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Techno-Economic Analysis of Tidal Energy Devices Within the Dinagat Islands in the Philippines

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Portions of Surigao del Norte, Southern Leyte Provinces, and Dinagat Islands are pre-identified by the Department of Energy (DOE) as potential deployment sites of tidal energy. In this study, a new approach to estimating tidal velocities is implemented by generating a synthetic tidal velocity profile over the area of interest using available data from tidal simulations and actual point measurements. Tidal current devices were tested over the area to estimate the Levelized Cost of Energy (LCOE) and further assessed for deployment feasibility. It was found that Evopod E1000 had a 0.14 × 10^6 kW indicative potential capacity with at least 0.16 \$/kWh cost of energy.

1. Introduction

Data from the Philippine's Department of Energy (DOE) state that Ocean Energy, despite having the largest potential among renewable energy sources, has not been utilized in the country yet. Among the different ocean energy technologies, only the tidal stream turbine has been gaining some attention in terms of research and development as it has a similar operation to horizontal axis wind turbines. As per the DOE, the Philippines currently has 8 tidal turbine projects with a total capacity of 24 MW, but all are in the pre-development stage. Based on the 2025 energy supply and demand projection from the DOE of all electric cooperatives located at Dinagat Islands, Surigao del Norte, and Southern Leyte Provinces, the total energy requirement is 97.11 MW. The present cost of renewable energy sources ranges from 0.05 \$/kWh to 0.12 \$/kWh, while conventional fuels such as coal and diesel fuel cost from 0.07 \$/kWh to 0.53 \$/kWh (IEEFA, 2018).

Abundo et al. (2012b) estimated the available tidal energy potential of sites identified by DOE in terms of energy density (MWh/m^2). These sites are Basiao Channel, Bohol/Talibon Strait, Cebu Harbor, San Juanico Strait, Surigao Strait, Gaboc Channel, Hinatuan Passage, and Basilan Strait. To assess the suitability of sites, a tool was developed by Abundo et al. (2012a) that integrates resource assessment, power estimation, site-device matching, energy density mapping, and device suitability capabilities. Tidal devices were pre-identified for the deployment sites mentioned, and a list of criteria was established for determining their suitability. These criteria include availability factor (A_f), capacity factor (C_f), energy per turbine, and LCOE. As for pre-identification of device deployment, Nasab and Kilby (2021) optimized the energy output of a tidal farm by replacement of device capacity. In 2015, Ang et al. (2015) created PhilSHORE, a webGIS-based application that identified appropriate areas of tidal device installation. It focused on consideration of the physical, environmental, and socio-economic impact for device placement. Common to the previous studies was the use of Delft3D to determine the tidal velocities. The resulting map was a depth-averaged monthly mean velocity. Another study by Villalba et al. (2021) used advanced circulation model to estimate the tidal velocity. The resulting potential tidal extraction sites were similar to Abundo et al. (2012b).

LCOE has been commonly used as the metric for evaluating different sources of energy. Tidal energy is no exception. Vasquez and Iglesias (2015) showed an LCOE mapping to visualize the cost of energy. Further, Vasquez and Iglesias (2016) focused on the performance of a tidal farm with a device spacing scenario for multiple device installations. Both studies employed a standard value of discount rate (i) of 10 % for LCOE calculation. Also, LCOE was used as a criterion in a sustainability study performed by Cipolletta et al. (2023) at Island of Crete, Greece for hybrid renewable energy mix deployment.

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In this study, the tidal velocities were derived by creating a synthetic velocity profile from PhilSHORE velocity raster data and tidal velocity simulation from Michael Castro, an Assistant Professor of the Chemical Engineering Department, University of the Philippines, at Raza Island, Philippines. The annual velocity profile of the Castro data at Raza Island was assumed to be the velocity distribution across all points in the proposed study area, with the PhilSHORE data as the monthly mean. This approach was adopted due to the unavailability of a velocity profile on each pixel data of the raster on the area of interest. As such, the resulting synthetic velocity profile used in the techno-economic study need not be validated.

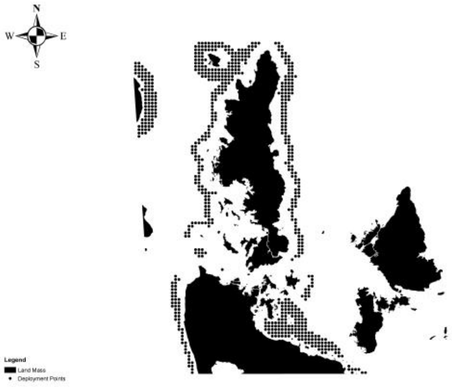

Figure 1: Regional research area

Table 1: Tidal devices specifications

Unit	Device	Manufacturer	Deployment type	Count	Blade diameter (d_r)	Swept Area (A_s)	Rated Power (P_r)	Rated velocity (v_r)	Cut-in velocity (v_i)	Cut-out velocity (v_o)
1	AR1000	Atlantis Resources Corporation	Seabed fixed	10.0		254.00	1,000.00	2.70	0.70	3.40
2	Evopod E35	Ocean Energy Limited	Floating	10.0		20.30	35.00	2.30	0.70	3.20
3	Evopod E1000	Ocean Energy Limited	Floating	10		201.00	1,000.00	3.60	0.70	4.10
4	SCHOTTEL Hydro Class II	SCHOTTEL GmbH	Floating	10.0	4.00		62.00	3.00	0.80	6.00
5	SCHOTTEL Hydro Class III	SCHOTTEL GmbH	Floating	10.0	5.00		54.00	2.60	0.70	4.60
6	SeaGen-S 2MW	Atlantis Resources Corporation	Seabed fixed	5.0		20.00	2,000.00	2.00	1.00	4.00
7	Tocardo T1	Tocardo	Floating	10.0	3.10	7.70	98.00	4.50	0.90	6.80
8	Tocardo T2	Tocardo	Floating	10.0	4.70	17.70	248.00	4.50	0.90	6.80

2. Objectives, scope and limitations, and assumptions

The area of interest is presented in Figure 1 with regional boundary coordinates of (10°30′0″N,125°14′0″E), (10°30′0″N,126°18′0″E), (9°30′0″N,125°18′0″E), (9°30′0″N,126°14′0″E). The deployment area of the turbines is within 5 km from the coastline, with each data pixel at 1000 m × 1000 m grid dimension or 1 km^2 grid area and its specifications showed in Table 1. No-build zones with corresponding buffer spacing are excluded using the following criteria: (1) 10 km spacing (MMDA, 2011) for active fault line and trenches that traverse along the Surigao del Norte Province from Philippine Institute of Volcanology and Seismology, (2) 1 km coastal zone (DENR et al., 2001) recreational areas for activities such as surfing, kayaking, scuba diving (City of Cape Town, 2014), (3) 3 km spacing (Maandal, 2021) for marine habitats and ecosystems such as marsh, fish hatchery, swamp, reef, and foreshore that provide marine economic activity, marine protected areas from

National Mapping and Resource Information Authority of the Philippines, and domestic ship routes or navigation lanes (Maandal, 2021), and (4) 0.5 km spacing (Proclamation No. 72, 2001) submarine cables crossing the Surigao del Norte - Southern Leyte.

To finalize the device suitability deployment, each pixel is evaluated using the following criteria: (1) LCOE is within the calibrated range of baseline LCOE that was stated in IRENA (2020), (2) device with the highest indicative project capacity, and (3) depth of device installation based on information from the General Bathymetric Chart of the Oceans (GEBCO, 2022).

3. Methodology

This work used the ArcMap of Esri's ArcGIS (Esri, 2022) to create an LCOE map along with Python programming language for calculations using Spyder as an integrated development environment of Anaconda computer software. First, the PhilSHORE raster velocity dataset was resized from 0.64 km^2 to 1.0 km^2 grid area. As a reference point of calculation, resized raster velocities (v_{res}) were extracted at Raza Island. To extrapolate the availability factor (A_f) and capacity factor (C_f) used in calculating the LCOE, correlation using Pearson's R (Wilcox, 2003) of v_{res} and tidal simulation data of Castro in the form of average monthly velocity ($\overline{v_x}$) on an annual basis was performed from the period of analysis of 2022 to 2036. The year with the highest correlation value was applied as reference velocity (v_{ref}) for synthetic velocity factor (v_{ar}) calculation. Note that v_{ar} is the quotient of v_{res} and v_{ref}. A velocity ratio profile (r) was generated from the tidal data of Castro denoted by the ratio of each data point to the corresponding $\overline{v_x}$ for the whole period of analysis to create the velocity pattern of the given simulation dataset. To generate the synthetic velocity (v_{arx}), v_{ar} and r were multiplied, which resulted in a dimensionless unit. Validation of the produced synthetic velocity profile by correlating it to the Castro data throughout the period of analysis using Pearson's R method. Finally, replication of the velocity profile was accomplished within the area of interest by performing the synthetic profile creation on each resized grid area data point.

For LCOE calculation, operating time (t_o) and turbine power output (d_o) are calculated from the synthetic velocity profile. A_f is the ratio of t_o and expected operating time (t_a) of 8760 h, and C_f is the quotient of d_o and tidal farm power capacity. Take note that both are taken as annual averages and used to calculate the annual energy generation (AEG), or annual energy generation as adopted from Ocean Energy Systems (2015). The first array of tidal deployment capital expenditures (CAPEX) and operational expenditures (OPEX) values of Ocean Energy Systems (2015) was calibrated using the inflation rate from Bangko Sentral ng Pilipinas (2022), as well as the tidal device reference LCOE from IRENA (2020) listed in Table 2. As shown in Equation 1, LCOE is estimated within the period of analysis of 15 y with inclusion of cable cost per distance (Cc) of 0.75 × 10^6 \$/km (Qiu, 2021). Take note that all values exceeding the maximum LCOE value in Table 4 are excluded from the analysis, and deployment sites with depth less than the device's d_r.

$$LCOE = \frac{CAPEX + Cc + \sum_{t=1}^{n} \frac{OPEX}{(1+i)^t}}{\sum_{t=1}^{n} \frac{AEG}{(1+i)^t}} \qquad \text{Eq(1)}$$

Table 2: Calibration of assumed variables from Ocean Energy System (2015) and IRENA (2020)

Variable	Minimum	Maximum
Project capacity	300 kW	10,000 kW
CAPEX	6,135.58 \$/kW	17,564.60 \$/kW
OPEX	192.49 \$/kW	1,395.54 \$/kW
LCOE range by device capacity	0.23 \$/kWh	0.52 \$/kWh

4. Results and discussions

The best year with the highest correlation value from the 15 y analysis period was 2034, with Pearson's R-value of 73 %. Tidal devices such as E35, Tocardo T1, SCHOTTEL Hydro Class II, and III are excluded for further analysis that had the following LCOE values of 1.16 \$/kWh, 0.53 \$/kWh, 0 \$/kWh, and 0.70 \$/kWh, exceeded the maximum calibrated limit of LCOE range stated in Table 2. Analogous to this study, Nasab and Kilby (2021) used SCHOTTEL 54 kW for tidal energy generation for low cut-in speed areas but excluded due to study’s scope and limitation. The results of the study of Cipolletta et al. (2023) are not comparable to the study due to different types of energy generation system. Criteria for analysis was similar like LCOE, offshore distance, and bathymetry was applied. Comparing the results to Abundo et al. (2012a), LCOE estimation in this study was similar to this study using regional scale approach but did not implement a device suitability analysis using its defined criteria. Also, a per pixel analysis was not included from the previous study. In viewpoint of Ang et al. (2015), techno-economic analysis was seen as a like using LCOE as evaluating parameter. Neither studies had not mentioned that potential sites within the research area of interest were feasible for tidal device deployments. In the results of Villalba et al. (2021), cost of energy is applied as feasibility decision parameter; but this study exercised LCOE as part of the decision criteria. It is confirmed that Banug Strait is feasible for device deployment in this study and Villalba et al. (2021). To further narrow down the device selection process, Table 3 shows the total indicative capacity per device, where E1000 is shown to have the highest capacity at 0.15 × 10^6 kW. It has 9 remarkable locations near or within the Banug Strait listed in Table 4 as well as other locations possible for energy extraction aligned with the limitations on LCOE provided in Table 4. The total indicative capacity available for Surigao del Norte is 0.14 × 10^6 kW and 0.01 × 10^6 kW for Southern Leyte. The potential location in Southern Leyte is discarded due to a depth of 11 m, which is lesser than the device's blade diameter length of 17.98 m. Lastly, the creation of an LCOE map in this study was adopted from Vasquez and Iglesias (2015) to illustrate the LCOE distribution provided by Figure 2.

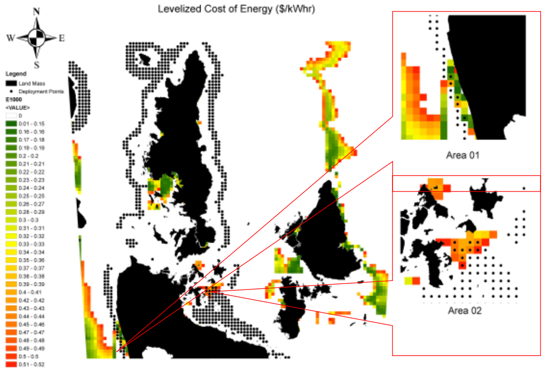

Figure 2: Evopod E1000 LCOE

Table 3: Potential site count per device according to deployment points and calibrated LCOE range from Table 2

Device	Number of sites	Potential capacity
AR1000	8	0.08 × 10^6 kW
E1000	15	0.15 × 10^6 kW
SeaGen-S 2MW	4	0.04 × 10^6 kW
Tocardo T2	21	0.05 × 10^6 kW

Table 4: E1000 LCOE of potential locations

Point	Latitude	Longitude	LCOE ($/kWh)	Remarkable locations
1	9°31'58.8"N	125°25' 1.2"E	0.16	Malimono, Surigao del Norte
2	9°33'10.8"N	125°24'25.2"E	0.41	Malimono, Surigao del Norte
3	9°33'46.8"N	125°24'25.2"E	0.24	Malimono, Surigao del Norte
4	9°34'58.8"N	125°23'49.2"E	0.40	Malimono, Surigao del Norte
5	9°35'34.8"N	125°23'49.2"E	0.20	Malimono, Surigao del Norte
6	9°41'34.8"N	125°41'13.2"E	0.51	Banug Strait
7	9°42'10.8"N	125°41'13.2"E	0.44	Banug Strait
8	9°42'46.8"N	125°40'37.2"E	0.45	Banug Strait
9	9°42'46.8"N	125°41'13.2"E	0.40	Banug Strait
10	9°42' 46.8"N	125°41'49.2"E	0.44	Banug Strait
11	9°42'46.8"N	125°42'25.2"E	0.51	Banug Strait
12	9°43' 22.8"N	125°40'37.2"E	0.45	Banug Strait
13	9°43' 22.8"N	125°41'49.2"E	0.40	Banug Strait
14	9°43'22.8"N	125°42'25.2"E	0.44	Banug Strait
15	9°52'22.8"N	125°16'37.2"E	0.18	San Ricardo, Southern Leyte

5. Conclusion and recommendation

The increasing power demand requires additional sources of energy to cope with the deficiency and avoid power interruptions. It is noted that sustainable energy resources are renewable compared to conventional ones. Capital investment for renewables tends to be high at the start but starts to decrease over time. Focusing to resource extraction, ocean energy is a promising renewable energy resource in the Philippines. Employment of exclusion parameters with buffer spacing and cable length limitation resulted to possible potential tidal energy extraction for a proposed area of interest. The use of LCOE, total indicative power capacity, and bathymetry as decision criteria are clearly defined to identify the viable locations of device installation. Techno-economic assessment of tidal devices is performed in this study, and it found that Evopod E1000 has an indicative potential capacity of 0.14×10^6 kW located in Surigao del Norte Province. This capacity can supply the Province's projected requirement of 0.0544×10^6 kW. The excess generation of 0.0856×10^6 kW can be added to the grid to compensate for deficiency of supply. The promising LCOE value of Evopod E1000 would replace the conventional sources where it costs high as 0.53 $/kWh for the cost of energy production. Utilizing tidal energy would avoid greenhouse gas emissions and promote the use of clean technology. The use of actual measurements or tidal simulations at different locations to calibrate the synthetic velocity profile would improve the resulting LCOE values. It is also suggested that additional limitations on exclusion parameters shall provide more feasible locations that are presented in this study. Performing a multi-criteria decision analysis would deliver a better understanding, especially when it comes to suitability analysis. Also, greenhouse gas emission avoidance accounting would be an additional highlight in promoting the use of tidal energy as clean technology.

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