Gas Oil.
[c] Marine Diesel Oil.
[d] Liquified Natural Gas.

Table 3
Ship types considered in previous literature that applied multicriteria decision making to shipping fuels.

Reference	Ship type
Rivarolo et al. (2023)	Sail yacht, passenger ferry, cruise ship, container ship
Rivarolo et al. (2021)	Small-size passenger ship operating in urban areas, large-size cruise ship
Montagna et al. (2022)	Sail yacht for leisure usage, cruise ship
Xing et al. (2021)	Inland, coastal, short sea, deep sea

criteria. Using the opinions of ship builders and operators can help identify reliable technical criteria, which was not a common approach in the assessed papers.

All 31 papers reviewed considered the economic pillar (Table 4), and 30 and 26 (out of 31) papers had environmental (Table 6) and technical aspects (Table 7) in their assessment, respectively. The number of papers that studied the social aspect numbered 16 (Table 5).

In terms of economic criteria, capital expenditure (CAPEX), operational expenditure (OPEX), and fuel cost were the most commonly used criteria. Almost every paper used CAPEX, which shows the importance of this parameter in comparing alternative fuels and the availability of data related to capital expenditure. OPEX consists of running costs for repair and maintenance; costs of consumables; total ownership costs during the life cycle; voyage costs; and resale value (Moshiul et al., 2023). Although fuel cost can be considered part of operational expenses, some authors chose to examine it separately, as fuel prices can often influence a shipowner's decision regarding fuel usage. The price of alternative fuels is affected by various factors such as fossil fuel prices, incentives and penalties to reduce the consumption of high-emission fuels, technological progress and reduced production costs, and the price of feedstocks.

Based on the price per unit of energy produced, Thepsithar et al. (2020) found that between 2009 and 2018 LNG (0.05-0.15 $/kWh of energy output from engine) can be cheaper than conventional fuels

Table 4
Economic criteria used in previous literature which applied multicriteria decision making to shipping fuels.

Reference	CAPEX[a]	OPEX[b]	Fuel Cost
Strantzali et al. (2023)	✓	✓	✓
Yang et al. (2023)	✓	✓	
Moshiul et al. (2023)	✓	✓	✓
Carvalho et al. (2021)	✓	✓	✓
Mandić et al. (2021)	✓	✓	✓
Andra Luciana et al. (2021)	✓		
Hansson et al. (2020)	✓	✓	✓
Kim and Seo (2019)	✓	✓	✓
Hansson et al. (2019)	✓	✓	✓
Ren and Lützen (2017)	✓	✓	✓
Ren and Liang (2017)	✓	✓	
Deniz and Zincir (2016)	✓	✓	
Ren and Lützen (2015)	✓	✓	
Aspen and Sparrevik (2020)	✓		
Maceiras et al. (2024)	✓		✓
Soltani Motlagh et al. (2023)	✓	✓	
Rivarolo et al. (2023)	✓	✓	
Rivarolo et al. (2021)	✓	✓	
Ashrafi et al. (2022)	✓	✓	✓
Jeong et al. (2018)	✓	✓	✓
Iannaccone et al. (2020)	✓	✓	✓
Zanobetti et al. (2023)	✓	✓	✓
Jeong et al. (2019)	✓	✓	✓
Munim et al. (2023)	✓	✓	✓
Bui et al. (2021)	✓	✓	✓
Xuan et al. (2022)	✓		✓
Liu et al. (2020)	✓		
Inal et al. (2022)		✓	✓
Montagna et al. (2022)	✓	✓	
Lu et al. (2020)	✓	✓	✓
Xing et al. (2021)	✓	✓	
Frequency of occurrence in reviewed papers	**30**	**26**	**19**

[a] Capital expenditure.
[b] Operational expenditure.

Table 5
Social criteria investigated in previous literature which applied multicriteria decision making to shipping fuels.

Reference	Job creation	Regulation	Public acceptability	Governmental and/or industrial support	Social responsibility
Strantzali et al. (2023)	✓	✓			
Yang et al. (2023)	✓		✓		
Moshiul et al. (2023)		✓	✓	✓	✓
Andra Luciana et al. (2021)					✓
Hansson et al. (2020)		✓			
Kim and Seo (2019)		✓		✓	
Hansson et al. (2019)		✓			
Ren and Lützen (2017)			✓	✓	
Ren and Liang (2017)		✓	✓		
Deniz and Zincir (2016)		✓			
Ren and Lützen (2015)			✓	✓	
Aspen and Sparrevik (2020)			✓		
Soltani Motlagh et al. (2023)		✓			
Ashrafi et al. (2022)		✓	✓		✓
Munim et al. (2023)		✓	✓		
Bui et al. (2021)				✓	
Lu et al. (2020)				✓	
Frequency of occurrence in reviewed papers	**2**	**10**	**8**	**5**	**3**

Table 6
Environmental criteria used by each paper which applied multicriteria decision making to shipping fuels.

Reference	GHG emission	NO_x and/or SO_x emission	Particulate matter	Land use change
Strantzali et al. (2023)	✓			
Yang et al. (2023)	✓			✓
Moshiul et al. (2023)	✓	✓	✓	
Carvalho et al. (2021)	✓	✓	✓	✓
Mandić et al. (2021)	✓	✓	✓	
Andra Luciana et al. (2021)				
Hansson et al. (2020)	✓	✓	✓	
Hansson et al. (2019)	✓	✓		
Ren and Lützen (2017)	✓	✓	✓	
Ren and Liang (2017)	✓	✓	✓	
Deniz and Zincir (2016)	✓	✓	✓	
Ren and Lützen (2015)	✓	✓	✓	
Aspen and Sparrevik (2020)	✓	✓		
Maceiras et al. (2024)	✓	✓	✓	
Soltani Motlagh et al. (2023)	✓			
Rivarolo et al. (2023)	✓	✓		
Rivarolo et al. (2021)	✓	✓		
Ashrafi et al. (2022)	✓	✓	✓	✓
Jeong et al. (2018)	✓	✓	✓	
Iannaccone et al. (2020)	✓	✓		
Zanobetti et al. (2023)	✓	✓		
Jeong et al. (2019)	✓	✓	✓	
Munim et al. (2023)	✓			
Bui et al. (2021)	✓	✓	✓	
Xuan et al. (2022)	✓	✓	✓	
Liu et al. (2020)				
Inal et al. (2022)	✓			
Montagna et al. (2022)	✓	✓		
Lu et al. (2020)				
Xing et al. (2021)	✓	✓		
Frequency of occurrence in reviewed papers	**27**	**22**	**14**	**3**

(such as MDO with 0.05-0.2 kWh of energy output from engine) and other alternative fuels (such as methanol 0.05-0.2 $/kWh of energy output from engine and biodiesel 0.15-0.25 $/kWh of energy output from engine). Solakivi et al. (2022) claimed that even when considering emission reduction policies (EU ETS and European Union energy taxation directive (EU ETD)), fossil-derived LNG and MDO will remain cheaper than other alternative fuels until 2050. Their results indicated the price of 0.05 $/kWh of fuel for LNG and 0.08 $/kWh of fuel for MDO, while the numbers for alternative fuels such as e-methanol and e-LNG are 0.12 and 0.1$/kWh of fuel, are predicted for 2050, respectively. They also indicate that bio-LNG (0.09 $/kWh of fuel) and biodiesel (0.13 $/kWh of fuel) will remain more expensive than their fossil counterparts. It is still possible that in the future, the production capacity of alternative fuels may increase, and therefore, their prices may decrease so that they may be able to compete with conventional fuels (Kouzelis et al., 2022). In previous studies, fuels are assessed either in terms of price per unit of energy output from the engine or price per unit of fuel energy content. The former approach accounts for both the energy density of the fuel and the engine efficiency.

Table 4 indicates the economic criteria used by each paper. Although many (19 papers) of the assessed papers considered the fuel cost as a criterion, only a few (4 papers) reported data for fuel costs; the remainder limited their analysis to a qualitative comparison. For example, Moshiul et al. (2023) reported the fuel price of 14 different shipping fuels including HFO (0.02-0.04 $/kWh), MGO (0.04-0.05 $/kWh), fossil LNG (0.02-0.03 $/kWh), e-LNG (0.08-0.39 $/kWh), fossil methanol (0.01-0.11 $/kWh), e-methanol (0.21-1.67 $/kWh), HVO (0.08-0.14 $/kWh), fatty acid methyl ester (0.07-0.12 $/kWh), e-hydrogen (0.05-0.12 $/kWh), bio-hydrogen (0.07-0.19 $/kWh), fossil ammonia (0.06-0.09 $/kWh), e-ammonia (0.08-0.09 $/kWh). All the costs are reported for 2021. Meanwhile, Hansson et al. (2020) considered the price of fossil LNG (0.02 $/kWh), fossil ammonia (0.09 $/kWh), and e-ammonia (0.12 $/kWh) for a 2030 scenario. Hansson et al. in another paper (Hansson et al., 2019) considered the price of HFO (0.03 $/kWh), fossil methanol (0.04 $/kWh), and fossil hydrogen (0.05 $/kWh), along with the prices for bio methanol (produced via biomass gasification, 0.08 $/kWh), e-hydrogen (0.13 $/kWh), and HVO (0.08 $/kWh), for a 2030 scenario. The prices of e-hydrogen and e-ammonia are considered as 0.18 and 0.14 $/kWh, respectively, (assuming 1.183 (European Central Bank, 2025) as the exchange ratio of euro to dollar in 2021) in the paper by Inal et al. (2022).

The reported results show that the researchers have found that e-fuels and biofuels remain more expensive than their fossil counterparts. Also, due to the nascent nature of e-fuel and biofuel supply chains, the uncertainties associated with their prices are higher than traditional fossil fuels. Depending on the scope and boundaries of the study, future

Table 7
Technical criteria evaluated in previous literature which examined multicriteria decision making as applied to shipping fuels.

Reference	Technology maturity	Safety	Availability (of fuel and infrastructure)	Adaptability	Reliability	Power generation system properties	Fuel properties
Strantzali et al. (2023)		✓	✓	✓			✓
Yang et al. (2023)	✓						✓
Moshiul et al. (2023)	✓	✓	✓		✓		✓
Carvalho et al. (2021)	✓	✓	✓	✓			✓
Mandić et al. (2021)		✓	✓	✓	✓		
Andra Luciana et al. (2021)		✓	✓	✓			
Hansson et al. (2020)		✓	✓		✓		
Kim and Seo (2019)					✓		
Hansson et al. (2019)		✓	✓		✓		
Ren and Lützen (2017)	✓	✓			✓	✓	✓
Ren and Liang (2017)	✓		✓		✓		
Ren and Lützen (2015)	✓						
Aspen and Sparrevik (2020)			✓				
Maceiras et al. (2024)		✓	✓	✓	✓		✓
Rivarolo et al. (2023)						✓	✓
Rivarolo et al. (2021)						✓	✓
Ashrafi et al. (2022)							
Jeong et al. (2018)		✓					
Iannaccone et al. (2020)		✓					
Zanobetti et al. (2023)		✓					✓
Munim et al. (2023)	✓	✓	✓				
Bui et al. (2021)							
Xuan et al. (2022)	✓	✓	✓	✓			✓
Inal et al. (2022)		✓	✓				✓
Montagna et al. (2022)						✓	
Lu et al. (2020)	✓		✓	✓	✓		
Xing et al. (2021)	✓	✓	✓		✓		
Jeong et al. (2019)		✓		✓	✓	✓	
Liu et al. (2020)							
Deniz and Zincir (2016)		✓	✓	✓	✓		
Soltani Motlagh et al. (2023)				✓			
Frequency of occurrence in reviewed papers	**10**	**18**	**16**	**10**	**12**	**5**	**11**

research could investigate the costs associated with fuel transport infrastructure, required modifications to the ship's power system, increased insurance premiums due to alternative-fuel risks, and potential losses in cargo capacity. Readers can refer to the paper by Gray et al. (2024) for more details on total ownership and fuelling infrastructure costs. Note that there is inherent dependence between some economic indicators, such as NPV, CAPEX, and OPEX, which should be considered in MCDM studies.

Among the reviewed papers, 15 articles did not investigate social aspects, whilst the other 16 papers investigated the social aspect by relying on expert opinion. The social criteria used in each paper are summarized in Table 5. From the social perspective, regulations were the most used criterion (used by 10 papers) followed by public acceptance, governmental and/or industrial support, and social responsibility which were considered in 8, 6, and 3 papers respectively. This means that, according to past studies, regulations should be used as a social indicator to complete the MCDM study for selecting the most sustainable alternative shipping fuel. Other social criteria such as "socio-economic development" (Moshiul et al., 2023) and "public health impact" (Ashrafi et al., 2022) were also indicated in the literature but less frequently.

Afshari et al. (2022) classified social sustainability indicators into four groups of "human rights and social life", "occupational indicators", "business-related indicators", and "legal, political, and governmental indicators". It is possible that decision makers have a different interpretation of these indicators. They also mentioned that four types of conflicts may arise due to the selection of indicators, which should be considered by researchers. The first one could be between the social pillar and the other pillars of sustainability (economic and environmental). The second one may arise between different indicators of sustainability. For example, people often support renewable energy projects because of job creation but also oppose them due to their concerns about landscape changes. The third conflict may arise between two affected societies because of cultural, regional, and socio-political differences. The fourth conflict may arise between two different affected sectors (such as agriculture and industry) due to differences in their interests.

From an environmental perspective, GHG emissions are considered in 27 papers and is the most used environmental criterion. This shows that researchers are most focused on the impact of using alternative fuels in reaching the goals set for global warming mitigation. NO_x and/or SO_x emissions and particulate matter are other widely used criteria because of IMO policies on air pollutants and global concerns on acidification. Table 6 summarizes information related to environmental criteria that are used in each paper.

Although technical indicators may not be related to sustainability from a social, environmental, or economic perspective, alternative fuels need to be assessed from a technical perspective to ensure that the technical viability of these alternatives is considered. From this perspective, safety is used by 18 papers and is the most used technical aspect due to its direct effect on the health of ship operators. The availability of fuel (including global production and bunkering capacity), the reliability of fuel supply, and the adaptability of the proposed fuel to existing ships (i.e. the ability of existing ships to use the proposed fuel) are other widely used technical aspects that are used in 16, 12, and 10 papers, respectively. Fuel properties (density, heating value) and power generation system properties (weight and volume of power generation systems), which are used in 5 papers, are two factors related to the performance of ships because they can reduce the carrying capacity of cargo or passengers and can affect the economic performance of vessels.

Although technology maturity is a very common technical aspect that is widely used in techno-economic analysis, only 10 papers considered this parameter. All data related to the criteria that are used in the technical assessment are summarized in Table 7. In this table,

availability (fuel, infrastructure) is related to the availability of storage and refuelling systems for alternative fuels, however, the types of fuel transfer methods from production sites to ports have not been considered in the reviewed articles. Among all reviewed papers, 11 assessed the sustainability of green fuels or biofuels, and all 11 papers considered technical aspects in their assessment.

2.3. Data gathering methods

To complete the decision matrix, it is vital to have sufficient and reliable data for each alternative concerning each criterion within the analysis. The relative importance or allowable trade-off (weights) of each criterion is also required within many MCDM methods. Obtaining performance data and weighting data is an inevitable part of every MCDM study. This data can also affect the final result of the decision-making process.

Table 8 shows how different authors gathered performance data to complete their decision matrix. In this table, "authors' judgment" means that the authors themselves assigned a score to each alternative. For example, in the paper by Carvalho et al. (2021) the authors assigned a number between 1 and 5 to each alternative as the score for different criteria. Ren et al. (Ren and Lützen, 2017) used a panel of experts to obtain the required performance data. In some cases, experts used Fuzzy linguistic terms to indicate how each alternative performed compared to each other alternative. An example of these linguistic terms is shown in Table 9.

Fifteen papers obtained all or parts of the required performance data from literature, and none of the papers reviewed used process simulation to obtain performance data. LCA was conducted in two papers only; Yang et al. (2023) and Jeong et al. (2019). The LCA method provides a holistic, quantitative, and systematic assessment of environmental impact (including but not limited to GHG emissions) of a potential alternative, such as replacing conventional shipping fuels with renewable ones. In addition, process simulation enables a more detailed investigation of material and energy consumption for producing a specific fuel (such as considering the kinetics of reaction or operating conditions) than correlations based on stoichiometry. These detailed simulations can increase the accuracy and reliability of the data used in the comparison of renewable shipping fuels. Also, in 6 papers, authors used modelling to obtain environmental and economic impacts. It should be noted that here "modelling" refers to the use of mathematical equations to calculate a specific aspect, such as environmental or economic impact, where the authors did not use predefined methods like LCA. For example, Iannaccone et al. (2020) used an activity-based modelling (bottom-up) approach to calculate the emissions from cruise ships and then multiplied total emissions by "potential factors" of each emitted species to obtain the environmental impact in four categories: eutrophication, rain acidification, global warming, and human toxicity. The potential factors are used to compare the relative importance of pollutants in each impact category. For example, the global warming potential factor of methane is 28, while this value is 1 for CO_2. The rain acidification potential factor of SO_x is 1.2, while it is 0.5 for NO_x.

Table 9
Linguistic terms and related triangular fuzzy numbers (Ren and Liang, 2017).

Linguistic Terms	Triangular Fuzzy Numbers
Extremely poor	(1, 1, 2)
Very poor	(1, 2, 3)
Moderately poor	(2, 3, 4)
Strongly poor	(3, 4, 5)
Moderate	(4,5,6)
Moderately good	(5, 6, 7)
Strongly good	(6, 7, 8)
Very good	(7, 8, 9)
Extremely good	(8, 9, 9)

Table 10 summarizes the methods that are used by authors to obtain criteria weights; it is obvious that previous researchers mainly used experts' opinions (18 out of 31 reviewed papers). This highlights the wide use of subjective weighting methods like the Analytic Hierarchy Process. The process of developing criteria weights based on experts' opinions has two steps. First, the authors must gather experts' opinions through surveys, interviews, or both. Then, they must calculate the weight of each criterion. Some authors like Yang et al. (2023), Mandić et al. (2021) used AHP or Fuzzy-AHP, while others like Moshiul et al. (2023) and Ashrafi et al. (2022) used statistical methods. The third group like Munim et al. (2023) and Strantzali et al. (2023) used Bayesian best-worst and revised SIMOS to calculate weights for criteria respectively. Some authors used their own judgments, and others used prior literature to obtain the weights for criteria.

2.4. Stakeholders

Table 11 shows the different stakeholders presented in the reviewed papers. Shipowners/Operators are the stakeholders most often considered and 15 papers used their opinions. This shows that shipowners and ship operators should be considered in decision-making for utilizing alternative shipping fuels because of their direct involvement in fuel use, its impact on vessel performance, and safety. Academia, including university professors and master's or PhD students, were involved in 11 studies, as they are more accessible to researchers compared to other

Table 8
Methods used to gather performance data in papers which applied multicriteria decision making to shipping fuels.

Method	Number of papers	Reference
Literature & authors' judgments	5	(Carvalho et al., 2021), (Xing et al., 2021), (Hansson et al., 2019), (Deniz and Zincir, 2016), (Inal et al., 2022)
Market research & experts' judgements	3	(Rivarolo et al., 2021), (Montagna et al., 2022), (Rivarolo et al., 2023)
Authors' judgments	1	Maceiras et al. (2024)
Experts' judgements	7	(Munim et al., 2023), (Kim and Seo, 2019), (Ren and Liang, 2017), (Soltani Motlagh et al., 2023), (Bui et al., 2021), (Liu et al., 2020), (Lu et al., 2020)
Literature	2	(Xuan et al., 2022), (Strantzali et al., 2023)
Literature & experts' judgement	4	(Mandić et al., 2021), (Ren and Lützen, 2017), (Ren and Lützen, 2015), (Aspen and Sparrevik, 2020)
Literature & modelling & experts' judgement & LCA[a]	1	Jeong et al. (2019)
Modelling & experts' judgement & LCA	1	Yang et al. (2023)
Literature & modelling	2	(Iannaccone et al., 2020), (Zanobetti et al., 2023)
Literature & modelling & experts' judgement	1	Hansson et al. (2020)
Modelling	1	Jeong et al. (2018)
N.A.	3	(Moshiul et al., 2023), (Ashrafi et al., 2022), (Andra Luciana et al., 2021)

[a] Life cycle assessment.

Table 10
Methods used to obtain criteria weights in multicriteria decision making.

Weighting data gathering method	Number of papers	Reference
Author's judgments	4	(Carvalho et al., 2021), (Xing et al., 2021), (Rivarolo et al., 2021), (Montagna et al., 2022)
Equal weighting	1	Rivarolo et al. (2023)
Experts' opinion	18	(Maceiras et al., 2024), (Munim et al., 2023), (Kim and Seo, 2019), (Ren and Liang, 2017), (Soltani Motlagh et al., 2023), (Bui et al., 2021), (Liu et al., 2020), (Strantzali et al., 2023), (Hansson et al., 2019), (Deniz and Zincir, 2016), (Inal et al., 2022), (Mandić et al., 2021), (Ren and Lützen, 2017), (Ren and Lützen, 2015), (Jeong et al., 2019), (Yang et al., 2023), (Moshiul et al., 2023), (Ashrafi et al., 2022)
Literature	3	(Iannaccone et al., 2020), (Zanobetti et al., 2023), (Hansson et al., 2020)
N.A.	2	(Jeong et al., 2018), (Andra Luciana et al., 2021)

Table 11
Stakeholder participation in each paper, which applied multicriteria decision making to shipping fuels.

Reference	Shipowners/operators	Fuel suppliers	Academics	Public	Government/authorities	Engineers
Strantzali et al. (2023)	✓	✓	✓	✓		
Yang et al. (2023)	✓		✓	✓	✓	
Moshiul et al. (2023)	✓					✓
Mandić et al. (2021)	✓		✓		✓	
Kim and Seo (2019)	✓					
Hansson et al. (2019)	✓	✓			✓	
Ren and Liang (2017)	✓		✓		✓	
Deniz and Zincir (2016)	✓					
Ren and Lützen (2015)			✓			
Maceiras et al. (2024)	✓					
Soltani Motlagh et al. (2023)			✓			✓
Ashrafi et al. (2022)	✓	✓	✓	✓	✓	✓
Jeong et al. (2019)	✓		✓			✓
Munim et al. (2023)	✓		✓		✓	✓
Bui et al. (2021)	✓				✓	
Inal et al. (2022)	✓		✓			
Lu et al. (2020)	✓		✓			

stakeholders. Authorities, engineers, and members of the public are less represented in the reviewed literature. Stakeholders' opinions can be obtained through surveys as per Ashrafi et al. (2022), through interviews as per Strantzali et al. (2023), or through a combination of both as per Kim and Seo (2019). Although port owners and operators play a major role in providing fuels for vessels, only Lu et al. (2020) included the perspective of port operators in their research.

2.5. MCDM methods

MCDM methods can be integrated with sustainability assessments to make decisions more structured, transparent, and reliable (Cinelli et al., 2014). Many MCDM methods consist of three steps: weighting; normalization; and aggregation.

2.5.1. Weighting

The weighting method enables researchers to calculate criteria weights that reflect the importance of or allowable trade-off between criteria and their impact on the decision-making process. Odu (2019), provided a classification for weighting methods which consist of 3 groups, namely: subjective, objective, and integrated. They also provided a brief overview of the mentioned weighting methods. The classification proposed by Odu (2019) is summarized in Table 12.

Table 12
Weighting method classification proposed by Odu (2019)

Weighting method group	Examples
Subjective	Point allocation, Direct rating, AHP, Simple Multi-attribute Ranking Technique (SMART), Swing, Ranking method, Delphi method, Nominal group technique
Objective	Entropy (Shannon, 1948), Criteria Importance Through Inter-criteria Correlation (CRITIC) (Diakoulaki et al., 1995), Standard deviation, Mean weight, Statistical variance procedure, Ideal point method
Integrated	Additive synthesis, Multiplication synthesis, Optimal weighting based on sum of squares, Optimal weighting based on relational coefficient of graduation

More specifically, Mukhametzyanov (2021) provided a comparative analysis of entropy, CRITIC, and standard deviation weighting methods. Subjective weighting methods depend on the opinions of decision-makers, while objective methods rely on the performance data of alternatives. In subjective weighting methods, the time required to collect stakeholders' opinions can be lengthy, depending on the number of criteria. For example, in the Analytical Hierarchy Process method, stakeholders need to compare each pair of criteria and decide on their relative importance or allowable trade-off. Also, if the final weight calculated by this method is not aligned with the stakeholders' expectations or if they want to change their opinions, the whole process needs to be repeated. Therefore, the weighting method needs to be determined according to the time available for the analysis, the number of criteria, and the number of engaged stakeholders.

2.5.2. Normalization

Due to the non-uniformity of dimensions in performance data (for example cost is measured in USD while GHG emission is measured in tCO_2eq/year), many MCDM studies need a normalization method to make performance data commensurate. Several normalization methods can be used. Aytekin (2021) provided a list of 11 different normalization formulas and a comparative analysis to show the advantages and disadvantages of different methods. A common normalization method is comparing each performance to a reference point, which may be the best or worst achieved/achievable performance value. In this case, the reference point is internal because it is obtained from the performance data itself. Equation (3) in Table 13 shows an example of this approach.

Table 13
– Normalization methods applied in the assessed papers.

Normalization method	Formulae	Reference
Linear normalization	$X_{ij}^{norm} = \frac{\left\|a_{ij} - a_j^{best}\right\|}{\left\|a_j^{worst} - a_j^{best}\right\|}$ or $X_{ij}^{norm} = \frac{\left\|a_{ij} - a_j^{worst}\right\|}{\left\|a_j^{worst} - a_j^{best}\right\|}$ (3) Where a_{ij} is the performance data of i^{th} alternative with respect to the j^{th} criterion. a_j^{best} and a_j^{worst} are the best and worst achieved performance data with respect to j^{th} criterion respectively. X_{ij}^{norm} is the normalized performance data of i^{th} alternative with respect to the j^{th} criterion.	Ren and Liang (2017)
Comparison with and external reference point	$X_{ij}^{norm} = a_{ij}/a_j^{EU}$ (4) In Equation (4), a_{ij} and a_j^{EU} is the performance data of i^{th} alternative and EU data with respect to the j^{th} criterion; respectively. X_{ij}^{norm} is the normalized performance data of i^{th} alternative with respect to the j^{th} criterion.	Iannaccone et al. (2020)
Vector normalization	$X_{ij}^{norm} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}}$ (5) Where a_{ij} is the performance data of i^{th} alternative with respect to the j^{th} criterion. X_{ij}^{norm} is the normalized performance data of i^{th} alternative with respect to the j^{th} criterion.	Moshiul et al. (2023)

Comparison to external reference points may also be used with Equation (3) when a_j^{best} and a_j^{worst} are specified by the decision maker(s) and are performance values not obtained by the alternatives being assessed.

Another method which is used by one of the reviewed papers (Iannaccone et al. (2020)), compares performance data with an external reference point (for example EU Gross Domestic Product (GDP) for economic performance) for normalization with the help of Equation (4) (Iannaccone et al., 2020) in Table 13.

Vector normalization is another method (commonly applied with the TOPSIS aggregation method), which is shown by Equation (5) in Table 13 for a benefit criterion (Vafaei et al., 2016).

If all performance data are converted to a unique value like USD (Jeong et al., 2018), there is no need for a normalization process, but finding an appropriate conversion factor to convert each criterion to a monetary value can be challenging. The choice of normalization method should be made in consultation with stakeholders to check whether a linear distribution of the normalized data is appropriate, or if it is necessary to use a non-linear normalization method.

2.5.3. Aggregation

According to Cinelli et al. (2020), MCDM methods can be categorized into two groups: (i) outranking relation, (ii) utility function. The utility-based group includes methods that aggregate the information into one parameter and are also known as performance aggregation-based approaches. Most of these methods involve normalization and some form of aggregation to develop a comprehensive score for ranking, classifying, or choosing the most preferred alternative. Examples are MAUT and WSM. The outranking group includes methods based on comparisons between pairs of alternatives to find if alternative A is better than B. These methods use pairwise comparisons of the alternatives, which leads to an outranking matrix. Two examples are ELECTRE and PROMETHEE.

Li et al. (2024) classified distance-based ranking methods into three groups; "by closeness score", "by original score", and "by positive score". They also provided extensions available for some of the ranking methods in each group. Kumar et al. (2017) categorized MCDM methods into three groups of "value measurement methods", "Goal, aspiration, and reference level models", and "outranking models". The "value measurement methods" and "Goal, aspiration, and reference level models" could be classified as a subcategory of distance-base models. It is also possible to combine multiple methods to solve a complex decision-making problem, which leads to a hybrid multi-criteria decision-making. Different methods, such as AHP, DEMATEL, VIKOR, TOPSIS, and ANP, have been applied in a hybrid decision-making approach in previous research (Zavadskas et al., 2016).

The criteria weights and normalized performance data may then be aggregated using an MCDM aggregation method to obtain a ranking of the alternatives. The WSM is the easiest and the most used aggregation method (Wang et al., 2009), but can give misleading results if incorrectly used (Hazelrigg, 2019). It is also easier to understand compared to other more intricate aggregation methods such as VIKOR and PROMETHEE. Equation (6) shows the WSM method.

Table 14
Weighting methods used in literature which applied multicriteria decision making to shipping fuels.

Weighting method	Number of articles	Reference number
Revised Simos	1	Strantzali et al. (2023)
Interview and/or survey	2	(Moshiul et al., 2023), (Ashrafi et al., 2022)
Authors' judgments	3	(Carvalho et al., 2021), (Rivarolo et al., 2021), (Xing et al., 2021)
AHP[a] or fuzzy AHP	13	(Yang et al., 2023), (Mandić et al., 2021), (Andra Luciana et al., 2021), (Kim and Seo, 2019), (Hansson et al., 2019), (Ren and Lützen, 2017), (Deniz and Zincir, 2016), (Ren and Lützen, 2015), (Maceiras et al., 2024), (Soltani Motlagh et al., 2023), (Jeong et al., 2019), (Bui et al., 2021), (Inal et al., 2022)
Literature review	4	(Hansson et al., 2020), (Iannaccone et al., 2020), (Zanobetti et al., 2023), (Montagna et al., 2022)
Fuzzy logarithmic least squares	1	Ren and Liang (2017)
SMAA[b]	1	Aspen and Sparrevik (2020)
Equal weighting	1	Rivarolo et al. (2023)
Bayesian BWM[c]	1	Munim et al. (2023)
Rough set	1	Xuan et al. (2022)
Fuzzy entropy	1	Liu et al. (2020)
Maximum deviation method	1	Lu et al. (2020)

[a] Analytical hierarchy process.
[b] Stochastic Multicriteria Acceptability Analysis.
[c] Best-Worst Method.

$$S_i = \sum_{j=1}^{n} \left(X_{ij}^{norm} * W_j \right) \quad (6)$$

Where S_i is the score of the i^{th} alternative, X_{ij}^{norm} is the normalized performance data of the i^{th} alternative with respect to j^{th} criterion, and W_j is the weight of j^{th} criterion. It should be noted that some MCDM methods like TOPSIS (Hwang and Yoon, 1981), PROMETHEE (Mareschal and Brans, 1994), EDAS (Ghorabaee et al., 2015), WASPAS, MOORA (Brauers, 2004), and VIKOR (Opricovic, 1998) have their own specific normalization and aggregation method while others like AHP need an aggregation method (like the WSM) after obtaining normalized data. The choice of aggregation method should be based on the goal of the MCDM study, which can be ranking (listing alternatives from best to worst), sorting (categorization of alternatives into specific classes), and selecting a specific subset of alternatives (Cinelli et al., 2020). Each aggregation method can be suitable for one or more of the above goals.

2.5.4. Weighting methods used in prior studies

As shown in Table 14, the most used method for weighting criteria is the AHP and the Fuzzy-AHP (13 out of 31 articles). Objective weighting methods are used in the minority of reviewed articles (3 out of the 31 papers), with methods such as SMAA (Aspen and Sparrevik, 2020), Rough-Set (Xuan et al., 2022), and Maximum Deviation (Lu et al., 2020) used. In Table 14, the "Interview and/or Survey" group includes articles in which the authors asked experts to specify their opinions about the importance of or allowable trade-off between criteria by allocating a numerical value to them. For example, Moshiul et al. (2023) and Ashrafi et al. (2022) asked experts to give their opinion on a 5-point Likert scale, and then they used statistical methods to define the criteria weights. Ashrafi et al. (2022) used a non-parametric test (the Friedman test) to obtain the ranking of sustainability criteria and Moshiul et al. (2023) used the mean of the achieved scores by each criterion in the survey. In Table 14, the "authors' judgment" group belongs to the articles in which the criteria weights are determined by the authors. For example, in the paper by Carvalho et al. (2021) the authors assigned a number between 1 and 3 to each criterion to indicate its importance or allowable trade-off.

Some researchers, such as Liu et al. (2020) assigned weights to each of the expert's opinions based on their knowledge, expertise, and experience, so the more an expert is qualified, the greater the impact of their opinions on the final weighting result. Liu et al. (2020) calculated the weight of each expert by using a group decision-making theory developed by Pérez et al. (Siebert et al., 2018) and calculated the deviation degree and uncertainty degree for each expert. The deviation degree expresses the deviation of each expert's opinion from another expert's opinion, with a lower deviation degree indicating higher accuracy. However, Ren and Liang (2017), Ren and Lützen (2017), and Hansson et al. (2019) used the weighted geometric average of experts' opinions as the criteria weights, assuming experts' opinions are equally important.

Table 15
Normalization method used by each paper in literature which applied multicriteria decision making to shipping fuels.

Reference	Normalization method
Yang et al. (2023)	q-ROLPBM[a]
Moshiul et al. (2023)	Vector normalization
(Carvalho et al., 2021), (Mandić et al., 2021), (Andra Luciana et al., 2021), (Hansson et al., 2020), (Hansson et al., 2019), (Ren and Liang, 2017), (Ren and Lützen, 2015), (Maceiras et al., 2024), (Soltani Motlagh et al., 2023), (Bui et al., 2021), (Inal et al., 2022)	Linear normalization
Ren and Lützen (2017)	Dempster-Shafer
Deniz and Zincir (2016)	Converting performance value to a number between 1 and 5
Rivarolo et al. (2023)	Performance value divided by the best value
Iannaccone et al. (2020)	Performance value divided by EU data
Lu et al. (2020)	Maximum deviation method

[a] Q-rung orthopair linguistic partition Bonferroni mean operator.

Table 16
Aggregation methods in literature which applied multicriteria decision making to shipping fuels.

Aggregation method	Number of articles	Reference
PROMETHEE[a]	**2**	(Munim et al., 2023), (Strantzali et al., 2023)
q-ROLPBM[b]	**1**	Yang et al. (2023)
TOPSIS[c] or Fuzzy TOPSIS	**7**	(Moshiul et al., 2023), (Ren and Liang, 2017), (Aspen and Sparrevik, 2020), (Soltani Motlagh et al., 2023), (Bui et al., 2021), (Xuan et al., 2022), (Liu et al., 2020)
WSM[d]	**13**	(Carvalho et al., 2021), (Mandić et al., 2021), (Andra Luciana et al., 2021), (Hansson et al., 2020), (Hansson et al., 2019), (Ren and Lützen, 2017), (Deniz and Zincir, 2016), (Maceiras et al., 2024), (Rivarolo et al., 2023), (Rivarolo et al., 2021), (Iannaccone et al., 2020), (Inal et al., 2022), (Montagna et al., 2022)
Not clearly defined	**4**	(Jeong et al., 2018), (Zanobetti et al., 2023), (Jeong et al., 2019), (Xing et al., 2021)
Not applicable	**2**	(Kim and Seo, 2019), (Ashrafi et al., 2022)
VIKOR[e]	**1**	Ren and Lützen (2015)
Prospect Theory	**1**	Lu et al. (2020)

[a] Preference Ranking Organization Method for Enrichment Evaluation.
[b] Q-rung orthopair linguistic partition Bonferroni mean operator.
[c] Technique of Order Preference by Similarity to the Ideal Solution.
[d] Weighted Sum Method.
[e] VIseKriterijumska Optimizacija I Kompromisno Resenje.

2.5.5. Normalization method used in prior studies

Table 15 shows the normalization methods used in the reviewed articles. Linear normalization is used by 13 papers and is the most used normalization method. Vector normalization is only used in 2 papers. It should be noted that in some of the reviewed papers, normalization was not needed because the authors used monetary values for performance data (Jeong et al., 2018) or assigned a number between 1 and 5 as the alternative's score for each criterion (Deniz and Zincir, 2016). There are some other methods such as those used by Iannaccone et al. (2020) where an external reference point was used for normalization (such as GDP of the European Union for normalization of the profitability of alternative fuels).

2.5.6. Aggregation methods used in prior studies

The final step in an MCDM study is aggregation, where the weights and the performance data are aggregated to compare the alternatives. Table 16 shows how many times different aggregation methods were used in the reviewed papers. While there are many aggregation methods like VIKOR, TOPSIS, and PROMETHEE, the WSM was the most common, and 13 out of 31 papers used this method because of its simplicity. TOPSIS and its Fuzzy version are the second most common with 7 papers. More complicated methods like PROMETHEE and VIKOR are used in two and one papers, respectively. It is worth noting that when the AHP method was used to obtain performance data, researchers used the WSM to aggregate criteria weights and normalized performance data.

The WSM, VIKOR, and TOPSIS are compensatory methods, meaning that weak performance in one criterion can be compensated by strong performance in another criterion. Researchers should consider whether such compensation is acceptable within sustainability analyses. If not, outranking methods such as PROMETHEE or ELECTRE should be employed, which allow for limited compensation or are non-

compensatory. This aligns with the limitations of compensatory methods for sustainability analysis and the strengths of non-compensatory methods for sustainability assessment as outlined by Cinelli et al. (2014).

Another concern regarding previously published papers is the selection of appropriate aggregation methods with respect to the selected weighting method. Weights derived from the AHP or BWM methods provide the importance of criteria but not the allowable trade-off between criteria. This means the AHP or BWM weighting methods should be used with non-compensatory aggregation methods (Cinelli et al., 2022). In 10 papers, the AHP weighting method is used with WSM (Mandić et al., 2021), (Andra Luciana et al., 2021), (Hansson et al., 2019), (Ren and Lützen, 2017), (Deniz and Zincir, 2016), (Maceiras et al., 2024), (Inal et al., 2022), TOPSIS (Soltani Motlagh et al., 2023), (Bui et al., 2021), and VIKOR (Ren and Lützen, 2015) ranking methods which are compensatory in nature. This indicates an arguably unsuitable combination of the selected weighting and aggregation methods. However, in one paper (Munim et al., 2023), the BWM is used with the PROMETHEE aggregation method, which is a valid combination of importance weights and an outranking based aggregation method.

Data type should also be considered when choosing the aggregation method. According to Cinneli et al. (Cinelli et al., 2022), distance-based aggregation methods are not suitable for qualitative ordinal data, even if these data are converted to a numerical scale. For example, in the paper by Strantzali et al. (2023), the PROMETHEE method is used to evaluate shipping fuels where some input data were ordinal (such as technology readiness level), which represents an appropriate selection of aggregation method with the nature of performance data. However, in some of the assessed papers (such as (Carvalho et al., 2021), (Mandić et al., 2021), (Aspen and Sparrevik, 2020), (Maceiras et al., 2024)), authors assigned ordinal scores to each alternative in a qualitative assessment and used the distance-based aggregation methods (WSM and TOPSIS) to rank alternatives using these ordinal scores. It may be argued that this is not a suitable aggregation method with respect to the data type.

In 21 out of 31 assessed papers, authors did not explicitly provide a rationale for selecting an MCDM method, often the MCDA method was chosen due to authors' familiarity, availability of software (Wątróbski et al., 2019), or prior applications of the method. According to the papers which explicitly stated the justification for selecting an MCDM method, TOPSIS was used because of its simple procedure and because it is less prone to rank reversal than AHP or ELECTRE (Moshiul et al., 2023), (Aspen and Sparrevik, 2020), (Bui et al., 2021). The use of fuzzy methods, Dempster-Shafer, and SMAA to include uncertainties associated with input data within the analyses (Kim and Seo, 2019), (Ren and Lützen, 2017), (Ren and Liang, 2017), (Aspen and Sparrevik, 2020), was justified. Justification for the use of AHP was due to its capability of managing both qualitative and quantitative criteria (Hansson et al., 2019), and PROMETHEE was selected for its geometric representation (Munim et al., 2023).

Table 17
Sensitivity analysis methods used in papers which applied multicriteria decision making to shipping fuels.

Method of sensitivity analysis	References
Change in criteria weights	(Yang et al., 2023), (Ren and Lützen, 2017), (Ren and Liang, 2017), (Ren and Lützen, 2015), (Rivarolo et al., 2021), (Iannaccone et al., 2020), (Bui et al., 2021), (Liu et al., 2020), (Inal et al., 2022)
Change in performance data	(Hansson et al., 2020), (Hansson et al., 2019), (Rivarolo et al., 2023), (Jeong et al., 2018), (Zanobetti et al., 2023)
Change in criteria weights and performance data	-
Stochastic (Monte Carlo)	(Zanobetti et al., 2023), (Hansson et al., 2020)
Deterministic (Manual alteration)	(Yang et al., 2023), (Ren and Lützen, 2017), (Ren and Liang, 2017), (Ren and Lützen, 2015), (Rivarolo et al., 2021), (Iannaccone et al., 2020), (Bui et al., 2021), (Liu et al., 2020), (Inal et al., 2022), (Hansson et al., 2020), (Hansson et al., 2019), (Rivarolo et al., 2023), (Jeong et al., 2018), (Zanobetti et al., 2023)
Change the MCDM method	Yang et al. (2023)

2.6. Sensitivity analysis

Sensitivity analysis is crucial in MCDM studies. It indicates how alterations to input parameters can affect the final result and can highlight the most influential parameter. The MCDM result depends on the weights of the criteria and the performance data, so sensitivity analysis can determine the robustness of the obtained ranking to perturbations in these.

Monte Carlo simulation is a helpful tool for sensitivity analysis, but it was only used by Zanobetti et al. (2023) and Hansson et al. (2020). Some authors like Hansson et al. (2019) considered changes in performance data in the sensitivity analysis, while others like Ren et al. (Ren and Liang, 2017) changed the criteria weights in different scenarios to check the robustness of their results. In total, 14 out of 31 papers conducted a sensitivity analysis. Table 17 shows which papers used a specific sensitivity analysis method. Only Yang et al. (2023) used different MCDM methods and input parameters for their model, in addition to changing criteria weights to evaluate the robustness of their results. It should be mentioned that no paper changed criteria weights and performance data at the same time.

To select a suitable MCDM method for a specific problem, first, the problem formulation should be assessed. This identifies whether the goal is to rank or sort alternatives, or choose a group of best alternatives, as well as whether the sets of alternatives are stable or can be changed due to the decision context. Also, the type of criteria should be identified to clarify their measurement scale (ordinal, interval, ratio), associated uncertainties, and structure (whether criteria are categorized). Secondly, it should be identified if the preference data are gathered directly or indirectly, what are the specifications of the aggregation method (compensation level, inconsistent preferences handling, decision context dependency), and how to exploit the preference model (unique result or scenario analysis, deterministic or stochastic sensitivity analysis, and single or group decision making). Thirdly, the ease of use, the required processing time, the number of alternatives and criteria that a method can handle, the acceptability of a method in the specific research area, and the available software for faster calculation should be analysed for a specific method (Cinelli et al., 2020). Answering each of these questions will narrow down the list of appropriate MCDM methods.

2.7. Optimal fuels selected in previous literature

In this section, the most suitable alternative shipping fuels proposed by prior papers are summarized. It is worth mentioning that the best option depends on the type of vessel, geographical specifications, the studied time frame, rules and policies implemented by national and international parties, the criteria considered, the stakeholders involved, and the fuels studied by each paper. It is uncommon in the literature to compare all the available or possible fuels at once, meaning that each paper compared a limited number of fuels.

As shown in Table 18, there is no consensus among research articles to date on the best alternative shipping fuel. A key reason is that these articles differed in terms of the fuels assessed and the criteria investigated. This variation is one of the key reasons why such studies should be conducted on a case-by-case basis, for each country, considering its specific policies, resources, and specifications of the shipping industry.

3. MCDM as a tool to compare alternative shipping fuels

A discussion of the key findings from prior sections as well as potential methods to improve future studies that use MCDM to compare

Table 18
Most suitable alternative shipping fuel selected in previous literature which applied multicriteria decision making to shipping fuels. For explanation of abbreviations, refer to Nomenclature.

Reference	Description	Selected Fuel	Assessed Fuels
Strantzali et al. (2023)	Reported the best fuels from the perspective of each stakeholder group. The best solution from the combination of all stakeholders' opinions is also reported.	Drop-in fuels including, Hydrothermal Liquefaction, fuel oil, Pyrolysis fuel oil, hydrogenated vegetable oil, Fatty Acid Methyl Ester	HFO, MGO, LNG, bio-LNG, e-LNG, fossil CH_3OH, blue CH_3OH, bio-CH_3OH, e-CH_3OH, drop-in (renewable gasoline), grey/blue H_2, green H_2, bio-H_2, fossil/blue NH_3, Green NH_3, bio-NH_3
Yang et al. (2023)	Alternative shipping fuels in the United Kingdom were assessed.	e-methanol	e-CH_3OH, solar-CH_3OH, bio-CH_4, ebiofuel-CH_3OH
Moshiul et al. (2023)	Criteria for alternative fuels for deep-sea shipping were ranked. Fuels were not compared.	No fuel is compared.	-
Carvalho et al. (2021)	Alternative fuels for Brazilian maritime trade were compared.	Fischer-Tropsch diesel	SVO, biodiesel, HVO, HDPO, FT-diesel, Alcohol-to-Diesel, bio-LNG, bio-CH_3OH, bio-C_2H_5OH, green H_2, green NH_3, e-diesel, e-LNG, e-CH_3OH
Mandić et al. (2021)	An analysis of alternative shipping fuels for use in coastal shipping traffic applications in Croatia.	Batteries	biofuels, LNG, H_2, LPG, batteries
Andra Luciana et al. (2021)	Liquified natural gas (LNG) and oil gas were compared as alternative shipping fuels.	LNG	LNG, oil gas
Hansson et al. (2020)	Green and fossil ammonia was compared with 10 other shipping fuels.	LNG	e-NH_3+ICE, fossil-NH_3+ICE, e-NH_3+FC, fossil-NH_3+FC, HVO + ICE, e-H_2+FC, fossil-H_2+FC, bio-CH_3OH + ICE, fossil-CH_3OH + ICE, liquified biogas + ICE, LNG + ICE
Kim and Seo (2019)	The importance of criteria for reducing SOx emissions from ships according to the opinions of Korean shipping companies was determined. Fuels were not compared.	Criteria are compared not the fuels.	-
Hansson et al. (2019)	Seven alternative fuels for deep-sea shipping in 2030 were compared.	LNG	HFO + ICE, CH_4(renewable & non-renewable) + ICE, CH_3OH (renewable & non-renewable) + ICE, H_2(renewable & non-renewable) + FC, HVO + ICE
Ren and Lützen (2017)	Three alternative energy sources for shipping were compared.	Nuclear power	LNG, wind power, nuclear
Ren and Liang (2017)	Three alternative fuels for shipping were compared.	Hydrogen	CH_3OH, LNG, H_2
Deniz and Zincir (2016)	Three alternative fuels for shipping were compared.	LNG	CH_3OH, C_2H_5OH, LNG, H_2
Ren and Lützen (2015)	Technologies to reduce emissions from shipping were compared.	LNG	low sulphur fuel, scrubber, LNG
Aspen and Sparrevik (2020)	The use of alternative fuels on Norwegian ferry crossings was compared.	Batteries	all-electric, plug-in-hybrid ferries in combination with biodiesel or liquified biogas or LNG
Maceiras et al. (2024)	The most promising alternative fuel for Spanish Navy ships was identified.	Hydrogen	CH_3OH, C_2H_5OH, LNG, H_2
Soltani Motlagh et al. (2023)	The authors identified the most effective decarbonization strategies for container shipping transportation.	Decarbonization techniques are compared not alternative fuels	-
Rivarolo et al. (2023)	Different alternative fuels for different vessel types were compared.	Sail yacht: Marine Diesel Oil Pax ferry for inland water navigation: Hydrogen. Cruise ship: LNG. Container ship: Marine Diesel Oil.	PEMFC + LH_2, PEMFC + CH_2, PEMFC + Metal Hydrides, SOFC + LNG, ICE + CH_3OH + MDO, ICE + MDO + LNG, ICE + MDO, ICE + NH_3
Rivarolo et al. (2021)	The authors compared different technologies for energy production and storage onboard, alternative to the standard internal combustion engine fuelled by diesel oil.	Small-sized passenger ships navigating in inland waters and protected areas: Hydrogen. Large-sized cruise ship operating in the open sea: Marine Diesel Oil.	PEMFC + LH_2, PEMFC + CH_2, SOFC + LNG, mGT + LNG, ICE + CH_3OH, ICE + LNG, ICE + MDO, ICE + NH_3
Ashrafi et al. (2022)	The authors developed & presented a set of sustainability criteria that are relevant for evaluating alternative shipping fuels.	Criteria are compared not fuels.	-
Jeong et al. (2018)	A hybrid ship was compared to an equivalent ship with conventional propulsion systems.	Diesel	Diesel mode, battery mode, hybrid mode.
Iannaccone et al. (2020)	The authors compared the sustainability performance of alternative fuel systems for large cruise ships.	LNG	LNG-based fuel systems: low-pressure dual fuel, high-pressure dual fuel, lean burn spark ignition, conventional MGO fuel system
Zanobetti et al. (2023)	Alternative ship power systems for decarbonized shipping were compared.	Hydrogen	LH_2-PEMFC, CH_2-PEMFC, Cryo-CH_2-PEMFC, LH_2-SOFC, LNG-based lean burn spark ignition, MGO-ICE

(continued on next page)

Table 18 (*continued*)

Reference	Description	Selected Fuel	Assessed Fuels
Jeong et al. (2019)	The authors evaluated three LNG-fuelled engine systems	Different propulsion systems running on LNG are compared.	Ultra-steam turbine, four-stroke medium speed engine, two-stroke low-speed engine systems
Munim et al. (2023)	Seven alternative energy sources for Bangladeshi shipping industry were compared.	Heavy Fuel Oil	LNG, NH_3, H_2, CH_4, HFO, LNG-wind hybrid, HFO-wind hybrid
Bui et al. (2021)	Alternative options for reducing harmful emissions produced by ships in a Swedish context were compared.	Low sulphur fuels	Low-sulphur fuels, HFO with scrubber, LNG, CH_3OH
Xuan et al. (2022)	The authors analysed the application characteristics of different clean energy technologies for the Chinese shipping industry.	For large coastal roll-on-roll-off (Ro-Ro) passenger vessels: LNG. For small inland river short-distance vessels: battery	LNG, LPG, CH_3OH, HVO, NH_3-FC, H_2-FC, battery powered
Liu et al. (2020)	Three different methods to reduce the environmental impact of shipping were evaluated.	Fuels are not compared.	-
Inal et al. (2022)	The authors analysed and compared hydrogen and ammonia for use in a fuel cell for shipping.	Renewable ammonia	H_2-FC, NH_3-FC
Montagna et al. (2022)	Traditional and innovative energy systems for maritime applications in a Mediterranean context were compared.	For the sail yacht for leisure usage: marine diesel oil For the cruise ship: marine diesel oil	PEMFC(metal hydrides, LH_2, CH_2), SOFC (LNG mGT), ICE (LNG + MDO, CH_3OH + MDO, NH_3 + MDO, MDO, NH_3 + H_2)
Lu et al. (2020)	The authors assessed scrubbers, low-sulphur fuels, and LNG to reduce SOx emissions in a Chinese context.	Low sulphur fuels	Scrubber, low-sulphur fuels, LNG
Xing et al. (2021)	The authors determined the most promising alternative shipping fuels	Methanol	Low sulphur HFO/MDO + ICE, H_2+ICE, H_2+FC, NH_3+ICE, NH_3+FC, renewable CH_4+ICE, renewable CH_3OH + ICE, renewable CH_3OH + FC, bioethanol + ICE, bioDME + ICE, biodiesel + ICE

alternative shipping fuels is provided in the following sections with regard to; fuel supply chain components, assessment criteria, data gathering methods, stakeholders included in the analysis, MCDM methods used, and the application of sensitivity analysis.

3.1. Fuel supply chain components

To provide a comprehensive ranking of alternative shipping fuels using MCDM methods, all parts of the fuel supply chain including the fuel production process, infrastructure required to deliver fuel from production sites to ports, and from ports to ships, and the vessels themselves, must be considered. Lack of attention to any of these components can lead to a large part of the economic, social, and environmental impacts of alternative fuels being unaccounted for. The type of fuel studied varies from country to country, depending on geographical conditions, available resources, production advantages, and various other factors. In addition, the ships visiting ports also affect the selection of fuels to be studied. In this regard, data on the type of ships visiting ports can be used in future studies to assess the effect of ship type on the final comparison of alternative shipping fuels. Furthermore, the type of ship needs to be considered because all ships cannot use all fuel types due to technical barriers such as vessel range, size, safety, and the type of engine (Hsieh and Felby, 2017).

The infrastructure required to deliver fuels from production facilities to ships is another important component in comparing alternative shipping fuels. For example, ammonia is easier to handle than hydrogen because of its physical and chemical properties. It is less flammable than hydrogen, it can be stored at higher temperatures (and as such demands less energy for refrigeration and storage), and its volumetric energy density is higher than liquid hydrogen; so ammonia may be preferable to hydrogen in terms of required infrastructure at ports (Inal et al., 2022). However, the most economic choice may be the alternative fuel in which there is no infrastructure change required in ports or ships, such as Fischer–Tropsch diesel. Considering infrastructure for fuel delivery and storage can be a subject for future studies that use MCDM to compare alternative shipping fuels. As storing alternative fuels requires specific infrastructure (for example: cryogenic storage for LNG, high-pressure storage for hydrogen, and strict safety measures for ammonia), future studies may include; infrastructure cost, availability of utilities (such as electricity, water, and natural gas), land availability, and land suitability needed to establish such facilities at the port under study. These aspects are typically considered during environmental impact assessments (EIA) of large-scale infrastructure projects, if data from such EIAs are available, it should be used in the MCDM. However, this data may not be available and as a detailed EIA may be beyond the scope of future studies that use MCDM to compare alternative shipping fuels, the criteria considered within such EIAs may serve as a guide to identifying criteria relevant to infrastructural developed that should be incorporated into MCDM future studies.

3.2. Assessment criteria

To enable a comprehensive comparison of the sustainability of alternative shipping fuels, the three pillars of economy, society, and environment should be considered. Also, technical parameters should be included to propose a technically feasible option. Safety is one of the technical indicators that can be considered for the assessment of fuel, which indicates how the use of alternative fuels affects the health of ship crews and port safety, and it can also affect the economic performance of the proposed fuel. For example, crew members on vessels fuelled by ammonia may expect higher wages because of the higher concerns for their health and safety than those running on conventional fuels. Among the pillars, the social pillar is the most challenging to assess, as there is no consensus among researchers on what indicators should be included and how to assess these (Siebert et al., 2018). Furthermore, the quantitative measurement of social impacts (which is preferred when using MCDM methods) is a challenging process. Job creation may be used as a social indicator in future research due to its simplicity in finding the related data and the possibility of quantitative analysis. To effectively include social aspects, future research can consider the degree of public acceptance from local communities close to ports or production facilities, the willingness and acceptance from harbour personnel, as well as the willingness of ship crews and passengers to travel on ships running on alternative fuels. Social lifecycle assessments for each alternative shipping fuel, covering the entire fuel supply chain from production to end use would be an ideal source of data which could be integrated

within future MCDM studies of alternative shipping fuels. Gathering data for such social lifecycle assessments will require surveys, interviews, or consultations with stakeholders from members of the public to experts.

Emissions due to the use of conventional fuels are mostly concentrated in the consumption phase (Thepsithar et al., 2020). However, different stages of alternative fuel production can affect their environmental performance. Biofuel production can result in high emissions due to the biomass production corresponding to the use of chemical fertilizers and land use change. Also, emissions mitigation from the production of e-fuels depends on the decarbonization of the electricity grid (Gilbert et al., 2018). The life cycle of fuels includes feedstock extraction or production, feedstock preparation and distribution, fuel synthesis and distribution, and fuel consumption. To obtain a comprehensive perspective on environmental impact due to the use of an alternative fuel, the aforementioned phases must be considered, which leads to a well-to-wake life cycle assessment. Meanwhile, most of the assessed studies focused on fuel consumption (tank-to-wake) emissions. From the environmental perspective, particulate matter, NO_x/SO_x emissions, and other environmental impacts like water consumption, eutrophication, and land use change can be included in future studies to provide a broad view of environmental impact. It should be highlighted that GHG emission, carbon footprint, and global warming are related to the same impact category, but they have scientific and conceptual differences; therefore, researchers should clearly select the appropriate one based on the scope and boundary of the study.

It should be noted that some fuels, such as hydrogen, methanol, and ammonia, are produced from natural gas (with or without carbon capture), with high technological maturity and are widely produced on an industrial scale, and therefore, their technical maturity is high. However, this is not true for novel fuels from renewable sources such as electrofuels like green methanol, green ammonia, or green hydrogen, and it is necessary to assess the technology maturity accurately for these novel fuels. The time frame of the study can alter the technical maturity of such novel fuels, meaning that these fuels may have higher TRL in the future due to progress in research and increases in investment by governmental bodies and private operators.

Table 19
Reference papers for process simulation of alternative shipping fuels and the provided information.

Reference	Process studied	Note
Choi et al. (2021)	CO_2 to CH_4	Kinetic models and constants are reported
Wątróbski et al. (2019)	CO_2 to CH_4	Equilibrium constants for $4H_2 + CO_2 \leftrightarrow 2H_2O + CH_4$ is reported
Aparicio (1997)	Methane reforming	Equilibrium constants for the water-gas shift reaction and methane steam reforming are reported
Uddin et al. (2022)	CO_2 to CH_4	Processes for CO_2 to CH_4 are studied
Pereira et al. (2022)	LNG production	Processes for LNG production are studied
Araújo and Skogestad (2008)	Ammonia synthesis	Process of ammonia synthesis is studied
Van-Dal and Bouallou (2013)	CO_2 to methanol	Process of methanol synthesis via CO2 hydrogenation is studied
Sánchez et al. (2020)	H_2 production	Process of H_2 production via alkaline water electrolysis is studied
Ni et al. (2006)	H_2 production	Process of H_2 production via proton exchange membrane water electrolysis is studied
Pasha et al. (2021)	Biodiesel	Process simulation of biodiesel synthesis is reviewed

3.3. Data gathering method

After defining alternatives and criteria, every MCDM study needs to obtain performance data (how alternatives perform with respect to each criterion) and weighting data (the relative importance or allowable trade-off of each criterion).

Performance data can be obtained by different methods, including modelling, process simulation, Life Cycle Assessment (LCA), literature review, survey/interviews with experts, or a combination of the above. When using modelling as a source of data, researchers obtain the required data by using mathematical models of the systems being assessed. Modelling can be used in the calculation of economic, environmental, and technical performance (Jeong et al., 2018). In the case of process simulation, researchers may develop a process simulation of fuel production pathways, using commercial software such as Aspen Plus. After that, it is possible to obtain the mass and energy balance and even some estimates of economic performance. The mass and energy balance provides the required data, such as the amount of energy and water consumption and greenhouse gas emissions needed for further assessment, such as LCA or technoeconomic analysis (TEA). Sensitivity analysis may also be combined with process simulations to identify key process parameters.

Although process simulation software is a powerful tool that can help future studies that use MCDM to find the most sustainable alternative shipping fuel, the collection of input information before starting the simulation is vital. This information includes but is not limited to; the process parameters (pressure, temperature, flow rates), kinetic constants of reactions, and thermodynamics of the process. As all this information may not be available, or information may be uncertain, some informed assumptions must be made to complete the simulation. Reference papers for process simulation of alternative shipping fuels are summarized in Table 19.

Conducting LCA studies is another method of obtaining performance data for future studies. LCA studies can be completed using commercial software and databases; however, finding appropriate databases for some alternative shipping fuel pathways may again be challenging or may contain uncertainties. Future studies can use LCA methods to have a holistic overview of the environmental performance of the studied fuels. ISO 14040/44 provides a comprehensive framework for conducting LCA studies. This framework consists of four major steps, including goal and scope definition, inventory analysis, impact assessment, and interpretation of results. Goal and scope should define the assessed fuels along with their production pathway, study system boundary (well-to-tank, tank-to-wake, well-to-wake, Fig. 2), and the functional unit. Researchers should decide whether to conduct attributional LCA or consequential LCA. In consequential LCA, the effect of replacing conventional fuels with alternative ones on other sectors and industries, such as agriculture (due to changes in biomass demand for biofuels), oil and gas (due to changes in fossil fuel demand), and energy generation (due to changes in power demand for e-fuels) are considered. In an attributional LCA, the study is limited to the defined system boundary and impacts are attributed to the inputs and processes included within the LCA. Functional units such as 1tonne-km of freight transportation, 1 person-km of passenger transportation, or 1 kWh of output energy from a ship power train may be used within the LCA.

These functional units will need to include the energy density of fuel and the efficiency of the ship power train. The ship type should be considered to ensure the selection of an appropriate functional unit based on the primary function of the ship (passenger transport or freight transport).

To complete the inventory analysis, processes can be grouped into foreground and background processes. For the foreground processes, input and output flows should be calculated by researchers, while these data are available from secondary sources for the background processes. Databases such as Ecoinvent can be used to complete inventory analysis. Literature can be the source to find data that is not available in

databases.

In addition to emissions to air, emissions to soil and water should also be considered to provide a comprehensive overview. Researchers should decide which impacts should be considered and either evaluate midpoint impacts (such as global warming potential, water consumption, and land use change used by Yang et al. (2023)) or endpoint impacts (such as impact on human health, impact on ecosystem, and impact on resources used by Bilgili (2021)). Although endpoint impacts are easier to interpret and facilitate decision-making (as they aggregate a large number of midpoint impacts into a few endpoint indicators), they are associated with higher uncertainty compared to midpoint impacts. The IMO regulations and perspectives can guide the selection of impacts.

In lieu of modelling or simulation, researchers may review existing literature (published articles and national/international reports) to obtain performance data. This method is used when the alternative fuel has already been investigated by other researchers or organizations. Data may also be obtained with the help of interviews or surveys with experts. These experts are representatives of stakeholders (defined in section 2.4). To obtain performance data from experts, pairwise comparison methods like the AHP proposed by Saaty (1987) can be helpful. In another method, experts assign a number as a score to each alternative, which can be a 1-5 or 1-10 Likert scale. It is also possible to obtain experts' opinions in linguistic terms and then convert these linguistic terms to Fuzzy or crisp numbers. These methods are mostly used when there is insufficient or unreliable data about the performance of alternatives. This issue could be due to the novelty of the alternative shipping fuel or because it is not possible to quantify the performance of the alternative shipping fuel for the desired criterion. For example, social aspects like public acceptance or social responsibility are hard to quantify. For this reason, most researchers who want to consider social impact primarily use expert opinions. It is worth noting that in some studies, there is a need to use the combination of the above approaches to obtain performance data.

Weighting data can be obtained by different means, such as literature reviews, surveys/interviews with stakeholders, or a combination of both. If an objective criterion weighting method is used, the weights are calculated directly from the performance data, removing the need to gather criteria weights from decision-makers or stakeholders. In some cases, authors cannot determine the criteria weights, so equal weighting was assumed for all criteria, or different weighting scenarios were used within the MCDM study (Rivarolo et al., 2023), (Zanobetti et al., 2023).

3.4. Stakeholders

Although government agencies have a vital role in developing policies related to the decarbonization of the shipping industry, this industry has a range of multidisciplinary stakeholders who have a complex relationship with each other and with this industry. Stakeholders may include policymakers, regulators, the owners and operators of ports, shippers and shipping agents, ship owners and operators, shipbuilders, fuel providers, and researchers (Council of the EU, 2023). As an example, Maersk, in its 2023 sustainability report, has introduced the following groups as its key stakeholders: employees; customers; investors; suppliers and business partners; authorities; NGOs; and communities (Sames and Köpke, 2012). The involvement of stakeholders is not just limited to obtaining weighting or performance data, and in some cases, stakeholders' opinions can be used to define the sub-criteria through surveys or interviews (Maceiras et al., 2024), (Cinelli et al., 2014). Stakeholder participation in a decision-making process is crucial, especially if their opinion is needed to complete the decision matrix or derive the criteria weights. Their opinions can alter the ranking of alternatives, therefore, suitable identification of stakeholders and their representatives is important in obtaining a reliable and non-biased result.

Stakeholders may have varying and conflicting judgments on the performance of alternatives or the criteria weights. Such differences can be due to variations in knowledge and understanding of the decision problem, as well as personal or organizational interests in the decision outcomes. These differences may bias the decision-making results. Researchers should clearly report engaged stakeholders with details such as age, expertise, gender, which organization they are representing, how they are related to the decision problem, and possible conflicts of interests. These records, along with clear sight of the data provided by each stakeholder can help in identifying possible biases in decision outcomes. MCDM methods provide features such as group decision making and objective weighting approaches in addition to transparent and traceable decision-making frameworks. Moreover, tools such as sensitivity analysis (performed on criteria weights and performance data) and scenario analysis can help decision makers to highlight the effect of biased inputs on results.

MCDM cannot eliminate issues such as policy-driven biases but still can be used to clearly track these biases and assess the sensitivity of the results obtained to changes in the input data. The opinions of port operators and managers can be used in future studies. Their opinions could alter the ranking of alternative shipping fuels due to their deep knowledge of relevant ship types, available infrastructure, and technical challenges associated with each fuel. For example, LNG requires cryogenic storage and usually needs about 4 times the space of regular fuel for an equivalent amount of energy (Hsieh and Felby, 2017) which needs to be assessed from the perspective of port operators. This would also be the case with e-methane; methane produced from reaction of renewable hydrogen and biogenic CO_2.

Opinions differ regarding group decision-making. From one perspective, groups can provide more accurate decisions, make more precise predictions, and propose more creative solutions, compared to individuals. However, some researchers found that group decision making can impose higher level of bias compared to individuals. Group decision making can be conducted by two different approaches. In the first approach, decision makers express their opinions independently, without any interaction or information exchange with each other. In contrast, decision makers can also engage in discussion to achieve a consensus. Each perspective has its own method and is assessed in more detail in the paper by Tindale and Winget (Tindale and Winget, 2019). In group decision-making, each stakeholder's perspective can lead to a distinct ranking. In the next step, stakeholders should reach a consensus on the best alternative. Huang et al. proposed a method based on criteria weights alteration, PROMETHEE, and linear optimization to facilitate reaching such a consensus (Huang et al., 2020).

3.5. MCDM method

There are many MCDM methods available and selecting the most appropriate one to use is a challenging process. For example, Cinelli et al. (2014) assessed five different MCDM methods (MAUT, AHP, ELECTRE, PROMETHEE, and dominance-based rough set approach (DRSA)) with 10 criteria which are necessary for sustainability studies to find the most suitable MCDM method. In another paper by Cinelli et al. (2020) a decision support system is proposed to help decision makers choose the most appropriate MCDM method among 205 different methods in a transparent and repeatable manner. They also provided a web-based tool that helps decision makers select the most appropriate MCDM technique by asking questions related to their research. These papers can be used as a guideline for researchers who want to use MCDM methods to compare the sustainability of alternative shipping fuels in the future.

The advantage of objective weighting methods is that they do not rely on stakeholder opinion and are therefore unbiased. Objective weighting methods determine the criteria weights based on the ability of criteria to differentiate between the alternatives under consideration. They can be used to provide an initial ranking of the alternatives to aid decision makers in determining a cohesive set of subjective criteria weights owing to the likely differences in opinions that will result when

consulting multiple different stakeholders. However, the final ranking results may differ from what stakeholders expect. Methods to combine objective and subjective weighting methods, such as the swing weight matrix proposed by Parnell (Parnell and Trainor, 2009), or the multiplicative combination proposed by Zeleny (Zelany, 1974) could also be implemented in future research to account for both subjective and objective criteria weights.

3.6. Fuzzy set theory

Fuzzy set theory is applied in MCDM studies when available information is insufficient for exact judgments, or crisp numbers are unable to represent the complexity and uncertainty of real-world decisions. However, including fuzzy theory increases the computational costs of MCDM studies (Kahraman, 2008). Subjective weighting methods rely on stakeholders' opinions; therefore, they reflect their perspectives, while objective weighting methods use the performance data as a source for calculating weights. If a subjective method is used, the uncertainty and ambiguity in the experts' opinions should be considered. Fuzzy theory is a powerful tool to express human opinion by using fuzzy numbers instead of one crisp number (Ren and Lützen, 2015). According to Zimmermann, "*Fuzzy set theory provides a strict mathematical framework (there is nothing fuzzy about fuzzy set theory!) in which vague conceptual phenomena can be precisely and rigorously studied*" (Zimmermann, 1991). In the fuzzy method, authors must allocate a fuzzy number to each linguistic term. The type of fuzzy number used (for example, triangular, trapezoidal) and which number should be allocated to each linguistic variable depends on the researchers' preference. Examples of this allocation can be found in the paper by Ren et al. (Ren and Lützen, 2017) where they used trapezoidal fuzzy numbers, and Bui et al. (2021) where triangular fuzzy numbers were used.

Several papers applied fuzzy theory to manage uncertainty included in the criteria weights (Kim and Seo, 2019), (Ren and Liang, 2017), (Ren and Lützen, 2015), (Jeong et al., 2019), (Bui et al., 2021), (Liu et al., 2020) and rankings (Ren and Liang, 2017), (Bui et al., 2021).

3.7. Sensitivity analysis

Every MCDM result depends on the input parameters, such as weights and performance data. The lack of available data on the performance of alternatives and the presence of uncertainties in these data (such as fuel price fluctuations, levels of improvements in the emission intensity of electricity generation, carbon footprints of biomass production, and increasing technological maturity of biomass-to-fuel processes) pose challenges for MCDM methods. One-factor-at-a-time sensitivity analysis (deterministic (Hansson et al., 2019)), Monte-Carlo simulations (stochastic (Zanobetti et al., 2023), (Hansson et al., 2020)), scenario analysis (Ren and Liang, 2017), the application of fuzzy decision-making methods, and engagement of experts by foresight techniques (such as the Delphi method) can be used to incorporate the aforementioned uncertainties into the MCDM. Sensitivity analysis can aid in identifying how changes to input parameters can change the ranking of alternatives. Stochastic methods, such as the Monte-Carlo simulation, can be implemented in future studies that use MCDM to compare alternative shipping fuels, instead of simple one-factor-at-a-time sensitivity analysis methods. Monte Carlo simulation provides a more robust analysis by developing numerous scenarios with random input parameters and can provide insight into the uncertainty of results obtained in the comparison of alternative shipping fuels.

4. A decision-making framework for choosing the most sustainable alternative shipping fuel

The key elements (such as criteria considered, data collection methods used for both weighting and performance, normalization methods, and aggregation methods) within the MCDM approach may impact the results obtained. It may, therefore, be necessary to carry out new studies on alternative shipping fuels in different countries or geographical regions, considering characteristics such as available resources; the number and types of ships visiting ports; existing infrastructure; and national and international laws and policies. The results of past research into the selection of alternative shipping fuels using MCDM cannot be directly applied without detailed consideration of different regions, as these key characteristics may differ. Also, having a systematic framework is crucial for conducting new research because without it, it is possible to have an incomplete stakeholder identification and involvement; a lack of focus on the whole fuel supply chain; and an absence of sensitivity analysis for evaluating the robustness of results. In this section, a framework is proposed for the comparison of alternative shipping fuels from a sustainability perspective using MCDM methods. The proposed framework tries to fill the research gaps by considering the necessity of regional, temporal, and policy making factors; the crucial role of stakeholder identification to enhance their engagement; the necessity of considering the whole fuel supply chain; and providing a clear procedure for the selection of methods for data gathering, normalization, and aggregation. This framework consists of four phases: 1) Goal and Scope Definition, 2) Data Gathering, 3) MCDM, and 4) Sensitivity Analysis. The framework is aligned with the standard MCDM procedure. Each of the phases are described as follows.

In phase 1, researchers must ***define the goal, scope, and time frame of the study***. By defining the goal, it is possible to define the assessment criteria. The scope of the study determines the involved stakeholders, port specifications, and available resources for fuel production. The time frame also indicates the available resources to produce fuels, meaning that some resources may or may not be available now or in the future. It also determines the policies and regulations that are or will be implemented. These regulations and policies affect the availability of resources such that some resources, like renewable hydrogen or biomass, may be more available due to specific geopolitical climate, regulations, and policies. It also can affect possible alternative fuels as the use of some specific fuels may be less favorable due to national or international regulations, or the production of some fuels may be supported by national or international authorities. Another element in this phase is identifying major ports and determining their characteristics (such as available infrastructure). This then leads to the identification of the visiting ship types to each of these ports. The visiting ship types can then influence the possible alternative fuels and their required infrastructure. The output of this phase is an identification of the potential alternative shipping fuels to be assessed.

In phase 2, researchers must ***gather the required data*** for comparing the alternative shipping fuels. They must define the data gathering methods for the performance of alternative shipping fuels for each relevant criterion. If they need stakeholder input, they must define the method of stakeholder engagement. The outputs of this phase will comprise the performance data.

In phase 3, researchers must define the method for gathering data regarding ***criteria weights*** and then define the method to be used when calculating criteria weights. The method to gather weighting data may be based on stakeholder input and, similar to the performance data gathering step, the method of stakeholder engagement and the subjective weighting method to be used must be defined. If objective weighting methods based on the performance data are to be used, the objective weighting method must be defined at this stage. The performance data must then be normalized using a ***normalization method*** clearly defined by researchers. The normalized performance data as well as the criteria weights are then aggregated using an ***aggregation method*** (which must be clearly defined by the researchers) to allow for the comparison and ***ranking of alternative shipping fuels***. The output of this phase is the ranking of alternative shipping fuels which is then subjected to sensitivity analysis in the next phase.

In phase 4, ***the sensitivity analysis method*** is defined (such as alteration of criteria weights, alteration of normalization method,

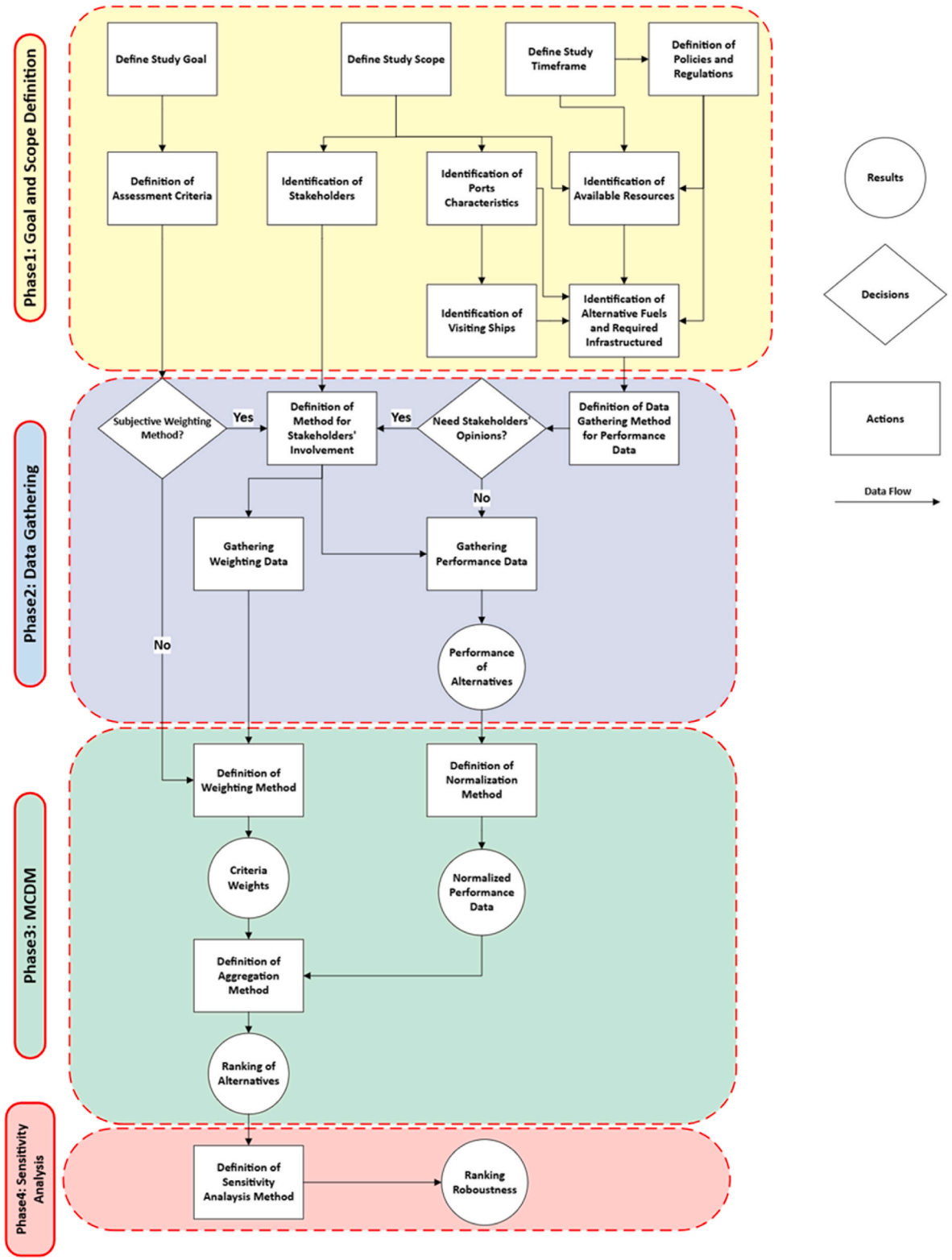


Fig. 4. Developed framework for multicriteria decision making as applied to shipping fuels.

alteration of aggregation method, one factor at a time deterministic sensitivity analysis, or multi factor stochastic sensitivity analysis), and implemented. The results of this sensitivity analysis are used to assess the robustness of the ranking of alternative shipping fuels from the MCDM process. The described framework is shown in Fig. 4.

The proposed framework is inspired by the LCA methodology according to ISO 14040/44 (Joint Research Centre: Institute for Environment and Sustainability, 2010) to ensure its robustness, systematic structure, and transparency (Table 20). Thus, the first phase is considered analogous to the definition of the goal and scope in LCA, with the difference that there is no need for a functional unit in the proposed framework. The data collection phase is aligned with the inventory assessment in LCA, with the difference that here, in addition to the performance data for the alternatives, the weights of the criteria must be

Table 20
Comparison of the proposed framework with LCA methodology according to ISO14040.

Phase name in the proposed framework	Phase name in the LCA methodology	Differences
Goal and scope definition	Goal and scope definition	Exclusion of the functional unit from the proposed framework
Data gathering	Inventory assessment	Both performance data and weighting data are required in the proposed framework
MCDM	Impact assessment	Ranking of the studied alternatives may not be possible due to the life cycle impact assessment method
Sensitivity analysis	Interpretation	The robustness of ranking and its sensitivity due to changes in input parameters are assessed in the proposed framework.

determined. The MCDM calculations phase is aligned with the impact assessment in LCA. The result of this phase is the ranking of alternatives. However, in LCA, depending on the assessment method and goal and scope definition, it may not be possible to rank the options under study. The fourth phase is analogous to the interpretation phase in LCA, with the difference that here the robustness of the ranking and the effect of input parameters on the results are examined. However, in LCA, the output of the fourth phase varies depending on the goal and scope definition and may include identifying hot spots or providing suggestions to improve the environmental performance.

5. Conclusion

The comparison of alternative shipping fuels to reduce the environmental impact of the shipping sector needs to consider both technical and sustainability perspectives. Multi-Criteria Decision-Making (MCDM) is a powerful tool for comparing and ranking alternatives whilst considering multiple different criteria. MCDM has been used previously to compare alternative shipping fuels from a sustainability perspective. In this paper, the existing literature that used this approach is assessed critically to identify trends and knowledge gaps. A perspective on the current application of MCDM to compare alternative shipping fuels is provided, along with a framework to address these knowledge gaps.

Infrastructure within the fuel supply chain is a key part of the delivery of alternative shipping fuels. Prior studies have investigated different shipping fuels; however, the authors did not find papers that considered the refuelling infrastructure, which can have a significant influence on economic and environmental performance, and thus on the final ranking of the alternative fuels. Furthermore, only 4 papers considered the type of ship in their analysis. In future works, considering the whole fuel supply chain system, consisting of fuel production, fuelling infrastructure, and ships, would make assessments more holistic.

In terms of the sustainability criteria used in previous studies; the social pillar is the least considered (16 out of 31 recorded papers). Regulations, public acceptance, governmental and/or industrial support, and social responsibility are the most used social indicators. The economic pillar is considered by all the reviewed papers, in which capital expenditure, operational expenditure, and fuel cost are the most commonly used economic indicators. The number of papers that assess fuels from technical and environmental perspectives are 26 and 30 (out of 31 papers), respectively. Safety, availability of fuel, reliability of fuel supply, and adaptability of the proposed fuel to existing ships are the most commonly used technical indicators. Considering technical maturity for novel electro-fuels can ensure a robust analysis from the technical perspective. Greenhouse gas, NO_x and/or SO_x, and particulate matter emissions are the most used environmental indicators in the reviewed papers. Using life cycle assessment methods can provide other environmental impacts of alternative shipping fuels from well-to-wake in future studies.

In relation to data-gathering methods, it was observed that the use of life cycle assessment to obtain performance data is rare. Also, no study assessed, used process simulation to obtain performance metrics for alternative shipping fuels production, and data from literature is the most commonly used method for gathering performance data. In terms of subjective methods for gathering data on criteria weights, the most commonly used method is using experts' opinions, while the use of authors' judgment is the least common approach.

In terms of the weighting method, the use of subjective weighting approaches was found to be more common than objective ones. The most used weighting methods are the Analytical Hierarchy Process and its fuzzy version and the direct use of authors' judgments. Other weighting methods like Stochastic Multicriteria Acceptability Analysis (SMAA), Fuzzy entropy, and maximum deviation are rarely used. Using an integrated subjective and objective weighting method can be implemented in future studies. With regards to normalization, linear normalization is the most common technique, while other methods like vector normalization and maximum deviation are rarely used. In terms of aggregation method, the Weighted Sum Method is the most common method used to aggregate weights and performance data, followed by Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and its fuzzy version. The VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), prospect theory, and q-Rung Orthopair Linguistic Partition Bonferroni Mean (q-ROLPBM) are the least common methods. Previously published studies exhibit arguably unsuitable combinations of criteria weights with MCDM aggregation methods, and input data types with MCDM aggregation methods. This study highlights that non-compensatory aggregation methods should be used with weights that determine the importance of criteria rather than the allowable trade-off between criteria. When using compensatory methods, researchers should clarify if compensation for poor performance in one criterion with strong performance in another criterion is desirable. In addition, distance-based aggregation methods are not suitable for criteria measured using an ordinal scale.

Shipowners and academics comprise the majority of stakeholders consulted in previous research, but only one paper considered a port operator as a stakeholder. Ports play a major role in decision-making for the implementation of alternative shipping fuels and the access and availability of alternative shipping fuels depend on the port's location and capacity.

Deterministic sensitivity analysis is the most common approach, whereas only 2 papers used Monte-Carlo simulation to conduct stochastic sensitivity analysis. Stochastic methods can be implemented in future studies. Changing the criteria weights and performance data values is more common than changing the multi-criteria decision-making method when conducting a sensitivity analysis.

Due to the inherent differences in previous studies in terms of the fuels, criteria, and vessels considered, as well as the studied location and timeline, there is no consensus in prior literature concerning the best alternative shipping fuel(s). Therefore, caution should be applied when using the existing literature to decide upon the best alternative shipping fuel(s) in a location, and a location-specific analysis should be conducted.

By considering the results of this paper, it can be concluded that current knowledge gaps can be filled in for future research by using process simulation and life cycle assessment for obtaining performance data, using objective weighting methods to obtain the importance of or allowable trade-off between criteria, considering ports as stakeholders, conducting stochastic sensitivity analysis by using Monte-Carlo simulation, and using different multi criteria decision methods as a means of sensitivity analysis.

A key challenge in the comparison of prior studies is non-uniformity in the grouping of sub-criteria. Using different terms for sub-criteria in prior studies made the process of categorizing sub-criteria difficult,

time-consuming, and posed challenges when comparing the results of prior studies. Another challenge was the lack of information provided by authors about their data-gathering or MCDM methods. A potential solution to these issues could be the use of a unified framework and terminology when using MCDM methods to assess alternative shipping fuels, as proposed in this work. By following this proposed framework, future work in this field could include a better description of data-gathering methods and MCDM methods, respectively to increase the transparency and comparability of future studies.

CRediT authorship contribution statement

Mohammadali Babanejadi Sorkhab: Conceptualization, Formal analysis, Methodology, Writing – original draft. **Nathan Gray:** Conceptualization, Writing – review & editing. **David Wall:** Supervision, Writing – review & editing. **Jerry D. Murphy:** Funding acquisition, Supervision, Writing – review & editing. **Richard O'Shea:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by Taighde Éireann - Research Ireland through the MaREI Centre for Energy, Climate and Marine (12/RC/2302_P2) and by the Sustainable Energy Authority of Ireland (SEAI) and the Irish Department of Transport through the ShipFuel-IE project (22/RDD/800).

Appendix 1. – Abbreviations and their definitions

Table A. 1
Abbreviations and their definitions in alphabetical order

Abbreviation	Definition
AHP	Analytical hierarchy process
ANP	Analytical network process
ASPID	Analysis and synthesis of parameters under information deficiency
BWM	Best-worst method
CAPEX	Capital expenditure
CH_2	Compressed hydrogen
LH_2	Liquid hydrogen
CRITIC	Criteria importance through inter-criteria correlation
DEA	Data envelopment analysis
DEMATEL	Decision-making trial and evaluation laboratory
DRSA	Dominance-based rough set approach
EDAS	Evaluation based on distance from average solution
EEDI	Energy efficiency design index
EIA	Environmental Impact Assessment
ELECTRE	Élimination et choix traduisant la realité
EU	European union
FT	Fischer-Tropsch
GDP	Gross domestic product
GHG	Greenhouse gas
HDPO	Hydrotreated pyrolysis oil
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
IMO	International maritime organization
ICE	Internal combustion engine
FC	Fuel cell
LCA	Life cycle assessment
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MACBETH	Measuring attractiveness through a categorical-based evaluation technique
MARPOL	International convention for the prevention of pollution from ships
MAUT	Multi-attribute utility theory
MCDM	Multi-criteria decision making
MDO	Marine diesel oil
MGO	Marine gas oil
mGT	Micro gas turbine
MSC	Mediterranean shipping company
MULTIMOORA	Multiple objective optimization on the basis of ratio analysis plus full multiplicative form
NAIADE	Novel approach to imprecise assessment and decision environments
NMVOCs	Non-methane volatile organic compounds
OPEX	Operational expenditure
PAIRS	Preference assessment by imprecise ratio statements
PEMFC	Proton exchange membrane fuel cell
PM	Particulate matter
PM10	Airborne particles that do not exceed 10 μm in diameter
PM2.5	All atmospheric aerosols with a maximum diameter of 2.5 μm
PROMETHEE	Preference ranking organization method for enrichment evaluation
Q-ROLPBM	Q-rung orthopair linguistic partition Bonferroni mean operator

(*continued on next page*)

Table A. 1 (*continued*)

Abbreviation	Definition
SMAA	Stochastic multicriteria acceptability analysis
SMART	Simple multi-attribute rating technique
SOFC	Solid oxide fuel cell
SVO	Straight vegetable oil
SWOT	Strengths, weaknesses, opportunities, and threats
TOPSIS	Technique of order preference by similarity to the ideal solution
TRL	Technology readiness levels
VIKOR	Visekriterijumska optimizacija i kompromisno resenje
VLSFO	Very low sulphur fuel oil
WASPAS	Weighted aggregated sum product assessment
WSM	Weighted sum method

Data availability

Data will be made available on request.

References

Abdel-Basset, M., Gamal, A., Chakrabortty, R.K., Ryan, M., 2021. Development of a hybrid multi-criteria decision-making approach for sustainability evaluation of bioenergy production technologies: a case study. J. Clean. Prod. 290, 125805. https://doi.org/10.1016/J.JCLEPRO.2021.125805.

Afshari, H., Agnihotri, S., Searcy, C., Jaber, M.Y., 2022. Social sustainability indicators: a comprehensive review with application in the energy sector. Sustain. Prod. Consum. 31, 263–286. https://doi.org/10.1016/J.SPC.2022.02.018.

Alam, M.M., Mohammad, R., Hira, F.A., 2021. Selection of alternative marine fuel technology based on literature review by applying appropriate multi-criteria decision-making method. Journal of Science, Technology and Innovation Policy 7 (2), 1–12. https://doi.org/10.11113/jostip.v7n2.83.

Čampara, L., Hasanspahić, N., Vujičić, S., 2018. Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines. In: SHS Web of Conferences, vol. 58, 01004. https://doi.org/10.1051/shsconf/20185801004.

Andra Luciana, T., Gasparotti, C., Rusu, E., 2021. Green fuels — a new challenge for marine industry. Energy Rep. 7, 127–132. https://doi.org/10.1016/j.egyr.2021.06.020.

Aparicio, L.M., 1997. Transient isotopic studies and microkinetic modeling of methane reforming over nickel catalysts. J. Catal. 165 (2), 262–274. https://doi.org/10.1006/JCAT.1997.1468.

Araújo, A., Skogestad, S., 2008. Control structure design for the ammonia synthesis process. Comput. Chem. Eng. 32 (12), 2920–2932. https://doi.org/10.1016/J.COMPCHEMENG.2008.03.001.

Ashrafi, M., Lister, J., Gillen, D., 2022. Toward a harmonization of sustainability criteria for alternative marine fuels. Maritime Transport Research 3. https://doi.org/10.1016/j.martra.2022.100052.

Aspen, D.M., Sparrevik, M., 2020. Evaluating alternative energy carriers in ferry transportation using a stochastic multi-criteria decision analysis approach. Transp. Res. D Transp. Environ. 86. https://doi.org/10.1016/j.trd.2020.102383.

Aytekin, A., 2021. Comparative analysis of the normalization techniques in the context of MCDM problems. Decision Making: Applications in Management and Engineering 4 (2), 1–25. https://doi.org/10.31181/DMAME210402001A.

Balcombe, P., et al., 2019. How to decarbonise international shipping: options for fuels, technologies and policies. Energy Convers. Manag. 182, 72–88. https://doi.org/10.1016/J.ENCONMAN.2018.12.080.

Bilgili, L., 2021. Comparative assessment of alternative marine fuels in life cycle perspective. Renew. Sustain. Energy Rev. 144 (17), 110985. https://doi.org/10.1016/j.rser.2021.110985.

Brauers, W.K., 2004. Optimization Methods for a Stakeholder Society, vol. 73. https://doi.org/10.1007/978-1-4419-9178-2.

Bui, K.Q., Ölçer, A.I., Kitada, M., Ballini, F., 2021. Selecting technological alternatives for regulatory compliance towards emissions reduction from shipping: an integrated fuzzy multi-criteria decision-making approach under vague environment. Proc. IME M J. Eng. Marit. Environ. 235 (1), 272–287. https://doi.org/10.1177/1475090220917815.

Campos-Guzmán, V., García-Cáscales, M.S., Espinosa, N., Urbina, A., 2019. Life cycle analysis with multi-criteria decision making: a review of approaches for the sustainability evaluation of renewable energy technologies. Renew. Sustain. Energy Rev. 104, 343–366. https://doi.org/10.1016/J.RSER.2019.01.031.

Carvalho, F., et al., 2021. Prospects for carbon-neutral maritime fuels production in Brazil. J. Clean. Prod. 326. https://doi.org/10.1016/j.jclepro.2021.129385.

Choi, C., et al., 2021. Determination of kinetic parameters for CO2 methanation (sabatier reaction) over Ni/ZrO2 at a stoichiometric feed-gas composition under elevated pressure. Energy Fuels 35 (24), 20216–20223. https://doi.org/10.1021/ACS.ENERGYFUELS.1C01534.

Cinelli, M., Burgherr, P., Kadziński, M., Słowiński, R., 2022. Proper and improper uses of MCDA methods in energy systems analysis. Decis. Support Syst. 163, 113848. https://doi.org/10.1016/J.DSS.2022.113848.

Cinelli, M., Coles, S.R., Kirwan, K., 2014. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol. Indic. 46, 138–148. https://doi.org/10.1016/J.ECOLIND.2014.06.011.

Cinelli, M., Kadziński, M., Gonzalez, M., Słowiński, R., 2020. How to support the application of multiple criteria decision analysis? Let us start with a comprehensive taxonomy. Omega (Westport). 96, 102261. https://doi.org/10.1016/J.OMEGA.2020.102261.

Council of the EU, 2023. REGULATION (EU) 2023/1805 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance). Off. J. Eur. Union 66, 48–100. https://doi.org/10.2771/793264.22.9.2023.

Deniz, C., Zincir, B., 2016. Environmental and economical assessment of alternative marine fuels. J. Clean. Prod. 113, 438–449. https://doi.org/10.1016/j.jclepro.2015.11.089.

Diakoulaki, D., Mavrotas, G., Papayannakis, L., 1995. Determining objective weights in multiple criteria problems: the critic method. Computers Ops Res 22 (7), 763–770.

European Central Bank, 2025. US dollar (USD). In: . Accessed: October. 17, 2025. [Online]. Available: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

European Union, 2021. Study on EU ETS for Maritime Transport and Possible Alternative Options of Combinations to Reduce Greenhouse Gas Emissions : Final Report. https://doi.org/10.2834/27271.

European Union, 2024. Consolidated Version of EU Directive 2003/87/EC 1–126. Brussels [Online]. https://eur-lex.europa.eu/eli/dir/2003/87/2024-03-01/eng. (Accessed 30 September 2025).

Farkas, A., Degiuli, N., Martić, I., Grlj, C.G., 2022. Is slow steaming a viable option to meet the novel energy efficiency requirements for containerships? J. Clean. Prod. 374, 133915. https://doi.org/10.1016/J.JCLEPRO.2022.133915.

Fulton, L.M., Lynd, L.R., Körner, A., Greene, N., Tonachel, L.R., 2015. The need for biofuels as part of a low carbon energy future. Biofuel Bioprod. Biorefining 9 (5), 476–483. https://doi.org/10.1002/bbb.1559.

Ghorabaee, M.K., Zavadskas, E.K., Olfat, L., Turskis, Z., 2015. Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). Informatica 26 (3), 435–451. https://doi.org/10.15388/INFORMATICA.2015.57.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. 172, 855–866. https://doi.org/10.1016/J.JCLEPRO.2017.10.165.

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J.D., 2021. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv. Appl. Energy 1, 100008. https://doi.org/10.1016/J.ADAPEN.2021.100008.

Gray, N., O'Shea, R., Smyth, B., Lens, P.N.L., Murphy, J.D., 2024. An assessment of decarbonisation pathways for intercontinental deep-sea shipping using power-to-X fuels. Appl. Energy 376, 124163. https://doi.org/10.1016/J.APENERGY.2024.124163.

Haase, M., Babenhauserheide, N., Rösch, C., 2020. Multi criteria decision analysis for sustainability assessment of 2nd generation biofuels. Proced. CIRP 90, 226–231. https://doi.org/10.1016/J.PROCIR.2020.02.124.

Hansson, J., Brynolf, S., Fridell, E., Lehtveer, M., 2020. The potential role of ammonia as marine fuel—based on energy systems modeling and multi-criteria decision analysis. Sustainability 12 (8), 3265. https://doi.org/10.3390/SU12083265, 2020, Vol. 12, Page 3265.

Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173. https://doi.org/10.1016/j.biombioe.2019.05.008.

Hazelrigg, G.A., 2019. A note on the weighted sum method. J. Mech. Des. 141 (10). https://doi.org/10.1115/1.4044326.

Hsieh, C.-W.C., Felby, C., 2017. Biofuels for the marine shipping sector [Online]. Available: https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf. (Accessed 21 March 2024).

Huang, H., De Smet, Y., Macharis, C., Doan, N.A.V., 2020. Collaborative decision-making in sustainable mobility: identifying possible consensuses in the multi-actor multi-

criteria analysis based on inverse mixed-integer linear optimization. Int. J. Sustain. Dev. World Ecol. 28 (1), 64–74. https://doi.org/10.1080/13504509.2020.1795005.
Hwang, C.-L., Yoon, K., 1981. Multiple attribute decision making: methods and applications - a state-of-the-Art survey. Lect. Notes Econ. Math. Syst. 186. https://doi.org/10.1007/978-3-642-48318-9.
Iannaccone, T., Landucci, G., Tugnoli, A., Salzano, E., Cozzani, V., 2020. Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. J. Clean. Prod. 260. https://doi.org/10.1016/j.jclepro.2020.121069.
Inal, O.B., Zincir, B., Deniz, C., 2022. Investigation on the decarbonization of shipping: an approach to hydrogen and ammonia. Int. J. Hydrogen Energy 47 (45), 19888–19900. https://doi.org/10.1016/j.ijhydene.2022.01.189.
International Energy Agency (IEA), Paris, 2024. The role of E-fuels in decarbonising transport. In: [Online]. Available: https://www.iea.org/reports/the-role-of-e-fuels-in-decarbonising-transport.
International Maritime Organisation (IMO), 2020. Fourth IMO GHG Study 2020 Executive Summary. London.
International Maritime Organization, 2022. 2022 guidelines for the development of a ship energy efficiency management plan (seemp) [Online]. Available: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.346%2878%29.pdf. (Accessed 29 January 2026).
International Maritime Organization, 2023. IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf.
International Maritime Organization, 2024. IMO and sustainable development. Accessed: May 13, 2024. [Online]. Available: https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/IMO%20SDG%20Brochure.pdf.
International Maritime Organization (IMO), 2021. 2022 Guidelines On The Method Of Calculation Of The Attained Energy Efficiency Existing Ship Index (EEXI). Accessed: Feb. 03, 2026. [Online]. Available: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.334(76).pdf.
Jamwal, A., Agrawal, R., Sharma, M., Kumar, V., 2021. Review on multi-criteria Decision Analysis in Sustainable Manufacturing Decision Making. Taylor and Francis Ltd. https://doi.org/10.1080/19397038.2020.1866708.
Jeong, B., Jang, H., Zhou, P., ung Lee, J., 2019. Investigation on marine LNG propulsion systems for LNG carriers through an enhanced hybrid decision making model. J. Clean. Prod. 230, 98–115. https://doi.org/10.1016/j.jclepro.2019.05.054.
Jeong, B., Oguz, E., Wang, H., Zhou, P., 2018. Multi-criteria decision-making for marine propulsion: hybrid, diesel electric and diesel mechanical systems from cost-environment-risk perspectives. Appl. Energy 230, 1065–1081. https://doi.org/10.1016/j.apenergy.2018.09.074.
Joint Research Centre: Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook : general guide for life cycle assessment : detailed guidance. Publications Office of the European Union. https://data.europa.eu/doi/10.2788/38479.
Kahraman, Cengiz, 2008. Fuzzy multi-criteria Decision Making : Theory and Applications with Recent Developments, p. 591 [Online]. https://books.google.com/books/about/Fuzzy_Multi_Criteria_Decision_Making.html?id=s2GOmBVdXYoC. (Accessed 23 January 2026).
Kim, A.R., Seo, Y.J., 2019. The reduction of SOx emissions in the shipping industry: the case of Korean companies. Mar. Pol. 100, 98–106. https://doi.org/10.1016/j.marpol.2018.11.024.
Kouzelis, K., Frouws, K., van Hassel, E., 2022. Maritime fuels of the future: what is the impact of alternative fuels on the optimal economic speed of large container vessels. Journal of Shipping and Trade (1), 1–29. https://doi.org/10.1186/S41072-022-00124-7, 2022 7:1, vol. 7.
Kumar, A., et al., 2017. A Review of Multi Criteria Decision Making (MCDM) Towards Sustainable Renewable Energy Development. Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.11.191
Li, Y., He, X., Martínez, L., Zhang, J., Wang, D., Liu, X.A., 2024. Comparative analysis of three categories of multi-criteria decision-making methods. Expert Syst. Appl. 238. https://doi.org/10.1016/j.eswa.2023.121824.
Liu, X., Tian, G., Fathollahi-Fard, A.M., Mojtahedi, M., 2020. Evaluation of ship's green degree using a novel hybrid approach combining group fuzzy entropy and cloud technique for the order of preference by similarity to the ideal solution theory. Clean Technol. Environ. Policy 22 (2), 493–512. https://doi.org/10.1007/s10098-019-01798-7.
Lu, C., Zhao, M., Khan, I., Uthansakul, P., 2020. Prospect Theory Based Hesitant Fuzzy multi-criteria Decision Making for Low Sulphur Fuel of Maritime Transportation. Tech Science Press. https://doi.org/10.32604/cmc.2020.012556.
Maceiras, R., Alfonsin, V., Alvarez-Feijoo, M.A., Llopis, L., 2024. Assessment of selected alternative fuels for Spanish navy ships according to multi-criteria decision analysis. J. Mar. Sci. Eng. 12 (1). https://doi.org/10.3390/jmse12010077.
Mandić, N., Ukić Boljat, H., Kekez, T., Luttenberger, L.R., 2021. Multicriteria analysis of alternative marine fuels in sustainable coastal marine traffic. Applied Sciences (Switzerland) 11 (6). https://doi.org/10.3390/app11062600.
Mareschal, B., Brans, J.P., 1994. The PROMETHEE-GAIA decision support system for multicriteria investigations. ULB Institutional Repository [Online]. Available: https://ideas.repec.org/p/ulb/ulbeco/2013-9367.html. (Accessed 11 August 2024).
MARITIME SINGAPORE: decarbonisation blueprint [Online]. Available: https://www.mpa.gov.sg/docs/mpalibraries/mpa-documents-files/sustainability-office/mpa-decarb-blueprint-2050a.pdf.
Martín-Gamboa, M., Dias, L.C., Quinteiro, P., Freire, F., Arroja, L., Dias, A.C., 2019. Multi-criteria and life cycle assessment of wood-based bioenergy alternatives for residential heating: a sustainability analysis. Energies 12 (22), 4391. https://doi.org/10.3390/EN12224391, 2019, Vol. 12, Page 4391.
Mediterranean Shipping Company, 2022. MSC SUSTAINABILITY REPORT 2022.
Møller – Mærsk A/S, A.P.. Maersk 2023 sustainability report [Online]. Available: https://www.maersk.com/~/media_sc9/maersk/corporate/sustainability/files/resources/2024/2023-maersk-sustainability-report.pdf.
Montagna, G.N., Piccardo, S., Rivarolo, M., Bellotti, D., Magistri, L., 2022. A multi-criteria approach for comparing alternative fuels and energy systems for marine applications. https://doi.org/10.46855/energy-proceedings-10183. In: https://www.energy-proceedings.org/?p=10183. Applied Energy Innovation Institute (AEii).
Moshiul, A.M., Mohammad, R., Hira, F.A., 2023. Alternative fuel selection framework toward decarbonizing maritime deep-sea shipping. Sustainability 15 (6). https://doi.org/10.3390/su15065571.
Mukhametzyanov, I.Z., 2021. Specific character of objective methods for determining weights of criteria in MCDM problems: entropy, CRITIC, SD. Decision Making: Applications in Management and Engineering 4 (2), 76–105. https://doi.org/10.31181/DMAME210402076I.
Munim, Z.H., Chowdhury, M.M.H., Tusher, H.M., Notteboom, T., 2023. Towards a prioritization of alternative energy sources for sustainable shipping. Mar. Pol. 152. https://doi.org/10.1016/j.marpol.2023.105579.
Nagy, J., Do Thi, H.T., Toth, A.J., 2023. Life cycle, PESTLE, and multi-criteria decision analyses of novel process for nitrogen recovery from reject water: combining electroconcentration and stripping methods. Water (Switzerland) 15 (18), 3231. https://doi.org/10.3390/W15183231/S1.
Ni, M., Leung, M.K.H, Leung, D. Y. C, 2006. Electrochemistry Modeling of Proton Exchange Membrane (PEM) Water Electrolysis for Hydrogen Production. In: 16th World Hydrogen Energy Conference 2006. WHEC, pp. 33–39.
Odu, G.O., 2019. Weighting methods for multi-criteria decision making technique. J. Appl. Sci. Environ. Manag. 23 (8), 1449. https://doi.org/10.4314/jasem.v23i8.7.
Opricovic, S., 1998. Multicriteria optimization of civil engineering systems. Faculty of Civil Engineering. Belgrade, 302 pp. - References - Scientific Research Publishing.". PhD Thesis. [Online]. https://www.scirp.org/reference/referencespapers?referenceid=1600129. (Accessed 11 August 2024).
Parnell, G.S., Trainor, T.E., 2009. Using the Swing Weight Matrix to Weight Multiple Objectives.
Pasha, M.K., Dai, L., Liu, D., Guo, M., Du, W., 2021. An overview to process design, simulation and sustainability evaluation of biodiesel production. Biotechnol. Biofuels (1), 129. https://doi.org/10.1186/S13068-021-01977-Z, 2021 14:1, vol. 14.
Pereira, M.A.M., Santos, L.F., Caballero, J.A., Ravagnani, M.A.S.S., Costa, C.B.B., 2022. Energy and economic comparison of five mixed-refrigerant natural gas liquefaction processes. Energy Convers. Manag. 272, 116364. https://doi.org/10.1016/J.ENCONMAN.2022.116364.
Ren, X., Li, W., Ding, S., Dong, L., 2020. Sustainability assessment and decision making of hydrogen production technologies: a novel two-stage multi-criteria decision making method. Int. J. Hydrogen Energy 45 (59), 34371–34384. https://doi.org/10.1016/J.IJHYDENE.2019.12.134.
Ren, J., Liang, H., 2017. Measuring the sustainability of marine fuels: a fuzzy group multi-criteria decision making approach. Transp. Res. D Transp. Environ. 54, 12–29. https://doi.org/10.1016/j.trd.2017.05.004.
Ren, J., Lützen, M., 2015. Fuzzy multi-criteria decision-making method for technology selection for emissions reduction from shipping under uncertainties. Transp. Res. D Transp. Environ. 40, 43–60. https://doi.org/10.1016/j.trd.2015.07.012.
Ren, J., Lützen, M., 2017. Selection of sustainable alternative energy source for shipping: multi-criteria decision making under incomplete information. Renew. Sustain. Energy Rev. 74, 1003–1019. https://doi.org/10.1016/J.RSER.2017.03.057.
Rivarolo, M., Piccardo, S., Montagna, G.N., Bellotti, D., 2023. A multi-criteria approach for comparing alternative fuels and energy systems onboard ships. Energy Convers. Manag. X 20. https://doi.org/10.1016/j.ecmx.2023.100460.
Rivarolo, M., Rattazzi, D., Magistri, L., Massardo, A.F., 2021. Multi-criteria comparison of power generation and fuel storage solutions for maritime application. Energy Convers. Manag. 244 (Sep). https://doi.org/10.1016/j.enconman.2021.114506.
Saaty, R.W., 1987. The analytic hierarchy process—what it is and how it is used. Math. Model. 9 (3-5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8. https://linkinghub.elsevier.com/retrieve/pii/0270025587904738.
Sames, Pierre C., Köpke, Martin, 2012. CO2 Emissions of the Container World Fleet. Proc. - Social and Behav. Sci. 48, 1–11. https://doi.org/10.1016/j.sbspro.2012.06.982. https://linkinghub.elsevier.com/retrieve/pii/S1877042812027188.
Shannon, C.E., 1948. A Mathematical Theory of Communication. Bell Syst. Tech. J. 27 (3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x. https://ieeexplore.ieee.org/document/6773024. (Accessed 29 July 2013).
Siebert, A., Bezama, A., O'Keeffe, S., Thrän, D., 2018. Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. J. Clean. Prod. 172, 4074–4084. https://doi.org/10.1016/j.jclepro.2017.02.146.
Siksnelyte, I., Zavadskas, E.K., Streimikiene, D., Sharma, D., 2018. An overview of multi-criteria decision-making methods in dealing with sustainable energy development issues. Energies 11 (10), 2754. https://doi.org/10.3390/EN11102754, 2018, Vol. 11, Page 2754.
Sánchez, M., Amores, E., Abad, D., Rodríguez, L., Clemente-Jul, C., 2020. Aspen plus model of an alkaline electrolysis system for hydrogen production. Int. J. Hydrogen Energy 45 (7), 3916–3929. https://doi.org/10.1016/J.IJHYDENE.2019.12.027.
Solakivi, T., Paimander, A., Ojala, L., 2022. Cost competitiveness of alternative maritime fuels in the new regulatory framework. Transp. Res. D Transp. Environ. 113, 103500. https://doi.org/10.1016/J.TRD.2022.103500.
Soltani Motlagh, H.R., Issa Zadeh, S.B., Garay-Rondero, C.L., 2023. Towards international maritime organization carbon targets: a multi-criteria decision-making

analysis for sustainable container shipping. Sustainability 15 (24), 16834. https://doi.org/10.3390/su152416834.
Strantzali, E., Livanos, G.A., Aravossis, K., 2023. A comprehensive multicriteria evaluation approach for alternative marine fuels. Energies 16 (22), 7498. https://doi.org/10.3390/EN16227498, 2023, Vol. 16, Page 7498.
Streimikiene, D., Balezentis, T., Krisciukaitien, I., Balezentis, A., 2012. Prioritizing sustainable electricity production technologies: MCDM approach. Renew. Sustain. Energy Rev. 16 (5), 3302–3311. https://doi.org/10.1016/J.RSER.2012.02.067.
Thepsithar, P., et al., 2020. Alternative Fuels for International Shipping.
Tindale, R.S., Winget, J.R., 2019. Group decision-making. Oxford Research Encyclopedia of Psychology. https://doi.org/10.1093/ACREFORE/9780190236557.013.262.
Uddin, Z., Yu, B.Y., Lee, H.Y., 2022. Evaluation of alternative processes of CO2 methanation: design, optimization, control, techno-economic and environmental analysis. J. CO2 Util. 60, 101974. https://doi.org/10.1016/J.JCOU.2022.101974.
UNCTAD. Division on Technology and Logistics. Trade Logistics Branch, 2022. Review of maritime transport 2022 : navigating stormy waters. UNITED NATIONS. https://digitallibrary.un.org/record/3995932?ln=en&v=pdf.
U.S. Department of Transport. DECARBONIZING THE MARITIME SHIPPING INDUSTRY Starter Guide to Reducing Greenhouse Gas Emissions from Maritime Shipping [Online]. Available: https://www.transportation.gov/sites/dot.gov/files/2023-09/OSTX-Momentum-Toolkit-Maritime-Shipping.pdf.
Vafaei, N., Ribeiro, R.A., Camarinha-Matos, L.M., 2016. Normalization techniques for multi-criteria decision making: analytical hierarchy process case study. IFIP Adv. Inf. Commun. Technol. 470, 261–268. https://doi.org/10.1007/978-3-319-31165-4_26/TABLES/6.
Van Houtven, G., Gallaher, M., Woollacott, J., Decker, E., 2022. Act now or Pay Later: the Costs of Climate Inaction for Ports and Shipping.
Van-Dal, É.S., Bouallou, C., 2013. Design and simulation of a methanol production plant from CO2 hydrogenation. J. Clean. Prod. 57, 38–45. https://doi.org/10.1016/J.JCLEPRO.2013.06.008.
Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009. Review on multi-criteria Decision Analysis Aid in Sustainable Energy decision-making. https://doi.org/10.1016/j.rser.2009.06.021.
Wątróbski, J., Jankowski, J., Ziemba, P., Karczmarczyk, A., Zioło, M., 2019. Generalised framework for multi-criteria method selection. Omega (Westport) 86, 107–124. https://doi.org/10.1016/J.OMEGA.2018.07.004.
Wu, D., Yang, Z., Wang, N., Li, C., Yang, Y., 2018. An integrated multi-criteria decision making model and AHP weighting uncertainty analysis for sustainability assessment of coal-fired power units. Sustainability 10 (6), 1700. https://doi.org/10.3390/SU10061700, 2018, Vol. 10, Page 1700.
Xing, H., Stuart, C., Spence, S., Chen, H., 2021. Alternative fuel options for low carbon maritime transportation: pathways to 2050. J. Clean. Prod. 297. https://doi.org/10.1016/j.jclepro.2021.126651.
Xuan, H., Liu, Q., Wang, L., Yang, L., 2022. Decision-making on the selection of clean energy technology for green ships based on the rough set and TOPSIS method. J. Mar. Sci. Eng. 10 (5). https://doi.org/10.3390/jmse10050579.
Yang, Z., Ahmad, S., Bernardi, A., long Shang, W., Xuan, J., Xu, B., 2023. Evaluating alternative low carbon fuel technologies using a stakeholder participation-based q-rung orthopair linguistic multi-criteria framework. Appl. Energy 332. https://doi.org/10.1016/j.apenergy.2022.120492.
Zanobetti, F., Pio, G., Jafarzadeh, S., Muñoz Ortiz, M., Cozzani, V., 2023. Decarbonization of maritime transport: sustainability assessment of alternative power systems. J. Clean. Prod. 417. https://doi.org/10.1016/j.jclepro.2023.137989.
Zavadskas, E.K., Govindan, K., Antucheviciene, J., Turskis, Z., 2016. Hybrid Multiple Criteria decision-making Methods: a Review of Applications for Sustainability Issues. Taylor and Francis Ltd. https://doi.org/10.1080/1331677X.2016.1237302.
Zelany, M., 1974. A concept of compromise solutions and the method of the displaced ideal. Comput. Oper. Res. 1 (3–4), 479–496. https://doi.org/10.1016/0305-0548(74)90064-1.
Zimmermann, H.-J., 1991. Fuzzy Set Theory — and its Applications. https://doi.org/10.1007/978-94-015-7949-0.