Tidal energy assessment with hydrodynamic modelling

Imran Ali[1], Andrew Ragai Henry Rigit[2], Omar bin Yaakob[3,4], Jane Labadin[5], Altaf Hussain Rajpar[6]
[1]Department of Electrical and Electronic Engineering, Universiti Malaysia Sarawak, Samarahan, Malaysia
[2]Department of Mechanical and Manufacturing Engineering, Universiti Malaysia Sarawak, Samarahan, Malaysia
[3]Marine Technology Centre, Universiti Teknologi Malaysia, Skudai, Malaysia
[4]School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Malaysia
[5]Institute of Social Informatics and Technological Innovations, Universiti Malaysia Sarawak, Samarahan, Malaysia
[6]Department of Mechanical Engineering, College of Engineering, Jouf University, Sakaka, Saudi Arabia

Article Info

Article history:

Received Feb 9, 2022
Revised Oct 11, 2022
Accepted Nov 3, 2022

Keywords:

Delft3D
Hydrodynamic modelling
Malaysia
Renewable energy
Tidal energy

ABSTRACT

The increasing demand for sustainable energy generation brings a need for tidal current energy resource exploration around the globe. Hydrodynamic modelling is an essential aspect to explore macro tidal sites. In the current research paper, a 2D hydrodynamic model is set up by utilizing the numerical application of Delft3D. The model is validated against the database results and the two macro tidal sites are identified along the coastline of Sarawak, Malaysia. The maximum available kinetic energy flux at the identified location is 0.6 kW/m2, during peak neap tide hours. This stands as a sound justification to have a detailed tidal energy assessment study in this area in future research.

Corresponding Author:

Imran Ali
Department of Electrical and Electronics Engneering, Universiti Malaysia Sarawak
Kota Samarahan, Sarawak, Malaysia
Email: 19020069@siswa.unimas.my

1. INTRODUCTION

Increasing concerns about sustainable energy generation have triggered considerable advancement in the tidal stream industry. The tidal stream industry is in the initial stage of converting the full-scale tested prototypes to a commercial level, therefore the planning of tidal stream sites needs to follow a strategy to maximize their potential [1]. Among the marine renewable energies, tidal stream, as well as tidal range technology, are the most promising renewable sources due to their highly predictable potential [2], [3]. Because of the increased prediction and accuracy rate of the tides, the output power of a particular tidal power plant is also highly predictable, which is an essential parameter in the cost-benefit evaluation phase. Compared to wind energy generation, the tidal stream flow highly depends upon the phases of the moon, and sun, and therefore tidal power prediction is comparatively more accurate [4]. Furthermore, the density of seawater is almost 800 times higher than the density of air, in this way the power generation by a Tidal energy converter (TEC) will be higher than the wind machine at an appropriate rated speed. Moreover, the extreme velocity of the wind can damage the wind machines, however, the TECs do not incorporate such damage because of the absence of extreme tidal flow velocities. Apart from the advantages of tidal stream technologies, they can lay minor negative impacts on the marine environment. The major drawbacks include the impact on the biota at the plant site, morphodynamics, and sediment transport. It is therefore important to have a detailed impact assessment before selecting the tidal stream energy site.

2. LITERATURE REVIEW

Oceans around the world possess a huge potential to harness clean energy and take a great part in the decarbonization of energy systems. The tidal power potential was theoretically computed to be approximately 7800 TWh/year worldwide [5]. A large segment of such a potential is yet to be explored. It is estimated by the year 2050, a cumulative replacement CO2 emissions can be reduced by 1.0 billion tonnes thereby generating 337 GW of clean energy from waves and tides [3]. Marine energy utilization contributes to the sustainable energy supply of the world. In the early stage installed marine energy capacity, considering wave and tidal energy from the year 2000 to 2010, Europe was dominant with an installed capacity of 241 MW, covering 91% of the World's installed marine energy capacity, as shown in Figure 1 [6]. Whereas, share from North America and Asia was 20 MW (7.5%) and 4.5 MW (1.8%), respectively. Afterward, there is no such remarkable progress in the installation of marine energy systems in Europe from the year 2010 to 2016. There was a cumulative addition of 6 MW only during that period, and hence decreasing its Worldwide share from 91% to 46% [6]. However, considerable growth in installed capacity can be seen in Asia, which increased from 4.5 MW to 262 MW, being dominant to have 49% share in the world's installed marine energy capacity [6]. Such a huge increase in installed capacity share in Asia is mainly because the Sihwal Lake Tidal power plant was commissioned in the vicinity of Seol, South Korea in 2011. Afterward, the number of marine projects are being promoted and supported by the Korean government due to its geographical location to receive the abundance of tidal flow from its three sites. It is estimated that tidal current energy resources along the southwest coast can generate up to 1000 MW of clean power production [7]. There has been continuous progress in research and innovation to bring advancements in Marine renewable energy, in parallel with other renewable energy sources.

Technological advancement of marine energy systems is the key feature to bring it to the commercial level. Marine energy researchers have tried their best to bring innovation in marine energy technology at an appreciatable level when considering other renewable energy systems, which can be seen from the number of patents filed worldwide in Figure 2. The majority of the patents for renewable energy systems are solar-based energy systems [6]. However, the maximum number of patents filed in marine energy was 1,533 in the year 2010 with an increase in relative change of 552%. The majority of the patents filed for renewable energy systems were from China, covering 66.6% of the total filed patents in the year 2016 [6]. The majority of the countries abundant with tidal current and the ocean current potential include South Korea, China, Norway, France, Canada, Australia, New Zealand, India, the Russi, the UK, and the USA [8]. However, other countries such as Malaysia, Spain, Taiwan, Indonesia, and Iran also have tidal current energy sites from where a significant amount of tidal energy can be generated [5], [9]–[11]. The considerable attention has been given for research in tidal energy exploration in these countries, and the new sites are explored for TEC installation and sea trials.

China is dominant to have an abundance of tidal stream energy generation sources in Asia. Having some of the tidal energy sites to be observed with tidal current speed more than 3.06 m/s while the majority in the range 2.06 to 3.06 m/s, China is estimated to generate about 61.3 TWh/year of energy [12].

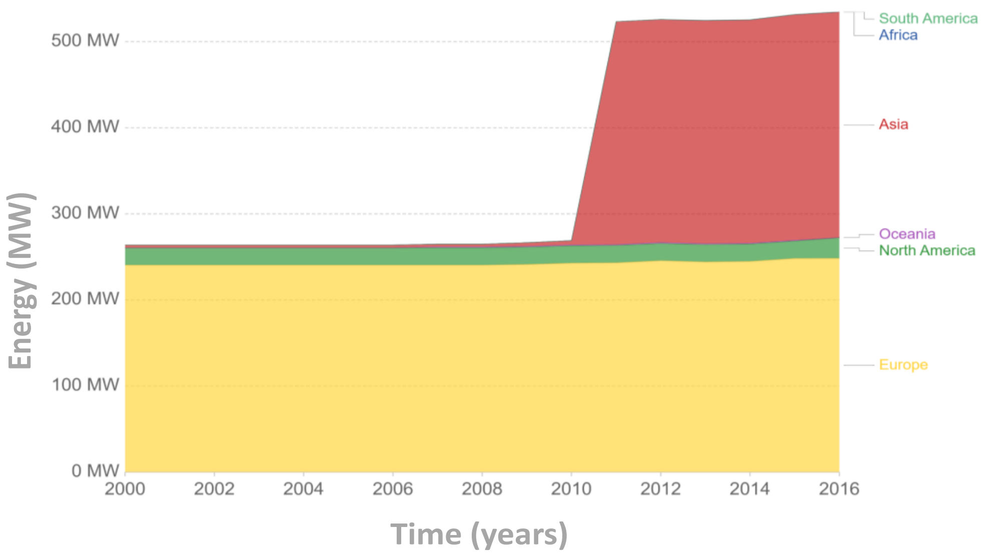


Figure 1. Marine energy capacity installed worldwide from the year 2000 to 2016 [6]

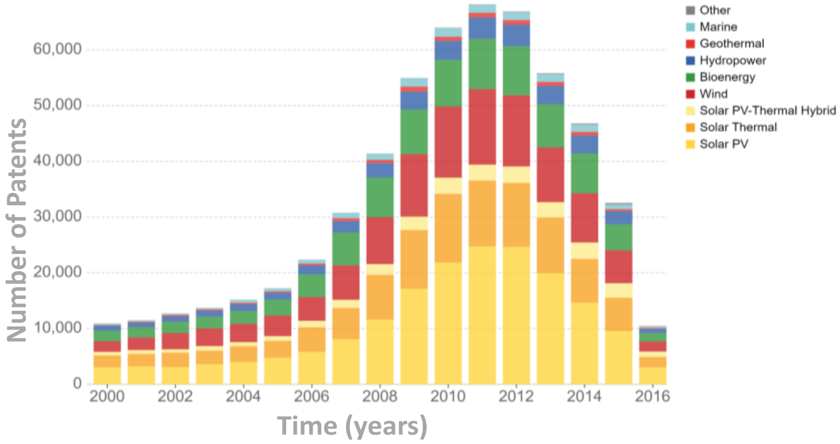


Figure 2. The number of patents filed in the World for renewable energy systems from the year 2000 to 2016 [6]

2.1. Tidal energy prospect in the Northern Indian Ocean

The Nothern Indian Ocean is divided into two seas namely the Arabian sea and the Bay of Bengal. It is shared by some of the South Asian countries including Myanmar, Bangladesh, India, Sri Lanka, Maldives, Pakistan, Iran, Oman, Yemen, and Somalia [13]. However, this section is focused to discuss the tidal energy prospect of Bangladesh, India, Pakistan, and Srilanka, as indicated by the boundary line in Figure 3. The Indian ocean is mainly distinguished due to the reversed monsoon season and ocean currents [14], [15]. The surface ocean currents prediction is shown in Figure 3, covering the portion of the Bangladesh and the Arabian Sea that is in the vicinity of India.

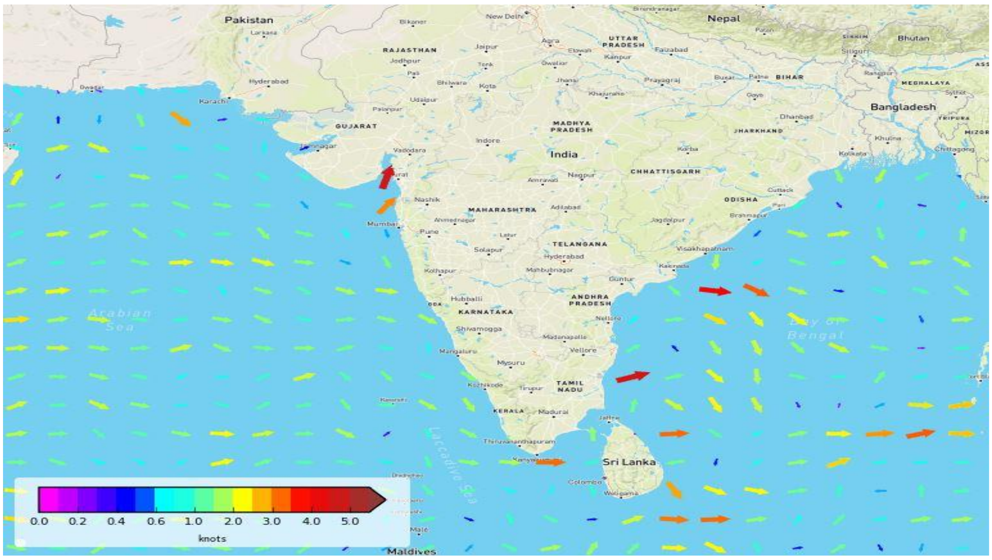


Figure 3. The surface current speed in knots in the Northern Indian Ocean is predicted on 14th June 2021

From the appraisal in Figure 3, Sri Lanka is noted to be the most dominant to have the potential tidal current. The sea surface current speed ranges 4 to 5 knots during the different times of a neap tide along all of its coastline. Whereas the main sites for India include the sites close to Tamil Nadu, Machlipatnam, Brahmagiri, and Surat, in these locations, the surface current speed up to 5 knots was noted during the neap tide on 14th June 2021. However, the potential sites can be further investigated by developing hydrodynamic models for these locations. In Pakistan, the tidal site near Karachi was observed to have a surface current speed of 3 knots.

Prediction for the wave height is shown in Figure 4. The wave energy is dissipated slowly over a very long distance from its origin. The distribution of wave heights in Figure 4 also reflects the patterns of wind in the Northern Indian ocean. The energy dissipated by the waves undergoes daily as well as seasonal variations, as it is originated from the wind [16]. It is clear from Figure 4, that the majority of the Indian coastline is dominant with a wave height of around 3 m. Although the waves are originated due to wind, wave power is still more predictable than wind energy generation [17]. Wave energy density is measured in kW/m which stands for the energy density per wave crest. A typical wave energy converter is optimized for the energy density ranges from 15 to 35 kW/m, whereas 20 kw/m is considered as a feasible site [18]. However, in tidal current-based energy generation, the tidal current speed of 1 to 1.5 m/s can be regarded as a good potential site [19].

A detailed hydrodynamic study can be carried out along the coastline of India to identify the exact locations to be the potential tidal current energy sites. Tidal energy development also needs the support of government officials and policymakers. Most countries with remarkable progress in tidal energy generation have set targets for renewable and ocean energy generation, to promote tidal energy development.

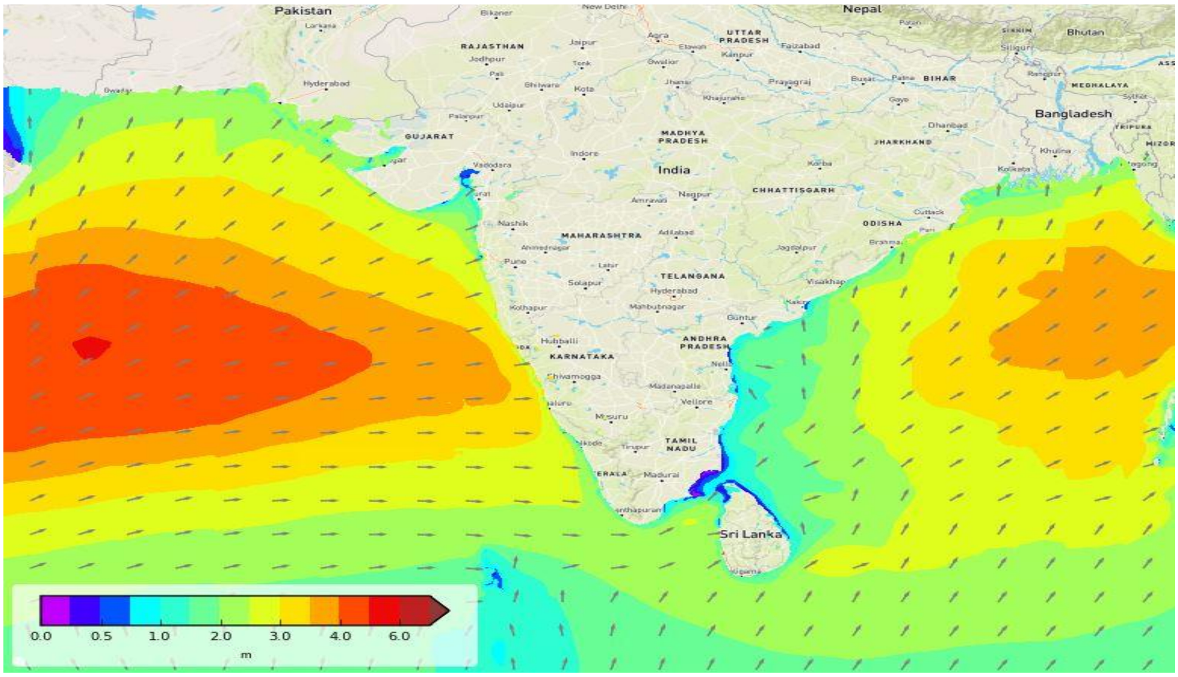


Figure 4. The wave height in the Northern Indian Ocean is predicted on 14th June 2021

3. HYDRODYNAMIC MODELLING FOR TIDAL ENERGY EXTRACTION

Hydrodynamic modeling for a particular location is accomplished using numerical models suchlike POM, Mike 21, and TELEMAC. However, for tidal energy assessment, Delft3D is widely used by the research community to solve the hydrodynamic problem with high resolution [1], [9], [10], [20]–[23]. The software is originally developed by Delft Hydraulics, and it is an open-source code freely available for everyone to use for academic studies. It solves the shallow water equations, by discretizing the model area that is covered by the curvilinear grid. For the batter result, the constructed grid should be well structured and well orthogonalized. The flow is mainly described by the two main variables namely water level and velocity. The density/pressure points (i.e water level points) are assigned at the center of each grid cell, whereas velocity is assigned perpendicular to grid sides. Such arrangement of the orthogonal physical quantities in a computational grid is called Arakawa C-grid (Delft3D). The time step condition to integrate the shallow water equation on the orthogonal grid can be computed based on the Courant number, which is expressed in (1) [24].

$$CFL_{wave} = 2\Delta t\sqrt{gH}\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}} < 1 \quad (1)$$

In the above equation, the time step is represented by $\mathbf{\Delta t}$, and **H** represents the total water depth, **g** denotes gravitational acceleration, and $\mathbf{\Delta x}$ and $\mathbf{\Delta y}$ stand for smallest grid distances [24].

To solve the shallow water equations for a hydrodynamic problem, the incompressible fluid is assumed during the simulation. The continuity and momentum equations solved by Delft3D-FLOW for a hydrodynamic problem are given below (Delft3D).

$$\frac{\partial \xi}{\partial t} + \frac{\partial[(d+\xi)U]}{\partial x} + \frac{\partial[(d+\xi)V]}{\partial y} = Q \quad (2)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - f \cdot V = -g\frac{\partial \xi}{\partial x} - \frac{g}{\rho_\circ}\int_{-d}^{\xi}\frac{\partial \rho'}{\partial x}dz + \frac{\tau_{sx}-\tau_{bx}}{\rho_\circ\cdot(d+\xi)} + \upsilon_h \nabla^2 U,$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} - f \cdot U = -g\frac{\partial \xi}{\partial x} - \frac{g}{\rho_\circ}\int_{-d}^{\xi}\frac{\partial \rho'}{\partial y}dz + \frac{\tau_{sy}-\tau_{by}}{\rho_\circ\cdot(d+\xi)} + \upsilon_h \nabla^2 V \quad (3)$$

$$\frac{\partial(\xi+d)c}{\partial t} + \frac{\partial(d+\xi)Uc}{\partial x} + \frac{\partial(d+\xi)Vc}{\partial y} = D_h \nabla^2 c - \lambda_d(d+\xi)c + R \quad (4)$$

According to (2) and (3) defines conservation of mass and momentum, respectively. According to (4) is used for salinity and transport. Where "**ζ**" denotes water level, "d" is relative water depth, "**U**" is the velocity in X direction and "**V**" is the velocity in Y direction, "**Q**" is the mass intensity in single grid cell, "*f*" denotes Coriolis constant, "$\boldsymbol{\upsilon_h}$" denotes horizontal eddy viscosity, "**ρ**" stands for seawater density, "$\boldsymbol{\tau_s}$" shows surface wind stress, "$\boldsymbol{\tau_b}$" is the bottom shear stress, and "**R**" is force on single grid cell.

The tidal energy assessment is mainly accomplished by two methods, i.e based on the actuator disc theory method or based on the momentum sink method [25]. Tidal energy assessment by Delft3D implies the momentum sink approach [22]. This is based on energy loss in the Navier Stokes equation when any obstacle is present in the water flow. In this way, an additional term for energy loss is added to the momentum equation. That obstacle (in Delft3D it is done by adding porous plate as an additional parameter) works in the same as an array of turbines will reduce the pressure of flow across the turbine (i.e momentum loss or momentum sink). In this way, energy extraction from the flow can be modeled. By adding the energy loss coefficient to the momentum equation, momentum in (3) in x-direction will become as;

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - f \cdot V = \frac{\partial}{\partial x}\left(\mu\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial U}{\partial y}\right) - \frac{1}{\rho}\left(\frac{\partial \rho}{\partial x}\right) + f_x - M_{sx} \quad (5)$$

as shown in (5), the additional term **fx** stands for the horizontal Reynolds stress, and $\mathbf{M_{sx}}$ shows momentum sink in x-direction that is perpendicular to the incoming flow [22]. Similarly, the momentum sink term can be added in the y and z direction when performing 2D and 3D tidal energy extraction modeling.

4. CASE STUDY OF SARAWAK MALAYSIA

Malaysian tidal power development still remains in early stage of feasibility investigation. Several research studies have been carried out in the last decade to identify suitable sites as well as to investigate the energy extraction potential of some of the identified sites. The first research investigation to assess the capability of Malaysian tidal power was performed by [26], in which the three main sites, namely Pulau Jambongan, Sibu, and Kota Belud, were identified as the main locations having the great potential for tidal stream energy harnessing. Afterward, other researchers also contributed to assessing the potential of tidal sites by developing the hydrodynamic models using Delft3D numerical tools. [20] explored the tidal current energy sites and seabed roughness at Strait of Malacca, they proposed the Pulau Pangkor as the most suitable location for installing TEC. Bonar *et al*. [27] developed the depth-averaged hydrodynamic model for further assessing the tidal power generation capability at the Strait of Malacca, by considering a row of tidal turbines as the actuator disc. Later on, [21] developed a Delft3D hydrodynamic model for the Malacca Strait focusing on the energy extraction feasibility at Tg Tuan Headland. Goh *et al*. [22] further investigated the resulting environmental effects due to energy extraction at the Strait of Malacca, by developing the Delft3D hydrodynamic model.

All of the above-mentioned research studies are focused in West Malaysia only, in which the characterizations of tidal energy sources, as well as their feasibility analysis, are sufficient for the onsite trails of prototype TECs. However, not much attention is given to study the tidal stream energy resources in East Malaysia. Rigit *et al*. [11] higher tidal flow occurs at the Sarawak in East Malaysia. Rigit *et al*. [11] is the numerical approach based on the tidal stream stations in Sarawak, in which Triso Island is identified as the site where the maximum tidal current speed is noted. However, the mapping by [11] without a hydrodynamic model is not sufficient for resource characterization. Therefore for current study, Delft3D numerical application is utilized for setting up the hydrodynamic model representing Sarawak state, in East Malaysia, to characterize the tidal energy resources along the coastline of Sarawak. In the first stage, a 2D hydrodynamic model is set up to understand the depth-averaged velocity profile. Then the power density is calculated to find out the suitable location of higher kinetic energy flux.

4.1. Model setup

Sarawak is the largest state of Malaysia, that is located on Borneo island in East Malaysia. It has a large coastline covering approximately 720 km (measured from google maps). The one side from the north is connected to the South China Sea, while the other sides share tertial borders with Indonesia and Burnie.

In order to investigate the tidal hydrodynamic characteristics, Delft3D numerical tools are utilized to build the regional model for tidal stream energy. In the first step, Arakawa C-grid is generated in sigma coordinates at the model area, as represented by Figure 5. The total grid length from west to east covers 574.5 km, and following the methodology by [9], the gird resolution close to the land boundary was set as 0.9 x 1.1 km, which was gradually increasing, and the grid resolution of 0.9x3 km is set at the open boundary. The flow at the area of interest is not disturbed by the instabilities at the open boundary as the distance is kept sufficiently far from the land boundary. After setting up the grid, the bathymetry for the proposed study area is derived from the general bathymetric chart for oceans (GEBCO) database for the oceans [28].

The bathymetry data were interpolated to the computational grid by Delft3D-QUICKIN, which is shown in Figure 6. The bathymetry at the western coast of Sarawak varies around 100 m. Whereas, the deep sea starts from the norther-east corner of the model domain. The bathymetry at this part of the South China sea is up to 2000 m, this comes under the vicinity of Brunei and Sabah borders of the Borneo island. South China sea close to Brunei and Sabah is deeper than 2000 m, which can be a potential source for the ocean thermal energy conversion (OTEC).

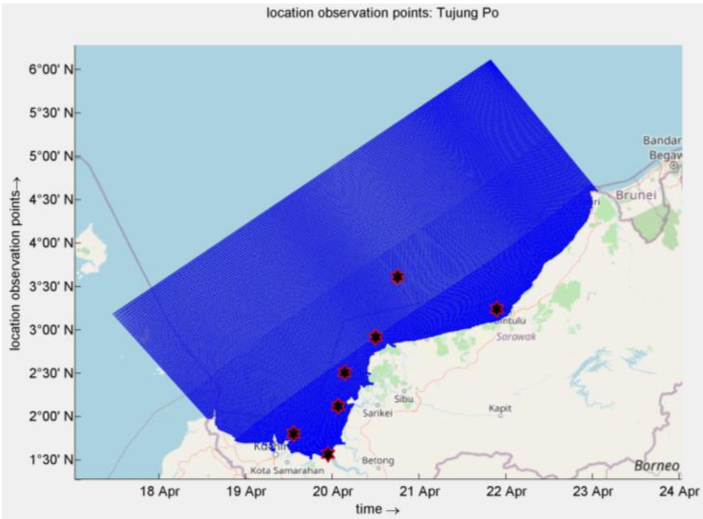


Figure 5. The grid generated along the coastline of Sarawak in East Malaysia

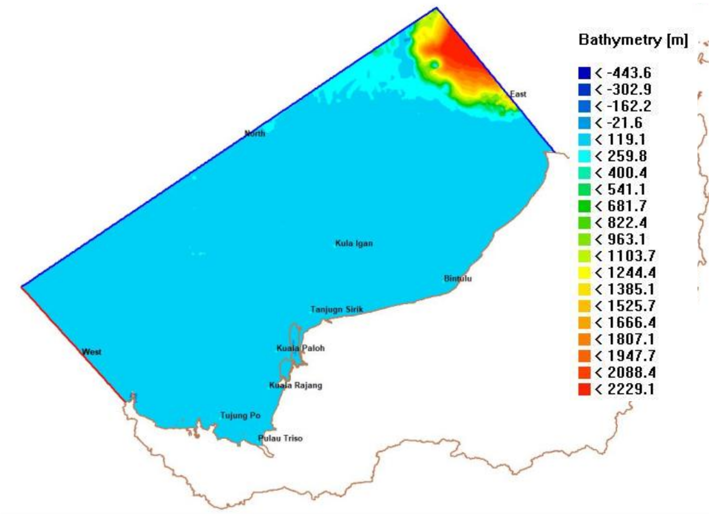


Figure 6. The bathymetry of the study area and locations of observation points

The time step for the simulation was set as 1 min, as followed by the other researchers [9]. The model has three open boundaries named West, North, and East, as shown in Figure 6. Initial conditions at the open boundaries were set as null free water levels. Whereas the boundary conditions at the open boundaries are derived from the TPXO database for tidal constituents [29].

The amplitude and phase of the eight major constituents M2, S2, N2, K2, K1, O1, P1, and Q1 are presented in Table 1. It can be observed that the magnitude of tidal constituents decrease from west to east along the Sarawak coastline. Such variations are mainly experienced due to regional bathymetry. A total of 7 observation points are selected to observe the tidal speed at these locations along the coastline, these are shown with names in Figure 6. The model is run for 15 days from 1st May 2021 to 15th May 2021, to cover the normal neap and spring tidal hours. The final simulation findings were analyzed using QUICKPLOT module of Delft3D, for power density analysis and model validation.

Table 1. Boundary conditions at the open boundaries of the model, a total of 8 tidal constituents are derived from the TPXO database

Constituent	West A		West B, North A		North B, East A		East B	
	Amplitude (m)	Phase	Amplitude (m)	Phase	Amplitude (m)	Phase	Amplitude (m)	Phase
M2	0.825	237.57	0.375	233.06	0.175	95.68	0.187	95.45
S2	0.285	277.16	0.127	268.58	0.076	123.26	0.0821	121.54
N2	0.176	213.08	0.084	209.03	0.035	88.39	0.037	87.38
K2	0.083	266.93	0.034	263.15	0.018	107.05	0.019	105.85
K1	0.343	228.16	0.334	228.89	0.357	194.23	0.359	194
O1	0.282	190.47	0.250	193.13	0.311	152.82	0.315	152.76
P1	0.112	225	0.107	226.47	0.111	190.23	0.111	190.18
Q1	0.059	172.18	0.051	180.1	0.060	135.6	0.060	135.6

5. RESULTS AND DISCUSSION

5.1. Validation

The infield data for the observation location in this model, shown in Figure 6, is not available. Therefore the model is validated with the water level result from the TPXO 9.2 TMD model. The TPXO database is used for generating the boundary condition as well as for validation of the simulation results. The database is established by Oregon State University, by applying Laplace Tidal formulae to the Ocean data acquired from the satellites, namely TOPEX/Poseidon and Jason [29]. However, TPXO is a global model, whereas in this study, we set up a regional model. The data for the two observation points named Pulau Triso and Bintulu can not be derived from the model, as these locations are close to the coastline which appears as land in the TPXO model.

While the simulation results from the observation point Tanjung Po, Kuala Rajang, Kuala Paloh, Tanjung Sirk, and Kuala Igan are compared with the water level from the TPXO. Validity of model has been ensured from value of RMSE and the correlation coefficient between database results and the simulation results. The results are presented in Table 2, in which a good agreement between simulation and database can be seen. None of the observation locations has a correlation coefficient below 0.9, while the Tanjung Sirik showed a very good agreement having the highest correlation coefficient of 0.96. The comparison between the simulation and database result of Tanjung Sirik is also shown in Figure 7. The simulation result is shown by the blue-colored continuous line and the TPXO result is indicated by the red-colored dotted line.

5.2. Tidal flow

The hydrodynamic model was impelled via density changes, local bathymetry, and tidal forces from the open boundaries. The current hydrodynamic model in this study is 2D, and hence the result of the velocity is depth-averaged. The depth-averaged velocity at Pulau Triso, Bintulu, Kuala Rajang, and Kuala Paloh is presented in Figure 8. While Figure 9 shows the depth-averaged velocity at Tanjung Po, Kuala Igan, and Tanjung Siik. From the time series analysis of both the figures, it can be concluded that the tidal current flow along the East Sarawak is very low. That’s why it is not feasible to generate the power.

Figure 8(a) shows the timeseries analysis of depth-averaged velocity (m/s) at the location Triso Island. The maximum depth-averaged velocity at this location is 0.25 m/s. The location Bintulu is the lowest site along the Eastern Sarawak coastline, and the maximum depth-averaged tidal velocity at this is up to 0.25 m/s during neap tide hours, as shown in Figure 8(b). Whereas among all observation sites, Kuala Rjanag received the highest tidal current velocity of 0.55 m/s, as shown in Figure 8(c). The maximum depth-averaged velocity at Kuala Paloh is 0.5 m/s, as shown in Figure 8(d). Figure 9(a) shows the time series data of depth-averaged velocity at Tanjung Po, where maximum velocity was noted as 0.53 m/s. The results of depth-averaged velocity at Kuala Igan and Tanjung Sirik are shown in Figure 9(b) and Figure 9(c), respectively. The increase of velocity at these locations is because of the unique geographic coastline at western Sarawak. The coastline converges roughly to a single place called Triso island, as a result, the water is accelerated towards this site. However, the water depth at these locations is not high enough to install the turbines, the deepwater location is Kuala Igan. The above-mentioned locations are in the vicinity of higher velocity, however, there is variation in the spatial distribution of the depth-averaged velocity.

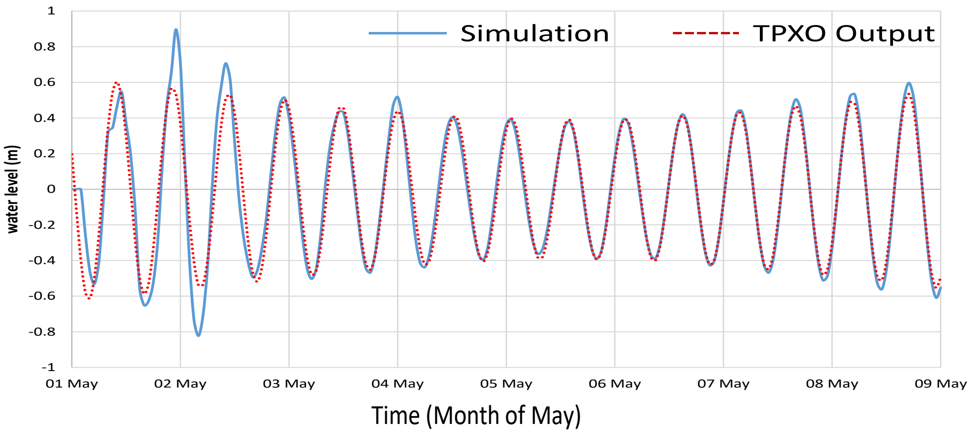
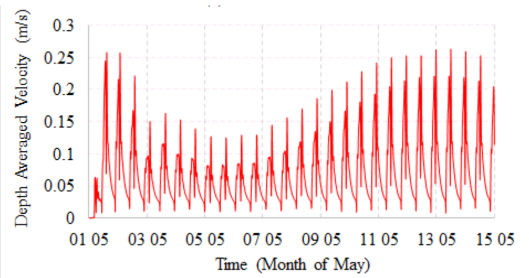
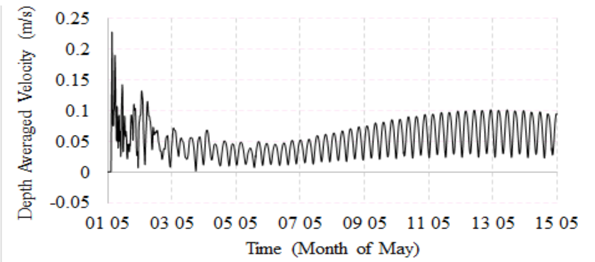


Figure 7. Comparison between simulation and TPXO database results of water level at Tanjung Sirik. The red-colored dotted line is water level data extracted from TPXO TMD model 9.2

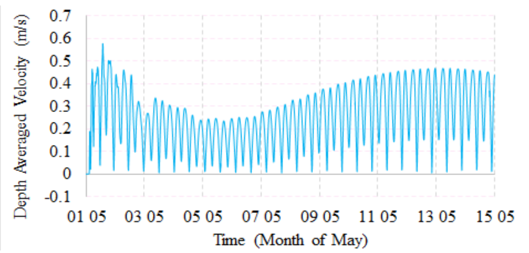
The spatial analysis of tidal stream velocity is presented in Figure 10. The results are during the neap flood tide during the peak flow speed, as it will help to identify the locations of higher tidal flow speed. The two main regions of higher depth-averaged velocity are identified in the vicinity of the observation points Tanjung Sirik and Tanjung Po. From the temporal analysis, the peak velocities at these locations were noted to be up to 0.55 m/s. However, the spatial analysis shows the depth-averaged velocity near Tanjung Po is up to 1 m/s and near Tanjung Sirik is 0.8 m/s. The available tidal velocities of these locations are not suitable for power generation on a larger scale, but the stand-alone TECs can be installed for small-scale power generation.



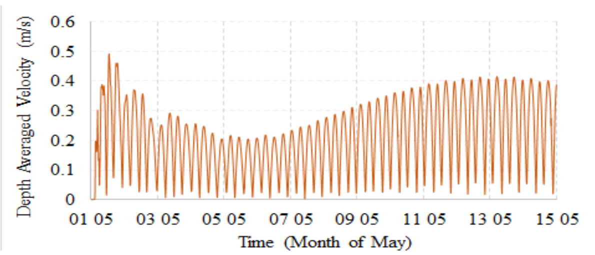
(a)



(b)



(c)



(d)

Figure 8. Depth averaged tidal streal velocity at the location (a) Pulau Triso, (b) Bintulu, (c) Kuala Rajang, and (d) Kuala Paloh

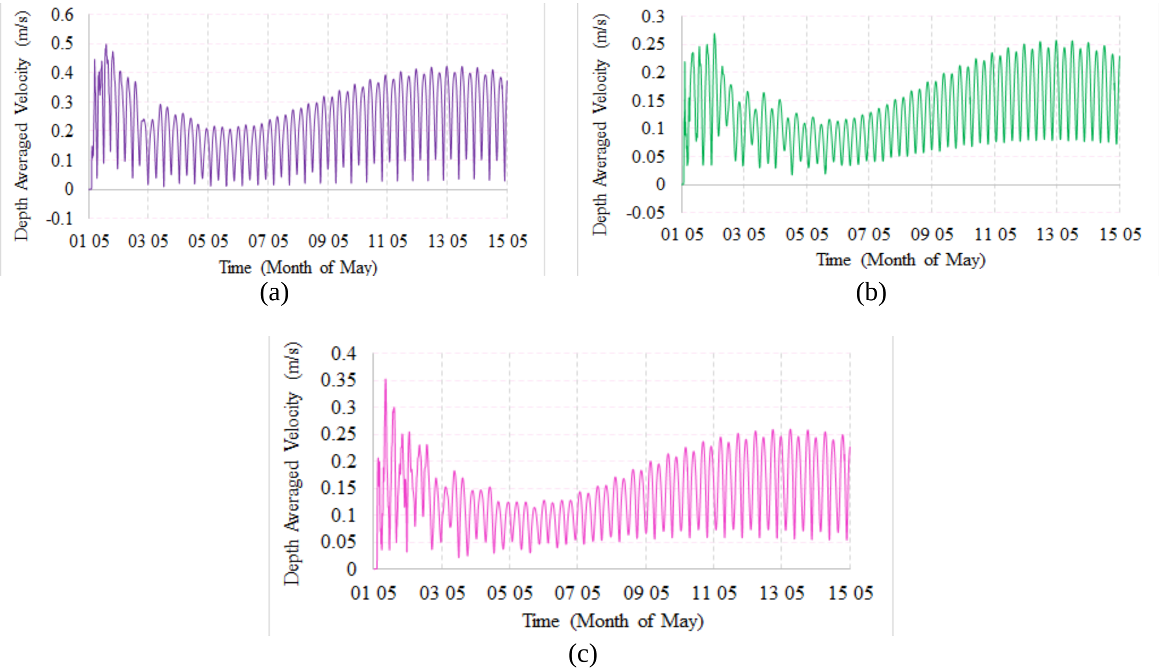


Figure 9. Depth averaged tidal stream velocity at the location (a) Tanjung Po, (b) Kuala Igan, and (c) Tanjung Sirik

Tabel 2. The validation results of the observation points

Observation Location	Correlation Coefficient	RMSE
Tanjung Po	0.934	0.28
Kuala Rajang	0.935	0.275
Kuala Paloh	0.948	0.209
Tanjung Sirik	0.965	0.096
Kuala Igan	0.952	0.094

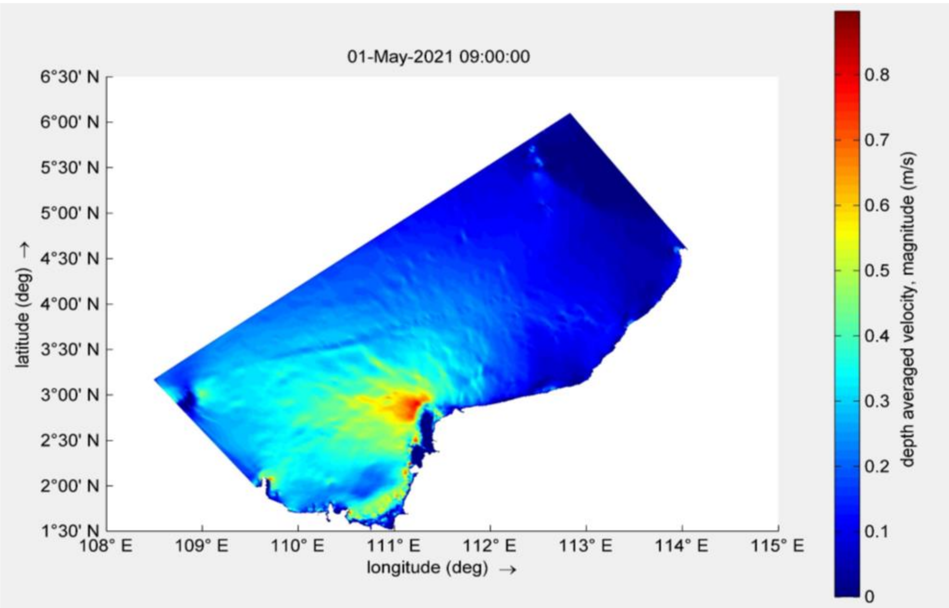


Figure 10. Spatial variation of depth-averaged tidal stream velocity in the model

5.3. Power flux

The kinetic energy flux or the tidal power flux density gives an instantaneous idea for site selection at the study area. It is calculated by the instantaneous mean Tidal power in (6). Tidal power given in (6):

$$\frac{P}{A} = \frac{1}{2}\rho u_{\infty}^{3} \tag{6}$$

The factor P/A indicates the available kinetic energy flux at the study area. **ρ** is the density of the seawater, which was taken 1024 kg/m3, and **u** is the unbounded tidal stream speed. The available spatial kinetic energy flux (kW/m2) is shown in Figure 11. It needs to be noted that the available kinetic energy flux does not mean the extractable kinetic energy. The extractable kinetic energy flux depends upon the coefficient of performance of the tidal current turbine and the environmental factors. Nevertheless, the available kinetic energy flux gives the first appraisal to identify the suitable site locations. It can be observed that the kinetic energy flux is only shown for area within vicinity of observation locations Tanjung Sirik and Tanjung Po, whereas at the other locations tidal current speed is too small which is not suitable for power generation. The available kinetic energy flux near Tanjung Sirik ranges around 0.3 kW/m2. However, for the area near Tanjung Po, it ranges from 0.4 to 0.5 kW/m2. Some areas with energy flux above 0.6 kW/m2 can also be noted. Therefore, this location can be suggested for the detailed tidal energy assessment study.

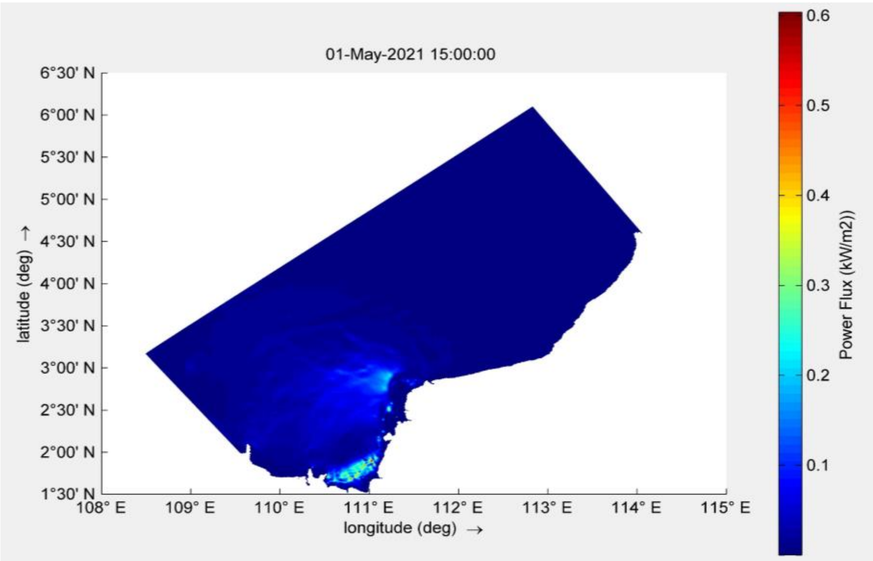


Figure 11. The available kinetic energy flux (kW/m2) at the study area

6. CONCLUSION

Oceans represent a huge potential for tidal energy harnessing. Among other renewable energy sources, tidal power generation has highest predictibility. The theoretical worldwide tidal current potential is 7800 TWh/year. However, a lot of its potential is yet to be explored. Hydrodynamic modeling is the key feature in exploring the macro tidal sties. In this study, a hydrodynamic model is developed for the case study of Sarawak Malaysia, to explore the macro tidal sites. For this, Delft3D numerical application is utilized to solve the Navier Stokes equations. The model is validated against the database results, and macro tidal sites are identified in the study area. The two locations of Tanjung Sirik and Tanjung Po are noted to be suitable sites along the Sarawak coastline. The depth-averaged tidal stream velocity was noted to be up to 1 m/s and the highest available kinetic energy flux was 0.6 kW/m2.

ACKNOWLEDGEMENTS

The authors would like to thank the Sarawak Research and Development Council (SRDC) and the Government of Sarawak State for providing funding for this study under grant number RDCRG/CAT/2019/21.

REFERENCES

[1] V. Ramos and G. Iglesias, “Performance assessment of Tidal Stream Turbines: A parametric approach,” *Energy Conversion and Management*, vol. 69, pp. 49–57, May 2013, doi: 10.1016/j.enconman.2013.01.008.

[2] F. Novico, E. H. Sudjono, A. Egon, D. Menier, M. Methew, and M. B. Pratama, “Tidal current energy resources assessment in the patinti strait, indonesia,” *International Journal of Renewable Energy Development*, vol. 10, no. 3, pp. 517–525, 2021, doi: 10.14710/ijred.2021.35003.

[3] A. B. e Melo and H. Jeffrey, “OES | OES Annual Report 2019: Overview of ocean energy activities in 2019AN ,” 2019, [Online]. Available: https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2019/.

[4] A. H. Rajpar, I. Ali, A. E. Eladwi, and M. B. A. Bashir, “Recent development in the design of wind deflectors for vertical axis wind turbine: a review,” *Energies*, vol. 14, no. 16, p. 5140, Aug. 2021, doi: 10.3390/en14165140.

[5] R. Espina-Valdés, E. Álvarez Álvarez, J. García-Maribona, A. J. G. Trashorras, and J. M. González-Caballín, “Tidal current energy potential assessment in the Avilés Port using a three-dimensional CFD method,” *Clean Technologies and Environmental Policy*, vol. 21, no. 6, pp. 1367–1380, Aug. 2019, doi: 10.1007/s10098-019-01711-2.

[6] H. Ritchie, M. Roser, and P. Rosado, “Renewable energy,” *Our World in Data*, 2022, [Online]. Available: https://ourworldindata.org/energy.

[7] J. Seo, J.-H. Yi, J.-S. Park, and K.-S. Lee, “Review of tidal characteristics of Uldolmok Strait and optimal design of blade shape for horizontal axis tidal current turbines,” *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109273, Oct. 2019, doi: 10.1016/j.rser.2019.109273.

[8] P. Gadonneix, F. B. De Castro, and R. Drouin, “2010 Survey of energy resources,” 2010. [Online]. Available: https://www.osti.gov/etdeweb/biblio/21467328.

[9] W.-B. Chen, H. Chen, L.-Y. Lin, and Y.-C. Yu, “Tidal current power resources and influence of sea-level rise in the coastal waters of Kinmen Island, Taiwan,” *Energies*, vol. 10, no. 5, p. 652, May 2017, doi: 10.3390/en10050652.

[10] K. Orhan and R. Mayerle, “Potential Hydrodynamic impacts and performances of commercial-scale turbine arrays in the strait of Larantuka, Indonesia,” *Journal of Marine Science and Engineering*, vol. 8, no. 3, p. 223, Mar. 2020, doi: 10.3390/jmse8030223.

[11] A. R. H. Rigit, A. Q. Jakhrani, S. A. Kamboh, W. H. Kong, and K. A. Samo, “Mapping of tidal stream energy resources in the coastline of sarawak,” *World Applied Sciences Journal*, vol. 22, no. 9, pp. 1252–1261, 2013, doi: 10.5829/idosi.wasj.2013.22.09.2727.

[12] H. Liu, S. Ma, W. Li, H. Gu, Y. Lin, and X. Sun, “A review on the development of tidal current energy in China,” *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1141–1146, Feb. 2011, doi: 10.1016/j.rser.2010.11.042.

[13] S. Monolisha, T. Platt, S. Sathyendranath, J. Jayasankar, G. George, and T. Jackson, “Optical classification of the coastal waters of the Northern Indian Ocean,” *Frontiers in Marine Science*, vol. 5, no. MAR, 2018, doi: 10.3389/fmars.2018.00087.

[14] A. H. Rajpar, A. E. Eladwi, I. Ali, and M. B. A. Bashir, “Reconfigurable articulated robot using android mobile device,” *Journal of Robotics*, vol. 2021, pp. 1–8, Feb. 2021, doi: 10.1155/2021/6695198.

[15] A. R. H. Rigit, I. Ali, T. C. Boon, and C. H. Chong, “Effect of number of electrodes on electrical performance of surface dielectric barrier discharge plasma actuator,” in *2020 13th International UNIMAS Engineering Conference (EnCon)*, Oct. 2020, pp. 1–4, doi: 10.1109/EnCon51501.2020.9299343.

[16] D. Khojasteh, D. Khojasteh, R. Kamali, A. Beyene, and G. Iglesias, “Assessment of renewable energy resources in Iran; with a focus on wave and tidal energy,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2992–3005, Jan. 2018, doi: 10.1016/j.rser.2017.06.110.

[17] C. H. Chong, A. R. H. Rigit, and I. Ali, “Wind turbine modelling and simulation using MATLAB/Simulink,” *IOP Conference Series: Materials Science and Engineering*, vol. 1101, no. 1, p. 012034, Mar. 2021, doi: 10.1088/1757-899X/1101/1/012034.

[18] J. Khan and G. S. Bhuyan, “Ocean energy: global technology development status,” *Ocean-Energy-Systems*, 2009. [Online]. Available: www.powertechlabs.com.

[19] L. Hammar, J. Ehnberg, A. Mavume, B. C. Cuamba, and S. Molander, “Renewable ocean energy in the Western Indian Ocean,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, pp. 4938–4950, Sep. 2012, doi: 10.1016/j.rser.2012.04.026.

[20] A. S. Sakmani, W. H. Lam, R. Hashim, and H. Y. Chong, “Site selection for tidal turbine installation in the Strait of Malacca,” *Renewable and Sustainable Energy Reviews*, vol. 21, pp. 590–602, 2013, doi: 10.1016/j.rser.2012.12.050.

[21] H. B. Goh, S. H. Lai, M. Jameel, H. M. Teh, and R. J. Chin, “Feasibility assessment of tidal energy extraction at the Tg Tuan coastal headland: A numerical simulation study,” *Sustainable Energy Technologies and Assessments*, vol. 38, 2020, doi: 10.1016/j.seta.2020.100633.

[22] H. B. Goh, S. H. Lai, M. Jameel, and H. M. Teh, “Potential of coastal headlands for tidal energy extraction and the resulting environmental effects along Negeri Sembilan coastlines: A numerical simulation study,” *Energy*, vol. 192, 2020, doi: 10.1016/j.energy.2019.116656.

[23] R. Carballo, G. Iglesias, and A. Castro, “Numerical model evaluation of tidal stream energy resources in the Ría de Muros (NW Spain),” *Renewable Energy*, vol. 34, no. 6, pp. 1517–1524, Jun. 2009, doi: 10.1016/j.renene.2008.10.028.

[24] N. D. Katopodes, “Methods for two-dimensional shallow-water flow,” in *Free-Surface Flow*, Elsevier, 2019, pp. 500–567.

[25] S. Draper, G. T. Houlsby, M. L. G. Oldfield, and A. G. L. Borthwick, “Modelling tidal energy extraction in a depth-averaged coastal domain,” *IET Renewable Power Generation*, vol. 4, no. 6, pp. 545–554, 2010, doi: 10.1049/iet-rpg.2009.0196.

[26] Y. S. Lim and S. L. Koh, “Analytical assessments on the potential of harnessing tidal currents for electricity generation in Malaysia,” *Renewable Energy*, vol. 35, no. 5, pp. 1024–1032, May 2010, doi: 10.1016/j.renene.2009.10.016.

[27] P. A. J. Bonar, A. M. Schnabl, W.-K. Lee, and T. A. A. Adcock, “Assessment of the Malaysian tidal stream energy resource using an upper bound approach,” *Journal of Ocean Engineering and Marine Energy*, vol. 4, no. 2, pp. 99–109, May 2018, doi: 10.1007/s40722-018-0110-5.

[28] General bathymetric Chart of the Oceans (GEBCO), “GEBCO data download,” *Gebco.Net*, 2021. https://download.gebco.net/.

[29] L. Padman, “Tide Model Driver (TMD) Manual,” *Arctic*, pp. 1–12, 2004.

BIOGRAPHIES OF AUTHORS

Imran Ali received his undergraduate degree in Energy and Environment Engineering from Quaid-e-Awam University of Engineering, Science, and Technology Nawabshah, Pakistan, in the year 2019. Later in the same year 2019, he joined Universiti Malaysia Sarawak, Malaysia for his Master of Engineering study in the field of Renewable Energy. He can be contacted at email: 19020069@siswa.unimas.my.

Prof. Ir Dr. Andrew Ragai Henry Rigit received the Bachelor of Engineering degree in Mechanical Engineering from City University in the year 1995. He received his Master of Science in Mechanical Engineering from Universiti Malaysia Sarawak, in the year 1997. He received his PhD. Degree in Mechanical Engineering from Imperial College London, in the year 2004. His research includes renewable energy, fluid dynamics, hydrodynamic modelling. He can be contacted at email: arigit@unimas.my.

Prof. Dr. Omar bin Yaakob currently works at the Marine Technology Centre [MTC], Universiti Teknologi Malaysia. Omar does research in Ship Design and Transportation Engineering, Marine environment and renewable energy. The Royal Institution of Naval Architects appointed him as a Fellow in 2010 and the UK Engineering Council accorded him a Chartered Engineer status in the same year. In addition, he was also appointed as an Associate of the Academy of Sciences Malaysia. He can be contacted at email: omaryaakob@utm.my.

Prof. Dr. Jane Labadin is a Professor at the Faculty of Computer Science and Information Technology as well as Research Fellow at the Institute of Social Informatics and Technological Innovation, Universiti Malaysia Sarawak (UNIMAS). She received her Ph.D. in Computational Mathematics specializing in Fluid Dynamics from the Imperial College of Science, Technology and Medicine, London, UK in 2002. Her Bachelor degree in Applied Mathematics was from the same university in 1995. She obtained her Master in Computation in 1997 from the University of Manchester, Institute of Science and Technology, UK. She is an active researcher evident from many internal and external research projects that she leads as well as from her publications. Her research interest is generally in computational modeling of dynamical systems which includes infectious disease modeling. She can be contacted at email: ljane@unimas.my.

Prof. Dr. Altaf Hussain Rajpar received his PhD degree in mechatronics Engineering, from Beijing Institute of Technology, China. He started working as Professor at the Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Pakistan from the year 2008 to 2019. In the year 2019, he joined joined Jouf University, Saudi Arabia, and currently he was working as Professor in the department of Mechanical Engineering at the same university. He can be contacted at email: ahrajpar@ju.edu.sa.