Sustainable maritime energy management: optimizing decision-making for marine fuels and renewable energy integration

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ABSTRACT

Marine fuels and renewable energy sources are critical in lowering carbon emissions and encouraging sustainable maritime practices. Their implementation promotes a more environmentally friendly and cleaner future for marine transportation. Effective decision-making is critical in the context of marine fuels and green energy for attaining sustainable energy management and progressing towards a greener and more ecologically friendly future. This research article emphasizes the importance of thoroughly assessing various energy options and their potential impacts on the atmosphere, economy, and society. It acknowledges the significance of incorporating renewable energy bases, energy efficiency processes, and greenhouse gas emission reductions into decision-making processes. This article presents optimal decision-making methodologies to meet the complexity of decision-making in this domain, which contains uncertainty and trade-offs. It investigates diverse decision-making frameworks, approaches for uncertainty analysis, and techniques for multi-objective optimization, stakeholder engagement strategies, and policy development concerns in sustainable energy management. Case studies from the real world are investigated to discover both effective and bad decision-making practices. These evaluations produce valuable insights for policymakers, energy managers, as well as stakeholders, allowing them to make successful decisions. We can expedite the adoption of clean energy solutions, reduce dependency on fossil fuels, alleviate the impacts of climate change as well as support the creation of a sustainable as well as strong energy system for present and future generations by incorporating the findings into decision-making processes.

Subjects Data Science, Databases, Emerging Technologies
Keywords Sustainable energy management, Marine fuels, Decision-making, Uncertainties, Trade-offs, Multi-objective optimization

INTRODUCTION

Improving sustainable energy management in regard to the use of marine fuels and green energy becomes ever more important as the world aims for a low-carbon, ecologically friendly future. The maritime sector, being heavily reliant on on conventional fossil fuels, plays a major role in generating greenhouse gas emissions and contributing to atmospheric pollution. Recognising the critical need for minimising the adverse environmental effects of maritime operations, an increasing emphasis is being placed on sustainable energy management practises that encourage the use of cleaner and more environmentally

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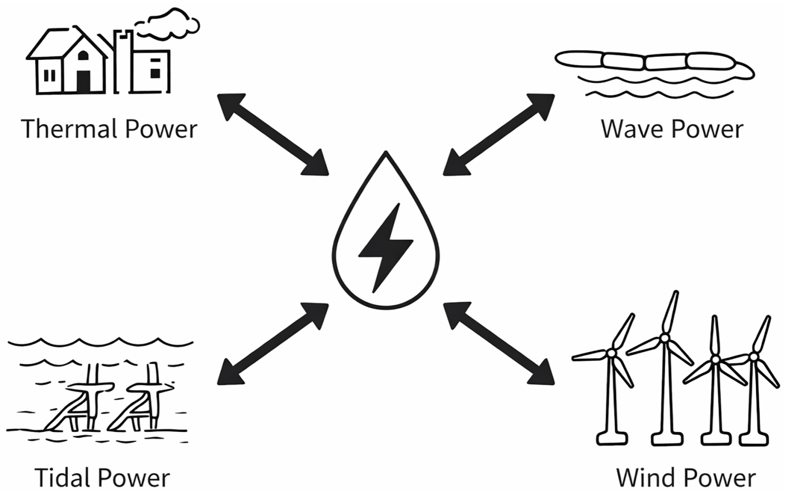

Figure 1 **Various types of Marine Renewable Energy (MRE) technologies.**
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friendly sources of energy. Because of their high carbon content and negative environmental implications, marine fuels, which have traditionally been dominated by heavy fuel oils and marine diesel oils, are being reviewed. As a result, the quest for alternative fuels and motor systems that reduces greenhouse gas emissions while also improving air quality has gained traction. Liquefied natural gas (LNG), bio-fuels, hydrogen, energy cells as well as electric propulsion are being investigated as possible alternatives for powering maritime vessels (*Kesieme et al., 2019*; *Livaniou & Papadopoulos, 2022*; *Elgohary, Seddiek & Salem, 2015*; *Al-Enazi et al., 2021*).

Optimising sustainable energy management in marine fuels and green energy necessitates thorough decision-making procedures that take into account a wide range of criteria. Environmental sustainability, economic viability, technological feasibility, and societal acceptance are among these factors. These issues must be balanced in order for energy management systems to be effective, efficient, and socially responsible. Furthermore, the topic of sustainable energy management is fraught with difficulties and uncertainties. Uncertainties are introduced into decision-making processes by technological improvements, market dynamics, legislative changes, and diverse stakeholder interests. Furthermore, decision-makers must balance competing goals, such as reducing emissions while retaining cost-effectiveness and effectiveness in operation. Marine Renewable Energies (MRE) development presents an appealing potential influence to the intended renewable energy blend for countries having coastal and ocean area. MRE can be defined as machineries that produce energy from the oceanic *via* wind, wave action, tides, as well as temperature differences in seawater presented in Fig. 1 (*Taormina, 2019*).

Investigations have concentrated on establishing robust frameworks, analytical tools, as well as methodologies to solve these problems and support optimal decision-making in sustainable energy management. These techniques seek to give decision-makers with the information and insights they need to evaluate various energy options, measure uncertainties, weigh trade-offs, engage stakeholders, as well as design effective policies. Significant advantages can be realised by improving sustainable energy management in marine fuels and green energy. These benefits include the reduction of greenhouse gas emissions and air pollutants, enhancement of energy efficiency, strengthening of energy security as well as stimulation of sustainable economic development. Moreover, adopting cleaner energy alternatives within the maritime sector can serve as a driving force for broader sustainability initiatives, inspiring other industries to embrace environmentally responsible energy practices (*Rahman et al., 2017*; *Dincer, 2000*).

Sustainable energy capacity management is critical for combating climate change, guaranteeing energy security, and supporting socioeconomic growth. To achieve sustainable energy management, decisions must be made that balance environmental preservation, social well-being, and economic viability. However, decision-making in this field is complicated because to the uncertainties caused by new technology, market dynamics, governmental changes, and intrinsic trade-offs between competing objectives. To improve sustainable energy management, it is critical to develop optimal decision-making approaches that can address these uncertainties and trade-offs (*Lehtonen, 2004*; *Ansari, Pandey & Alenezi, 2022*; *Swart & Raes, 2015*; *Ansari et al., 2020*; *Moallemi et al., 2022*).

The purpose of this study article is to look into and offer optimal decision-making methodologies for sustainable energy management in the context of marine fuels and green energy. It investigates numerous aspects of decision-making, giving policymakers, energy managers, and stakeholders engaged with the energy transition with useful insights and practical recommendations. The study focuses on five main areas: decision-making frameworks, uncertainty analysis, multi-objective optimisation, stakeholder interaction, and policy considerations, all of which are important for establishing successful and sustainable decision-making practises.

To begin, decision-making frameworks provide an organized way for evaluating various options and making educated decisions. This study evaluates the strengths and limits of existing frameworks in sustainable energy management, emphasising the necessity for adaptive frameworks capable of absorbing uncertainties and embracing diverse objectives. Then, due to growing technologies, market dynamics, and regulatory changes, there are uncertainties in sustainable energy management. To assess and manage uncertainties, uncertainty analysis methodologies such as probabilistic modelling, scenario analysis, and sensitivity analysis are investigated. The study equips decision-makers with methods to assess the risks and opportunities associated with various courses of action. Furthermore, multi-objective optimisation approaches are required for dealing with trade-offs amongst sustainability variables for instance environmental impact, economic feasibility as well as social acceptance. Decision-makers can develop solutions that strike a balance between competing aims by optimising numerous objectives at the same time. To ease the identification of optimal solutions, the study investigates procedures such as multi-criteria decision analysis (MCDA), Pareto-based approaches as well as evolutionary algorithms.

Furthermore, stakeholder engagement is critical in making sustainable energy decisions. Involving a wide range of stakeholders promotes transparency, inclusivity, and legitimacy in decision-making processes (*Ansari et al., 2021*; *Few, Brown & Tompkins, 2007*; *Mathur, Price & Austin, 2008*). This study looks into tactics for effective stakeholder involvement and methods for incorporating stakeholder preferences and values into decision-making. Ultimately, in sustainable energy management, policy considerations and governance frameworks impact decision-making processes. The study examines the impact of policy tools, rules, and governance frameworks on decision consequences. It assesses the effectiveness of policy tools such as feed-in tariffs, carbon pricing mechanisms, and standards for energy efficiency for encouraging sustainable energy management practises.

The study article includes real-world case studies which offer concrete insights into decision-making issues and the consequences in sustainable energy management. The analysis of successful and poor decision-making procedures in these case studies can provide significant insights for future decision-making practises. This research article seeks to enhance optimal decision-making approaches for sustainable energy management. The study provides a basis for informed and effective decision-making processes by tackling uncertainties and trade-offs using robust decision-making frameworks, uncertainty analysis, multi-objective optimisation, stakeholder interaction, and policy considerations. The findings have the potential to assist policymakers, energy managers, and stakeholders in adopting sustainable energy management decisions that are aligned with environmental, social, and economic objectives, thereby aiding the transition to a more resilient and economically viable energy future.

For clarity and readability, the rest of this manuscript is structured into several key segments. "Related Works" delivers an extensive review of prior literature, highlighting existing knowledge and research progress related to sustainable energy management within maritime systems. "Materials and Methods" outlines the adopted research design. In this section, the assortment of evaluation criteria as well as the identification of decision alternatives is described, followed by an explanation of how the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach is applied to carry out the prioritization process. "Results" offerings the consequences of the empirical analysis where the six alternatives for sustainability-oriented energy management are assessed and comparatively ranked. "Discussion" provides a comprehensive discussion of the findings, offering interpretation of the results and reflecting on how they contribute to advancing sustainable energy practices in marine applications. The final section, "Conclusions", closes the article by briefing the significant insights gained, explaining broader policy and practical implications, and proposing directions for further scholarly work in sustainable maritime energy management.

RELATED WORKS

This research article's related work section thoroughly evaluates existing literature and studies pertinent to optimal decision-making methodologies for sustainable energy management. Its goal is to establish the present level of knowledge, identify research gaps, and emphasise the contributions and limits of prior field investigations. By expanding on previous work, this section establishes the backdrop for the proposed research and lays the groundwork for additional investigation.

Kurian (2017) emphasises the necessity of solid science in ensuring the water–energy–food (WEF) Nexus's efficient implementation. The article examines recent research on governance factors, normative and institutional components of the nexus approach, implementation, and tools to assist decision-makers in promoting sustainable development. *Namany, Al-Ansari & Govindan (2019)* employed several advanced analytical techniques including agent-based simulation, mathematical optimisation and game-theoretic modelling to study how decisions evolve across the WEF nexus. Their use of these computational models provides policy planners with strategic support, enabling them to identify resource management options that achieve desired objectives while simultaneously reducing ecological burdens.

Kanter et al. (2018) examine agricultural trade-off analysis in order to comprehend interactions as well as complexities from field to farm and region to continent. The report breaks down agricultural trade-off analysis into four parts and underlines the requirement for transdisciplinary approaches to accomplish sustainable intensification in agriculture and effectively implement the Sustainable Development Goals (SDGs). *Liu et al. (2018)* suggest a systematic strategy for more completely implementing nexus concepts, taking into account linkages across sectors, sizes, and regions. The article emphasises the significance of connecting the nexus approach to the SDGs and incorporating ignored drivers and areas to improve policy-making and governance for integrated SDG implementation.

Adshead et al. (2019) create indicators and a systems model to evaluate infrastructure-related targets for reaching the SDGs. The analysis highlights the ability of cross-sectoral infrastructure investments and policies to fulfil several SDG targets and emphasises the infrastructure system's interdependence. *Alghassab (2023)* provides a fuzzy TOPSIS-based framework for assessing and ranking sustainable energy transition alternatives. The proposed framework was applied to a real-world scenario in the Kingdom of Saudi Arabia, offering practitioners a robust decision-support mechanism that helps them navigate the challenges and ambiguities associated with energy transition, while also aligning decisions with broader sustainable development targets.

Bartke & Schwarze (2015) investigate sustainability concepts and methodologies for land-use decisions including greenfield development *vs* brownfield regeneration. The study compared stylized techniques with normative sustainability concepts and stakeholder requirements, emphasising the importance of prioritising the user requirements of decision-makers in sustainability assessment tools. *Hocine et al. (2018)* offer multi-segment fuzzy goal programming (MS-FGP) as an efficient way for making decisions under high uncertainty. The approach has been verified in the optimisation of the renewable energy portfolio for power generation in Italy, demonstrating potential in enabling sustainable renewable energy source portfolios under uncertain circumstances.

Hutton et al. (2018) examine the SDGs in coastal Bangladesh, looking for potential trade-offs between poverty alleviation, economic growth, environmental integrity, and fairness. To establish coherent and policy-relevant socio-ecological strategies, the study emphasises the significance of integrated models and co-developed decision frameworks including stakeholders. *Govindan & Al-Ansari (2019)* present a unique computational structure which integrates "algorithmic resilience thinking" in order to construct adaptive and robust interconnected systems. In a Qatari case study, the framework was applied to evaluate risks within the water–food nexus concerning outdoor agricultural activities, demonstrating its effectiveness in detecting and mitigating emerging threats across interconnected natural resource systems. Table 1 presents a comparative analysis of related works, highlighting the methodologies, contributions, and limitations of each study. The current research fills the identified gaps by applying the Fuzzy TOPSIS method to enhance decision-making in sustainable energy management.

In final analysis, these associated researches provide useful insights into improving sustainable energy management, overcoming uncertainties, and managing trade-offs in the setting of the WEF Nexus and the SDGs. They emphasise the need of solid knowledge, multidisciplinary strategies, and decision-making tools in reaching sustainable development goals as well as applying sustainable energy management practises. In this work the emphasis is placed on applying the Fuzzy TOPSIS technique to support decision-making in sustainable energy management. Although various studies have explored different decision models in this area, the application of Fuzzy TOPSIS specifically for evaluating sustainable energy alternatives remains relatively underexplored. By employing this method, the study aims to better address the inherent uncertainties, conflicting objectives, and complex evaluation challenges involved in selecting suitable sustainable energy strategies. This section presents a thorough examination of the existing literature, identifying the gaps as well as opportunities where the Fuzzy TOPSIS technique can help advance the area. Researchers hope that this study will help practitioners, policymakers, and scholars better understand and apply the Fuzzy TOPSIS method in policymaking for sustainable energy management.

MATERIALS AND METHODS

This section describes the systematic method for evaluating decision-making processes in sustainable energy management for marine fuels and green energy. In the beginning a process of identifying criteria and alternatives was done in order to build an extensive collection of elements affecting decision-making. To accurately reflect the various facets of sustainable energy management, criteria such as Effectiveness, Adaptability, Robustness, Stakeholder Engagement, and Decision Quality were carefully specified. Furthermore, a variety of alternatives have been discovered for presenting various approaches for sustainable energy management, including Probabilistic Modeling (PM), Scenario Analysis (SA), Pareto-based Approaches (PA), Multi-Criteria Decision Analysis (MCDA), Evolutionary Algorithms (EAs), and Policy Instruments and Regulations (PIR). The identified alternatives were then ranked and prioritised using the Fuzzy TOPSIS approach according to their applicability and efficacy. To deal with uncertainties and ambiguity in the decision-making process, which are frequent in actual circumstances, the Fuzzy TOPSIS process integrates fuzzy logic (*Tooranloo, Ayatollah & Iranpour, 2018*; *Alshahrani et al., 2022*; *Nourani & Najafi, 2023*; *Alassery et al., 2022*; *Agrawal, Khan & Ansari, 2022*; *Alharbi et al., 2022*; *Attaallah et al., 2023*). In order to determine how close each alternative is to the positive ideal solution, which represents the best efficiency, and the negative ideal

Table 1 **Comparative analysis of related works.**

Study	Focus	Methodology	Key findings/contributions	Limitations
Kurian (2017)	WEF Nexus implementation and governance factors	Literature review, normative and institutional analysis	Emphasizes the need for robust science and governance tools for sustainable development in the WEF Nexus.	Lacks specific decision-making frameworks for practical application.
Namany, Al-Ansari & Govindan (2019)	Dynamic decision-making within the WEF Nexus	Mathematical optimization, agent-based modeling, game theory	Provides strategic guides for policymakers to manage resources and minimize environmental impacts effectively.	Limited focus on specific decision-making methodologies and their practical implications.
Kanter et al. (2018)	Agricultural trade-offs and sustainable intensification	Trade-off analysis	Highlights the need for transdisciplinary approaches to achieve sustainable agriculture and implement SDGs effectively.	Focuses on agriculture; less emphasis on energy management.
Liu et al. (2018)	Implementing nexus concepts and integrating SDGs	Systematic strategy analysis	Stresses the importance of connecting nexus concepts with SDGs and incorporating neglected drivers for better policy-making.	May not fully address the complexities of sustainable energy management.
Adshead et al. (2019)	Infrastructure-related targets for SDGs	Systems modeling and indicator development	Demonstrates how cross-sectoral infrastructure investments can meet multiple SDG targets, emphasizing infrastructure interdependence.	Focuses on infrastructure rather than energy management.
Alghassab (2023)	Assessment and ranking of sustainable energy transition alternatives	Fuzzy TOPSIS-based framework	Provides a framework for evaluating and ranking energy transition options, applied in Saudi Arabia.	Limited scope of application and theoretical explanation in the context of broader sustainable energy management.
Bartke & Schwarze (2015)	Land-use decisions and sustainability concepts	Comparison of normative sustainability concepts and stakeholder requirements	Highlights the importance of considering user requirements in sustainability assessment tools for land-use decisions.	Primarily focused on land-use rather than energy management.
Hocine et al. (2018)	Multi-segment fuzzy goal programming for decision-making under uncertainty	MS-FGP (Multi-Segment Fuzzy Goal Programming)	Proposes an efficient method for optimizing renewable energy portfolios under high uncertainty, tested in Italy.	Application limited to renewable energy portfolios without broader context.
Hutton et al. (2018)	SDGs trade-offs in coastal Bangladesh	Integrated models and stakeholder decision frameworks	Focuses on trade-offs between poverty alleviation, economic growth, and environmental integrity, emphasizing integrated models.	Limited applicability to global energy management issues.
Govindan & Al-Ansari (2019)	Computational framework for algorithmic resilience thinking	Algorithmic resilience thinking framework	Introduces a framework for assessing risks and enhancing resilience in integrated natural resource systems, applied in Qatar.	Mainly focuses on water-food nexus, not specifically on energy management.
Current research work	Fuzzy TOPSIS method in sustainable energy management decision-making	Fuzzy TOPSIS-based decision-making approach	Addresses the complexities, uncertainties, and trade-offs in sustainable energy management by applying the Fuzzy TOPSIS method, providing a robust tool for evaluating and selecting sustainable energy options	Limited prior application of Fuzzy TOPSIS in this context, aiming to fill this gap and enhance decision-making in sustainable energy management.

solution, which signifies the worst performance, throughout the specified criteria, the method first determines how far away each alternative is from both. Fuzzy membership functions, which take into account the imprecision of data and expert judgements, are used to assess how close every substitute is to the positive ideal result as well as how far it is from the negative ideal result. The Fuzzy TOPSIS method, which compares these distances to produce a thorough ranking of possibilities, enables the researchers to determine the best decision-making strategies for sustainable energy management in the maritime industry. The usage of the Fuzzy TOPSIS practice in this study ensures a thorough and well-informed examination of the alternatives, making it easier to choose sensible and well-balanced solutions to advance a future for marine transport that is more environmentally friendly and sustainable.

Identification of criteria

The research's selection of criteria is essential since it offers a framework for evaluating decision-making processes. The researchers can thoroughly assess the performance of the alternatives by identifying pertinent criteria including Effectiveness, Adaptability, Robustness, Stakeholder Engagement, and Decision Quality. In order to compare various approaches to decision-making systematically and consistently, the defined criteria act as objective benchmarks. It makes sure that all pertinent elements of sustainable energy management are taken into account, allowing the researchers to provide informed advice that is thorough. Additionally, the precise definition of the evaluation criteria aids in coordinating the evaluation procedure with the particular aims and objectives of sustainable energy management in the marine industry. It guarantees that the chosen strategies support the overarching goal of lowering carbon emissions, advancing greener energy options, and assisting a sustainable and reliable energy system.

(1) Effectiveness: Evaluate the degree to which the suggested decision-making processes help to accomplishing long-term energy management objectives such as lowering greenhouse gas emissions, expanding renewable energy integration, as well as enhancing energy efficiency.
(2) Adaptability: Examine the decision-making frameworks' capability to handle uncertainty and adjust to shifting conditions, taking into account aspects such as technological improvements, changing market dynamics, and regulatory shifts.
(3) Robustness: Evaluate the decision-making processes' robustness in the appearance of uncertainty as well as unforeseen circumstances, to guarantee the proposed solutions can resist disruptions and give dependable results.
(4) Stakeholder engagement: Examine the inclusiveness and efficacy of decision-making stakeholder engagement procedures, taking into account elements such as representation, openness, responsibility, as well as the ability to accommodate various viewpoints and interests.
(5) Decision quality: Considering factors such as precision, uniformity, fairness, as well as the ability to manage different objectives and trade-offs when evaluating the quality of judgements made using the presented methodologies.

Identification of alternatives

The ability to thoroughly explore various approaches and solutions for sustainable energy management makes the identification of alternatives of utmost relevance. The researchers represent the whole range of accessible options and their possible implications by taking into account a varied range of alternatives, such as Probabilistic Modeling, Scenario Analysis, Pareto-based Approaches, Multi-Criteria Decision Analysis, Evolutionary Algorithms, and Policy Instruments and Regulations. The researchers can identify the most suitable and successful methods for tackling the difficulties and complexities of sustainable energy management in the maritime industry through the examination of alternatives. With the help of this procedure, decision-makers can be sure that their choices are well-informed and that their strategies are most compatible with the specific needs and goals of sustainable energy management, thereby promoting a greener and increasingly environmentally conscious future for marine transportation.

(1) Probabilistic modeling: In this method, uncertainties in sustainable energy management are quantified using probabilistic approaches such as Monte Carlo simulation or Bayesian inference. It enables decision-makers to analyse the likelihood of various outcomes and make educated decisions using probability distributions.

(2) Scenario analysis: Scenario analysis is creating and analysing a number of likely future scenarios in order to capture a variety of prospective futures in sustainable energy management. Decision-makers can assess the robustness of various tactics throughout these circumstances, allowing them to find resilient and flexible solutions.

(3) Multi-Criteria Decision Analysis (MCDA): MCDA is a decision-making procedure that evaluates different solutions statistically based on several criteria or objectives. It entails developing decision criteria, giving weights to each criterion according to stakeholder preferences, then comparing alternatives to such criteria to determine the best answer.

(4) Pareto-based approaches: These strategies seek solutions that fall on the Pareto frontier, which denotes the trade-off connection between several objectives. Decision-makers can uncover compromise options that balance competing aims, such as affordability and environmental impact, by optimising numerous objectives at the same time.

(5) Evolutionary algorithms: To find the best possible solutions, evolutionary algorithms, including genetic algorithms or particle swarm optimisation, replicate natural evolution. These algorithms are capable of handling complex decision-making situations with several variables and objectives, allowing decision-makers to investigate an extensive variety of potential solutions and uncover high-quality possibilities.

(6) Policy instruments and regulations: This option entails investigating the efficacy of various policy tools and regulations, including feed-in tariffs, tax breaks, renewable portfolio standards, as well as carbon pricing mechanisms, in impacting decision-making procedures and encouraging sustainable energy management.

Fuzzy TOPSIS based MCDM approach

The Fuzzy TOPSIS MCDM strategy is a sophisticated and versatile approach to dealing with decision-making situations that include numerous criteria and uncertainties. Fuzzy logic is used in this technique to deal with inexact and ambiguous evidence, which is typical in real-world decision-making scenarios. The Fuzzy TOPSIS approach identifies ideal and anti-ideal solutions across available alternatives according to their proximity to positive and negative ideal solutions, accordingly. The Fuzzy TOPSIS technique gives a comprehensive ranking of options by taking into account both the distance to the ideal solution as well as the distance to the anti-ideal solution, enabling decision-makers to choose the optimal choice that properly balances numerous criteria (*Turk, 2022*; *Chatterjee & Das, 2023*; *Saputro, Figueira & Almada-Lobo, 2022*; *Chaeron et al., 2023*; *Salehabadi & Ruparathna, 2022*; *Yang et al., 2023*; *Khatri et al., 2023*; *Barahmand & Eikeland, 2022*). The capability to handle uncertainty and ambiguity in decision-making allows it to be particularly ideal for complicated and ambiguous challenges where accurate facts may not be accessible. Decision-makers may reach well-informed decisions by offering a clear and systematic rating of alternatives. Furthermore, the strategy enables the insertion of stakeholder preferences as well as the measurement of sensitivity to shifts in criteria weights, resulting in a strong and adaptable tool for dealing with real-world decision-making difficulties.

Fuzzy TOPSIS is especially appropriate for this study since it successfully tackles the intricacies and ambiguities that are present in decisions pertaining to sustainable energy management. Fuzzy TOPSIS uses fuzzy logic to address the ambiguity as well subjectivity that are frequently present in real-world scenarios, in contrast with conventional MCDM strategies like Analytical Hierarchy Process (AHP) or Simple Additive Weighting (SAW), which might have difficulty with ambiguity as well as imprecise data. This enables a more nuanced assessment of the options, where the criteria may represent the actual nature of the context for making decisions by taking on a range of values instead of being rigidly binary. While other MCDM techniques, such as ELECTRE or PROMETHEE, also provide strong frameworks for decision-making, they might not be as adaptable as Fuzzy TOPSIS in handling fuzzy criteria and preferences. Fuzzy TOPSIS offers a more accurate and dependable tool for decision-making by enabling a thorough and realistic evaluation of alternatives. This makes it the ideal option for handling the trade-offs along with uncertainties related to sustainable energy management. The following Fig. 2 shows the fuzzy TOPSIS based MCDM scheme utilized in this research work.

The implementation of the Fuzzy-TOPSIS approach in this exploration proved to be useful in analysing and rating various decision-making approaches for sustainable energy management in marine fuels and green energy. The problem's multi-criteria structure, combined with the domain's inherent uncertainties, needs a comprehensive decision-making framework. The Fuzzy TOPSIS technique successfully tackles imprecision and uncertainty in the decision-making procedure by using fuzzy logic. The approach discovers the most appropriate and successful decision-making procedures based on their nearness to the positive ideal result as well as distance from the negative

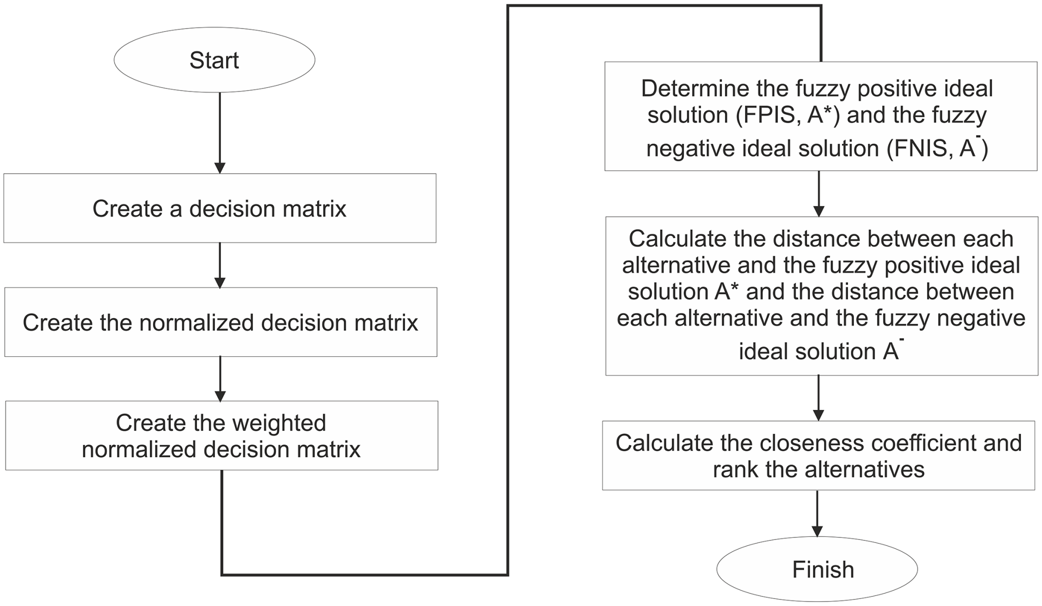

Figure 2 **Fuzzy TOPSIS based MCDM approach.** Full-size DOI: 10.7717/peerj-cs.3625/fig-2

ideal result using systematic review. This enables the researchers to acquire valuable knowledge into the strengths and shortcomings of each technique, facilitating the selection of the best solutions for achieving long-term energy management objectives. The Fuzzy TOPSIS-based MCDM technique improves the research's reliability and rigour by guaranteeing that the approaches adopted are well-balanced and competent of navigating the complicated issues and uncertainties of sustainable energy management in the maritime productiveness.

RESULTS

The findings of this research depend on comments and observations made by fifty-five knowledgeable decision-makers who are specialists and researchers in the field of sustainable energy management. Their invaluable input and knowledge serve as a solid foundation for the conclusions and suggestions made in this study. It is possible to conduct a thorough and in-depth examination of decision-making processes in the sustainable energy management area thanks to the varied viewpoints and expertise of the contributing decision makers, which enhance the validity as well as trustworthiness of the study's outcomes. By utilising the information of these 55 decision-makers, the research provides insightful and practical information that may assist energy managers, guide stakeholders, as well as inform the development of policies to encourage sustainable practises and reducing environmental impacts in the marine fuels as well as green energy sectors. The outcomes of this research work are discussed below.

Step 1: Create a decision matrix

The Fuzzy TOPSIS tactic is used in this research to rank six alternatives according to five criteria. The following Table 2 provides an understandable description of the

Table 2 Characteristics of criteria.

	Name	Type	Weight
1	Effectiveness	+	(0.200, 0.200, 0.200)
2	Adaptability	+	(0.200, 0.200, 0.200)
3	Robustness	+	(0.200, 0.200, 0.200)
4	Stakeholder engagement	+	(0.200, 0.200, 0.200)
5	Decision quality	+	(0.200, 0.200, 0.200)

Table 3 Fuzzy scale.

Code	Linguistic terms	L	M	U
1	Very low	1	1	3
2	Low	1	3	5
3	Medium	3	5	7
4	High	5	7	9
5	Very high	7	9	9

decision-making procedure for sustainable energy management in the marine sector by outlining the many types of criteria that were utilized in the evaluation and the appropriate weights assigned to every criterion.

The Fuzzy scale employed in the model is displayed in the following Table 3.

Each alternative was assessed against the selected criteria, and the outcomes are presented in the decision matrix. In situations where more than one expert was involved in the assessment, the values shown in Table 4 reflect the average (mean) scores gathered from all participating specialists.

Step 2: Development of the normalized decision matrix

After constructing the initial decision matrix, the next stage involves converting the values into a normalized form. This step ensures that all criteria are positioned on a comparable measure irrespective of their unique units or ranges. Using the identified positive ideal solution (representing the most desirable performance) as well as the negative ideal result (representing the least desirable performance), the normalization process is carried out according to the standard mathematical expressions. These formulas allow each alternative's performance to be transformed proportionally, so that meaningful comparisons can be made across all criteria.

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right); \quad c_j^* = max_i\, c_{ij}; \quad \textit{Positive ideal solution}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right); \quad a_j^- = min_i\, a_{ij}; \quad \textit{Negative ideal solution.}$$

The results of the normalization process, which convert all criterion values into a comparable scale, are summarized in Table 5. This table provides the normalized decision matrix, illustrating the relative performance of each alternative across all evaluation criteria.

Table 4 Decision matrix.

	Effectiveness	Adaptability	Robustness	Stakeholder engagement	Decision quality
PM	(4.600, 6.600, 8.600)	(2.400, 4.400, 6.200)	(3.000, 5.000, 7.000)	(3.600, 5.600, 7.400)	(3.400, 5.400, 7.200)
SA	(3.600, 5.600, 7.600)	(1.800, 3.800, 5.800)	(3.600, 5.600, 7.000)	(2.800, 4.800, 6.200)	(3.800, 5.800, 7.600)
MCDA	(3.800, 5.800, 7.600)	(4.800, 6.800, 8.200)	(4.600, 6.600, 8.000)	(4.800, 6.800, 8.200)	(3.600, 5.600, 7.600)
PA	(4.000, 6.000, 7.600)	(3.600, 5.600, 7.000)	(3.600, 5.600, 7.200)	(2.600, 4.600, 6.600)	(2.400, 4.400, 6.400)
EA	(4.200, 6.200, 7.800)	(4.200, 6.200, 7.600)	(4.200, 6.200, 7.600)	(4.000, 6.000, 7.400)	(4.000, 6.000, 7.400)
PIR	(2.400, 4.400, 6.400)	(2.200, 4.200, 6.200)	(2.000, 4.000, 6.000)	(2.800, 4.600, 6.600)	(2.800, 4.800, 6.800)

Table 5 A normalized decision matrix.

	Effectiveness	Adaptability	Robustness	Stakeholder engagement	Decision quality
PM	(0.535, 0.767, 1.000)	(0.293, 0.537, 0.756)	(0.375, 0.625, 0.875)	(0.439, 0.683, 0.902)	(0.447, 0.711, 0.947)
SA	(0.419, 0.651, 0.884)	(0.220, 0.463, 0.707)	(0.450, 0.700, 0.875)	(0.341, 0.585, 0.756)	(0.500, 0.763, 1.000)
MCDA	(0.442, 0.674, 0.884)	(0.585, 0.829, 1.000)	(0.575, 0.825, 1.000)	(0.585, 0.829, 1.000)	(0.474, 0.737, 1.000)
PA	(0.465, 0.698, 0.884)	(0.439, 0.683, 0.854)	(0.450, 0.700, 0.900)	(0.317, 0.561, 0.805)	(0.316, 0.579, 0.842)
EA	(0.488, 0.721, 0.907)	(0.512, 0.756, 0.927)	(0.525, 0.775, 0.950)	(0.488, 0.732, 0.902)	(0.526, 0.789, 0.974)
PIR	(0.279, 0.512, 0.744)	(0.268, 0.512, 0.756)	(0.250, 0.500, 0.750)	(0.341, 0.561, 0.805)	(0.368, 0.632, 0.895)

Step 3: Construction of the weighted normalized decision matrix

Once the normalization is completed, the next operation is to integrate the relative prominence of every criterion. This is done by smearing the assigned weights to the normalized fuzzy standards. In other words, each normalized value is multiplied by its conforming criterion weight. This procedure produces the weighted normalized decision matrix that reproduces not only the presentation of every alternative but also the priority level of each evaluation criterion. The computation is performed using the mathematical expression provided below.

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_{ij},$$

where $\tilde{w}_{ij}$ represents weight of criterion c_j.

The following Table 6 shows the weighted normalized decision matrix.

Step 4: Identification of the fuzzy positive and negative ideal solutions (FPIS, A* $\textit{FNIS}, A^-$)

At this stage, the goal is to establish the benchmark values that represent the most favorable and least favorable performance for each criterion. The fuzzy positive ideal solution (FPIS, A*) corresponds to the optimal condition, while the fuzzy negative ideal solution (FNIS, A$^-$) denotes the poorest outcome. These reference points are mathematically expressed as follows:

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*\} = \left\{\left(\max_j v_{ij} | i \in B\right), \left(\min_j v_{ij} | i \in C\right)\right\}$$

Table 6 **The weighted normalized decision matrix.**

	Effectiveness	Adaptability	Robustness	Stakeholder engagement	Decision quality
PM	(0.107, 0.153, 0.200)	(0.059, 0.107, 0.151)	(0.075, 0.125, 0.175)	(0.088, 0.137, 0.180)	(0.089, 0.142, 0.189)
SA	(0.084, 0.130, 0.177)	(0.044, 0.093, 0.141)	(0.090, 0.140, 0.175)	(0.068, 0.117, 0.151)	(0.100, 0.153, 0.200)
MCDA	(0.088, 0.135, 0.177)	(0.117, 0.166, 0.200)	(0.115, 0.165, 0.200)	(0.117, 0.166, 0.200)	(0.095, 0.147, 0.200)
PA	(0.093, 0.140, 0.177)	(0.088, 0.137, 0.171)	(0.090, 0.140, 0.180)	(0.063, 0.112, 0.161)	(0.063, 0.116, 0.168)
EA	(0.098, 0.144, 0.181)	(0.102, 0.151, 0.185)	(0.105, 0.155, 0.190)	(0.098, 0.146, 0.180)	(0.105, 0.158, 0.195)
PIR	(0.056, 0.102, 0.149)	(0.054, 0.102, 0.151)	(0.050, 0.100, 0.150)	(0.068, 0.112, 0.161)	(0.074, 0.126, 0.179)

Table 7 **The positive and negative ideal solutions.**

	Positive ideal	Negative ideal
Effectiveness	(0.107, 0.153, 0.200)	(0.056, 0.102, 0.149)
Adaptability	(0.117, 0.166, 0.200)	(0.044, 0.093, 0.141)
Robustness	(0.115, 0.165, 0.200)	(0.050, 0.100, 0.150)
Stakeholder engagement	(0.117, 0.166, 0.200)	(0.063, 0.112, 0.151)
Decision quality	(0.105, 0.158, 0.200)	(0.063, 0.116, 0.168)

$$A^- = \left\{\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\right\} = \left\{\left(\min_j v_{ij} | i \in B\right), \left(\max_j v_{ij} | i \in C\right)\right\}.$$

Here $\tilde{v}_i^*$ denotes the maximum value of criterion i across all alternatives, while $\tilde{v}_1^-$ represents the minimum value of the same criterion. These values serve as the boundaries for evaluating performance with B and C corresponding to the fuzzy positive and negative ideal solutions, respectively. The computed FPIS and FNIS for all criteria are concise in Table 7 below.

Step 5: Determining the separation measures from ideal solutions

At this step the analysis quantifies how far each alternative deviates from the fuzzy positive ideal solution (A^*) as well as how near it is to the fuzzy negative ideal solution (A^-), thereby capturing the relative positioning of every option between the best and worst possible outcomes. These distances indicate how closely each option aligns with the best possible scenario (A^*) and how distant it is from the worst-case consequence (A^-). Using the defined distance formulas, the separation values are derived for each alternative, as given below.

$$S_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*) \quad i = 1, 2, \ldots, m$$

$$S_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad i = 1, 2, \ldots, m.$$

The symbol d represents the measure of distance between two fuzzy numbers. For two triangular fuzzy numbers expressed as (a_1, b_1, c_1) and (a_2, b_2, c_2) the distance between them can be determined using the following mathematical expression:

Table 8 Distance from positive and negative ideal solutions.

	Distance from positive ideal	Distance from negative ideal
PM	0.132	0.14
SA	0.17	0.103
MCDA	0.029	0.244
PA	0.159	0.117
EA	0.06	0.214
PIR	0.247	0.027

$$d_v\left(\tilde{M}_1, \tilde{M}_2\right) = \sqrt{\frac{1}{3}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2\right]}.$$

Remember that $d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right)$ as well as $d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right)$ are crisp figures.

Table 8 below presents the calculated distances of each alternative from both the FPIS and FNIS.

Step 6: Compute the closeness coefficient and determine the final ranking

In the final stage, the closeness coefficient for each alternative is obtained. This value expresses how near each alternative is to the ideal solution while bearing in mind both its distance from the positive and negative ideal references. Once these coefficients are calculated using the formula below, the alternatives can then be ranked accordingly where a higher closeness coefficient indicates a more preferable option:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}.$$

The most suitable option is the one that has the smallest distance from the FPIS and the largest distance from the FNIS. After computing these measures, the closeness coefficients and the corresponding ranks for each alternative are presented in Table 9.

The following Fig. 3 below depicts the proximity coefficient of each possibility.

The ranked alternatives are determined according to their Fuzzy Relative Closeness Coefficient (FRCC) values after applying the Fuzzy TOPSIS approach to the decision-making problem in sustainable energy management. The FRCC measures how close each alternative is to the ideal answer, taking into account both the positive and negative features. After analysing the FRCC numbers in this study, it is discovered that MCDA appears as the top-ranked alternative. MCDA provides a complete decision-making framework that takes into account many criteria and stakeholder preferences. It is an effective strategy in sustainable energy management because of its capacity to include multiple perspectives and balance competing objectives. MCDA enables informed choices as well as transparent and inclusive processes by methodically analysing options against preset criteria and assigning weights to each criterion.

After MCDA, Evolutionary Algorithms (EAs) are ranked as the second best option. EAs are well-suited to complicated decision-making problems involving various variables and objectives. These algorithms use natural evolution-inspired concepts to examine a large

Table 9 Closeness coefficient.

	Ci	Rank
PM	0.515	3
SA	0.377	5
MCDA	0.894	1
PA	0.424	4
EA	0.78	2
PIR	0.097	6

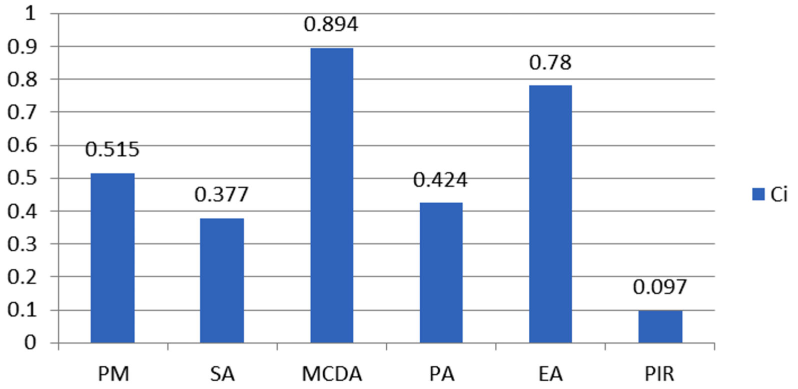

Figure 3 Closeness coefficient of each alternative.

Full-size DOI: 10.7717/peerj-cs.3625/fig-3

range of possible approaches and select optimal ones. EAs can optimise objectives including environmental effect, economic feasibility, and social acceptance in the setting of sustainable energy management, allowing decision-makers to discover compromise solutions that balance opposing aims.

The third-ranked option is Probabilistic Modelling, which provides a solid foundation for dealing with uncertainty in sustainable energy management decisions. Decision-makers may determine the likelihood of alternative events and make informed choices according to probability distributions by quantifying uncertainty using probabilistic approaches such as Monte Carlo simulation or Bayesian inference. Considering uncertain conditions, probabilistic modelling is a powerful tool for risk evaluation, scenario planning, and decision-making. Amongst the alternatives, Pareto-based Approaches rank fourth. These techniques are concerned with simultaneously optimising several objectives while taking into account the trade-offs between various sustainability factors. Decision-makers can analyse and select options that balance competing goals, such as cost-effectiveness and environmental impact, by locating solutions on the Pareto frontier. Pareto-based approaches offer a systematic and thorough methodology for addressing the trade-offs involved in decisions about sustainable energy management.

Scenario Analysis places fifth among options, highlighting its significance in decision-making procedures. Scenario Analysis improves decision-making transparency, inclusivity, as well as legitimacy by considering the viewpoints, interests, and values of many stakeholders. Decision-makers can build a sense of ownership and enhance social acceptance of sustainable energy management programmes by incorporating communities, industry leaders, environmental organisations, and policymakers.

Ultimately, Policy Instruments and Regulations are the sixth option. Policy tools and regulations, while not a decision-making strategy in and of themselves, play an important role in shaping decision consequences in sustainable energy management. Policy frameworks that are effective, such as feed-in tariffs, tax breaks, and energy efficiency requirements, can incentivise sustainable practises and drive decision-making processes. Decision-makers may establish a favourable atmosphere for sustainable energy management practises by connecting policy instruments with objectives for sustainability.

The ranking alternatives based on the Fuzzy TOPSIS method offer a variety of viable options to decision-makers in sustainable energy management. These alternatives, which include MCDA, Evolutionary Algorithms, Probabilistic Modelling, Pareto-based Approaches, Scenario Analysis, and Policy Instruments and Regulations, provide a variety of tools and techniques for dealing with uncertainties, trade-offs, and stakeholder concerns. Decision-makers can make educated choices and adopt appropriate decision-making processes for sustainable energy management by assessing the strengths and limits of each possibility.

DISCUSSION

This study's discussion part provides an in-depth examination of the research findings as well as the consequences for sustainable energy management in the marine industry. The research article emphasises the need of good decision-making in order to attain a greener and more environmentally friendly future. The study emphasises the importance of integrating renewable energy sources, energy efficiency measures, as well as greenhouse gas emission reductions into decision-making processes by examining various energy options and their possible consequences on the environment, economy, and society. Furthermore, the research highlights the complexities of decision-making in this sector, which includes coping with uncertainty and trade-offs.

The research presents optimal decision-making approaches to meet the issues of decision-making in sustainable energy management for marine fuels and green energy. These methodologies include various decision-making frameworks, approaches to uncertainty analysis, as well as multi-objective optimisation techniques. Furthermore, the discussion portion digs into key stakeholder involvement tactics and policy development challenges to ensure effective sustainable energy management. The study explores real-world scenarios throughout the research to get insights into both productive and ineffective decision-making practises. These assessments provide critical lessons and learning opportunities for policymakers, energy managers, and stakeholders. These stakeholders may make educated and successful decisions through integrating these insights into their methods for making decisions, which can accelerate the implementation of clean energy solutions, reduce reliance on fossil fuels, and minimise the negative effects of climate change.

The efficiency of recognised decision-making methodologies such as MCDA, EAs, Probabilistic Modelling, Pareto-based methodologies, Scenario Analysis, as well as Policy Instruments and Regulations must be reviewed rigorously. By evaluating case studies, empirical proof, and comparative assessments, both academics and practitioners can assess the real-world relevance and success of various approaches. This evaluation can give information on their ability to tackle the complexities, unpredictability, and trade-offs inherent in decisions about sustainable energy management. The flexibility and adaptability of decision-making techniques in the face of changing technologies, market conditions, as well as regulatory changes are critical considerations. Sustainable energy management is a continuously developing sector, and decision-making frameworks must be adaptable to new innovations and unexpected scenarios. Researchers should look for ways to improve the adaptability and resilience of the suggested strategies by incorporating techniques like dynamic modelling, scenario planning, as well as sensitivity analysis.

The effectiveness of policy tools and regulations for impacting decision-making processes and encouraging sustainable energy management must be evaluated on a regular basis. Future study should examine policy frameworks as well as governance structures in order to identify best practises, gaps, and opportunities for development. Furthermore, the research might examine the impact of various policy instruments on decision outcomes, as well as their interconnections and potential policy synergies to improve sustainable energy management. It is essential to investigate the possibility of integration and synergy between the indicated decision-making techniques. Combining several methodologies, such as MCDA with EAs, or Probabilistic Modelling with Scenario Analysis, may result in more complete and rigorous decision-making frameworks. To maximise their efficacy in sustainable energy management, researchers must investigate the advantages, obstacles, and implementation tactics for combining these approaches. The findings can be expanded to include decision-making procedures customised specifically for deep uncertainty in sustainable energy management. Deep uncertainty occurs when the choice space, prospective outcomes, as well as underlying system dynamics are highly unpredictable and difficult to model. Investigating strategies such as robust decision-making, flexible pathways, and decision-making with ambiguity may offer useful insights into dealing with deep uncertainty in decisions about sustainable energy management.

Considering the complexity and multidimensionality of sustainable energy management, increasing cross-disciplinary interaction is required. Future research should foster collaboration among academics from many disciplines, such as engineering and policy studies. This interaction has the potential to promote the development of comprehensive decision-making frameworks that take into account technological, socioeconomic, and environmental variables holistically. The results reported in this research have important implications for developing a sustainable and resilient energy system for current and future generations. The marine sector may play a critical role in cutting carbon emissions and encouraging sustainable practises by incorporating renewable energy sources, energy-saving measures, and smart decision-making processes. As consequence, this study assists to the larger goal of promoting a more beneficial to the environment and greener future for maritime transportation.

CONCLUSIONS

The research article presented optimal decision-making methodologies for sustainable energy management while accounting for uncertainty and trade-offs. Alternatives have been identified and evaluated based on their applicability and efficacy using a variety of ways. The results of this research provide policymakers, energy executives, and stakeholders participating in sustainable energy management with useful insights, as well as a variety of tools and techniques for navigating complexities and obstacles. By combining these approaches, more informed and efficient decision-making processes can be created, supporting the achievement of long-term energy management objectives. However, it is critical to recognise the research's limitations. In accordance with the particular setting and extent of sustainable energy management, the recommended decision-making processes may differ in their application and efficacy. Furthermore, because it is based on subjective input and the precision of fuzzy linguistic variables and membership functions, the Fuzzy TOPSIS technique has its own limits. Future research in this field should address these limitations and look for ways to improve. Potential areas for additional investigation include empirical validation, inclusion of technical improvements, evaluation of long-term repercussions, integration of numerous sectors, and addressing multiple stakeholder desires. We can increase sustainable energy management and accelerate the transition to a greener, more sustainable future by strengthening decision-making processes and solving these difficulties.

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Author Contributions

- Mohammed Alghassab conceived and designed the experiments, performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The code and raw data are available in the Supplemental Files.

Supplemental Information

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