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Research Article

# Tidal current power in Capalulu strait, North Maluku: A feasibility study

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**Abstract.** The Indonesian government has set goals for increasing the use of renewable energy in the coming years. Currently, Indonesia relies heavily on non-renewable energy sources, which poses a threat to the environment due to the country's growing energy needs. This study aims to assess the potential for developing a tidal power plant in Capalulu Strait, North Maluku. Using hydrodynamic modelling, the study identified two potential locations at coordinates 1.877°S – 125.328°E (Capa-2) and 1.863°S – 125.323°E (Capa-4) which were selected for having median current speeds exceeding 1.8 m/s and maximum current speeds exceeding 3.5 m/s. The study tested a hypothetical implementation of KHPS Gen5 instrument(s) by Verdant Power, a 5 m diameter turbine with a rated nominal power of 37 kW and a maximum rated power of 56 kW. A power plant layout was designed to be placed at Capa-2 and Capa-4, each location accommodating 45 turbines. The development of this power plant is estimated to produce up to 22 GWh per year. Financial analysis resulted in a LCOE of IDR 5,930/kWh. However, this price is still high compared to the national electricity tariff of IDR 1,027.70/kWh. Variations in the number of turbines also may not result in a lower LCOE than the national tariff. Nevertheless, the estimated cost of generating electricity is still competitive compared to diesel, which is around IDR 5,804/kWh.

**Keywords:** Renewable energy, Tidal current, Hydrodynamic modelling, LCOE, Capalulu strait



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## 1. Introduction

Based on report year 2022, Indonesia remains dependent on conventional energy sources (IESR, 2022). This dependence may only continue to increase in line with growing energy needs, potentially leading to negative environmental impacts. The Indonesian government has recognized this issue and has targeted the use of new and renewable energy in the future. In accordance with Government Regulation No. 79 of 2014 on National Energy Policy, the target for new and renewable energy (NRE) mix by 2025 is at least 23% and around 31% by 2050 (Indonesian Government, 2014).

As one of the most expansive archipelagic nations globally, Indonesia boasts a staggering array of over 17,000 islands spanning from Sabang to Merauke. This extensive maritime domain encompasses more than 75% of the Republic of Indonesia's territory, accentuating the immense wealth of oceanic resources at its disposal. The diverse ecosystems and marine habitats that thrive within these waters harbor untold potential for sustainable energy generation, positioning Indonesia as a veritable powerhouse in the realm of ocean energy. The nation's vast expanse of coastal waters offers a wealth of opportunities for harnessing renewable energy sources such as tidal, wave, and ocean thermal energy (ASELI, 2014). As Indonesia strives to diversify its energy portfolio and

reduce its reliance on fossil fuels, the development of ocean energy assumes paramount importance in achieving the ambitious targets set forth in its renewable energy mix. By unlocking the latent energy potential of its oceans, Indonesia can not only bolster its energy security and resilience but also catalyze economic growth, promote environmental sustainability, and pave the way for a more prosperous and equitable future for its citizens. Thus, the pursuit of ocean energy represents a pivotal challenge and opportunity in Indonesia's quest for a cleaner, greener, and more sustainable energy landscape.

Utilizing ocean energy for electricity generation represents a pivotal strategy for harnessing marine resources sustainably (Wilberforce *et al.* 2019; Quirapas & Taeihagh, 2021). A myriad of ocean energy sources, including salinity gradients, ocean thermal energy, tidal range and currents, and ocean waves, offer vast potential for powering our communities using a diverse array of technologies. Salinity gradients, for instance, present opportunities for osmotic power generation, where the difference in salt concentration between freshwater and seawater is exploited to produce electricity (IEA, 2020). Similarly, ocean thermal energy conversion (OTEC) systems capitalize on temperature differentials between the warm surface waters and colder deep ocean waters to drive turbines and generate power. Tidal energy, arising from the gravitational

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forces exerted by the moon and sun, can be harnessed through tidal stream generators or tidal barrages, while ocean waves offer kinetic energy that can be captured using wave energy converters. Each of these energy sources holds the promise of delivering dependable, sustainable, and cost-competitive electricity solutions, paving the way for a cleaner and more resilient energy future. By tapping into the immense power of the oceans, we can not only reduce our reliance on finite fossil fuels but also mitigate environmental impacts associated with conventional energy generation, thereby fostering a more sustainable and equitable world for generations to come.

One of the most promising avenues for renewable energy development in Indonesia lies in the realm of tidal energy, as highlighted by Adcock and Draper (2014) and further supported by Adcock *et al.* (2015). The predictable and consistent nature of tidal phenomena presents a formidable opportunity for sustainable energy generation, as emphasized by recent studies such as those conducted by Kurniawan *et al.* (2021a; 2021b). Unlike some other renewable sources, tidal energy exhibits remarkable reliability and predictability, characteristics that are essential for ensuring stable and consistent power generation. This inherent consistency not only enhances the feasibility of integrating tidal energy into the national energy grid but also mitigates concerns related to intermittency that often plague other renewable sources like solar and wind power. As Indonesia continues to grapple with the challenges posed by its energy landscape, harnessing the abundant tidal energy resources presents a compelling pathway towards achieving energy security, reducing greenhouse gas emissions, and fostering sustainable development on both local and national scales. Through strategic investments in tidal energy infrastructure and continued research and development efforts, Indonesia stands poised to unlock the vast potential of its coastal waters and emerge as a leader in the global transition towards a clean and sustainable energy future.

Tidal energy holds significant promise in addressing the energy needs of rural communities, offering a reliable and sustainable source of power (Dreyer *et al.*, 2017; Khare & Bhuiyan, 2022). Rural areas often face considerable challenges in accessing and securing reliable energy sources, exacerbated by factors such as low population density, limited economic activity, inadequate infrastructure, and geographical isolation. Traditional energy options may be scarce or prohibitively expensive in these contexts, leaving communities vulnerable to energy insecurity and economic hardship (Hanley & Nevin, 1999; Ramachandran *et al.*, 2021). However, the inherent predictability of tidal energy presents a compelling solution to these challenges, offering a consistent and renewable source of power that can be harnessed to meet the needs of remote and underserved areas. Moreover, in a vast archipelagic nation like Indonesia, where many rural communities are situated along coastal regions, the abundant availability of marine renewable energy resources further accentuates the viability of tidal energy as a sustainable alternative. By leveraging these natural assets and investing in the development of tidal energy infrastructure, Indonesia can empower rural communities, stimulate economic growth, and advance its broader objectives of achieving energy security and environmental sustainability. Thus, tidal energy stands poised to play a transformative role in enhancing the resilience and prosperity of rural communities across the Indonesian archipelago (Ramachandran *et al.*, 2021).

ASELI (2014), Firdaus *et al.* (2017) and Pratama (2020), summarized the potential sites for tidal energy in Indonesian Waters. Among them, the most popular site is Larantuka Strait, located at East Nusa Tenggara Province, connecting the Flores and Adonara Islands. Based on measurement and numerical

investigations, this site is found to generate current speed up-to 3.5 m/s (Ajiwibowo *et al.*, 2017a; Orhan & Mayerle, 2017; 2020; Firdaus *et al.*, 2020).

In addition, other popular sites are Bali, Badung, Toyopakeh, Alas, and Lombok Straits (Blunden *et al.*, 2013; Orhan *et al.*, 2015; Purba *et al.*, 2015; Orhan *et al.*, 2016; Firdaus *et al.*, 2019; Brown *et al.*, 2019; Kurniawan *et al.*, 2021a). These are located at between Eastern Java, Bali, Penida, Lombok, and Sumbawa Islands. Current velocity at these sites is lower than in Larantuka Strait, where the maximum current speed ranging from 2.5 to 3.0 m/s. Researcher also conducted investigations at sites with a lesser potential (max speed < 2.5 m/s), such as in Sunda, Bangka, Lepar, Mansuar, and Patinti Straits (ASELI, 2014; Ajiwibowo *et al.*, 2017b; Ajiwibowo & Pratama, 2022; Novico, *et al.*, 2021).

Nonetheless, the current challenge in further developing the real-scale project lies in its financial viability. Many of the mentioned sites are situated near cities where fossil fuel-based energy infrastructures have been firmly established. Consequently, the price of tidal energy remains relatively high compared to current energy sources, as evidenced in (Kurniawan *et al.*, 2021a). Conversely, locations such as Lepar, Mansuar, and Patinti Straits are nestled within rural areas and remote islands that heavily rely on diesel energy. Although the current speed at these straits is relatively low, their financial viability may prove to be higher due to the exorbitant cost associated with diesel energy. Thus, while each site presents unique challenges, there exists a tangible potential for tidal energy to offer a sustainable and economically viable alternative to conventional energy sources, particularly in areas burdened by high diesel costs and remote geographical constraints.

In this context, Capalulu Strait is among the most interesting sites. It has a great current speed (max speed up-to 3.5 m/s (Orhan *et al.*, 2016; Kusuma, 2021) and is at a remote location. It is located at Sula Islands Regency of North Maluku Province (Figure 1). Currently, North Maluku Province is ranked 4th of 38 for the lowest electrification ratio in Indonesia, valued at 87.42% (Databoks, 2023). Further, Sula Islands Regency is separated by the Molucca Sea, about 350 km away from the province's capital, Ternate. This condition complicates the electrification challenge. Report said until mid-year 2023, there are events where the local people can only access electricity from 6 pm to 7 am (Transtimur, 2023). Therefore, there is an urgency of conducting investigation of tidal energy potential at Capalulu Strait, which currently still poorly understood.

This study presents a numerical modelling study for the investigation of tidal energy potential at Capalulu Strait, which currently still poorly understood and yet to be addressed in prior works. The scope of this study includes tidal flow modeling, site selection, energy estimation, and economic feasibility investigation of the development of a tidal power plant in the Capalulu Strait. By delving into these multifaceted aspects, this study aims to fill the existing knowledge gap and provide valuable insights into the viability and potential benefits of establishing a tidal power plant within the confines of the Capalulu Strait. Through meticulous analysis and rigorous examination, this research endeavors to offer a comprehensive understanding of the untapped tidal energy resources in this region, thereby paving the way for informed decision-making and sustainable energy development initiatives.

## 2. Methodology

### 2.1 Hydrodynamic Modelling

This study utilizes Delft3D-4 software (Lesser *et al.*, 2004) to simulate tidal flow at the study site. Delft3D-4 is a modeling tool

developed by Deltares that is capable of describing hydrodynamic phenomena, sediment transport, morphology, and water quality in river, estuary, and coastal areas (Hasan et al., 2015; Kurniawan et al., 2017; Kurniawan et al., 2020; Pratama et al., 2020; Kurniawan et al., 2021b; Martin et al., 2022; Wijaya et al., 2022). The simulation solves non-linear equations in shallow waters derived from the 3D Navier-Stokes equations for incompressible free-surface flow. The governing equations of Delft3D-4 consist of the continuity equation and the momentum equations can be found in Deltares (2014) and for the present study modeling adapted from Ajiwibowo & Pratama (2022), they can be written in Eq. (1) to (3).

$$\frac{\partial \zeta}{\partial t} + u \frac{\partial(\zeta + d)u}{\partial x} + v \frac{\partial(\zeta + d)v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{w}{(\zeta + d)} \frac{\partial u}{\partial \sigma} = f v - \frac{1}{\rho_0} P_x + F_x + \frac{1}{(\zeta + d)^2} \frac{\partial}{\partial \sigma} \left( \nu_v \frac{\partial u}{\partial \sigma} \right) + M_x \tag{2}$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{w}{(\zeta + d)} \frac{\partial v}{\partial \sigma} = -f u - \frac{1}{\rho_0} P_y + F_y + \frac{1}{(\zeta + d)^2} \frac{\partial}{\partial \sigma} \left( \nu_v \frac{\partial v}{\partial \sigma} \right) + M_y \tag{3}$$

Where  $\zeta$  is the water level above mean sea level;  $x, y$  are the Cartesian coordinates;  $u, v$ , are the horizontal velocity components in the  $x$  and  $y$  directions;  $d$  is the water depth;  $\sigma$  is the Sigma or scaled vertical coordinate.  $f$  is the Coriolis parameter,  $\rho_0$  is the reference density of water;  $P_x, P_y$  are the Gradient hydrostatic pressure in the  $x$  and  $y$  directions;  $F_x, F_y$  are the Radiation stress gradients in the  $x$  and  $y$  directions;  $\nu_v$  is the vertical eddy viscosity; and  $M_x, M_y$  are the Momentum sink/source in the  $x$  and  $y$  directions.

This study applies the two-dimensional modeling approach which has shown it capable of producing satisfactory results (Pratama et al., 2020; Kurniawan et al. 2021a; 2021b). A three-

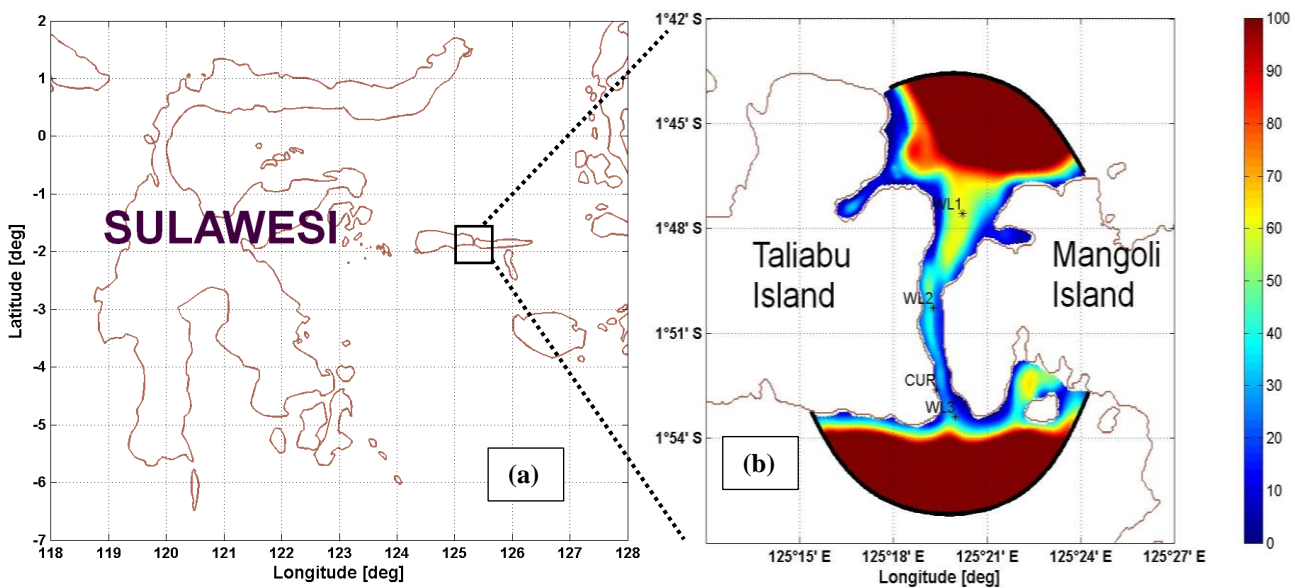
dimensional approach promised a more comprehensive result, however in this study the validation data is only available in 2D. The modeling domain adopts a curvilinear grid in spherical coordinate with a spatial resolution of 25 m x 85 m for the finest grid and 111 m x 111 m at the boundary. As can be seen in Figure 1, the modeling domain covers the Capalulu Strait as well as the northern and southern waters of the strait with the coordinate boundaries ranging from 1.936° S to -1.726° S and 125.256° E to 125.404° E (approximately 16 km x 22 km).

The bathymetric data used as a reference was obtained from BATNAS and was corrected against the Navionics navigation map for some sea areas that are still interpreted as land by BATNAS (BIG, 2018; Navionics, 2022). The TPXO database was used to generate the tidal harmonic constituents from Egbert & Erofeeva (2002) i.e.,  $M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_f, M_m, M_4, MS_4,$  and  $MN_4$  at open boundaries (Figure 1). The simulation was run for 30 days with a 1-minute time step. The density of seawater was 1025 kg/m<sup>3</sup>, the eddy viscosity was 1 m<sup>2</sup>/s, and the seabed roughness coefficient was 65 in the U and V directions using the Chézy equations, applied uniformly along the domain (Deltares, 2014).

### 2.2 Model Skill Index

Model reliability is quantified by comparing the modelled water level and current velocity against the observed data. First, the modelled water levels are compared to TPXO9 data at three observation points at the North (WL1), within Capalulu Strait (WL2), and the South (WL3) during January 2022. Their locations are shown in Figure 1. The TPXO9 data (Egbert & Erofeeva, 2002) is used since no water level observation data is available near the study area. In addition, the modelled current velocities are compared to the observed data supplied by the Indonesian Navy within a month campaign i.e., January 2015, denoted as CUR in Figure 1.

The quality of model validation is quantified using the Pearson's correlation coefficient ( $r$ ) and the root mean squared error ( $RMSE$ ). The formula of  $r$  and  $RMSE$  is expressed in Eq. (4) and (5), where  $x_i$  is the  $i$ -th observation data,  $\bar{x}$  is the average of observation data,  $y_i$  is the  $i$ -th modelled data,  $\bar{y}$  is the average of modelled data, and  $n$  is the amount of the data,



**Fig. 1** Study area showing (a) map of Sulawesi Island and (b) model domain, bathymetry (in meters), open boundary locations (black lines) and model validation locations.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (4)$$

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(x_i - y_i)^2}{n}} \quad (5)$$

2.3 Site Selection and Power Estimation

Site selection in this work follows a direct-simplistic approach (Ajiwibowo et al., 2017b; Pratama, 2020; Kurniawan et al., 2021a). Flow speed is the primary parameter in determining the potential sites. The first criterion used are the maximum and median flow speed. The median employed since it indicates the middle value of current speed at each site. Higher peak and median are one of the indicators of a higher capacity factor. The second criterion is the water depth, where prior works that the suggested depth is between 15 – 50 meters. A shallower or larger depth may also be applicable especially when a specific turbine deployed, such as in Walker & Thies (2021).

In this study, the actual power output (*P*) is estimated. This metric is defined in Neill et al. (2021), or in other studies defined as the technical power (Firdaus et al., 2017, 2019; Kurniawan et al., 2021a; Ajiwibowo & Pratama, 2022). The *P* is defined as the power generated by a tidal turbine device, considering theoretical power of the flow along with the efficiency and properties of the turbine. It is noted that the turbine produces disturbance to the flow (e.g., Housby & Christopher, 2016; Mateos & Hartnett, 2020; Pratama, 2020), however it is neglected in this study. The formula is expressed in Eq. (6).

$$P = 0.5\eta\rho AV^3 \quad (6)$$

Where *P* is the actual power output (Watt),  $\eta$  turbine’s efficiency,  $\rho$  is water density (kg/m<sup>3</sup>), *A* is turbine’s swept area, (m<sup>2</sup>), and *V* is the flow speed (m/s). A generic turbine is assumed for this location with 5 m diameter (equals to 19.6 m<sup>2</sup> swept area), 0.38 efficiency, and 1.0 m/s cut-in-speed. The turbine is mounted at the seabed with 1-meter clearance to the seabed.

2.4 LCOE

The Levelized Cost of Electricity (LCOE) is a method used to calculate the average cost per unit of electricity generated by a power generation system. The LCOE is calculated by dividing the total net present value cost of building, operating, and maintaining the power generation system by the net present total amount of electricity generated over the operational life of the system. The calculation of LCOE can be used to determine the feasibility of developing a power generation system. By calculating the LCOE, it can be determined how much the cost of selling electricity from the generated energy is, allowing for the determination of whether the cost is viable to be carried over the investment period (Kurniawan et al., 2021a). The calculation of LCOE is performed using Eq. (7).

$$LCOE = \frac{\sum \frac{(CapEx + OpEx)}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}} \quad (7)$$

Where:

- LCOE : Levelized cost of electricity
- CapEx : Capital expenditure
- OpEx : Operational expenditure

- E<sub>t</sub>* : Energy generated at year *t*
- r* : Interest rate

3. Results and Discussion

3.1 Model Validation

Figure 2 shows the comparison between the modelled and observed water level at WL1 to WL3 respectively. Firstly, the tide at Capalulu Strait is mixed type and based on the figures, there is a visible difference between the North and South of the strait. WL3 is a mixed diurnal tide, meanwhile WL1 and WL2 are mixed semi-diurnal tide. These tidal differences induce a continuous head gradient and generate an energetic flow along the strait and further amplify by the geometry of the strait.

Moreover, the comparison of water levels revealed trends and phases that exhibit strong agreement with TPXO9 data, further validating the accuracy of the model outputs. At each of the observation locations (WL1, WL2, and WL3), the correlation coefficients (*r*) and Root Mean Square Errors (*RMSE*) demonstrate exceptional agreement, with values of 0.999; 0.024, 0.996; 0.039, and 0.996; 0.025, respectively. The average correlation coefficient (*r*) and *RMSE* across all three observation

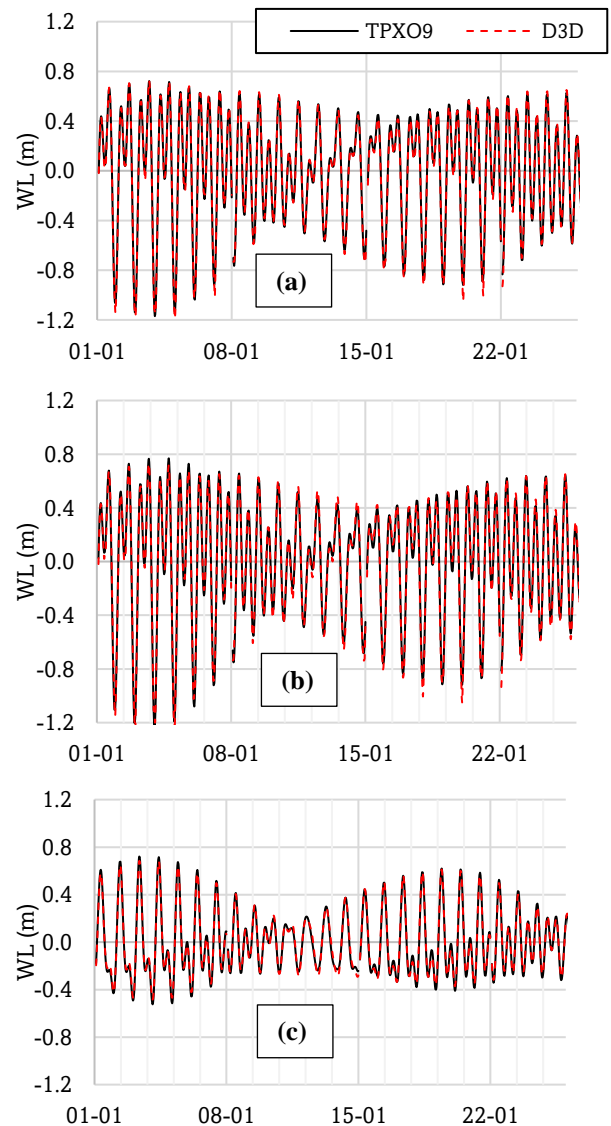
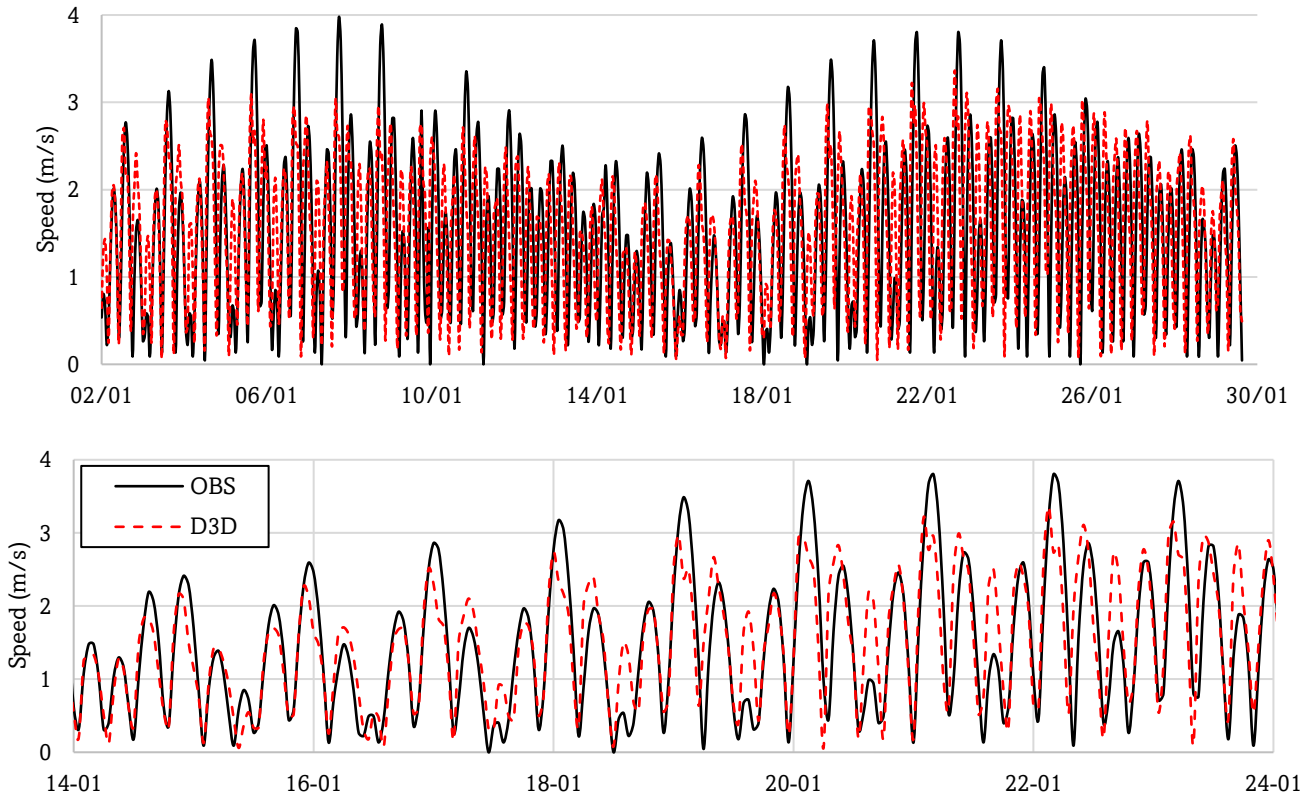


Fig. 2 Water Level Validation at (a) WL1; (b) WL2; (c) WL3



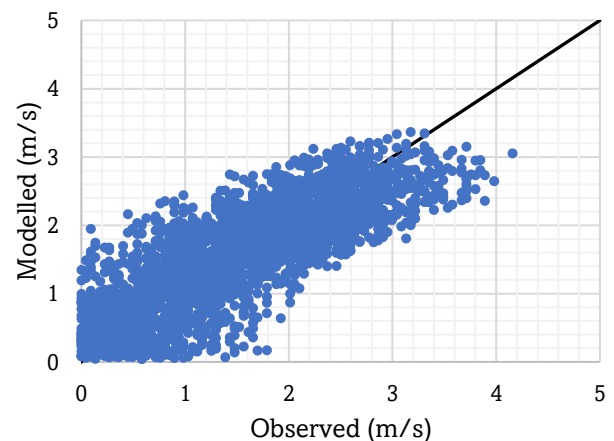
**Fig. 3** Current speed validation during January 2015 (top) and a detailed during neap (15-01-2015) and spring (23-01-2015) tides phase (bottom).

points stand at an impressive 0.997 and 0.029 m, respectively. Notably, a minor discrepancy in water levels during the ebb phase was observed between the simulation results and TPXO9 data. This discrepancy may be attributed to the limitations of TPXO9 resolution, which may inadequately represent the intricate details of the Capalulu Strait's water dynamics. Despite this slight disparity, the overall consistency and accuracy of the model in reproducing water level variations underscore its robust performance in simulating tidal dynamics. It has been observed that TPXO9 relies solely on barotropic tides, neglecting factors such as stratification, baroclinicity, or variations in depth (Egbert & Erofeeva, 2002). Therefore, for current study, this validation of the model's capability in replicating water level trends enhances confidence in its suitability for simulating tidal dynamics within the Capalulu Strait and adjacent coastal regions.

Figure 3 offers January 2015 and a detailed time-series comparison of current velocities between the model (D3D) and Indonesian Navy observations data (OBS) across both spring and neap tide conditions. Notably, the observations reveal the presence of energetic flow events characterized by velocities exceeding 3.5 m/s, indicative of the dynamic nature of tidal currents in the area. The model's underestimation of these velocities is also notable, potentially attributed to the exclusion of the Indonesian throughflow (ITF) in the model. Indonesian waters stand out due to their location between the Pacific and Indian Oceans, serving as the sole pathway for the global ocean conveyor belt, known as the ITF (Sprintall *et al.*, 2009; Gordon *et al.*, 2010; Feng *et al.*, 2018). Consequently, the combined current in any Indonesian strait comprises both the ITF current and tidal currents. However, the Delft3D model solely predicts tidal currents, leading to discrepancies between actual measurements and the numerical model results.

Specifically, the peak flow velocities during neap and spring tides are observed to be approximately 2.2 m/s and 3.5 m/s, respectively, underscoring the significant variability in tidal dynamics across different tidal phases. The model successfully reproduced the observed flow where the high velocity amplitude and the phase were in reasonably a good match. By comparing the modelled and observed data, the  $r$  and  $RMSE$  are 0.820 and 0.518 m/s, respectively, which assures that the model is capable of correctly simulating flow at Capalulu Strait.

In addition, in Figure 4, a meticulous comparison between the observed and the modelled current speeds is depicted in a scatter plot format. This comparison reveals a compelling alignment between the two datasets, with the points exhibiting a scattered distribution around the linear line. Such congruence indicates that the model adeptly replicates the amplitude of the



**Fig. 4** Scatter plot of the observed and modelled current speed.

observed current speeds, underscoring its fidelity in capturing the dynamic flow patterns within the studied region. Building upon this analysis, these comprehensive evaluations serve to validate the accuracy and reliability of the Delft3D model in simulating tidal current patterns, thereby enhancing the understanding of the complex hydrodynamic processes governing the studied marine environment.

3. 2 Potential Area

In the initial stage of the analysis, the potential area for tidal energy extraction is delineated through a meticulous examination of current velocity distributions during extreme tidal phases, specifically the highest high tide (high spring tide) and the lowest low tide (low spring tide). This approach, known as the instantaneous flow speed method, allows for the identification of areas exhibiting optimal flow characteristics under both tidal conditions. The potential area is thus defined as the region demonstrating favorable current characteristics across these contrasting tidal states. Drawing upon the simulation results depicted in Figure 5, it becomes evident that the identified potential area resides in the southern segment of the Capalulu Strait, coinciding with its narrowest geometry. This particular locale is distinguished by its shallow depths and constricted width, as illustrated in Figure 1. Such geomorphic features are indicative of enhanced flow velocities, as the narrow channel acts to accelerate tidal currents, thereby accentuating the potential for efficient energy extraction.

The identification of potential areas and points based on instantaneous velocity analysis can be seen in Figure 6. This method has been used in previous study to find the sites with highest velocity (Ajiwibowo et al., 2017a; Kurniawan et al., 2021a). Region with high velocity is located from the southern end to the middle of the strait, where the velocity peaked from 2.0 to 4.0 m/s. This is much higher than previously studied tidal energy sites at Sunda, Bangka, and Lepar Strait with maximum peak flow speed only around 1.0 to 2.0 m/s (Pratama et al., 2020; Ajiwibowo et al., 2017b; Ajiwibowo et al., 2022). Further, this strait is comparable to Larantuka Strait in East Nusa Tenggara, Indonesia which is known to be one of the best tidal sites in Indonesian Water (Ajiwibowo et al., 2017a).

In locating the potential sites, besides based on the instantaneous velocity analysis as presented in Figure 6, the temporal-mean based analysis is performed (Pratama, 2020). Figure 7 provides a comprehensive overview of the spatial

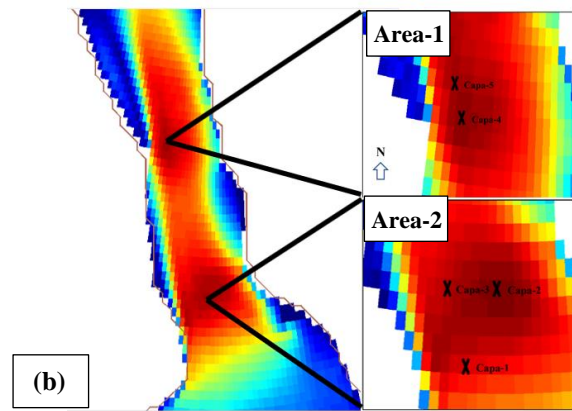
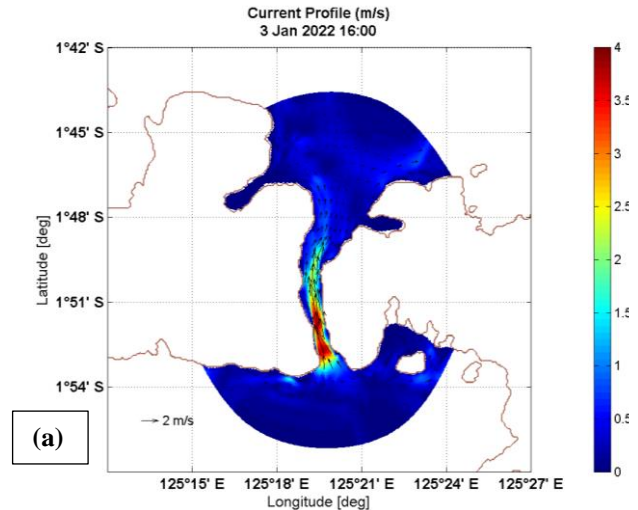


Fig. 6 Current profile showing (a) highest current speed condition and (b) detailed current profile as well as the potential area locations.

distribution of mean flow speeds throughout January 2022. Unlike representations that capture a single snapshot in time, this visualization offers insights into the average flow speeds over the course of the month, encapsulating variations in velocity from low to high as well as transitional speeds. The analysis reveals notable patterns, with peak mean velocities reaching up to 2.0 m/s concentrated within two distinct localized regions situated at the southern extremity of the strait. A closer examination of the plan view elucidates the underlying dynamics driving these velocity gradients, indicating that the narrowing width of the strait plays a pivotal role in shaping the observed flow patterns. As the channel constricts, fluid dynamics dictate an increase in flow velocity, leading to the formation of these pronounced velocity hotspots. This nuanced understanding of flow dynamics is crucial for informing strategic decisions related to the deployment of renewable energy infrastructure, as it enables stakeholders to identify optimal locations for harnessing tidal energy resources effectively and maximizing energy yields.

Further, Figure 7 displays a more detail visuals on the mean flow speed. The water depth is overlaid marked as dashed lines, isobath of 10, 20, 30, 40, and 50 meters. Figure 7(a) shows that the localized high flow speed regions lie above the shallow and narrow section of the strait. This depth is ranging from 20 to 30 meters. Additionally, the northwards and southwards flow are separately analysed, as presented in Figure 7(b) and 7(c). The southwards and northwards flow are asymmetry. Firstly, the

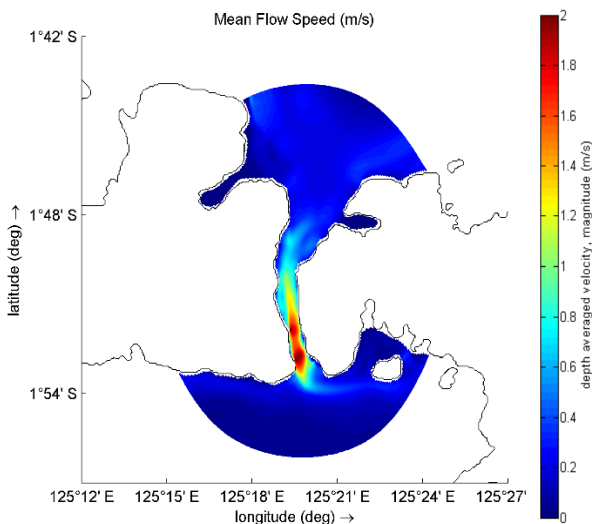
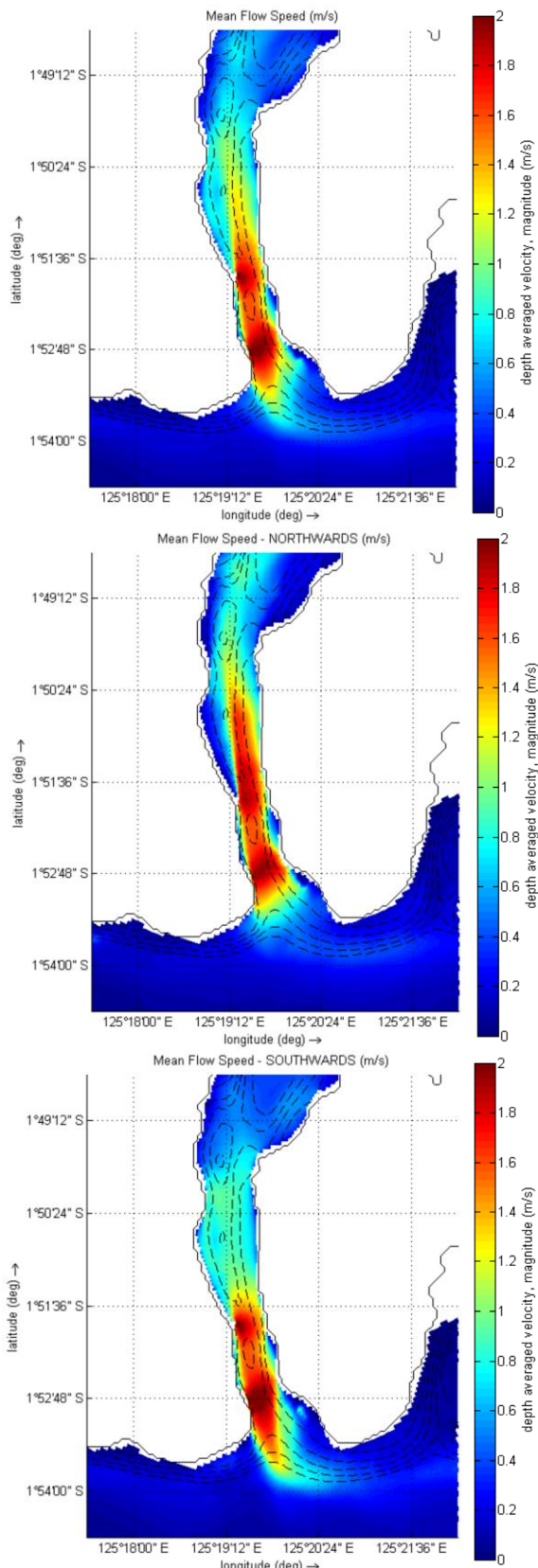


Fig. 5 Mean flow speed during January 2022

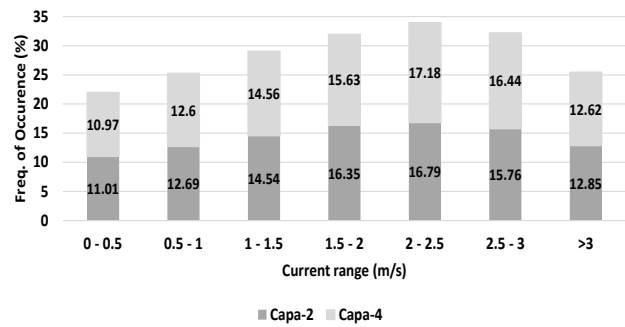


**Fig. 7** Detailed view of (a) mean flow speed, (b) mean northwards flow, and (c) mean southwards flow during January 2022. Dashed lines are isobath of 10, 20, 30, 40, and 50 meters.

peak of southwards flow (2.1 m/s) is slightly higher than the northwards flow (1.9 m/s). Second, the flow pattern is different. While the cells of high flow speed are still in the same regions, this energetic region is extended longer to north for the

**Table 1**  
Median Flow Speeds at Potential Sites

Location	Area	Latitude (deg)	Longitude (deg)	Depth (m)	Median Flow Speed (m/s)
Capa-1	2	-1.883	125.327	25.28	1.731
Capa-2	2	-1.877	125.328	19.45	1.862
Capa-3	2	-1.877	125.325	24.11	1.797
Capa-4	1	-1.863	125.323	25.96	1.879
Capa-5	1	-1.862	125.323	28.23	1.747



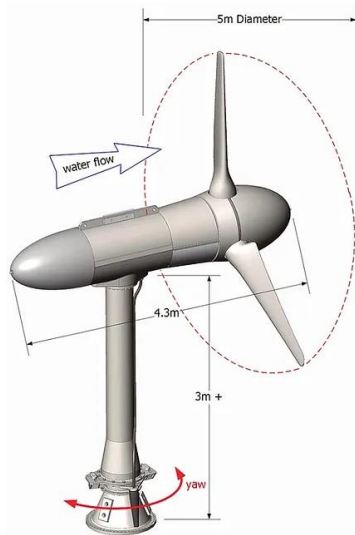
**Fig. 8** Frequency of occurrence of current at Capa-2 and Capa-4

northwards flow and only slightly extended to south for the southwards flow. In the southwards flow, the fluxes are flushed to the deep-water ocean (about 150 – 300 meters) therefore this extend is shorter.

In summarizing the potential location selection derived from the analysis, Table 1 presents a concise overview. A total of five prospective locations have been identified and designated as Area-1 and Area-2, characterized by water depths ranging from 19 to 28 meters. Positioned at the southern entrance of the strait, these areas are situated approximately 2 kilometers apart. Despite this separation, both regions exhibit similar median velocities, hovering around 1.8 m/s, with Capa-2 and Capa-4 showcasing slightly higher values. Consequently, these two sites have been earmarked as prime candidates for turbine installation. For a more comprehensive understanding of the flow dynamics at Capa-2 and Capa-4, Figure 8 offers a detailed overview. The frequency distribution of flow speeds within 0.5 m/s bins, ranging from 0 to 3.0 m/s, has been meticulously calculated. Notably, both sites display analogous distributions, with flow speeds evenly distributed across all bins. This uniformity underscores the consistency and reliability of flow patterns at these locations, affirming their suitability for tidal energy extraction.

### 3. 3 Power Estimation

The outcomes of the hydrodynamic modeling endeavor yield the depth-averaged velocity as the primary current velocity metric. This value represents the average velocity of the current throughout the water column, providing a comprehensive snapshot of flow dynamics within the studied area. However, for the purpose of estimating power production potential, it is imperative to consider the velocity at the turbine height, where the tidal turbines would be positioned. In this study, it is assumed that the velocity at turbine height is equivalent to the depth-averaged velocity. While this assumption simplifies the calculation process, it is important to



**Fig. 9** Verdant KHPS Gen5 (Verdant Power, 2019)

acknowledge potential variations in velocity profiles across the water column. Nonetheless, by adopting this approach, the study aims to provide a conservative estimate of power production potential, ensuring that the projected outputs remain grounded in realistic scenarios. This meticulous consideration of velocity metrics underscores the rigor and accuracy of the power production estimates derived from the hydrodynamic modeling efforts, facilitating informed decision-making processes regarding tidal energy project development within the Capalulu Strait.

The annual power production estimate is influenced by the cut-in speed, rated power, and water-to-wire efficiency specifications. To quantify and provide a first estimation of the generated power, The KHPS Gen5 turbine from Verdant Power was tested in this case as illustrated in Figure 9. In this study, it is assumed that the turbine operates at its maximum rated power of 56 kW (Verdant Power, 2019). The turbine starts rotating when the flow reaches 1 m/s, until the generator reaches its maximum power of 56 kW. The results of the technical power calculation for the turbine at location Capa-2 for 1-15 January 2022, can be seen in Figure 10.

Based on the results of the hydrodynamic modeling, it is estimated that a total of 90 instruments deployed at Capa-2 and

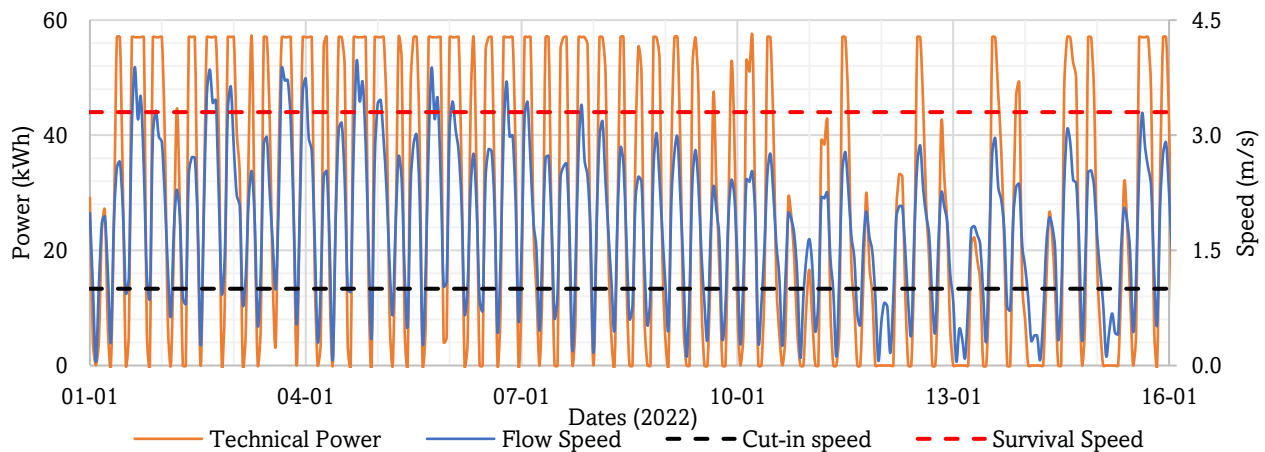
**Table 2**  
Estimated Power in Capa-2 and Capa-4 (in year 2022)

Month	Power (kWh)	
	Capa-2	Capa-4
January	21,128.91	21,308.90
February	18,965.56	19,124.95
March	21,368.61	21,559.15
April	20,354.70	20,577.03
May	20,816.41	20,951.28
June	19,453.88	19,484.15
July	20,507.35	20,712.83
August	21,462.67	21,625.73
September	20,412.10	20,765.02
October	20,833.74	21,059.07
November	19,756.35	19,946.26
December	20,349.04	20,549.62
<b>Total</b>	<b>245,409.33</b>	<b>247,663.99</b>

Capa-4 can produce 245,409 kWh and 247,663 kWh respectively in one year (Table 2). There were 6,684 hours in 2022 where the flow was above 1 m/s at Capa-2, resulting in a technical power capacity of 36.72 kW per year. Meanwhile, at Capa-4 were 6,696 hours and a technical power capacity of 36.99 kW was obtained, which is close to the nominal power specification of 37 kW.

### 3.4 Financial Analysis

The budget plan encompasses two main components: capital expenditure (*CapEx*) and maintenance and operational expenditure (*OpEx*). Capital expenditure pertains to one-time expenses that cover the fabrication and installation costs essential for establishing the tidal energy project infrastructure. Fabrication costs involve the manufacturing and assembly of components such as turbines and support structures, while installation costs encompass the deployment of these elements, including the setup of power plants and necessary navigation support facilities. On the other hand, maintenance and operational expenditure consist of recurring expenses incurred on an annual basis or at regular intervals to ensure the efficient functioning of the tidal energy system. Operational costs encompass activities such as monitoring, control, and



**Fig. 10** Estimated Power Production in Capa-2



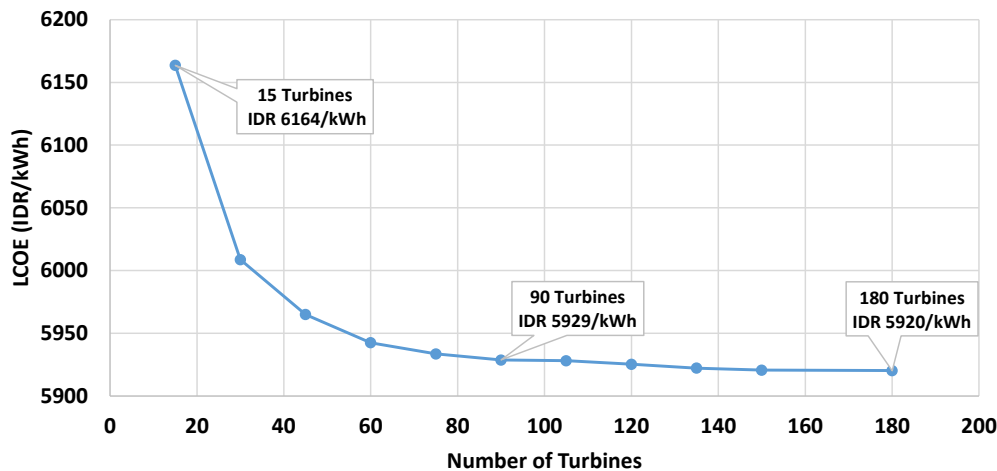


Fig. 11 LCOE based on number of turbines variations.

administration, while maintenance costs cover routine upkeep, repairs, and servicing to maintain optimal operational performance.

Based on the findings of Kurniawan *et al.* (2021a), the development of the Capalulu Strait tidal power plant requires around IDR 1.8 trillion as initial *CapEx* and approximately IDR 580 billion for *OpEx* expenses over 25 years. The calculation was performed with an interest rate of 3.6% and a constant inflation rate of 3.7%. The total cost adjusted with present value is approximately IDR 2.07 trillion, while the total electricity production over 25 years after discounting is 304.681 million kWh. Using the Levelized Cost of Energy (LCOE) calculation method, the financial analysis results show an electricity price of IDR 5,930/kWh to repay the capital in 2050.

The Minister of Energy and Mineral Resources (*Kementerian Energi dan Sumber Daya Mineral*) Regulation No. 4 of 2020 allows PLN to purchase electricity directly from renewable energy-based generators (MEMR, 2020). The cost of electricity supply without transmission costs is referred to as the Generation Basic Provision Cost or *BPP Pembangkitan*. The selling price of electricity must be below or equal to the national provision cost, which is IDR 1,027.70/kWh. The planned generation cost of the Capalulu Strait Tidal Plant is still more than three times higher than the requirement set by the Ministry of Energy and Mineral Resources. Hence, it can be concluded that the planned generation cost at the power plant site is still far from commercial viability.

The calculation of the LCOE was carried out with various variations of the number of installed turbines. Figure 11 shows the electricity price from 15 to 180 turbines. It was found that the electricity price will decrease when more turbines are installed, however, the graph of the decrease in electricity price flattened when the number of turbines exceeded 60. The electricity price does not decrease much from IDR 5,928/kWh even when the number of turbines reaches 180 units. Nevertheless, the estimated cost of generating electricity is still competitive compared to diesel power plants, which is around IDR 5,804/kWh (Lazard, 2014).

#### 4. Conclusion

A hydrodynamic modeling was conducted to simulate tidal current at Capalulu Strait. The model validation, both water level and current velocity, suggests that the model can simulate the hydrodynamic condition in the study area with satisfactory accuracy. The results of the modeling indicated two potential locations for ocean tidal power plants, each at 1.877°S –

125.328°E (Capa-2) and 1.863°S – 125.323°E (Capa-4). Both locations have median current speeds over 1.8 m/s and maximum current speeds exceeding 3.5 m/s. To quantify the potential power, a generic turbine is tested (adapted from KHPS Gen5 of Verdant Power) which features 5-meter diameter turbines with a nominal power of 37 kW and a maximum power of 56 kW.

It is estimated that a power plant field with 90 turbines located at the two potential sites can generate up to 22 GWh per year. It is important to notice that this estimation assumed a constant power coefficient and neglecting the hydrodynamics changes due to the tidal turbines (blockage effect ratio). A rough estimation is conducted and found that the development of this ocean energy power plant at Capalulu Strait costed an initial capital of approximately IDR 1.8 trillion and operational funding of about IDR 580 billion for 25 years. The Levelized Cost of Energy (LCOE) method is used with an interest rate of 3.60% and an inflation rate of 3.70% per year. This financial analysis resulted in an LCOE price of IDR 5,930/kWh. Furthermore, the price of electricity generated by this ocean energy power plant is still relatively expensive compared to the national tariff of IDR 1,027.70/kWh but comparable to the diesel electricity prices, which is estimated to be around IDR 5,804/kWh.

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#### References

Adcock, T.A.A. & Draper, S. (2014). Power extraction from tidal channels-Multiple tidal constituents, compound tides and overtides.

- Renew. Energy*, 63, 797–806. <https://doi.org/10.1016/j.renene.2013.10.037>
- Adcock, T.A.A., Draper, S., & Nishino, T. (2015). Tidal power generation – A review of hydrodynamic modelling. Proceedings of the Institution of Mechanical Engineers, Part A. *Journal of Power and Energy*, 229(7):755-771. <https://doi.org/10.1177/0957650915570349>
- Ajiwibowo, H., & Pratama, M.B. (2022) Hydrodynamic Model and Tidal Current Energy Potential in Lepar Strait, Indonesia. *International Journal of Renewable Energy Development*, 11(1),15-25. <https://doi.org/10.14710/ijred.2022.37028>
- Ajiwibowo, H., Lodiwa, K.S., Pratama, M.B., & Wurjanto, A. (2017a) Field Measurement and Numerical Modeling of Tidal Current in Larantuka Strait for Renewable Energy Utilization. *International Journal of Geomate*, 13(39), 15-25. <https://doi.org/10.21660/2017.39.98548>
- Ajiwibowo, H., Lodiwa, K.S., Pratama, M.B., & Wurjanto, A. (2017b) Numerical Model of Tidal Current for Power harvesting in Bangka Strait. *International Journal of Earth Sciences and Engineering*, 10(4), 3100-3110. <https://doi.org/10.21276/ijee.2017.10.0415>
- ASELI. (2014). Potensi Energi Laut Indonesia. *Asosiasi Energi Laut Indonesia*.
- BIG (2018). Badan Informasi Geospasial - *Batimetri Nasional*. [Online], <https://tanahair.indonesia.go.id/demnas/#/batnas>. Accessed on 3 August 2023.
- Blunden, L.S., Bahaj, A.S., & Aziz, N.S. (2013). Tidal current power for Indonesia? An initial resource estimation for the Alas Strait. *Renew. Energy* 49:137–142. <https://doi.org/10.1016/j.renene.2012.01.046>
- Brown, A.J.G., Lewis, M., Barton, B.I., Jeans, G., & Spall, S.A. (2019). Investigation of the Modulation of the Tidal Stream Resource by Ocean Currents through a Complex Tidal Channel. *Journal of Marine Science and Engineering*, 7(10). 341. <https://doi.org/10.3390/jmse7100341>
- Databoks (2023). *Rasio-Elektrifikasi*, [Online], <https://databoks.katadata.co.id/tags/rasio-elektrifikasi>. Accessed on 20th Jan 2024
- Deltares. 2014. *Delft3D Flow – User Manual*. Netherland.
- Dreyer, S. J., Polis, H. J., Jenkins, L. D. (2017). Changing Tides: Acceptability, support, and perceptions of tidal energy in the United States. *Energy Research & Social Science*, 29,2017,72-83, <https://doi.org/10.1016/j.erss.2017.04.013>.
- Egbert, G.D., & Erofeeva, S.Y. (2002). Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology* 19.2 (2002): 183-204. [https://doi.org/10.1175/1520-0426\(2002\)019%3C0183:EIMOB0%3E2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019%3C0183:EIMOB0%3E2.0.CO;2).
- Feng, M., Zhang, N., Liu, Q., Wijffels, S. (2018). The Indonesian throughflow, its variability and centennial change. *Geosci. Lett.* 5, 3. <https://doi.org/10.1186/s40562-018-0102-2>.
- Firdaus, A.M., Houlsby, G.T. & Adcock, T.A.A. (2017). Opportunities for tidal stream energy in Indonesian Waters. *Proceedings of the 12th EWTEC*, Cork: Ireland. <https://users.ox.ac.uk/~spet1235/TIDRES-03-887.pdf>
- Firdaus, A.M., Houlsby, G.T., & Adcock, T.A.A. (2019). Resource estimates in Lombok Straits, Indonesia. *Proceedings of the 13th European Wave and Tidal Energy Conference*, September, 1669. <https://ora.ox.ac.uk/objects/uuid:646dbfd0-db16-4834-8535-0ec6d4dd7b39/files/m45a1cfba611248bb314bb67101b9ca4b>
- Firdaus, A.M., Houlsby, G.T., & Adcock, T.A.A. (2020). Tidal energy resource in Larantuka Strait, Indonesia. *Energy*, 173(2), 81–92. <https://doi.org/10.1680/jener.19.00042>
- Gordon, A.L., Sprintall, J., Van Aken, H.M., Susanto, D., Wijffels, S., Molcard, R., Ffield, A., Pranowo, W., Wirasantosa, S. (2010). The Indonesian throughflow during 2004–2006 as observed by the INSTANT program. *Dyn Atmos Ocean* 50:115–128. <https://doi.org/10.1016/j.dynatmoce.2009.12.002>.
- Hanley, N. & Nevin, C. (1999). Appraising renewable energy developments in remote communities: the case of the North Assynt Estate, Scotland. *Energy Policy*, 27(9), 527-547. [https://doi.org/10.1016/S0301-4215\(99\)00023-3](https://doi.org/10.1016/S0301-4215(99)00023-3)
- Hasan, G.J., Kurniawan, A., Ooi, S.K., Hekstra, M., Broekema, Y.B., & Bayen, S. (2015). Pollutants in mangrove ecosystems: A conceptual model for evaluating residence time. *Proceeding of ICWFM 2015: 5th International Conference on Water & Flood Management*.
- Houlsby, G. & Christopher, V. (2016). The power available to tidal turbines in an open channel flow. *Proceedings of the Institution of Civil Engineers - Energy*. 170:1, 12-21. <https://doi.org/10.1680/jener.15.00035>.
- IEA (2020), International Energy Agency - *Ocean Energy Systems*, [Online]. <https://www.ocean-energy-systems.org/>, Accessed 20 January 2024
- IESR (2022). Indonesia Energy Transition Outlook 2023: Tracking Progress of Energy Transition in Indonesia: Pursuing Energy Security in the Time of Transition. Jakarta: *Institute for Essential Services Reform (IESR)*. <https://iesr.or.id/en/pustaka/indonesia-energy-transition-outlook-ieto-2023>
- Indonesian Government (2014). *Indonesian Government Legislation No. 79 of 2014 on National Energy Policy*. <https://peraturan.bpk.go.id/Home/Details/5523/pp-no-79-tahun-2014>
- Khare, V. & Bhuiyan, M.A. (2022). Tidal energy-path towards sustainable energy: A technical review, *Cleaner Energy Systems*, 3(2022), 100041. <https://doi.org/10.1016/j.cles.2022.100041>.
- Kurniawan, A., Barli, P.P.A., Pratama, M.B., & Fitriadhy, A. (2021a). Potential Study of Tidal Stream Turbine Farm at Toyapakeh Strait, Bali. *ILMU KELAUTAN: Indonesian Journal of Marine Sciences*, 26(3), 155–162. <https://doi.org/10.14710/ik.jms.26.3.155-162>.
- Kurniawan, A., Satria, R.A., Pratama, M.B. (2020). Analyzing Tsunami Hazard using Numerical Modelling: Study Case Palu, Sulawesi Tengah, Indonesia. *IOP Conference Series: Materials Science and Engineering* 982 (1), 012036. <http://doi.org/10.1088/1757-899X/982/1/012036>
- Kurniawan, A., Tay, S.H.X. & Ooi, S.K. (2021b). Numerical investigation of tide and sea level anomalies propagation in Malacca Strait. *Terr. Atmos. Ocean. Sci.*, 32, 571-582. <https://doi.org/10.3319/TAO.2021.10.12.01>
- Kurniawan, A., Wisha, U.J., Husrin, S., Karjadi, E.A. (2017). Tidal Bore Generation at the Estuaries of The East Coast of Sumatra. *Proceeding of The 37th IAHR World Congress 2*, 3587. <https://www.iahr.org/library/infor?pid=2883>
- Kusuma, C. (2021). Tidal Flow Renewable Energy Potential in the Capalulu Strait. *IOP Conf. Ser.: Mater. Sci. Eng.*, (1052). <http://doi.org/10.1088/1757-899X/1052/1/012028>
- Lazard. (2014). Lazard’s Levelized Cost of Energy Analysis – *Version 8.0. Lazard*. <https://www.seia.org/research-resources/lazards-levelized-cost-energy-analysis-v80>
- Lesser, G.R., Roelvink, J.A., van Kester, J.A.T.M., & Stelling, G.S. (2004) Development and validation of a three-dimensional morphological model. *Coastal Engineering*, 51(8-9), 883-915. <https://doi.org/10.1016/j.coastaleng.2004.07.014>
- Martin, R.J., Kurniawan, A., Nugroho, E.O., Wijaya, F.S., Muhammad, I.F. & Fauzi N. (2022). The effect of land subsidence on hydrodynamic conditions in Pekalongan coast. *IOP Conference Series: Earth and Environmental Science* 1065 (1), 012009. <http://doi.org/10.1088/1755-1315/1065/1/012009>
- Mateos, L.F., & Hartnett, M. (2020). Hydrodynamic Effects of Tidal-Stream Power Extraction for Varying Turbine Operating Conditions. *Energies* 2020, 13, 3240. <https://doi.org/10.3390/en13123240>.
- MEMR. (2020). *Ministry of Energy and Mineral Resources* Bill No. 4 of 2020 on the Second Revision of Bill No. 50 of 2017 on Utilization of Renewable Energy Sources for the Provision of Electric Power. [Online], <https://jdih.esdm.go.id/index.php/web/result/2032/detail>. Accessed on 4 November 2023.
- Navionics (2022). *Navionics Web Application*. [Online], [www.navionics.com](http://www.navionics.com). Accessed on 3 August 2023.
- Neill, S.P., Haas, K.A., Thiébot, J. & Yang, Z. (2021). A review of tidal energy—Resource, feedbacks, and environmental interactions. *Journal of Renewable and Sustainable Energy*, 13, 062702. <https://doi.org/10.1063/5.0069452>
- Novico, F., Sudjono, E. H., Egon, A., Menier, D., Methew, M., & Pratama, M. B. (2021). Tidal Current Energy Resources Assessment in the Patinti Strait, Indonesia. *International Journal of Renewable Energy Development*, 10(3), 517–525. <https://doi.org/10.14710/ijred.2021.35003>
- Orhan, K. & Mayerle, R. (2017). Assessment of the tidal stream power potential and impacts of tidal current turbines in the Strait of Larantuka, Indonesia. *Energy Procedia* 125:230–239. <https://doi.org/10.1016/j.egypro.2017.08.199>

- Orhan, K. & Mayerle, R. (2020). Potential Hydrodynamic Impacts and Performances of Commercial-Scale Turbine Arrays in the Strait of Larantuka, Indonesia. *J. Mar. Sci. Eng.*, 2020, 8, 223. <https://doi.org/10.3390/jmse8030223>
- Orhan, K., Mayerle, R., & Widodo, W. (2015). Assessment of energy production potential from tidal stream currents in Indonesia. *Energy Procedia*, 76:7–16. <https://doi.org/10.1016/j.egypro.2015.07.834>
- Orhan, K., Mayerle, R., Narayanan, R., & Pandoe, W. (2016). Investigation of the energy potential from tidal stream currents in Indonesia. *Coastal Engineering Proceedings*, 1(35), management.10. <https://doi.org/10.9753/icce.v35.management.10>
- Pratama (2020). Modelling Tidal Energy Extraction in Sunda Strait, Indonesia. *Master Thesis: The University of Edinburgh, UK*.
- Pratama, M. B., Venugopal, V., Ajiwibowo, H., Ginting, J. W., & Novico, F. (2020). Modelling Tidal Flow Hydrodynamics of Sunda Strait, Indonesia. *ILMU KELAUTAN: Indonesian Journal of Marine Sciences*, 25(4), 165–172. <https://doi.org/10.14710/ik.ijms.25.4.165-172>
- Purba, N.P., Kelvin, J., Sandro, R., Gibran, S., Permata, R.A.I., Maulida, F., & Martasuganda, M.K. (2015). Suitable Locations of Ocean Renewable Energy (ORE) in Indonesia Region – GIS Approached. *Energy Procedia* 65:230-238, <https://doi.org/10.1016/j.egypro.2015.01.035> .
- Quirapas, M.A.J.R. & Taeihagh, A. (2021). Ocean renewable energy development in Southeast Asia: Opportunities, risks and unintended consequences, *Renewable and Sustainable Energy Reviews*, 137, 110403, <https://doi.org/10.1016/j.rser.2020.110403> .
- Ramachandran, R., Kularathna, A.H.T.S., Matsuda, H. & Takagi, K. (2021). Information flow to increase support for tidal energy development in remote islands of a developing country: agent-based simulation of information flow in Flores Timur Regency, Indonesia. *Energy Sustain Soc* 11, 26. <https://doi.org/10.1186/s13705-021-00302-8>
- Sprintall, J., Wijffels, S.E., Molcard, R., Jaya, I. (2009). Direct estimates of the Indonesian throughflow entering the Indian Ocean: 2004–2006. *J Geophys Res* 114:C07001. <https://doi.org/10.1029/2008JC005257> .
- Transtimur (2023). Pemadaman Listrik di Desa Kou Kecamatan Mangoli Timur Kabupaten Kepulauan Sula Maluku Utara, [Online], <https://transtimur.com/2023/05/05/listrik-di-pulau-mangoli-mati-warga-sebut-pln-tidak-becus/> . Accessed on 20th Jan 2024
- Verdant Power. (2019). Final License Application for New License Rosevelt Island Tidal Energy Project FERC No. 12611 *Exhibit E Environmental Report*. New York: Verdant Power.
- Walker, S. & Thies, P.R. (2021). A review of component and system reliability in tidal turbine deployments, *Renewable and Sustainable Energy Reviews*, 151(2021), <https://doi.org/10.1016/j.rser.2021.111495> .
- Wijaya, F.S., Kurniawan, A., Yuanita, N., Nugroho, E.O. & Martin, R.J. (2022). Numerical modelling of land subsidence effect on coastal sediment transport in Pekalongan. *IOP Conference Series: Earth and Environmental Science* 1065 (1), 012022. <https://doi.org/10.1088/1755-1315/1065/1/012022>
- Wilberforce, T., Hassan, Z.E., Durrant, A., Thompson, J., Soudan, B., & Olabi, A. G. (2019). Overview of ocean power technology, *Energy*, (175), 165-181, <https://doi.org/10.1016/j.energy.2019.03.068> .



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