

Article

Concept Selection of Hybrid Wave–Current Energy Systems Using Multi-Criteria Decision Analysis

Cheng Yee Ng ^{1,*}  and Muk Chen Ong ² ¹ Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Malaysia² Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, 4036 Stavanger, Norway; muk.c.ong@uis.no

* Correspondence: chengyee.ng@utp.edu.my

Abstract

Hybrid marine energy platforms that integrate wave energy converters (WECs) and hydrokinetic turbines (HKTs) offer potential to improve energy yield and system stability in marine environments. This study identifies a compatible WEC–HKT integrated system concept through a structured concept selection framework based on multi-criteria decision analysis (MCDA). The framework follows a two-stage process: individual technology assessment using eight criteria (efficiency, TRL, self-starting capability, structural simplicity, integration feasibility, environmental adaptability, installation complexity, and indicative cost) and pairing evaluation using five integration-focused criteria (structural compatibility, PTO feasibility, mooring synergy, co-location feasibility, and control compatibility). Criterion weights were assigned through a four-level importance framework based on expert judgment from 11 specialists, with unequal weights for the individual evaluation and equal weights for the integration stage. Four WEC types (oscillating water column, point absorber, overtopping wave energy converter, and oscillating wave surge converter) and four HKT types (Darrieus, Gorlov, Savonius, and hybrid Savonius–Darrieus rotor) are assessed using literature-derived scoring and weighted ranking. The results show that the oscillating water column achieved the highest weighted score among the WECs with 4.05, slightly ahead of the point absorber, which scored 3.85. For the HKTs, the Savonius rotor led with a score of 4.05, surpassing the hybrid Savonius–Darrieus rotor, which obtained 3.50, by 0.55 points. In the pairing stage, the OWC–Savonius configuration achieved the highest integration score of 4.2, surpassing the PA–Savonius combination, which scored 3.4, by 0.8 points. This combination demonstrates favorable structural layout, PTO independence, and mooring simplicity, making it the most promising option for early-stage hybrid platform development.



Academic Editor: George Lavidas

Received: 12 August 2025

Revised: 23 September 2025

Accepted: 27 September 2025

Published: 3 October 2025

Citation: Ng, C.Y.; Ong, M.C.Concept Selection of Hybrid Wave–Current Energy Systems Using Multi-Criteria Decision Analysis. *J. Mar. Sci. Eng.* **2025**, *13*, 1903. <https://doi.org/10.3390/jmse13101903>**Copyright:** © 2025 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).**Keywords:** hybrid marine energy systems; wave energy converter; hydrokinetic turbine; multi-criteria decision analysis; concept selection

1. Introduction

Global climate change is accelerating the shift toward low-carbon energy systems. In 2023, the average global surface temperature reached 1.45 °C above pre-industrial levels, making it the hottest year on record [1]. Energy production and consumption remain the largest contributors to greenhouse gas emissions, accounting for about 73 percent of the global total emissions [2]. Yet, fossil fuels still supply more than 80 percent of the

world's primary energy needs [3]. Reducing this dependence is therefore critical, not only to mitigate emissions but also to support a more resilient and equitable transition to cleaner energy. This transition must address the energy trilemma, which includes the challenge of achieving energy sustainability, supply security, and affordability at the same time [4]. Diversifying renewable energy sources is essential to improve energy system resilience and reduce regional dependence on weather-sensitive generation.

Ocean energy provides an alternative to more established technologies such as solar and wind. Although both have expanded rapidly, they are intermittent and site dependent. Ocean energy resources, including waves, tides, and marine currents, are more stable and predictable [5]. These resources are particularly suitable for islands, coastal regions, and shelf environments.

Wave and current energies are two types of ocean energy that behave differently. Wave energy tends to be more dynamic and peaks during storms. Current energy is more consistent across sea states. When combined, they provide complementary power profiles that reduce variability and improve generation reliability [6]. Wave energy converters (WEC) operate by capturing the oscillatory motion of surface waves. While hydrokinetic turbines (HKT) convert the kinetic energy of ocean or tidal currents. Most developments in WEC and HKT have focused on individual technologies.

Hybrid energy systems have the potential to reduce structural and mooring costs, optimize energy capture, and enhance viability in remote or low-infrastructure areas [6]. However, integration of WEC and HKT systems into shared platforms has received limited attention. Recent studies have highlighted a growing interest in floating hybrid platforms, particularly wave–wind and wave–current systems, with advances in optimization, control, and integration showing significant performance improvements [7–12].

Previous reviews have primarily focused on surveying individual WEC or HKT technologies or discussing hybrid potential in qualitative terms. Few have developed a structured, transparent decision-making framework for early-stage hybrid concept screening. This study addresses that gap by applying a two-stage multi-criteria decision analysis (MCDA) workflow that combines a defined scoring rubric, expert weighting, normalization, and sensitivity checks. The contribution is integrative but distinct in providing a replicable and transparent framework that identifies high-synergy WEC–HKT pairings and establishes a methodological foundation for subsequent design and techno-economic evaluation.

2. Methodology

This section introduces the multi-criteria decision analysis (MCDA) framework applied for the concept selection of hybrid wave–current energy systems. The approach is organized into two stages. First, individual wave energy converters (WECs) and hydrokinetic turbines (HKTs) are evaluated using eight technical, structural, and economic criteria derived from literature and expert judgment. Second, the top-ranked devices from each category are paired and assessed against five integration criteria to examine their compatibility on a shared platform. The overall workflow is summarized in Figure 1, which illustrates the process from input data collection through scoring, normalization, weighting, ranking, and final hybrid concept selection.

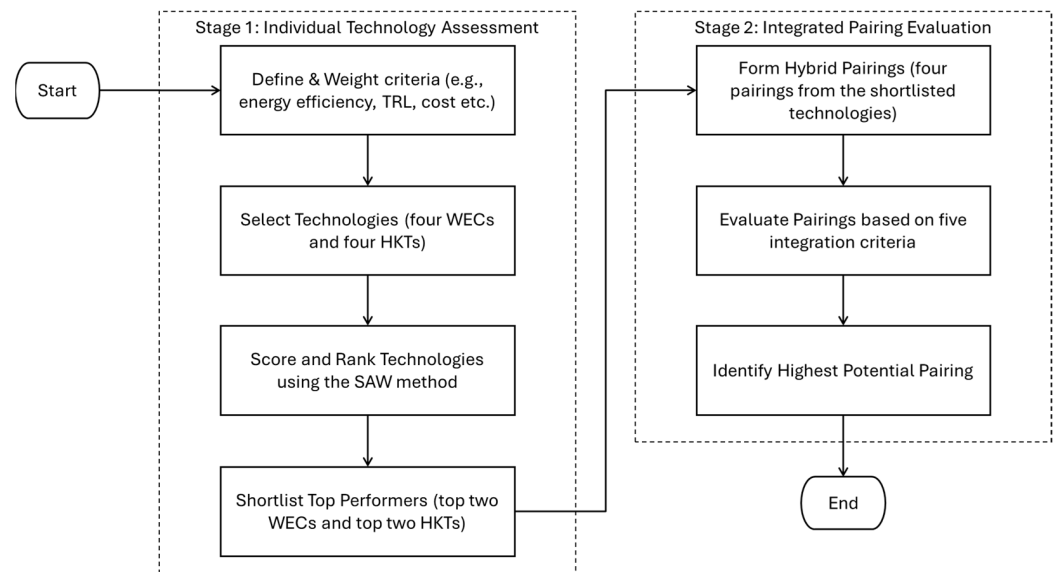


Figure 1. MCDA framework for hybrid WEC–HKT concept selection.

2.1. Overview of Multi-Criteria Decision Analysis (MCDA)

Full-scale test data for marine hybrid energy systems remain limited. Most wave and current energy technologies are still at the pre-commercial or prototype stage. Examples include the Oyster wave surge converter [13] and the Wave Dragon overtopping system [14]; both WECs underwent full-scale testing but did not reach commercial deployment. In terms of HKTs, various ducted horizontal-axis hydrokinetic turbines have been tested in riverine or coastal environments [15–17]. Commercially, companies like Verdant Power [18] and Waterotor [19] have also developed prototype turbines for tidal and river current applications, although these efforts remain at a pilot scale.

Early-stage design decisions must therefore rely on literature data, simulation results, and qualitative assessments. A multi-criteria decision analysis (MCDA) framework is adopted in this study to support technology selection under such constraints.

MCDA allows structured comparison of multiple technologies using a consistent set of evaluation criteria [20,21]. It is particularly suitable for early-phase concept development where technical performance, maturity, integration feasibility, and cost must be assessed concurrently [22]. The approach enables the use of published performance data, technology readiness levels (TRL), and qualitative indicators such as structural simplicity and platform compatibility. It also enhances transparency in the decision process and supports defensible selection of viable hybrid configurations [23].

MCDA has been widely used in renewable energy research [20,21]. It has been applied to compare solar, wind, and ocean energy systems [24,25] and to support site selection for offshore farms [26,27]. It is also used in hybrid system evaluation, where a balance between efficiency, reliability, and deployment feasibility must be considered. Recent studies have adopted MCDA in marine energy contexts, including assessment of floating wind–wave systems, co-located farm designs, and hybrid WEC–HKT platforms [6].

2.2. Evaluation Criteria

The evaluation criteria are derived from prior studies on hybrid renewable systems and marine energy applications. These criteria are chosen to reflect technical performance, maturity, integration feasibility, environmental adaptability, and economic potential [21].

The eight evaluation criteria used in this study are as follows:

- i. Energy conversion efficiency
- ii. Technology readiness level (TRL)

- iii. Self-starting capability
- iv. Structural simplicity
- v. Ease of integration into hybrid platforms
- vi. Environmental adaptability
- vii. Installation complexity
- viii. Indicative Levelized Cost of Energy (LCOE) or CAPEX trend

These criteria have been applied in previous MCDA frameworks for hybrid marine energy systems and platform selection [6,21,24,26–28]. Efficiency and TRL represent widely accepted indicators of technical performance and maturity [24]. Self-starting capability, structural simplicity, and integration feasibility reflect practical considerations for hybrid system design and component compatibility [28]. Environmental adaptability and installation complexity influence ease of deployment in nearshore or offshore environments [27]. When project-specific financial data are unavailable, LCOE or capital cost trends serve as proxies for economic viability [25].

The evaluation criteria selected for this study are outlined in Table 1, along with their definitions to clarify their relevance in assessing early-stage hybrid marine platform development.

Table 1. Evaluation criteria and descriptions.

Category	Criterion	Description
Technical Performance	Efficiency/Energy Capture	Expected energy conversion performance under typical conditions
	Technology Readiness Level (TRL)	Maturity level based on deployment history and validation
	Self-Starting Capability	Ability to initiate energy conversion without external input
Structural Integration	Structural Simplicity	Fabrication, maintenance, and reliability of structural design
	Ease of Integration	Compatibility with hybrid platforms and shared systems
	Environmental Adaptability	Performance under variable sea states and deployment conditions
Economics Feasibility	Installation Complexity	Infrastructure, lifting, and anchoring requirements
	Indicative LCOE/CAPEX Trend	Relative economic feasibility based on cost indicators

2.3. Weight Assignment

Each evaluation criterion is assigned to a weight reflecting its importance in early-stage hybrid marine platform development. The weighting strategy prioritizes energy performance, technology maturity, and integration feasibility, in line with the literature [29]. These initial weights are proposed based on engineering judgment and established MCDA studies focused on renewable energy and hybrid systems [6,21,24,26–28].

To validate and refine these weights, a direct rating survey was conducted with 11 industry experts from energy-related organizations in the UK, Malaysia, Thailand, and Denmark. The panelists bring expertise in offshore renewable energy, hybrid energy systems, and offshore structural engineering, ensuring that the weights are assigned based on practical industry experience.

Figure 2 illustrates the distribution of professional roles within the expert panel. The panel consists of a balanced mix of technical specialists and decision-makers, which helps ensure that the assigned weights reflect both practical expertise and strategic considerations.

Meanwhile, Figure 3 presents the panel's industry experience, which further supports the reliability and informed nature of the input provided.

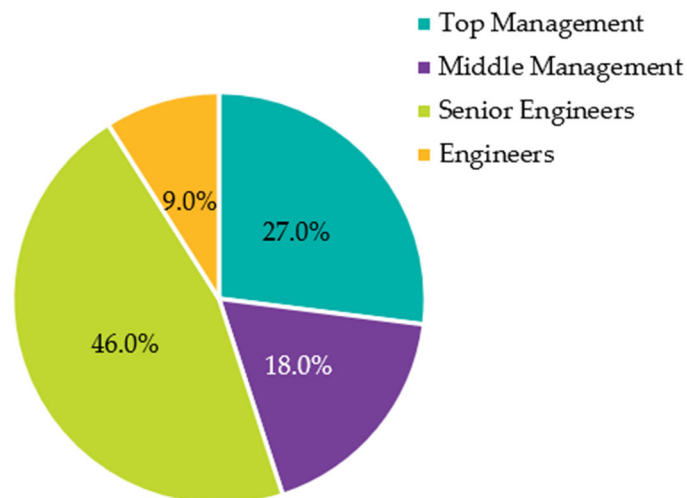


Figure 2. Distribution of professional roles within the expert panels.

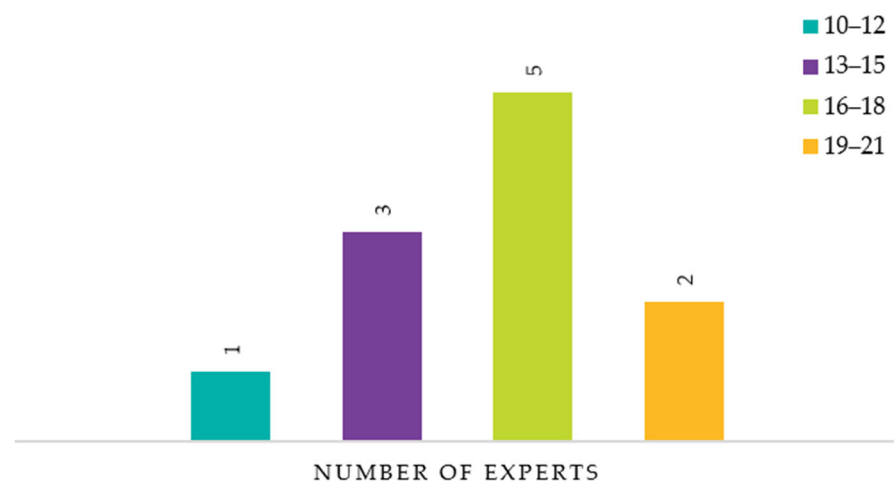


Figure 3. Industry experience of the expert panels.

The 11 expert panels evaluated the relative importance of eight criteria using a raw 1–10 Likert scale, where 1 indicated not important and 10 indicated extremely important. These raw scores are reported in Table A1 (Appendix A). To ensure comparability across experts and criteria, the scores are converted to ranks within each expert's set of eight criteria, with tied values assigned to the average of the ranks they span. The full per-expert ranking matrix (r_{ij}) is provided in Table A2 (Appendix A), together with the resulting rank sums (R_i).

The rank sums for each criterion (R_i) are then computed as follows [30]:

$$R_i = \sum_{j=1}^m r_{ij}$$

$\bar{R}$ is the average rank sum expected if there were no agreement:

$$\bar{R} = \frac{m(n+1)}{2}$$

where m is the number of experts and n is the number of criteria. Inter-rater agreement is quantified using Kendall's coefficient of concordance (W), calculated as follows [30]:

$$W = \frac{12 \sum_{i=1}^n (R_i - \bar{R})^2}{m^2(n^3 - n)}$$

For this study, $m = 11$ and $n = 8$, resulting $W = 0.78$, which indicates a substantial level of agreement among the experts.

To derive the final weights for use in the evaluation, the raw scores were normalized to a 0–1 range. The mean and standard deviation (SD) of the normalized ratings for each criterion, together with the final normalized weights, are summarized in Table 2.

Table 2. Normalized importance ratings provided by the 11 expert panels for each evaluation criterion.

Expert Panel (EP)	Efficiency	TRL	Self-Start	Simplicity	Integration	Adaptability	Installation	LCOE/CAPEX
EP 1	1	0.9	0.4	0.7	0.8	0.6	0.6	0.9
EP 2	1	1	0.3	0.6	0.9	0.7	0.5	1
EP 3	1	0.6	0.1	0.7	0.9	0.6	0.6	0.8
EP 4	0.9	0.8	0.5	0.6	0.7	0.6	0.6	0.8
EP 5	1	0.9	0.4	0.8	0.9	0.7	0.7	0.9
EP 6	0.9	0.9	0.5	0.7	0.8	0.6	0.6	0.9
EP 7	0.9	1	0.3	0.6	1	0.8	0.6	0.7
EP 8	1	0.9	0.2	0.6	0.9	0.7	0.6	0.8
EP 9	0.9	0.6	0.4	0.7	0.8	0.7	0.6	0.6
EP 10	1	0.9	0.5	0.7	0.8	0.7	0.7	0.8
EP 11	1	0.8	0.2	0.8	1	0.7	0.7	0.9
Mean	0.96	0.85	0.35	0.68	0.86	0.67	0.62	0.83
SD	0.050	0.137	0.137	0.075	0.092	0.065	0.060	0.110

As detailed in Table 3, efficiency received the highest weight of 0.20 due to its direct influence on total energy yield and overall system performance [31,32]. Technology Readiness Level (TRL), ease of integration, and indicative LCOE/CAPEX trends each carry high weights of 0.15, as these factors critically affect deployment risk, cost-effectiveness, and project viability [33,34]. Structural simplicity, environmental adaptability, and installation complexity are assigned weights of 0.10 [6]. Lastly, self-starting capability carries a lower weight of 0.05, given its variable relevance, which depends on specific control strategies and device types [35].

Table 3. Evaluation criteria and assigned weights.

Category	Criterion	Weight
Technical Performance	Efficiency/Energy Capture	0.20
	Technology Readiness Level (TRL)	0.15
	Self-Starting Capability	0.05
Structural Integration	Structural Simplicity	0.10
	Ease of Integration	0.15
	Environmental Adaptability	0.10
Economic Feasibility	Installation Complexity	0.10
	Indicative LCOE/CAPEX Trend	0.15
Total		1.00

2.4. Technology Selection

Technologies are selected to be representative, integrable, and supported by recent evidence in literature. The selection followed three criteria: (i) relevance to hybrid platform deployment in nearshore or floating contexts, (ii) sufficient maturity and presence in recent literature, and (iii) availability of performance data that allow transparent scoring within the MCDA framework. Device families with limited data, poor compatibility with the intended hybrid scope, or requiring substantially different infrastructure are excluded.

Four WEC families are considered. Oscillating Water Columns (OWCs) are included due to their compact geometry, simple PTO arrangement, and extensive validation record. The Wells turbine subclass is a core focus of this study due to its historical significance in OWC research and the availability of a robust dataset from well-documented projects. While research has progressed to include more advanced designs such as Impulse turbines, the Wells variant remains a valid and important subject for analysis in the context of our selected technologies [12]. Point Absorbers (PAs) are selected for their modularity and favorable capture width ratio, with recent studies highlighting design and monitoring improvements for practical deployment [7,26]. Overtopping devices (OWECs) are retained to represent gravitational head-based concepts; although structurally heavier, their performance in irregular states remains well-documented in recent reviews [6,36]. Finally, Oscillating Wave Surge Converters (OWSCs/OSWECs) are included for their predictable near-shore performance, supported by recent simulation and hybrid-integration studies [12]. Other WEC types, such as attenuators and submerged pressure-differential devices, are excluded due to limited maturity and scarce integration-relevant data [37].

Vertical-axis HKTs are prioritized for their compact geometry, bidirectional flow tolerance, and suitability for hybrid integration. Lift-based designs are represented by the Darrieus and Gorlov turbines, chosen for their efficiency and recent optimization evidence [31,38–40]. Drag-based turbines, represented by the Savonius rotor, are included for their mechanical simplicity and self-starting capability, with recent CFD and design studies demonstrating enhanced performance [41–43]. A hybrid Savonius–Darrieus turbine is also considered to capture ongoing advances in combining lift and drag operation for improved startup and moderate efficiency [43,44]. By contrast, ducted axial-flow turbines are excluded, despite recent reports of enhanced peak performance, because their hydrodynamic scale, clearance requirements, and maintenance demands are less compatible with compact nearshore hybrid platforms [45,46].

Figures 4a–d and 5a–d illustrate these selected WEC and HKT types, respectively, highlighting their varied operating principles and structural designs relevant to hybrid marine energy integration. Meanwhile, Tables 4 and 5 summarize the key features and integration-relevant characteristics of the WEC and HKT technologies.

Table 4. Wave Energy Converter (WEC) Technology Selections.

Code	Type	Description	Remarks
W1	Oscillating Water Column (OWC)	Air compression drives the turbine	Compact, easy to integrate
W2	Point Absorber (PA)	Buoyant body oscillates in heave	High capture width ratio, modular
W3	Overtopping Wave Energy Converter (OWEC)	Water flows into the elevated reservoir	Good surge response, heavy structure
W4	Oscillating Wave Surge Converter (OWSC)	Bottom-hinged flap rotates with wave motion	Predictable, suited for nearshore

Table 5. Hydrokinetic Turbine (HKT) Technology Selections.

Code	Type	Description	Remarks
H1	Darrieus (H-type) Turbine	Lift-based, vertical axis	High efficiency, not self-starting
H2	Gorlov Helical Turbine	Helical variant of Darrieus	Smoother torque, bidirectional
H3	Savonius Turbine	Drag-based, vertical axis	Self-starting, simple, lower efficiency
H4	Hybrid Savonius–Darrieus Turbine	Combines lift and drag	Better startup with moderate efficiency

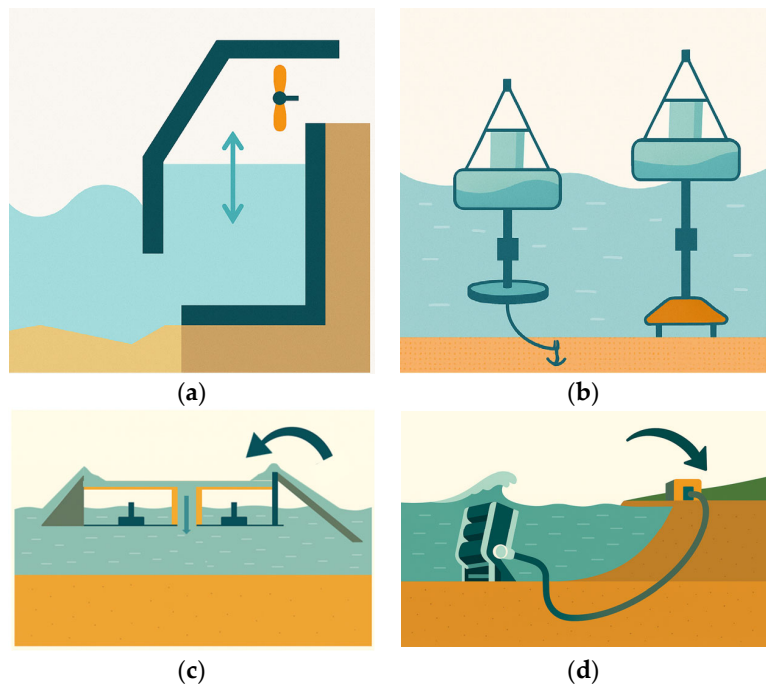


Figure 4. Conceptual drawings for the selected WECs: (a) W1—Oscillating Water Column, (b) W2—Point Absorber, (c) W3—Overtopping Wave Energy Converter, and (d) W4—Oscillating Wave Surge Converter.

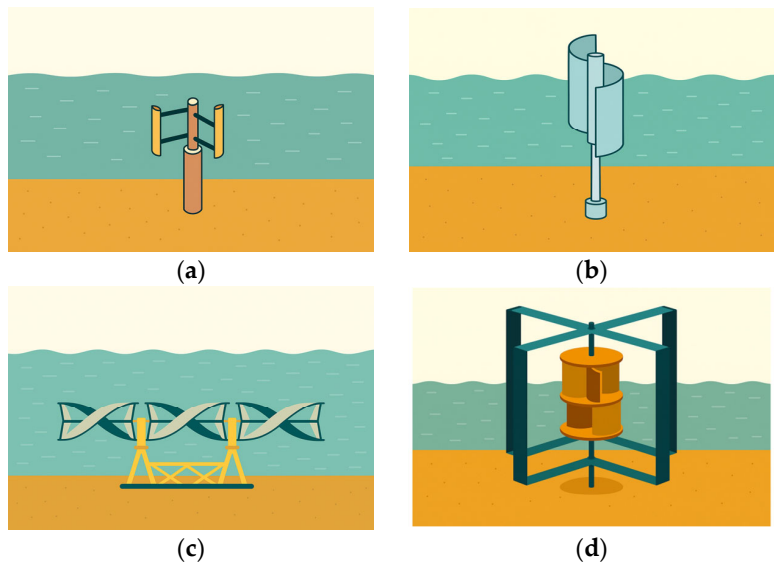


Figure 5. Conceptual drawings for the selected HKTs: (a) H1—Darrieus, (b) H2—Gorlov Helical Turbine, (c) H3—Savonius Turbine, and (d) H4—Hybrid Savonius–Darrieus Turbine.

All selected technologies remain at the prototype or pre-commercial stage, with experimental validation but limited commercial deployment [7–11]. Nonetheless, available data are sufficient for comparative evaluation using the MCDA framework.

2.5. Scoring and Ranking

Each selected Wave Energy Converter (WEC) and Hydrokinetic Turbine (HKT) technology is evaluated against the eight criteria listed in Table 6 using a standardized five-point ordinal rubric. The rubric defines performance levels ranging from 1 (Very Poor) to 5 (Excellent), based on both quantitative thresholds (e.g., energy conversion efficiency, TRL, CAPEX estimates) and qualitative descriptors (e.g., integration ease, structural simplicity).

Table 6. Technology Scoring Rubric.

Criterion	Score 1 Very Poor	Score 2 Poor	Score 3 Moderate	Score 4 Good	Score 5 Excellent
Energy Efficiency	<10% conversion efficiency	10–20% efficiency	20–30%, validated in the lab	30–40%, with simulation and pilot data	>40% with strong field or validated lab performance
Technology Readiness Level (TRL)	TRL 1–3: Concept only	TRL 4: Component/lab validation	TRL 5–6: Prototype or pilot stage	TRL 7–8: Field-tested or near-commercial	TRL 9: Operational deployment in real marine settings
Self-Starting Capability	The technology is unable to self-start or requires significant external intervention across the operational conditions of a given site.	Requires external input or complex triggering under most conditions, leading to significant downtime.	Partially self-starts under some of the site’s environmental conditions.	Consistent startup with some environmental dependence. The technology can reliably self-start across a majority of the site’s expected conditions.	The technology is fully autonomous and reliably self-starts across the full range of environmental conditions for its chosen deployment site.
Structural Simplicity	Highly complex, hard to fabricate or maintain	Moderately complex, many moving parts	Balanced: typical marine complexity	Simple construction; some modularity	Very simple, modular, easy to maintain, and scalable
Ease of Integration	Incompatible with the platform or requires a total redesign	Difficult, needs major adaptation	Moderate: fits with adaptation	Integrates with minimal modification	Plug-and-play compatibility with hybrid platforms
Environmental Adaptability	The technology is inoperable or experiences frequent structural failure in the intended deployment environment.	Operates with a narrow bandwidth, requiring limited sea states and facing significant downtime.	Performs acceptably in average operating conditions for the site, but performance degrades in more extreme conditions.	Operates efficiently under a wide range of conditions typical of the site.	The technology is highly resilient, able to maintain peak performance across the full range of environmental conditions for the chosen deployment site.
Installation Complexity	Requires large vessels, deepwater, or heavy lifting	High logistical requirement	Moderate operations, feasible for coastal deployment	Easy installation in typical conditions	Rapid, low-cost installation in shallow or moderate water depths
Indicative LCOE/CAPEX	>1.0 USD/kWh, very high CAPEX	0.7–1.0 USD/kWh, high CAPEX	0.5–0.7 USD/kWh, moderate cost	0.3–0.5 USD/kWh, lower cost potential	<0.3 USD/kWh, strong scalability, and cost reduction prospects

Scores are assigned based on a combination of peer-reviewed literature, validated experimental results, numerical simulations, and documented technology roadmaps. For quantifiable metrics such as efficiency and TRL, score assignment follows defined performance bands. For qualitative aspects like self-starting capability or environmental adaptability, scoring is guided by engineering judgment aligned to rubric definitions and supported by published case data.

For qualitative criteria such as ‘Self-Starting Capability’ and ‘Environmental Adaptability’, scores are determined in relation to the specific environmental profile of each site. This approach ensures the framework remains site-agnostic, adaptable, and unbiased across different locations. This allows the rubric to evaluate a technology’s resilience across

a range of marine environments, from a mild sea state like the South China Sea to a more critical one like the North Sea.

Meanwhile, for the indicative LCOE and CAPEX criteria, the scores are based on device-class cost estimates drawn from peer-reviewed literature and technology roadmaps. These figures represent the cost of the core energy converter and are suitable for this study's early-stage concept selection. It is important to note that these values do not include project-specific costs such as those related to mooring and foundation systems, grid connection infrastructure, or detailed operation and maintenance (O&M) strategies. This approach ensures a consistent and fair preliminary comparison between technologies without being skewed by site-specific project variables.

Following the scoring process, the Simple Additive Weighting (SAW) method is applied [47] to aggregate the normalized criterion scores and derive overall performance values for each WEC, HKT, and hybrid pairing. The selection of SAW was a deliberate choice over more complex multi-criteria decision-making (MCDM) alternatives, such as TOPSIS, AHP, and PROMETHEE, for its superior suitability in early-stage concept screening. SAW is one of the most widely used and computationally efficient MCDM methods [48,49]. Its fundamental simplicity, based on a weighted sum of normalized scores, provides a high degree of transparency and ease of interpretation [48,50]. This makes it particularly effective for the initial phase of the study, where the primary objective is to rapidly rank and shortlist technologies from a diverse set of criteria [51]. Unlike more iterative and data-intensive methods, SAW's direct application streamlines the assessment process, allowing for a robust and defensible selection of promising candidates without unnecessary complexity [47]. This makes it an ideal tool for evaluating a mix of both quantitative (e.g., indicative cost) and qualitative (e.g., structural simplicity) criteria.

Each criterion is assigned a weight based on its importance, as shown in Table 3. The score for each technology is then computed as the weighted sum of its ratings across all criteria [52]:

$$S_{ij} = \sum_{j=1}^n w_j \cdot x_{ij}$$

where:

- S_i is the total weighted score of technology of the i th WEC or HKT,
- w_j is the weight of the j th evaluation criterion (as per Table 1),
- x_{ij} is the assigned score (from 1 to 5) of i th technology under criterion j ,
- $n = 8$ is the number of evaluation criteria.

Each raw score is directly multiplied by its corresponding weight, and the summation yields a total score. Technologies are then ranked in descending order of S_i . The top two WECs and top two HKTs with the highest total scores are selected for hybrid integration in the next evaluation stage (Section 2.6). This scoring process ensures a transparent, replicable, and criteria-weighted evaluation of candidate technologies using published data and expert-informed scoring.

2.6. Pairing Evaluation

In the second stage, the two highest-ranked WEC and HKT technologies are combined to form four hybrid WEC–HKT pairings. Each pairing is evaluated for integration compatibility using five critical integration criteria:

- i. Structural Compatibility
- ii. PTO Feasibility
- iii. Mooring Synergy
- iv. Co-location Feasibility

v. Control Compatibility

Each pairing is scored using a five-point ordinal rubric as shown in Table 7, where a score of 1 represents very poor integration feasibility and 5 denotes excellent integration potential. The scoring rubric includes qualitative descriptors grounded in platform co-design experience and integration studies for hybrid marine energy systems.

Table 7. Integrated technology compatibility rubric.

Criterion	Score 1 Very Poor	Score 2 Poor	Score 3 Moderate	Score 4 Good	Score 5 Excellent
Structural Compatibility	Devices are physically incompatible; integration is not feasible	Major conflicts in geometry or motion	Minor structural compromises required	Compatible with adjustments	Seamless integration on a common structure or pontoon
PTO Feasibility	PTOs interfere or cannot be co-located	Shared structure causes mechanical or dynamic conflicts	Separate PTOs with acceptable space allocation	Efficient independent operation	Fully independent PTO systems; no physical or dynamic conflict
Mooring Synergy	Mooring needs differ entirely; high installation complexity	Mooring loads or dynamics may conflict	Moderate overlap in mooring requirements	Compatible mooring system is feasible	Can share a simple mooring layout with balanced load distribution
Co-location Feasibility	Devices disturb each other's flow or motion significantly	Risk of partial flow interference	Acceptable with spatial planning	Good spatial separation, stable flow regime	Completely distinct flow domains; optimal spatial utilization
Control Compatibility	Control systems conflict or destabilize each other	Fully separate controls required	Independent control is feasible with minor coordination	Coordinated or passive control integration is possible	Highly synergistic; passive or unified control possible

To ensure consistency with Stage 1 scoring, the SAW method is also applied in this stage. The total integration score, S_k for each pairing, k , is computed as follows [52]:

$$S_k = \sum_{j=1}^m w'_j \cdot x_{kj}$$

where:

- S_k is the total integration score of k th hybrid pairing,
- w'_j is the weight for criterion j th integration criterion,
- x_{kj} is the score (1 to 5) of the pairing k under criterion j ,
- $m = 5$ is the number of integration criteria.

This allows systematic comparison of pairing viability, with higher scores indicating more compatible and integrable hybrid systems. The pairing with the highest total score is recommended for subsequent platform-level design and simulation.

3. Results

This section presents the results of the comparative evaluation of selected WECs and HKT technologies using the MCDA framework introduced in Section 2. Weighted scores are calculated for each technology based on the defined performance criteria. The outcomes support technology ranking and inform hybrid pairing selection, as discussed in the following subsections.

3.1. Evaluation of Wave Energy Converter (WEC) Technologies

The comparative evaluation of four WEC technologies reveals notable performance differences across the assessed criteria. Table 8 presents the scoring matrix, including the individual scores and supporting rationale for each criterion based on the 1–5 rubric. To determine the overall ranking, these scores were weighted according to the criteria weights

outlined in Table 3 and aggregated using the SAW method described in Section 2.5. The resulting weighted totals and rankings are presented in Table 9.

The Oscillating Water Column (OWC) (W1) achieves the highest total score of 4.05, reflecting strong performance in efficiency [12], TRL, self-starting capability, and ease of integration. Its passive air chamber design, mature deployment history, and well-established operation in nearshore environments [53] make it a robust and practical choice for integrated coastal systems. The Point Absorber (PA) (W2) secures second place with a total score of 3.85. It demonstrates excellent energy capture and adaptability to diverse wave climates. Although it involves more complex power take-off (PTO) mechanisms, its flexibility in array configurations supports broader integration possibilities [54].

The Oscillating Wave Surge Converter (OWSC) (W4) ranks third with a total score of 3.40. This system benefits from good adaptability and moderate efficiency, but it requires precise flap control and has limited full-scale deployments [12], which reduces its overall maturity and ease of integration. The Overtopping Wave Energy Converter (OWEC) (W3) scores the lowest at 2.80, primarily due to its structural and installation complexity. Although it can achieve high energy capture under optimized conditions, its large footprint, civil works demand, and higher capital costs [55] pose deployment challenges in constrained or remote environments.

Table 8. Scoring Matrix for Wave Energy Converter (WEC) Technologies.

Criteria	W1		W2		W3		W4	
	Score	Remark	Score	Remark	Score	Remark	Score	Remark
Efficiency/ Energy Capture	3	System efficiency ~25–30%; pneumatic losses [6,56]	5	High CWR; up to 50% efficiency under resonance [6,32]	4	30–40% overtopping efficiency with optimized ramps [6,56]	4	Moderate-to-high capture efficiency with tuning [6,32]
TRL	5	Deployed in Mutriku, Pico—TRL 9 [6,7,56]	4	Numerous prototypes at sea; TRL 7–8 [6,11,32]	3	Wave Dragon, CROWN at TRL 6–7 [6,7,56]	3	Tested at small scale; limited full deployments [6,11,32]
Self-Starting Capability	5	Fully passive system; no control required [6,56]	4	Passive float operation with some damping control [6,11,32]	5	Ramp fills naturally; no startup energy needed [6,56]	4	Wave-induced flap motion is automatic [6,32]
Structural Simplicity	4	Simple chamber + air turbine setup [6,56]	3	More complex PTO and drivetrain than W1 [6,32]	2	Large ramp + reservoir; significant civil works [6,56]	3	Flap and hinge systems need precision but are manageable [6,32]
Ease of Integration	5	Well-suited for integration with breakwaters or platforms [6,7,28,56]	4	Flexible mooring allows integration in arrays [6,11,32]	3	Shared PTO is possible but complicated [6,7]	4	Can co-locate with fixed seabed platforms [6,7,11]
Environmental Adaptability	4	Performs well in nearshore environments [6,7,56]	4	Omnidirectional; suitable for most wave climates [6,11,32]	3	Effective in moderate-high wave height zones [6,7,32]	4	Tolerates varying wave direction and depth [6,11,56]
Installation Complexity	3	Requires ducting and structural support [6,7,56]	3	Moderate complexity in float positioning [6,11,32]	2	Heavy structures; complex to deploy [6,7]	4	Simpler than OWEC; anchored to the seabed [6,11]
Indicative LCOE/ CAPEX	4	Mature design; medium cost and risk [6,7,56]	3	Varied cost due to PTO system differences [6,11,32]	2	High CAPEX due to platform and turbine requirements [6,7]	3	Custom flap drives cost but are within mid-range [6,11]

Overall, the findings show that technologies with simpler structure, higher maturity, and easier integration, such as OWC and PA, perform better under this analysis framework.

Table 9. Weighted Scoring and Ranking of Wave Energy Converter (WEC) Technologies Based on Performance Criteria.

Criterion	Weight	W1	W2	W3	W4
Efficiency/Energy Capture	0.20	0.60	1.00	0.80	0.80
TRL	0.15	0.75	0.60	0.45	0.45
Self-Starting Capability	0.05	0.25	0.20	0.25	0.20
Structural Simplicity	0.10	0.40	0.30	0.20	0.30
Ease of Integration	0.15	0.75	0.60	0.30	0.60
Environmental Adaptability	0.10	0.40	0.40	0.30	0.30
Installation Complexity	0.10	0.30	0.30	0.20	0.30
Indicative LCOE/CAPEX	0.15	0.60	0.45	0.30	0.45
Total Score		4.05	3.85	2.80	3.40
Ranking		1st	2nd	4th	3rd

3.2. Evaluation of Hydrokinetic Turbine (HKT) Technologies

The comparative assessment of four hydrokinetic turbine technologies shows distinct performance profiles across multiple criteria. Table 10 presents the scoring matrix, and Table 11 shows the weighted scores and rankings derived using the SAW method.

The Savonius turbine (H3) ranks the highest with a total weighted score of 4.05, highlighting its strengths in self-starting capability, ease of integration, and low cost [41]. Its drag-based operation enables reliable performance in low-flow conditions, making it attractive for simple and modular deployment scenarios [57]. The hybrid Savonius–Darrieus turbine (H4) scores 3.50, placing second. It benefits from combining drag and lift mechanisms, which improve self-starting and energy capture. The design offers a balance between performance and structural complexity, with moderate scores across most criteria.

The Gorlov helical turbine (H2) achieves a total score of 3.40, ranking third. It shows good performance in efficiency and integration, aided by smoother torque characteristics and bidirectional flow adaptability [58]. However, it has relatively low scores in cost and structural simplicity. The Darrieus (H-type) turbine (H1) receives the lowest score of 3.25, mainly due to its poor self-starting ability [59] and moderate integration performance. While it remains strong in energy capture and TRL, these advantages are offset by practical limitations in real-world deployment.

Table 10. Scoring Matrix for Hydrokinetic Turbine (HKT) Technologies.

Criteria	H1		H2		H3		H4	
	Score	Remark	Score	Remark	Score	Remark	Score	Remark
Efficiency/ Energy Capture	4	Peak $C_p \sim 0.35\text{--}0.4$ (Experiment & CFD) [31,38,43]	4	$C_p \sim 0.31$ under optimized design; smoother torque (CFD only) [31,60]	2	$C_p \sim 0.15\text{--}0.25$ (Field/lab validated) [41,42]	3	$C_p \sim 0.27$, (Experiment & CFD) [43,60]
TRL	4	Pilot- and full-scale use (e.g., EDF projects) [31,36,38]	3	Demonstrated in a small demo stage; limited commercial use [31,60]	4	Widely deployed in rivers and lab-tested [39,41,42]	2	Novel suited with a few small-scale implementations [43,60]
Self-Starting Capability	1	Requires external initiation or variable-pitch mechanisms [36,38]	2	Helical twist improves self-starting, but is still limited [31,60]	5	Naturally self-starts in low flows thanks to drag design [41,42]	4	Self-start enabled by Savonius section [43,60]
Structural Simplicity	3	Curved blades & vertical setup—moderately complex [36,38,44]	3	Complex helical geometry: single axis simplifies structure [31,39,61]	5	Simple scoops; easy to fabricate [39,41,42]	4	Hybrid geometry adds moderate complexity [11,43,60]

Table 10. *Cont.*

Criteria	H1		H2		H3		H4	
	Score	Remark	Score	Remark	Score	Remark	Score	Remark
Ease of Integration	3	Vertical layout fits stacking, but lacks self-start plug-and-play [36,38,61]	4	Smoother torque via helical design aids platform integration [31,39,43]	5	Passive and modular—easily deployed under platforms [41,42,62]	4	Hybrid more versatile than H1/H2 in platform settings [11,31,43]
Environmental Adaptability	3	Sensitive to flow speed and TSR range [36,38,61]	4	Handles unsteady flow better than straight-Darrieus [31,39,43]	4	Performs well in turbulent/shallow environments [41,42,62]	4	Maintains broad performance envelope of drag + lift [11,31,43]
Installation Complexity	3	Requires alignment systems; moderate installation needs [36,38,61]	3	Similar mounting to Darrieus; helical adds minor complexity [31,39,43]	4	Compact unit; low logistics [41,42,62]	4	Modular shallow-depth install [11,31,43]
Indicative LCOE/CAPEX	3	Moderate cost from fabrication and control infrastructure [31,36,38,39,43,61]	3	Slightly higher cost due to blade shaping [31,39,43]	5	Low-cost materials & maintenance [41,42,62]	4	Higher cost offset by efficiency gains [11,43,61]

Table 11. Weighted Scoring and Ranking of Hydrokinetic Turbine (HKT) Technologies Based on Performance Criteria.

Criterion	Weight	H1	H2	H3	H4
Efficiency/Energy Capture	0.20	0.80	0.80	0.40	0.60
TRL	0.15	0.60	0.45	0.60	0.30
Self-Starting Capability	0.05	0.05	0.10	0.25	0.20
Structural Simplicity	0.10	0.30	0.30	0.50	0.40
Ease of Integration	0.15	0.45	0.60	0.75	0.60
Environmental Adaptability	0.10	0.30	0.40	0.40	0.40
Installation Complexity	0.10	0.30	0.30	0.40	0.40
Indicative LCOE/CAPEX	0.15	0.45	0.45	0.75	0.60
Total Score		3.25	3.40	4.05	3.50
Ranking		4th	3rd	1st	2nd

The results emphasize the balance between efficiency, complexity, and operability. Technologies like Savonius, although less efficient, offer robust performance in broader deployment contexts due to their simplicity and adaptability.

3.3. Evaluation of WEC–HKT Pairings Configurations

This section presents the findings of the integration feasibility evaluation of hybrid wave–current systems by combining the top two WECs and HKTs identified in Sections 3.1 and 3.2. The selected technologies are the Oscillating Water Column (W1) and Point Absorber (W2), paired with the Savonius turbine (H3) and the Hybrid Savonius–Darrieus rotor (H4). These technologies represent the most promising candidates for hybridization on a shared offshore platform. Each WEC is matched with both HKT options, resulting in four configurations: W1H3 (OWC + Savonius), W1H4 (OWC + Hybrid), W2H3 (PA + Savonius), and W2H4 (PA + Hybrid).

Figure 6 presents a representative schematic of a hybrid wave–current energy system. The diagram illustrates the general integration concept, where incident waves are converted by a Wave Energy Converter (WEC) and ocean currents are harnessed by a Hydrokinetic Turbine (HKT). Both devices are mounted on a shared offshore platform equipped with mooring lines for station-keeping. Each energy conversion pathway operates independently through its respective power take-off, but both contribute to a common

power distribution and export system. The schematic is intended as a conceptual outline to illustrate integration principles rather than a finalized engineering design. As an illustrative example, hybrid platforms are typically considered in moderate water depths of 20–50 m, where both wave and tidal resources are co-located. Reported conditions in recent reviews show wave climates with significant wave heights (H_s) of 1–3 m and peak periods (T_p) of 6–10 s, under which WECs have achieved 20–45% system efficiency [6,38]. Similarly, tidal or residual currents in the range of 1.0–2.5 m/s are commonly documented in coastal straits and shelves, supporting HKT operation with peak C_p values of 0.35–0.40 in experimental or field-validated studies [6,38]. These values are not site-specific but illustrate the representative conditions under which the WEC provides stable pneumatic or hydrodynamic conversion from moderate waves, while the HKT ensures reliable self-starting performance from predictable currents. Together, the hybrid platform enhances overall energy yield and stability compared with single-technology deployment.

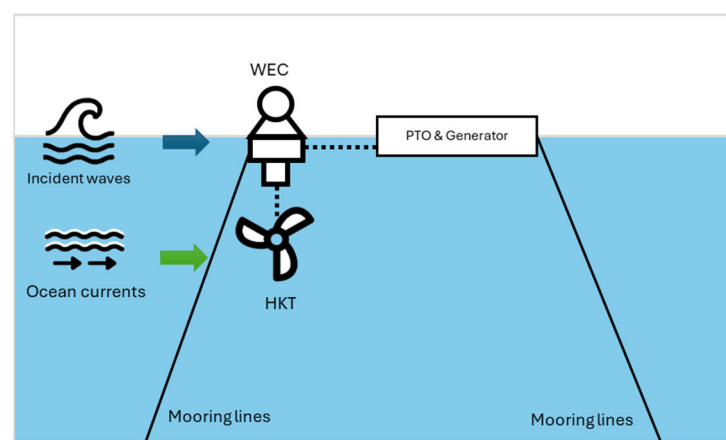


Figure 6. A representative schematic of a hybrid wave–current energy system.

The integration performance of each pairing is evaluated using five criteria, as summarized in Tables 12–15.

Table 12. Scoring matrix for WEC–HKT (W1H3) pairing.

Criterion	Score	Remark
Structural Compatibility	4	OWC chambers can be mounted on a floating or semi-submerged platform, while Savonius turbines are compact and vertically oriented, enabling co-location without structural interference [6,7,38]
Power Take-Off (PTO) Feasibility	4	OWC operates through an air turbine, typically Wells or impulse type, while Savonius uses a mechanical rotating shaft. The PTO systems are mechanically decoupled, reducing integration risk [6,38,41]
Mooring Synergy	4	Both devices can be secured with conventional bottom-fixed spread or taut mooring systems. No directional mooring is required, simplifying layout [6,7,11]
Co-location Feasibility	5	OWC captures wave energy at the platform front, while Savonius is driven by water currents and can be placed downstream or peripherally. This spatial separation minimizes hydrodynamic interference [6,11,56]
Control Compatibility	4	Both systems operate passively. Their independent control strategies minimize load conflicts, simplifying supervisory logic [6,38,41]
Total Score	21	

Table 13. Scoring matrix for WEC–HKT (W1H4) pairing.

Criterion	Score	Remark
Structural Compatibility	3	Hybrid rotor adds drag and bulk; more difficult to position adjacent to OWC without impacting air chamber function [6,7,38].
Power Take-Off (PTO) Feasibility	3	Hybrid rotor requires more robust shafting or generator space, harder to colocate with OWC turbine chamber [6,38,41].
Mooring Synergy	3	Still feasible but requires reinforcement due to hybrid rotor load variations [7,11].
Co-location Feasibility	4	Spatially manageable but tighter clearances and stability concerns [6,11].
Control Compatibility	3	Requires distinct operational logic for both devices; more challenging if integrated in one supervisory control and data acquisition (SCADA) system [6,7].
Total Score	16	

Table 14. Scoring matrix for WEC–HKT (W2H3) pairing.

Criterion	Score	Remark
Structural Compatibility	3	Point absorber uses vertical heave motion, which can conflict with the vertical axis rotor frame [6,32,38].
Power Take-Off (PTO) Feasibility	3	Both PTO systems are modular and can be separated, but vibration coupling may occur if on the same deck [6,11,38].
Mooring Synergy	4	Mooring loads are similar (vertical + low lateral), allowing a shared anchor grid [7,11,63].
Co-location Feasibility	3	Requires careful placement to avoid flow interference; point absorber may induce localized turbulence [6,11,32].
Control Compatibility	4	Independent operation feasible; some coordination for platform stability [6,11,62,64].
Total Score	17	

Table 15. Scoring matrix for WEC–HKT (W2H4) pairing.

Criterion	Score	Remark
Structural Compatibility	2	Hybrid rotor is bulky and may disturb the floating motion of the point absorber; risk of structural resonance [6,7,38]
Power Take-Off (PTO) Feasibility	2	Competing shaft and generator requirements; higher risk of mechanical conflict [11,38,41]
Mooring Synergy	3	May require separate or asymmetric mooring to support both dynamics [7,11,63]
Co-location Feasibility	2	Low—both need distinct spatial domains; a hybrid rotor may experience disturbed inflow [6,11,56]
Control Compatibility	3	Synchronizing buoy and rotor control is difficult; it likely needs two separate controllers [6,11,62,64]
Total Score	12	

The W1H3 (OWC–Savonius) pairing achieves the highest total score of 21, demonstrating strong integration potential. The chamber-based design of the OWC is structurally compatible with the vertically compact Savonius rotor. Their respective PTO systems, air turbine, and mechanical shaft operate independently with minimal interference. The spatial arrangement allows effective co-location, as the OWC faces incoming waves while the Savonius operates in the current flow below. Both systems exhibit low control complexity,

enabling streamlined supervisory control. This configuration is well-suited for deployment on nearshore or semi-submerged platforms.

The W1H4 (OWC–Hybrid Savonius–Darrieus) configuration scores 16, indicating moderate integration potential. While the hybrid rotor offers enhanced efficiency, its larger structural footprint introduces challenges in co-location and control integration. Structural modifications and reinforced mooring may be required to support stable operation. This pairing may be suitable for applications prioritizing power output over structural simplicity.

The W2H3 (PA–Savonius) pairing scores 17, suggesting viable integration with design precautions. The drag-based operation of the Savonius may interact with the heaving motion of the point absorber, potentially causing dynamic interference. However, co-location and mooring can be managed with careful layout. This pairing remains feasible for floating systems with proper separation and control strategies.

The W2H4 (PA–Hybrid Rotor) configuration scores 12, the lowest among the four. Structural and control incompatibilities are pronounced, especially due to the hybrid rotor's mass and asynchronous dynamics. Co-location is limited by spatial conflict and potential resonance, making this pairing the least favorable for integration.

The raw scores are normalized by multiplying each by their respective criterion weight. The resulting weighted scores and overall rankings are summarized in Table 16. The W1H3 (OWC–Savonius) pairing emerges as the most promising hybrid configuration due to its favorable spatial layout, operational independence, and mooring simplicity. It offers a practical pathway for early-stage hybrid deployment, particularly in shallow or near-shore environments. Conversely, the W2H4 (PA–Hybrid Rotor) pairing demonstrates limited integration feasibility and is not recommended for shared platform applications.

Table 16. Weighted Scoring and Ranking for WEC–HKT Hybrid Pairings.

Criterion	Weight	W1H3	W1H4	W2H3	W2H4
Structural Compatibility	0.20	0.8	0.6	0.6	0.4
Power Take-Off (PTO) Feasibility	0.20	0.8	0.6	0.6	0.4
Mooring Synergy	0.20	0.8	0.6	0.8	0.6
Co-location Feasibility	0.20	1	0.8	0.6	0.4
Control Compatibility	0.20	0.8	0.6	0.8	0.6
Total Integrated Score		4.2	3.2	3.4	2.4
Ranking		1st	3rd	2nd	4th

3.4. Sensitivity Analysis

A sensitivity analysis was performed to validate the weighting process and resulting rankings, where each criterion weight is varied by $\pm 10\%$ and $\pm 20\%$ using deterministic perturbation analysis with proportional adjustment of the remaining weights. This procedure is commonly recommended in MCDA studies to verify the stability of results under reasonable changes in expert-assigned weights [65]. The recalculated weighted scores and ranks for WECs, HKTs, and hybrid pairings are presented in Tables 17–19. The results show that the top-ranked WEC (W1), HKT (H3), and hybrid pairing configuration (W1H3) remained unchanged across all perturbation levels, while only minor shifts occurred among lower-ranked alternatives. This confirms that the final rankings are robust and reliable despite moderate variations in the assigned weights.

In addition to weight perturbation, a one-at-a-time sensitivity test was carried out to examine the robustness of the integration feasibility scores for the top two pairings, W1H3 and W2H3. This test applies to a conservative adjustment where W1H3 is reduced by one point on a given criterion while W2H3 is simultaneously increased by one point.

Table 17. Sensitivity analysis results for WEC rankings under $\pm 10\%$ and $\pm 20\%$ weight perturbations.

WEC	Base Score	Rank	−10% Score	Rank	+10% Score	Rank	−20% Score	Rank	+20% Score	Rank
W1	4.05	1	3.645	1	4.455	1	3.24	1	4.86	1
W2	3.85	2	3.465	2	4.235	2	3.08	2	4.62	2
W4	3.4	3	3.06	3	3.74	3	2.72	3	4.08	3
W3	2.8	4	2.52	4	3.08	4	2.24	4	3.36	4

Table 18. Sensitivity analysis results for HKT rankings under $\pm 10\%$ and $\pm 20\%$ weight perturbations.

HKT	Base Score	Rank	−10% Score	Rank	+10% Score	Rank	−20% Score	Rank	+20% Score	Rank
H1	3.25	4	2.925	4	3.575	4	2.6	4	3.9	4
H2	3.4	3	3.06	3	3.74	3	2.72	3	4.08	3
H3	4.05	1	3.645	1	4.455	1	3.24	1	4.86	1
H4	3.5	2	3.15	2	3.85	2	2.8	2	4.2	2

Table 19. Sensitivity analysis results for Pairing rankings under $\pm 10\%$ and $\pm 20\%$ weight perturbations.

Pairing	Base Score	Rank	−10% Score	Rank	+10% Score	Rank	−20% Score	Rank	+20% Score	Rank
W1H3	4.2	1	3.78	1	4.62	1	3.36	1	5.04	1
W1H4	3.2	3	2.88	3	3.52	3	2.56	3	3.84	3
W2H3	3.4	2	3.06	2	3.74	2	2.72	2	4.08	2
W2H4	2.4	4	2.16	4	2.64	4	1.92	4	2.88	4

As shown in Table 20, W1H3 consistently retained a higher total score of 20 compared with 18 for W2H3 across all five criteria. This outcome confirms that the score margin between W1H3 (baseline 21) and W2H3 (baseline 17) is both substantive and stable against reasonable criterion-level variations. The finding strengthens that W1H3 remains the most feasible configuration under conservative assumptions.

Table 20. One-at-a-time sensitivity test for W1H3 vs. W2H3 (± 1 score).

Criterion Varied (± 1)	W1H3 Score (−1)	W2H3 Score (+1)	Margin (W1H3—W2H3)	Remark
Structural Compatibility	20	18	+2	W1H3 > W2H3
Power Take-Off Feasibility	20	18	+2	W1H3 > W2H3
Mooring Synergy	20	18	+2	W1H3 > W2H3
Co-location Feasibility	20	18	+2	W1H3 > W2H3
Control Compatibility	20	18	+2	W1H3 > W2H3

3.5. Implications for Concept Design

The evaluation results presented in Section 3.3 offer direct implications for early-stage hybrid platform design, particularly in guiding the configuration of shared structural systems, mooring strategies, and control architectures. Among the four pairings, the W1H3 (OWC–Savonius) configuration ranks highest due to its strong spatial separation, independent PTO systems, and simple mooring layout. These characteristics reduce integration complexity, making W1H3 a viable candidate for preliminary engineering development.

From a platform layout perspective, the spatial decoupling of WEC and HKT components allows the OWC to be mounted at the platform front to maximize wave exposure, while the Savonius rotor can be deployed beneath or downstream to harness current flows. This spatial arrangement minimizes hydrodynamic interference, a factor highlighted by [8,14,35], and supports modular system design.

In terms of simulation setup, the structural compatibility and control independence observed in W1H3 simplify the CFD modeling process. Since both devices operate passively

with minimal real-time interaction, domain partitioning, boundary condition assignment, and time-stepping requirements can be independently optimized, aligning with best practices in marine energy simulation [10,24,35]. For instance, the air–water interaction in the OWC chamber can be modeled with free-surface and compressible flow techniques, while the Savonius rotor requires multiphase flow treatment with dynamic mesh capabilities. The decoupled nature of these subsystems reduces simulation overhead and improves convergence reliability.

These findings also inform prototype planning and scaling. The independent PTO mechanisms (air turbine vs. shaft generator) reduce inter-system mechanical coupling, enabling isolated lab-scale testing of each subsystem before full integration. According to [4,35], such staged testing facilitates iterative refinement and risk reduction in early TRL development. Furthermore, the shared mooring feasibility simplifies the physical design of anchoring and tethering systems, particularly in nearshore environments where seabed conditions can be leveraged to support both devices simultaneously [14,28,31].

Beyond integration feasibility, practical deployment requires consideration of reliability, maintainability, and economic viability. OWCs face durability challenges related to turbine wear, chamber sealing, and structural fatigue under repeated loading, while Savonius rotors, though mechanically simple, may be prone to bearing fatigue and cyclic hydrodynamic loads [35,62]. Maintainability depends on platform accessibility and modular PTO design, which can facilitate staged replacement and reduce downtime.

Recent work on hybrid offshore microgrids has highlighted the importance of predictive O&M strategies, such as deep learning models for battery degradation, to ensure long-term reliability and cost control [66]. Similarly, techno-economic analyses of extreme hybrid systems, such as the South Pole case study, underline the challenges of maintaining and operating integrated platforms in harsh or isolated environments [67]. Applied concepts like renewable-powered floating data centers further demonstrate the trajectory toward real-world hybrid deployment, emphasizing system resilience and practicality [68,69]. Economically, hybridization can partially offset structural and mooring costs by co-locating devices on a shared platform, but overall viability depends on reducing CAPEX and OPEX and achieving lower LCOE as prototypes mature. Recent deployments have shown gradual progress, with LCOE reductions from £300/MWh in 2018 to £259/MWh in 2023 [62,64], yet hybrid WEC–HKT systems remain at relatively low TRLs.

Finally, while the present study provides a structured comparison of WEC–HKT hybrid configurations, several limitations should be noted. First, the evaluation combines mixed performance metrics such as system efficiency and power coefficient (C_p), which may introduce comparability challenges. Second, the analysis does not incorporate explicit uncertainty bands for expert ratings or model inputs, and future work should adopt probabilistic or fuzzy approaches to better capture variability. Third, the expert panel is relatively small, and although Kendall’s W indicated acceptable consistency, potential bias remains due to the limited sample size. Finally, as this work is positioned as an early-stage concept selection study, the evaluation necessarily relies on literature data and expert judgment. To address these limitations, future research will advance the top-ranked W1H3 pairing through detailed CFD modelling, structural layout development, and laboratory-scale validation, supported by techno-economic assessment. These activities will provide quantitative validation to complement the present integrative analysis.

4. Conclusions

This study presented a structured concept selection approach for hybrid wave–current energy generation systems using a multi-criteria decision analysis (MCDA) framework. By systematically evaluating four shortlisted WEC–HKT pairings across five key integration

criteria, the study identified the OWC–Savonius (W1H3) configuration as the most feasible option for co-located deployment. This pairing demonstrated strong compatibility in structural layout, PTO independence, mooring simplicity, and operational control, making it suitable for early-stage engineering development.

The findings reinforce the importance of selecting technologies not only based on individual performance but also on system-level integration feasibility. Pairings with decoupled energy extraction mechanisms and minimal spatial or dynamic interference, such as W1H3, tend to outperform more complex hybrid configurations. In contrast, the PA–Hybrid Rotor (W2H4) pairing revealed significant structural and control limitations, underscoring the need for caution in forced hybridization of mechanically intensive systems.

The concept selection outcomes provide a practical decision-making foundation for technology developers, enabling focused design, simulation, and prototyping efforts on the most promising hybrid configurations. The novelty of this work lies in integrating a transparent MCDA workflow, incorporating expert weighting, Kendall’s W, and sensitivity analysis, into the hybrid marine energy context. While earlier studies have reviewed WECs, HKTs, or hybrid systems descriptively, few have established a reproducible evaluation framework for concept screening. By addressing this gap, the study provides a methodological foundation for advancing hybrid platform design. As a next step, the W1H3 system will be advanced through detailed CFD modelling, structural layout development, and laboratory-scale validation. Parallel techno-economic analysis will also be conducted to evaluate its viability in specific site conditions and deployment scenarios.

Author Contributions: Conceptualization, C.Y.N. and M.C.O.; methodology, C.Y.N. and M.C.O.; validation, C.Y.N. and M.C.O.; formal analysis, C.Y.N.; investigation, C.Y.N. and M.C.O.; data curation, C.Y.N. and M.C.O.; writing—original draft preparation, C.Y.N.; writing—review and editing, C.Y.N. and M.C.O.; visualization, C.Y.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets generated and analyzed during the current study, including criteria definitions, scoring rubrics, raw expert responses, weighting calculations, and pairing evaluation sheets, are openly available in Zenodo at <https://doi.org/10.5281/zenodo.17149692>.

Acknowledgments: The authors gratefully acknowledge the 11 expert panel members who contributed their time and insights to the survey that supported this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HKT	Hydrokinetic Turbine
WEC	Wave Energy Converter
MCDA	Multi-Criteria Decision Analysis
TRL	Technology Readiness Level
OWC	Oscillating Water Column
PA	Point Absorber
OTD	Overtopping Device
OWSC	Oscillating Wave Surge Converter
Cp	Power Coefficient
CFD	Computational Fluid Dynamics

Appendix A

Table A1. Raw Ratings from Expert Panel for Each Criterion.

Expert Panel (EP)	Efficiency	TRL	Self-Start	Simplicity	Integration	Adaptability	Installation	LCOE/CAPEX
EP 1	10	9	4	7	8	6	6	9
EP 2	10	10	3	6	9	7	5	10
EP 3	10	6	1	7	9	6	6	8
EP 4	9	8	5	6	7	6	6	8
EP 5	10	9	4	8	9	7	7	9
EP 6	9	9	5	7	8	6	6	9
EP 7	9	10	3	6	10	8	6	7
EP 8	10	9	2	6	9	7	6	8
EP 9	9	6	4	7	8	7	6	6
EP 10	10	9	5	7	8	7	7	8
EP 11	10	8	2	8	10	7	7	9

Table A2. Per-expert ranking matrix (r_{ij}) with ties averaged.

Expert Panel (EP)	Efficiency	TRL	Self-Start	Simplicity	Integration	Adaptability	Installation	LCOE/CAPEX
EP 1	8	6.5	1	4	5	2.5	2.5	6.5
EP 2	7	7	1	3	5	4	2	7
EP 3	8	3	1	5	7	3	3	6
EP 4	8	6.5	1	3	5	3	3	6.5
EP 5	8	6	1	4	6	2.5	2.5	6
EP 6	7	7	1	4	5	2.5	2.5	7
EP 7	6	7.5	1	2.5	7.5	5	2.5	4
EP 8	8	6.5	1	2.5	6.5	4	2.5	5
EP 9	8	3	1	5.5	7	5.5	3	3
EP 10	8	7	1	3	5.5	3	3	5.5
EP 11	7.5	4.5	1	4.5	7.5	2.5	2.5	6
Sum of ranks	83.5	64.5	11	41	67	37.5	29	62.5

References

1. Nullis, C. *Climate Change Indicators Reached Record Levels in 2023*; WMO; World Meteorological Organization: Geneva, Switzerland, 2024.
2. International Energy Agency. *World Energy Outlook 2023*; International Energy Agency: Paris, France, 2023.
3. Igini, M. Fossil Fuel Comprised 82% of Global Energy Mix in 2023. Available online: <https://earth.org/fossil-fuel-accounted-for-82-of-global-energy-mix-in-2023-amid-record-consumption-report/> (accessed on 25 May 2025).
4. World Energy Council. *World Energy Trilemma 2024: Evolving with Resilience and Justice*; World Energy Council: London, UK, 2024.
5. U.S. Department of Energy. Advantages of Marine Energy. Available online: <https://www.energy.gov/eere/water/advantages-marine-energy> (accessed on 25 July 2025).
6. Chen, P.; Wu, D. A review of hybrid wave-tidal energy conversion technology. *Ocean Eng.* **2024**, *303*, 117684. [\[CrossRef\]](#)
7. Cipolletta, M.; Crivellari, A.; Moreno, V.C.; Cozzani, V. Design of sustainable offshore hybrid energy systems for improved wave energy dispatchability. *Appl. Energy* **2023**, *347*, 121410. [\[CrossRef\]](#)
8. Neshat, M.; Sergiienko, N.Y.; da Silva, L.S.; Mirjalili, S.; Gandomi, A.H.; Abdelkhalik, O.; Boland, J. Hybrid Wave-wind System Power Optimisation Using Effective Ensemble Covariance Matrix Adaptation Evolutionary Algorithm. *arXiv* **2025**, arXiv:2505.20720. [\[CrossRef\]](#)
9. Huang, Y.; Yuan, B.; He, H.; Na, J.; Feng, Y.; Li, G.; Zhao, J.; Wong, P.K.; Cui, L. Control-Oriented Modelling and Adaptive Parameter Estimation for Hybrid Wind-Wave Energy Systems. *IET Renew. Power Gener.* **2025**, *19*, e70104. [\[CrossRef\]](#)
10. Bon, T.; Van Craenenbroeck, V.; Meyers, J. How thermally-induced secondary motions in offshore hybrid wind-solar farms improve wind-farm efficiency. *arXiv* **2024**, arXiv:2410.13005.
11. Kumar, S.; Panagant, N.; Arzaghi, E.; Baalisampang, T.; Garaniya, V.; Abbassi, R. A multi-objective optimisation framework for a standalone hybrid offshore renewable energy system with electrical and hydrogen loads. *Energy* **2025**, *330*, 136826. [\[CrossRef\]](#)
12. Su, X.; Chen, J.; Yuan, L.; Xu, W.; Xiong, C.; Wang, X. Current Status of Development and Application of Ocean Renewable Energy Technology. *Sustainability* **2025**, *17*, 5648. [\[CrossRef\]](#)

13. Whittaker, T.; Folley, M. Nearshore oscillating wave surge converters and the development of Oyster. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2012**, *370*, 345–364. [\[CrossRef\]](#)
14. Kofoed, J.P.; Frigaard, P.; Friis-Madsen, E.; Sørensen, H.C. Prototype testing of the wave energy converter wave dragon. *Renew. Energy* **2006**, *31*, 181–189. [\[CrossRef\]](#)
15. Malipeddi, A.R.; Chatterjee, D. Influence of duct geometry on the performance of Darrieus hydroturbine. *Renew. Energy* **2012**, *43*, 292–300. [\[CrossRef\]](#)
16. Belloni, C. Hydrodynamics of Ducted and Open-Centre Tidal Turbines. Ph.D. Thesis, University of Oxford, Oxford, UK, 2013.
17. Khan, M.J.; Bhuyan, G.; Iqbal, M.T.; Quaicoe, J.E. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Appl. Energy* **2009**, *86*, 1823–1835. [\[CrossRef\]](#)
18. Verdant Power. Marine Energy Solutions. Available online: <https://verdantpower.com/> (accessed on 5 May 2025).
19. Waterotor. Low Cost Power from Slow Moving Water. Available online: <https://waterotor.com/> (accessed on 5 May 2025).
20. Wang, J.-J.; Jing, Y.-Y.; Zhang, C.-F.; Zhao, J.-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278. [\[CrossRef\]](#)
21. Pohekar, S.D.; Ramachandran, M. Application of multi-criteria decision making to sustainable energy planning—A review. *Renew. Sustain. Energy Rev.* **2004**, *8*, 365–381. [\[CrossRef\]](#)
22. Müller-Carneiro, J.; Rodrigues, C.; Dias, L.C.; Antunes, C.H.; Mattos, A.L.; Freire, F. A multi-criteria framework for the ecodesign of bio-based materials at early development stages. *J. Clean. Prod.* **2023**, *427*, 139268. [\[CrossRef\]](#)
23. Cui, Z.; Latif, E.; Stevenson, V. Decision-Making Framework to Identify the Optimal Hybrid Renewable Energy System for Switching UK Representative Domestic Buildings Towards the Net-Zero Target. In *Resilient and Responsible Smart Cities*; Springer: Cham, Switzerland, 2023; pp. 229–241. [\[CrossRef\]](#)
24. Alhijazi, A.A.K.; Almasri, R.A.; Alloush, A.F. A Hybrid Renewable Energy (Solar/Wind/Biomass) and Multi-Use System Principles, Types, and Applications: A Review. *Sustainability* **2023**, *15*, 16803. [\[CrossRef\]](#)
25. Chawla, K. Use of Multi-Criteria Decision Analysis for Energy Planning. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, USA, 2015.
26. Hall, S. GIS-Based Multi-Criteria Decision Analysis for Marine Energy Site Selection: A Case Study Comparison Between Puerto Rico and Hawaii. 2024. Available online: <https://digitalcommons.conncoll.edu/envirohp> (accessed on 5 May 2025).
27. Mahdy, M.; Bahaj, A.S. Multi criteria decision analysis for offshore wind energy potential in Egypt. *Renew. Energy* **2018**, *118*, 278–289. [\[CrossRef\]](#)
28. López, M.; Rodríguez, N.; Iglesias, G. Combined floating offshore wind and solar PV. *J. Mar. Sci. Eng.* **2020**, *8*, 576. [\[CrossRef\]](#)
29. Moreno-Rocha, C.M.; Nuñez-Alvarez, J.R.; Rivera-Alvarado, J.; Ruiz, A.G.; Buelvas-Sanchez, E.A. Buelvas-Sanchez. Multi-criteria evaluation and multi-method analysis for appropriately selecting renewable energy sources in Colombia. *MethodsX* **2025**, *14*, 103248. [\[CrossRef\]](#)
30. Legendre, P. Species associations: The Kendall coefficient of concordance revisited. *J. Agric. Biol. Environ. Stat.* **2005**, *10*, 226–245. [\[CrossRef\]](#)
31. Chen, D.; Ma, Y.; Hu, C.; Zhao, T. Efficiency optimization of twin vertical-axis helical hydrokinetic turbines (VAHHTs) based on Taguchi method. *Appl. Ocean Res.* **2023**, *138*, 103618. [\[CrossRef\]](#)
32. Fairley, I.; Smith, H.; Robertson, B.; Abusara, M.; Masters, I. Spatio-temporal variation in wave power and implications for electricity supply. *Renew. Energy* **2017**, *114*, 154–165. [\[CrossRef\]](#)
33. Jülich, F. MCDA for Sustainability Assessment—Insights to Helmholtz Association Activities: Working Paper; Helmholtz Working Group MCDA for Sustainability Assessment; Helmholtz: Berlin, Germany, 2022.
34. Ashabi, A.; Mostafa, M.; Hryshchenko, A.; Bruton, K.; O’Sullivan, D.T.J. Assessing power-to-heat technologies for industrial electrification: A multi-criteria decision analysis approach. *Energy Convers. Manag. X* **2025**, *25*, 100882. [\[CrossRef\]](#)
35. Saini, G.; Saini, R.P. Comparative investigations for performance and self-starting characteristics of hybrid and single Darrieus hydrokinetic turbine. *Energy Rep.* **2020**, *6*, 96–100. [\[CrossRef\]](#)
36. Domenech, J.; Eveleigh, T.; Tanju, B. Marine Hydrokinetic (MHK) systems: Using systems thinking in resource characterization and estimating costs for the practical harvest of electricity from tidal currents. *Renew. Sustain. Energy Rev.* **2018**, *81*, 723–730. [\[CrossRef\]](#)
37. Drew, B.; Plummer, A.R.; Sahinkaya, M.N. A review of wave energy converter technology. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2009**, *223*, 887–902. [\[CrossRef\]](#)
38. Bhagat, R.; Kumar, D.; Sarkar, S. Design modification and performance prediction of ellipsoid cross-flow hydrokinetic turbine. *Renew. Energy* **2023**, *219*, 119475. [\[CrossRef\]](#)
39. Kirke, B. Towards more cost-effective river hydrokinetic turbines. *Energy Sustain. Dev.* **2024**, *78*, 101370. [\[CrossRef\]](#)
40. Kirke, B. Hydrokinetic and ultra-low head turbines in rivers: A reality check. *Energy Sustain. Dev.* **2019**, *52*, 1–10. [\[CrossRef\]](#)

41. Shanegowda, T.G.; Shashikumar, C.M.; Gumptapure, V.; Madav, V. Numerical studies on the performance of Savonius hydrokinetic turbines with varying blade configurations for hydropower utilization. *Energy Convers. Manag.* **2024**, *312*, 118535. [\[CrossRef\]](#)
42. Chaudhari, V.N.; Shah, S.P. Performance enhancement of savonius hydrokinetic turbine using split airfoil blade: A numerical investigation. *Renew. Energy* **2024**, *224*, 120158. [\[CrossRef\]](#)
43. Nath, B.; Biswas, A.; Das, B.; Misra, R.D. Design, optimization and analysis of a modified Savonius hydro-kinetic turbine (MSHT) with curved winglet and straight blade. *Energy Convers. Manag.* **2024**, *314*, 118699. [\[CrossRef\]](#)
44. Hassan, M.; Bryant, M.; Mazzoleni, A.; Granlund, K. Technoeconomic optimization of coaxial hydrokinetic turbines. *Renew. Energy* **2025**, *239*, 122041. [\[CrossRef\]](#)
45. Naik, K.; Liao, Y.; Jiang, B.; Martins, J.R.R.A.; Sun, J. Control Co-Design of a Ducted Hydrokinetic Turbine. In Proceedings of the 2024 American Control Conference (ACC), Toronto, ON, Canada, 10–12 July 2024; IEEE: Piscataway, NJ, USA, 2024; pp. 2558–2563. [\[CrossRef\]](#)
46. Sanin-Villa, D.; Sierra-Del Rio, J.; Zuluaga, D.H.; Galvis-Holguin, S. Enhancing Axial Flow in Hydrokinetic Turbines via Multi-Slot Diffuser Design: A Computational Study. *Appl. Syst. Innov.* **2025**, *8*, 129. [\[CrossRef\]](#)
47. Taherdoost, H.; Madanchian, M. Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia* **2023**, *3*, 77–87. [\[CrossRef\]](#)
48. Taherdoost, H. Analysis of Simple Additive Weighting Method (SAW) as a MultiAttribute Decision-Making Technique: A Step-by-Step Guide. *J. Manag. Sci. Eng. Res.* **2023**, *6*, 21–24. [\[CrossRef\]](#)
49. Abbo, M.S.; da Silva, P.I. Multi criteria selection of RETs sites using Simple Additive Weighting (SAW). In *Micro Perspectives for Decentralized Energy Supply, Proceedings of the International Conference, Bangalore, India, 23–25 April 2015*; Universitätsverlag der TU Berlin: Berlin, Germany, 2015; Volume 2, pp. 121–124.
50. Biswas, T.K.; Chaki, S. Applications of Modified Simple Additive Weighting Method in Manufacturing Environment. *Int. J. Eng.* **2022**, *35*, 830–836. [\[CrossRef\]](#)
51. Prabowo, A.A.; Supriyanto, A. Comparison of AHP and SAW Methods for Predicting Career Interests of SMAN 1 Karanganyar Demak Students. *Sist. J. Sist. Inf.* **2025**, *14*, 643–657. [\[CrossRef\]](#)
52. Ibrahim, A.; A Surya, R.A. The Implementation of Simple Additive Weighting (SAW) Method in Decision Support System for the Best School Selection in Jambi. In Proceedings of the Journal of Physics: Conference Series, the 2nd International Conference on Applied Sciences Mathematics and Informatics, Bandar Lampung, Indonesia, 9–11 August 2018; Institute of Physics Publishing: Bristol, UK, 2019. [\[CrossRef\]](#)
53. Rollano, F.T.; Santos, A.; Cavagnaro, R.J.; Hunter, S.; Denniss, T. Efficiency Analysis of the Wave-to-Grid Energy Conversion of the UniWave200 Wave Energy Converter. *IEEE Trans. Sustain. Energy* **2025**, *16*, 752–760. [\[CrossRef\]](#)
54. Abaei, M.M.; Arzaghi, E.; Bao, M.; Garaniya, V.; Abdussamie, N.; Pichard, A.; Abbassi, R. Performance evaluation of point-absorber wave energy converters; energy extraction and structural integrity aspects. *Ocean. Eng.* **2025**, *317*, 119983. [\[CrossRef\]](#)
55. Joensen, B.; Bingham, H.B. Economic feasibility study for wave energy conversion device deployment in Faroese waters. *Energy* **2024**, *295*, 130869. [\[CrossRef\]](#)
56. Pennock, S.; Coles, D.; Angeloudis, A.; Bhattacharya, S.; Jeffrey, H. Temporal complementarity of marine renewables with wind and solar generation: Implications for GB system benefits. *Appl. Energy* **2022**, *319*, 119276. [\[CrossRef\]](#)
57. Vermaak, H.J.; Kusakana, K.; Koko, S.P. Status of micro-hydrokinetic river technology in rural applications: A review of literature. *Renew. Sustain. Energy Rev.* **2014**, *29*, 625–633. [\[CrossRef\]](#)
58. Pineda, J.C.; Rubio-Clemente, A.; Chica, E. Optimization of a Gorlov Helical Turbine for Hydrokinetic Application Using the Response Surface Methodology and Experimental Tests. *Energies* **2024**, *17*, 5747. [\[CrossRef\]](#)
59. Patel, V.; Eldho, T.I.; Prabhu, S.V. Performance enhancement of a Darrieus hydrokinetic turbine with the blocking of a specific flow region for optimum use of hydropower. *Renew. Energy* **2019**, *135*, 1144–1156. [\[CrossRef\]](#)
60. Chaudhari, V.N.; Shah, S.P. Numerical investigation on the performance of an innovative Airfoil-Bladed Savonius Hydrokinetic Turbine (ABSHKT) with deflector. *Int. J. Thermofluids* **2023**, *17*, 100279. [\[CrossRef\]](#)
61. Zupone, G.L.; Amelio, M.; Barbarelli, S.; Florio, G.; Scornaienchi, N.M.; Cutrupi, A. Lcoe evaluation for a tidal kinetic self balancing turbine: Case study and comparison. *Appl. Energy* **2017**, *185*, 1292–1302. [\[CrossRef\]](#)
62. Cahill, B.G.; Davies, S.E.; Johnson, N.E.; Kist, S.; Zarate, L.; Leung, P. Accelerating the Commercialization of Marine Renewable Energy Through Parallel Deployments of Multiple Hydrokinetic Power Systems. In Proceedings of the Offshore Technology Conference (OTC), Houston, TX, USA, 6–9 May 2024; Society of Petroleum Engineers (SPE): Richardson, TX, USA, 2024. [\[CrossRef\]](#)
63. Icaza, D.; Borge-Diez, D. Technical and economic design of a novel hybrid system photovoltaic/wind/hydrokinetic to supply a group of sustainable buildings in the shape of airplanes. *Heliyon* **2023**, *9*, e14137. [\[CrossRef\]](#)
64. Cahill, B.; Caspard, M.; Johnson, N.; Davies, S.; Leung, P. Growing International Operations: Multiple Deployments of Multiple Hydrokinetic Power Systems in 2023. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 1–4 May 2023. [\[CrossRef\]](#)

65. Więckowski, J.; Sałabun, W. Sensitivity analysis approaches in multi-criteria decision analysis: A systematic review. *Appl. Soft Comput.* **2023**, *148*, 110915. [[CrossRef](#)]
66. Toms, A.M.; Li, X.; Rajashekara, K. Optimal Microgrid Sizing of Offshore Renewable Energy Sources for Offshore Platforms and Coastal Communities. *arXiv* **2025**, arXiv:2505.05305. [[CrossRef](#)]
67. Babinec, S.; Baring-Gould, I.; Bender, A.N.; Blair, N.; Li, X.; Muehleisen, R.T.; Olis, D.; Ovaitt, S. Techno-economic analysis of renewable energy generation at the South Pole. *Renew. Sustain. Energy Rev.* **2024**, *193*, 114274. [[CrossRef](#)]
68. Quaranta, E.; Georgakaki, A.; Letout, S.; Mountraki, A.; Ince, E.; Gea Bermudez, J. *Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union—2024 Status Report on Technology Development, Trends, Value Chains and Markets*; Publications Office of the European Union: Luxembourg, 2024.
69. Sun, J.; Gong, Z.; Agarwal, A.; Noghabi, S.; Chandra, R.; Snir, M.; Huang, J. Exploring the Efficiency of Renewable Energy-based Modular Data Centers at Scale. In Proceedings of the 2024 ACM Symposium on Cloud Computing, Redmond, WA, USA, 20–22 November 2024.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.