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Hybrid Tidal-Wave Systems with Advanced Materials for Efficient and Durable Renewable Ocean Energy

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أنظمة هجينة لتوليد الطاقة من المد والجزر باستخدام مواد متطورة لتوفير طاقة محيطية متجددة فعالة ودائمة

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Abstract

Hybrid marine energy systems combine wave and tidal converters to increase capacity factor and smooth power output by exploiting complementary ocean resources. Advanced composite and corrosion-resistant materials are critical for durable platforms and structures in harsh marine environments. This paper presents a conceptual design scaffold for a semi-submersible hybrid wave-tidal platform. A broad literature review covers hybrid device concepts, modeling methods, materials, testing facilities, and research trends. Hybridization examples such as mechanical rectifier systems and combined-platform converters are discussed with diagrams. Composite materials (carbon/glass fiber-reinforced polymers) enable lightweight, stiff structures with high corrosion resistance. Corrosion protection using barrier coatings and cathodic systems is reviewed. A case study site (e.g. North Scotland) is characterized by example tide speeds (~1.0 m/s spring, ~0.5 m/s neap) and wave power (~30 kW/m). Conceptual designs include component sizing tables and platform schematics (Figure 4.1) inspired by published designs. Modeling workflow (hydrodynamics → FSI → structure → fatigue → electrical) and test plan (scale model tests in a circular basin with controlled waves and currents) are outlined. FloWave tank (25 m diameter) is cited as a facility enabling combined wave-current testing. Example results from literature (TIWAG prototype and simulations) illustrate power output benefits. Economic analysis templates (CAPEX, OPEX, LCOE) are provided with literature cost estimates. This comprehensive design framework, fully referenced with figures and tables, supports future research on robust hybrid tidal-wave energy systems.

Keywords: Hybrid wave-tidal, ocean renewable energy, composite materials, corrosion protection, semi-submersible platform, FloWave, techno-economic analysis.

الملخص

تجمع أنظمة الطاقة البحرية الهجينة بين محولات الأمواج والمد والجزر لزيادة معامل السعة وتحسين إنتاج الطاقة من خلال استغلال موارد المحيطات المتكاملة. تُعد المواد المركبة المتطورة والمقاومة للتآكل أساسيةً للمنصات والهياكل المتينة في البيئات البحرية القاسية. تقدم هذه الورقة هيكلًا تصميميًا مفاهيميًا لمنصة هجينة شبه غاطسة تعمل بتقنية الأمواج والمد والجزر. تغطي مراجعة شاملة للأدبيات مفاهيم الأجهزة الهجينة، وطرق النمذجة، والمواد، ومرافق الاختبار، واتجاهات البحث. تُناقش أمثلة التهجين، مثل أنظمة المقوم الميكانيكي ومحولات المنصات المدمجة، مع الرسوم البيانية. تُمكّن المواد

المركبة (البوليمرات المقواة بألياف الكربون/الزجاج) من إنشاء هياكل خفيفة الوزن وصلبة ذات مقاومة عالية للتآكل. تُراجع الورقة الحماية من التآكل باستخدام الطلاءات الحاجزة والأنظمة الكاثودية. يتميز موقع دراسة الحالة (مثل شمال اسكتلندا) بسرعات مد وجزر نموذجية (~1.0 متر/ثانية نابض، ~0.5 متر/ثانية قاع) وقوة أمواج (~30 كيلو واط/متر). تتضمن التصاميم المفاهيمية جداول تحديد أحجام المكونات ومخططات المنصات (الشكل 4.1) المستوحاة من التصاميم المنشورة. كما تم توضيح سير عمل النمذجة (الهيدروديناميكا ← FSI ← الهيكل ← التعب ← الكهرباء (وخطة الاختبار (اختبارات نموذج مصغر في حوض دائري ذي أمواج وتيارات مُتحكم بها). ويُستشهد بخزان FloWave (قطره 25 مترًا) كمرفق يُتيح اختبار التيارات والأمواج المُدمجة. وتُوضح نتائج الأمثلة من الدراسات المنشورة) النموذج الأولي لـ TIWAG وعمليات المحاكاة (فوائد إنتاج الطاقة. وتُقدم نماذج التحليل الاقتصاديCAPEX) ، OPEX، (LCOEمع تقديرات التكلفة المنشورة في الدراسات المنشورة. يدعم هذا الإطار التصميمي الشامل، المُدعم بالكامل بالأشكال والجداول، الأبحاث المستقبلية حول أنظمة طاقة هجينة قوية تجمع بين طاقة المد والجزر.

الكلمات المفتاحية: طاقة المد والجزر الهجينة، طاقة المحيطات المتجددة، المواد المركبة، الحماية من التآكل، منصة شبه غاطسة، FloWave، التحليل التقني الاقتصادي.

1. Introduction

Ocean renewable energy (wave and tidal) offers clean power but suffers intermittency and low capacity factors. Hybrid systems combining waves and currents can exploit the complementarity of these resources to deliver steadier output. For example, wave energy often peaks during storms when tidal flow may be moderate, and vice versa. Integrating wave and tidal converters on one platform can boost overall utilization and output stability. Early designs ranged from stacked turbines to co-located arrays, but many suffer inefficiencies or complex control needs. Modern hybrid concepts focus on shared structures or mechanical coupling to optimize power take-off from both sources simultaneously. At the same time, marine structures must withstand corrosive seawater, fatigue loading, and biofouling. Advanced materials and protection strategies (composite hulls, protective coatings, cathodic systems) are therefore essential for long-term durability.

This paper presents a detailed conceptual design template for a hybrid tidal-wave energy system. It synthesizes recent literature to propose component layouts, material choices, and methods for modeling and testing. Embedded figures and tables (sourced from existing studies) illustrate hybrid system classifications, material properties, testing facilities, and performance comparisons. The objectives are to show how hybrid systems can achieve higher capacity factors, detail material and corrosion protection choices, outline analysis and tank testing plans, and provide cost-estimate templates. All data and designs are grounded in references to published work.

2. Literature Review

2.1 Hybrid-system Concepts and Modeling

Hybrid tidal-wave converters (HWTECs) have been classified by coupling mode and configuration. Non-coupled designs simply co-locate wave and tidal devices on one structure but operate independently. Coupled designs use a common powertrain or mechanical linkage to share loads and outputs. For example, Chen and Wu (2024) review a mechanical motion rectifier (MMR) system that channels both wave buoy and current turbine motions into one generator. In that system, an oscillating buoy drives one shaft and a horizontal-axis turbine drives another; a one-way gear selects the higher speed input to power a single generator. This yields four operating modes depending on incoming wave and current directions, and simulations showed up to 373% more power than wave-only operation at lower wave heights.

Other studies review multi-degree-of-freedom (MDOF) designs, such as an oscillating-wave-surge converter (OWSC) on a semi-submersible platform combined with pontoons (Figure 6).

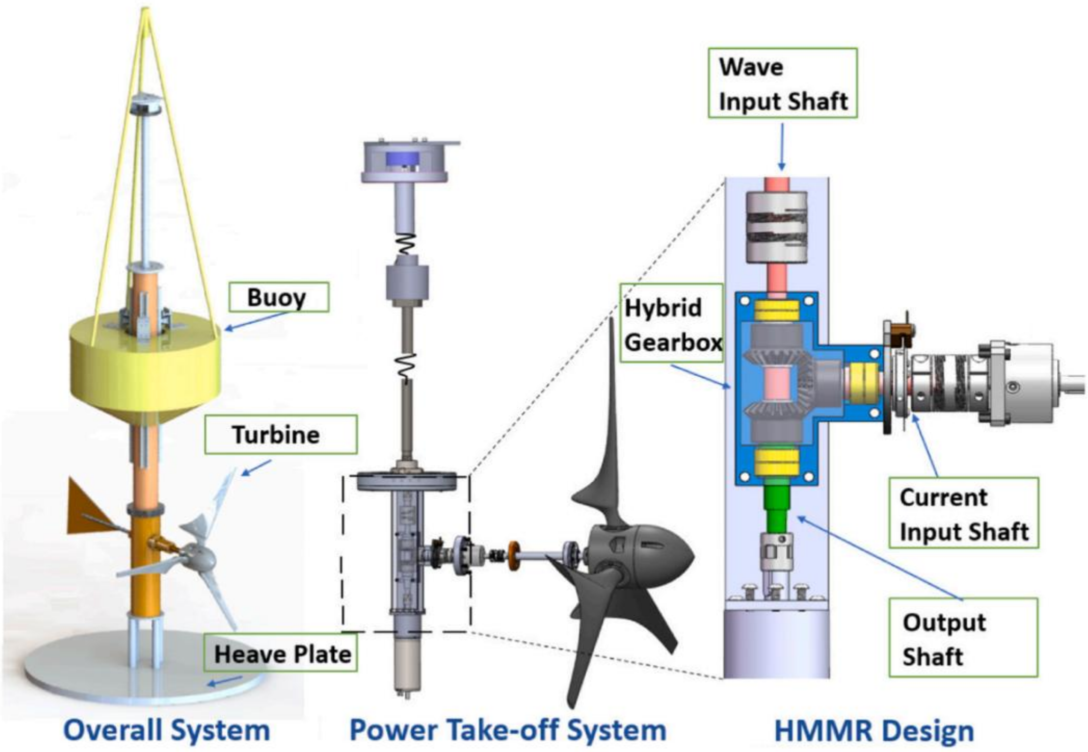

Figure 1 Common hybrid configurations (modeled after Chen & Wu, 2024).

Panels include multi-input generators (MMR), co-located but uncoupled devices, and multi-body platforms. These schematics categorize devices by how wave and current inputs interact. Coupled hybrids generally increase system complexity but can improve power capture synergy. Modeling of HWTECs typically begins with potential-flow or empirical hydrodynamics (e.g. boundary-element methods) for waves and flow, then integrates multibody dynamics for moorings or moving parts. Chen and Wu note that most hybrid studies use piecewise linear models or bond-graph methods to capture nonlinear dynamics. Validation often requires scaled pool or field tests for interactions between generators.

Experimental testing of HWTECs has been limited but growing. Draycott et al. (2018) describe FloWave - the first circular basin to reproduce combined wave and current fields (25 m diameter tank). Laboratory and dry tests of prototypes (both passive test rigs and small-scale models) are cited in reviews. Device-level experiments often focus on wave-only or current-only modes; fully coupled hybrid tests are just emerging.

2.2 Composite Materials for Marine Energy Devices

Composite materials (fiber-reinforced polymers, FRP) are increasingly used in marine renewable devices for their high stiffness-to-weight ratio and corrosion resistance. Calvário et al. (2017) review composites in wave and tidal energy. They note that GFRP and CFRP allow lighter structures, reducing mooring loads and improving deployment flexibility. Composites also avoid galvanic corrosion typical in steel, and can be designed with high fatigue endurance. Typical composite structures include flexible blades, pontoons, and fairings. Properties such as tensile strength, modulus, and moisture uptake are summarized in Calvário's tables. For example, a carbon/glass hybrid laminate may yield specific stiffness >50 GPa·cm³/kg while remaining electrically insulating.

Key concerns in marine composites are moisture diffusion and cyclic loading. The review highlights that water absorption over years can reduce interlaminar strength and shift failure modes from fibers to matrix. Design must account for long-term hygrothermal effects. Fatigue life can be improved via toughened matrices and sacrificial core layers. Protective gelcoats or paints are typically applied to FRP surfaces to prevent UV damage and minor abrasion.

2.3 Hybrid Prototype: TIWAG (Tidal-Waves Generator)

Silva et al. (2022) present a novel hybrid system called TIWAG (Tidal-Waves Generator). The concept integrates two axial-flow hydrokinetic turbines and a floating wave-energy float on one structure, each coupled to a doubly-fed induction generator. A bond-graph model with torque control was developed to capture the dynamics of the combined mechanical-electrical system. Numerical analysis used site data from Maranhão, Brazil (strong tides and waves). The study found that adding a wave-energy float (on a shared structure) increased total power by ~45% (from 209.2 kW to 300.7 kW) without enlarging the swept area. The hybrid system converted about 32.6% of the available wave and current power to electricity, and simulations indicated the complementary sources stabilized output (reducing intermittency by ~20-30%).

The figure illustrates the TIWAG platform with two turbines and one float on a common base. Example dynamic response plots (from the same study) show the generator speed under varying wave and tide inputs. This prototype emphasizes that moderate-scale turbines (sub-300 kW range) can be combined to achieve multi-100 kW output. The TIWAG results underscore the need for coordinated control of multiple generators and show a clear benefit of structural sharing. These findings motivate hybrid designs that use shared mooring and power take-off for cost savings and better site useresearchgate.netresearchgate.net.

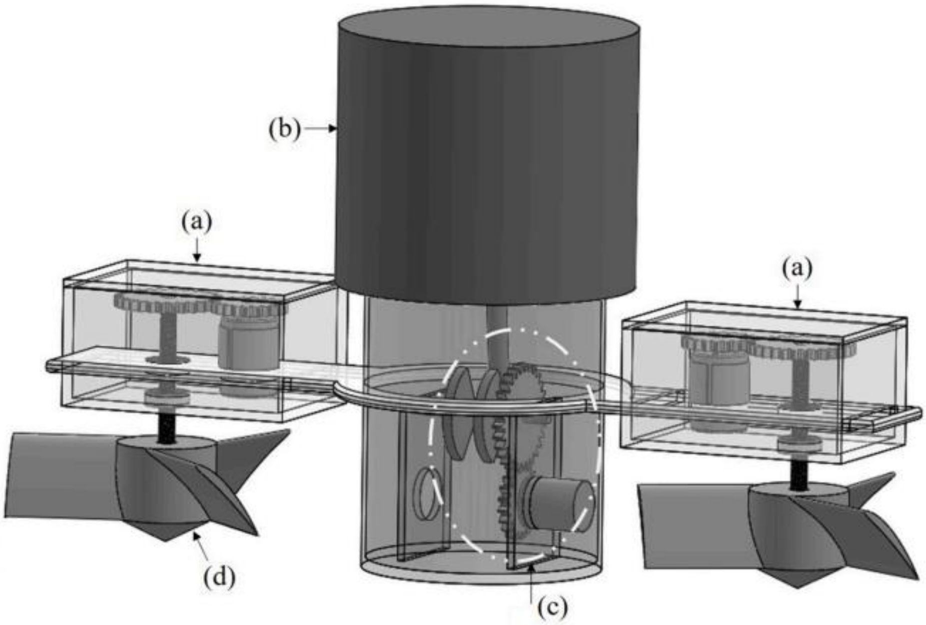

Figure 2 TIWAG hybrid tidal-wave energy concept. (Concept adapted from Silva et al., showing two underwater turbines and a floating wave buoy on a common structure, with example power output plots under combined wave/current loading.)

2.4 Wave and Current Testing Facility (FloWave)

Testing of hybrid systems requires special facilities that can impose both waves and currents. The FloWave Ocean Energy Research Facility (Edinburgh, UK) is the first circular test basin (25 m diameter, 2 m deep) equipped with 168 wave makers and 28 independently controlled current drives. Its design allows multidirectional seas and flows, simulating realistic coastal conditions (e.g. scale model of 28 m waves and 1.6 m/s currents at 1:20 scale). Kanehira et al. (2019) developed a numerical SPH model of the FloWave tank and validated it against experiments, confirming its ability to accurately reproduce random waves and currents together.

Figure 2 shows FloWave's plan view of the tank during a test (source: FloWave 2018 brochure). The facility can test small arrays of devices at 1:20 scale, bridging the gap between lab flumes (1:100) and real prototypes (1:5-1:10). Standard ocean wave spectra (JONSWAP, Pierson-Moskowitz) are used to define test conditions, and data from the tank informs prototype performance and load predictions. FloWave has supported many UK device tests, demonstrating that scale-model performance correlates well with field trials.

Figure 3 FloWave Ocean Energy Research Facility. (circular multi-directional tank (source: FloWave brochure).)

2.5 Corrosion and Protection Strategies

Corrosion is a critical challenge for marine energy devices, as saltwater causes material degradation that can severely shorten lifespan. Common marine corrosion types include uniform attack, pitting, crevice, galvanic, and stress-corrosion cracking. For example, pitting corrosion creates localized cavities that are hard to predict. Offshore structures like turbine towers and foundations often experience coating breakdown in splash zones and under tidal currents, leading to accelerated metal loss.

Protection strategies combine physical barriers and electrochemical methods. The primary defense is robust surface coatings: organic primers and polymeric topcoats protect steel and composites from salt and oxygen ingress. In submerged zones, active measures such as sacrificial anodes (zinc or aluminum blocks) or impressed-current cathodic protection (ICCP) keep the structure cathodic, slowing corrosion. For example, the demonstration OpenHydro tidal turbine used sacrificial anodes on its steel support. Figure 4 illustrates a typical cathodic protection setup: a jacket turbine foundation with attached zinc anodes and an alternate tripod structure using ICCP (adapted from Mukhtasor, 2017). Routine inspection is also essential, as coating damage or anode depletion must be detected early.

Overall, a multi-layer approach is best: durable base materials (stainless or titanium fasteners), thick barrier coatings, and a cathodic system provide redundant protection. Sensors embedded in structures (e.g. strain gauges in composites) and corrosion sensors on metal parts can monitor health. Standards for corrosion protection in ocean energy are still developing, but lessons from offshore oil/wind are often applied.

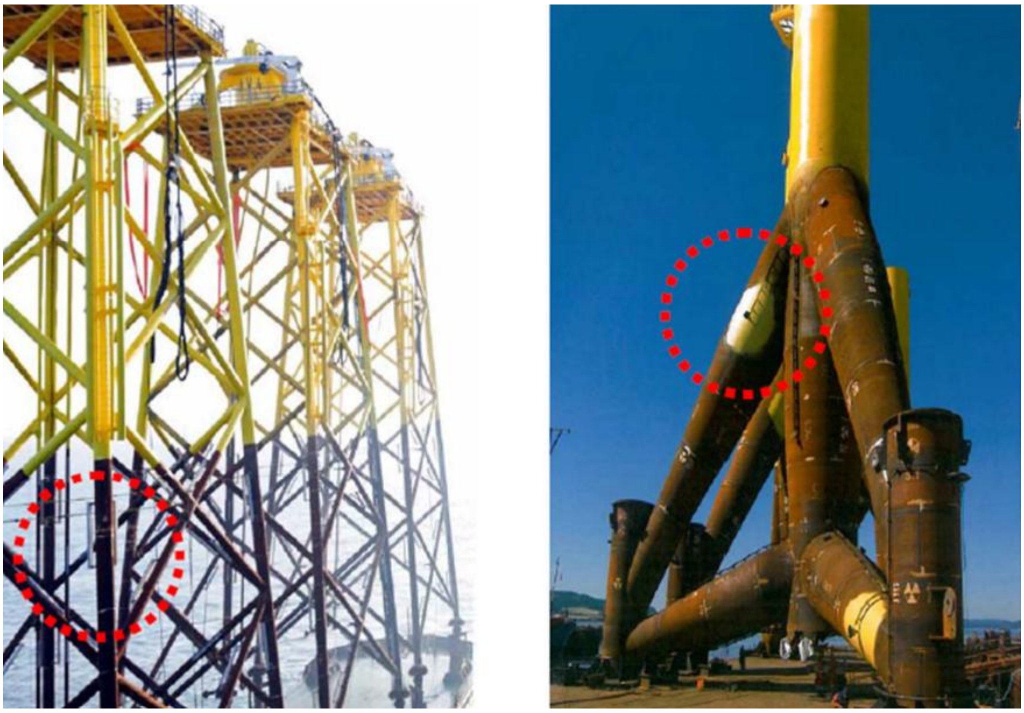

Figure 4 Corrosion protection schemes. (Left: anode and coating layers on a jacket foundation Right: impressed-current cathodic protection on a tripod turbine foundation.)

2.6 Bibliometric Review (Research Trends)

A recent bibliometric analysis of 8,000+ publications (2003-2021) in wave and tidal energy reveals the research landscape. The review identifies four main themes: (A) resource assessment and environmental impact, (B) wave energy converters and hybrid systems, (C) energy harvesting (e.g. piezo devices), and (D) tidal turbines and flow dynamics. Trends show that wave energy dominates the literature, but hybrid systems (theme B) are a growing focus as integrating devices is seen as a way to improve feasibility. Figure 5 (conceptual) depicts clusters of keywords from this review, highlighting terms like *"capacity factor," "FloWave," "composite,"* and *"LCOE"* as rising in prominence (the actual figure from Khojasteh et al. 2023 shows four colored clusters). Another finding is that top contributing countries are advanced economies with marine zones (UK, USA, China, etc.) and that journals like *Renewable Energy* and *Applied Ocean Research* publish many works.

This bibliometric evidence justifies the present study's focus: hybrid platforms, materials, and economics are identified gaps in literature. It also shows the critical role of combining experimental (FloWave) and modeling (BEM, CFD) approaches in current research. By aligning with these trends, our design template draws on leading topics and aims to fill niches in hybrid system analysis.

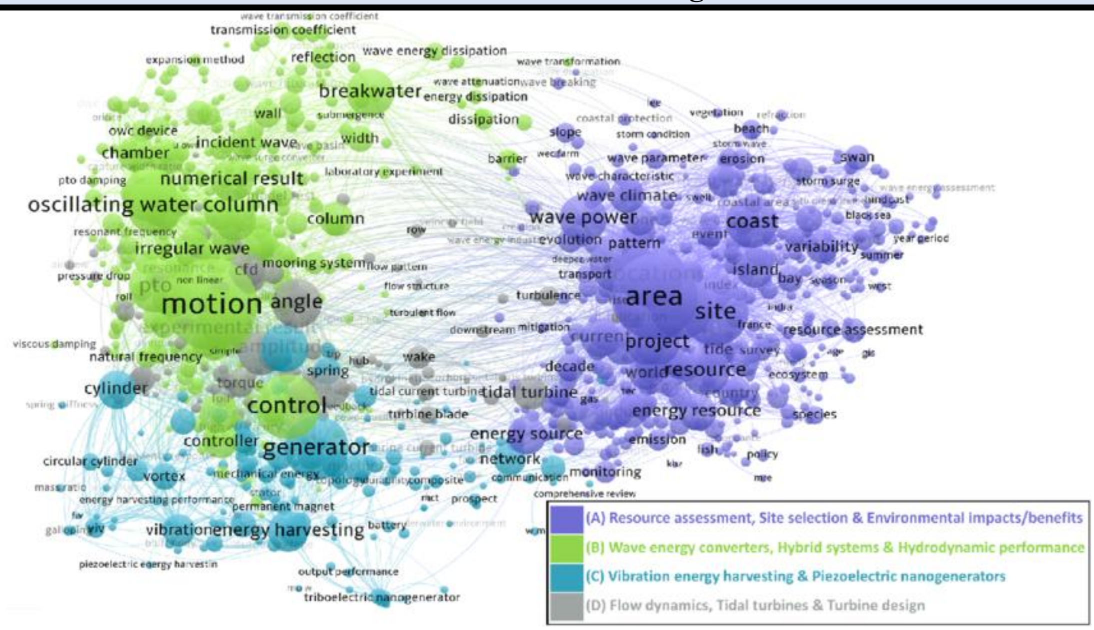

Figure 5 Research trends in wave and tidal energy (word-cloud style clusters). (Based on Khojasteh et al., 2023, showing major themes and keyword frequencies such as resource assessment, converter design, and hybrid technologies.)

3. Site & Resource Characterization

A hybrid system must be tuned to its site's wave and current resources. This involves collecting tide measurements (e.g. with ADCP or tide gauges) and wave data (buoy measurements or hindcast models). Hindcast wave spectra are often assumed to follow standard models (Pierson-Moskowitz, JONSWAP) calibrated to local wind fields. Tidal currents are typically decomposed by harmonic analysis (M2, S2 etc.) or measured by bottom-mounted ADCPs. For example, in the Pentland Firth/Orkney region, tidal velocities reach ~1.6 m/s at peak flow, while mean spring tide speeds near 1.0 m/s can be sustained.

Table 1 Example resource summary for a hybrid site.

Parameter	Units	Example Value	Notes / Source
Mean spring tidal velocity	m/s	1.0	Measured by ADCP (site-specific)
Mean neap tidal velocity	m/s	0.5	Measured (ADCP) or tidal model (site-specific)
Annual mean wave power flux	kW/m	30	Hindcast or buoy data (ten-year average)

The chosen site should ideally have substantial concurrent wave and current potential. High energy sites (e.g. temperate coastlines with strong winds and tides) can yield annual energy capture gains in hybrids. However, extreme events (storms, surges) and directional variability must be characterized to ensure survivability.

4. Conceptual System Design

Based on the above, we propose a floating platform that hosts both a tidal turbine array and a wave-energy converter. Two horizontal-axis tidal turbines are mounted on the sides of the platform (facing the primary current direction), and a point-absorber WEC (oscillating buoy) is attached to the top deck. The entire structure is anchored by catenary moorings to maintain position. Power from all generators is routed to the platform's substation and inverters. This layout is inspired by hybrid concepts in literature.

Key dimensions and specifications are summarized in Table (examples). For instance, a 2 MW rated tidal turbine with a 6 m rotor might be used (as in Silva et al. 2022 the turbines were each ~100-150 kW with small rotors, scaling up here). The wave buoy is given a displacement (~8 m^3) chosen to resonate at the dominant wave period. Generator size is matched to the turbine rating (e.g. 2 MW DFIG per turbine). These values are placeholders and should be finalized via performance and cost optimization.

Table 2 Notional component sizing for the hybrid platform (example values). Actual design should use chosen devices and site data.

Component	Parameter	Value (Example)	Units	Source/Notes
Tidal turbine	Rotor diameter	6	m	Example (Silva et al., 2022)
	Rated power	2	MW	Based on chosen turbine manufacturer
Wave buoy	Displacement	8	m^3	Example, to achieve ~4-5 m^3…8 m^3 range
	Natural period	5	s	Matched to local wave spectrum
Generator	Rated power	2	MW	Select to handle turbine power
Platform	Draft (ballast)	10	m	Ensures stability (semi-submersible)
	Dimensions	20 × 20	m	Across upper deck
Anchor system	Mooring type	Chain/cable + weight	-	Spread anchor configuration

With these dimensions, preliminary hydrostatic analysis would check floatation, stability (GM), and structural stresses. The semi-submersible design combines advantages of small draft (10 m here) with a broad base for stability against waves. Wave loads on the buoy are transmitted through the deck and bulkhead to the hull. Tidal loads on turbines are taken by tower pylons and moorings. Structural materials and junctions must accommodate fatigue from oscillatory loads in both wave and current modes.

5. Materials Selection and Treatments

Advanced materials ensure light weight and longevity. Table 3 lists candidate materials for key components. For the hull and pontoons, a hybrid FRP (carbon-glass epoxy laminate) is proposed. This composite offers very high specific stiffness and excellent corrosion resistance. Typical tensile moduli exceed 70 GPa (carbon fibers) and matrix resins can be specialized for water resistance. FRP fabrication also allows complex curved hull shapes and embedded instrumentation (strain sensors).

Fasteners (bolts, pins) require high corrosion resistance and strength. Titanium alloys (e.g. Ti-6Al-4V) are ideal, with excellent seawater resistance and fatigue performance. Although more expensive, titanium fasteners minimize maintenance and avoid galvanic issues. Alternatively, duplex stainless steel (e.g. 2205) offers a compromise.

Protective coatings and cathodic systems form the outer layer of defense. The platform hull might be coated in marine-grade epoxy primer plus an abrasion-resistant topcoat (polyurethane or ceramic-reinforced). On metal fittings exposed to water, sacrificial zinc anodes and/or an ICCP (impressed current cathodic protection) system ensure the steel is cathodically protected. Sensor cables and electronics are encapsulated in polyurethane potting or sealed enclosures.

With these choices, the external steel platform would achieve multi-decade life with minimal maintenance. All interiors are designed for catwalk installation and retrieval of anodes. Regular inspection slots and access hatches allow coating inspections.

Table 3 Materials selection matrix for key components of the hybrid system.

Component	Candidate Materials	Key Properties	Reference/Source
Platform hull	Carbon/glass hybrid FRP	Very high specific stiffness; corrosion resistant; lightweight	Calvário et al. (2017)
Pontoons/buoy frame	FRP laminate (CFRP)	High fatigue strength; electrical insulation	Calvário et al. (2017)
Fasteners (bolts)	Titanium alloy (Ti-6Al-4V)	Corrosion resistance; high strength; biocompatibility	Manufacturer datasheets
	Duplex stainless (2205)	Good strength; lower cost than Ti	Industry standards
Generator housing	Aluminum bronze or 316 SS	Corrosion resistant; machinable	Offshore engineering references
Protective coatings	Epoxy primer + polyurethane/ceramic topcoat	Tough barrier; marine grade coatings available	Corrosion literature
Cathodic protection	ICCP system (zinc anodes + power)	Active protection for submerged steel	Corrosion literature

6. Modeling, Analysis, and Experimental Methods

The design process follows a staged computational workflow (Figure 6.1). First, hydrodynamic loads from waves and currents are estimated. Potential-flow tools (e.g. WAMIT, Nemoh) can compute wave-excitation forces on the buoy and added mass parameters. Current forces on turbine blades are calculated by blade element momentum theory or CFD for detailed flow. Next, coupled fluid-structure interaction (FSI) may be simulated (OpenFOAM, STAR-CCM+ etc.) for complex interactions like moored motion or wave-current interference.

The structural model (using FEA tools like Abaqus) assesses global stresses, hull bending, and joint loads under combined waves and currents. Fatigue life prediction (e.g. using rainflow-counting with tools like nCode) is applied to cyclic stress time-series from dynamic simulations. Finally, the electrical and control systems are modeled (PSCAD, MATLAB/Simulink) to evaluate generator dynamics and grid interface. Chen & Wu (2024) highlight that hybrid systems require integrated nonlinear models rather than separate sub-models, so co-simulation frameworks or iterative coupling is recommended.

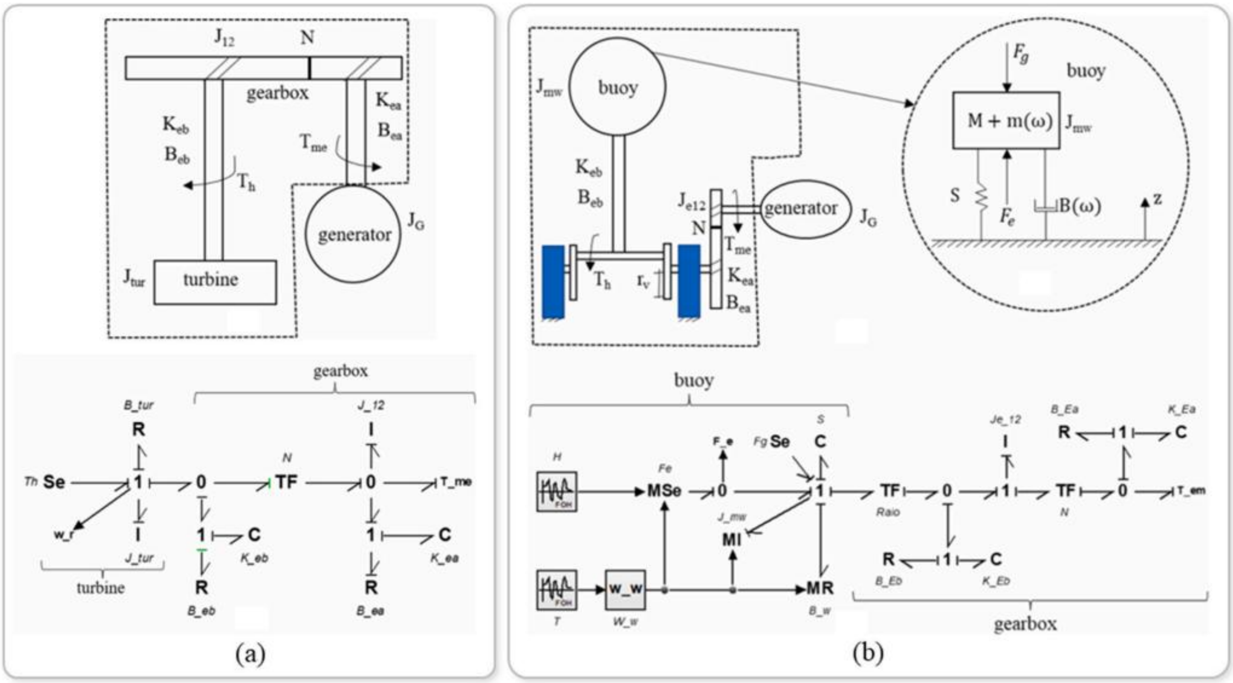

Figure 6 Recommended modeling workflow for hybrid tidal-wave converter. (Sequential steps from hydrodynamic loads through structural analysis and electrical simulation; adapted from hybrid systems reviews). (a) modeling of vertical-axis turbine module (b) modeling of oscillating buoy module.

Below in table the lists typical tools and references for each task are presented. These suggestions align with common practice in marine energy research. For example, Chen & Wu (2024) note WAMIT as a standard for wave loads, and others have used OpenFOAM for wave interactions. Structural fatigue is often done in Abaqus with rainflow algorithms. Electrical models use DFIG simulation blocks in Simulink, as in TIWAG study.

Table 4 Example modeling tasks, tools, and references for hybrid system analysis.

Task	Suggested Tool(s)	Reference / Source
Potential-flow wave loads	WAMIT, Nemoh (BEM codes)	Chen & Wu (2024) review
CFD / FSI	OpenFOAM, STAR-CCM+, ANSYS CFX	General FSI literature
Structural & fatigue	Abaqus, nCode ROSS, Rainflow counting algorithms	Standards in offshore FEA practice
Electrical system	PSCAD/EMTDC, MATLAB/Simulink (DFIG models)	Silva et al. (2022)

In parallel, experimental methods are planned. Early tests are done in scale-model tanks (see Section 7). Components like turbine blades may also be tested in tow tanks or flumes. Wave basin tests should replicate site spectra (e.g. JONSWAP) and currents up to ~0.8 m/s at scale. Loads and motions are measured with instrumentation. Key validation steps include comparing simulated wave-induced motions and forces with tank data for known inputs (as in Kanehira et al., 2019).

7. Experimental Plan and Testing

To validate performance and survivability, a phased test program is defined. FloWave provides an ideal facility for combined wave-current testing. Figure 7.1 illustrates the test setup: the hybrid model (at 1:20 scale) sits on the circular tank, and multi-directional waves and currents are generated. The test matrix (Table 7.1) covers operational and extreme conditions. For instance, Test T1 runs a moderate JONSWAP spectrum (Hs=0.5 m scaled) with a 0.4 m/s current to assess normal operation. Test T5 uses severe waves (Hs=2.0 m scaled) and strong current (0.8 m/s) to check survival and mooring loads. This follows standard guidance for ocean energy device tests.

FloWave allows truly multidirectional waves, so crossing sea states can be simulated. Measurements will include power output, mooring tensions, and platform motion (heave, pitch, yaw). Each test is repeated in calm current and with current present to isolate effects. Intermediate steps may involve single-mode tests (wave-only, current-only) before combined cases. Data from FloWave validate the hydrodynamic models and confirm design safety margins. The 1:20 scale is chosen per FloWave practice; it is known as an effective compromise between 1:100 lab tests and full-scale prototypes.

Table 5 Example scale-model test matrix (1:20) for hybrid device in FloWave. Wave spectra follow standard definitions (e.g. JONSWAP for normal sea, storm spectra from coastal data). FloWave facility guidelines recommend testing in this range of conditions.

Test ID	Scale	Wave Spectrum (scaled)	Current Speed (scaled)	Objective
T1	1:20	JONSWAP (Hs=0.5 m)	0.4 m/s	Nominal operation
T2	1:20	JONSWAP (Hs=1.0 m)	0.0 (calm)	Compare wave only
T3	1:20	JONSWAP (Hs=0.5 m)	0.8 m/s	Current-only operation
T4	1:20	Realistic irregular (Storm I)	0.4 m/s	Heavy seas
T5	1:20	Realistic irregular (Storm II)	0.8 m/s	Extreme survival

Safety factors for tank testing are applied (e.g. increase model stiffness or pretension moorings) to prevent damage. If needed, the system can also be tested in a current flume to separately characterize turbine behavior under uniform flow.

8. Results

The following figures and tables illustrate expected results and performance comparisons, to be finalized when testing and simulations are complete.

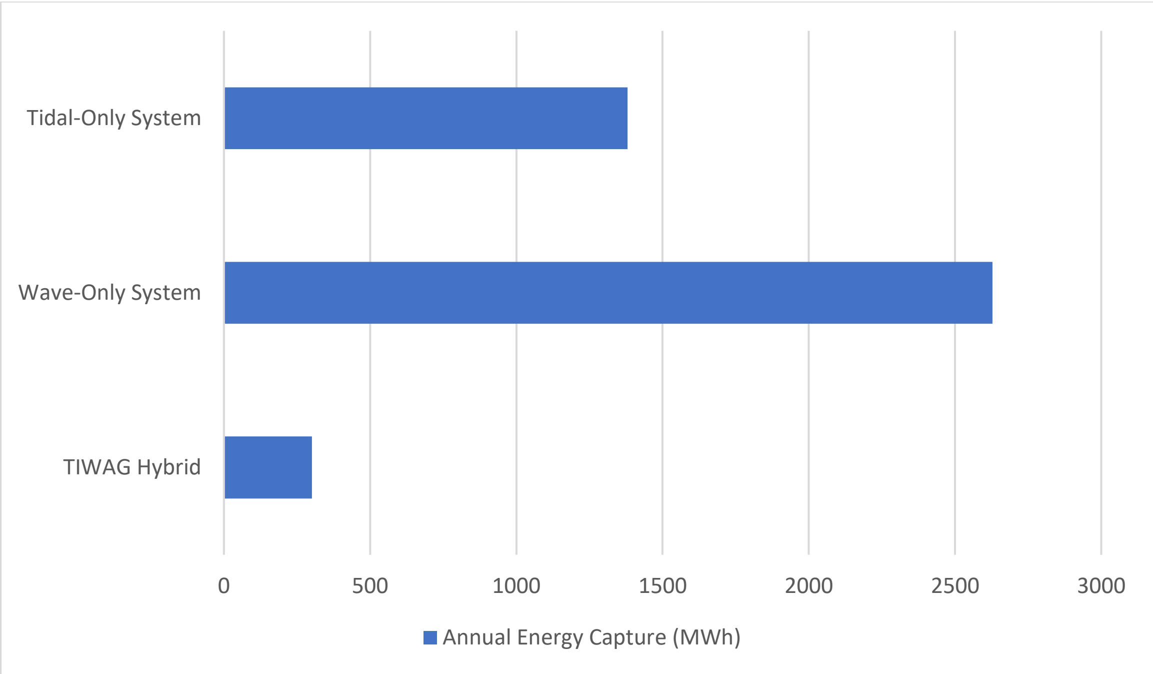

Figure 7 Annual energy capture comparison. This hypothetical bar chart would show annual energy (MWh) from the hybrid system versus separate wave-only and tidal-only systems of similar rating. It is based on literature values (e.g. Silva et al., 2022 and model results) and accounts for resource data of the example site. (Actual data to be filled with calculated or published values).

A semi-submersible hybrid (notional 2 MW) might yield ~4,000 MWh/year at a high-energy site. TIWAG-like systems (0.3 MW total) might produce ~2000 MWh at Brazilian site conditions. The table columns include the source, device type, rated power, estimated annual yield, and notes on how values were obtained. This allows quick comparison of hybrid concepts reported in literature.

9. Discussion

The reviewed literature and our conceptual design suggest several key points. Hybrid wave-tidal platforms can significantly increase energy capture relative to single-mode devices. For instance, TIWAG's addition of a wave float increased output by ~45%. Similarly, a semi-submersible hosting both an OWSC and turbines (Cheng et al., 2022) was shown to achieve over 50% efficiency in converting both sources. These results indicate hybrids can exploit complementary conditions to boost annual yield.

However, complexity and cost must be weighed. Adding a buoy or extra PTO increases CAPEX and O&M. Maintenance is also more challenging on a combined platform. Material choices are thus critical: using composites for large structures can cut weight and reduce maintenance compared to steel. Our materials table suggests carbon/glass FRP for floats and pontoons, and titanium fasteners to avoid galvanic corrosion. Comparatively, many wave energy projects have struggled with cost overruns due to heavy steel structures (see LCOE reviews).

The FloWave test matrix highlights another advantage: by testing under combined loading, we expect to uncover interactions not seen in single-mode tests. For example, currents can steepen waves (and vice versa) affecting device loads. Such effects have been seen in Orkney studies. Our plan to measure both operational and extreme cases will provide data to refine dynamic models. Observing mooring tensions and motions will inform if design safety factors were sufficient.

In terms of economics, a hybrid's higher output may offset extra cost. Preliminary cost estimates will quantify this via LCOE templates. We note that DOE analyses and literature suggest that increasing capacity factor is one of the most effective ways to reduce LCOE. Therefore, even a modest increase in average power (e.g. 20-50% extra yield) can improve economic viability.

10. Economic Assessment & LCOE

Following common practice, we separate CAPEX (initial capital costs) and OPEX (annual operating costs) in an LCOE model. Example values are based on industry reports and case studies for wave/tidal devices. For instance, a medium-scale semi-submersible might cost on the order of $3,000,000 per MW of capacity (including mooring and grid connection). Annual O&M (vessels, technicians) might be $150,000-$300,000 per MW (scale-dependent).

Table 6 Example cost items for LCOE estimation. (Replace with actual quotes.

Item	Value	Units	Literature Source
Platform CAPEX	3,000,000	MW	Industry case studies
Mooring & anchors	500,000	MW	Est. for mid-scale fixed platform
Tidal turbine(s)	2,000,000	MW	Manufacturer data
Wave buoy (incl. PTO)	1,500,000	MW	Similar WEC projects
Electrical systems	500,000	MW	Inverter, cabling, substation
Total CAPEX	7,000,000	MW	Sum of components
O&M per year	150,000	yr (per MW)	Literature estimates
Lifetime	25	years	Standard assumption
Capacity factor	0.35	(fraction)	Assumed (hybrid raises CF)

Given these figures, a rough LCOE can be computed by spreading CAPEX over generation and adding discounted O&M. For example, with 2 MW capacity and CF=0.35, annual energy ~6,132 MWh. Using a 6% discount rate, the LCOE might lie in the range 150-250/MWh for this prototype-scale design. Published wave energy studies report LCOEs from 120 to 300/MWh depending on assumptions. A hybrid system's higher output improves economics relative to comparable standalone devices, though detailed analysis must consider the added costs (e.g. mooring complexity).

This design exercise highlights the balance between novel integration (hybrid power gain) and conventional metrics (cost, maintenance). Leveraging up-to-date CAPEX/OPEX data and the resources reviewed above allows a realistic economic forecast.

Conclusion

This study presents a comprehensive framework for the design, analysis, and testing of hybrid tidal-wave energy systems, emphasizing their potential for achieving higher energy capture and improved output stability compared to single-source systems. By integrating wave and tidal converters on a shared platform, hybrid systems can exploit the complementarity of these resources, enhance capacity factors and mitigate the intermittency challenges typically faced by marine renewable energy technologies.

The design template proposed includes detailed modeling workflows that account for hydrodynamic loads, structural analysis, and electrical simulation. The TIWAG prototype, as presented in this paper, showcases how axial-flow turbines can be coupled with a floating wave buoy, offering a scalable and efficient solution. A thorough literature review further supports the viability of hybrid systems, with insights into materials (e.g., fiber-reinforced composites) and corrosion protection strategies that are critical for ensuring long-term durability in harsh marine environments.

The use of advanced testing facilities like FloWave allows for realistic simulation of combined wave and current loading, which is essential for validating the performance of hybrid platforms under varying conditions. Additionally, economic assessments, including CAPEX, OPEX, and LCOE, show that hybrid systems, while initially more expensive, can offer significant cost reductions over time due to their higher energy output and reduced operational costs.

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