

POTENTIAL, CHALLENGES, AND STRATEGIES FOR MARINE WAVE ENERGY DEVELOPMENT IN INDONESIA TO SUPPORT THE 2060 NET-ZERO EMISSION TARGET: A SYSTEMATIC REVIEW

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Received: 07/09/2026 | Revised: 17/09/2026 | Accepted: 02/10/2026 | Published: 06/10/2026

Abstract

Indonesia possesses vast renewable energy potential, yet the utilization of ocean wave energy remains minimal compared to solar or hydropower. This study aims to analyze the potential, technological challenges, and formulate strategies for developing ocean wave energy in Indonesia to support the 2060 Net Zero Emission (NZE) target. The method employed is a Systematic Literature Review (SLR) combined with qualitative policy analysis of the PLN RUPTL documents and NZE roadmap. The results indicate that the southern coasts of Java, Sumatra, and Nusa Tenggara have an average wave power density of 15–25 kW/m, which is technically feasible for exploitation. However, the commercialization of Wave Energy Converter (WEC) technology in Indonesia is hindered by the high Levelized Cost of Energy (LCOE) ranging from US\$0.30–0.80/kWh, challenging tropical marine environmental conditions (biofouling, corrosion, extreme waves), and the absence of specific regulatory incentives. Comparative studies with the Philippines, Brazil, and India reveal that Indonesia lags behind in three key aspects: regulatory incentives, technology testing facilities, and dedicated research funding allocation. This article recommends acceleration strategies through hybrid system integration (wave-wind-solar), the development of pilot projects in remote areas (3T) for diesel substitution, the formulation of a 2024–2060 marine technology roadmap, and the revision of RUPTL to include at least 500 MW of wave energy in the 2025–2035 portfolio.

Keywords : Ocean Wave Energy, WEC, Renewable Energy Policy, Net Zero Emission, RUPTL, Indonesia

INTRODUCTION

The global energy transition demands accelerated utilization of New and Renewable Energy (NRE) to mitigate climate change. Indonesia, as the world's largest archipelagic country with a coastline of over 108,000 km, possesses abundant renewable energy potential, including ocean energy, which remains underutilized. The government has targeted a 23% renewable energy mix by 2025 and a Net Zero Emission (NZE) target by 2060 or sooner (Ministry of Energy and Mineral Resources, 2022). This target aligns with Indonesia's commitment in the Paris Agreement to reduce emissions by 31.89% through its own efforts and 43.20% with international assistance by 2030 (UNFCCC, 2022). Despite the ambitious NZE target, Indonesia's installed renewable energy capacity is still dominated by hydropower (micro-hydro and hydropower), geothermal, and solar power. Ocean energy, particularly wave energy, remains largely untouched in commercial power generation portfolios. According to data from the Directorate General of New, Renewable Energy and Energy Conservation (2023), Indonesia's installed marine energy capacity is still below 1 MW, while its technical potential is estimated at 18 GW (BPPT, 2020). This wide gap between theoretical potential and actual field performance indicates structural barriers, both technologically, economically, and policy-wise.

Unlike tidal energy, which already has a 10 MW Ocean Current Power Plant (PLTAL) in the Larantuka Strait, wave energy is still in the research and development stage in Indonesia. However, recent oceanographic studies show that Indonesia's southern waters have high and consistent wave characteristics throughout the year, influenced by the Australian Monsoon, which produces a long fetch in the Indian Ocean (Rusu & Onea, 2019; Prasetya et al., 2020). Previous research has focused more on wave resource mapping using numerical modeling such as SWAN (Simulating Waves Nearshore) or WW3 (WaveWatch III). Several studies have estimated wave power density in various coastal areas in Indonesia (Sutapa & Pratama, 2020; Fadhil & Prasetyo, 2023). However,

literature comprehensively evaluating technological readiness, economic analysis, integration with national policies (such as the RUPTL), and comparisons with other tropical countries remains very limited. This research gap serves as the basis for this research. Therefore, this study aims to: (1) analyze the current potential of ocean wave energy in Indonesia based on the latest literature; (2) identify barriers to the commercialization of WEC technology from technical, economic, and regulatory aspects; (3) conduct a comparative study with other tropical countries that are more advanced in wave energy development; and (4) formulate a development strategy that is integrated with the NZE 2060 target. The main contribution of this study is the preparation of a roadmap for the development of Indonesian ocean wave energy 2024–2060 which can be a reference for policy makers and future researchers.

2. RESEARCH METHOD

2.1. Research Design

This study employed a qualitative approach using the Systematic Literature Review (SLR) method, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol (Page et al., 2021). The SLR method was chosen because it provides a comprehensive synthesis of previous studies and identifies patterns, trends, and gaps in the literature

2.2. Data Collection

Data collection was conducted through article searches in leading databases: Scopus, IEEE Xplore, Web of Science, ScienceDirect, and Sinta (for national literature). Keywords used in the search included:

"wave energy potential Indonesia"

"Wave Energy Converter (WEC) techno-economic"

"Indonesia's marine renewable energy policy"

"ocean wave power density tropical"

"hybrid wave energy system"

The inclusion criteria were set as follows: (1) scientific journal articles or indexed proceedings; (2) published between 2014 and 2024 to ensure up-to-date data; (3) discussing aspects of potential, technology, economics, or policy of ocean wave energy; (4) full text available. Exclusion criteria: (1) review articles that will be used as secondary references; (2) non-scientific publications (blogs, news, opinions); (3) studies that are not relevant to the context of Indonesia or tropical regions.

2.3. Data Analysis

In addition to SLR, this study also conducted an analysis of policy documents, in particular: Minister of Energy and Mineral Resources Regulation Number 11 of 2021 concerning the EBT Roadmap PLN Electricity Supply Business Plan (RUPTL) Document 2021–2030 Roadmap to NZE 2060 (Ministry of Energy and Mineral Resources, 2022) IEA-OES (Ocean Energy Systems) annual report 2020–2023

Data were analyzed descriptively and comparatively to map existing conditions, identify gaps, and formulate strategic recommendations. A comparative approach was used to compare wave energy development in Indonesia with other tropical countries (the Philippines, Brazil, and India) with similar resource characteristics.

3. RESULTS AND DISCUSSION

3.1. Potential Wave Energy Resources in Indonesia

The characteristics of ocean waves in Indonesia are strongly influenced by two major monsoon systems: the Asian Monsoon (December–February) and the Australian Monsoon (June–August). These seasonal patterns produce significant spatial and temporal variations in wave energy potential across coastal areas. Based on a synthesis of various recent studies (Rusu & Onca, 2019; Prasetya et al., 2020; Fadhil & Prasetyo, 2023), the southern coast of Java, western Sumatra, and East Nusa Tenggara (NTT) have the highest wave energy potential in Indonesia. Wave power density in these areas ranges from 15 to 25 kW/m, with an average significant wave height (H_s) of 1.5–2.5 meters and a wave energy period (T_e) of 8–12 seconds.

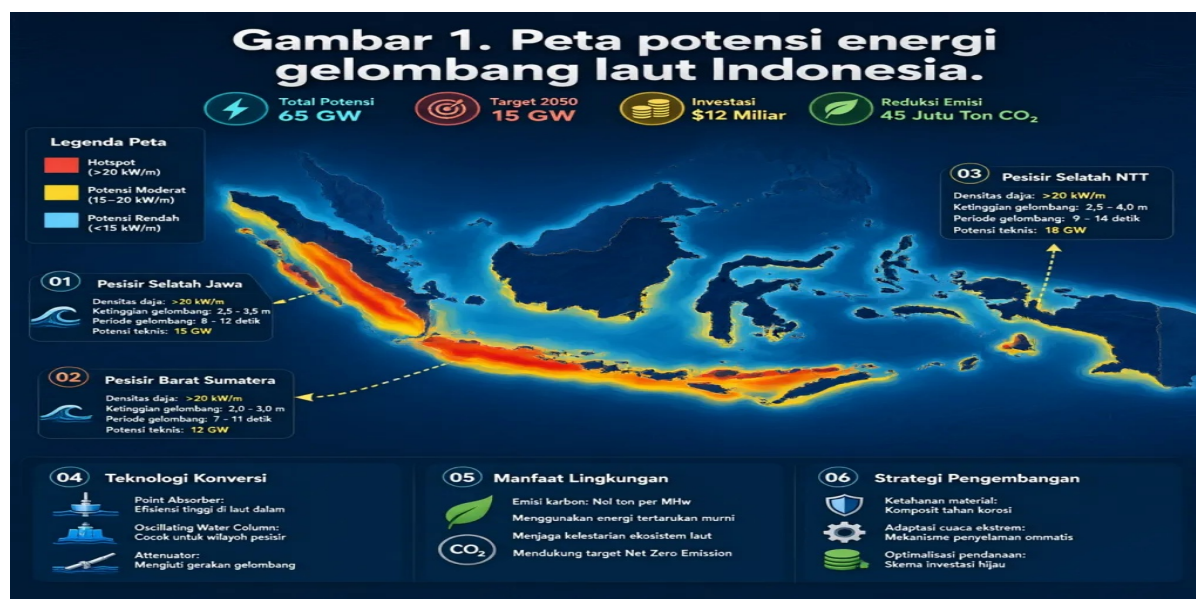


Figure 1. Map of Indonesia's ocean wave energy potential. Areas with a red-orange gradient indicate wave power densities >20 kW/m (hotspots), while yellow indicates moderate potential of 15–20 kW/m. The main hotspots are located along the southern coast of Java, West Sumatra, and East Nusa Tenggara.

Source: ERA5 Reanalysis data processed by the author (2024)

While this figure is considered "moderate" globally—in contrast to coastal areas like Scotland, Portugal, or Western Australia, which can reach >50 kW/m—a density of 15–25 kW/m is well-suited for the implementation of newer generation WEC technologies specifically designed for fetch-limited waters. It should be noted that many commercial WEC projects in Europe were initially developed at sites with similar power densities before the technology matured enough to be exported to higher resource locations (IEA-OES, 2023). In addition to power magnitude, the spectral characteristics of the waves are also important to consider. Waves off the southern coast of Java are dominated by swells (long waves) originating from the Indian Ocean, resulting in a more concentrated energy distribution at certain frequencies. This benefits the WEC design, which can be tuned to respond to these dominant frequencies (Setiawan et al., 2021).

3.2. Wave Energy Converter (WEC) Technology Readiness

Globally, over a hundred WEC designs have been proposed in the literature, but only a handful have reached commercial Technology Readiness Level (TKT). Based on the IEA-OES (2023) classification, WEC technologies can be grouped into several main categories, with varying degrees of maturity.

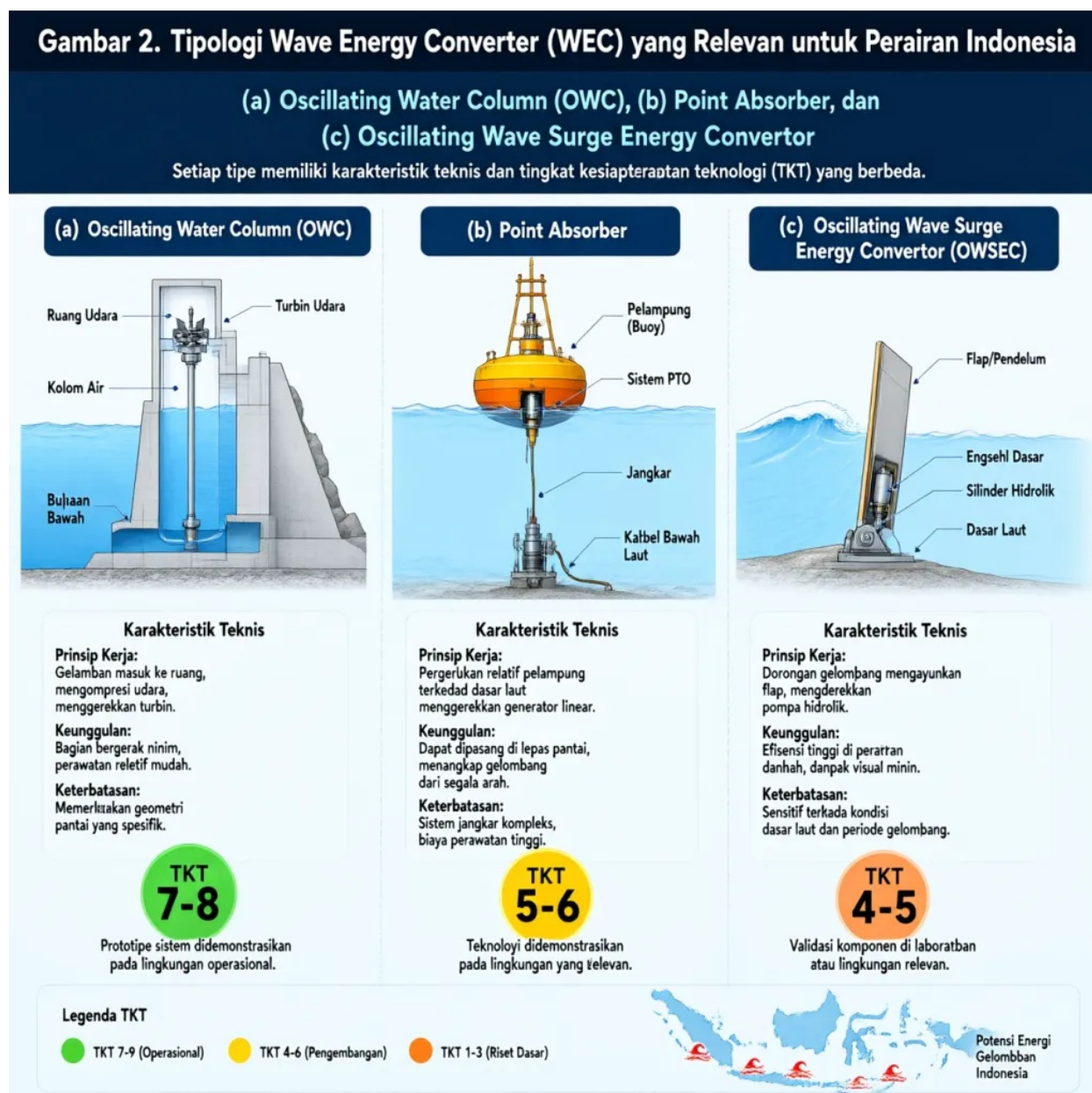


Figure 2. Wave Energy Converter (WEC) typologies relevant to Indonesian waters: (a) Oscillating Water Column (OWC), (b) Point Absorber, and (c) Oscillating Wave Surge Energy Converter. Each type has different technical characteristics and levels of technological readiness (TKT).

Source: Modified from IEA-OES (2023) and Rahman et al. (2022)

For Indonesian water conditions, the three WEC technologies most recommended in the current literature are:

a. Oscillating Water Column (OWC)

An OWC utilizes the oscillation of a water column within a confined space to drive an air turbine (typically a Wells turbine or an impulse turbine). This technology is suitable for installation on breakwaters or coral reefs along the southern coast. The main advantage of an OWC is that the mechanical and electrical components are above sea level, thus better protected from seawater and easier to access for maintenance. The OWC TKT has reached 7–8, with several commercial projects operating in Europe and Asia (Falcão, 2021).

b. Point Absorber

A point absorber consists of a buoy that oscillates relative to a reference structure (either a fixed structure on the seabed or a reference buoy). This relative motion is converted into electricity via a Power Take-Off (PTO) system, which can be a linear generator, a hydraulic system, or a mechanical system. This technology is efficient for

offshore use and can be combined with offshore wind turbines in hybrid systems. The TKT of point absorbers is in the range of 6–7, with several demonstration projects operating in Scotland and Portugal.

c. Oscillating Wave Surge Energy Converter (OWSC)

OWSC consists of vertical panels that oscillate horizontally due to wave action. This panel movement drives a hydraulic system, which then drives a generator. This technology is suitable for shallow waters with depths of 10–25 meters. The TKT of OWSC is still in the range of 5–6, with pilot projects such as AquaOx in Europe. The main challenge for WEC technology in Indonesia is the lack of design adaptation to tropical marine conditions. The widespread biofouling phenomenon (attachment of marine organisms) in tropical waters with surface temperatures of 28–30°C can drastically reduce energy conversion efficiency if anti-fouling materials are not applied (Rahman et al., 2022). Furthermore, the risk of corrosion due to high salinity (35–37 ppt) and warm sea surface temperatures requires specialized composite materials, which are currently expensive and for which the supply chain is not yet available domestically.

3.3. Analysis of Challenges and Obstacles

The main obstacles to the commercialization of wave energy in Indonesia can be classified into three main aspects: economic, regulatory, and environmental-social.

3.3.1. Economic Challenges: Remaining High LCOE

The Levelized Cost of Energy (LCOE) is the most commonly used economic indicator to compare various energy sources. Based on data from IRENA (2023) and IEA-OES (2023), the current global LCOE for wave energy is still in the range of US\$0.30–0.80/kWh, significantly higher than solar energy (<US\$0.05/kWh), onshore wind (US\$0.03–0.06/kWh), and geothermal energy (US\$0.07–0.12/kWh).

GAMBAR 3 : PERBANDINGAN LEVELIZED COST OF ENERGY (LCOE)

berbagai sumber energi di Indonesia tahun 2024

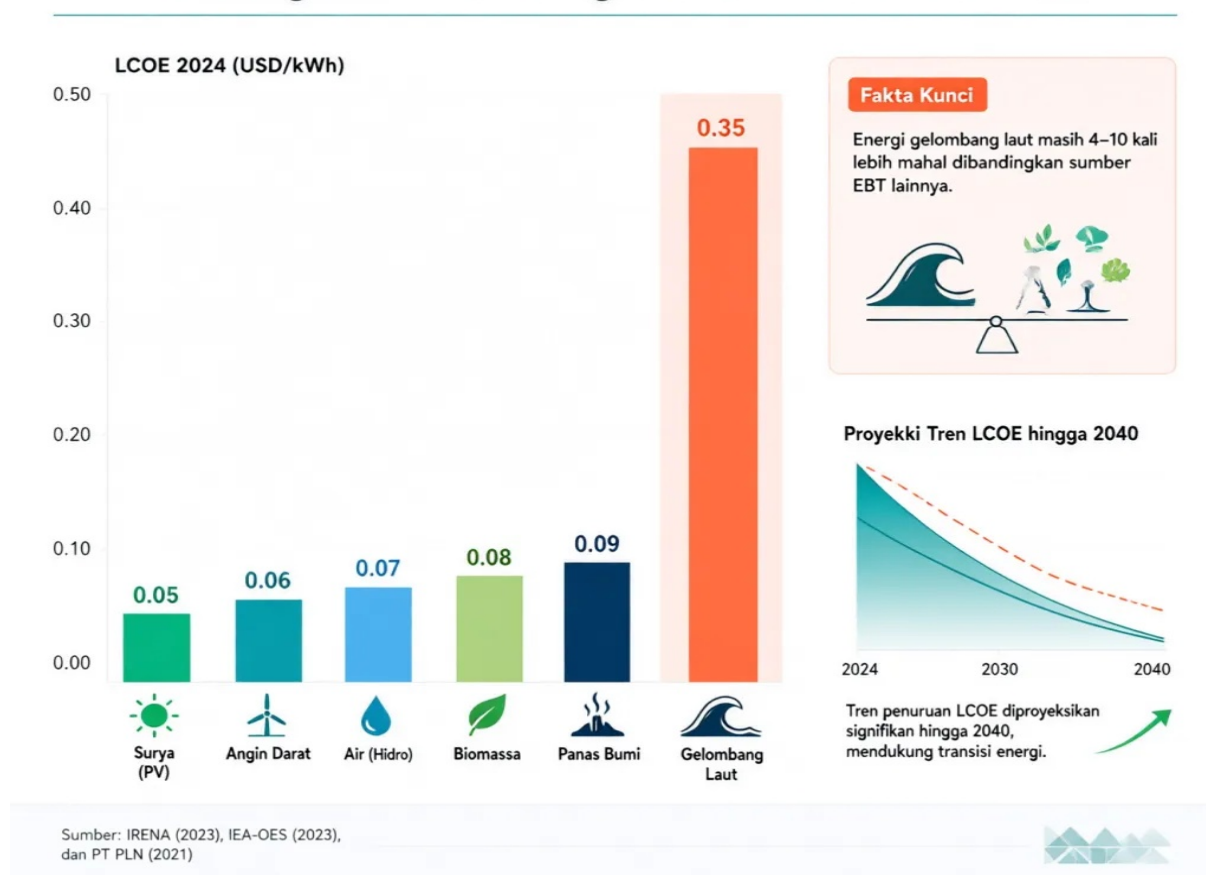


Figure 3. Comparison of Levelized Cost of Energy (LCOE) of various energy sources in Indonesia in 2024. Ocean wave energy is still 4–10 times more expensive than other renewable energy sources, although the LCOE downward trend is projected to be significant until 2040.

Source: IRENA (2023), IEA-OES (2023), and PT PLN (2021)

In Indonesia, initial investment (CAPEX) and maintenance (OPEX) costs will be higher than the global average due to the lack of domestic supply chains for WEC components. Rough estimates suggest that the LCOE of wave energy in Indonesia could reach US\$0.50–1.00/kWh in the early stages of commercialization, before learning effects and economies of scale occur. For comparison, the average PLN electricity tariff for residential customers is around US\$0.10/kWh, making wave energy uncompetitive without incentives. However, it is important to note that the global LCOE of wave energy has fallen by approximately 40% in the past 5 years (from US\$0.80/kWh to US\$0.48/kWh), and is projected to reach US\$0.25/kWh by 2030 through economies of scale and material innovation (IEA-OES, 2023). This learning curve suggests that early policy interventions can accelerate cost reductions.

3.3.2. Regulatory and Policy Challenges

In PLN's 2021–2030 RUPTL document, wave energy is not included in the installed capacity plan until 2030. However, according to a 2020 study by the Indonesian Agency for the Assessment and Application of Technology (BPPT), the technical potential of wave energy in Indonesia reaches 18 GW, with an economic potential of 4.5 GW. This lack of allocation indicates that PLN still views wave energy as an immature technology. Furthermore, the lack of a Feed-in Tariff (FiT) scheme or a dedicated renewable energy auction for ocean energy discourages investors. The current FiT scheme (ESDM Ministerial Regulation No. 50/2017 and its amendments) only covers biomass, biogas, geothermal, wind, solar, and water currents—without explicitly mentioning wave energy.

3.3.3. Environmental and Social Challenges

Utilization of coastal areas has the potential to create conflicts with traditional fishermen and the tourism sector. WEC structures installed near the coast can alter current and sedimentation patterns, impacting coastal ecosystems and fishing activities. Furthermore, the ecological impacts of WEC structures on marine biodiversity require a specific environmental impact analysis (EIA). From a social perspective, coastal communities' acceptance of new technologies is also a challenge. Education and local community involvement from the planning stage are crucial to ensure that wave energy development provides direct economic benefits to coastal communities, not just project developers.

3.4. Comparative Study with Other Tropical Countries

To provide a global perspective and identify best practices, this research conducted a comparative study with three tropical countries that have wave resource characteristics similar to Indonesia.

Table 1. Comparison of ocean wave energy development in tropical countries

Aspect	Indonesia	Philippines	Brazil	India
Wave power density (kW/m)	15–25	12–18	15–22	10–20
Installed capacity	<1 MW	50 kW (pilot)	100 kW (test site)	150 kW (commercial)
Special regulatory incentives	There isn't any yet	FiT specifically for marine energy	Research subsidies	MNRE fund allocation
Testing facilities (WETS)	There isn't any yet	There isn't any yet	WETS Pecém (2020)	Vizhinjam (2019)
Dedicated research funding allocation	Limited	There is (ERC)	There is (EPE)	₹50 crore (MNRE)

Source: Cruz et al. (2021), Silva et al. (2020), IEA-OES (2023)

Philippines: A study by Cruz et al. (2021) showed that the west coast of Luzon has a wave power density of 12–18 kW/m, lower than that of Indonesia. However, the Philippines has successfully implemented a 50 kW OWC pilot project in Ilocos Norte Province since 2019, integrated with a local micro-hydro system. This success was driven by a special Feed-in Tariff incentive for ocean energy established by the Philippine Energy Regulatory Commission (ERC).

Brazil: Silva et al. (2020) reported that Brazil's northeastern coast has a wave potential of 15–22 kW/m, similar to that of Indonesia. Brazil has been developing the Wave Energy Test Site (WETS) in Pecém since 2020, which provides testing infrastructure for technology developers. This model could be adopted by Indonesia through collaboration between BRIN (National Agency for Research and Innovation) with the national shipbuilding industry and technical universities.

India: Although not a purely tropical country, India has successfully operated a 150 kW OWC plant in Vizhinjam, Kerala, since 2019. This success was supported by funding from the Ministry of New and Renewable Energy (MNRE), which allocated ₹50 crore (approximately US\$6 million) specifically for ocean energy research. India has also included ocean energy in its broader National Offshore Wind Energy Policy. Implications for Indonesia: This comparison shows that countries with similar potential waves have taken concrete steps through three approaches: (1) special regulatory incentives, (2) the development of testing facilities, and (3) the allocation of dedicated research funds. Indonesia lags behind in all three aspects, necessitating more aggressive and coordinated policy interventions.

3.5. Material Challenges and Technology Adaptation for Tropical Waters

One technical hurdle often overlooked in the literature is the adaptation of WEC materials to tropical conditions. Studies by Rahman et al. (2022) and Nugraha & Santoso (2024) identified three main challenges:

a. Biofouling

Tropical waters with sea surface temperatures of 28–30°C have biofouling rates 2–3 times higher than subtropical waters. The attachment of marine organisms (especially barnacles and algae) to WEC structures can reduce energy conversion efficiency by up to 30% within 6 months if not regularly cleaned. Solutions currently being developed include silicone-based anti-fouling coatings, nanocomposite materials, and ultrasonic cleaning systems. However, these solutions are still 2–3 times more expensive than conventional coatings.

b. Corrosion

High salinity (35–37 ppt) and warm water temperatures accelerate corrosion in steel structures. Fiber-reinforced polymer (FRP) composite materials are more corrosion-resistant, but their production costs are 40–60% higher. Research by Nugraha & Santoso (2024) shows that developing a hybrid WEC structure (FRP for submerged components, steel for supporting structures) can reduce costs by up to 25% without sacrificing durability.

c. Extreme Waves

Indonesia's southern waters are vulnerable to extreme waves triggered by the La Niña phenomenon and tropical cyclones in the Indian Ocean. WEC designs must be able to withstand significant waves of up to 6–8 meters, requiring a higher safety factor and impacting structural costs. A survival mode approach—where WECs can "hide" from extreme waves—needs to be adapted to Indonesian conditions.

3.6. Critical Analysis of PLN's 2021–2030 RUPTL

PLN's 2021–2030 RUPTL allocates 20.9 GW of renewable energy capacity by 2030, dominated by solar (11.4 GW), hydro (4.6 GW), geothermal (3.3 GW), and wind (1.6 GW). However, not a single megawatt is allocated to wave energy. However, according to a 2020 study by the Indonesian Agency for the Assessment and Application of Technology (BPPT), Indonesia's technical potential for wave energy reaches 18 GW, with an economic potential of 4.5 GW. This lack of allocation indicates that PLN still views wave energy as an "immature" technology. This argument can be refuted by referring to the learning curve of WEC technology. According to IEA-OES data (2023), the global LCOE of wave energy has fallen 40% in the past five years and is projected to reach US\$0.25/kWh by 2030 through economies of scale and material innovation.

Gambar 4. Proyeksi penurunan LCOE energi gelombang global 2020–2040 berdasarkan learning curve teknologi

Learning rate diperkirakan sebesar -15% per doubling kapasitas terpasang global.

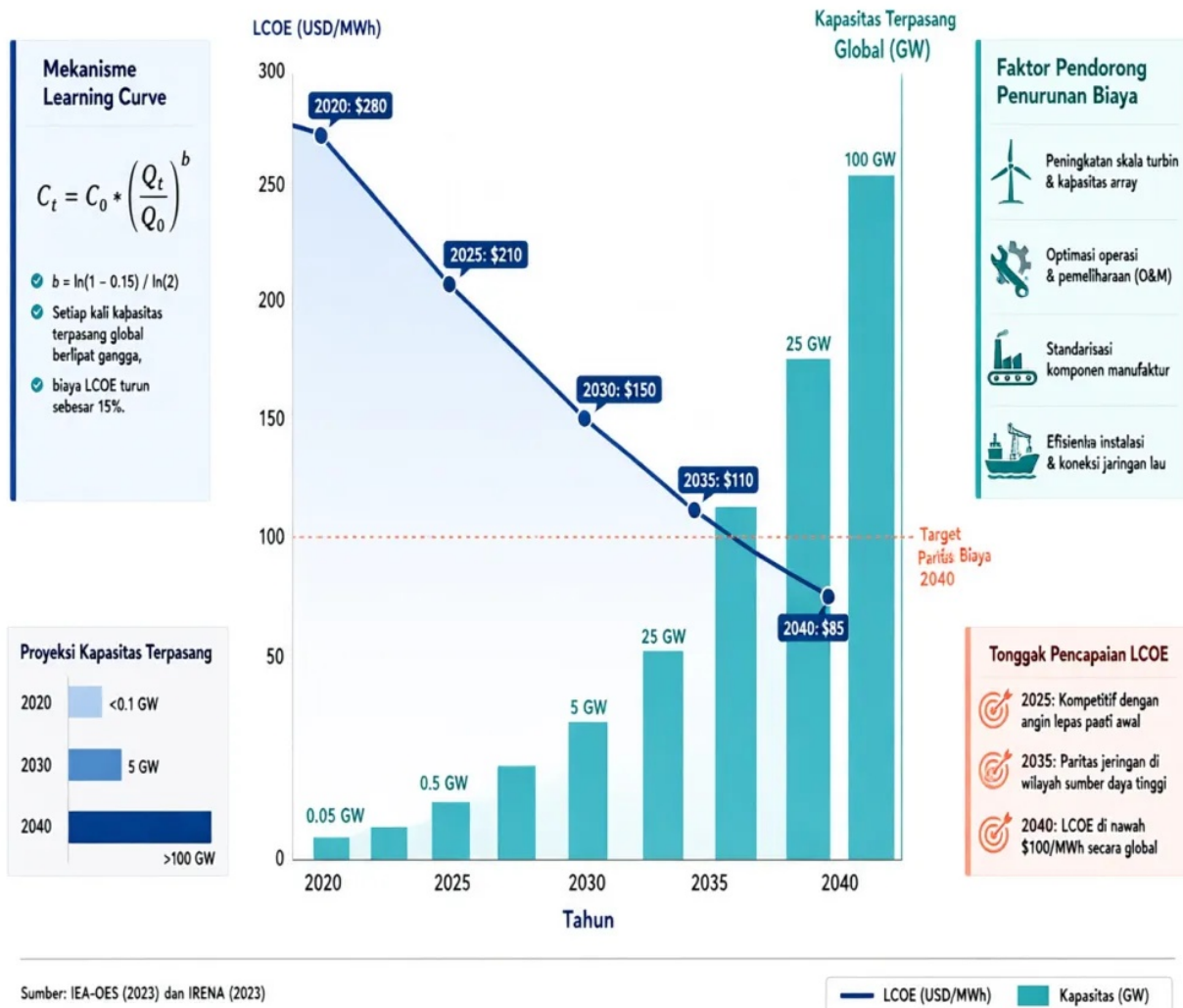


Figure 4. Projected decline in LCOE of global wave energy from 2020 to 2040 based on the technology learning curve. The learning rate is estimated at -15% per doubling of global installed capacity.

Source: IEA-OES (2023) and IRENA (2023)

Furthermore, international experience shows that early policy interventions can accelerate cost reductions. Germany, for example, successfully reduced the LCOE of solar by 80% in 10 years through an aggressive Fiscal Transaction (FiT) scheme. A similar approach could be applied to wave energy in Indonesia.

Policy Recommendation: The government needs to revise the RUPTL (Regional Power Generation Plan) to include a minimum of 500 MW of wave energy in the 2025–2035 installed capacity plan, with a focus on the 3T (Underdeveloped and Remote Areas) regions that currently rely on diesel-powered plants (PLTD). Cross-subsidies from PLTD revenues (which have a high BPP, reaching US\$0.20–0.30/kWh in remote areas) can be used to cover the LCOE gap of WEC in the initial stages.

3.7. Development Strategy Towards NZC 2060

Based on the analysis of potential, challenges, and comparative studies, this research formulates four main strategies to accelerate the development of ocean wave energy in Indonesia:

3.7.1. Hybrid System Development

Integrating WEC with wind and solar power plants (PLTB) into a single off-grid or microgrid system can improve the economics and reliability of electricity supply. Lower wave energy fluctuations (because wave energy arrives with a lag after the wind subsides) can complement solar and wind, stabilizing the grid and reducing battery requirements.

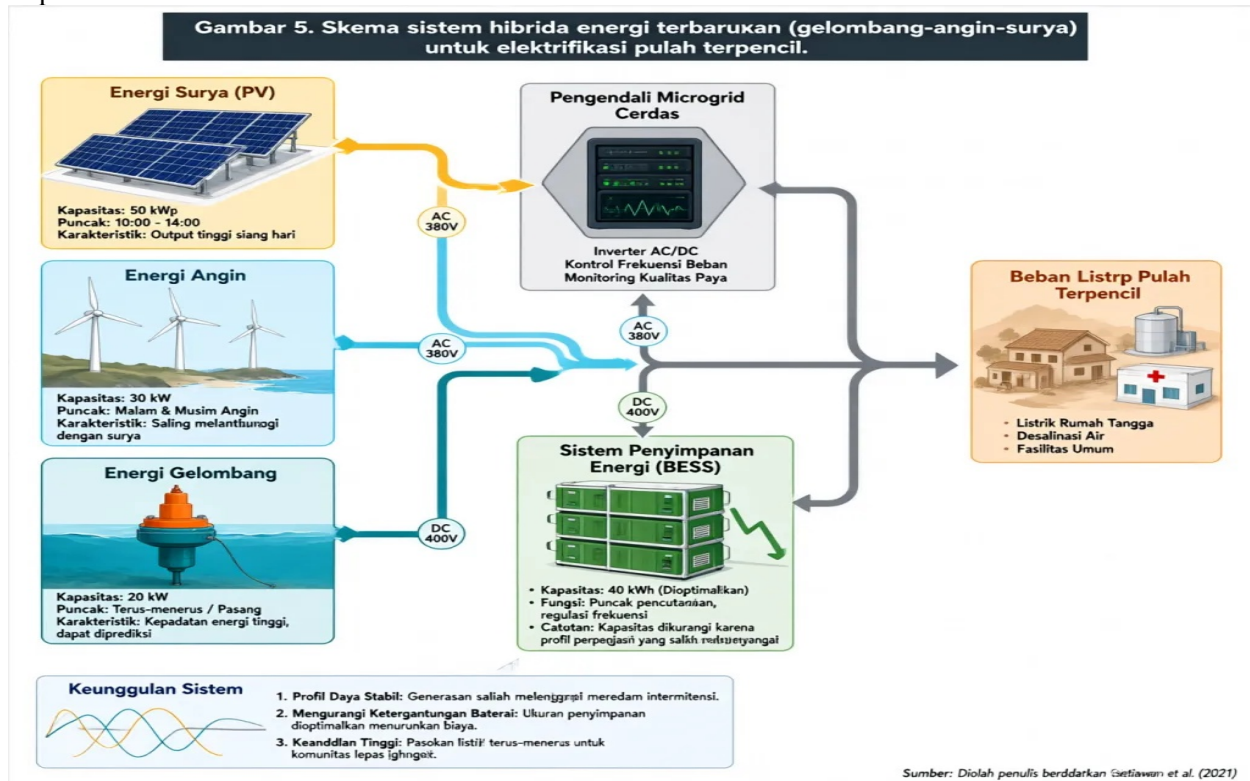


Figure 5. Schematic of a hybrid renewable energy system (wave-wind-solar) for remote island electrification. The combination of these three energy sources results in a more stable power profile and reduces reliance on battery storage.

Source: Processed by the author based on Setiawan et al. (2021)

A study by Setiawan et al. (2021) shows that a WEC-Solar-Wind hybrid system for islands in Eastern Indonesia can achieve an LCOE of US\$0.25–0.35/kWh—still higher than diesel power in some locations, but with zero emissions and higher supply reliability.

3.7.2. Focus on the 3T Regions

Rather than directly targeting the Java-Bali grid, initial development should focus on remote islands in the 3T (Underdeveloped, Frontier, and Outermost) regions, which currently rely on Diesel Power Plants (PLTD). Substituting diesel with WEC would provide higher economic value (avoiding fuel logistics costs, which can reach 30–50% of the PLTD's BPP) and immediate social impact. This approach also has political advantages: the 3T electrification program is a national priority, making it easier to gain budgetary and regulatory support.

3.7.3. Fiscal and Regulatory Incentives

The government should include wave energy in its tax incentive (tax allowance) scheme and set a higher ceiling on electricity purchases by PLN for the initial commercialization phase, as previously applied to geothermal energy. The Contracts for Difference (CfD) scheme implemented in the UK could also be adopted to provide revenue certainty for WEC developers. In addition, the government needs to issue specific regulations that include wave energy in the definition of renewable energy that receives incentives, as well as develop national technical standards (SNI) for safe and reliable WEC devices.

3.7.4. Marine Technology Roadmap 2024–2060

This study proposes a roadmap for the development of Indonesian ocean wave energy in four phases, as shown in Figure 6.



Figure 6. Roadmap for the development of Indonesian ocean wave energy 2024–2060 in four phases: (1) Research & Pilot Project, (2) Demonstration & Initial Commercialization, (3) Medium Scale, and (4) Maturity & NZC.

Source: Processed by the author

Phase 1 (2024–2028): Research & Pilot Project

Research on adaptation of WEC materials to tropical conditions (biofouling, corrosion)

Pilot project of 100 kW OWC on the south coast of Java or NTT

Preparation of regulations and fiscal incentives

Target installed capacity: 0.1 MW

Phase 2 (2029–2035): Demonstration & Early Commercialization

Construction of a national Wave Energy Test Site (WETS) in a strategic location

WEC-Solar-Wind hybrid project for 50 islands in the 3T region

Implementation of special Feed-in Tariff incentives for marine energy

Target installed capacity: 50 MW

Phase 3 (2036–2045): Medium Scale

Domestic WEC industry through BRIN collaboration with national shipyards

Integration with the national grid (Java-Bali-Sumatra)

LCOE target drops to US\$0.15–0.20/kWh

Target installed capacity: 500 MW

Phase 4 (2046–2060): Maturity & NZC

Wave energy is becoming a significant part of the national renewable energy mix

Competitive LCOE: US\$0.10–0.15/kWh

Target installed capacity: 2–4 GW

Contribution to NZC 2060: 5–8% of emissions reduction target

CONCLUSION

Indonesia has significant potential for ocean wave energy, particularly along the southern coasts of Java, Sumatra, and Nusa Tenggara, with a power density of 15–25 kW/m. Although technically feasible, the commercialization of WEC technology remains hampered by its high LCOE (US\$0.30–0.80/kWh), tropical environmental challenges (biofouling, corrosion, extreme waves), and the lack of specific regulatory support. Comparative studies with the Philippines, Brazil, and India show that Indonesia lags behind in terms of regulatory incentives, technology testing facilities, and dedicated research funding. To achieve the NZC 2060 target, wave energy development cannot stand alone. An integrative strategy is needed that includes: (1) integration of WEC-Solar-Wind hybrid systems to improve economics and reliability; (2) an initial focus on electrification of 3T regions to substitute diesel power plants; (3) implementation of fiscal incentives and special regulations; and (4) preparation of a measurable marine technology roadmap for 2024–2060. The government also needs to revise the RUPTL by including a minimum of 500 MW of wave energy in the 2025–2035 installed capacity plan. Further research is recommended in three areas: (1) adaptation of WEC materials to tropical conditions, particularly anti-biofouling coatings and FRP composite structures; (2) economic modeling of WEC-Solar-Wind hybrid systems in various 3T locations; and (3) environmental and social impact assessment of the installation of WEC structures in Indonesian coastal waters.

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