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Preliminary assessment of nearshore wave energy in Morotai for remote electrification in Indonesia

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ABSTRACT

As one of Indonesia's outermost islands, North Morotai requires focused infrastructure development, particularly in the renewable energy sector, and this study presents an initial assessment of nearshore wave energy potential around Cape Sopi using numerical modeling. The analysis employed MIKE21 software (by DHI) and utilized 30 years of global wave and wind data from the validated ERA5 model to produce high-resolution annual wave climate data near the coast. Five key sites (Sopi, Totobako, Cape Sopi, Aru, and Loleo) were selected, each with two depth points (5 m and 40 m), to evaluate annual wave conditions and estimate wave energy resources. Results show that dominant wave energy periods across all locations range from 9 to 11 s, with wave heights varying by site: 0.4–0.8 m at Sopi 1; 0.8–1.2 m at Sopi 2 and both Totobako sites; 1.4–2.0 m at Aru and Loleo; and 1.6–2.2 m at Cape Sopi. Cape Sopi emerged as the most energetic site, offering up to 90 MWh/m of wave energy annually, while Sopi 1 (sheltered within Sopi Bay) recorded the lowest, at approximately 12 MWh/m. Seasonally, around 75% of annual wave energy is concentrated between October and March, with the remaining 25% during April to September. The findings provide both technical and strategic contributions to Indonesia's renewable energy and electrification efforts. The study establishes a validated baseline for nearshore wave energy assessment under local conditions, offering essential input for Wave Energy Converter (WEC) design and supporting evidence-based planning for clean energy deployment in remote islands.

Keywords: Wave energy, Numerical modeling, Morotai, Renewable energy, MIKE21.

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1. INTRODUCTION

Morotai Island is a border regency located at the northernmost tip of Eastern Indonesia. The regency is situated between 2°00' and 2°40' North Latitude, and 128°15' and 129°08' East Longitude. Geographically, Morotai Island lies between the island of Halmahera and the Pacific Ocean. Morotai Island encompasses 2,337.15 km^2 of land area (BPS-Statistics of Pulau Morotai Regency, 2024). To the north, the region of Morotai Regency is bordered by the Pacific Ocean, the eastern region by the Halmahera Sea, the southern region by the Morotai Strait, and the western region by the Halmahera Sea (BPS-Statistics of Pulau Morotai Regency, 2024). The state's border area of North Maluku Province (including Morotai Island) constitutes a national strategic area (President of the Republic of Indonesia, 2015). As a national strategic area, Morotai holds significant national influence in terms of state sovereignty, national defense and security, economy, society, culture, and/or environment.

Morotai Island possesses significant geostrategic and geo-economic advantages (Government of the Republic of Indonesia, 2014). The geostrategic advantage of Morotai lies in the policy to enhance the role of Leo Wattimena Airport, a World War II relic with a substantial runway capacity, as an international hub in Eastern Indonesia. The geo-economic advantages of Morotai include its position as an outer island in the northeast of Indonesia, close to Japan and Taiwan. It is situated on the Indonesian Archipelagic Sea Lanes III, part of the Asia-Pacific trade route, and is rich in natural resources. Additionally, it lies along the migration route of tuna fish and boasts numerous natural, cultural, and historical tourist attractions.

Morotai Island boasts approximately 42 tourism potentials, divided into 22 marine tourism destinations, 8 historical tourism destinations, and 9 cave and waterfall tourism destinations (Mouw et al., 2022). According to the mapping by the Central Statistics Agency (BPS) in 2023, Morotai has 77 tourist attractions, with around 51 located in South Morotai (BPS-Statistics of Pulau Morotai Regency, 2024). The number of tourists visiting Morotai has consistently increased from 2015 to 2022 (Rahmawati, 2024). In 2015, the number of tourists was 3,733, whereas in 2022, it reached 42,780, including 172 international (Morotai Regency Government, 2024). Based on the calculation of Willingness To Pay (WTP) by tourists visiting Morotai, the total value of marine tourism in Morotai Island is estimated at Rp. 205,907,250,990.3 per year, assuming a total of 26,455 visitors (Mouw et al., 2022).

The development of Morotai, particularly in peripheral areas, has not progressed due to obstacles such as land acquisition, infrastructure, and electricity availability. The sources of electricity generation in Morotai Regency remain limited and are insufficient to meet the island's electricity demand. According to data from State Electricity Company (PLN) Unit Daruba in Morotai Regency, the electricity demand is approximately 1,250 kW, whereas the current generation capacity is only 800 kW (Permana et al., 2012; Bahrah et al., 2020). The currently operating power plant to meet the electricity demand is a Diesel Power Plant (DPP). The fuel required for the operation of the DPP is sourced from a depot located in North Halmahera Island. The supply of fuel is dependent on weather conditions; adverse weather can disrupt the fuel supply (Bahrah et al., 2020).

The potential energy resources in North Maluku Province (including Morotai) are very limited and small-scale, such as small-scale hydropower. Other identified renewable energy potentials include biomass, solar power, wind energy, ocean currents, and geothermal energy (Sugiyono, 2012). The renewable energy source that has been developed in Morotai is Solar Power Plant. In 2016, the central government constructed the automated PLTS Daruba system with a capacity of 600 kW, although its operation still frequently encounters issues (Ministry of Energy and Mineral Resources, 2016). This PLTS consists of 1,348 solar modules and 14 on-grid inverters, designed to convert from diesel power (Ministry of Energy and Mineral Resources, 2016).

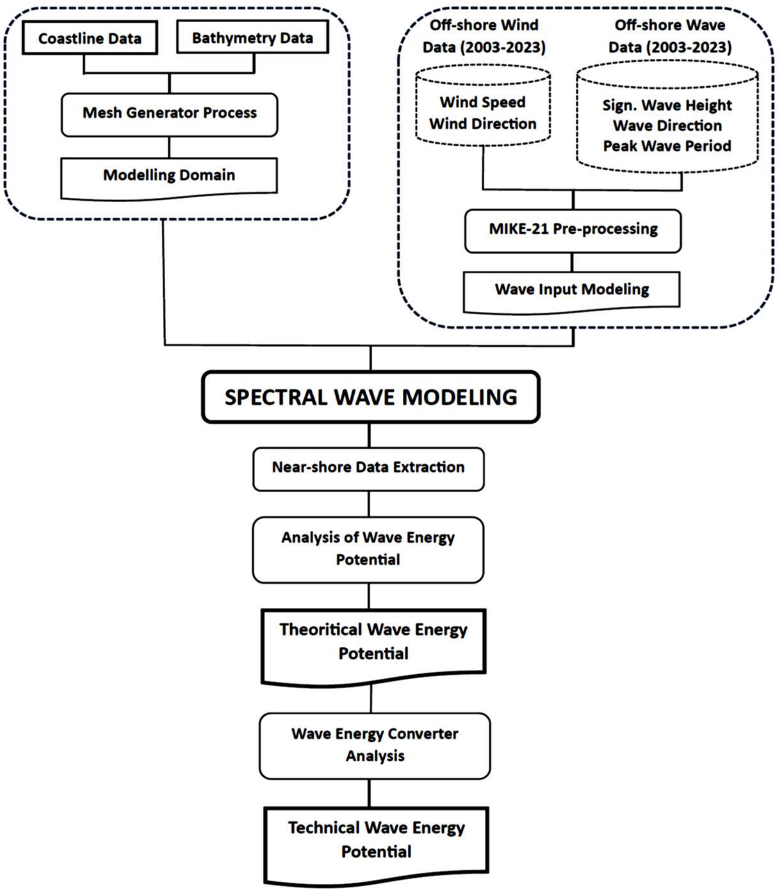

Fig. 1. Steps of study

A preliminary study on wave energy in Indonesia's outermost islands has been done by Rahman et al. (2016), including the southern pacific region, such as Marore island (Sangihe, North Sulawesi). However, the renewable energy, including wave energy potential in Morotai has not been extensively identified and studied. Due to its geographical position, Morotai has significant wave energy potential, as it faces the vast and highly wavy Pacific (Li et al., 2018; Habibie et al., 2021; Posterari and Waseda, 2022).

In comparison with other sources of renewable energy, wave energy offers several advantages. When compared to wind or solar energy, ocean wave energy can be more reliable and cheaper, due to its higher energy density (Samad and Suchithra, 2021). Additionally, wave energy is considered more environmentally friendly while its potential can be very well estimated (Akar and Akdoğan, 2016). The energy from ocean waves is abundant around the globe, with higher reliability to meet the demand compared to solar or wind energy (Mundaca-Moraga et al., 2021). With the predictable periods of constant power, it is also more economical and reliable due to its small storages installed on the converters (Roesler, 2011). Studies have shown that wave energy converters (WECs) could be low-cost alternatives to fossil fuel generators in Pacific Island countries due to the high cost of imported fuel (Bosserelle et al., 2015).

Many areas in Morotai still lack access to electricity, including northern Morotai, particularly around Cape Sopi in Morotai Jaya District. Cape Sopi is an open beach directly facing the Pacific Ocean. In Morotai Jaya District, there are at least 10 tourist attractions with potential for development (Morotai Regency Government, 2024).

Objective of this study is to evaluate the wind and wave conditions in the northern waters of Morotai, and to identify

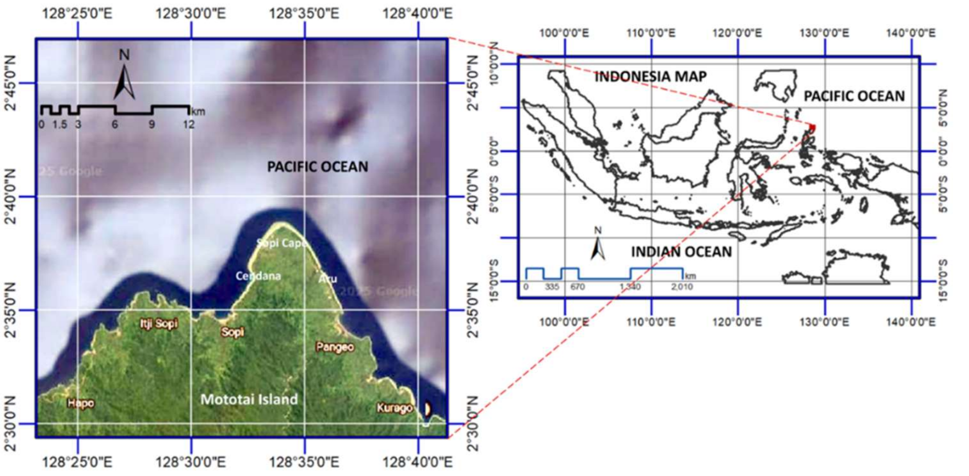

Fig. 2. Location and area of study

Table 1. Software/application used in this study

Software/application	Version/year	Usage	Developer
Ocean data viewer (ODV)	v4.7.6/2016	Extraction of wind/wave data from NC files	Reiner Schlitzer, https://odv.awi.de
Google earth pro	v7.3.6.9796/2024	Digitization of coastlines	Google LLC
Pivot table	MS Excel 2021	Model result analysis, preparation of wave (height-period) scatter diagram and power matrices	Microsoft
Global mapper	v13/2011	Spatial data processing	Blue Marble Geographics
MIKE zero	2011	Pre- and post-processing of wave modelling data, such as spatial data, wind/wave data, model result extraction, creating plots etc.	Danish Hydraulic Institute
Spectral wave model	2011	For spectral wave modelling	Danish Hydraulic Institute
WR Plot	8.0.2/2018	Calculation of distribution frequency of wave data	Lake Environmental

Table 2. List of data used in this study

Data	Source	Spatial resolution/location	Temporal resolution
Bathymetry	Geospatial information agency (BIG), 2018	180 m/6-arcsec	2018
Coastline	Google Earth, 2024		December 2020
Wind data (direction and speed)	The copernicus climate change service (C3S), 2024	0.5 deg	January – December 1994-2023 (3 h interval)
Wave data (direction, peak period & significant wave height)	European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2023)	0.5 deg	January – December 1994-2023 (3 h interval)
Mean significant wave height data	AVISO Satellite altimetry data	1º x 1º	2018 (daily data)

the ocean wave energy potential and its locations. To date, no specific studies have examined the wave energy potential, let alone the optimal selection of WEC for Morotai. Therefore, this study represents the first research addressing these topics. The results of this study are expected to provide the basis for policy-making and energy planning in Morotai, allowing wave energy to substitute for existing conventional energy sources.

2. MATERIALS AND METHODS

2.1 Steps of Study

This study began by collecting secondary data for modeling input (Fig. 1). The main stage in this study is spectral wave (SW) modeling to describe wave propagation from offshore to the coastline.

2.2 Location and Area of Study

Area of study and modeling domain is located at North Morotai and the surrounding waters (Fig. 2). The energy potential study focuses on the coast around Cape Sopi.

2.3 Software and Data

The software used in the study includes software for data preprocessing, modeling and post-processing of the modeling results (Table 1).

One of the main stages of this study is spectral wave modeling, which simulates wave conditions at a specified time and location. This model not only simulates the mainwave parameters such as significant height, wave period and wave direction but also a two-dimensional spectrum that describes the frequency distribution and direction of wave energy (Cavaleri, 2017). Numerical studies on nearshore wave energy have been done using SWAN (Simulating Waves Nearshore), which is the third-generation model developed for modelling deep waters (Monteiro and Sarmento, 2019). SWAN has been used in the studies of nearshore wave energy such as in Sea of Iroise, western Europe (Guillou et al., 2015), the Iberian nearshore (Rusu, 2018), Leeward Island, Portugal (Monteiro and Sarmento, 2019), and in the southern pacific region namely in Cuyo island, Palawan, Philippines (Pacaldo et al., 2022).

The current study, however, uses the MIKE-21 SW Flexible Mesh Model. This model is very reliable in simulating the growth, decay and propagation of swell and wind waves on offshore and nearshore areas (Danish Hydraulic Institute, 2017). Directionally decoupled parametric formulation was used to assess nearshore and coastal wave conditions involving the transformation of offshore or global wave model (Danish Hydraulic Institute, 2014). For maximum relative water depth bigger than 0.8, the spectrum from MIKE 21 Spectral Wave agrees well with OceanWave3D, which is a fully nonlinear model (Joensen and Bingham, 2023). Mike 21 SW was used by Deshpande et al. (2022) to estimate wave energy potential in the coast of Ullal, India, with a good agreement of the significant wave height (Hs) between the simulated and measured values.

The main data used in this study are spatial data to build the modeling domain and wind and wave data as input for spectral wave modeling (Table 2).

2.4 Modeling Scenario

Spectral wave modeling was carried out for 1 year to cover 4 seasons. The input wave and wind data values are averages based on 1994–2023 data with 3 h intervals. The input values and modeling setup are presented in Table 3.

2.5 Wave Energy Potential Calculation

The integral wave parameters as the output of the SW model are calculated from the wind and swell parts of the spectrum. The parameters used to calculate the wave energy are Hs and Te (the mean energy period) (Danish Hydraulic Institute, 2014). Potential ocean wave power at one observation point in units of kilowatts per meter of wave crest length (kW/m) is proportional to about half of the square of Hs multiplied by Te, as shown by Eq. (1). Based on these calculations, various energy potentials from ocean waves can be predicted in various places in the world.

Table 3. Model Setup and Input Data

Item	Value	Description
Domain	37 km x 36 km	452 nodes; 688 meshes
Time	1 year (Jan - Dec)	The input values are the average data 1994–2023
	Spectral wave model	
Basic equations	Spectral formulation: Directionally decoupled parametric Time formulation: Quasi stationary	Default MIKE (Danish Hydraulic Institute 2017)
Solution technique	Low order, fast algorithm	Default MIKE (Danish Hydraulic Institute 2017)
Water level condition	No water level variation	This model only used Spectral wave model
Current conditions	No current variation	This model only used Spectral wave model
Wind forcing	Varying in time, constant along line	Average value based wind data 1994-2023
Wave breaking	Specified gamma	Default MIKE (Danish Hydraulic Institute 2017)
Bottom friction	Nikuradse roughness (0.04 m)	Default MIKE (Danish Hydraulic Institute 2017)
Initial conditions	JONSWAP	Suitable for the conditions of the research area
Boundary conditions	Varying in time, constant along line	Average value based wave data 1994–2023

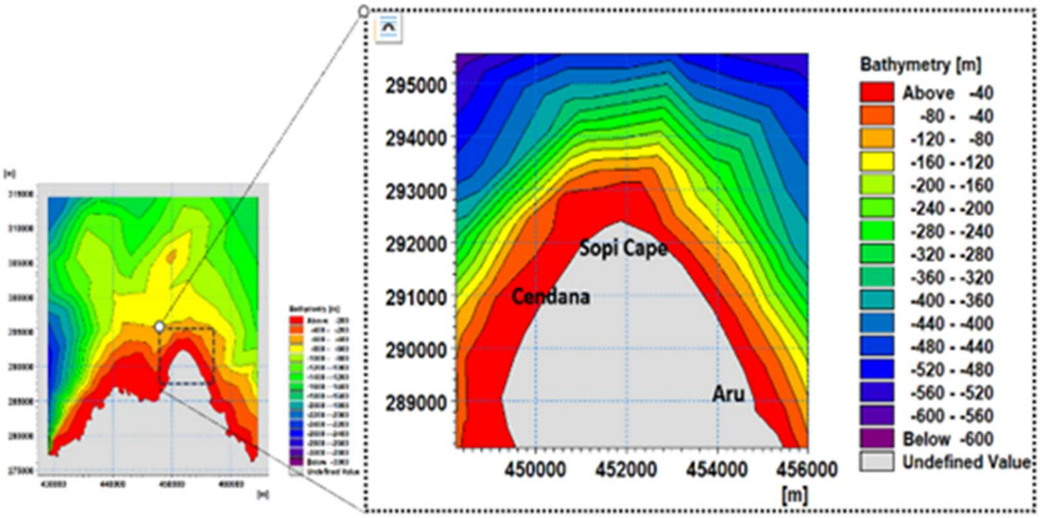

Fig. 3. Bathymetry in northern Morotai

$$P = \frac{\rho g^2}{64\,\pi} {H_s}^2 T_e \tag{1}$$

where P equals potential ocean wave power, ρ the water density, g the gravitational acceleration, Hs the significant wave height and Te the wave energy period. The wave height parameter used is significant wave height, which is the highest average of a third of the wave height from the zero up crossing from the valley to the wave crest.

3. Results and Discussion

3.1 Bathymetry

Bathymetry plays a crucial role in wave transformation and energy potential, as it influences how offshore waves propagate, refract, and dissipate as they move toward the coast. The relatively steep seabed slope and proximity of deep waters in Morotai suggest that wave energy arriving from offshore experiences less dissipation before reaching nearshore zones, which is advantageous for WEC systems, especially those requiring deeper or intermediate water depths for optimal operation. The bathymetry in the study area varies from 0 m to more than 2000 m (Fig. 3). The slope of the bottom of the waters near the coast is around 15%. At a distance of 500 m from the coastline it is generally around 40 m deep.

This result aligns with Rahman et al. (2016), who evaluated wave energy potential on various outer Indonesian islands and emphasized the importance of deep-

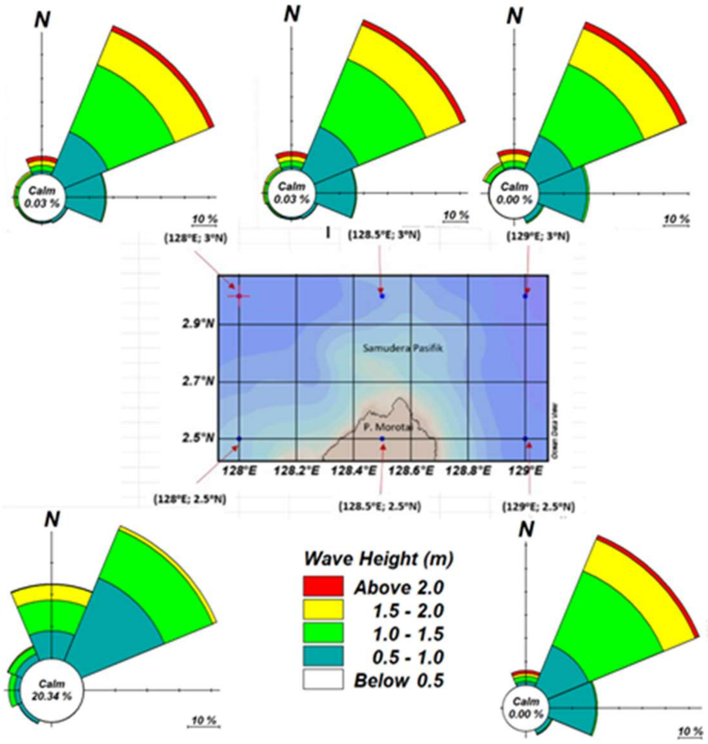

Fig. 4. Wave roses in northern Morotai waters, representing annual wave direction (with the "north-up" convention) and Hs distribution in meters (shown by the color scales)

water exposure and open-ocean orientation for high energy yield. The bathymetric conditions off Morotai, including the rapid deepening of the seabed, would contribute to the island's exposure to more energetic wave conditions, as suggested by the recorded wave heights (1.8–2.2 m during peak seasons) and maximum wave heights up to 2.6 m (Rahman et al., 2016). The steep bathymetry and rapid depth increase are also consistent with the findings by Purba et al. (2019), which support the potential for high-energy wave conditions, particularly in northern Morotai.

Pacaldo et al. (2022), although the study primarily focused on wave climate and energy resource potential in Cuyo Island, also acknowledged that bathymetry and coastal configuration influence wave height attenuation and WEC suitability. Cuyo's more sheltered configuration and gradual slope contributed to lower nearshore wave heights compared to offshore, which impacted the estimated extractable wave energy. By contrast, the steeper and deeper bathymetric profile off northern Morotai would likely reduce wave energy loss, potentially increasing the efficiency of WEC deployment closer to shore.

3.2 Offshore Wave Conditions

The 30-year wave climate data from the north coast of Morotai (1994–2023) are characterized by a dominant northeast wave direction (over 60% annually) and seasonal wave heights ranging from 1.1–2.2 m with maxima reaching 2.6 m, which supports the findings from previous studies (Fig. 4). The pronounced wave activity during the west season (where 94.3% of waves are 1.8–2.2 m and 90% originate from the northeast) corresponds closely with the monsoonal trends described in the study of Cuyo Island by Pacaldo et al. (2022), which also recorded northeast-dominant wave directions and peak wave energy during the west season.

During the east season (June to August), wave heights are predominantly within the 1.1–1.4 m range (79.1%), with wave directions mainly from the northeast to east (44%). In the first transition season (March to May), the dominant wave height increases to 1.4–1.8 m (47.6%), primarily originating from the northeast (83.8%). Similarly, in the second transition season (September to November), dominant wave heights remain within the 1.4–1.8 m range (66.1%), with a continued northeast directional dominance (53.7%). This confirms the study by Li et al. (2018) who used numerical modeling over the northwest Pacific, which confirms stronger wave activity in summer and autumn, predominantly from eastern sectors, supporting Morotai's exposure to northeast and east swell. Habibie et al. (2021) also observed seasonal wave energy variation in Indonesia, noting higher stability and power flux in areas exposed to open ocean swell, as is the case for Morotai.

While Morotai's wave heights suggest moderate energy potential, the consistent wave directionality and exposure to the Pacific indicate it could support small to medium-scale wave energy systems. This aligns with the wave energy feasibility criteria outlined by Posterari et al. (2022), who emphasized the importance of consistent resource availability and seasonal predictability for wave energy projects in Pacific island environments.

3.3 Spectral Wave Model

3.3.1 Wave Model Validation

Before simulating/modeling wave propagation in North Morotai waters, we validated the offshore global wave data taken from the ERA5 model using wave data based on altimetry satellite imagery. Combined with precise satellite location data, altimetry measurements yield sea-surface heights. It is a very well established technique with mature sensors and defined methods, after more than 30 years of satellite missions dedicated to this field (Hauser et al., 2023). In this study, the offshore wave data were compared with those obtained from AVISO data. AVISO is the French Active Archive Data Center for multi-satellite altimeter missions, which carries out post-processing, archiving, the analysis and also the distribution of the altimetry data for the French Space Agency CNES (Centre National d'Etudes Spatiales) (Centre National d'Etudes Spatiales, 2024). With the resolution of 1 degree, the AVISO dataset is developed by binning and averaging monthly values.

Based on daily average wave data during 2018 at coordinates (129°E, 3°N), we found that the ERA-5 wave height data are in very good agreement with the AVISO wave height data, with a Normalized Root Mean Square Deviation value of 10.32%. This is in accordance with what was done by Yang et al. (2021) where the correlation coefficient of wave height between ERA-5 and AVISO SWH was 0.849. The validation of long-term wave height data using ERA-5 and its agreement with AVISO satellite data is also consistent with the findings of Aswad et al. (2021), highlighting the reliability of ERA-5 reanalysis data for wave energy assessments in Indonesian waters. Aswad et al. (2021) demonstrated that the ERA-5-derived Hs for the western waters of Lampung showed strong statistical agreement with AVISO satellite altimetry data, reporting a correlation coefficient (R) of 0.8691, RMSE of 0.277 m, and a MAPE of 16.355%, all indicating high model performance and suitability for wave energy evaluation. Similarly, the Morotai data validation also references a Normalized Root Mean Square Deviation of 10.32%, and correlates well with prior literature that reports correlation coefficients between 0.849–0.8691 and RMSE values within a comparable range.

Other studies show that based on significant wave height climatologies and trends over 1992–2017, the reanalysis and hindcast datasets (including ERA-5) generally show similarity in spatial variation and magnitude (Timmermans et al., 2020). Shi et al. (2021) and Liu et al. (2022) showed that ERA-5 data generally showed good agreement with in-situ measurements with respect to Hs and mean wave period (Tm). For assessing wave energy resources, ERA-5 data also provided valuable insights, with a relatively good concordance with satellite data, albeit slightly lower energy values (Rusu, 2021).

Hence, the findings among these studies affirm the validity of using ERA-5 data as a baseline for wave climate and energy resource assessments across different Indonesian maritime zones. They confirm that ERA-5 reanalysis, when calibrated or verified against satellite products like AVISO, offers reliable spatiotemporal resolution for regional-scale wave modeling, making it a robust tool for identifying potential wave energy sites such as those off Morotai. This alignment enhances confidence in the reproducibility and generalizability of wave energy studies using reanalysis data across the Indonesian archipelago. Another example of validating a wave model against satellite imagery data was done by comparing Wavewatch 3 wave model against satellite image Topex/Poseidon which shows a correlation of 0.94 and RSME of 0.32 m (Rizal et al., 2022).

One important limitation of this study is the absence of in-situ measurements from the nearshore region of Morotai, such as wave buoy or ADCP data, which would have allowed for more accurate model calibration, particularly in the complex 5-meter depth zone. Due to logistical constraints during the course of this research, obtaining these ground-truth observations was not feasible. However, we acknowledge the critical role such data would play in refining wave transformation models. Future studies should aim to incorporate in-situ measurements to further validate and improve model predictions, thereby enhancing the robustness of wave modeling in nearshore environments.

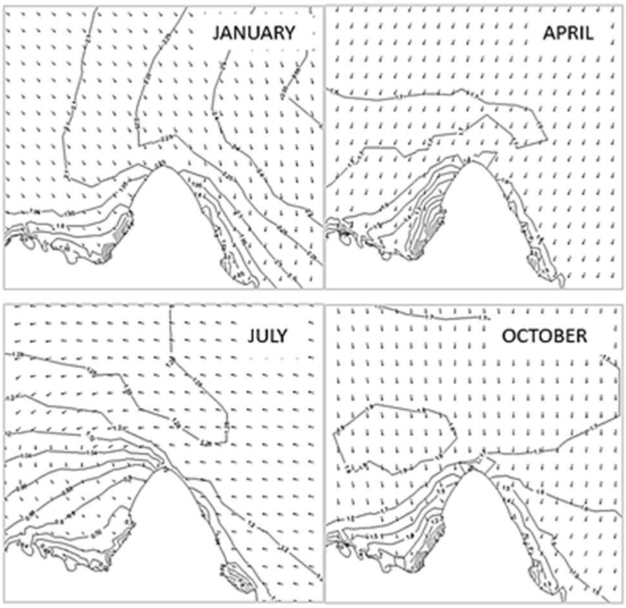

Fig. 5. Typical wave transformation throughout the year in northern Morotai (isolines represent areas with the same waveheights, arrows represent directions)

3.3.2 Nearshore Wave Propagation

The wave propagation patterns and seasonal dynamics observed in the Cape Sopi region of northern Morotai exhibit notable similarities to findings in other regional and global studies. In Cape Sopi and its surrounding areas, wave directions are predominantly from the northwest to northeast sectors, with a distinct shift to the east around July. This seasonally driven variation in wave direction is consistent with monsoonal influences observed in studies such as Pacaldo et al. (2022), who found that wave heights and energy fluxes in the Philippines vary significantly between northeast and southwest monsoon seasons. Furthermore, studies by Guillou and Chapalain (2015) in the Sea of Iroise and Houekpoheha et al. (2015) in Benin highlight how coastal morphology and wave refraction cause incident wave energy to reorient toward the shoreline—an effect also prominently seen in Cape Sopi, where refraction persistently redirects wave energy toward the coast regardless of the original incident direction, as seen in Fig 5.

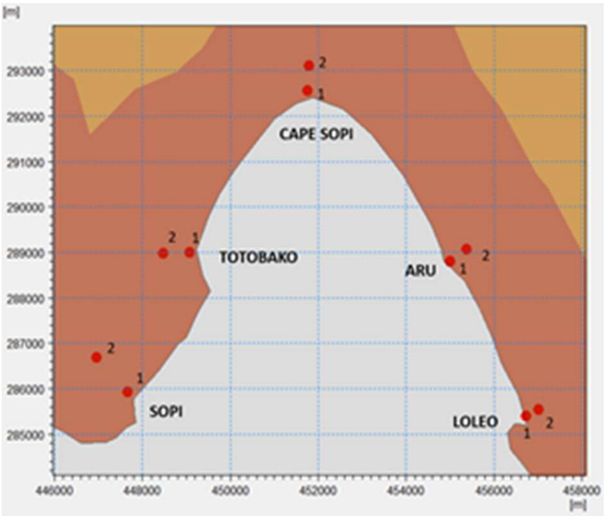

Fig. 6. Locations of observation points in northern Morotai (point 1. at 5 m, and 2. at 40 m)

An evaluation of nearshore wave conditions (and consequently the wave energy potential) around Cape Sopi was conducted by extracting results from the SW model at five distinct locations: Sopi, Totobako, Cape Sopi, Aru, and Loleo. At each site, model outputs were analyzed at two different water depths, approximately 5 and 40 m, to capture variations in wave characteristics across the nearshore profile, as illustrated in Fig. 6.

The selection of observation points around Cape Sopi is aimed at estimating the spatial variability of wave energy potential and assessing the technical feasibility of harnessing this energy using various types of WECs suited to different water depths. Determining the water depths at these locations is crucial for evaluating the energetic characteristics of incoming swells as they approach the shoreline (Houekpoheha et al., 2015). Variations in bathymetric profiles around the cape naturally result in unequal distances of the observation points from the coastline. The details of these observation points are presented in the table below.

Assessment of nearshore wave energy was carried out using MIKE21 modeling at five locations (Sopi, Totobako, Cape Sopi, Aru, and Loleo) and analyzing two distinct water depths (5 and 40 m). This approach is consistent with those of Guillou et al (2015), who used an unstructured SWAN grid to capture fine-scale nearshore dynamics in the Iroise Sea. Pacaldo et al. (2022) also applied similar depth-stratified modeling to assess nearshore transformation processes in Cuyo Island. The inclusion of bathymetric influence on wave transformation is particularly critical, as seen in the work by Houekpoheha et al. (2015), where shoaling and refraction dramatically increased energy concentration in the surf zone.

In the case of North Morotai, particularly around Cape Sopi, the nearshore bathymetry is characterized by a steep seabed slope, with depths of approximately 40 m reached within 500 m from the coastline. Under such conditions, the dissipation of wave energy due to bottom friction and depth-limited wave breaking is minimal because the majority of the wave transformation occurs in relatively deep water until very close to the shore. As shown in previous studies, bottom friction effects become significant primarily in shallow, gently sloping bathymetric profiles where the wave orbital motion interacts extensively with the seabed.

Table 4. Wave energy observation sites

Site Name	Location (UTM 52N)		Depth (m)	Distance from coastline (m)
	Easting	Northing		
Sopi 1	447661	285919	5	160
Sopi 2	446946	286689	40	1100
Totobako 1	449066	289003	5	190
Totobako 2	448464	288974	40	760
Cape Sopi 1	451760	292556	5	170
Cape Sopi 2	451786	293105	40	700
Aru 1	455002	288800	5	100
Aru 2	455377	289074	40	560
Loleo 1	456738	285401	5	30
Loleo 2	457018	285532	40	320

Similarly, the influence of the wave breaking index is most pronounced in surf zones over gradual slopes, where wave height decay occurs over longer distances (Battjes and Janssen, 1978).

For steep coastal slopes, such as those in Morotai, the short shoaling distance limits the cumulative impact of bottom friction and depth-limited breaking on incident wave energy (Guillou and Chapalain, 2015; Pacaldo et al., 2022). This is supported by our model results, which show minimal difference in wave height and power between observation points at 40 m and 5 m depths for exposed sites such as Cape Sopi. Consequently, variations in the bottom friction coefficient or the wave breaking index within the commonly accepted parameter ranges would have negligible effect on the estimated wave energy potential. This is consistent with findings from other steep-slope coastal environments where deep-water wave energy is preserved until the point of breaking very close to shore (Houekpoheha et al., 2015).

3.3.3 Annual variations of Hs

Fig. 7 shows the rose plots of annual wave data at the observation points, illustrating both Hs and wave direction. The plots reveal that the majority of incoming waves, particularly those with higher Hs values, originate from the north and northeast, as observed at Cape Sopi, Aru, and Loleo. In contrast, wave activity at Sopi and Totobuko (both located on the western side of Cape Sopi) is predominantly from the north and northwest, with generally lower Hs values.

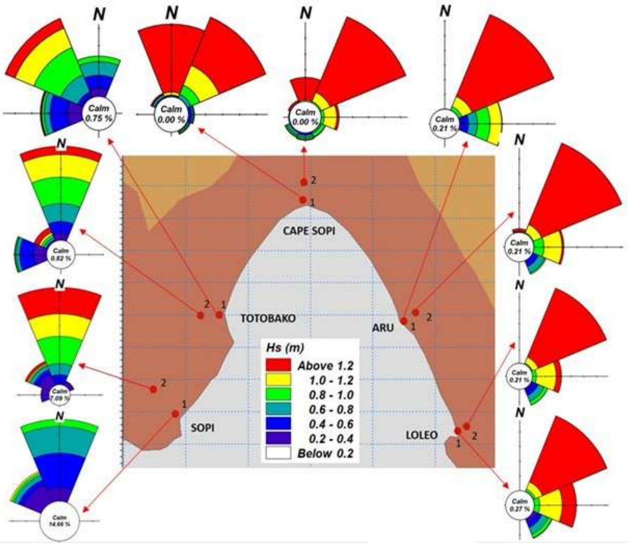

Fig. 7. Wave rose diagram at study locations (point 1. at 5 m, and 2. at 40 m) representing annual wave direction (with the ”north-up” convention) and Hs distribution in meters (shown by the color scales)

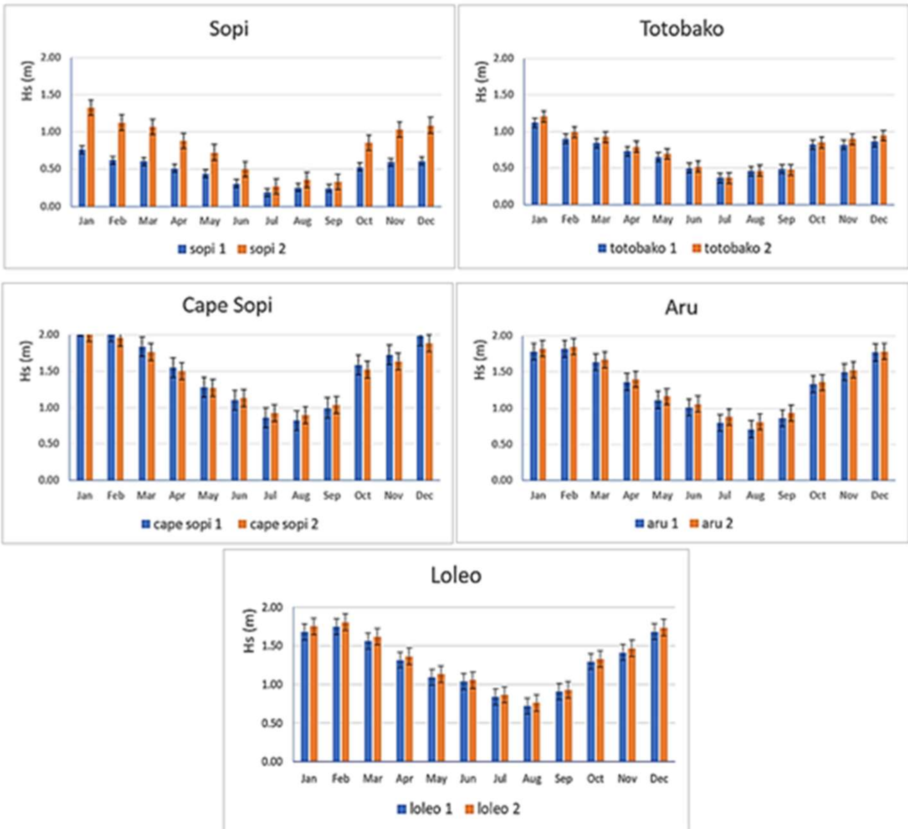

Fig. 8. Hs monthly average at 5 locations

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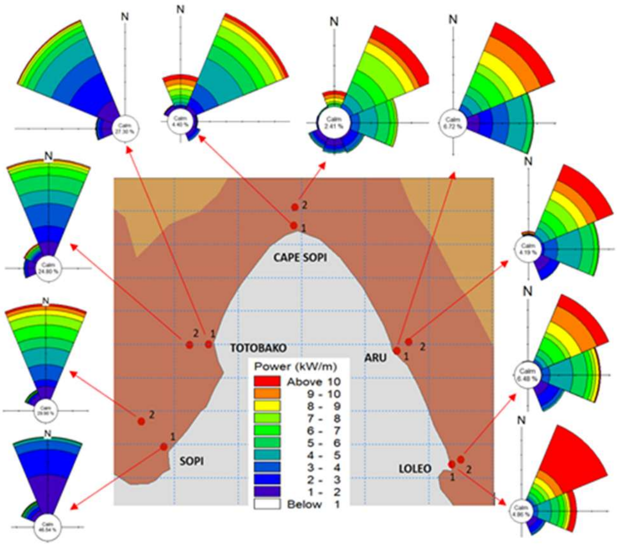

Fig. 9. Power rose diagram at study locations (point 1 at 5 m, and 2 at 40 m), representing annual wavepower direction (with the ”north-up” convention) and magnitude in kW/m (shown by the color scales)

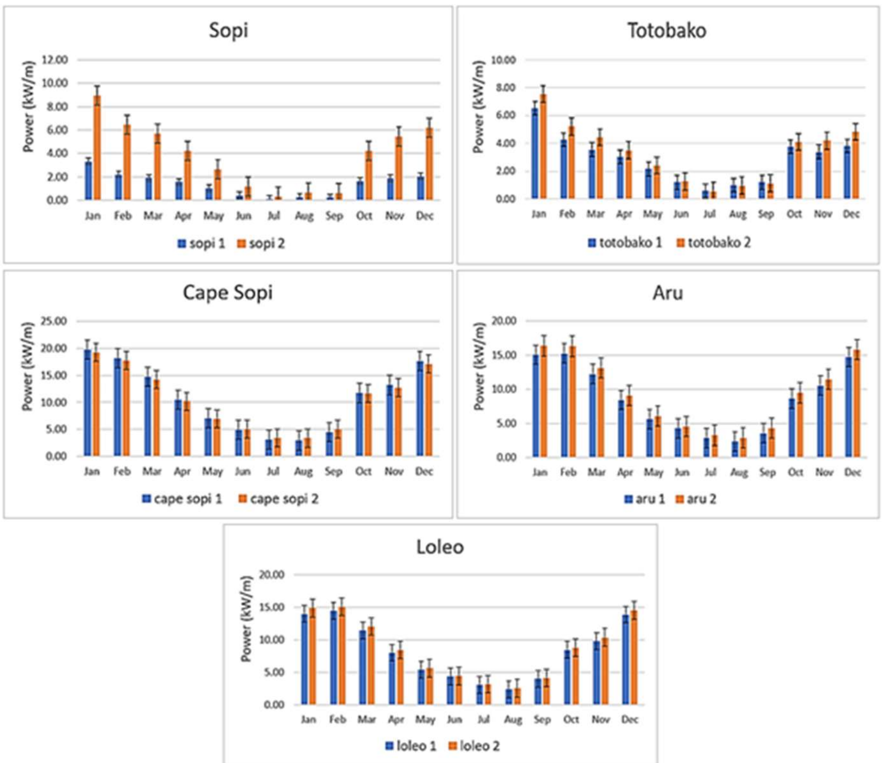

Fig. 10. Annual wave power variations

Across all locations, the seasonal variability of Hs follows a typical monsoon-driven tropical pattern, reaches its peak during December–January, declines to its lowest levels around July–August, and then rises again toward the end of the year (Fig. 8). In Cape Sopi, the Hs value exceeds 2 m in January, reducing to approximately 1 meter by June, and rising again towards the year's end, peaking in December. The wave height patterns are generally consistent between the 5 m and 40 m water depths, with the exception of Sopi, where Hs at 5 m is approximately half of that at 40 m. This discrepancy is likely due to the sheltered position of Sopi 1, located behind a cape on the island’s western side, which limits its exposure to the dominant northeast wave direction. The annual average Hs values are 0.47 m at Sopi 1 and 0.80 m at Sopi 2, while Totobuko, Cape Sopi, Aru, and Loleo exhibit higher averages of 0.80, 0.76, 1.46, 1.35, and 1.32 m, respectively.

This seasonal fluctuation aligns with findings from other island and coastal studies in tropical regions. For example, Pacaldo et al. (2022) reported higher Hs during the northeast monsoon (~1.35 m) and lower values during the southwest monsoon (~0.52 m) for Cuyo Island, while Rahman et al. (2016) identified similar temporal patterns in wave energy potential across various Indonesian outer islands. These similarities reinforce the influence of seasonal monsoon systems on wave climate in the western Pacific region and underscore the potential for predictable, cyclic wave energy availability.

3.3.4 Annual Variations and Directional Plots of Wave Power

Fig. 9 presents rose plots illustrating the annual wave power distribution at the observation points, measured in kW/m. The data indicate that the highest wave power, exceeding 20 kW/m, predominantly originates from the north-northeast direction, with Cape Sopi experiencing the greatest intensity. Moderate wave power levels, ranging from 15 to 20 kW/m, are observed in the Aru and Loleo regions. In contrast, Sopi and Totobuko exhibit lower wave power values, remaining below 10 kW/m for the majority of the year.

Fig. 10 presents the monthly average wave power (Pw) per unit length of wave crest (kW/m) over a typical year, derived from the SW model outputs at various observation points. Across all locations, wave power peaks during December–January, declines to its minimum around July–August, and gradually increases toward the end of the year. The wave power values are generally consistent between the 5 m and 40 m depth observations, with the notable exception of Sopi, where the wave power at 5 m depth is less than half of that observed at 40m.

Table 5. Annual average wave power at locations

Location	Wave power (kW/m)	
	5 m depth	40 m depth
Sopi	1,40	3,38
Totobako	2,87	3,34
Cape Sopi	10,66	10,53
Aru	8,60	9,37
Loleo	8,25	8,65

The annual average wave power (kW/m) at the studied sites is summarized in Table 5. Among these, Cape Sopi exhibits the highest annual mean wave power, exceeding 10 kW/m, followed by Aru and Loleo. In contrast, Sopi and Totoboko demonstrate relatively low wave energy potential, with average values considered insufficient for effective electricity generation. These findings align with previous studies indicating that the annual mean wave power density in the southern Pacific Ocean generally remains below 10 kW/m (Hernández et al., 2022; Posterari et al., 2022). Compared to a similar study conducted by Pacaldo et al. (2022) in Palawan, Philippines (located within the same regional context) the present results indicate slightly higher wave power values. In Palawan, Pacaldo et al. (2022) reported Hs ranging from 1 to 1.4 m and annual power densities between 2.6 and 5 kW/m, attributed to shorter energy periods of approximately 5 to 6 s. Furthermore, when compared with other research on Indonesia’s outermost islands in the southern Pacific, such as Marore in North Sulawesi, where Rahman et al. (2016) reported an annual mean wave power of approximately 3.7 kW/m, the sites of Cape Sopi, Aru, and Loleo show relatively greater wave energy potential.

The data presented in the table and the corresponding monthly average graphs indicate that Cape Sopi exhibits the highest wave energy potential, followed by Aru and Loleo. In contrast, the energy potential at Sopi and Totobako is significantly lower compared to the other three locations. Notably, the monthly averages at Sopi and Totobako do not exceed 10 kW/m, as shown in Fig. 10. Nevertheless, the wave (sea-state) scatter diagrams reveal that, under certain conditions, wave power at these sites may surpass 10 kW/m, suggesting the presence of intermittent high-energy events, which will be further examined in the following discussion.

3.3.5 Power Matrices and Annual Wave Energy Potentials

Figs. 11 and 12 present the annual wave scatter tables for the observation sites located at water depths of 5 and 40 m, respectively. Each table categorizes sea states based on Hs and energy period (Tp), represented along the rows and columns. The data entries include: (a) the average wave power density (kW/m) potentially extractable under each sea state, (b) the annual occurrence duration of each sea state in hours, and (c) the corresponding annual energy yield (kWh/m) available per meter of wave crest.

The sea-state scatter diagrams indicate that the dominant wave energy periods across the study sites range between 9 and 11 s. The predominant significant wave heights vary by location, with values ranging from 0.4 to 0.8 m at Sopi 1, 0.8 to 1.2 m at Sopi 2 and Totobako (1 and 2), 1.4 to 2.0 m at Aru and Loleo, and 1.6 to 2.2 m at Cape Sopi. Analysis of the power matrices in conjunction with occurrence hours reveals that Sopi 1 does not meet the minimum wave-power threshold of 10 kW/m required for most WECs. In contrast, the other sites demonstrate varying degrees of suitability, with operational durations ranging from 300 to 500 h per year at Sopi 2 and Totobako, approximately 3500 hs at Loleo, 4000 h at Aru, and up to 4500 h annually at Cape Sopi. Furthermore, as illustrated in Fig. 12, the average annual energy available for each sea-state, presented in terms of energy density (kWh/m), is calculated by performing an element-wise (Hadamard) product between the power and occurrence matrices, as shown in Eq. (2), ensuring direct correspondence between identical matrix elements (i,j) (Sheng, 2018):

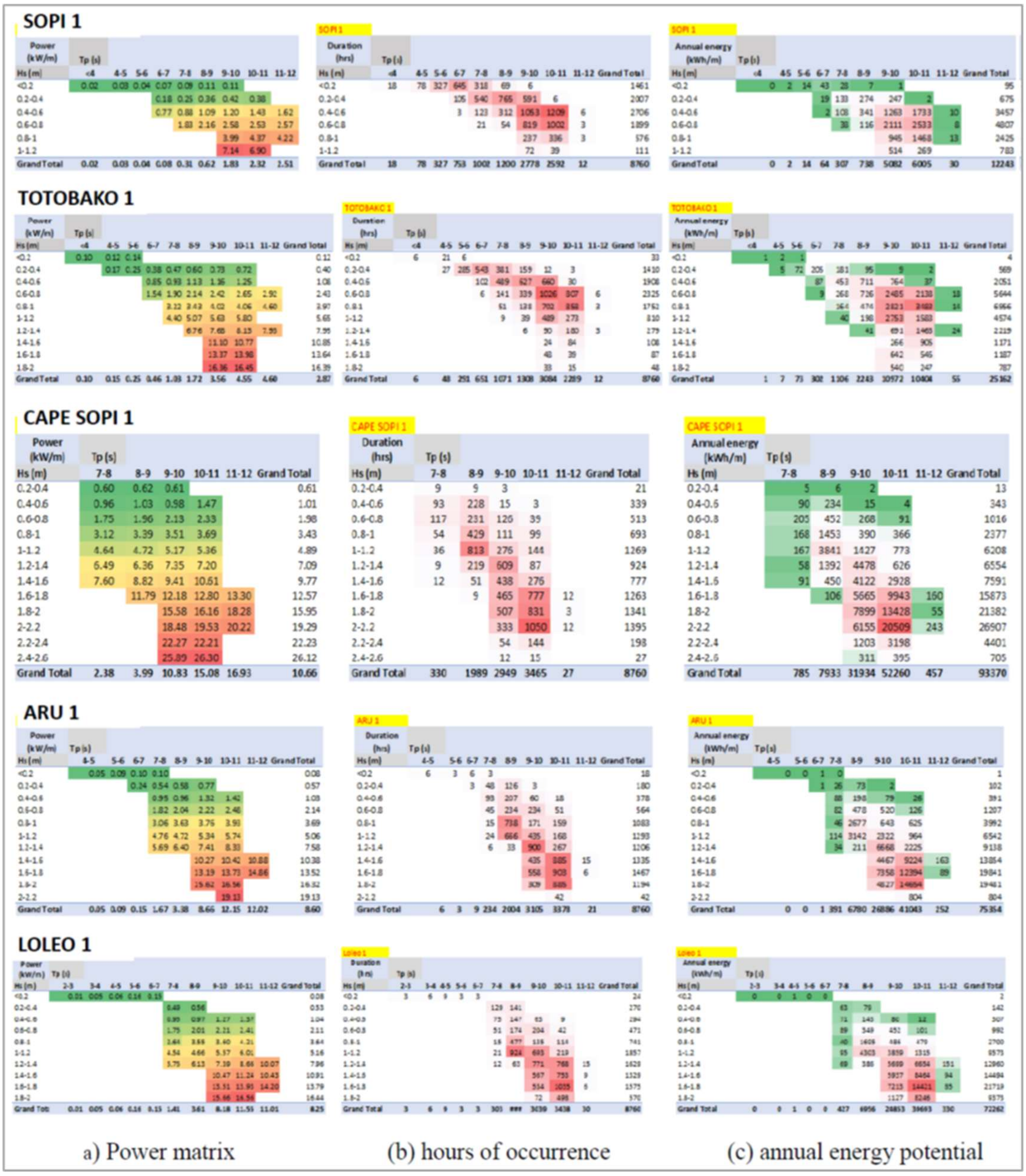

Fig. 11. Annual sea-state scatter diagram at 5 m deep sites

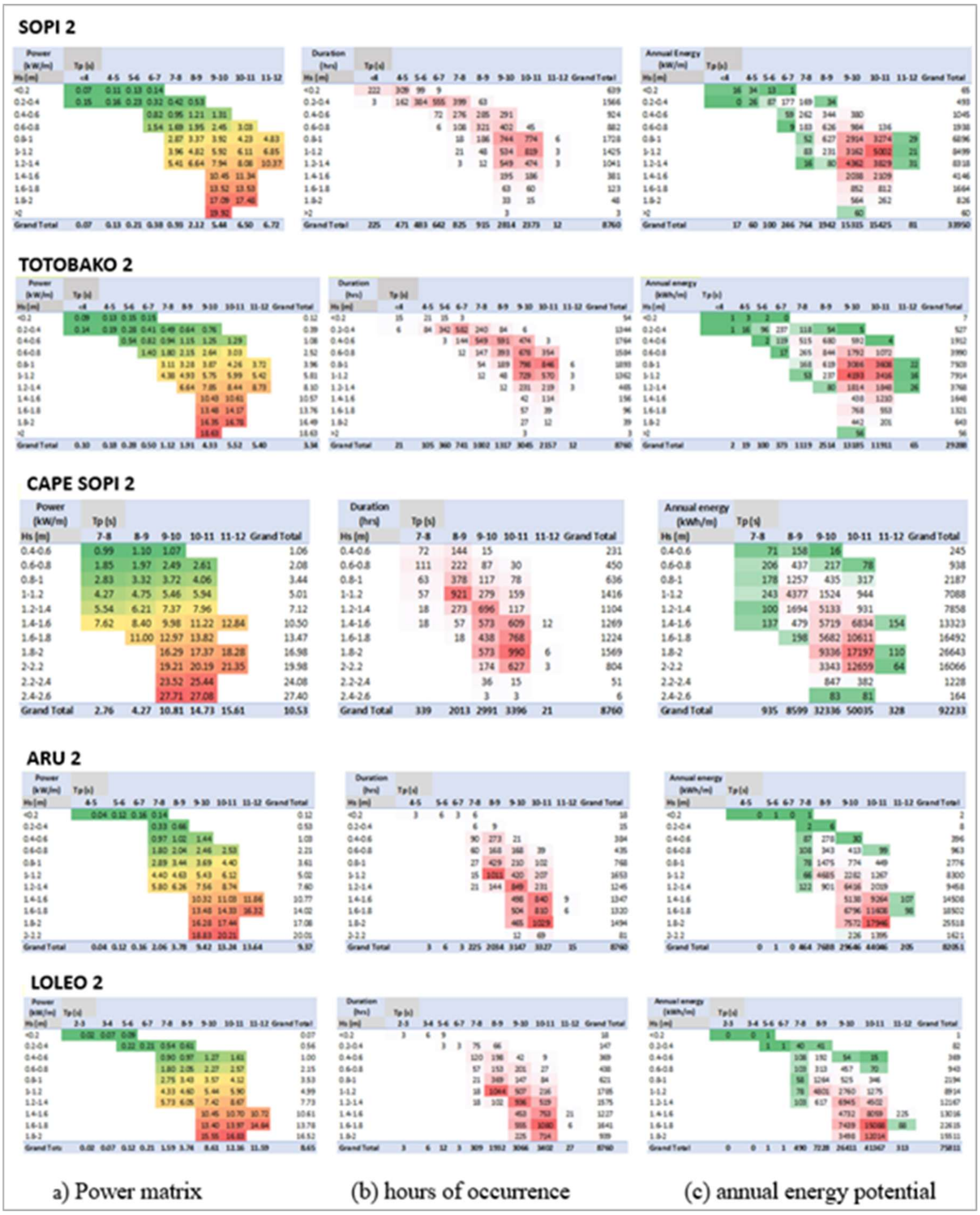

Fig. 12. Annual sea-state scatter diagram at 40 m deep sites

$$E_{(i,j)} = PowerMatrix_{(i,j)} \circ Occurrence_{(i,j)} \quad (2)$$

where E is the annual energy per unit wave-crest length (kWh/m), PowerMatrix is the wave-power density (kW/m), and Occurrence represents the annual duration of each sea-state (hour).

The total energy in 1 meter of wave crest per year for each site is summarized in Table 6 below.

Table 6 indicates that Cape Sopi, located at the northern tip of Morotai Island, exhibits the highest annual wave energy potential, estimated at approximately 90 MWh/m. This is followed by the eastern sites, Aru and Loleo, with potential yields around 75 MWh/m. In contrast, substantially lower energy levels are observed along the western coastline and within the Sopi Bay area. The distribution of wave energy is notably influenced by seasonal variations in wave climate, with approximately 70%–75% of the annual energy potential concentrated between October and March, while the remaining 25% is available from April to September.

Table 6. Annual wave energy (in MWh/m) at locations

Location	Wave energy resource (MWh/m)	
	5 m depth	40 m depth
Sopi	12,24	33,95
Totobako	25,16	29,29
Cape Sopi	93,37	92,23
Aru	75,35	82,05
Loleo	72,26	75,81

The study of wave energy potential presents numerous and significant benefits, serving as a foundation for sustainable energy development, environmental protection, economic growth, and technological advancement. It provides crucial data for policymakers to formulate effective renewable energy strategies, particularly in harnessing wave energy. Additionally, it supports long-term energy planning by assessing the feasibility and potential of wave energy infrastructure. Research in this field drives technological innovation, for more efficient and cost-effective WEC technologies. WEC types of oscillating water column (OWC) or point absorber (PA) could be considered, whichever suitable depending on water depth, distance from coastline, and the wave climates (Guo et al., 2022).

In the Morotai case study, the dominant wave energy period ranges from 9 to 11 s, with significant wave heights at energetic sites (e.g., Cape Sopi) typically between 1.6 and 2.2 m. These conditions correspond well with the optimal operating ranges of several mature WEC technologies. For instance, OWC devices generally achieve peak efficiency when the incident wave period lies between approximately 7 and 12 s and the significant wave height is in the range of 1–3 m (Falcão, 2010; Sheng, 2018). This places Morotai's conditions near the center of the OWC performance envelope, particularly for shoreline and nearshore fixed-chamber designs that benefit from consistent swell exposure.

Similarly, PA WECs, which operate most efficiently within wave periods of 6–12 s and moderate to high sea states, could also be suitable for the region (Guo et al., 2022). However, PAs typically require deeper water and mooring systems, making them more appropriate for deployment at the 40 m sites identified in our study. Based on the annual wave scatter data (Figs. 11–12), more than 70% of the wave resource at Cape Sopi, Aru, and Loleo falls within the period–height envelope recommended for these devices, suggesting high capture potential.

Therefore, the integration of these site-specific wave characteristics with proven WEC performance envelopes supports the technical feasibility of deploying either OWC or PA systems in northern Morotai, with the choice depending on deployment depth, grid connection, and maintenance considerations.

3.3.6 Economic Feasibility in Brief

In many Pacific regions, the levelized cost of energy (LCoE) for WEC technologies such as Pelamis has been estimated to range between USD 200 and USD 467 per MWh (equivalent to USD 0.20–0.47/kWh) at high-energy wave sites such as Tonga ('Eua) and French Polynesia; for more sheltered locations, costs can reach USD 814–1,818 per MWh (Bosserelle et al., 2015). These figures are comparable to, and in some cases competitive with, urban diesel generation costs on certain islands, particularly those reliant on expensive imported fuels. For example, the cost of generating wave energy has been estimated at USD 209–467 per MWh on 'Eua Island, Tonga, and USD 282–629 per MWh in South Rarotonga, Cook Islands—comparing favorably with the cost of solar and diesel generation, which can reach up to USD 700/MWh and USD 500/MWh, respectively (Wilson, 2016).

The capital expenditure (CAPEX) for a Pelamis unit in the Pacific includes device procurement, installation, transportation, and mooring, with a total of USD 4.74–6.30 million per unit. Operational and maintenance (O&M) costs—including refitting and decontamination—are estimated at USD 1.72–8.48 million over a 25-year operational lifespan (Bosserelle et al., 2015). Pilot-scale LCoE values from projects along the U.S. Pacific coast range from USD 0.37–1.22/kWh, excluding discount rates, suggesting that wave energy is currently economically uncompetitive. However, there is potential for future viability; it has been determined that annual energy production must increase by 20% to 100%, depending on the device, to achieve the frequently reported 30% capacity factor (Chang et al., 2018). Although current costs remain relatively high, global trends indicate a promising decline in LCoE: the EU-SCORES study projects that by 2030, wave energy LCoE could fall below €100/MWh (≈USD 0.10/kWh), and by 2035 drop below €70/MWh (≈USD 0.07/kWh), making it competitive with offshore wind (Satymov, 2024)

Guo et al. (2023) analyzed the LCoE of various WECs and found that Wave Dragon achieved the lowest LCoE compared to Pelamis and AquaBuOY, with values varying according to technical and financial parameters. Their findings indicate that reducing CAPEX, operational expenditure (OPEX), and the discount rate, combined with implementing a single-step investment strategy, could significantly lower the LCoE to as low as USD 0.296/kWh, thereby enhancing the economic feasibility of wave energy.

From a local economic perspective, such as that of Morotai Island, this comparison is critical. If the current subsidized electricity cost (primarily diesel-based and inclusive of transport premium) is around USD 0.10/kWh, wave energy remains relatively more expensive. However, in the absence of subsidies, and when accounting for potential logistical efficiencies and policy incentives in remote areas, wave energy could become increasingly viable for development.

This study provides both technical and strategic contributions to Indonesia's renewable energy and electrification initiatives. Technically, the modeling and site-specific evaluation conducted in northern Morotai establish a validated numerical baseline for assessing nearshore wave energy potential under Indonesian wave climates. The detailed characterization of wave power, energy periods, and seasonal variability offers essential input for the design and optimization of suitable WEC technologies, such as oscillating water column and point absorber systems. Strategically, the identification of high-energy zones at Cape Sopi, Aru, and Loleo supports evidence-based planning and policy formulation for renewable energy deployment in remote and outer islands. The findings strengthen the national effort to diversify clean energy sources, reduce reliance on diesel generation, and promote sustainable electrification across Indonesia's coastal regions.

4. CONCLUSION

This study presents a comprehensive assessment of the wave energy potential along the northern coast of Morotai Island, with a focus on the region around Cape Sopi. Using MIKE21 spectral wave model and 30 years of ERA5 wind and wave data, the analysis identifies Cape Sopi as the most energetic location, offering annual wave energy potentials of up to 93 MWh/m. In contrast, sites within more sheltered areas such as Sopi Bay exhibit significantly lower values, reinforcing the importance of exposure and bathymetric configuration in site selection for wave energy exploitation. The analysis reveals that dominant wave energy periods across all sites range from 9 to 11 s, with significant wave heights varying spatially: 0.4–0.8 m at Sopi Bay area, 0.8–1.2 m at Totobako, 1.4–2.0 m at Aru and Loleo, and 1.6–2.2 m at Cape Sopi. Seasonal analysis reveals that 70%–75% of the wave energy is concentrated between October and March, corresponding with the northeast monsoon season. The energy-rich regions identified, particularly Cape Sopi, Aru, and Loleo, are promising candidates for deploying WECs such as oscillating water columns or point absorbers, tailored to local depth and wave period characteristics. The accuracy of this study would benefit from the integration of updated field measurements, especially nearshore topographic and bathymetric data.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no known financial interests or personal relationships that could have influenced, or be perceived to have influenced, the research presented in this paper.

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