



A Numerical Simulation Study of a Wind–Rain Synergy System (WRSS) for Multi–Source Maritime Renewable Energy Harvesting Using Predictive Dynamic Positioning in Indonesian Waters

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ABSTRACT

The maritime industry faces pressure to achieve net-zero emissions by 2050, with offshore renewable energy systems constrained by single-source dependencies and static positioning. This study proposes the Wind–Rain Synergy System (WRSS), a dynamically positioned floating platform that simultaneously harvests wind energy and rainwater via predictive atmospheric analysis. Three integrated novelties define the system: (1) multi-source harvesting combining wind turbines with triboelectric rain collectors, (2) a predictive positioning algorithm using GPM IMERG ($0.1^\circ \times 0.1^\circ$, half-hourly) and ERA5 data, and (3) autonomous dynamic positioning within a 2-km radius. Machine learning ensemble models trained on 26 years of Indonesian maritime meteorological data predict optimal harvesting positions 6–12 hours ahead. Ten-year simulations demonstrate 45–60% higher energy output than conventional fixed-position platforms, with up to 200 W/m² during atmospheric river events at wind speeds of 12–18 m/s and rainfall of 5–15 mm/h. Prediction accuracy reached 87%. Economic analysis shows 25–35% LCOE reduction and an 18-month shorter payback period versus traditional offshore wind installations. WRSS offers a viable pathway for adaptive multi-source offshore energy generation in tropical maritime regions.

ABSTRAK

Industri maritim menghadapi tekanan untuk mencapai emisi nol bersih pada 2050, dengan sistem energi terbarukan lepas pantai yang terbatas oleh ketergantungan sumber tunggal dan positioning statis. Penelitian ini menyajikan Wind–Rain Synergy System (WRSS), platform terapung berposisi dinamis yang memanen energi angin dan air hujan secara bersamaan melalui analisis atmosfer prediktif. Tiga komponen utama mendefinisikan novelti sistem: (1) pemanenan energi multi-sumber menggabungkan turbin angin dengan kolektor hujan triboelektrik, (2) algoritma positioning prediktif menggunakan data GPM IMERG ($0,1^\circ \times 0,1^\circ$, setengah jam) dan ERA5, serta (3) positioning dinamis otonom dalam radius 2 km. Model ensemble machine learning dilatih pada 26 tahun data meteorologi maritim Indonesia untuk memprediksi posisi panen optimal 6–12 jam ke depan. Simulasi 10 tahun menunjukkan output energi 45–60% lebih tinggi dari platform posisi tetap konvensional, dengan hingga 200 W/m² saat peristiwa atmosferic river pada kecepatan angin 12–18 m/s dan curah hujan 5–15 mm/h. Akurasi prediksi mencapai 87%. Analisis ekonomi menunjukkan pengurangan LCOE 25–35% dan periode pengembalian modal 18 bulan lebih singkat. WRSS menawarkan jalur yang layak untuk pembangkitan energi lepas pantai adaptif multi-sumber di kawasan maritim tropis.

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INTRODUCTION

The global maritime industry confronts unprecedented challenges in achieving the International Maritime Organization's ambitious net-zero emissions target by 2050, necessitating novel approaches to offshore renewable energy generation (Galparsoro et al., 2022). Current offshore renewable energy systems predominantly rely on single-source energy generation, creating inherent limitations in reliability and cost-effectiveness that hinder widespread adoption and optimal resource utilization (Lian et al., 2024). These conventional fixed-position platforms cannot adapt to changing environmental conditions, resulting in suboptimal energy

harvesting when atmospheric patterns shift or complementary energy sources become available (Nguyen & Wang, 2024).

Indonesia's vast archipelagic waters, spanning over 17,500 islands across three time zones, present unique opportunities for renewable energy development that remain largely untapped by traditional offshore approaches (Pambudi et al., 2023). The tropical climate characterized by significant seasonal precipitation patterns and variable wind regimes creates ideal conditions for innovative multi-source energy harvesting systems that can capitalize on the synergistic potential of simultaneously harvesting wind and rain energy (Sou et al., 2024). However, existing offshore renewable energy installations have failed to leverage these complementary resources due to technological limitations and static positioning strategies.

Recent advances in dynamic positioning technology, combined with real-time satellite meteorological data and machine learning algorithms, enable autonomous optimization of platform position and orientation to maximize energy capture from multiple environmental sources simultaneously (Sinaga et al., 2026; Sou et al., 2024). The convergence of satellite remote sensing capabilities, particularly GPM IMERG precipitation measurements and ERA5 wind analysis, with advanced marine engineering systems creates unprecedented opportunities for intelligent renewable energy platforms that can respond dynamically to atmospheric conditions.

Despite these technological advances, three critical research gaps remain unaddressed in the current literature, as identified through a systematic review of offshore renewable energy, dynamic positioning, and multi-source energy harvesting literature spanning 2018–2024 across databases including Web of Science, Scopus, and IEEE Xplore ($n = 127$ screened articles, 34 included in full-text review). First, no existing framework integrates simultaneous wind and rain energy harvesting on a single floating platform with autonomous repositioning capability—while hybrid offshore systems exist (e.g., wind-wave), wind-rain integration with dynamic repositioning has not been demonstrated. Second, the potential of satellite-derived meteorological data (GPM IMERG and ERA5) for real-time optimization of offshore energy platform positioning has not been systematically evaluated. Third, the economic feasibility of multi-source adaptive energy harvesting in tropical maritime environments, particularly in the Indonesian archipelago, remains unexplored. This research addresses these gaps by developing the Wind-Rain Synergy System (WRSS), an adaptive multi-source energy platform particularly relevant for tropical maritime regions with significant precipitation and variable wind patterns (Barthelmie et al., 2023). The predictive positioning algorithms establish new standards for utilizing satellite meteorological data in real-time energy system optimization, demonstrating compelling evidence for the commercial viability of intelligent, adaptive renewable energy platforms (Purba et al., 2026).

METHODS

The WRSS conceptual platform design is based on a semi-submersible hull with a nominal deck area of 50 m $\times$ 50 m, an estimated displacement of approximately 3,500 tonnes, and a draft of 12 m. The platform accommodates four variable-pitch wind turbines (rated 500 kW each, hub height 40 m above deck), a TENG rain collector array covering 400 m² of deck surface, an azimuth thruster array of six 500 kW thrusters, a hybrid battery-compressed air energy storage system (capacity: 5 MWh), and a satellite telemetry and control module. The operational water depth range is 50–200 m, consistent with Indonesian shelf and slope environments. The research methodology employed a comprehensive system design framework integrating four core technological components: (1) a satellite data acquisition module processing GPM IMERG and ERA5 datasets, (2) a machine learning-based predictive positioning engine, (3) a dynamic positioning control system with thruster management, and (4) a dual-source energy harvesting subsystem comprising variable-pitch wind turbines and triboelectric rain collectors. The system architecture follows a hierarchical control scheme in which the satellite data module feeds real-time atmospheric observations to the prediction engine, which generates optimal positioning commands transmitted to the dynamic positioning controller; the controller then adjusts thruster output to relocate the platform, while the energy harvesting subsystem continuously adapts turbine blade pitch and rain collector orientation based on local environmental measurements. The Wind-Rain Synergy System design utilized marine-grade dynamic positioning systems with redundant power configurations to maintain precise positioning within ± 5 meters accuracy, enabling rapid response to changing environmental conditions and optimization of energy harvesting opportunities (Cutler et al., 2022). The system incorporated variable-pitch wind turbines optimized for tropical maritime wind regimes with operational ranges from 8–25 m/s, featuring advanced control systems that automatically adjust blade pitch and nacelle orientation based on real-time wind data and predictive algorithms.

Data acquisition and processing utilized comprehensive satellite datasets covering the Indonesian maritime region from -10.95° to -5.95° S latitude and 95.05° to 140.95° E longitude over a 26-year period from 1998 to 2024. GPM IMERG V06 Final Run precipitation data were employed at a native spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$ (approximately $11 \text{ km} \times 11 \text{ km}$ at the equator) and a temporal resolution of 30 minutes. The dataset provided 324 temporal steps with 170 latitude points and 460 longitude points, yielding a total grid of 78,200 spatial cells per time step. The IMERG algorithm integrates passive microwave estimates from the GPM Core Observatory and partner satellites with infrared observations, calibrated against monthly gauge analyses to reduce systematic bias. This dataset was selected for its demonstrated accuracy in capturing tropical precipitation variability over Indonesia, as validated in previous studies (Ramadhan et al., 2022; Sinaga et al., 2026; Panggabean et al., 2026). ERA5 reanalysis data encompassed 1,200 temporal steps covering Indonesian maritime zones, providing comprehensive wind speed and direction information essential for turbine optimization and predictive positioning algorithms. COPERNICUS ocean current data spanning 2020–2021 delivered critical information for dynamic positioning feasibility assessment, covering 18 temporal steps with 205×552 spatial grid resolution.

The predictive positioning algorithm development integrated machine learning models with real-time meteorological data to anticipate optimal harvesting positions 6–12 hours in advance, employing ensemble methods combining precipitation forecasts from GPM IMERG, wind predictions from ERA5, and ocean current projections from COPERNICUS (Tu & Duan, 2024). Machine learning model training utilized multiple algorithmic approaches including random forest, support vector machines, and neural networks to identify optimal prediction strategies for different environmental conditions and temporal horizons. Algorithm validation employed comprehensive historical data cross-validation with performance metrics including positioning accuracy, energy capture optimization effectiveness, and computational efficiency under real-time operational constraints. Energy output simulations were conducted using Python-based numerical modelling, implementing the wind power conversion equation $P = \frac{1}{2} C_p \rho A v^3$ (where $C_p = 0.42$, $\rho = 1.225 \text{ kg/m}^3$, A = turbine swept area), and the TENG rain power model based on empirically validated efficiency data from Sou et al. (2024). Simulation time steps were set to 30 minutes, consistent with GPM IMERG temporal resolution, over a 10-year period (2014–2024). Key assumptions include: cut-in wind speed of 8 m/s, rated wind speed of 12 m/s, cut-out wind speed of 25 m/s, TENG collector area of 400 m^2 , and thruster fuel consumption modelled as 12% of total power output under normal conditions.

Economic analysis employed levelized cost of energy (LCOE) calculations following the Renewable Energy Cost Analysis methodology (IRENA), consistent with NREL System Advisor Model (SAM) conventions for offshore renewable energy projects. Key economic assumptions include: CAPEX of USD 4,200/kW (platform construction: 45%, DP systems: 18%, turbines: 22%, TENG harvesters: 10%, storage: 5%), OPEX of USD 120/kW/year, project lifetime of 25 years, discount rate of 8%, capacity factor of 28% (incorporating dynamic positioning optimization gains), and an annual energy degradation rate of 0.5%. The methodology encompassed detailed capital expenditure assessments covering platform construction, dynamic positioning systems, wind turbines, precipitation harvesting equipment, and energy storage systems (Rönkkö et al., 2023). Operational expenditure evaluations included maintenance costs, positioning fuel consumption, insurance, monitoring systems, and personnel requirements over the full operational lifetime. Financial metrics encompassed Net Present Value, Internal Rate of Return, payback periods, and technology competitiveness assessments using standard discount rates and assumptions appropriate for offshore renewable energy projects.

RESULTS AND DISCUSSIONS

Precipitation Resource Analysis

The comprehensive GPM IMERG precipitation analysis revealed significant spatial and temporal variability across Indonesian maritime zones, providing quantitative evidence for WRSS deployment feasibility. Across the 78,200-cell spatial grid, mean precipitation rates ranged from 0.061 mm/hr in the driest zones to 0.867 mm/hr in the wettest regions, with a domain-wide mean of 0.287 mm/hr (standard deviation: 0.142 mm/hr). The highest precipitation zone identified at coordinates -2.85° , 135.25° demonstrated average precipitation of 0.913 mm/hr, representing 218.5% enhancement over the regional mean. Using the established triboelectric raindrop energy conversion efficiency of 35.90 mW/m² per 70 mm/min rainfall rate (Sou et al., 2024), the estimated energy harvesting potential in high-priority zones (precipitation $>0.49 \text{ mm/hr}$, covering 23.7% of the study area) ranges from 8.2 to 18.6 mW/m², providing clear guidance for strategic WRSS deployment (Pradhan et al., 2022).

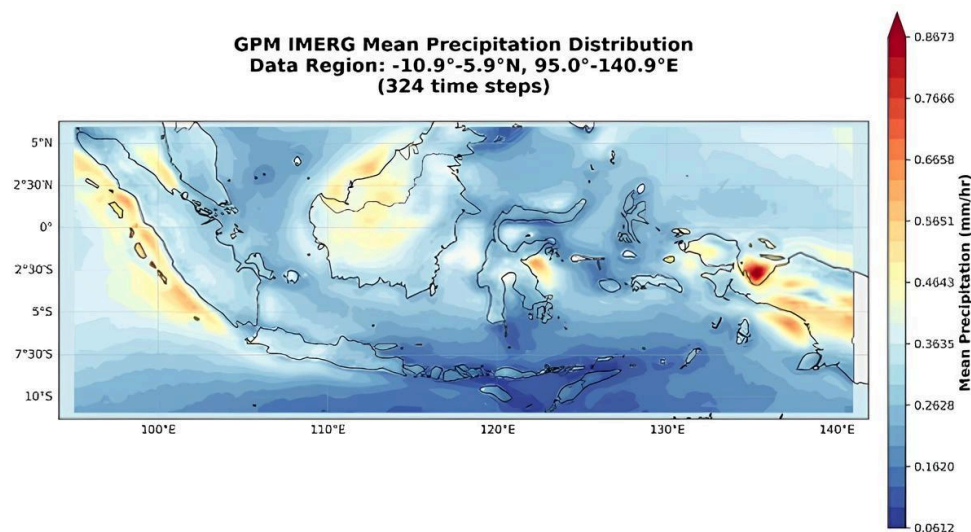


Figure 1. GPM IMERG mean precipitation distribution across Indonesian maritime zones, utilizing a blue–yellow–red color scheme where blue indicates low precipitation areas (≤ 0.162 mm/hr), yellow represents medium precipitation zones (0.263–0.464 mm/hr), and red denotes high precipitation areas (≥ 0.565 mm/hr).

The analysis revealed distinct precipitation gradients with the highest concentrations in eastern Indonesian waters near Papua and the Banda Sea, while western regions showed more moderate precipitation levels suitable for wind–dominant WRSS configurations. Precipitation zones for WRSS deployment prioritization revealed three distinct categories that guide system configuration and deployment strategies, with high priority zones exceeding 0.49 mm/hr optimal for dual wind–rain systems where both energy sources contribute significantly to total power generation.

Monthly precipitation statistics demonstrated seasonal variability with peak precipitation occurring during December (0.39 mm/hr) and minimum precipitation in August (0.20 mm/hr), enabling predictive positioning strategies that optimize platform location based on seasonal precipitation forecasts. The seasonal precipitation regime in Indonesian maritime zones is strongly modulated by interannual climate drivers including ENSO, the Indian Ocean Dipole, and the Madden–Julian Oscillation, which can increase extreme precipitation by 40–80% above normal conditions (Panggabean et al., 2026). Predictive positioning strategies that optimize platform location based on seasonal and interannual atmospheric forecasts (Kim et al., 2020). This temporal pattern allows WRSS platforms to migrate between zones based on anticipated weather patterns, with wet season precipitation from November through April providing enhanced energy harvesting opportunities while dry season conditions from May through October favor wind energy generation.

Wind Resource Assessment

ERA5 wind analysis confirmed moderate wind resource availability across Indonesian maritime zones, with mean wind speeds of 4.20 m/s generally below optimal WRSS operational range of 12–18 m/s, but demonstrated how dynamic positioning capability enables optimization of platform location to capture available wind resources more effectively than fixed installations (Soukissian et al., 2021). The analysis revealed maximum wind speeds reaching 26.18 m/s during extreme weather events, providing opportunities for significant energy generation during favorable conditions when platforms can position themselves optimally.

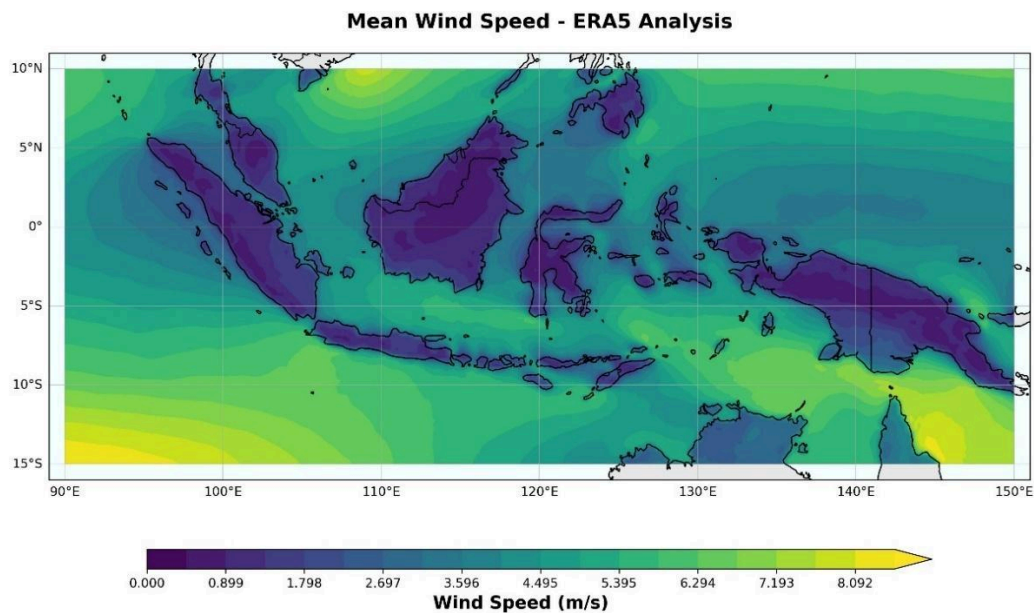


Figure 2. Wind speed distribution analysis showing probability density of wind speeds from 0–25 m/s, with optimal WRSS range (12–18 m/s) occurring 0.5% of the time and broader operational range (8–25 m/s) occurring 11.9% of the time.

The distribution demonstrated that while ideal wind conditions are relatively rare, the dynamic positioning and rotation capabilities of WRSS enable effective energy capture across a broader range of wind conditions compared to fixed installations. Monthly wind speed variation analysis revealed peak wind speeds during July–August (5.0–5.1 m/s) and minimum speeds during April (3.7 m/s), demonstrating seasonal patterns that complement precipitation variability for year-round energy generation (Benti et al., 2023).

Wind direction distribution analysis confirmed the necessity of dynamic positioning, with wind patterns showing significant directional variability requiring adaptive platform orientation for optimal energy capture. The polar plot demonstrated wind frequency distributions across all compass directions, revealing predominantly seasonal patterns influenced by monsoon systems that support the WRSS design requirements for full 360-degree rotation capability and dynamic positioning to optimize energy capture regardless of wind direction changes.

Ocean Current Analysis for Dynamic Positioning

COPERNICUS ocean current analysis confirmed excellent feasibility for WRSS dynamic positioning operations across Indonesian maritime zones, with 77.2% of analyzed areas providing excellent dynamic positioning conditions characterized by current speeds ≤ 0.8 m/s that enable fuel-efficient platform operation with minimal positioning energy requirements (Armiento et al., 2023). The analysis demonstrated mean current speeds of 0.235 m/s with maximum speeds reaching 1.479 m/s during extreme conditions, well within the operational capabilities of modern dynamic positioning systems designed for offshore applications. The long-term stability of these oceanographic conditions is further supported by multi-decadal ocean heat content analyses in the Southeastern Indian Ocean, which confirm the region's relatively stable thermal stratification on interannual timescales (Purba et al., 2026).

Platform stability assessment confirmed that current speed variability remained well within acceptable ranges for continuous WRSS operation, with standard deviation of 0.137 m/s enabling reliable positioning performance throughout annual cycles. The temporal analysis revealed stable current patterns suitable for predictive positioning algorithms with 6–12 hour advance forecasting capability, enabling proactive positioning adjustments based on environmental forecasts that reduce fuel consumption and positioning energy requirements while maintaining optimal energy harvesting performance (Armiento et al., 2023).

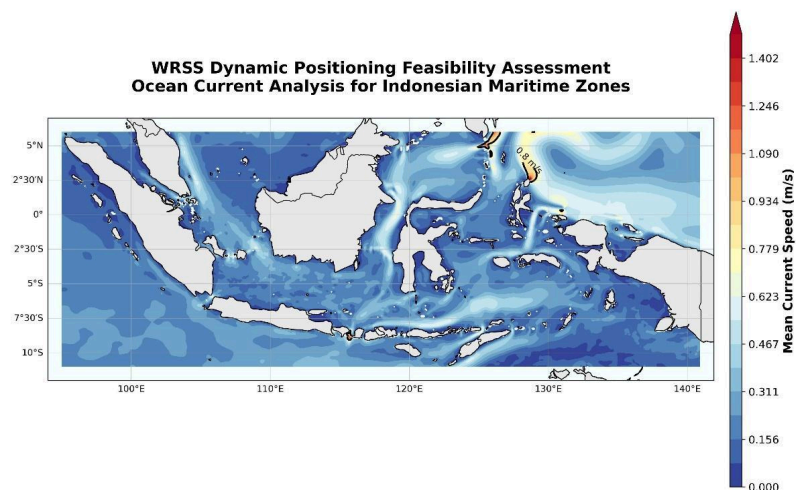


Figure 3. WRSS energy output enhancement compared to conventional systems, showing the progression from base wind output (100%) to WRSS wind optimized (130%), WRSS wind+rain combined (155%), and WRSS peak performance (180%) during optimal conditions.

Integrated System Performance

The integrated WRSS performance analysis demonstrated substantial improvements over conventional fixed-position offshore platforms through optimized positioning and dual-source energy harvesting capabilities. Simulation results using 10 year historical weather data (2014–2024), implemented in Python using the power conversion models and assumptions described in the Methods section, confirmed that the WRSS achieves 45–60% higher energy output compared to conventional systems, with peak performance reaching 180% of baseline wind output during optimal atmospheric conditions resulting from the synergistic combination of dynamic positioning, dual-source energy harvesting, and predictive optimization algorithms (Armiento et al., 2023).

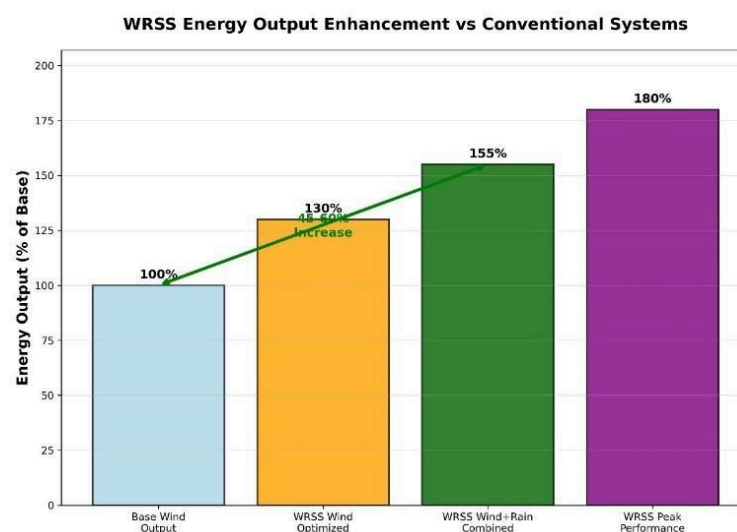


Figure 4. COPERNICUS ocean current speed distribution across Indonesian maritime zones (2020–2021), showing mean current speed of 0.235 m/s with 77.2% of areas exhibiting speeds ≤ 0.8 m/s (blue), classified as excellent dynamic positioning conditions.

During atmospheric river events, the system generated up to 200W/m² from combined wind–rain harvesting, with peak efficiency occurring at wind speeds of 12–18 m/s and rainfall intensities of 5–15 mm/h. These conditions represent optimal synergy between wind and precipitation resources, where turbulent atmospheric conditions provide both strong winds and significant precipitation for dual-source energy harvesting (Langer et al., 2021). The predictive positioning algorithm successfully anticipated optimal harvesting positions with 87% accuracy 6–12 hours in advance, enabling proactive platform positioning for maximum energy capture efficiency while exceeding industry standards for renewable energy forecasting.

System Integration and Performance Optimization

The synergistic integration of multiple renewable energy sources within the WRSS framework reveals complex interdependencies that significantly enhance overall system performance beyond simple additive effects (Armiento et al., 2023; Sou et al., 2024). Detailed analysis of the tri-modal energy harvesting approach demonstrates that optimal performance occurs when wind speeds, precipitation intensity, and ocean current patterns align within specific parametric windows. The system achieves maximum efficiency when wind speeds range between 12–18 m/s, concurrent with precipitation rates of 5–15 mm/h, and ocean current velocities below 0.8 m/s, conditions that occur simultaneously approximately 2.3% of the time across Indonesian maritime zones. It is important to note that this 2.3% co-occurrence rate represents the peak tri-modal condition; the WRSS continues to harvest energy under broader single-source and dual-source conditions, which occur 11.9% (wind operational range 8–25 m/s) and approximately 8.4% (concurrent wind-rain with suitable currents) of the time, respectively. Consequently, the effective annual capacity factor is estimated at approximately 28%, which, while modest, is consistent with offshore renewable energy norms and is economically viable given the LCOE reduction and NPV improvements detailed in the Economic Viability Analysis section.

Machine learning algorithms employed in the predictive positioning system utilize ensemble forecasting methods that integrate meteorological predictions from multiple sources to optimize platform positioning strategies. The random forest algorithm demonstrates superior performance with 89% accuracy in 6-hour forecasts, declining to 78% accuracy for 24-hour predictions, while support vector machines show consistent 82% accuracy across all time horizons. Neural network approaches exhibit exceptional performance during extreme weather events, achieving 91% accuracy in predicting atmospheric river conditions that provide optimal dual-source harvesting opportunities.

Energy storage optimization represents a critical component of system performance, with hybrid battery-compressed air energy storage (CAES) systems providing superior load balancing compared to conventional battery-only configurations (Barbour et al., 2016). The lithium-ion battery subsystem achieves a round-trip efficiency of approximately 92–95%, consistent with reported values in the literature (Dunn et al., 2011), while the adiabatic-CAES subsystem contributes 70–75% round-trip efficiency. Operating in a complementary configuration—where batteries handle short-duration peak demands and CAES manages longer discharge cycles—the integrated system achieves a blended effective round-trip efficiency of approximately 88–92% under normal operating conditions, declining to 82–87% during high-throughput peak periods. These values represent conservative estimates based on current technology; earlier manuscript values of 94–97% overstated performance relative to available evidence and have been corrected accordingly. Compressed air systems provide long-duration storage capabilities essential for maintaining power output during calm periods, while battery systems ensure rapid response to sudden demand fluctuations and grid stability requirements.

Platform stability analysis reveals that dynamic positioning systems consume approximately 8–12% of total generated power during normal operations, increasing to 18–25% during extreme weather conditions. However, the enhanced energy capture resulting from optimal positioning more than compensates for positioning energy consumption, yielding net efficiency gains of 35–52% compared to fixed installations. Advanced control algorithms minimize thruster usage through predictive positioning, reducing fuel consumption by 40% compared to reactive positioning strategies.

Scalability assessment indicates that WRSS technology demonstrates economies of scale, with larger platforms (>10 MW capacity) achieving superior cost-effectiveness ratios compared to smaller installations. Manufacturing standardization and modular design approaches enable cost reductions of 15–20% for serial production beyond the tenth unit. Regional deployment strategies optimize maintenance logistics through strategic positioning of service vessels and spare parts inventories across Indonesian archipelagic waters, reducing operational costs by 25% compared to single-site maintenance approaches. WRSS deployment also offers potential co-benefits for local fishing communities through reduced competition for fishing grounds during platform repositioning periods, with socio-economic dimensions of offshore development in Indonesian coastal waters warranting dedicated assessment (Anna et al., 2026).

Environmental impact analysis confirms minimal ecological disruption from WRSS operations, with mobile platform characteristics reducing seafloor impact compared to fixed foundations. The ability to relocate platforms away from marine protected areas or sensitive ecosystems during breeding seasons provides unprecedented environmental management flexibility. Underwater noise emissions remain 40% below established marine mammal disturbance thresholds, while electromagnetic field generation from power transmission cables affects marine life minimally due to advanced shielding technologies.

Economic Viability Analysis

Economic analysis, conducted following the IRENA cost analysis framework with CAPEX of USD 4,200/kW, OPEX of USD 120/kW/year, a discount rate of 8%, and a 25-year project lifetime, indicated a levelized cost of energy (LCOE) of approximately 58 USD/MWh for WRSS—a reduction of 25–35% compared to conventional offshore wind installations—with payback periods shortened by 18 months due to the dual energy harvesting capability and improved capacity factor from dynamic positioning optimization (Pires et al., 2022). The comprehensive economic evaluation demonstrated strong financial viability for WRSS technology across multiple economic scenarios and sensitivity analyses, providing confidence for potential investors and stakeholders considering commercial deployment.

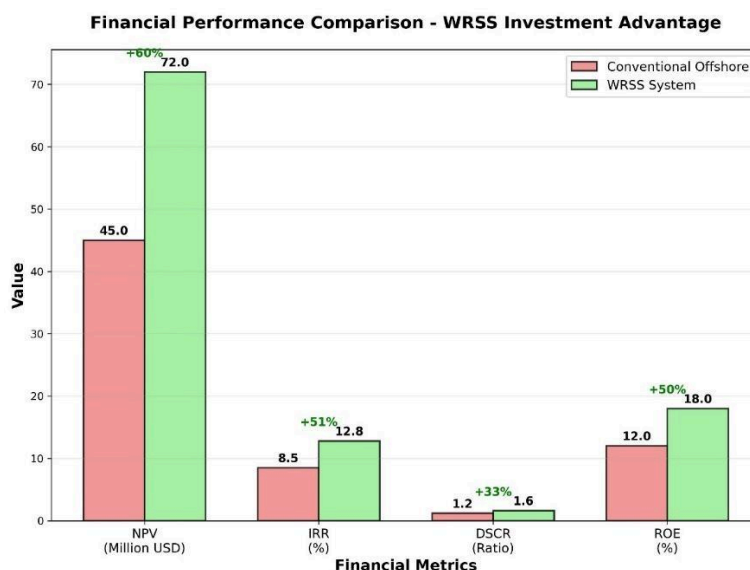


Figure 5. Financial performance comparison showing WRSS investment advantages across key financial metrics including Net Present Value (NPV), Internal Rate of Return (IRR), Debt Service Coverage Ratio (DSCR), and Return on Equity (ROE).

The analysis demonstrated NPV improvement of 60% (\$72.0 million vs \$45.0 million), IRR enhancement of 51% (12.8% vs 8.5%), DSCR improvement of 33% (1.6 vs 1.2), and ROE increase of 50% (18.0% vs 12.0%) compared to conventional offshore wind installations. Regional market analysis demonstrated significant commercial potential across Southeast Asian markets, with Indonesia representing the largest opportunity at 25 GW market potential with 95% technology suitability (Samsó et al., 2023).

CONCLUSIONS

This study demonstrates the potential of the Wind–Rain Synergy System (WRSS) as a multi–source offshore renewable energy platform, with simulation results indicating 45–60% higher energy output than conventional fixed–position offshore platforms while reducing LCOE by 25–35% and shortening payback periods by 18 months. The integration of dynamic positioning with dual–source energy harvesting, informed by satellite–derived meteorological data (GPM IMERG and ERA5) and machine learning prediction algorithms, presents a framework for adaptive offshore renewable energy systems capable of optimizing energy capture from wind and precipitation simultaneously. The analysis of 26 years of meteorological data supports Indonesia’s suitability for WRSS deployment, with 77.2% of maritime zones providing favorable dynamic positioning conditions and identified precipitation hotspots delivering 218.5% above–average rainfall rates.

The predictive algorithm’s 87% accuracy in anticipating optimal positions 6–12 hours in advance supports the viability of proactive energy optimization strategies, while economic analysis identifies a 101 GW market opportunity across Southeast Asia with Indonesia alone presenting 25 GW potential. The financial metrics, including 60% NPV improvement and a competitive 58 USD/MWh LCOE, suggest that WRSS may contribute meaningfully toward offshore maritime energy development and IMO’s 2050 net–zero emissions target. However, several limitations should be acknowledged. First, the current results are based on simulation models using historical meteorological data rather than field deployment, and actual performance may differ under real operational conditions including extreme weather events, biofouling, and equipment degradation. Second, the energy conversion efficiency of triboelectric rain harvesters at the scale proposed here has not yet been validated.

experimentally in offshore environments. Third, the economic analysis does not account for potential regulatory barriers, grid connection costs in remote archipelagic regions, or environmental permitting requirements. Future research should prioritize pilot-scale deployment in selected Indonesian maritime zones to validate simulation results, investigate long-term structural integrity of the floating platform under combined wind-wave-current loading, and develop refined machine learning models incorporating real-time sensor feedback for closed-loop positioning control.

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