TIDAL IN-STREAM ENERGY RESOURCE AND CONVERSION DEVICE SUITABILITY ANALYSIS IN THE NORTHERN PHILIPPINES

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ABSTRACT: Because of the Philippines' archipelagic setting, there is a tremendous potential of extracting the country's future energy demands from the oceans. Ocean energy resources, however, are the least-explored forms of renewable energy in the country. Tidal current energy conversion, for instance, just recently started to draw interest in terms of R&D works due to the resource's reliability and predictability, and its similarity to the mature concept of wind energy conversion. This paper presents research being undertaken as part of project PhilSHORE, which shall cover performance suitability analysis of 20 existing tidal in-stream energy conversion (TISEC) devices in tidal sites in the northern Philippines. Resource assessment was first carried out by hydrodynamically simulating tide models in Delft 3D. Results were compared and validated against one-year hourly tide height data in five tidal stations from the International Hydrographic Organization (IHO). The model using bathymetry data from the General Bathymetric Chart of the Oceans (GEBCO) and the global tidal solution TPXO7.2 as inputs resulted to the highest R^2 value of 0.962. Results from said model were then used for site-device analysis. The 20 devices pre-identified in the study were adopted from the shortlisting of active TISEC developers made by the International Renewable Energy Agency (IRENA). A database of their operational characteristics was developed as basis for numerical computing. The suitability of the devices were assessed based on three factors: annual energy yield; capacity factor (CF); and availability factor (AF). One-year hourly velocity and energy density data from the hydrodynamic simulations were considered in the computations. Resulting energy density maps revealed that the top site is Luzon Strait, yielding an annual energy density of 2.60 MWh/m^2. On the otherhand, Deep Green exhibited the best suitability among 20 devices with an estimated 577 MWh annual energy yield, 13.14% CF and 65.78% AF in Luzon Strait.

1. INTRODUCTION

Being surrounded vastly by waters, the Philippine's current energy mix may be complimented by the energy that can be extracted from its oceans. However, ocean energy resource, like tidal current and wave energy, are the least-explored forms of renewable energy (RE) in the country [1]. Tidal energy resource assessment has recently drawn the interest of the Philippine government due to its huge potential in terms of providing decentralized energy options for last-mile communities within the archipelago and to compliment other viable RE sources like solar and wind.

A project called the "Tidal Current Energy Integrated Resource Assessment and Spatial Planning Tool," also known as PhilSHORE, was commissioned in 2014 to assess the tidal energy potential of the country and to design a multi-site, multi-device and multi-criteria decision support tool for the development of tidal current energy in the Philippines. The project is still on-going as of the writing of this paper and is expected to be completed by the end of 2016. This paper focuses on the site-device suitability analysis component as part of the research being undertaken for the project. Moreover, a quick background on hydrodynamic modelling component was discussed to give an overview on how the potential sites were selected for site-device suitability analysis.

2. METHODOLOGY

The general framework of the study is shown in Figure 1. A comprehensive survey of existing devices for tidal current energy conversion was first carried out and their operational characteristics were integrated into one database. After suitable tidal sites were identified, performance of the devices were analyzed by estimating and mapping out their energy yield, capacity and availability given a one-year velocity data in the identified sites. All numerical calculations and mapping are executed in MATLAB using pre-formulated computational scripts.

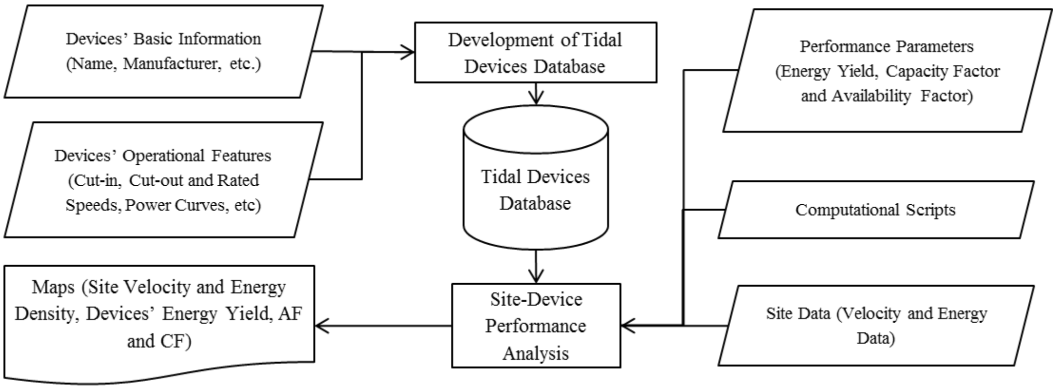

Figure 1. General Framework for Site-Device Analysis.

2.1 Identification of Sites for Analysis

Results from the hydrodynamic modelling component of the northern part of the country was chosen as case study for this paper. One-year energy density map (Figure 2) based from the GEBCO-TPXO 7.2 model was used to identify the preferred sites for analysis. The computational software Delft 3D Flow was utilized in simulating the behavior of the waters in Northern Luzon. Resulting data files were then imported to MATLAB for mathematical estimation of magnitude and direction of the instantaneous depth-averaged velocity, as well as the energy density on the site.

Sites for investigation were chosen according to two criteria: a) maximum annual available energy density, and b) proximity to islands (i.e. less than 10 km away from the nearest shore). Four sites were selected, namely: Luzon Strait #1; and sites near the islands of Dinem; Balintang; and Mavudis. Luzon. Strait #1 is 23.8km away from the nearest coast but was especially considered because it has the highest available energy density within the domain. Table 1 summarizes the characteristics of these sites.

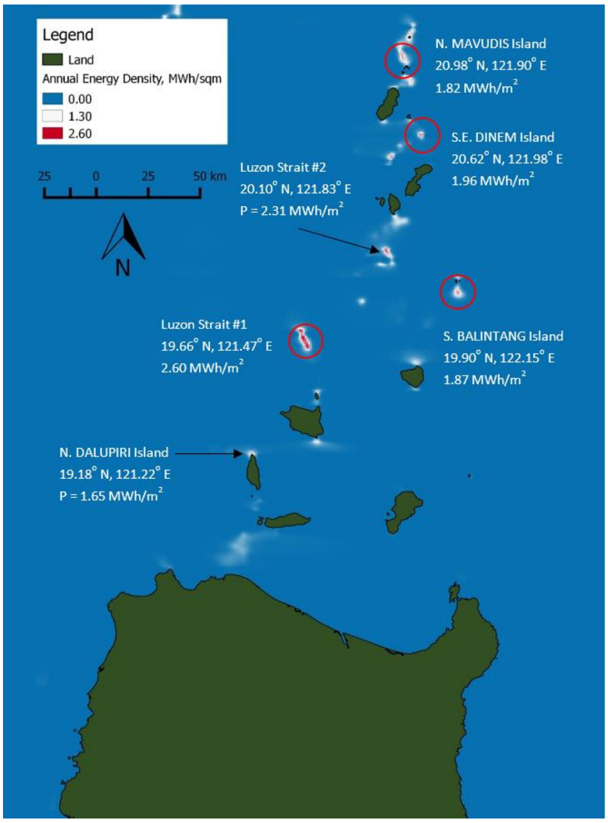

Figure 2. Available Energy Density Map Based from the GEBCO-TPXO 7.2 Model.

Table 1. Summary of Annual Energy Density and Location of the Selected Sites.

Site	Name	Latitude	Longitude	Distance to nearest coastline (km)	Annual Available Energy Density (Wh/m^2)
1	Luzon Strait #1	19.6637	121.4703	23.80	2,603,333.11
2	S.E. Dinem Island	20.6231	121.9808	9.23	1,963,956.53
3	S. Balintang Island	19.9019	122.1490	5.33	1,869,351.94
4	N. Mavudis Island	20.9827	121.8996	5.50	1,818,519.40

2.2 Development of TISEC Devices Database

The database of TISEC devices was developed through a comprehensive survey of existing tidal technologies. Since the goal of this study is to assess the performance of devices when subjected to the identified sites, their operational characteristics (i.e. cut-in speed, cut-out speed, rated speed, rated power, capture area, water-to-wire efficiency and power curves) were essentially surveyed. Economic characteristics of devices could have been a good criterion to facilitate cost comparison among the different devices but was shelved in this study due to lack of financial data of most devices. Results of the technology survey conducted are summarized in Table 2. Moreover, the pre-identified devices in this list were based on a shortlisting of active tidal device developers made by the International Renewable Energy Agency (IRENA) [2,3].

Table 2. Summary of Operational Data of the TISEC Devices.

Device Name	Rated Power (kW)	Rated Speed (m/s)	Cut-in Speed (m/s)	Cut-out Speed (m/s)	Company	Ref
HS1000	1,500	3.00	1.10	4.60	Hammerfest Strøm	[4]
AR1000	1,000	3.00	0.60	4.50	Atlantis Resources Corporation	[5]
MCTSeagen	2,500	3.00	0.70	4.00	Siemens/Marine Current Turbines	[6]
CorMat	500	3.00	1.00	3.50	Nautricity	[5]
EvopodE35	35	2.00	0.70	3.20	Oceanflow Energy Limited	[5]
EvopodE1000	1,000	4.00	0.70	4.20	Oceanflow Energy Limited	[5]
OpenCenter	250	3.00	0.70	4.00	OpenHydro	[27]
TocardoT100	43	2.00	0.40	4.00	Tocardo International BV	[5]
TocardoT200	87	2.00	0.40	4.00	Tocardo International BV	[5]
KPHS5mDia	85	3.00	0.70	4.00	Veradant Power, Inc.	[5]
KPHS10mDia	500	3.00	0.70	4.00	Veradant Power, Inc.	[5]
HyTide	500	3.00	1.00	5.00	Voith Hydro Ocean Current Technologies	[5]
SIT3m	70	4.00	0.90	6.75	Schottel Hydro	[5,6]
SIT4m	62	3.00	0.80	6.00	Schottel Hydro	[5,6]
SIT5m	54	3.00	0.70	4.60	Schottel Hydro	[5,6]
DeepGreen	500	2.00	0.50	4.00	Minesto AB	[7]
CC050A	125	3.00	1.00	4.10	Clean Current Power Systems, Inc.	[8]
ENCO25F4	25	3.00	1.50	4.00	New Energy Corporation, Inc.	[9]
ENCO10F4	10	3.00	1.50	4.00	New Energy Corporation, Inc.	[10]
ENCO05F4	5	3.00	1.50	4.00	New Energy Corporation, Inc.	[11]

Identified devices are mostly axial-flow turbines except the Deep Green (Minesto AB) and the ENCO devices (New Energy Corporation, Inc). The Deep Green device involves a tethered underwater kite with an attached axial-flow turbine [7]. Meanwhile, the ENCO devices are cross-flow turbines [11].

2.3 Site-Device Suitability Analysis

There are several criteria that can be used as reference in decision-making for site-device suitability analysis as suggested by Abundo, M. (2012) [12]. These are: the devices' technical (energy yield, capacity and availability factors), economic (relative levelized cost of energy) and environmental (significant impact factor) characteristics. The suitability of each device can be determined by assigning suitability scores based on these criteria. This paper considers only the technical criteria and the following detailed the quantitative estimation of each criterion.

Energy Yield (Annual). As shown in Figure 1, the power output of a device subjected to the resource at hand is calculated for different regions of operation (before cut-in speed, between cut-in and rated speed, between rated and cut-out speed, and at cut-out speed and beyond). Annual energy yield is just the summation of hourly power outputs for the location with the corresponding device for one year. The data file containing hourly depth-averaged velocities from hydrodynamic modelling for 8784 hours or 1 year was used as an input series to calculate the power generated using the equations below. Total energy produced by the device/power plant over a given period:

$$E = \sum Power_T(t) \tag{1}$$

$$Power_T\ (t) = \begin{cases} zero, U(t) < U_{cut-in} \\ \frac{1}{2}\rho\eta A(U(t))^3,\ U_{cut-in} < U(t) < U_{rated} \\ Power_{rated}, U_{rated} < U(t) < U_{cut-out} \\ zero, U(t) \geq U_{cut-in} \end{cases}, \tag{2}$$

where P_T is the turbine power, ρ is the fluid density, η is the device efficiency, A = swept area, U = velocity.

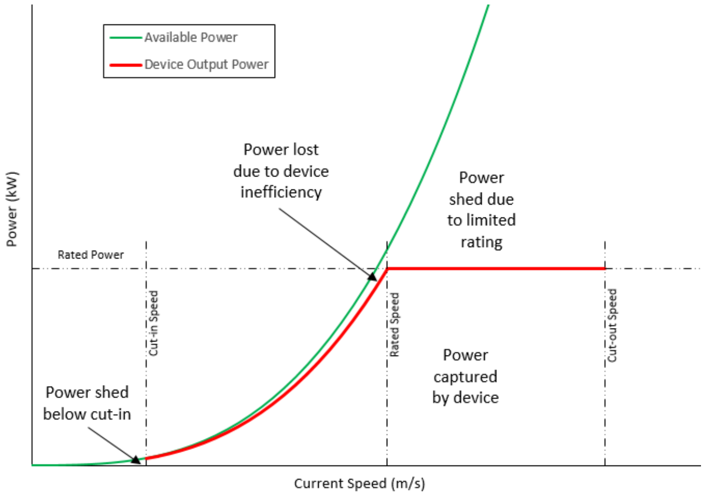

Figure 1. Example of a Tidal In-Stream Energy Conversion Device Power Curve.

Capacity Factor (CF). The percentage of actual energy produced during the period covered, versus the total energy that could have been produced if the power plant (P_T) was operating at rated power (P_{Trated}) during available times of operation. CF can be estimated using the equation below.

$$CF = \frac{\sum P_T(t)}{\sum P_{T_{rated}}(t)} \tag{3}$$

Availability Factor (AF). The ratio of the total number of operating time (when $U_{cut-in} < U(t) < U_{cut-out}$) and the total time.

The above technical parameters were computed using MATLAB-based scripts and were outputted as maps for visualization and analysis.

3. DISCUSSION OF RESULTS

3.1 Tidal Current Conditions in the Selected Sites

Figure 4 shows the histogram of velocity for the four selected sites. It was noted that Luzon Strait #1 has the highest annual available energy (refer to Table 1). While this site has the lowest occurrences of velocities below 0.8 m/s compared to the three other sites as shown in Figure 4, it's frequency of velocities from 0.81 m/s to 1.0 m/s is second to the S.E. Dinem Island site. For velocities above 1.01 m/s, on the other hand, Luzon Strait #1 has the highest frequency among all sites. All 4 sites have a similar general trend where the highest frequency of velocities are within the range of 0.41-1.00 m/s.

Moreover, current direction diagrams are also shown in Figure 4. Tidal current for all sites generally run through the East-West directions.

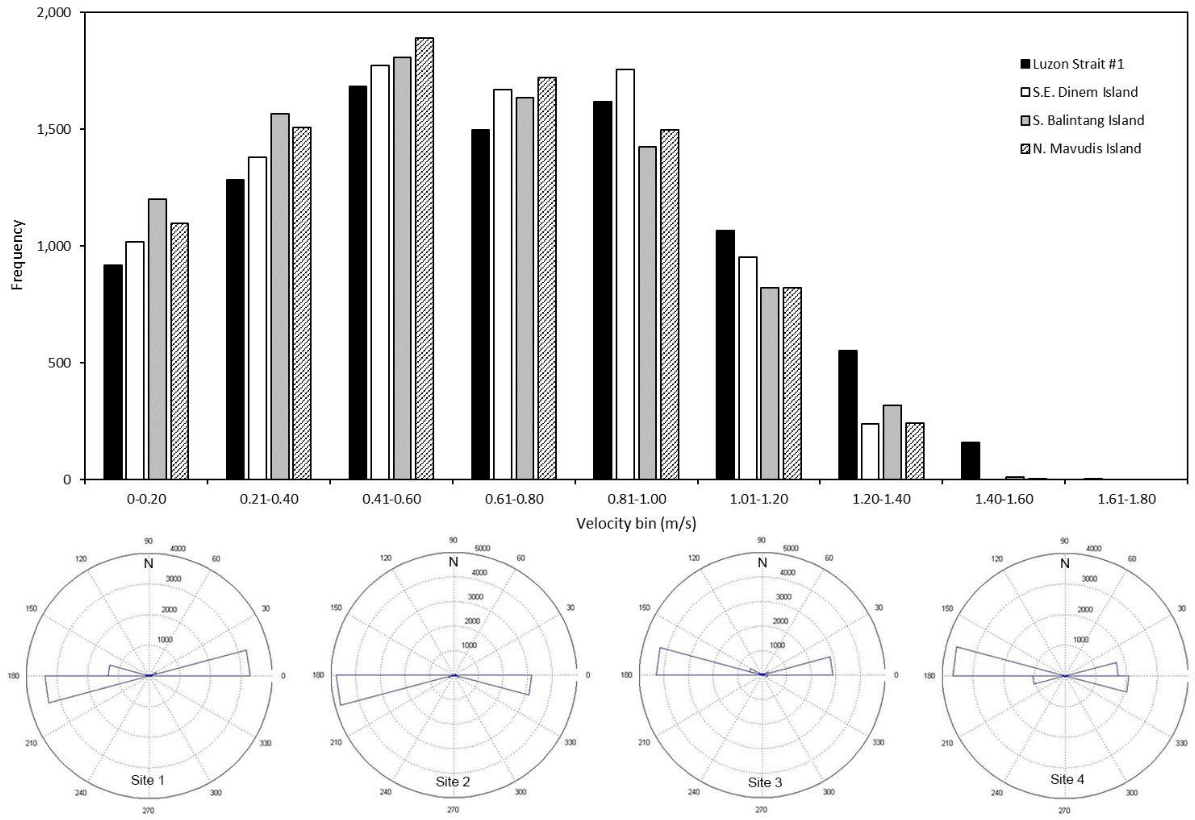

Figure 4. One Year Velocity Histogram and Direction Diagrams at the 4 Selected Sites.

3.2 Devices' Performance Analysis in the Selected Sites

Luzon Strait #1. Figure 5 shows the annual energy yield of the 20 devices for Site 1. The devices can be grouped by power rating and outstanding performances for each group can be identified. For devices with less than 500 kW power rating, the Open Center device by Open Hydro stands out for its highest energy conversion among the group. For devices with a 500 kW rating, the DeepGreen device by Minesto AB exceeded the 3 other devices in energy conversion. The Seagen device by Marine Current Turbines, meanwhile, is noted also for its highest energy conversion among devices with a rating of at least 1,000 kW.

Figure 6 shows the capacity factors of the devices arranged in decreasing order of rated power. We note here the unusual spike in capacity factors for DeepGreen (500 kW), Tocardo T200 (87 kW) and Tocardo T100 (43 kW). While the Tocardo devices seemed unremarkable in terms of annual energy yield as presented in Figure 5, their capacity and availability factors (Figure 6 & Figure 7) highly exceeded those of other devices, except for DeepGreen.

The availability factor is dependent to the device's cut-in speed. A device with a lower cut-in speed allows higher availability than those with higher cut-in speeds specifically in sites with relatively low tidal current velocities. We may note from the tidal current velocity histogram as shown in Figure 4 that site 1 has velocities greater than 1.41 m/s to be in its extreme tail-end. This is why the ENCO turbines (crossflow turbines) have extremely low availability factors due to their high cut-in speeds of 1.5 m/s (see Table 2 and Figure 7). The sharp deviation in capacity factors of DeepGreen and Ocean Center is also noted in Figure 7.

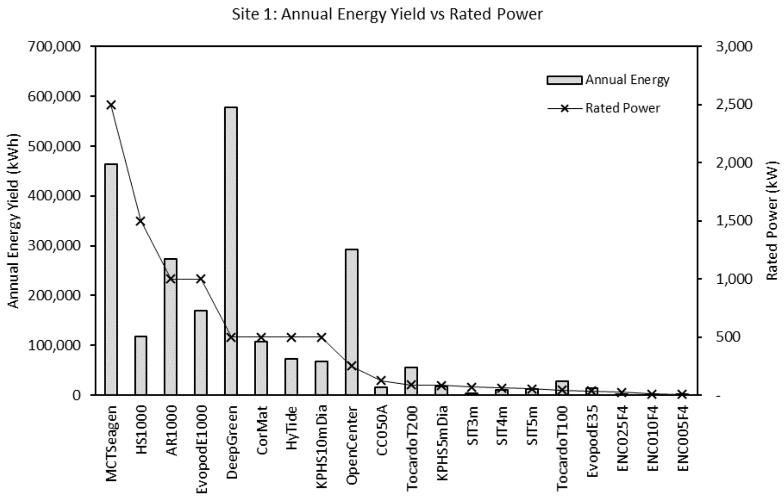

Figure 5. Annual Energy Yield in Site 1 and Rated Power of the 20 Devices.

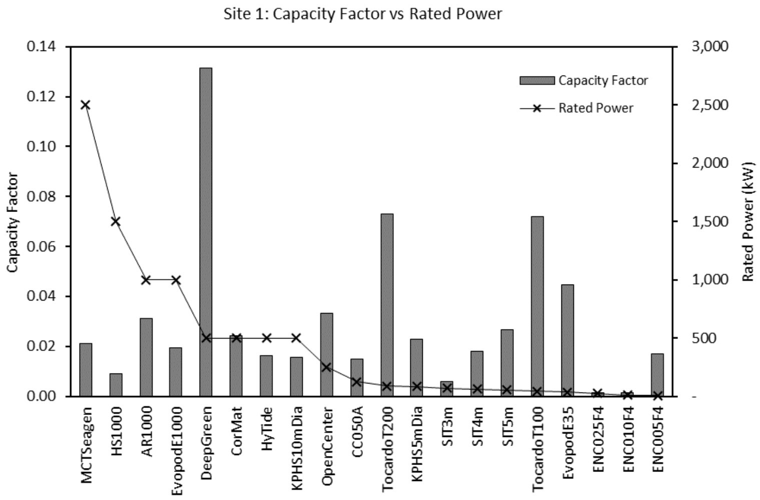

Figure 6. Capacity Factor in Site 1 and Rated Power of the 20 Devices.

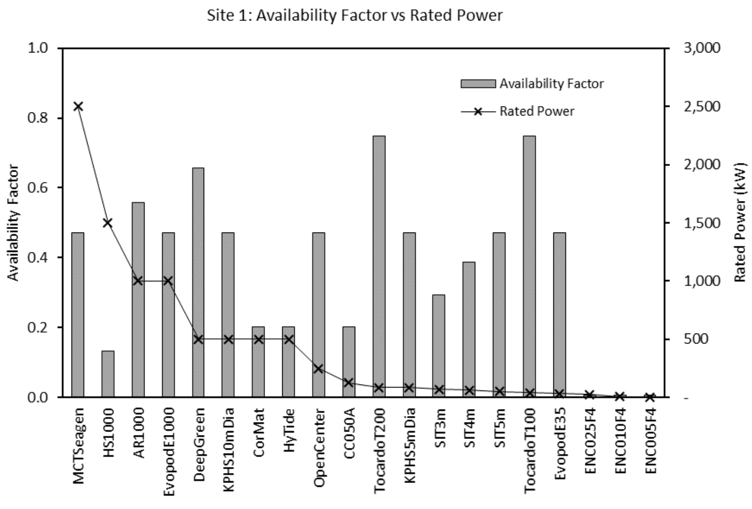

Figure 7. Availability Factor in Site 1 and Rated Power of the 20 Devices.

Table 3. Performance Parameters of the Top 3 Devices for Luzon Strait #1.

Device Name	Rated Power (kW)	Rated Speed (m/s)	Cut-in Speed (m/s)	Cut-out Speed (m/s)	Annual Energy Yield (kWh)	CF	AF
Deep Green	500	2.00	0.50	4.00	577,104	13.14 %	65.78 %
TocardoT200	87	2.00	0.40	4.00	55,797	7.30 %	74.94 %
TocardoT100	43	2.00	0.40	4.00	27,177	7.20 %	74.94 %

The results indicate that DeepGreen (500 kW) is the most suitable device for the site Luzon Strait #1 for maximum tidal energy conversion. The two (2) Tocardo devices will also provide optimum energy conversion at lower capacities. The choice for the most appropriate device depends on the intended energy use (capacity required) from the site's tidal energy and the cost of the project development. Table 3 summarizes the specifications and the performance parameters of these 3 devices in Site 1. Figures 8 shows the energy yield maps for the 3 chosen devices.

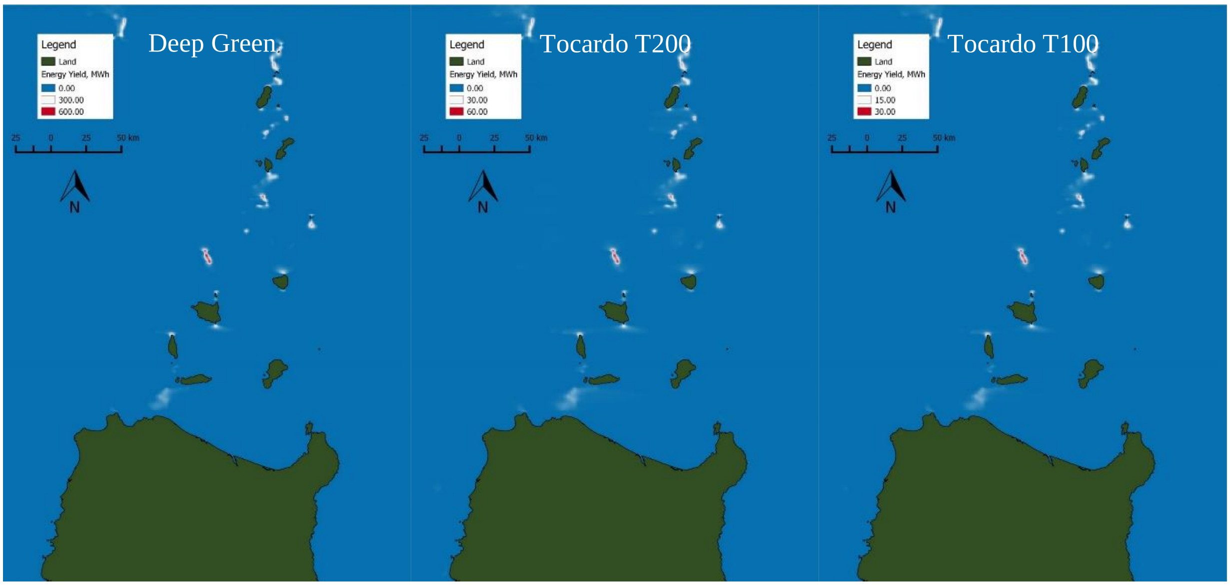

Figure 8. Annual Energy Yield Maps of the 3 Preferred Devices for Site 1.

Sites 2,3 and 4. The output and performance characteristics for the devices in the 3 other sites are shown in Figures 9 to 11. As summarized in Table 2, Site 2 in S.E. Dinem Island, Site 3 in S. Balintang and Site 4 in N. Mavudis Island yield annual energy densities of 1.96 MWh/m2, 1.87 MWh/m2 and 1.82 MWh/m2, respectively.

Similar to the results for site 1 in Luzon Strait #1, the DeepGreen device yields the highest amount of energy for all sites, outperforming all devices of different power rating. Figure 9 (first column) shows this with the devices ranked according to decreasing order of power rating. The OpenCenter and Tocardo T200 also exhibit superior energy yield with respect to devices with rating of less than 500 kW.

DeepGreen exhibits the best capacity factor, followed by Tocardo T200 and T100, across all sites. Meanwhile, the devices with the top 3 availability factors, from highest to lowest, are the Tocardo T200, Tocardo T100 and DeepGreen across sites 2, 3 and 4.

The performance trends of the devices for sites 2, 3 and 4 are similar to their performance in site 1, as previously discussed, with the top best devices in all sites and in order as DeepGreen, Tocardo T200 and Tocardo T100. Table 4.7 summarizes these performance parameters for all sites.

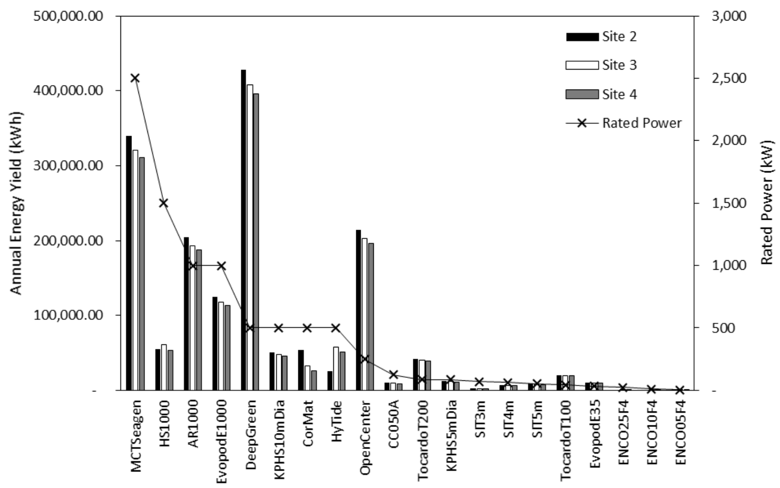

Figure 9. Annual Energy Yield in Sites 2 to 4 and Rated Power of the 20 Devices.

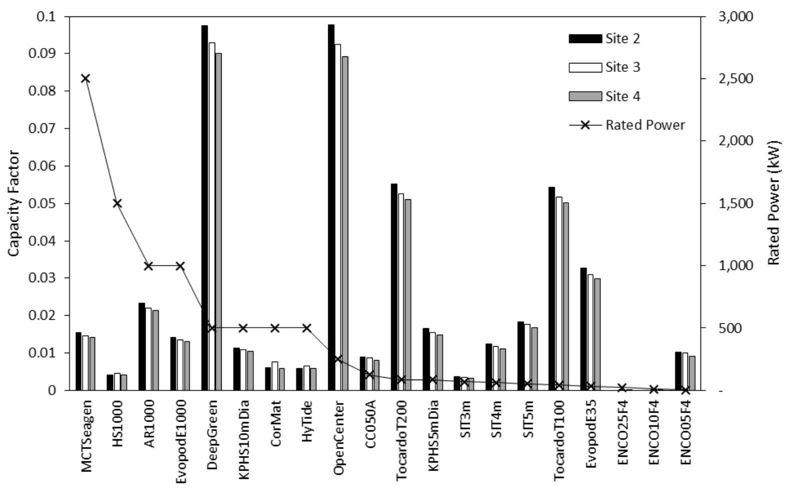

Figure 10. Capacity Factor in Sites 2 to 4 and Rated Power of the 20 Devices.

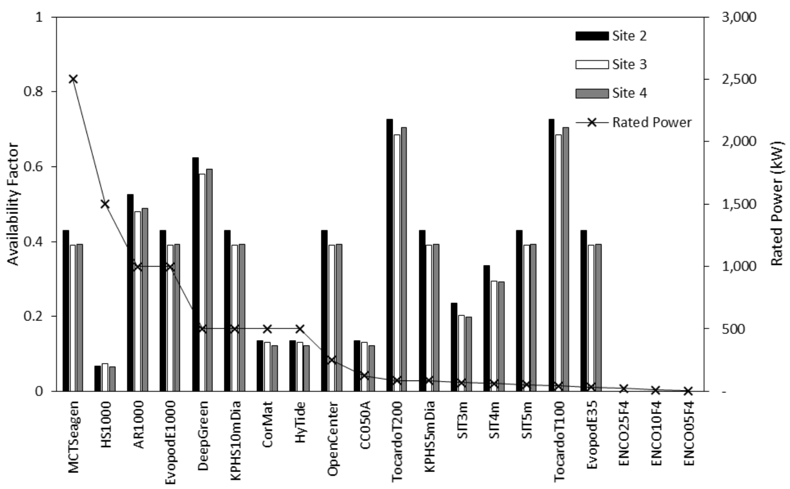

Figure 11. Availability Factor in Sites 2 to 4 and Rated Power of the 20 Devices.

Table **Error! No text of specified style in document.**.1 Performance Parameters of the Top 3 Devices for Each Chosen Site.

Site	Device Name	Rated Power (kW)	Rated Speed (m/s)	Cut-in Speed (m/s)	Cut-out Speed (m/s)	Annual Energy Yield (kWh)	CF	AF
1	Deep Green	500	2.00	0.50	4.00	577,104	13.14 %	65.78 %
	TocardoT200	87	2.00	0.40	4.00	55,797	7.30 %	74.94 %
	TocardoT100	43	2.00	0.40	4.00	27,177	7.20 %	74.94 %
2	Deep Green	500	2.00	0.50	4.00	427,927	9.74 %	65.78 %
	TocardoT200	87	2.00	0.40	4.00	42,176	7.30 %	74.94 %
	TocardoT100	43	2.00	0.40	4.00	20,494	7.20 %	74.94 %
3	Deep Green	500	2.00	0.50	4.00	407,687	9.28%	58.04%
	TocardoT200	87	2.00	0.40	4.00	40,144	5.25%	68.52%
	TocardoT100	43	2.00	0.40	4.00	19,497	5.16%	68.52%
4	Deep Green	500	2.00	0.50	4.00	395,354	9.00%	59.38%
	TocardoT200	87	2.00	0.40	4.00	39,066	5.11%	70.34%
	TocardoT100	43	2.00	0.40	4.00	18,972	5.02%	70.34%

4. SUMMARY AND CONCLUSION

The available annual energy density map for Northern Luzon, which was generated based from hydrodynamically simulating GEBCO-TPXO 7.2 model, was used in the study to identify sites that may be suitable for tidal development. These sites for investigation were chosen according to their annual energy density and proximity to islands. The site Luzon Strait #1 exhibited the highest annual available energy (2.60 MWh/m2) within the domain. The other three sites, namely, S.E. Dinem Island (1.96 MWh/m2), S. Balintang Island (1.87 MWh/m2) and N. Mavudis Island (1.82 MWh/m2) were the top 3 high energy density sites that have close proximity to islands. These four sites were chosen for resource-device suitability analysis. There were 20 tidal energy extraction devices investigated for the chosen sites. Common to all four sites, the emerging top devices suitable for the available resource are the Deep Green (500kW), Tocardo T200 (87kW) and Tocardo T100 (43kW). The Deep Green device exhibited a range of 9.00-13.14% CF for the 4 sites and an energy yield of 577 MWh for the site Luzon Strait #1. Tocardo T200 and Tocardo T100 exhibited the CF ranges of 5.11-7.30% and 5.02-7.20%, respectively. Their one-year energy yield for Luzon Strait #1 are 56 MWh and 27 MWh, respectively.

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] O. D. G. De Luna, “Hydrodynamic Modeling and Resource-Device Suitability Analysisof Northern Luzon for Tidal Stream Energy Resource Assessment.” University of the Philippines Diliman, 2016.
[2] R. Kempener and F. Neumann, “Tidal Energy Technology Brief,” International Renewable Energy Agency, 2014.
[3] L. Mofor, J. Goldsmith and F. Jones, “Ocean Energy Technology Readiness, Patents, Deployment Status and Outlook,” International Renewable Energy Agency, 2014.
[4] Stein Andersen, Andritz hydro Hammerfest: Email Correspondence (stein.andersen@andritz.com), February 23, 2015.
[5] D. Vennetti, "Technology survey for renewable energy integrated to bridge constructions: Wave and tidal energy," Tech. Rep. No. 109, 2012.
[6] R. Bedard, "Survey and Characterization: Tidal In-Stream Energy Conversion (TISEC) Devices," EPRI, USA, TP-004-NA, 2005.
[7] Anders Jansson, Minesto AB: Email correspondence (anders.jansson@minesto.com), January 19, 2015.
[8] Stothers, Russel, Clean Current Power Systems, Inc.: Email correspondence (russel.stothers@cleancurrent.com), December 9, 2014.

[9] "New Energy Corporation," [Online]. Available: http://www.newenergycorp.ca/Portals/0/documents/ datasheets/ ENC.025.DataSheet.pdf. [Accessed 10 December 2014].
[10] "New Energy Corporation," [Online]. Available: http://www.newenergycorp.ca/Portals/0/documents/ datasheets/ENC.005.010.DataSheet.pdf. [Accessed 10 December 2014].
[11] "New Energy Corporation," [Online]. Available: http://www.newenergycorp.ca/Portals/0/documents/ datasheets/ENC.005.010.DataSheet.pdf. [Accessed 12 December 2014].
[12] L. S. M. Abundo, "Integrated Tidal Resource Investigation , Device , and Energy Tool (TRIDEnT) for Multi-Site , Multi-Device Evaluation of Tidal In-Stream Energy," University of the Philippines Diliman, 2012.