Towards a prioritization of alternative energy sources for sustainable shipping

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Full reference:
Munim, Z.H., Chowdhury, M.M.H., Tusher, H.M., Notteboom, T., 2023, Towards a prioritization of alternative energy sources for sustainable shipping, Marine Policy, Volume 152, June 2023, 105579,
https://doi.org/10.1016/j.marpol.2023.105579

Abstract
Studies on the prospects of the use of alternative fuels in the maritime industry have rarely been assessed in the context of developing countries. This study assesses seven alternative energy sources for shipping in the context of Bangladesh with a view to ranking their prospects based on sustainability as well as identifying the energy transition criteria. Data were collected from maritime industry experts, including seafarers, shipping company executives, government representatives, and academics. The Bayesian Best-Worst Method (BWM) was used for ranking nine criteria related to the suitability and viability of the considered alternative energy sources. Next, the PROMETHEE-GAIA method is applied for priority analysis of the seven energy alternatives. The findings reveal that capital cost, alternative energy price, and safety are the most important factors for alternative energy transition in Bangladesh. Apart from the benchmark HFO, Liquified Natural Gas (LNG), HFO-Wind, and LNG-Wind hybrids are considered the most viable alternatives considering their sustainability. The findings of the study can guide policymakers in Bangladesh in terms of promoting viable energy sources for sustainable shipping.

Keywords: alternative fuel; hydrogen; wind propulsion; hybrid energy; best-worst method.

1. Introduction

It has been widely discussed that commercial shipping is responsible for a significant amount of the global greenhouse gas (GHG) emissions (Inal & Deniz, 2020). Carbon Dioxide (CO_2), Sulfur Oxides (SOx), Nitric Oxides (NOx), Carbon Monoxide (CO), hydrocarbons, and other particulates significantly affect the environment, with all being emitted from the burning of traditional marine fuel, i.e. heavy fuel oil or HFO (Eyring et al., 2005). The International Maritime Organization (IMO) estimates that the maritime shipping industry contributes 2.5 to 3 percent of annual human-produced carbon dioxide and is a significant source of SOx, NOx, and PM, which are highly toxic, create air pollution, and cause acid rain (IMO, 2018). Efforts have been made to counteract such emissions from shipping operations by the IMO adopting a set of regulations at a global level, complemented by regional regulatory initiatives by such bodies as the European Commission. One such effort is the IMO's International Convention for the Prevention of Pollution from Ships (MARPOL), of which Annex VI is dedicated to the setting of limitations on the main air pollutants contained in ships' exhausts (*MARPOL*, 1973). Further plans and initiatives include the implementation of Tier III requirements, the Energy Efficiency Design Index (EEDI) for new ships, the Energy Efficiency Existing Ships Index (EEXI), the Carbon Intensity Indicator (CII) – which includes an A-to-E ship rating mechanism, and the strengthening of the Ship Energy Efficiency Management Plan (SEEMP) for all ships (Moreno-Gutiérrez et al., 2019; Psaraftis, 2021). Recent studies have focused on optimizing ships' energy management by analyzing factors such as ship type, voyage data, and environmental conditions to create distinct efficiency models (Fan et al., 2023; Fan et al., 2022). Further, the shipping decarbonization discussion has also focused heavily on market-based measures (Psaraftis et al., 2021) such as the possible global implementation of a carbon tax, or the planned inclusion of shipping in the EU Emissions Trading Scheme (ETS) as part of the 'Green Deal' (Hughes, 2020; Wang et al., 2021; Wettestad and Gulbrandsen, 2022).

Emissions from shipping are directly associated with energy sources and consumption levels of ships. Differing operational and technical efficiency measures have been envisaged in the MARPOL convention to reduce GHG emissions from ships. Based on Öztürk & Başar (2022), technical energy efficiency measures can be achieved through hull design, propulsion choice, maneuvering, and machinery systems efficiency. Operational efficiency measures include weather routing, cargo handling, ballast water, and speed optimization (Öztürk & Başar, 2022). The use of alternative marine fuels and energy sources is one of the technical efficiency measures that offers significant emission reduction potential (Ampah et al., 2021). The 72nd session of the Marine Environment Committee (MEPC) of IMO adopted some crucial directions to decarbonize shipping in order to make shipping sustainable.[1] A reduction of CO_2 in shipping of approximately 40 percent by 2030 compared to 2008 levels is envisaged, where extensive support for research and development on alternative fuels is solicited from shipowners worldwide.

Over the last two decades, the number of potential alternative fuel and energy sources for shipping has increased. Liquified natural gas (LNG), fully electric energy, methane, methanol, biodiesel, hydrogen, and ammonia have received the most attention (Ampah et al., 2021). While these are considered the main energy sources for ship propulsion, solar and wind energy technologies have also been investigated (Nyanya et al., 2021), but mostly as secondary energy sources in a hybrid propulsion setting with existing marine fuels such as HFO or LNG. Schøyen and Steger-Jensen (2017) discussed the potential for GHG emission reduction through nuclear propulsion, but there is uncertainty when it comes to ports and canals access restrictions from the port states. Among the possibilities, LNG and electric propulsion have been already proven technologically for merchant vessels. Based on life cycle assessments (LCA), it was found that hydrogen, ammonia, and methane have a higher potential in terms of GHG emission reduction (Chen & Lam, 2022; Perčić et al., 2022; Strazza et al., 2010), while battery technology and fuel cells are particularly promising for short-sea shipping and short-distance ferry operations (Perčić et al., 2022). However, the latter alternatives are yet to be proven viable for long-haul merchant shipping where ship sizes and sailing distances are considerably larger. Despite massive R&D efforts in and resource allocations to alternative ship energy sources, approximately 95 percent of the world's merchant fleet in Gross Tonnage (GT) capacity and around 98 percent of the fleet in terms of numbers is still powered by very low sulfur intermediate fuel oil (VLS IFO), very low sulfur marine diesel oil (VLS MDO), very low sulfur marine gas oil (VLS MGO), or IFO 380 combined with scrubbers (based on January 2021 data from Clarksons Research). Among the alternative fuels, only LNG is

[1] See https://www.imo.org/en/MediaCentre/IMOMediaAccreditation/Pages/MEPC72.aspx, accessed on July 10, 2022.

being adopted on a reasonable scale, mostly as part of dual-fuel propulsion solutions (UNCTAD, 2021). Container carrier CMA CGM was the first to order ULCSs with engines using LNG, which began operations in 2020. Since the second half of 2022, there is a noticeable increase in container vessel orders involving methanol-powered large containerships (placed by Maersk, COSCO and CMA CGM or associated vessel charterers), while also ammonia and some other low carbon fuels are being considered as ship fuels of the future.

Shipping decarbonization poses specific challenges to developing countries, both at the level of local bunkering needs as well as when considering nationally flagged vessels. While most previous studies in this context have focused mainly on developed countries, such as Norway (Aspen & Sparrevik, 2020) and Sweden (Hansson et al., 2019), this study focuses on Bangladesh. Being a developing country, maintaining a sustainable energy source is a difficult task, especially since the ships calling at Bangladeshi ports fully rely on imported energy sources for bunkering. The number of commercial vessels under the Bangladesh flag has increased rapidly over the last decade. The total registered fleet in Bangladesh saw a rapid increase reaching 4,262,260 dwt in 2022 compared to only 975,300 dwt in 2010 (UNCTAD, 2022). Meanwhile, under the Bangladeshi flag, shipowners do not enjoy any incentive as compared to the commercial flags or so-called "open registries" (such as Panama, Liberia or Honduras to name a few), where they provide shipowners with a set of facilities including easy ship registration, lower tax rate, and no binding citizenship requirements on management or manning, which results in a lower operational cost (Corres & Pallis, 2008). However, operators of the 477 Bangladeshi-flagged ships (UNCTAD figures for 2021) receive protection through the Flag Vessel (Protection) Ordinance 1982, which protects local shipowners by promising that at least 40 percent of sea-borne foreign trade in relation to the country shall be carried by Bangladeshi-flagged vessels. As a result, the business strategy and the investment structure differ from most traditional shipowners which in turn affects their investment in green shipping measures, such as the utilization of alternative fuels. Nevertheless, Bangladeshi ships sailing internationally must conform to the global decarbonizing efforts in the shipping industry, which poses a unique challenge to address green shipping measures differently than others.

The present study investigates the perception of shipowners, operators, academics, regulators, and classification societies in adopting alternative energy sources in the Bangladeshi shipping context, thereby exploring the potential likelihood of measures taken by other developing nations with similar resource constraints and protective shipping regulations. Hence, the following research questions (RQs) are formulated:

RQ1: What are the factors that influence the adoption of alternative fuels in the shipping industry of developing countries?

RQ2: What is the perceived sustainability ranking of alternative fuels among Bangladeshi maritime professionals?

By employing the Bayesian Best-Worst Method (BWM) and Preference Ranking Organization Method for Enrichment Evaluation- Geometrical Analysis for Interactive Assistance (PROMETHEE-GAIA) in a novel hybrid multi-criteria decision-making (MCDM) approach, this study reveals the prospect of seven alternative energy sources for future ship propulsion in Bangladesh along with an assessment of nine criteria affecting the ships' energy choice. Employing both the Bayesian BWM and the PROMETHEE has the potential to augment stakeholder decision-making capacities by increasing transparency in the choice of alternative energy sources for the shipping industry. This approach not only contributes to the existing body of knowledge but also introduces new perspectives to the associated decision-making process.

The next section presents a review of extant literature on MCDM studies in assessing alternative fuels or energy sources for maritime shipping. Section 3 presents the data collection approach and methodology employed in this study. Section 4 reveals the ranking of the criteria for alternative energy deployment in Bangladesh context and priority of considered alternatives. Section 5 discusses practical and scientific implications of the results. Section 6 concludes with a summary of the key findings and future research directions.

2. Literature review on multi-criteria decision-making in the context of alternative ship fuels

In order to develop a MCDM framework for the assessment of alternative energy sources for ship propulsion for sustainable maritime shipping in a developing country context, we need (1) assessment criteria, and (2) alternatives to be assessed. This study follows a systematic approach to the identification and selection of relevant criteria and alternatives. As such, we conducted a systematic literature search in the Scopus and Web of Science database (WOS) with the following Boolean expression:

(("alternative fuel*" OR "alternative energy") AND ("maritime" OR "shipping") AND ("Multi-criteria" OR "MCDM" OR "MCDA"))

The search revealed nine collective exhaustive records from Scopus and WOS databases. After manually screening the studies for relevance, six studies were found relevant. Two were removed for non-relevance, while one study was omitted for incomplete reporting of the data collection and analysis procedure. A summary of the studies is provided in Table 1.

Table 1: *Summary of relevant MCDM studies*

No	Study	Study context	Method	Criteria used	Alternatives used
1	Aspen & Sparrevik (2020)	Norwegian ferry crossings	SMAA, TOPSIS	GHG emissions, NOx emissions, Acquisition cost, Fuel access, Public acceptance	All-electric propulsion, Electric-LNG hybrid, Electric-LBG hybrid, Electric-Biodiesel hybrid
2	Inal & Deniz (2020)	Not reported	AHP	Safety, Emissions, Efficiency, Cost, Lifetime, Power Output, Fuel Type, Size	PEMFC, AFC, PAFC, D/O MCFC, LNG MCFC, D/O SOFC, LNG SOFC
3	Hansson et al. (2020)	Swedish maritime	AHP	Investment cost for propulsion, operational	Elec-NH3, NG-NH3, Elec-NH3

		stakeholders		cost, fuel price, acidification, climate change, health impact, available infrastructure, reliable supply of fuel, safety, upcoming legalization	FC, NG-NH3 FC, HVO, Elec-H2 FC, NG-H2 FC, Bio-MeOH, NG-MeOH, LBG, LNG
4	Hansson et al. (2019)	Swedish maritime stakeholders	AHP	Same as Hansson et al., (2020	HVO, Elec-H2 FC, NG-H2 FC, Bio-MeOH, NG-MeOH, LBG, LNG
5	Ren & Liang (2017)	Not reported	Fuzzy logarithmic least squares, fuzzy TOPSIS	CO2 emission reduction, NOx emission reduction, SOx emission reduction, PM emission reduction, capital cost, operational cost, technology maturity, reliability, capacity, comply with regulations, social acceptance	Methanol, LNG, Hydrogen
6	Ren & Lützen (2017)	Not reported	Fuzzy AHP	Technology maturity, reliability, storage efficiency, infrastructure, capital cost, bunker price, repair & maintenance cost, training cost and	Nuclear power, LNG, Wind power

	crew wage, SOx emission reduction, NOx emission reduction, GHG emission reduction, PM reduction, social acceptance, government support, safety	

2.1. Criteria for alternative energy assessment

For the assessment of alternative energy sources for ship propulsion in the Bangladeshi context, based on commonality among the reported criteria in Table 1, we selected nine criteria that have been used in multiple studies (see Table 2). C1–C3 cover the economic dimension, C4–C6 the technical dimension, and C7–C9 the environmental and social dimensions. A brief description of each criterion is presented in Table 2.

*Table 2**:** Selected assessment criteria*

No	Criterion	Description
C1	**Capital cost** (Aspen & Sparrevik, 2020; Hansson et al., 2019; Inal & Deniz, 2020; Ren & Liang, 2017)	Initial investment cost for the alternative propulsion technology engine and related on-board infrastructure such as fuel tanks, pipelines, sensors, alarm systems, etc. per installed engine capacity.
C2	**Operating cost** (Hansson et al., 2019; Ren & Liang, 2017)	Cost for training and education of crew on-board on alternative energy sources, increase in wages due to special skills requirements, and repair and maintenance cost of engine and related on-board infrastructures.

C3	**Alternative fuel/energy price** (Hansson et al., 2019; Ren & Lützen, 2017)	Market price of the alternative fuel or energy and price difference with traditional low sulfur fuels. The cost of most alternative energy sources is higher than regular heavy fuel oil per ton-mile, while the price is also influenced by the fuel's availability for a given demand.
C4	**Technical maturity** (Ren & Liang, 2017; Ren & Lützen, 2017)	The implementation level of the alternative energy technology in the shipping industry without faults as a result of cumulative learning curve effects.
C5	**Available infrastructure** (Hansson et al., 2019; Ren & Lützen, 2017)	The compatibility and availability of supporting facilities such as the distribution/bunkering network for alternative energy along the major maritime trade routes including major ports.
C6	**Safety** (Hansson et al., 2019; Inal & Deniz, 2020; Ren & Lützen, 2017)	Risks associated with the handling of the alternative energy on-board and at berth, such as risk of fire, explosions, and health damage to crews. This criterion also includes the magnitude of risks and impacts associated with potential ship incidents (collisions, technical malfunctions, etc.).
C7	**GHG emission reduction** (Aspen & Sparrevik, 2020; Ren & Lützen, 2017)	The potential of GHG emission reduction from alternative energy sources. GHG mainly includes CO_2, CH_4, and N_2O.
C8	**Compliance with regulations** (Hansson et al., 2019; Ren & Liang, 2017)	The degree of compliance with existing and anticipated new shipping emission regulations due to alternative energy use.
C9	**Public acceptance** (Aspen & Sparrevik, 2020; Ren & Liang, 2017)	The degree of acceptance of the alternative energy source by the general public and society at large. The public's perceived environmental and safety impacts of the energy sources is partly shaped by available

	information via official channels and social media.

2.2. Alternative energy sources for ship propulsion

Six alternative fuel and energy sources are evaluated in this study along with HFO as a benchmark (see Table 3). Based on the summary of reviewed studies in Table 1, alternative forms of energy are battery-electric, biofuels, and natural gas (Aspen & Sparrevik, 2020). Other types of alternative marine fuels that are being discussed for their suitability and viability include liquified natural gas (LNG), liquefied biogas (LBG), methanol derived from natural gas, renewable methanol, hydrotreated vegetable oil (HVO), ammonia and hydrogen (Hansson et al., 2019; Ren & Liang, 2017). While fuel alternatives like battery-electric power and biodiesel have the potential to reduce greenhouse gas emissions and improve environmental performance in the shipping industry, they also have some limitations that need to be addressed before they can become widely adopted in the shipping industry (Acar, & Dincer, 2020). These limitations include limited infrastructure and range for battery-powered vessels (Wang, & Wright, 2021) and feedstock availability, scalability, and high production costs for biodiesel (Liang, Xu, & Zhang, 2013)

Among the plethora of alternatives, electric propulsion for shipping has been shown to be preferred in the context of Norway (Aspen & Sparrevik, 2020), whereas renewable hydrogen is preferred in the Swedish context (Hansson et al., 2019). Diesel oil (Inal & Deniz, 2020) and hydrogen (Ren & Liang, 2017) are preferred in other contexts too. Therefore, it is evident that the choice of alternative marine energy sources is not constant, instead varying with regard to multiple external factors such as fuel availability, price differentials between fuel sources, operating cost structures of nationally flagged ships, and the maritime trade context in which the ships will be deployed.

Focusing on a developing country adds an additional layer to the extant literature, which typically focuses on mature economies with strongly developed shipping sectors. In the context of Bangladesh, the seven alternative fuel and energy sources are considered relevant for sustainable shipping considering a timeline of 10 years (Table 3). Electric propulsion has been excluded; unlike Norway, electric energy production in Bangladesh does not come from renewable sources and is largely dependent on coal and gas power plants. Nuclear propulsion is also not feasible in the Bangladesh context due to high capital cost requirements and public acceptance issues. The first nuclear power plant development project (currently under development) in Bangladesh has been criticized heavily by the general public as well as environmental activists. HVO, a form of biodiesel, was reported to be particularly relevant for the Swedish context (Hansson et al., 2019), and comparatively expensive (see Figure 7 in Appendix). Hence, this energy source was also excluded from the present study. Therefore, we considered LNG, ammonia, hydrogen, and methane. Furthermore, considering recent developments in wind propulsion technology, and its potential for emission reduction when used in combination with other propulsion technologies (Nyanya et al., 2021), the HFO–wind and LNG–wind hybrids are also assessed, in the Bangladeshi context. Wind-assisted ship propulsion solutions cover a wide array of technologies, i.e., large rigid sails (wingsails) or soft sails; hull sails; suction wings that create an upward lifting force similar to the wings on airplanes; small rigid sails on deck which can utilize both wind and solar energy; towing sky sails or kites; wind turbines installed on deck; or the installation of rotors which are vertical spinning cylinders utilizing the Magnus Effect for ship propulsion (Chou et al., 2021; Inal et al., 2022).

*Table 3**:** List of alternative energy sources evaluated*

No	Alternative energy	Description
A1	LNG	LNG production involves pretreatment and liquefaction of natural gas by lowering the temperature to minus 162 degrees Celsius (Ashrafi et al., 2022). There are 286 LNG ships in operation in the world as of May 2022,[2] most of which have dual-fuel capability.
A2	Ammonia	Blue ammonia production involves steam methane reforming, Haber-Bosch process and liquefaction of hydrogen (Ashrafi et al., 2022). Ammonia becomes liquid at a temperature of minus 33.6 degrees Celsius.
A3	Hydrogen	Blue hydrogen production involves steam methane (CH_4) reforming into CO_2 and hydrogen (H_2), followed by the

[2] Accessed from https://afi.dnv.com/Statistics?repId=1, on May 15, 2022.

		liquefaction of hydrogen by lowering the temperature to minus 253 degrees Celsius (Ashrafi et al., 2022). As blue hydrogen creates CO_2 during the reforming process, its environmental footprint is dependent on the presence of any carbon capture utilization and storage solutions (CCUS). An alternative is to opt for green hydrogen, which involves splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) through electrolysis using renewable electricity such as solar, wind or hydropower, followed by the liquefaction of the hydrogen (Notteboom & Haralambides, 2023).
A4	Methane	Methane production involves steam natural gas reforming (Brynolf et al., 2014).
A5	HFO	HFO production involves refining crude oil. The majority of the world's commercial shipping fleet sails on very low sulfur HFO (see Figure 5 in Appendix).
A6	LNG–wind hybrid	LNG–wind is a viable alternative as LNG ships are already sailing in the world's waters. Wind as a secondary energy source can be installed on existing vessels.
A7	HFO–wind hybrid	HFO–wind is a viable alternative as the Bangladesh fleet is mainly sailing on HFO and wind as a secondary energy source can be installed on existing vessels.

3. Data and methodology

This study utilizes two MCDM methods for assessing the alternatives fuel or energy prospects for the Bangladesh shipping industry. Such a hybrid approach by combining two MCDM methods for the evaluation of emission reduction in shipping is not new; see, for example, Ren and Lützen (2015). In the present study, the *Bayesian BWM* was used for estimating the weights of each of the nine criteria. The Bayesian BWM (Mohammadi and Rezaei, 2020) is an extension to the original BWM (Rezaei, 2015). In the original BWM inputs from experts are analysed separately, and then the outcome weights are usually combined using the arithmetic or geometric mean aggregation approach. This does not account for variations in individual expert inputs such as outliers. The Bayesian BWM provides a solution to this issue and offers aggregate weights using a propabilistic approach relying on the Bayesian estimation procedure. Futher, the Bayesian BWM introduced the credeal ranking that provides a confidence score on the preference of one criterion over another. This improves robustness of the estimated weights. For more detail on the Bayesian estimation procedure, we refer to Mohammadi and Rezaei (2020). In the second stage, the *PROMETHEE-GAIA* methodology was used for identifying the priority of the alternative energy sources based on the estimated weights from Bayesian BWM and the expert ratings on the perceived feasibility of each of the energy sources under each of the criteria.

3.1. Data collection

After developing the MCDM framework with the identified criteria and alternatives, we designed a best–worst method (BWM) survey for data collection based on expert input. The BWM survey is different from traditional Likert-scale surveys as well as other MCDM method surveys, e.g., Analytic Hierarchy Process (AHP). The survey question structure is explained in Steps 2 and 3 in Section 3.2. The authors contacted experts in Bangladesh with relevant backgrounds, particularly seafarers in navigation and engineering positions at ships, shipping company executives and managers, government representatives, and academics in the maritime field. The selection of the respondents was done carefully following a judemental smaling approach to ensure validity and reliability of the results. The survey was piloted to five potential respondents for validity before distributing to a larger pool of potential respondents. Data with inconsistent inputs were removed. The final outcomes were also discussed with several respondents and they validated the results.

Data were collected in the first two weeks of May 2022. The respondents were asked to consider the following three system boundaries when participating in the survey:

- Ships calling at Bangladeshi ports;
- Ships owned by Bangladeshi shipowners and companies;
- Ships for commercial merchant shipping only including container, bulk and tanker shipping.

Initially, 32 responses were received; four were deleted due to staring lining and three due to inconsistent response patterns. An overview of the 25 respondents is presented in Table 4.

Table 4: Overview of the respondents

Job Status/Affiliation	**Frequency**	**Percentage**
Academics	3	12.00 %
Government representatives	3	12.00 %
Seafarer – Engineering	6	24.00 %
Seafarer – Navigation	7	28.00 %
Ship designers, naval architects	1	4.00 %
Shipping company executives/managers	5	20.00 %
Years of experience	**Frequency**	**Percentage**
11–15 years	2	8.00 %
1–5 years	10	40.00 %
16–20 years	2	8.00 %
6–10 years	6	24.00 %
More than 20 years	5	20.00 %
Level of Education	**Frequency**	**Percentage**
Bachelor's degree/diploma/equivalent	8	32.00 %
Doctorate/PhD	1	4.00 %
Master's degree	16	64.00 %
Grand Total	**25**	**100.00 %**

3.2. Bayesian best–worst method for criteria assessment

The BWM was first proposed by Rezaei (2015). BWM uses a simplified pairwise comparison process compared to other MCDM studies such as analytic hierarchy process (AHP). Applications of BWM are evident in the maritime shipping context such as for evaluating environmental impacts of ship recycling processes (Soner et al., 2021), or for port governance model selection for the implementation of green port management (Munim et al., 2020), freight transportation modelling (Li et al. , 2020), logistics performance measurement (Rezaei et al., , 2018), and inland port selection (Liang et al., , 2021; Chowdhury & Munim, 2022). The MCDA has been found prevalent in the existing research and more importantly in the maritime research arena.

Later, the *Bayesian BWM* was introduced by Mohammadi and Rezaei (2020) for group decision-making utilizing probability theory. Application of Bayesian BWM is evident in risk assessment of autonomous shipping in the cyber physical space (Tusher et al., 2022). The Bayesian BWM for estimating the weights of assessment criteria can be employed in the following four steps.

STEP1. Identification of criteria

In any MCDM study, the first step is to identify the set of criteria, which is the same in Bayesian BWM. Based on a systematic literature review of MCDM studies on alternative fuel and energy assessment for shipping, nine criteria were identified (see earlier Table 2): (C1) capital cost, (C2) operational cost, (C3) alternative fuel/energy price, (C4) technical maturity, (C5) available infrastructure, (C6) safety, (C7) GHG emission reduction, (C8) compliance with regulations, and (C9) public acceptance. An MCDM framework by combining the nine criteria with the seven alternatives of Table 3 is proposed in Figure 1. The set of criteria can be expressed as in Eq (1):

$$C = \{C_1, C_2, C_3, \ldots, C_9\} \qquad \text{Eq (1)}$$

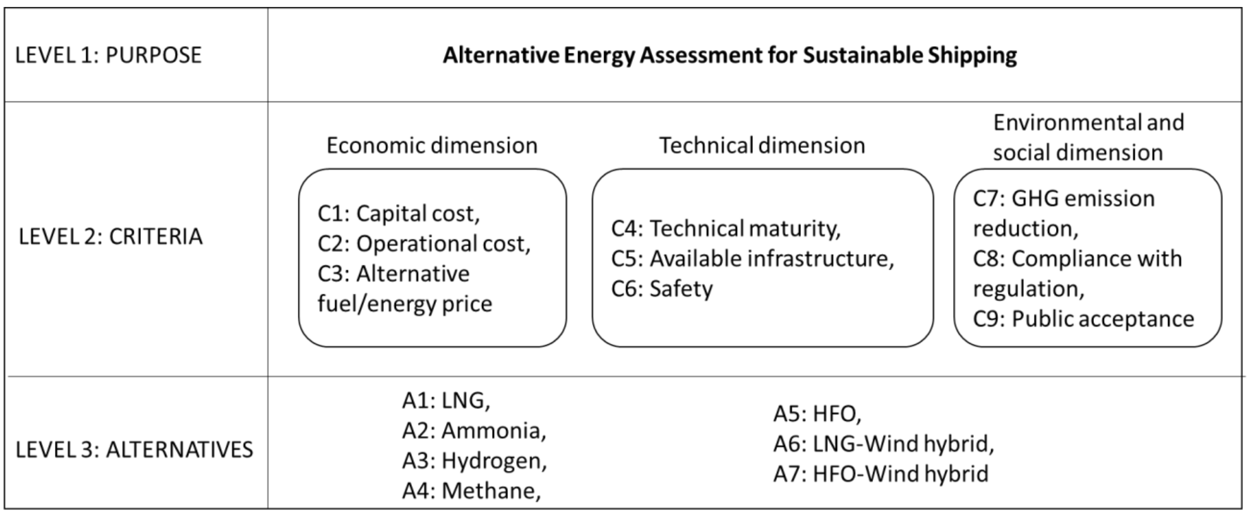


*Figure 1***:** *MCDM framework for alternative energy assessment*

STEP2. Formation of Best-to-others vector

Once the set of criteria is finalized, the second step in Bayesian BWM is to identify the 'most important' or the 'best' criterion, and then compare it with the rest of the criteria. This forms the best-to-others (BO) vector, which is one of the inputs in the weight estimation procedure of the criteria. The BO vector can be expressed mathematically as in Eq (2):

$$BO = (x_{B1}, x_{B2}, x_{B3}, \ldots, x_{Bn}) \qquad \text{Eq (2)}$$

Here, x_{Bj} refers to the preference of the best criterion C_B over the criterion $C_j \in C$.

STEP3. Formation of others-to-worst vector

The third step is to identify the 'least important' or the 'worst' criterion, and then compare the rest of the criteria with it. This forms the others-to-worst (OW) vector, which is another input in the weight estimation procedure of the criteria. The OW vector can be expressed mathematically as in Eq (3):

$$OW = (x_{1W}, x_{2W}, x_{3W}, \ldots, x_{nW}) \qquad \text{Eq (3)}$$

Here, x_{jW} refers to the preference of the criterion $C_j \in C$ over the worst criterion C_W.

STEP4. Estimate the criteria weights for each respondent

In Bayesian BWM, after deriving the BO and OW vectors as inputs, the weights of the criteria can be estimated. According to Mohammadi and Rezaei (2020), the nine criteria under assessment can be considered as random events, and their weights will be the likelihood the event occurring. Hence, the probability mass function (PMF) of the OW can be expressed as a multinomial distribution as in Eq (4):

$$P(OW|w) = \frac{(\sum_{j=1}^{n} x_{jW})!}{\prod_{j=1}^{n} x_{jW}\,!} \prod_{j=1}^{n} w_j^{x_{jW}} \qquad \text{Eq (4)}$$

Here, w the probability distribution.

Since the OW vector indicates preference of other criteria over the worst criterion, and BO indicates preference of the best criterion over others, the weights of BO can be expressed as in Eq (5):

$$BO \sim multinomial\ (1/w) \qquad \text{Eq (5)}$$

Due to the sum-to-one and non-negativity properties of MCDM weights, the weight vector can be estimated using a Dirichlet distribution, as expressed in Eq (6):

$$Dir(w|\alpha) = \frac{1}{B(\alpha)} \prod_{j=1}^{n} w_j^{\alpha_j - 1} \qquad \text{Eq (6)}$$

Here, the Dirichlet distribution has the parameter $\alpha \in R^n$.

For aggregate weight estimation for all expert inputs in BWM, the aggregate weight (w^{agg}) and individual expert weight ($w^{1:k}$) can be estimated given the best-to-other vector ($BO^{1:k}$) and other-to-worst vector ($OW^{1:k}$) for all experts $\forall k = 1,2,3,\ldots,K$. Eq (7) expresses the joint probability distribution.

$$P(w^{agg}, w^{1:k} \mid BO^{1:k}, OW^{1:k}) \qquad \text{Eq (7)}$$

Given the aggregate weight (w^{agg}), an individual expert weight (w^{k}) must be within its bounds. Thus, w^{k} given w^{agg} will be Eq (8).

$$w^{k}|w^{agg} \sim Dir(\gamma * w^{agg}), \forall k = 1,2,3,\ldots,K. \qquad \text{Eq (8)}$$

Here, γ follows a $gamma$ (0.1,0.1) distribution parameter.

3.3. PROMETHEE-GAIA for alternative fuels assessment

The preference ranking organisation method for enrichment evaluations (PROMETHEE) is a well-known MCDM method developed in the 1980s for decision making analysis (Brans and Vincke, 1985; Brans, Vincke and Mareschal, 1986). Later, PROMETHEE-GAIA methodology was developed by Mareschal and Brans (1988). The study adopts PROMETHEE I, II, and GAIA separately to analyze and graphically represent the results utilizing the Bayesian BWM weights of the criteria as derived earlier. The PROMETHEE method has widespread application in the analysis of shipboard machinery systems (Animah & Shafiee, 2021), dry port research (Komchornrit, 2017; Chowdhury & Munim, 2022), logistics provider selection (Chen et al., 2010), and renewable energy sources (Andreopoulou et al. , 2018).

In this process, each alternative (n) is compared with the remaining alternatives (n-1) in A. A is a set of seven possible alternative fuels and energy sources (A1, A2, A3….A7). PROMETHEE I considers both the leaving flow $\phi^{+}(a)$ *(see Eq. (9))* and entering flow $\phi^{-}(a)$ *(see Eq. (10))*, while PROMETHEE II takes the net flow $\phi(a)$ into account *(see Eq. (14)).*

$$\phi^{+}(a) = \frac{1}{n-1}\sum\pi(a,x) \qquad x \in A \qquad \text{Eq (9)}$$

Here $\phi^+(a)$, measures how an individual alternative "a" outranks the rest of the alternatives. The higher value of $\phi^+(a)$ indicates a better position of alternative "a". Conversely, $\phi^-(a)$ measures how a specific alternative "a" is outranked by the other alternatives. The lower value of $\phi^-(a)$ indicates a better position of alternative "a" than the rest of the alternatives.

$$\phi^-(a) = \frac{1}{n-1}\sum\pi(x, a) \qquad x \in A \qquad \text{Eq (10)}$$

3. 3. 1. PROMETHEE I: Partial Ranking

Based on the $\phi^+(a)$ and $\phi^-(a)$, PROMETHEE I computes the partial ranking (P^I, I^I, R^I), where P^I indicates preference, I^I indicates indifference, R^I indicates incomparability between two alternatives.

$$aP^Ib \quad \text{if} \quad \left\{\begin{matrix} \phi^+(a) > \phi^+(b) \ and \ \phi^-(a) < \phi^-(b), \\ or \\ \phi^+(a) = \phi^+(b) \ and \ \phi^-(a) < \phi^-(b), \\ or \\ \phi^+(a) > \phi^+(b) \ and \ \phi^-(a) = \phi^-(b) \end{matrix}\right\} \qquad \text{Eq (11)}$$

Considering aP^Ib, a higher power of alternative "a" is associated with a lower weakness of alternative "b" as shown in *Eq (11)*. The scenario explains that the information on both outranking and outranked flows is consistent and may be considered as *sure*.

$$aI^Ib \quad \text{if} \quad \{\phi^+(a) = \phi^+(b) \ and \ \phi^-(a) = \phi^-(b)\} \qquad \text{Eq (12)}$$

In the scenario of aI^Ib, both leaving and entering flows are *equal* as shown in *Eq (12)*.

$$aR^Ib \quad \text{if} \quad \left\{\begin{matrix} \phi^+(a) > \phi^+(b) \ and \ \phi^-(a) > \phi^-(b), \\ or \\ \phi^+(a) < \phi^+(b) \ and \ \phi^-(a) < \phi^-(b) \end{matrix}\right\} \qquad \text{Eq (13)}$$

Since a higher power of one alternative is associated with a lower weakness of the other, the conditions as expressed in *Eq (13)* appears as inconsistent. Therefore, in aR^Ib, alternatives remain incomparable and the process cannot determine which of the alternatives is better.

3. 3. 2. PROMETHEE II: Complete Ranking:

PROMETHEE II consists of the (P^{II}, I^{II}) complete ranking. It can be derived by analyzing the net flow and can be expressed mathematically as *Eq (14)*.

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \qquad \text{Eq (14)}$$

It creates a balance between the leaving and entering flows as shown in *Eq (15)*. A higher score of net flow indicates a better position of the alternative.

$$aP^{II}b \;\; if \begin{Bmatrix} \phi(a) > \phi(b), \\ or \\ \phi(a) = \phi(b) \end{Bmatrix} \qquad \text{Eq (15)}$$

Unlike PROMETHEE I, PROMETHEE II makes it possible to compare all the alternatives. Therefore, Brans and De Smet (2016) strongly suggested the application of both PROMETHEE I and II. Though the complete ranking is easy to use, assessing the potential of incomparability among alternatives often enhances the quality of decision-making.

3. 3. 3. Geometrical Analysis for Interactive Assistance (GAIA)

The GAIA visual modeling approach is based on the PROMETHEE principles (Mareschal and Brans, 1988). The method assumes that each alternative is not characterized by criteria values, rather by the vector of mono-criteria flows $S_i(a_r)$, $i=1,2,...,k$, explained in Eq (16).

$$S_i(a_r) = \frac{1}{p-1}\sum_{s=1}^{P}[p_i(a_r, a_s) - p_i(a_s, a_r)] \qquad \text{Eq (16)}$$

Therefore, each alternative can be represented in a *k*-dimensional vector space by an q_r vector *as follows:*

$$q_r = [(S_1\ (a_r), S_2(r), \dots \dots \dots ..., S_k(a_r)] \qquad \text{Eq (17)}$$

The criteria representation in GAIA requires a multi-dimensional space since the number of criteria (k) is often higher than two. Based on the mathematical formulation, the model for selecting alternative fuels and energy sources in this study was processed using Visual PROMETHEE Academic Edition software-version 1.4.0.0.

4. Results

4.1. Weights of criteria

The aggregate weights of the nine criteria based on the inputs from the 25 experts were estimated using the MATLAB software[3]. Mohammadi and Rezaei (2020) also proposed a credal ranking of criteria in Bayesian BWM. Traditionally, MCDM methods provide ranking of criteria based on weights of criteria. In addition to that, credal ranking provides the relative importance of each criterion over others. Figure 1 presents the credal ranking of the assessed nine criteria. (C1) Capital cost (weight: 0.1308) is the most important criterion for alternative fuel and energy source implementation in the Bangladeshi shipping industry. (C3) Alternative fuel/energy price (weight: 0.1222) and (C6) safety (weight: 0.1179) are the second and third most important criteria. The least important criterion is (C9) public acceptance (weight: 0.0779).

The values on the directed links in Figure 2 indicate the credal ranking of the criteria. Following Mohammadi and Rezaei (2020), credal ranking values can be considered as confidence scores. For example, we can interpret with a 0.73 confidence that (C1) capital cost is more important than (C3) alternative fuel/energy price, while we can interpret with a 0.82 confidence that (C1) capital cost is more important than (C6) safety. The estimated weight values and credal ranking of the criteria are reported in Table 5.

Table 5: Ranking of criteria based on estimated weights

Weights of criteria									
Criteria	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)
Weights	0.1308	0.1172	0.1222	0.1057	0.1047	0.1179	0.1061	0.1175	0.0779
Credal ranking of criteria									
Criteria	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)

[3] See https://github.com/Majeed7/BayesianBWM, accessed on June 25, 2022.

(C1)	0.000	0.834	0.730	0.971	0.974	0.821	0.966	0.829	1.000
(C2)	0.166	0.000	0.359	0.816	0.839	0.481	0.816	0.495	1.000
(C3)	0.270	0.641	0.000	0.900	0.913	0.627	0.891	0.641	1.000
(C4)	0.029	0.184	0.100	0.000	0.535	0.175	0.491	0.178	0.996
(C5)	0.026	0.161	0.087	0.465	0.000	0.154	0.459	0.155	0.994
(C6)	0.179	0.519	0.373	0.826	0.846	0.000	0.823	0.512	1.000
(C7)	0.034	0.184	0.109	0.509	0.541	0.177	0.000	0.180	0.997
(C8)	0.171	0.505	0.359	0.822	0.845	0.488	0.821	0.000	1.000
(C9)	0.000	0.000	0.000	0.004	0.006	0.000	0.004	0.000	0.000

[(C1) capital cost, (C2) operational cost, (C3) alternative fuel/energy price, (C4) technical maturity, (C5) available infrastructure, (C6) safety, (C7) GHG emission reduction, (C8) compliance with regulations, and (C9) public acceptance]

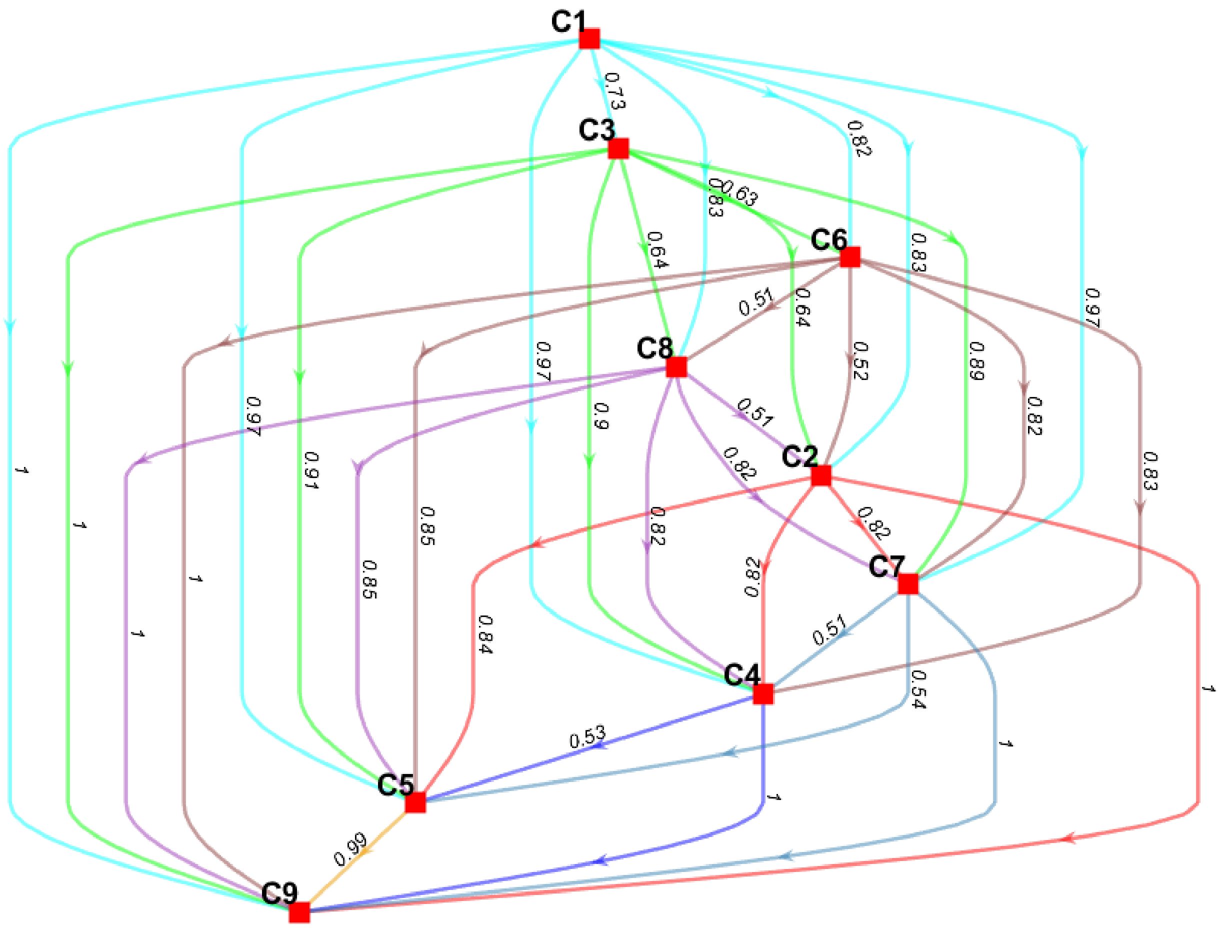


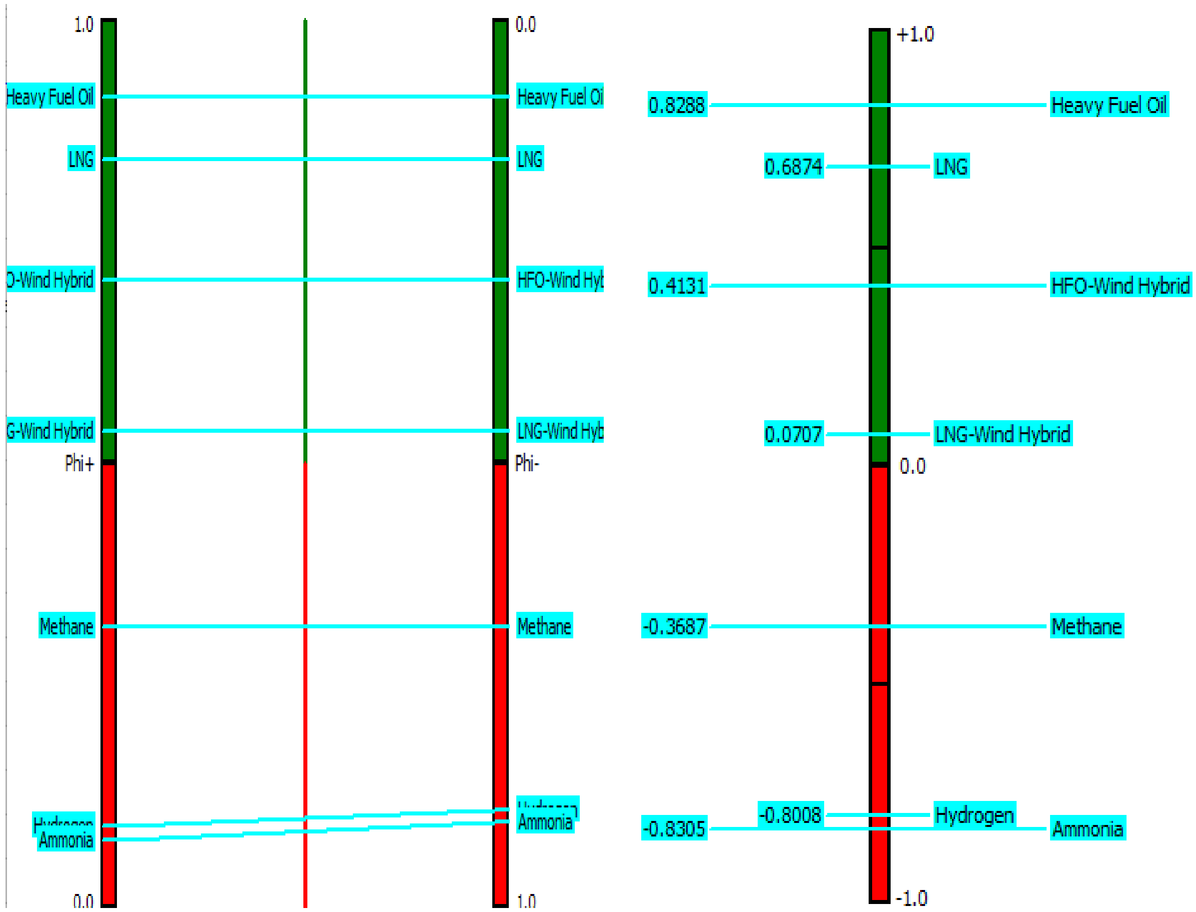
Figure 2: Credal ranking of criteria

[(C1) capital cost, (C2) operational cost, (C3) alternative fuel/energy price, (C4) technical maturity, (C5) available infrastructure, (C6) safety, (C7) GHG emission reduction, (C8) compliance with regulations, and (C9) public acceptance]

4.2. Preference ranking of alternative fuels and energy sources

To identify the preference ranking of alternative energy for the shipping industry in Bangladesh, PROMETHEE I and II were operationalized utilizing the weights of alternative energy selection decision criteria from Table 5. PROMETHEE I is graphically represented by two columns where the left column corresponds to the $\phi^+(a)$, phi (+ve) scores; and the right column corresponds to the $\phi^-(a)$, phi (-ve) scores (see Figure 3; a) representing the leaving flow and entering flow for the ranking of preferred alternative energy sources respectively. The horizontal connecting lines between the two columns represent the position of an individual alternative in the leaving flow and the entering flow. Intersecting horizontal lines represent incomparable alternatives in the partial ranking (i.e., PROMETHEE I).

Few of the alternative energy sources, i.e., heavy fuel oil (HFO), LNG, HFO–wind hybrid and LNG–wind hybrid occupy the upper positions (i.e., *positive phi*) in PROMETHEE I (see Figure 3; a), indicating an ascending preference order over all the other alternatives. On the other hand, methane, hydrogen, and ammonia occupy *negative phi* positions in PROMETHEE I, indicating a descending less preferred options over the other alternatives. No horizontal lines intersect with each other, therefore, the preferential ranking among alternatives can be done without any limitation. PROMETHEE II presents the complete ranking of the alternatives. The results suggest that HFO (0.8288) is the most preferred alternative energy source for the Bangladeshi shipping industry, followed by LNG (0.6874), HFO–wind hybrid (0.4131) and LNG–wind hybrid (0.0707). Methane (-0.3687), hydrogen (-0.8008), and ammonia (-0.8305) have *negative phi* scores, representing the least preferred sources of energy for ship propulsion (see Figure 3; b).



(a) PROMETHEE I: Partial Ranking (b) PROMETHEE II: Complete Ranking

Figure 3: Preference ranking of alternative fuels

Figure 4: GAIA plane of alternative energy and decision criteria

Figure 4 presents the GAIA plane, visually representing the effects of the change in criteria weights. The figure indicates the preference of alternative energy sources based on a range of corresponding criteria. The results depict that the preference of LNG and LNG–wind hybrid correlates with the stronger emphasis on GHG emission reduction, public acceptance, and compliance with regulations. In addition, capital and operational cost, safety, available infrastructure and fuel price also have control over the preference of LNG and LNG–wind hybrid as alternative energy sources. However, changing the weights of any of the decision criteria does not result in a clear preference for energy alternatives hydrogen, methane, and ammonia. The overall ranking of alternative energy sources and the ranking of factors influencing the selection have been presented in Figure 5.

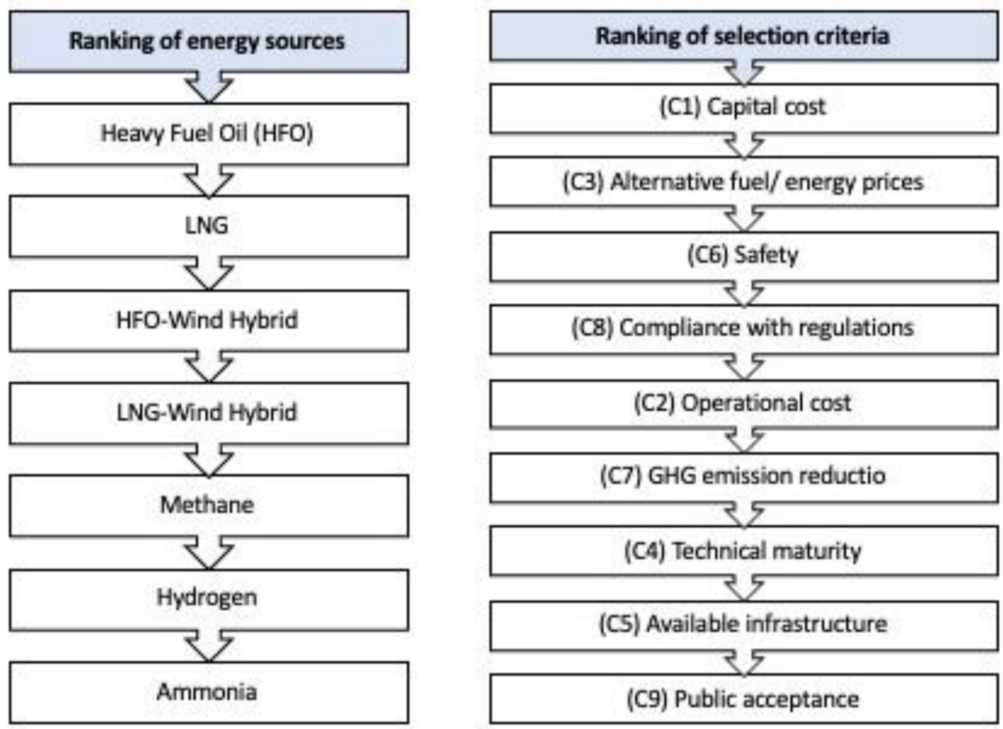


Figure 5: Summary of rankings

5. Discussion

5.1. Contribution to literature

This study contributes to the academic literature in several ways. First, we assessed alternative fuel and energy sources for future sustainable shipping in the context of a developing country, i.e., Bangladesh. Considering focus of earlier studies related to the selection of alternative energy sources for shipping (Aspen & Sparrevik, 2020; Hansson et al., 2019), the context of the current study matters as it can differ significantly between countries and regions. For instance, fully battery-electric propulsion can be viable as a sustainable solution in the Norwegian context, as almost 100 percent of the electricity of the country is produced from renewable sources. Moreover, the coastal topology of Norway and its strong reliance on maritime links with mainland Europe and the Baltic imply many short-distance shipping routes populated with smaller vessels. The combination of short shipping distances and small vessel scale make battery-electric propulsion a more obvious and viable option. On the contrary, fully electric propulsion cannot be a viable alternative in countries where the majority of the electricity is produced from coal or gas power plants. From this perspective, the present study presents a novel framework for assessing alternative fuel and energy sources for shipping in a developing country with protectionist regulatory regimes.

Second, nine criteria were identified based on a systematic literature review approach. The three most important criteria, in order of importance, are capital cost, alternative fuel/energy price, and safety. These three factors were most emphasized in the literature as well. The three least important factors are technical maturity, available infrastructure, and public acceptance. Future MCDM or LCA studies, particularly those using estimated real data instead of survey-based scores, should allocate lower weights to these three criteria.

Third, in the proposed MCDM framework, HFO–wind and LNG–wind hybrids are considered as prospective alternative fuel and energy sources. Previous MCDM based studies have not considered hybrid models in their assessment. Although HFO is still most preferred by the industry professionals of Bangladesh, LNG is the second most preferred alternative. HFO–wind and LNG–wind hybrids are ranked third and fourth, demonstrating significant potential. The results conform with Contarinis et al. (2020) and *Energy Technology Perspectives* (2020) suggesting the preference of LNG as a future alternative to traditional fossil fuels like oil and coal. It is a cleaner-burning fuel that produces fewer emissions than the other fuels, making it an attractive option for reducing greenhouse gas emissions from shipping. Furthermore, the study also conforms with literature exhibiting the feasibility of LNG-Wind Hybrid and HFO-Wind Hybrid as alternative energy in shipping. Ina et al. (2022) and Ammar & Seddiek (2022) suggest that HFO-wind hybrids and LNG-wind hybrids have the potential to significantly reduce fuel consumption and emissions in the shipping industry while being economically feasible at the same time. Further, our findings contribute to the literature by providing perceptual evidence that hydrogen, ammonia, and methane *may not be viable* in a developing country like Bangladesh, despite the strong focus on these renewables in developed country contexts.

Finally, from the methodological perspective, this study presents a novel application of two MCDM methods. The use of Bayesian BWM method for criteria weight estimation is likely to overcome aggregation bias in MCDM studies as it estimates aggregate weights for the expert groups relaying on probability theory. The PROMETHEE-GAIA method was used for priority estimation of the seven alternatives for energy sources. PROMETHEE-GAIA not only provides the priority of the alternatives, but also shows how priorities can vary with varying weights of criteria. For instance, HFO and HFO–wind hybrid are most preferred when experts emphasize safety, capital cost, available infrastructure, and alternative fuel/energy price. However, when the emphasis shifts to GHG emission reduction, public acceptance, and compliance with regulations, LNG and LNG–wind hybrid become the most preferred alternatives.

5.2. Implications for industry

The study also has relevance for business practitioners and policymakers. One of the key implications for the industry is that the shipping companies in Bangladesh, as well as in other developing nations with similar resource and regulatory contexts, could potentially utilize the proposed MCDM framework for assessing their preference of and support for alternative energy sources. The sustainability of alternative energy sources for shipping depends largely on their long-term feasibility as well as their potential positive implication in the industry. The bottleneck in the supply and distribution of alternative energy sources could be affected by the lack of terminal capacity as well as their carrier fleet insufficiency. For example, China's domestic fleet is only capable of meeting 49 percent of its LNG demands (Yin & Lam, 2022). Therefore, merely adopting a specific type of energy source would not prove feasible if the entire supply chain is not sure to be sustainable in the long-term.

Both HFO–hybrid and LNG–hybrid have been viewed as alternatives followed by pure HFO and LNG in the context of Bangladesh. However, the maturity of the hybrid options is a far stretch since they are both price-sensitive to implement, and the lack of verified and objective data makes it hard to predict their desired outcomes (Rojon & Dieperink, 2014). On the other hand, these wind-hybrid options were contemplated for fuel savings up to 35 percent (Ballini et al., 2017), as well as the lowest GHG emitter alternatives compared to the other liquid renewable fuels (Köhler, 2019).

In addition, the long-term sustainability depends on a sustainable production capability of a specific alternative energy source. For example, green hydrogen produced through water electrolysis using green power in principle yields more environmental sustainability than blue hydrogen production (Chen & Lam, 2022; Notteboom & Haralambides, 2023). On the other hand, dual fuel engines where both LNG and conventional types of fuel can be used are proposed as cost-effective solutions for newbuilds considering the future uncertainty around fuel prices, availability of fuels and bunkering facilities, and price differentials between energy sources (Abadie & Goicoechea, 2019). A major challenge in ranking these energy alternatives is the lack of in-situ consumption data for specific energy sources, along with their process-components, which make a significant contribution in the overall emission estimates (Merien-Paul et al., 2019). Nowadays, state-of-the-art energy efficiency models are employed for simulation, optimization and emission prediction of specific fuel types taking into account the data from the ship as well as from the environment (Fan et al., 2022). Such energy efficiency models could be improved by incorporating insights from detailed analyses of decision-making processes, like the one conducted in this study.

The potential contributions of this study are summarized in Table 6.

Table 6: Summary of contribution and implication of results

Contribution to literature	**Implication in the industry**
Charting out a systematic procedure for assessing alternative energy sources for shipping in the context of a developing nation.	Proposing a novel MCDM approach for stakeholders to ensure energy security by adopting a balanced mix of energy sources that have long-term feasibility.
Highlighting the similarity of expert views of developing countries with the others about the most important factors influencing the use of alternative fuels.	Providing an opportunity to evaluate expert opinion with respect to practical implementation challenges associated with utilizing (hybrid) energy sources.
Featuring the potential of hybrid energy sources (e.g., HFO-wind, LNG-wind) while demonstrating the incompatibility for hydrogen, ammonia and methane as energy sources for shipping in developing nations.	Highlighting the scarcity of comprehensive data related to fuel processing and emission and subsequent lack of opportunity to make informed decisions in the maritime industry.

Proposing a novel hybrid MCDM framework combining BWM & PROMETHEE-GAIA methods that features unique advantages such as criteria-sensitive ranking along with an opportunity to manipulate priorities and see results.	

6. Conclusion

This study explored the perspective of Bangladeshi maritime professionals on their choices of alternative fuel and energy sources for future shipping development. A hybrid MCDM approach was utilized to rank the choices based on several criteria considering environmental, technical, regulatory, economic, and safety aspects. The results largely conform with the emerging trends of sustainable alternative energy choices for the shipping industry. For example, similar to the results of Hansson et al. (2019), this study also found HFO and LNG as the most preferred energy sources for future shipping in the Bangladeshi context. In addition, the underlying factors affecting the choice of alternative energy sources in the present study correspond with previous analyses related to economic, regulatory, and safety facets (Hansson et al., 2019; Ren & Liang, 2017). Although this study centers on a particular context, its findings and contributions hold significance beyond the context of the study and may corroborate worldwide endeavors to promote sustainability in shipping. Furthermore, the perceptions and attitudes of key stakeholders in the maritime industry towards the adoption of alternative energy sources has been addressed in the study. Hence the study advances insights in the transition to alternative energy sources in the global shipping industry.

Future studies are expected to investigate alternatives fuel and energy prospects in other developing country contexts using the proposed MCDM framework. Comparative studies with other contexts can reveal the true prospects of alternative energy sources for sustainable shipping. The use of real data for each alternative under the set of criteria, when available in the future, should be considered as well. In the context of Bangladesh, future studies need to examine which policy changes are required to implement viable alternative energy sources in the industry.

Appendix

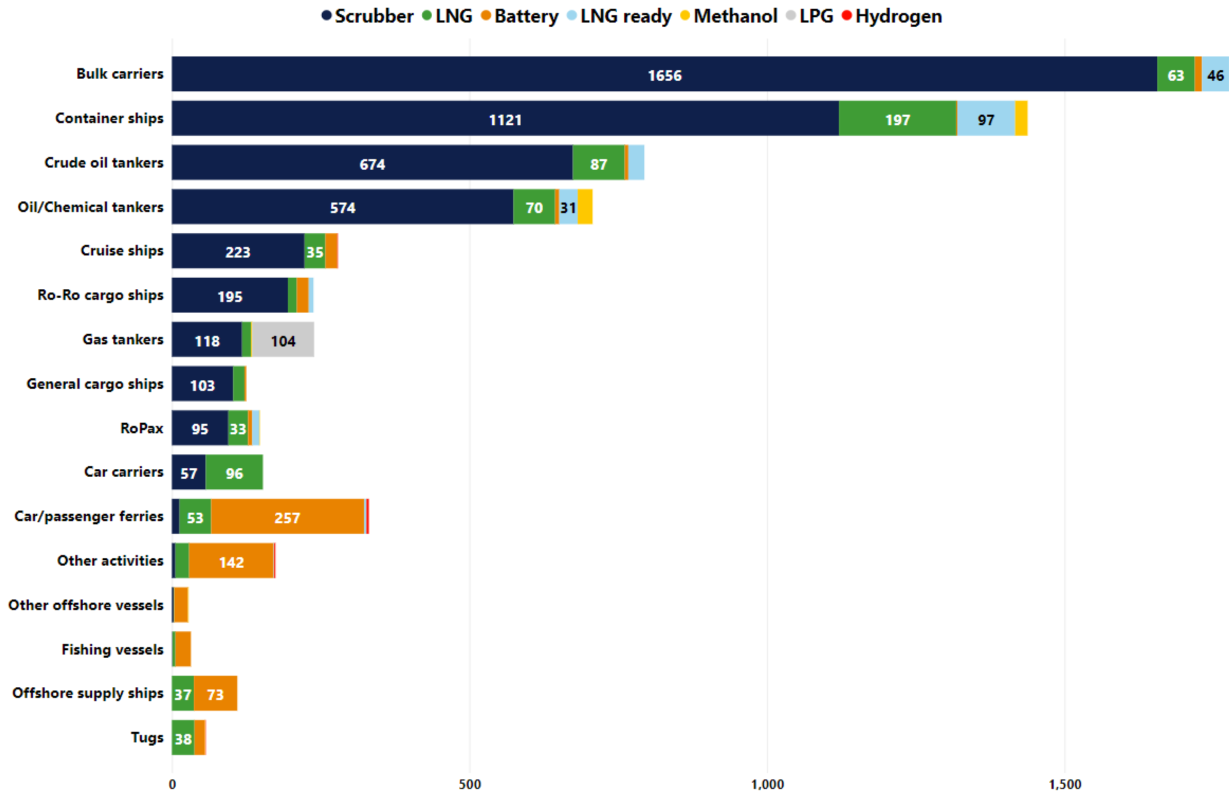


Figure 6: Number of ships on alternative fuel and energy in operation and on order

(Source: https://afi.dnv.com/Statistics?repId=0)

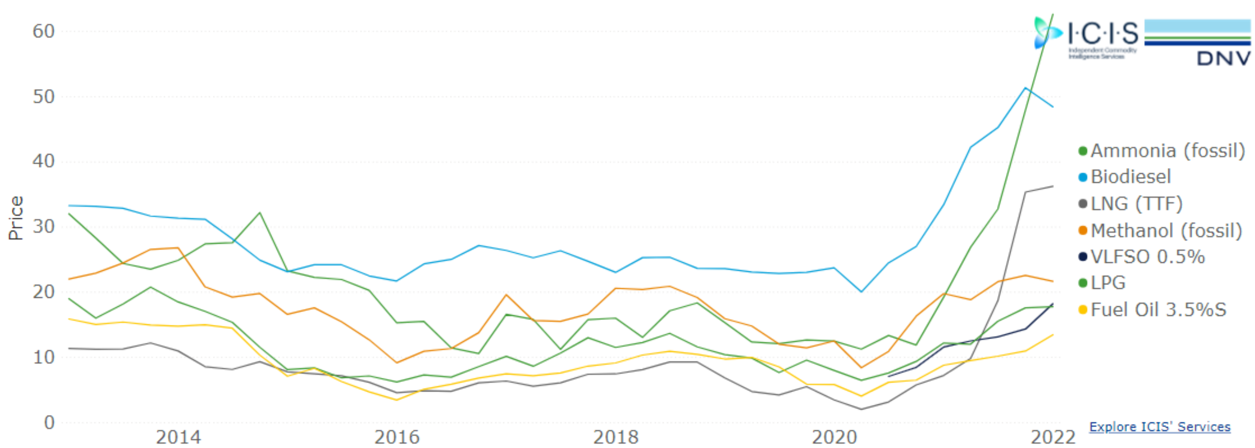


Figure 7: Alternative fuel prices

(Source: https://afi.dnv.com/Statistics?repId=4)

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