Resource Assessment of Tidal Stream Power in Pakiputan Strait, Davao Gulf, Philippines

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Abstract-During the last years, there are ongoing efforts on the development of tidal energy conversion systems in the Philippines. This study conducts tidal energy resource assessment in the Pakiputan Strait following a methodology outlined as stage 2a tidal resource assessment published by the European Marine Energy Centre (EMEC). The study assessed the preliminary results of the tidal velocities at Pakiputan Strait with a mean spring peak velocity (Vmsp) of 1.7m/s at 3m from the water surface from 15 days of continuous data collection using a seabed-mounted acoustic Doppler current profiler. This corresponded to an estimated Annual Energy Production (AEP) of 1350kWh/y for 1m^2 of capture area of the generic device. Sensitivity analysis showed that the spatial distribution of hydrodynamic model results does not vary significantly with variations in certain input parameters. It further showed that a 10% decrease in the nominal value of Vmsp on-site led to a 15% decrease in the nominal value of AEP, while a 10% increase in the nominal value of Vmsp led to a 30% increase in the nominal value of AEP, assuming that the considered Vmsp still corresponded to the velocity distribution from observations. A static survey and the use of computational fluid dynamics modeling are recommended to further enhance the analysis of the study.

Keywords-tidal energy; ocean renewable energy; resource assessment; Davao Gulf

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I. INTRODUCTION

The global interest in renewable energy has increased over the past decade, mainly due to the global mandate to mitigate anthropogenic climate change. One of the renewable energy technologies that are exploited nowadays is ocean energy. The ocean provides a vast source of potential energy that can be captured through tidal, wave, salinity gradient, and ocean thermal energy conversion systems [1]. Energy from tidal currents is one of the most promising renewable energies due to the several advantages compared to other renewable energy sources [2]. Among its advantages are the high predictability of tidal currents [3], the higher density of seawater (over 800 times that of air) that assures larger potential energy as compared to wind [2], lesser environmental impact compared to tidal barrage facilities [4], and d) the absence of extreme flow velocities that might damage the equipment or complicate its maintenance [4]. The last point mentioned depends on the strong flow profile brought by the local bathymetry near the TEC deployment site [5]. With highly predictable tidal current benefits in tidal stream energy conversion, it has a high potential to contribute to the decarbonization of the energy supply and, at the same time, provide energy security [1].

In exploring a potential site for ocean energy extraction, the first consideration is the energy resource assessment [6]. One

method of identifying potential sites is by analyzing tidal range distributions and resources. This method was particularly followed by the authors in [7] in order to select tidal range sites in East Malaysia suitable for power generation. Another method is by producing a hydrodynamic model and analyzing its outputs. In the northern part of the Gulf of California in Mexico, a detailed qualification of the theoretical tidal range energy, performed using level from a depth-averaged barotropic hydrodynamic model and 0-D operation modeling approach was applied to determine the power that can be extracted at four key sites [3]. In [1], Delft3D modeling suite was used in assessing the Strait of Larantuka, Indonesia, wherein the flow conditions of the tidal stream were considered for the energy conversion. The bathymetric data have been obtained with the use of a Single-beam Echo Sounder (SBES) and SRTM15 Plus to have a more accurate determination of the potential energy to be harnessed, and the resource assessment showed that the Strait of Larantuka in Indonesia has a potential for the production of ocean renewable energy with current velocities up to 3-4m/s and average kinetic power densities around $10kW/m^2$ [1]. The same modeling suite was also used in [8] along with MIKE system, to observe the morphological behavior of the Nhat Le estuary which is located in the north-central coast of Vietnam.

Numerous numerical modeling methods have been used in many researches in order to understand the hydrodynamic characteristic of the tidal stream energy sites and the current turbine technology. An example of this is the investigation of the tidal induced Lagrangian circulation in the north-western coastal waters of Brittany, France, including islands, shoals, and straits with strong potential for tidal turbine farm implementation [9]. With the increase of interest in different renewable energy sources, the Philippines is now exploring ocean renewable technologies as alternative energy sources that can be implemented in potential areas.

The current study aims to assess the tidal stream power in Pakiputan Strait, Davao Gulf, Philippines and to locate a potential site for the implementation of the tidal energy converter system. The structure of the assessment follows the steps described by the EMEC, which start from the regional assessment and site selection through the estimation of current speed and spatial distribution using hydrodynamic modeling. The preliminary results of this study show that tidal current velocities above 0.5m/s exist in the identified area. These currents could drive a generic energy harvesting device and occur frequently enough to ensure significant availability of power.

II. BACKGROUND INFORMATION OF THE STUDY SITE

A. The Philippine Oceans and Coasts

The Philippines, is an archipelago with 7,641 islands, with a total coastline stretching at 36,289km [10]. It is bounded by the Philippines Sea to the east, the Celebes or Sulawesi Sea to the south, the Sulu Sea to the southwest, the West Philippine Sea to the west, and the South China Sea to the north [11]. It has three major island groups, namely Luzon, Visayas, and Mindanao. The Sibuyan Sea separates Luzon and the Visayas. The islands in the Visayas are surrounded by the Visayan and

Camotes Seas. The Bohol Sea extends down to the north of Mindanao, with several straits connecting the internal and marginal seas to the ocean [10].

The total land area amounts to $298,170km^2$, with a sea area of $1,830km^2$, 6% of which are considered marine protected areas [12]. The population has reached 109,763,425 in 2020, with around 62% living in the coastal areas [12]. It was ranked 83rd among 221 countries with exclusive economic zones (EEZ) with an overall Ocean Health Index score of 71 [13]. The national ocean economy contributed US$ 11.9 billion in 2015, amounting to 7% of the Gross Domestic Product (GDP) [12]. Some of the key contributors to this belong to coastal and marine tourism (25%), fisheries and aquaculture (20%), manufacturing (19%), and port and shipping (12%) sectors [12]. The country's coastal and marine habitats include coral reefs $(25,060km^2)$, natural mangroves $(2,472.68km^2)$, mudflats, and tidal swamps $(2,000km^2)$, seagrass $(978km^2)$, and planted mangroves $(765.14km^2)$ [12]. The blue economy initiatives that the country focuses on are sustainable fisheries and aquaculture, sustainable tourism, sustainable ports, marine renewable energy, marine biotechnology, pollution reduction, and habitat restoration and management [12].

The Davao Gulf is a 308,000-hectare body of water found in the southeastern part of Mindanao [14]. It is one of the richest zones for fish production in the country and is considered as one of the priority conservation areas of the Sulu-Sulawesi Marine Ecoregion. There are currently 19 marine protected areas in the 5 cities and 5 municipalities surrounding the gulf [15]. It is home to a diverse species of cetaceans with at least 15 identified species identified in 2018 [16]. According to the Permanent Service for Mean Sea Level (PSMSL), there is a tide gauge station located at 7.08333°N, 125.633333°E, in the Davao Gulf. It was considered a Revised Local Reference (RLR) station in 2010. There are two neighboring RLRs in the Davao Gulf, one in Mati, Davao Oriental and the other in Makar, General Santos City [17]. Aside from being home to diverse marine life, marine traffic is a commonality in the Davao Gulf. There were usually around 5 to 11 arrivals per day and about the same number of departures from July 22, 2020, to August 19. The majority of the vessels arriving in the port are cargo vessels with several tankers. Other ports in the Davao Gulf include the Davao Therma South port (6.9621405°N, 125.48615°E), and the Davao Anchorage port (7.0515755°N, 125.65395°E) [18].

B. Oceanographic Conditions

In the Philippine Straits Dynamics Experiment (PhilEx), global ocean models were used to investigate the internal circulation in the Philippine archipelago, both spatially and temporally. However, realistic modeling was difficult for a global model due to the numerous straits and small interior seas [19]. In general, the bathymetry of the Philippine waters between islands is highly complicated, consisting of narrow shelves, steep slopes, and deep basins connected by shallow sills. Ocean circulation is highly influenced by the bathymetry, the seasonally reversing northeast monsoon, locally known as Amihan, and southwest monsoon, locally known as Habagat, and the tidal and nontidal circulation between the South China Sea and the Western Pacific [20]. In addition to the reversing

winds, the monsoon brings a change in the rainfall pattern, which affects the surface layer thermohaline seasonal stratification [21]. The Amihan brings less rainfall while the Habagat more. Comparing actual rainfall for a specific year to the average annual cycle, however, reveals precipitation anomalies, which may affect the surface layer thermohaline stratification [21]. This can be further complicated due to the interannual El Niño or La Niña phenomena [21]. Numerous factors make the analysis of the circulation within the Philippines challenging. However, with further studies, a better understanding of these dynamics can be achieved.

C. Ocean Energy Potential

The Philippines' Department of Energy (DOE) estimates the theoretical ocean energy potential of the country to about 170GW, which was based on an assessment done by the Mindanao State University – Iligan Institute of Technology (MSU-IIT) [22]. Since then, several studies have been conducted in line with ocean energy resource assessment in the country. One such study reviews the ocean energy status in Southeast Asia [23]. It focuses not only on the potential resource but also the enabling and hindering factors, particularly in government initiatives that affect its development. In the study, a map of the potential sites for tidal in-stream energy, wave energy, and Ocean Thermal Energy Conversion (OTEC) in the Philippines was presented. For tidal-instream energy, four sites were identified, namely the Luzon Strait, San Bernardino Strait, Surigao Strait, and Basilan Strait.

In its National Renewable Energy Program (NREP), which started implementing in 2011, the Philippines' DOE has targeted to increase the country's renewable energy capacity to an estimated 15,304MW by 2030. This included an ocean energy share of 70.5MW, with a target of achieving the country's first ocean energy facility, a 10MW pilot ocean thermal energy conversion plant in Cabangan, Zambales, in 2018 [24, 25]. However, in 2019, the DOE moved to update its target after falling short of its original goals. Instead, it has focused on increasing the share of renewables in the total generation, instead of capacity, with a targeted 20,000MW installed capacity by 2040 [25, 26]. There are 8 awarded ocean projects by the DOE as of June 30, 2020, as presented in Table I. All the projects, however, are still in the pre-development stage, with 3 projects that have to determine their target capacity. The total capacity of the projects amounts to 26.00MW [27]. It is worth noting that 7 of these awarded projects involve tidal in-stream energy technology. This is a testament to its commercial readiness and maturity in terms of research and development.

III. METHODOLOGY AND APLLICATION

A. Methodology

The process flow diagram of the methodology for the pre-feasibility assessment is shown in Figure 1. The inputs for the hydrodynamic model, such as bathymetry and grid resolution, are mainly based on the area of interest. A desktop was conducted to identify the potential sites in Davao Gulf. The area of interest was narrowed down into Pakiputan Strait with a two-day transect survey.

TABLE I.　　AWARDED OCEAN ENERGY PROJECTS BY THE DOE AS OF JUNE 30, 2020

Region	Location	Technology	Developer	Type of contract	Total capacity (MW)
III	Cabangan, Zambales	OTEC	Bell Pirie Power Corp.	Pre-development	5.00
V	San Bernardino Strait, Matnog, Sorsogon	TISE	H&WB Corp.	Pre-development	5.00
VIII	Northwest Capul, Northern Samar	TISE	Oceantera Energy Corp.	Pre-development	TBD
	San Bernardino Strait, between Bicol Peninsula and Samar Leyte Corridor, Area 2OP	TISE	H&WB Corp.	Pre-development	5.00
	Capul Pass, Dalupiri Island, San Antonio, Northern Samar, TISEC-Project Site (Area 6)	TISE	Poseidon Renewable Energy Corp.	Pre-development	TBD
	San Bernardino Strait and Northern Samar, TISEC-Project Site (Area 4&5)	TISE	Poseidon Renewable Energy Corp.	Pre-development	TBD
	San Bernardino Strait, between Bicol Peninsula and Samar Leyte Corridor, Area 3OP	TISE	H&WB Corp.	Pre-development	5.00
XIII	Gaboc Channel, Surigao del Norte	TISE	Adnama Power Resources Corp.	Pre-development	6.00

The surface and depth-averaged velocities, along with their GPS coordinates, obtained from the transect survey were post-processed to identify potential locations for a tidal turbine. Bathymetry data were collected. Continuous on-site data collection of tidal currents was also carried out to collect empirical data as inputs for a harmonic analysis. The bathymetry data and the results of the harmonic analysis were used as inputs to the hydrodynamic modeling. Finally, a forecast estimate of the mean electrical power and annual energy production was determined from the collected tidal current data.

Desktop Study → Data collection → Harmonic Analysis → Hydrodynamic Modelling

Fig. 1.   Methodology flow diagram.

B. Site Selection

This research closely follows the methodology of site definition and selection described in Assessment of Tidal Energy Resource, a document prepared in consultation with The European Marine Energy Centre Ltd (EMEC) and with other interested parties in the UK marine energy community [6]. The site selection methodology used in the study was the Stage 2a, which is the first stage of the pre-feasibility of the tidal resource assessment [6]. The determined region was Davao Gulf. The channel considered was Pakiputan Strait in the northern part of the gulf, with the aim of selecting a localized area for the tidal energy converter implementation.

C. Estimation of Current Speeds

The modeling suite used in the hydrodynamic modeling was Delft3D [28]. Other inputs, such as the grid, land boundary file, and enclosure, were also generated from the modules included in Delft3D. Rectangular structured grids were used to coincide with the given grid resolution for each stage of the resource assessment. For stages 1 and 2a, the grid resolutions should be less than 5km and 500m, respectively [6]. As shown in Figures 2, 3, the model has a grid resolution of 1km for the regional assessment (Stage 1) and a grid resolution of 100m for the pre-feasibility assessment (Stage 2a). In Stage 2a, the area of interest was narrowed down into a channel. The bathymetry data were acquired from the French Research Institute for Exploitation of the Sea (IFREMER) [29-31] and the General Bathymetric Chart of the Oceans (GEBCO) [32]. The raw bathymetric data were processed with DELFT 3D as shown in Figures 4-5. The bathymetric data from the 2020 gridded bathymetry of GEBCO have soundings with spacing of approximately 450m. However, the soundings for IFREMER bathymetric data were not specified in the obtained raw data. As for the harmonic analysis, 15 tidal constituents (O1, K1, P1, N2, NU2, M2, L2, S2, K2, MK3, M4, S4, M6, S6, and M8) were extracted from the empirical tidal velocity data that were continuously collected on site for 15 days. The amplitudes and phases of these tidal constituents were used in the tidal forcing needed by the model. Aside from the open boundary, physical parameters and flow conditions were also added. Parameters such as salinity, temperature, and other meteorological inputs were not yet considered in the simulation of the model.

Observation points were added in the model to check the modeled tidal currents in specific areas.
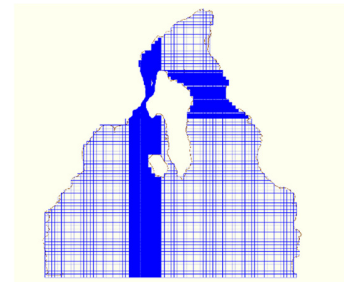

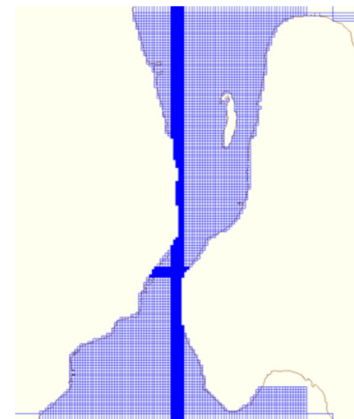Fig. 2.   Davao Gulf 1km grid resolution.

Fig. 3.   Pakiputan Strait 100m grid resolution.
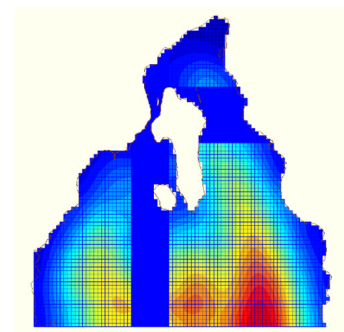

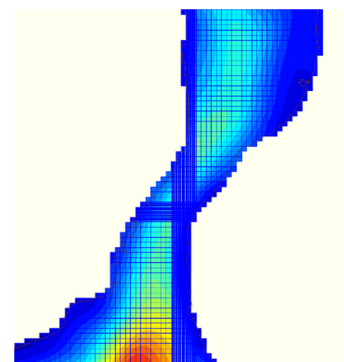Fig. 4.   Bathymetric data for Davao Gulf.

Fig. 5.   Bathymetry for Pakiputan Strait.

Several simulations were made, as a part of the sensitivity analysis, with varied inputs. It was found out that non-astronomical attribute files have a significant influence on the output of the model. Three simulations showed more realistic results. From these three simulations, it was determined, using their respective East vs. North graphs (see Figure 6), that the current in Pakiputan Strait is reversing. This was also evident in the results of the harmonic analysis for the eccentricity of all the harmonic constituents that are almost equal to 1.
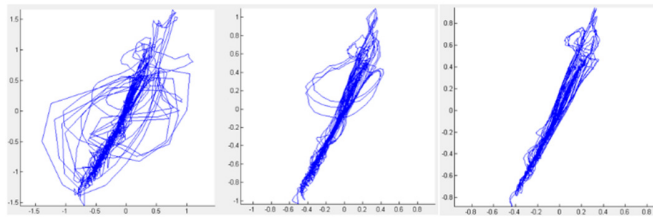
Fig. 6.   East vs. North components (m/s).

The potential sites from the spatial variation of the depth-averaged velocities, as shown in Figure 7, were similar to those that can be identified from the desktop study. However, though the spatial variation gave similar sites to those from the desktop study, the current velocities from the model did not show a positive linear relationship with the actual current velocities obtained from the 15-day data collection. Hence, to improve the model performance and outputs, the grid, location of the open boundary, tidal forcing, and other parameters of the model must be reviewed. In the new model, the number of layers will be increased to generate predicted surface velocities and not just depth-averaged velocities. The new hydrodynamic model will then be validated using in-situ measurements.
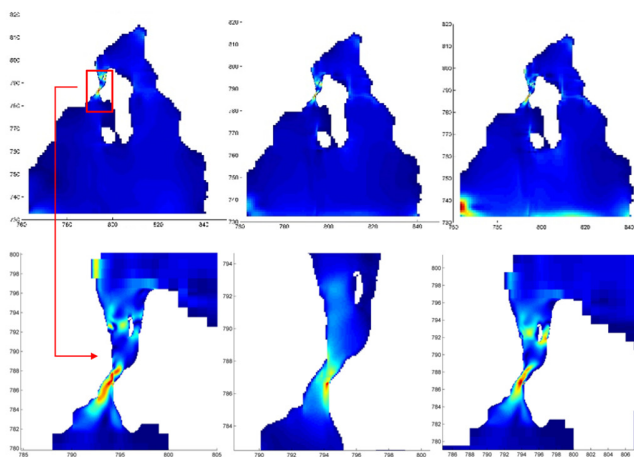

Fig. 7.   Spatial variation for depth-averaged velocities.

D. Energy Yield

An estimate of the mean electrical power and annual energy production from tidal in-stream energy was obtained simulating a generic device, as described in [6]. A generic device was used for the study since no device had yet been tested. The available power $P_{av(i)}$ for every vertical bin i across the depth of the water is given by:

$$P_{av(i)} = 0.5\rho AU_i^3 \quad (1)$$

where ρ is the density of seawater, assumed constant for simplicity at $1025kg/m^3$, A is the capture area of the device, assumed to be $1m^2$ (bin size), and U_i^3 is the tidal stream velocity at the bin.

Combining this with the rotor efficiency η_R, the electrical power per bin $P(U_i)$ is given by:

$$P(U_i) = P_{av(i)} \cdot \eta_R \quad (2)$$

For a generic device, η_R was considered to rise from 38% at cut-in speed to reach 45% at the rated velocity. The rated velocity was taken as 71% of the mean spring peak velocity V_{msp} at the hub height. The Vmsp is defined in [6] as the peak velocity that has been reached for 10min during the whole month from the results of a static field survey, model, or harmonic analysis. From the results of a static field survey conducted during February 2020 to collect empirical data for harmonic analysis, the Vmsp was estimated to be at 1.7m/s at a hub height of 3m below the water surface (i.e. Vmsp $=U_3$). The data set was comprised of velocity data collected at 1min intervals for each 1m vertical bin across the depth continuously over a 15-day period on the same site. This Vmsp of 1.7m/s was significantly higher compared to that which had been determined from an earlier transect survey using a boat-mounted Acoustic Doppler Current Profiler (ADCP) on the same site conducted in August 2019, generating a value of 1.5m/s. Hence, the rated velocity for the generic device was determined as $0.71 \times 1.7 \approx 1.2$m/s.

The cut-in speed (the minimum velocity required for device operation) was assumed constant at 0.5m/s. This assumption greatly simplified the analysis without imposing significant limitations on the accuracy, since the available energy from tidal currents at speeds below 0.5m/s is usually less than 5% of the total available energy. A velocity distribution $f(U_i)$ is also defined to be derived from the tidal harmonic analysis [6]. The data set from the 15-day data collection was instead used to develop $f(U_i)$. As part of the preliminary results, this distribution was assumed to represent an annual distribution. The chart in Figure 8 displays the energy yield from a generic device, showing $P_{av(i)}$, $P(U_i)$, and $f(U_i)$.
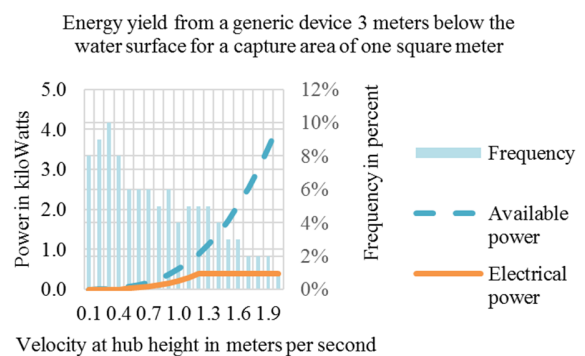

Fig. 8.   Velocity distribution and estimated power from the site.

The mean annual electrical power P_{mean} was obtained by combining the velocity distribution $f(U_i)$ with the average absorbed power for each velocity bin $P(U_i)$ by using (3):

$$P_{mean} = \sum_{i=1}^{N_B} P(U_i) \cdot f(U_i) \quad (3)$$

The number of vertical bins N_B considered was only one (i.e. the 1m vertical bin at 3m below the water surface). After taking the summation, P_{mean} was determined to be at 0.154kW for 1m^2 of the capture area.

E. Sensitivity Analysis

Performing sensitivity analysis on the hydrodynamic model showed that varying the input parameters to the model resulted in a visually similar spatial distribution of the currents in Pakiputan Strait. Figure 9 illustrates several results from these variations. Certain inputs to the model, particularly the tidal constituents and the bathymetry data, were kept constant during the sensitivity analysis.
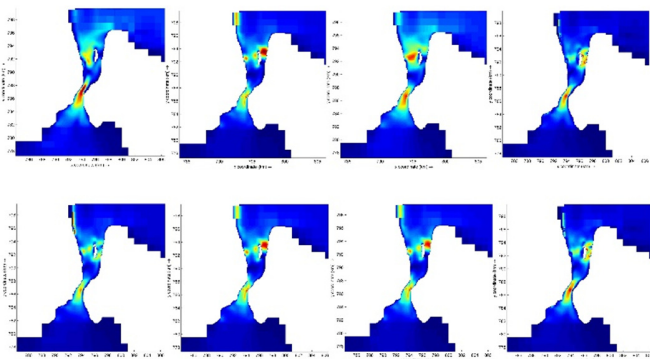

Fig. 9.   The hydrodynamic model spatial results did not vary significantly with varying input parameters.

Due to the inherent dependence of the nominal value of energy and power to the cube of the nominal value of tidal velocities, as shown in (1), it was reasonable to expect significant variations of power corresponding to any changes in observed velocity values.

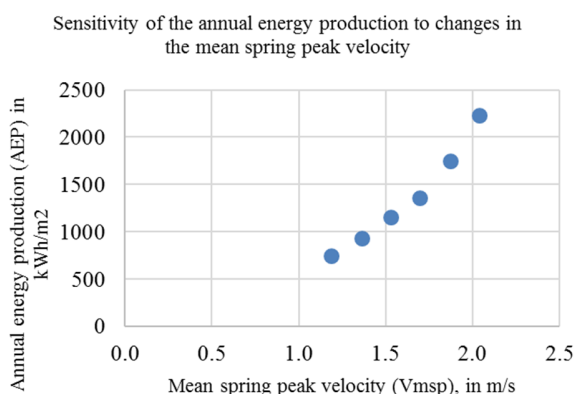Sensitivity of the annual energy production to changes in the mean spring peak velocity

Fig. 10.   AEP varied significantly with varying Vmsp.

Sensitivity analysis (Figure 10) showed that a 10% decrease in the nominal value of the Vmsp on site will lead to a 15%

decrease in the nominal value of the AEP. This observation was also true for every 10% decrease up to 30%. On the other hand, a 10% increase in the nominal value of the Vmsp on site led to a 30% increase in the nominal value of AEP. Checking for sensitivity beyond a 20% increase in the nominal value of the Vmsp was not realistic because the velocity distribution shows no instances of such velocities occurring. This analysis assumed that the considered Vmsp still corresponded to the velocity distribution derived from observations.

IV.   CONCLUSION

Based on preliminary results, Pakiputan Strait is a candidate site for the deployment of a tidal energy conversion system. From the results of a static field survey conducted during February 2020 and the collected empirical data for harmonic analysis, the Vmsp was to be at 1.7m/s at a hub height of 3m below the water surface (i.e. Vmsp = U_3). The data set was comprised of velocity data collected at 1min intervals for each 1m vertical bin across the depth continuously over a 15-day period on the same site. The velocities from modeled and empirical data show that tidal power from a generic device will be potentially available for the 60% of the time. The results of the study are not yet conclusive and could be improved by the collection of more data and conducting a field survey as a validation step. Much motivation could be derived from the preliminary results, as it responds to technological questions by showing tidal velocities that can run a generic device. Similarly, it beckons the need to design devices suitable to harness the resource given in this site. Additional sections of the channel could be used as generation sites once the identification of constraints is completed at the end of the resource assessment and during its further stages.

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