Numerical simulation of tides for the assessment of tidal in-stream energy in selected sites in the Philippines

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Abstract. The Philippines has an untapped potential of ocean renewable energy, and one of the appropriate tidal energy converters for the country is in-stream tidal energy. The archipelagic nature of the country along with its position between the Pacific Ocean and West Philippine Sea results in high tidal currents due to the narrow transitions between the two large bodies of water. This study aims to assess the potential in-stream energy in the Visayas-Mindanao region using numerical simulation. Using the Advanced Circulation Model (ADCIRC) in the modelling of tides, four (4) locations in the study area with the highest simulated depth-averaged current velocities are identified, namely, Liloan Port, Hilutungan Channel, Surigao Strait and Banug Strait. Among the selected stations, Banug Strait between the Islands of Bayagnan and Awasan produces the highest energy density of 253.2 kW-h/m². Using an 18-m diameter turbine, it is estimated to have a monthly energy output of 64.4 MW-h, which is estimated to support 260 households on average. The annual energy output of the said 18-m diameter turbine is 773.3 MW-h.

1. Introduction

Ocean renewable energy is targeted to produce 70.5 MW by 2030 in the Philippines, as stated by the Energy Act of 2008. However, as of 2019, the only ocean renewable energy being developed is the tidal in-stream plant located at San Bernardino Strait, which is expected to produce 3 MW and to be commissioned on 2024, and no other ocean renewable energy source is being developed in the near-future.

The majority of renewable energy, such as solar and wind, are both expensive to construct/install and hard to integrate with the existing electricity distribution system, because of their unpredictable behaviour and the distance of the energy farms to the demand as stated by Lewis et al. (2019). Tidal energy on the other hand is quite promising because of their low variability power output and high predictability, making them suitable for efficient energy production [1]. There are currently two ways of harnessing tidal energy: (1) in-stream, which uses turbines underwater harnessing energy from the velocity head of tidal currents; and (2) tidal barrages, which utilizes a man-made structure to create a head difference between the ebb and flood tide situated at estuaries. The archipelagic nature of the Philippines and its geographical location between the Pacific Ocean and West Philippine Sea results into high tidal currents, making tidal in-stream energy a significant energy source, with an estimated energy of ~200 GW, in which ~40-60 GW are estimated to be extractable [2]. The extractable in-stream energy, in the form of energy density, can be calculated by first obtaining the power density, computed using the equations:
where $p$ is the power density, $E_d$ is the energy density per swept-area of the turbine, $n$ is the efficiency of the turbine, $\rho$ is the fluid density (~1025 kg/m$^3$ for seawater), $V$ is the flow velocity in meter per second, and $t$ is in time.

Energy density represents the energy extractable per square meter of the swept-area of the turbine. The swept-area is the area that the rotor blades of the turbines spin if viewed directly from the front, facing the center of the blades.

The simulated velocities for a certain time series from the hydrodynamic model can be used in equations (1) and (2) to compute for the power and energy, respectively, at different points in time which can reflect the variability of the tidal currents through time. The computed power and energy for different points in time can be totalled in order to obtain the annual power and energy for each site.

The Philippine Department of Energy (DOE) identified eight (8) tidal energy potential sites in the country, namely, Bohol Strait, Basiao Channel, Surigao Strait, Gaboc Channel, Hinatuan Passage, San Bernardino Strait, Basilan Strait, and San Juanico Strait. This research aims to determine other potential sites not identified by DOE by estimating the extractable energy through numerical modelling.

Given that most of the tidal energy potential sites are located in Visayas, the study area is selected in this region as shown in Figure 1.

![Figure 1. Tidal Stations (black points) and Study Area](image)

2. Methodology

2.1. Tidal Data

Tide data from the National Mapping and Resource Information Authority (NAMRIA) are gathered for the calibration of the hydrodynamic model. The available tide data at Cebu and Surigao stations, shown in Figure 1 are used in the validation of the model.
2.2. Bathymetry Data
The major input for model generation is the bathymetric data from the General Bathymetric Charts of the Oceans (GEBCO) with a resolution of 15 seconds and is then used to create the Advanced Circulation (ADCIRC) hydrodynamic model for the study area.

2.3. Model Generation
The model that is used in the simulation of tides is the Advanced Circulation (ADCIRC) model developed by Leutitch and Westerink. It uses the continuity and momentum equations which are discretized using finite element method for space and finite difference method for time [3]. Specifically, ADCIRC-2DD1 is used, therefore the simulated velocities are depth-averaged velocities. The extent of the ADCIRC hydrodynamic model used in this study is presented in Figure 2. The model uses an unstructured computational mesh with a mesh resolution of around 200 m at the island boundaries and around 3-5 km at the ocean boundaries. The model has a total of 1,293,920 elements and 655,416 nodes, while the waterbody study area has a size of 70,638 km². The friction coefficient used is the generally accepted seabed Manning’s friction coefficient, which is 0.02, while the time step used is 2 seconds. For this study, the simulation timing has been set to December 1–31, 2018, so that the simulated tide can be compared with the actual recorded tidal data from NAMRIA for calibration.

2.4. Model Validation
The open ocean boundaries of the model were forced using tidal constituents K1, M2, N2, O1 and S2 available from the Le Provost tidal database for the Philippine Sea boundary and from the TPXO tidal database along the other ocean boundaries. The simulated tidal heights compared to the actual tidal heights for December 1 to 31, 2018 for both Surigao and Cebu stations shown in Figure 3 and Figure 4 resulted to a Root-Mean-Squared Error (RMSE) of 0.18 and 0.19 m, respectively, and an R-square of 0.8 for both.
3. Results and Discussion

From the results of the numerical simulation using ADCIRC, four (4) sites within the model domain (Figure 5) with tidal velocities greater than 0.5 m/s, were located. The locations are: Liloan Port for Point 1, Hilutungan Channel for Point 2, Surigao Strait for Point 3 and Banug Strait for Point 4.
Using equations (1) and (2), the simulated velocities for the selected four (4) sites can be used to solve the extractable monthly energy from these sites. The simulated velocities for the sites shown in Figure 5 is used to compute for the cumulative energy. For this research, the cut-in speed is assumed to be 0.5 m/s, where cut-in speed simply means that it is the minimum speed for the turbine to create any energy. The overall efficiency of the turbine is assumed to be 44.69% [4], which is estimated from the proposed turbines to be used in the San Bernardino Strait Tidal Stream Power Plant currently under development in the Philippines. The cumulative energy produced for the identified potential sites presented in Figure 6 shows that Banug Strait (Point 4) has the highest energy per square meter produced, with a value of 253.23 kW-h/m².

![Cumulative Energy Density (Wh/m²) Produced](image)

**Figure 6.** Cumulative Energy Produced for December 2018

Using an 18-meter diameter turbine, Banug Strait (Point 4) is computed to have a monthly energy output of 64.4 MW-h. Knowing that the monthly average energy demand of one household in the Philippines is 248.1 kW-h, then one 18 meter diameter turbine with overall efficiency of 44.69% can support 260 households on average for a month.

Preliminary estimation of cost per kW-h was conducted in addition to the computation of energy output of the selected four (4) sites. To do this, this study used the estimated cost of the San Bernardino Strait In-stream Tidal Power Plant which will install three 500-kW turbines at 1.2 billion Pesos (25 million US dollars) project cost. Based on the computed energy output of the selected 4 sites, the turbine power rating per location was specified. For example, the maximum simulated velocity in Banug Strait is 1.9 m/s producing 436 kW, therefore the turbine should only be rated at 400kW. Taking ratio and proportion of the power rating and cost of the San Bernardino Strait Power Plant, the estimated project costs for the selected 4 sites were calculated assuming three turbines will be used. Based on the computed energy output, the cost per kW-h of the 4 sites were estimated, as presented in Table 1. The capital recovery factor is computed as 0.1275 using a 12% recovery rate for a duration of 25 yrs. The lowest cost per kW-h is in Banug Strait. Using the power rate of the closest Province, the electricity at Surigao Del Norte is charged at 10.3 Php/kW-h as of May 2019. This is still lower as compared to the computed 17.60 Php/kW-h for Banug Strait which is estimated based on the capital cost only.
Table 1. Preliminary estimates of project cost and estimate cost per kW-h for the four identified potential sites

| Sites   | Locations          | Ideal Turbine Rating (kW) | Estimated Initial Project Cost (PhP) | Estimated Cost per kW-h (PhP/kWh) |
|---------|--------------------|---------------------------|-------------------------------------|----------------------------------|
| 1       | Liloan Port        | 100                       | 240,000,000                          | 29.44                            |
| 2       | Hilutungan Channel | 200                       | 480,000,000                          | 51.13                            |
| 3       | Surigao Strait     | 300                       | 720,000,000                          | 32.33                            |
| 4       | Banug Strait       | 400                       | 960,000,000                          | 17.60                            |

1Based on the estimated project cost of San Bernardino In-Stream Tidal Power Plant

4. Conclusion
The results of the study provide a quantitative view of the extractable energy in the study area as preliminary resource assessment. Given the four (4) highest tidal current velocity locations, it is Point 4, located between Bayagnan Island and Awasan Island at Banug Strait, that has the highest velocity values for in-stream tidal energy in the Surigao area based on ADCIRC tide simulations. The results show that the extractable monthly energy at this location is 64.4 MW-h using an 18-meter diameter (D18) turbine which could support 260 households on average. The D18 turbine annual electrical output for Banug Strait is computed to be 773.3 MW-h. Preliminary estimates of cost per kW-h of energy production show that tidal energy for the selected sites is still more expensive than existing power rates in Surigao. Nonetheless, this study shows that there is a promising tidal energy that could be extracted in Banug Strait near Surigao Province.

5. Recommendations
It is recommended to perform actual measurement of tidal currents for more accurate results. Further study should be conducted using 3D hydrodynamic modelling to be able to consider the varying velocities at different depths, as well as a longer simulation of the tides up to 1 year, to have a more accurate estimate of annual energy produced. It is also recommended to study other sites in the Philippines not considered in this research. A more in-depth study should be made in analysing the cost and benefits of tidal energy compared to existing non-renewable energy sources.

6. References
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