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# Multi-Criteria Ranking of Power Supply Options for Long-Endurance Autonomous Marine Pollution Monitoring Platforms Using Entropy-Weighted VIKOR and ELECTRE

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## Abstract:

Autonomous marine pollution-monitoring platforms must operate for extended periods in remote, harsh sea environments with limited maintenance access, making power-source selection a critical design choice. This study develops a transparent multi-criteria decision-making (MCDM) framework to compare five candidate power options, hybrid systems, wave energy converters, photovoltaic modules, fuel cells, and small wind turbines, against criteria spanning technical performance, economic cost, and environmental impact. Criterion weights are derived objectively using the entropy method, and the alternatives are ranked using two complementary MCDM techniques: VIKOR, which identifies compromise solutions closest to an ideal point, and ELECTRE, an outranking approach based on concordance/discordance pairwise comparisons. Both methods consistently select hybrid power systems as the top option, with wave energy ranked second. Solar and fuel-cell solutions fall in intermediate positions, while small wind turbines rank lowest across evaluations. A sensitivity analysis that perturbs criterion weights by  $\pm 10\%$ ,  $\pm 20\%$ , and  $\pm 30\%$  confirms that the

ranking order remains stable over a broad range of weighting scenarios. The proposed entropy-VIKOR-ELECTRE framework provides a quantitative and defensible basis for selecting robust power systems for long-endurance autonomous marine pollution-monitoring deployments.

**Keywords:** Marine pollution monitoring; Autonomous Ocean platforms; Renewable power systems; VIKOR; ELECTRE

### ***1. Introduction***

Marine pollution continues to degrade coastal and open-ocean ecosystems, affecting biodiversity, food security, and maritime economies[1]. Oil spills, chemical discharges, plastics, and nutrients all contribute to long-term deterioration of water quality and habitat conditions. Continuous and spatially distributed monitoring is therefore essential for detecting emerging pollution events, assessing the effectiveness of control measures, and supporting regulatory decisions[2]. Conventional ship-based surveys and fixed monitoring stations, however, are expensive and provide limited temporal and spatial coverage[3]. In response, autonomous marine platforms such as instrumented buoys, gliders, and unmanned surface or underwater vehicles are increasingly used to collect real-time environmental data in remote or hazardous waters (e.g., for long-term water quality and ecosystem status assessments) [4] [5-7]. These autonomous devices are often deployed in challenging oceanic conditions and are expected to operate over extended periods without human intervention[8]. Their performance and reliability are directly linked to the power supply systems that support them. Powering

these devices efficiently is complex in the dynamic, often harsh marine environment, requiring power solutions that are reliable, efficient, sustainable, and low-maintenance [9, 10].

The performance of these autonomous platforms is strongly constrained by the design of their power systems. Sensors, data logging, communication, and, where relevant, propulsion impose continuous or intermittent energy demands over deployment periods lasting weeks to months. At the same time, devices operate in harsh marine conditions, often far from maintenance facilities[11]. Power systems must therefore provide reliable long-duration operation with minimal servicing, withstand corrosion and biofouling, and comply with environmental and safety requirements. Meeting these demands with a single energy technology is difficult, which has motivated growing interest in renewable and hybrid power supply solutions tailored to marine monitoring applications[12, 13]. A conceptual overview of such a system, including its main subsystems and power interfaces, is illustrated in Figure 1.

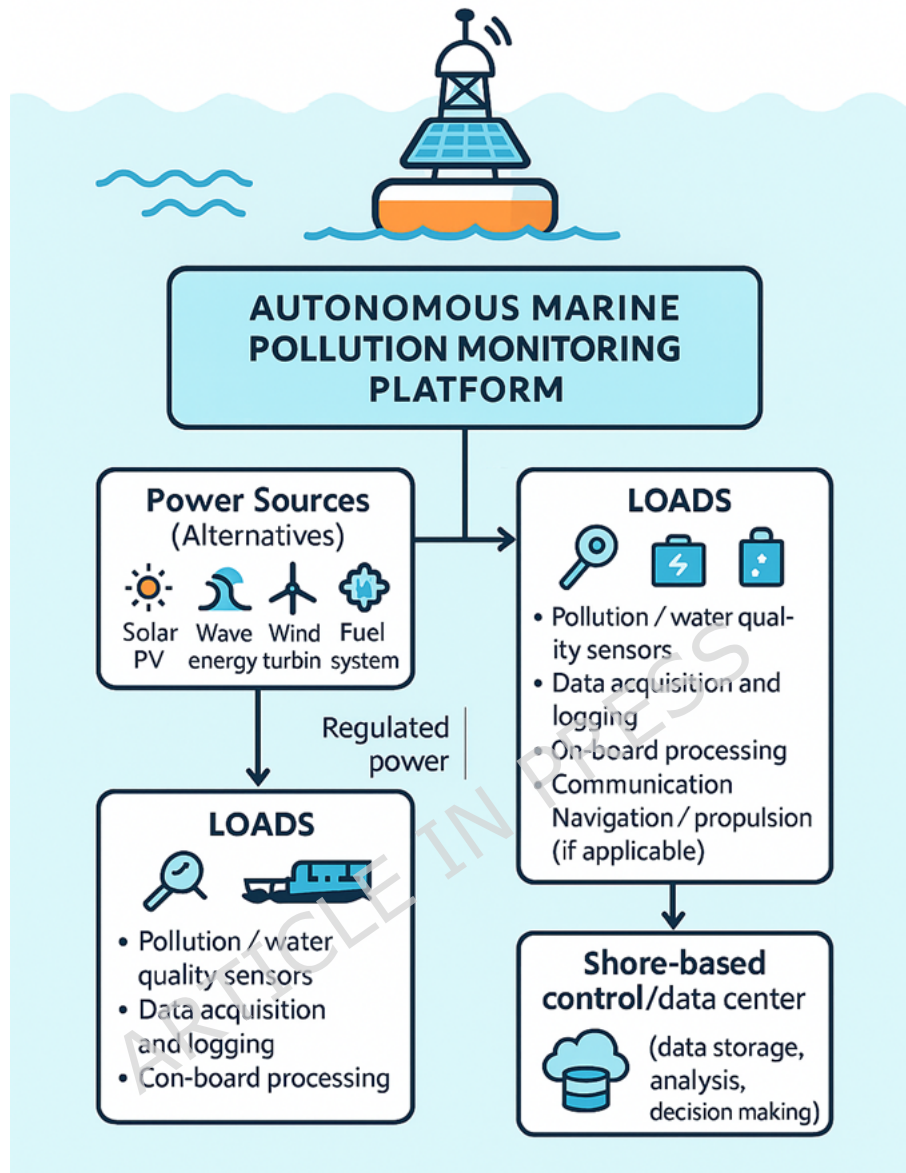


Figure 1. Conceptual architecture of an autonomous marine pollution monitoring platform, illustrating the interaction between environmental energy sources, power generation and storage units, and the main sensing, communication, and control loads linked to the shore-based data center.

Several power technologies are currently in use or under consideration for autonomous marine pollution monitoring platforms. Solar photovoltaic (PV)

modules are widely deployed on surface buoys due to their technological maturity, simple integration, and low environmental impact. Still, their output strongly depends on solar irradiance and can be unreliable at high latitudes, in winter, or under persistent cloud cover and biofouling[13]. Wave energy converters can exploit the relatively predictable wave climate in many ocean regions. They may supply power both day and night, yet they introduce mechanical complexity, structural loads, and maintenance requirements that can be prohibitive for small platforms[14]. Small wind turbines offer attractive performance in some offshore environments, but their effectiveness on compact autonomous devices is limited by wind variability, structural constraints, and service requirements[15]. Fuel cells can provide high energy density and stable output, enabling long-endurance missions even in deep or low-energy environments. Still, they require complex fuel logistics and involve higher capital and operational costs[16]. Hybrid systems that combine two or more sources, such as solar-wave or solar-wind-fuel cell configurations, seek to exploit complementary generation profiles and increase overall reliability, at the cost of greater design and integration complexity. Because each option offers a different mix of advantages and drawbacks across energy density, reliability, maintenance, environmental impact, and cost, selecting an appropriate power system is a non-trivial multi-criteria problem[17].

Table 1 summarizes key research efforts in this domain and compares them with the current study's focus on prioritizing power supply options for

autonomous marine pollution detection devices using VIKOR and ELECTRE methods.

**Table 1.** Comparison of Recent MCDM Applications in Marine and Energy Systems with the Present Study.

Study	Problem Focus	Methodology	Criteria Considered	Key Finding	Comparison with the Present Study
[18]	Optimal site selection for wind-PV-seawater pumped storage (SPS) plants	Fuzzy MCDM (TIFNs), Entropy, TODIM	Resource availability, sustainability, risk, uncertainty	Qingtian Bay is identified as the best SPS site	Focus on site selection; our study focuses on power supply prioritization for autonomous marine devices
[19]	Sustainable transition in marine transport (electric ferries)	WASPAS with fuzzy aggregation (FWWAA/FHWGA)	Technical, operational, environmental, and cost	A new electric ferry fleet is most advantageous	Focus on marine transport systems; our study targets energy

					systems for pollution detection.
[20]	Control method selection for unmanned underwater vehicles	MCDA (TOPSIS, COPRAS, MAUT, MOOSRA)	Simulation-based performance, consistency analysis	Variability in rankings across methods	Focus on method comparison; our study applies VIKOR & ELECTRE for consistent ranking.
[21]	Prioritization of industrial water pollution control methods	TOPSIS	Effectiveness, environmental impact, cost, feasibility, compliance	Membrane filtration ranked highest	Focus on pollution control methods; our study on power supply systems for detection devices

Multi-criteria decision-making (MCDM) methods have been widely employed to support complex choices in renewable energy planning, marine engineering, and environmental management. Several recent studies

highlight the importance of incorporating uncertainty, fuzzy environments, and hybrid decision frameworks in energy-related applications. For example, fuzzy-based control strategies have been applied to hybrid power systems to enhance power quality and operational stability, demonstrating the effectiveness of intelligent decision-making under dynamic conditions [22]. Similarly, advanced hybrid MCDM approaches, such as SWARA-WASPAS in spherical fuzzy environments, have been used to prioritize low-carbon policies, underscoring the importance of integrating weighting and ranking techniques in sustainability-oriented decision-making problems [23]. In addition, methodological frameworks for energy system development under uncertainty have been proposed, showing that systematic multi-criteria evaluation is essential when dealing with conflicting technical, economic, and environmental objectives [24]. Practical applications, such as evaluating barrage systems on the Euphrates River for clean energy generation, further demonstrate the need to assess renewable energy alternatives using comprehensive criteria that reflect real-world operational constraints.

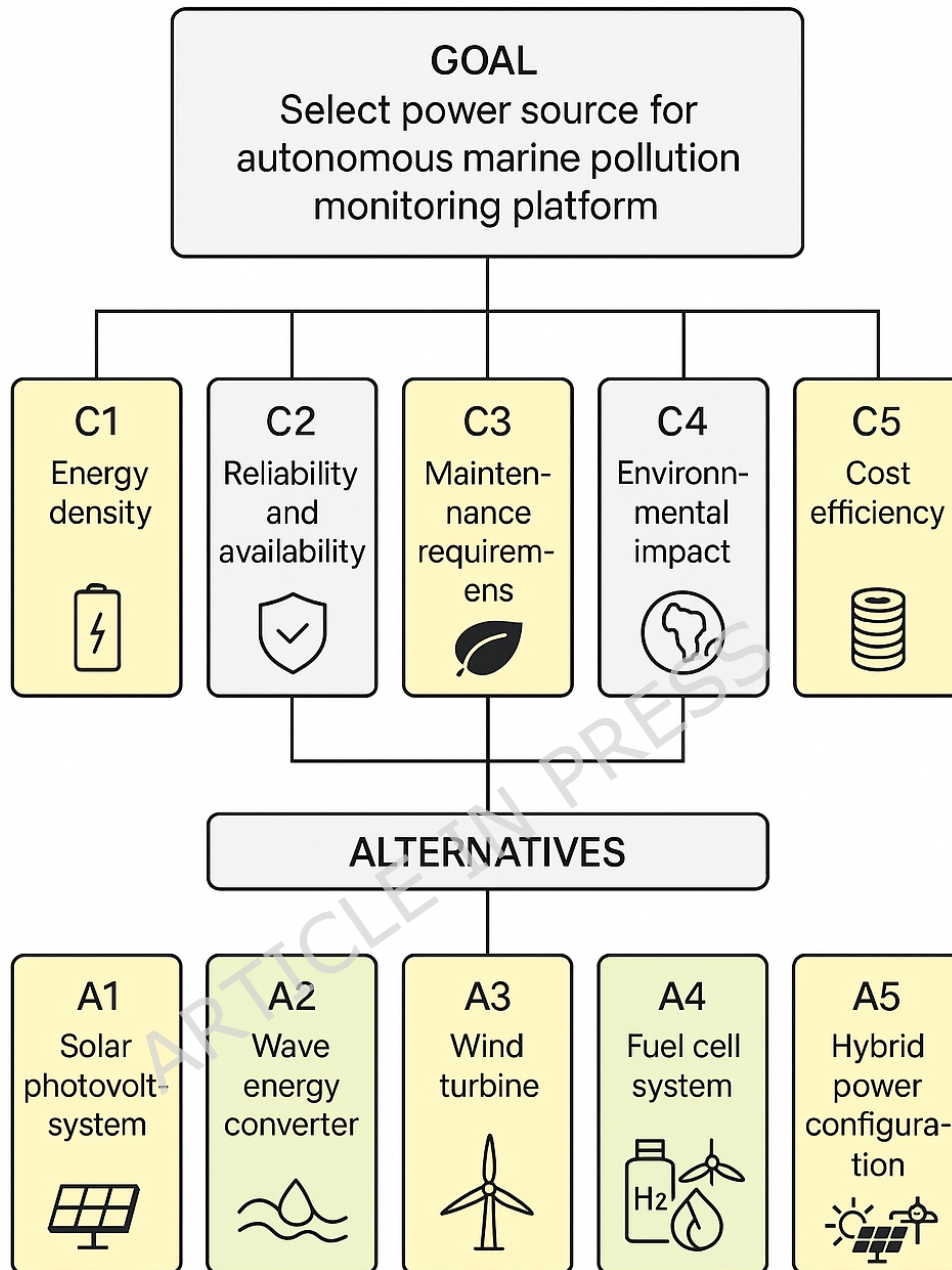
Despite these advances, existing studies primarily focus on large-scale energy systems, policy prioritization, or control strategies, while giving limited attention to power supply selection for autonomous marine monitoring platforms, particularly using combined outranking and compromise-based MCDM methods. Furthermore, many studies rely on a single decision-making technique or subjective weighting schemes, which may reduce robustness. Therefore, a clear research gap exists in developing

a robust, objective, and application-specific decision framework for selecting power supply systems in autonomous marine environments. The present study addresses this gap by integrating entropy-based objective weighting with two complementary MCDM methods, VIKOR and ELECTRE. Unlike prior studies, the proposed approach combines compromise ranking and outranking analysis within a unified framework, ensuring both stability and reliability of results. In addition, the study focuses on a previously underexplored application domain, namely long-endurance autonomous marine pollution monitoring systems, thereby providing both methodological advancement and practical relevance.

To address this gap, the present study develops a hybrid MCDM framework for ranking five candidate power supply options, solar power, wave energy, wind turbines, fuel cells, and hybrid systems, for autonomous marine pollution monitoring platforms. Expert judgments on five evaluation criteria (energy density, system reliability, maintenance requirements, environmental impact, and cost efficiency) are aggregated and used to determine objective criterion weights via the entropy method. The alternatives are then evaluated using two complementary MCDM techniques: VIKOR (ViseKriterijumska Optimizacija i Kompromisno Resenje), which identifies compromise solutions by balancing group utility and individual regret, and ELECTRE (ELimination et Choix Traduisant la REalité), which relies on concordance and discordance indices to establish pairwise

outranking relations. The overall decision hierarchy linking the goal, criteria, and alternatives is shown schematically in Figure 2.

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**Figure 2.** Decision hierarchy used for the multi-criteria evaluation of power supply options, linking the overall goal to the set of technical, environmental, and economic criteria and to the candidate power alternatives.

Accordingly, a hybrid entropy-VIKOR-ELECTRE framework is adopted to ensure both compromise optimality and outranking robustness, which are not simultaneously addressed in conventional single-method approaches. The main contributions of this study can be summarized as follows:

- It formulates the power supply selection for autonomous marine pollution monitoring platforms as a structured multi-criteria decision problem with clearly defined technical, environmental, and economic criteria.
- It integrates entropy-based objective weighting with a combined VIKOR-ELECTRE analysis to obtain robust rankings that are simultaneously compromise-oriented and outranking-based.
- It provides a comparative evaluation of five practically relevant power options, highlighting the conditions under which hybrid systems, wave energy, solar power, fuel cells, and wind turbines are suitable.
- It conducts sensitivity analyses on the criterion weights to test the stability of the rankings and to assess how changes in decision-maker priorities affect the preferred solution.

Together, these elements provide a transparent, quantitative basis for designing reliable, sustainable power systems tailored to autonomous marine pollution-monitoring applications.

## ***2. Methodology***

The selection of a suitable power system for autonomous marine pollution-monitoring platforms requires the simultaneous consideration of several technological alternatives and a broad set of often-conflicting evaluation criteria. To structure this inherently complex decision problem, the present work adopts a Multi-Criteria Decision-Making (MCDM) framework. It applies two complementary techniques, VIKOR and ELECTRE, to derive a rational ranking of candidate power sources based on expert judgements and processed assessment data. The methodological procedure is organized into three main stages: (i) collection and aggregation of expert evaluations, (ii) definition of the decision hierarchy, including the selection of relevant criteria and alternatives, and (iii) implementation of the MCDM analyses and synthesis of the final prioritization results. The use of expert-based data reflects practical constraints in obtaining long-term empirical measurements for autonomous marine systems, where controlled experimental datasets are often unavailable.

### *2.1. Data Collection and Aggregation*

Expert judgement was the primary source of information used to evaluate the candidate's power supply options. A structured questionnaire was prepared

to assess the performance of each alternative against the selected criteria, drawing on input from specialists in marine energy systems, ocean observing platforms, and environmental monitoring. Shandong University of Science and Technology in China confirmed that all questionnaires and the online protocol were completed, and that the obtained data are confidentially retained to preserve the anonymity of the respondents. The survey combined quantitative ratings with brief qualitative justifications to capture both numerical preferences and contextual insights. The data used in this study are not derived from direct empirical measurements but rather from structured expert evaluations designed to reflect realistic operational conditions of autonomous marine energy systems.

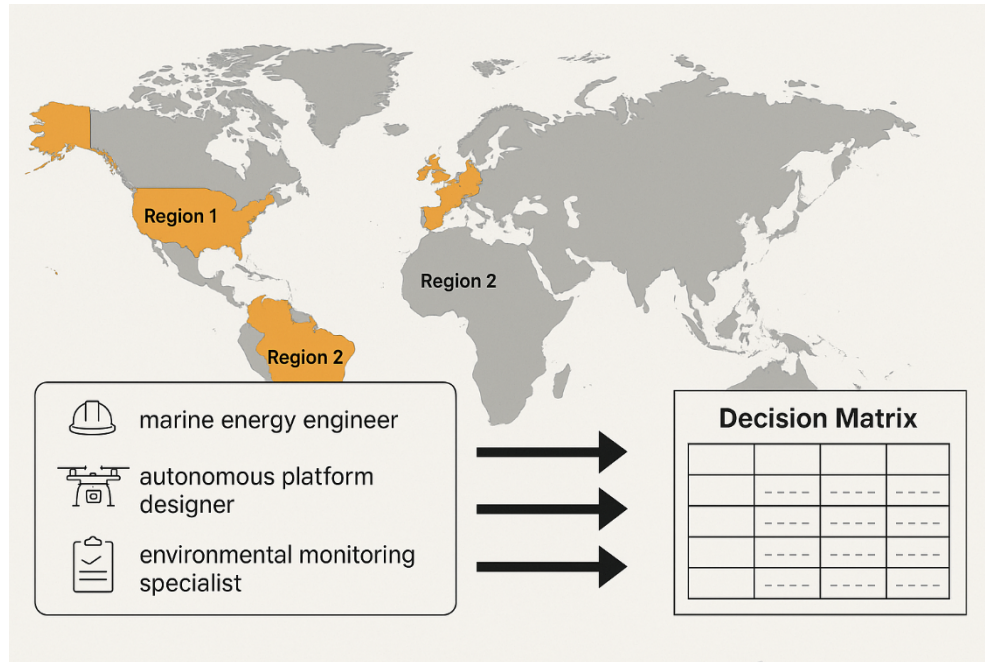
The questionnaire was structured into two main parts. The first part collected background information on the experts, including their field of expertise, years of experience, and involvement in marine energy or autonomous systems. The second part required experts to evaluate each alternative against the selected criteria using a standardized rating scale. To ensure reliability, responses were screened for logical consistency, and incomplete or contradictory entries were excluded. In addition, the composition of the expert panel was examined to ensure balanced representation across academic, industrial, and applied research perspectives, thereby enhancing the credibility and representativeness of the evaluation process.

To avoid a location-specific bias, experts were recruited from multiple institutions and from geographically dispersed coastal regions (including different seas and climate zones). This dispersion ensured that the assessments reflect a range of operational conditions, such as variations in wave climate, solar irradiance, maintenance logistics, and regulatory frameworks. Only respondents with demonstrated experience in the design, deployment, or operation of autonomous marine platforms or marine renewable energy systems were included in the final panel. Individual responses were screened for completeness and internal consistency and then aggregated to obtain representative scores for each criterion-alternative pair. These aggregated values form the decision matrix used in the subsequent MCDM analysis.

To ensure transparency in the scoring process, each expert assigned ratings using a predefined ordinal scale, which was then converted into numerical values for analysis. The aggregated scores for each criterion-alternative pair were calculated as mean values of expert responses, while variability among responses was examined to confirm consistency and avoid extreme bias. The resulting dataset, therefore, represents a consensus-based evaluation rather than a hypothetical, arbitrary assignment. In addition, basic statistical properties of the aggregated data were examined to assess robustness. Measures of central tendency and dispersion, including mean values and variability across expert responses, were analyzed to ensure that the evaluation matrix is stable and not dominated by outliers or inconsistent

judgments. This step enhances the reliability of the input data used in the subsequent MCDM analysis.

Although recent MCDM methods such as FN-MABAC, RIM, and SPOTIS have been developed to improve ranking stability and uncertainty handling, the present study adopts VIKOR and ELECTRE due to their complementary theoretical foundations and proven applicability in energy system evaluation. The combination of compromise-based and outranking-based methods provides both global and pairwise decision insights, which are particularly relevant for the considered problem. Future research may include comparative analyses with these newer approaches to further validate the robustness and generalizability of the results. At the same time, the entropy method is applied to derive objective weights for the evaluation criteria before implementing the VIKOR and ELECTRE procedures. The geographical dispersion and disciplinary background of the expert panel are summarised in Figure 3.

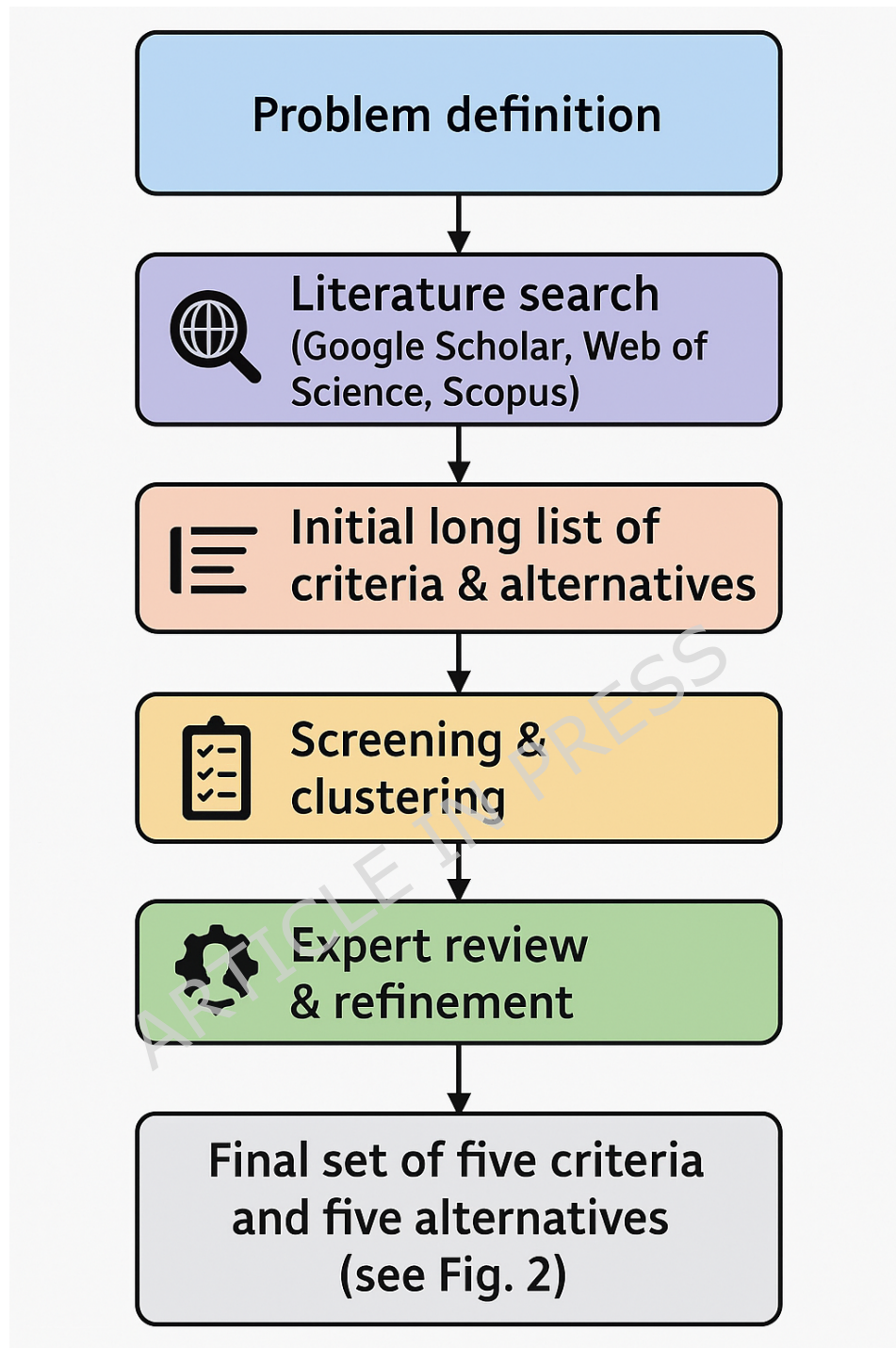


**Figure 3.** Geographical distribution of the 50 experts contributing to the survey, grouped into two macro-regions: Region 1 (North, Central, and South America) and Region 2 (Western Europe and North/West Africa). Arrows indicate how their evaluations are aggregated into the decision matrix used for the MCDM analysis.

## 2.2. *Criteria and Alternatives Selection*

The decision model construction began with the identification of appropriate evaluation criteria and feasible power supply options. A targeted literature survey was conducted across databases such as Google Scholar, Web of Science, and Scopus, focusing on autonomous marine platforms, marine renewable energy systems, and long-endurance ocean monitoring. From this body of work, an initial long list of criteria and technologies was compiled, then screened and clustered. The selection of these criteria is also consistent with previous studies on energy system evaluation under uncertainty and in

fuzzy decision environments, in which reliability, environmental impact, and economic feasibility are identified as dominant factors influencing system performance and sustainability. To keep the framework tractable while retaining the dimensions most frequently highlighted in the literature and by practitioners, five criteria were retained: energy density, reliability and availability, maintenance requirements, environmental impact, and cost efficiency. In parallel, five power supply alternatives were selected based on technological maturity and demonstrated or proposed use in marine applications: solar photovoltaic systems, wave energy converters, wind turbines, fuel cell systems, and hybrid power configurations. The resulting decision hierarchy, linking the overall goal, the five criteria, and the five alternatives, is presented in Figure 2. The procedural steps followed in deriving this final set, from problem definition, through literature screening and consolidation, to expert review and refinement, are summarised schematically in Figure 4, which also highlights the role of expert judgement in validating the criteria and alternatives used in the subsequent MCDM analysis.



**Figure 4.** Schematic overview of the procedure used to select evaluation criteria and power supply alternatives, from problem definition and literature search (Google Scholar, Web of Science, Scopus) to expert review and derivation of the final set of five alternatives, summarized in Figure 2.

### 2.3. *Hybrid MCDM Process Using VIKOR and ELECTRE*

To obtain a reliable ranking of power supply options, a hybrid Multi-Criteria Decision-Making scheme was adopted that combines VIKOR and ELECTRE. Using two conceptually different methods enables both compromise-oriented ranking and outranking relationships to be explored, thereby strengthening the robustness of the conclusions. The procedure starts from the expert-based decision matrix described in Sections 2.1–2.2. Criterion weights are derived objectively by the entropy method, which measures the information content and discriminating power of each criterion in the matrix. These weights are then used in parallel VIKOR and ELECTRE analyses. VIKOR (VIseKriterijumska Optimizacija i Kompromisno Resenje) seeks an alternative that is closest to the ideal solution by balancing the group utility and the maximum individual regret. For each option, the utility measure  $S$ , the regret measure  $R$  and the aggregated index  $Q$  are computed and used to obtain a compromise ranking. ELECTRE (ELimination Et Choix Traduisant la REalité) adopts an outranking philosophy: alternatives are compared pairwise using concordance and discordance indices, and dominance relations are established to identify non-dominated options and to construct a partial preorder.

The selection of the entropy–VIKOR–ELECTRE framework is motivated by the need to address the multi-dimensional and conflicting nature of the decision problem. VIKOR is particularly suitable for identifying compromise solutions

that are closest to the ideal alternative, allowing a balanced evaluation of technical, economic, and environmental criteria. In parallel, ELECTRE provides an outranking approach based on concordance and discordance analysis, enabling pairwise comparisons of alternatives and improving robustness in the presence of conflicting performance values. Compared with other commonly used MCDM methods, such as TOPSIS or PROMETHEE, which primarily focus on distance-based ranking or preference flows, the combined use of VIKOR and ELECTRE allows both compromise solution identification and dominance analysis within a unified framework. In contrast, simple weighted-sum methods are limited in their ability to capture trade-offs and conflicts among criteria. Therefore, the integrated approach adopted in this study provides a more reliable and defensible basis for selecting optimal power supply systems under complex decision conditions.

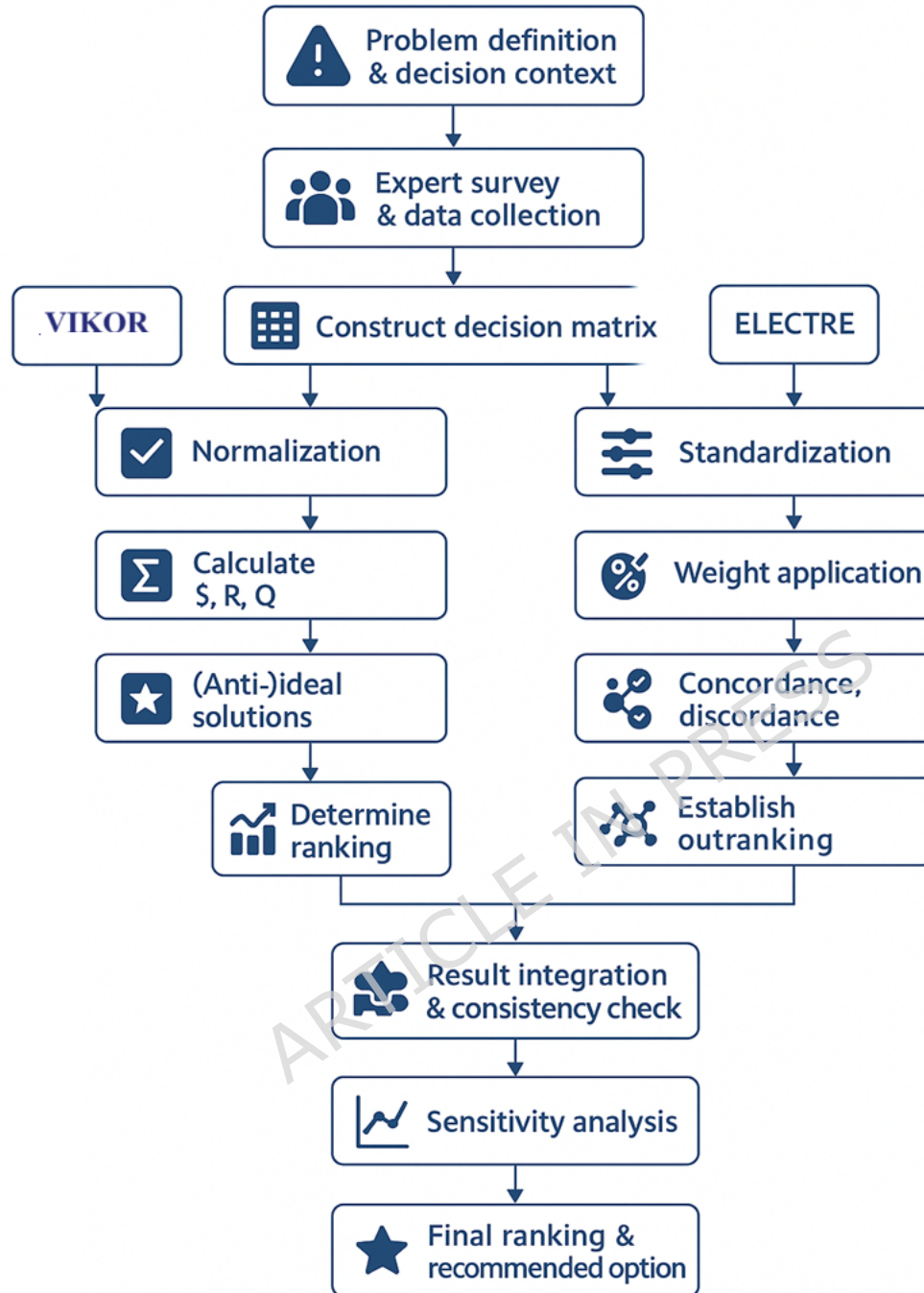
Table 2 summarises the main computational steps of the two methods as implemented in this study. The rankings obtained from VIKOR and ELECTRE are then compared and synthesised; convergence between the two is interpreted as evidence of a stable solution, while discrepancies are examined to understand method-specific sensitivities.

**Table 2.** Main computational steps of the VIKOR and ELECTRE methods.

Ste	VIKOR procedure	ELECTRE procedure
p		

1	Start from a weighted decision matrix.	Start from a weighted decision matrix.
2	Normalize performances for all criteria. This normalization process ensures comparability across criteria with different units and scales while preserving the relative differences among alternatives.	Normalize/standardize performances for all criteria.
3	Identify ideal and anti-ideal values for each criterion.	Compute concordance and discordance sets for each ordered pair of alternatives.
4	Compute utility measure $S_i$ and regret measure $R_i$ for each alternative.	Calculate concordance and discordance indices for each pair.
5	Derive the VIKOR index $Q_i$ using $S_i$ , $R_i$ and the compromise parameter $v$ .	Construct the outranking relation and apply threshold rules to determine dominance.
6	Rank alternatives according to increasing $Q_i$ , subject to acceptable advantage and stability conditions.	Derive a ranking or partial preorder based on the outranking relation (non-dominated and dominated alternatives).

Finally, a weight-perturbation sensitivity analysis is performed to test how changes in decision-maker preferences affect the ordering of alternatives. The overall hybrid workflow, from data collection to final recommendation, is depicted schematically in Figure 5.



**Figure 5.** Schematic representation of the hybrid MCDM workflow adopted in this study, showing the common stages of data collection and entropy-based weighting, the parallel application of VIKOR and ELECTRE, and the subsequent integration, sensitivity analysis, and final selection of the preferred power supply option.

Rather than focusing solely on computational procedures, the combined use of VIKOR and ELECTRE is intended to provide complementary insights for decision-making. VIKOR supports the identification of balanced solutions under conflicting criteria, whereas ELECTRE highlights dominance relationships relevant to practical engineering decisions. This dual perspective is particularly important in marine energy system design, where trade-offs among reliability, cost, and environmental performance must be carefully evaluated rather than merely numerically ranked.

### ***3. Results and discussion***

The hybrid application of the VIKOR and ELECTRE methods provides a structured basis for ranking the five candidate power supply systems for autonomous marine pollution monitoring platforms. Using the entropy-derived criterion weights and the normalized expert assessments, the decision matrix is first analysed with VIKOR to obtain the utility (S), regret (R) and compromise (Q) indices for each alternative, leading to an initial ordering. ELECTRE is then employed to construct concordance and discordance indices, establish outranking relations, and identify non-dominated options. The subsequent comparison of the two rankings verifies their coherence and highlights any method-dependent differences. On this basis, an overall prioritisation of power supply options is derived, and its stability is examined through a weight-perturbation sensitivity analysis, providing insight into the robustness of the recommended solution.

#### ***3.1. VIKOR Method Results***

Expert judgments serve as the empirical basis for the VIKOR analysis. Fifty specialists in marine energy systems, autonomous ocean platforms, and environmental monitoring rated the five power supply alternatives, solar power, wave energy, wind turbines, fuel cells, and hybrid systems, against the five evaluation criteria defined in Section 2 (energy density, reliability and availability, maintenance requirements, environmental impact, and cost efficiency). The survey used a discrete numerical scale (from “very poor” to “excellent”) and asked each expert to provide scores for all criterion-alternative combinations. Individual responses were first screened for completeness and apparent inconsistencies. For each criterion, the experts' ratings were averaged, yielding a single consensus score for each alternative-criterion pair. These consensus values constitute the initial decision matrix.  $X = [x_{ij}]$ , where  $i$  indexes the alternatives and  $j$  the criteria. Because the criteria are expressed on a standard ordinal scale but represent different physical dimensions, the decision matrix was normalised before applying VIKOR. A linear normalisation scheme was adopted, transforming each entry  $x_{ij}$  into a dimensionless score  $f_{ij}$  between 0 and 1. For benefit-type criteria the transformation

$$f_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

was used, whereas for cost-type criteria the inverse form

was applied. This yields the normalised decision matrix  $F = [f_{ij}]$ , in which higher values consistently denote better performance.

Objective criterion weights were then obtained using the entropy method. For each criterion  $C_j$ , the entropy value  $e_j$  was computed from the distribution of  $f_{ij}$  across alternatives; criteria that discriminate strongly among alternatives exhibit lower entropy and therefore receive higher weights. The normalised weights  $w_j$  (with  $\sum_j w_j = 1$ ) were then derived from the entropy measures. In this way, the relative influence of each criterion in the subsequent analysis is determined by the information content of the expert assessments rather than by arbitrary subjective assignment.

Using the weighted, normalised decision matrix, the VIKOR algorithm was implemented to evaluate the joint performance of the five alternatives. For each alternative  $A_i$ , the group utility measure  $S_i$  and the individual regret measure  $R_i$  were first calculated as

$$S_i = \sum_j w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-}, R_i = \max_j [w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-}], \text{ where } f_j^* \text{ and } f_j^- \text{ denote the best and worst}$$

normalised performances for criterion  $C_j$ , respectively. The compromise index  $Q_i$ , which balances the overall deviation from the ideal solution and the worst single-criterion deviation, was then obtained from

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*}, \text{ with } v = 0.5 \text{ representing equal importance of}$$

group utility and individual regret, and  $S^*$ ,  $S^-$ ,  $R^*$ ,  $R^-$  being the best and worst values of  $S_i$  and  $R_i$  across all alternatives.

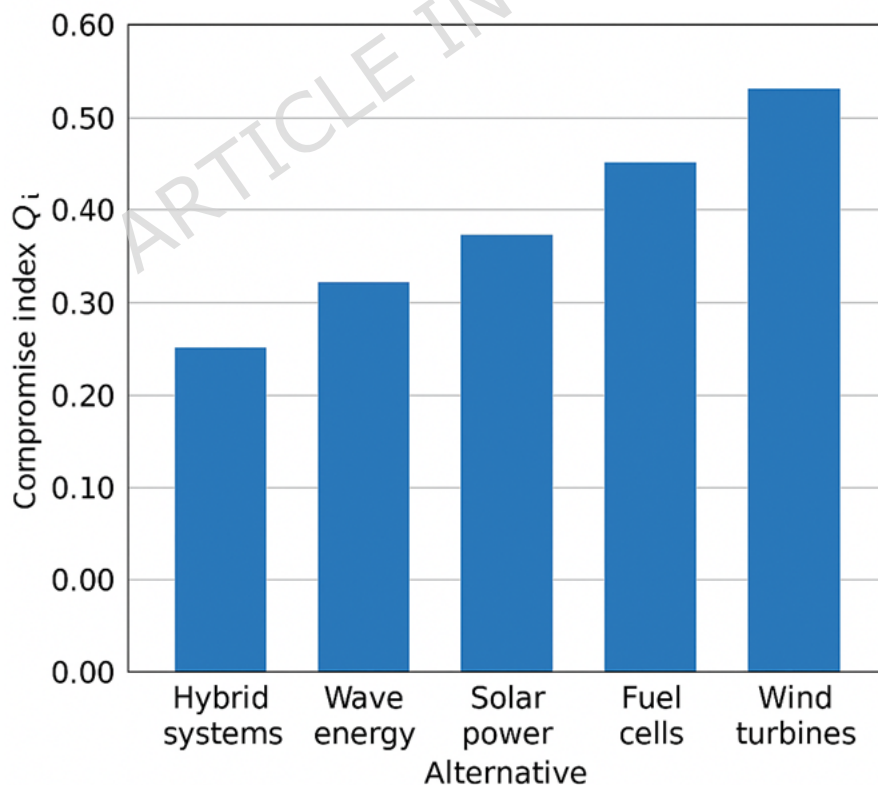
The resulting compromise indices are shown in Table 3. Lower  $Q_i$  values indicate alternatives that are closer to the ideal solution and are therefore more desirable.

**Table 3.** VIKOR compromise index  $Q_i$  and ranking of power supply alternatives.

Alternative	$Q_i$	VIKOR rank
Hybrid systems	0.3 0	1
Wave energy	0.4 7	2
Solar power	0.5 2	3
Fuel cells	0.5 5	4
Wind turbines	0.6 0	5

Hybrid systems achieve the smallest compromise index ( $Q = 0.30$ ), indicating the closest proximity to the ideal solution when all criteria are considered simultaneously. This result reflects both favourable aggregate performance (low  $S_i$ ) and the absence of any pronounced weakness in a single criterion (moderate  $R_i$ ). Wave energy and solar power occupy intermediate positions, with cap  $Q$  values of 0.47 and 0.52, respectively, suggesting that these technologies are viable but less well-balanced than hybrid configurations.

Fuel cells ( $Q = 0.55$ ) perform well in terms of energy density but are penalised by cost and maintenance considerations, while wind turbines show the least attractive compromise profile ( $Q = 0.60$ ), mainly due to reliability and maintenance challenges in harsh marine conditions. To provide an intuitive visual summary of the VIKOR results, Figure 5 presents a bar chart of the compromise indices  $Q_i$  for all alternatives, ordered from best to worst. The marked separation between hybrid systems and the other options confirms their superiority as a power supply solution for autonomous marine pollution monitoring platforms, whereas the clustering of wave energy, solar power, and fuel cells at intermediate  $Q_i$  values suggest that their relative attractiveness is more sensitive to changes in decision-maker preferences.



**Figure 5.** VIKOR compromise indices  $Q_i$  for the five power supply alternatives. Lower  $Q_i$  values indicate closer proximity to the ideal solution; hybrid systems emerge as the preferred option, while wind turbines show the least favourable compromise performance.

### 3.2. *ELECTRE Method Results*

To validate and cross-examine the VIKOR findings, the ELECTRE (Elimination and Choice Expressing Reality) method was applied. This method offers a pairwise outranking approach that focuses on dominance relationships between alternatives rather than direct numerical aggregation. This method evaluates Concordance (the degree to which one alternative is at least as good as another across most criteria) and Discordance (the extent of disagreement on any criterion) to establish outranking relations. Using the same normalized decision matrix and entropy-based weights as applied in VIKOR, the ELECTRE analysis computed Concordance and Discordance scores for each alternative. Higher Concordance and lower Discordance scores indicate stronger overall dominance over other alternatives. Hybrid Systems achieved the highest Concordance score (0.85) and the lowest Discordance score (0.10), signifying a clear outranking position over all other options. Wave Energy (Concordance 0.75, Discordance 0.20) and Solar Power (0.70, 0.25) performed well, while Fuel Cells and Wind Turbines recorded the weakest dominance, with higher discordance values reflecting substantial limitations in one or more criteria. The detailed scores and resulting ELECTRE ranks are presented in Table 4, which confirms the ranking order

established in the VIKOR method, further strengthening the validity of Hybrid Systems as the optimal choice.

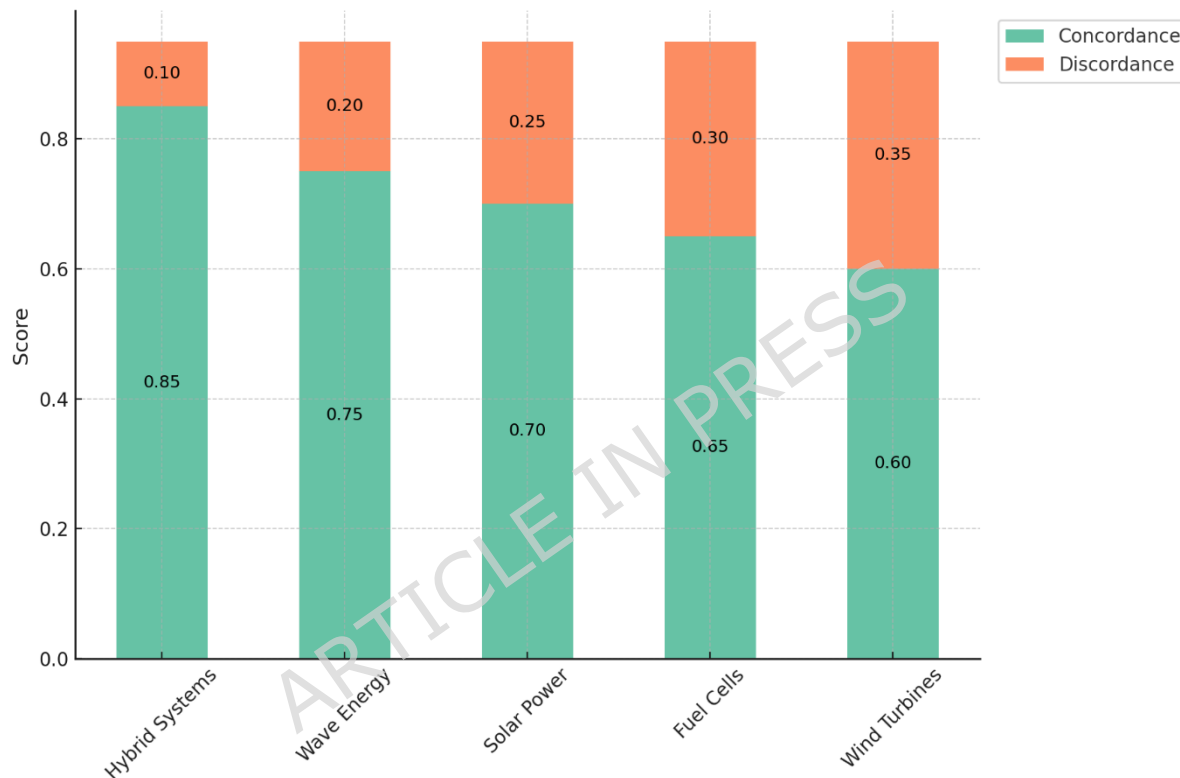
**Table 4.** Concordance and Discordance scores with resulting rankings for power supply alternatives based on ELECTRE analysis. Higher Concordance and lower Discordance values indicate stronger outranking performance. Hybrid Systems rank first, demonstrating dominant suitability across evaluation criteria.

Alternative	Concordance Score	Discordance Score	ELECTRE Rank
Hybrid Systems	0.85	0.10	1
Wave Energy	0.75	0.20	2
Solar Power	0.70	0.25	3
Fuel Cells	0.65	0.30	4
Wind Turbines	0.60	0.35	5

Figure 6 presents a stacked bar chart showing the Concordance and Discordance scores for each power supply alternative, calculated using the ELECTRE method. This visual not only quantifies each alternative's dominance strength but also offers insights into their relative weaknesses in specific criteria. It reveals that Hybrid Systems exhibit the most favorable score profile, characterized by the highest Concordance score (0.85) and the lowest Discordance score (0.10). This indicates that Hybrid Systems consistently outrank all other alternatives in pairwise comparisons, signifying broad-based superiority across most, if not all, evaluation criteria. The minimal Discordance reflects that no single criterion severely undermines

Hybrid performance, reinforcing its status as a balanced and reliable energy solution for autonomous marine operations. In contrast, Wave Energy and Solar Power demonstrate intermediate levels of Concordance (0.75 and 0.70, respectively) and moderately higher Discordance values (0.20 and 0.25). This suggests that while these alternatives can outperform others in certain criteria, they lack consistent dominance across the board. Their elevated Discordance scores imply vulnerabilities in specific dimensions, for Wave Energy, these may relate to mechanical complexity and durability. At the same time, for Solar Power, the intermittency of sunlight in marine environments can be a limiting factor. Fuel Cells and Wind Turbines present the least favorable profiles. Fuel Cells have a Concordance of 0.65 and Discordance of 0.30, while Wind Turbines show a Concordance of 0.60 and the highest Discordance score (0.35) among all alternatives. These scores reflect limited dominance in pairwise comparisons and significant weaknesses in critical criteria, such as high maintenance demands, fuel logistics (Fuel Cells), inconsistent energy output, and structural challenges in marine settings (Wind Turbines). The progressive increase in Discordance values from Hybrid Systems to Wind Turbines reflects a worsening performance profile and growing divergence from the ideal solution. This gradient visually reinforces the hierarchical ranking established numerically, confirming that Hybrid Systems are the most robust and suitable option, with consistently superior and stable performance across criteria. Moreover, the strong alignment between VIKOR and ELECTRE rankings, both methods

positioning Hybrid Systems first and Wind Turbines last, enhances the credibility and reliability of the decision-making outcome. This convergence across different MCDM approaches suggests that the results are not method-dependent, thereby providing high confidence in the recommendation of Hybrid Systems for powering autonomous marine pollution detection devices.



**Figure 6.** Concordance and Discordance scores for each power supply alternative based on ELECTRE analysis. Higher Concordance and lower Discordance indicate stronger dominance in pairwise comparisons. Hybrid Systems demonstrate the most favorable profile, confirming their suitability for autonomous marine applications.

### 3.3. Final Prioritization and Comparative Analysis

The application of both VIKOR and ELECTRE methods enabled a comprehensive evaluation of the five power supply alternatives by addressing the decision problem from complementary perspectives. While VIKOR provided a compromise-based ranking focused on proximity to the ideal solution, ELECTRE used pairwise outranking relationships to highlight dominance in performance across multiple criteria. The convergence of results from both methods offers robust validation for the prioritization of alternatives and strengthens the credibility of the final decision (see Table 5).

**Table 5.** Comparative rankings of power supply alternatives obtained by VIKOR and ELECTRE methods, highlighting method consistency and minor ranking differences.

Alternative	VIKOR Rank	ELECTRE Rank
Hybrid Systems	1	1
Wave Energy	2	2
Solar Power	4	3
Fuel Cells	3	4
Wind Turbines	5	5

The rankings produced by both methods exhibit close agreement, particularly regarding the top two and bottom alternatives. The minor discrepancy between Solar Power and Fuel Cells rankings (third and fourth positions swapped between methods) highlights a sensitivity to methodological differences. Still, it does not impact the identification of the optimal solution. This alignment, especially for the top-ranking Hybrid Systems and second-

ranked Wave Energy, underscores the consistency and reliability of the evaluation. Such an agreement indicates that the strengths and weaknesses identified for each alternative are robust and confirms that the prioritization is largely insensitive to the choice of MCDM technique.

Hybrid Systems emerged clearly as the top-ranked alternative in both methods. Their superior ranking is attributed to the ability to mitigate intermittency and operational limitations of single-source energy systems by effectively combining multiple renewable sources, such as solar and wave energy. The hybrid approach enhances energy reliability, reduces maintenance requirements, and ensures greater environmental compatibility. It is ideally suited for autonomous marine pollution detection devices that must operate reliably in isolated and variable marine conditions. Wave Energy Converters, consistently ranked second, showed notable strengths due to their predictable, steady power generation. However, their mechanical complexity and maintenance challenges limited their suitability compared to hybrid systems.

The minor inconsistency observed between the rankings of Solar Power and Fuel Cells reflects the different decision logics of the two methods. VIKOR emphasizes proximity to the ideal solution, while ELECTRE focuses on pairwise dominance relationships. As a result, alternatives with similar performance levels may change positions depending on whether global compromise or local dominance is emphasized. This variation does not

indicate instability but rather highlights the sensitivity of intermediate-ranked alternatives to methodological perspective.

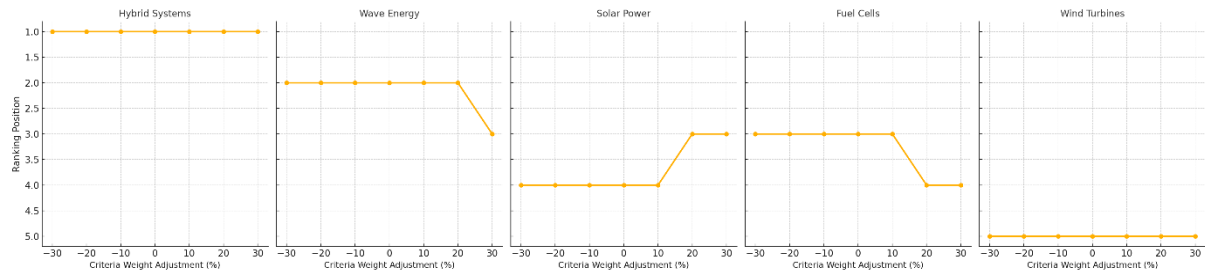
Solar Power and Fuel Cells occupied the next positions. Solar Power, ranked third by ELECTRE and fourth by VIKOR, demonstrated a reasonable balance of environmental benefits and low maintenance, but was constrained by the intermittency and geographical dependency of sunlight availability. Fuel Cells, inversely ranked third by VIKOR and fourth by ELECTRE, were recognized for their high energy density and independence from environmental conditions but were hampered by logistical complexities and higher operational costs.

Wind Turbines consistently ranked fifth, indicating significant drawbacks for small-scale autonomous applications. Issues such as high maintenance requirements, structural complexity, and variability in power generation severely limited their practicality for long-duration autonomous marine missions. The strong alignment between the rankings from both VIKOR and ELECTRE, combined with sensitivity analysis, confirmed that minor adjustments in criteria weights did not alter the identification of Hybrid Systems as the optimal solution. This robustness reinforces confidence in recommending Hybrid Systems as the most viable and sustainable power supply choice for autonomous marine pollution detection applications.

#### *3.4. Sensitivity Analysis*

A sensitivity analysis was conducted to assess the stability of rankings produced by the VIKOR and ELECTRE methods under systematic variations in criterion weights. The main goal of this analysis is to ensure the robustness and credibility of the chosen alternative (Hybrid Systems) across a range of possible scenarios. The analysis independently varied the weights of the five criteria (energy density, system reliability, maintenance requirements, environmental impact, and cost efficiency) by  $\pm 10\%$ ,  $\pm 20\%$ , and  $\pm 30\%$  from their original entropy-derived values.

The sensitivity analysis strongly reinforced Hybrid Systems' position as the optimal and most robust solution. As shown in Figure 7, Hybrid Systems' ranking did not change despite substantial variations in the criteria weights, confirming their clear advantage in effectively balancing performance across energy density, reliability, maintenance, environmental compatibility, and cost efficiency. This result suggests that selecting Hybrid Systems as the best alternative is optimal under baseline conditions and resilient to shifts in decision-maker preferences or uncertainties in expert judgments. Wave Energy maintained a robust secondary position, indicating that it is a reliable alternative, though less versatile than Hybrid Systems. Its slight sensitivity to extreme weight changes highlights areas of potential vulnerability, especially when priorities shift significantly toward criteria like energy density and reliability. Despite this, Wave Energy's overall stability in second place suggests it is also a strong candidate, especially suited to contexts where hybrid solutions may be less feasible or more costly.



**Figure 7.** Sensitivity analysis of the ranking positions for power supply alternatives under systematic adjustments of individual criteria weights ( $\pm 10\%$ ,  $\pm 20\%$ ,  $\pm 30\%$ ). Rankings closer to position 1 reflect higher priority and optimality. Hybrid Systems consistently maintained the highest priority (Rank 1), demonstrating exceptional stability and robustness across all weighting variations. Wave Energy exhibited moderate robustness, maintaining Rank 2, with only slight sensitivity under significant adjustments ( $+30\%$ ), particularly when increasing energy density or decreasing reliability weights. Solar Power and Fuel Cells demonstrated some vulnerability, with occasional interchangeability at intermediate rankings when subjected to substantial changes in criteria weights. Wind turbines consistently ranked last, confirming their unsuitability and emphasizing clear robustness as the lowest priority across all criteria adjustments.

In addition to weight variations, it is important to consider the potential influence of performance score variations assigned to alternatives. Although the present study focuses on weight-based sensitivity, uncertainty in expert evaluations may also affect ranking results. Future work should extend the analysis to include perturbations in the decision matrix, enabling a more comprehensive assessment of model robustness under data uncertainty.

A more comprehensive robustness analysis could be achieved through additional approaches, such as global sensitivity analysis involving simultaneous perturbations of both weights and performance scores, scenario-based analysis reflecting different environmental operating conditions, and stochastic simulations, such as Monte

Carlo methods, to evaluate ranking stability under data uncertainty. In addition, rank stability and potential rank-reversal behavior could be examined to identify parameter ranges within which the ranking remains unchanged. These extensions are recommended for future research to further enhance the robustness of the proposed framework.

### *3.5. Discussions and Limitations*

This study's comprehensive multi-criteria decision-making (MCDM) analysis effectively prioritizes power supply alternatives for autonomous marine pollution detection systems. Utilizing both VIKOR and ELECTRE methods provided complementary insights, enhancing the reliability and robustness of the decision-making process. Hybrid Systems consistently ranked as the most favorable alternative across all evaluation methods and sensitivity scenarios, reinforcing their suitability for ensuring long-term reliability, minimal maintenance, and environmental sustainability in demanding marine environments. Their inherent advantage lies in capitalizing on the complementary nature of various renewable energy sources, thereby overcoming individual weaknesses such as intermittency and geographical limitations. Wave Energy Converters emerged as a strong secondary option, offering consistent, predictable power generation, particularly beneficial in regions with significant wave activity. While their mechanical complexity and higher maintenance requirements pose operational limitations, they remain viable when hybrid systems are impractical due to logistical or economic constraints.

Despite their superior performance, hybrid systems pose practical challenges that must be addressed in real-world applications. These include increased system complexity, higher initial investment costs, and integration challenges arising from multiple energy sources and storage components. In marine environments, additional concerns such as corrosion, component reliability, and maintenance logistics may further complicate system deployment. Therefore, while hybrid systems offer clear performance advantages, their implementation requires careful engineering design and context-specific feasibility assessment.

Solar Power and Fuel Cells were moderately suitable, with distinct operational advantages and drawbacks. Solar Power provides simplicity and environmental benefits but is constrained by geographical and weather-related intermittency. Fuel Cells offer high energy density and operational consistency irrespective of weather conditions, but face significant logistical, cost, and maintenance challenges, especially in remote marine locations. The interchangeability in their rankings under specific sensitivity scenarios indicates context-dependent suitability, highlighting the need to carefully consider local conditions, operational priorities, and infrastructure availability when selecting between these alternatives. Wind Turbines consistently ranked as the least suitable alternative due to considerable operational challenges, including high maintenance requirements, structural complexity, and unreliable energy output for small autonomous platforms. Despite their effectiveness in large-scale offshore applications, their

deployment for autonomous marine pollution-detection devices remains impractical.

Although this study provides a robust and systematic prioritization of power supply alternatives, it is essential to acknowledge certain limitations. Firstly, the evaluation relied significantly on expert-derived input, introducing potential subjectivity and bias in the weighting and scoring processes. Even with normalization and entropy-based weighting methods designed to reduce biases, complete objectivity is inherently challenging in MCDM contexts. Future research could incorporate real-world operational performance data from deployed marine systems to further validate the outcomes. Secondly, the sensitivity analysis, while comprehensive, examined only variations in criterion weighting. It did not explore uncertainties inherent in criteria performance scoring or in external environmental factors that could affect long-term performance evaluations. Expanding sensitivity analyses to include these uncertainties could further strengthen the decision-making framework. Finally, economic factors such as long-term cost-benefit analyses, life-cycle costs, and regional economic incentives and constraints were not exhaustively explored. Detailed financial modeling could refine prioritization, offering deeper insights into cost-effective deployment strategies tailored to specific geographic and operational contexts.

Recent advancements in artificial intelligence and real-time monitoring technologies offer promising opportunities to extend the proposed decision-making framework. Deep learning-based approaches for real-time system

monitoring can enable continuous assessment of power system performance under changing environmental conditions[25]. In this context, operational data collected from sensors deployed on autonomous platforms can be dynamically integrated into the evaluation process, allowing performance scores of alternatives to be updated over time. Furthermore, adaptive artificial intelligence models can be incorporated into decision support systems to improve the quality of multi-criteria evaluation through continuous learning from historical and real-time data. Such integration would enable dynamic ranking updates rather than relying on static assessments, thereby enhancing the system's responsiveness to environmental variability. As a result, future extensions of this work could focus on developing AI-assisted MCDM frameworks capable of supporting real-time, data-driven, and adaptive decision-making, ultimately improving the resilience, reliability, and sustainability of autonomous marine energy systems.

#### ***4. Conclusions***

Selecting appropriate power supply systems is critical to the reliability and effectiveness of autonomous marine pollution detection devices, given the challenging operational conditions and environmental constraints of aquatic environments. This study systematically prioritized five alternative energy solutions using integrated VIKOR and ELECTRE methods. Hybrid Systems emerged as the optimal solution, consistently ranking first across both methods, attributed to their balanced performance in reliability, energy

density, environmental compatibility, and maintenance requirements. Sensitivity analysis reinforced this result, demonstrating robust stability with Hybrid Systems maintaining their top ranking (Rank 1) across all criteria weight adjustments ( $\pm 10\%$ ,  $\pm 20\%$ ,  $\pm 30\%$ ). Wave Energy consistently ranked second, with minimal vulnerability, appearing only under significant (+30%) weighting changes in the reliability and energy density criteria. Solar Power and Fuel Cells exhibited moderate suitability (Ranks 3–4), suggesting their deployment is context-dependent, while Wind Turbines consistently ranked last (Rank 5), highlighting their clear unsuitability. Overall, Hybrid Systems represent the most reliable, robust, and sustainable power supply choice for autonomous marine environmental monitoring devices.

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**Author Contribution:**

**L.Q and T.L:** Formal investigation, Methodology, and Data collection, writing original draft, writing - review & editing. **Y.W:** Writing - review & editing, Project administration, Resources, Supervision, Validation. **X.Z and P,J:** Formal investigation, Methodology, and Data collection, writing original draft. **M.A and D.W:** Formal investigation, Methodology, and Data collection, writing original draft.

**Human Participant Consent:** Informed consent was obtained from all experts involved in the study.

**Ethical Approval:**

- All methods were carried out in accordance with relevant guidelines and regulations.
- The Ethics Committee of Shandong University of Science and Technology in China approved the study.
- We confirm that this paper involves online questionnaire surveys completed by university learners. Informed consent was obtained from all subjects and their legal guardian(s).

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