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Review of Resources from the Perspective of Wave, Tidal, and Ocean Thermal Energy Conversion

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ABSTRACT

The conversion of Ocean Renewable Energy (ORE) sources to electricity could meet increasing energy demand and diversify the energy supply in Malaysia. Possessing a long coastline overlooking the South China Sea (SCS) and the Malacca strait has encouraged the Malaysian government to promote ORE and assess available resources to reduce its dependence on fossil fuels. However, most of the previous attempts to assess the potential of Malaysian ORE resources have focused primarily on theoretical resource assessment, which in practice may not reflect the viability and suitability of the resource. Other technical and practical issues must be accounted for as well. This paper presents a brief description of ORE conversion technologies and reviews the existing studies on regional ORE resources in Malaysia with an emphasis dedicated to wave energy, tidal energy, and Ocean Thermal Energy Conversion (OTEC). It also highlights the essential technical and practical constraints limiting or excluding the utilization of ORE sources. While some ORE resources, particularly the OTEC, appear to be theoretically promising for exploitation in Malaysia, this review has shown a lack of precise resource mapping linked to socio-economic and environmental constraints.

1. Introduction

In recent years, increasing energy demand and consumption have forced Malaysia to worry about the security of the energy supply needed to sustain its economic growth. Therefore, the search for alternative sources such as renewable energy sources has become unavoidable. Malaysia has begun promoting renewable energy to reduce its reliance on fossil fuels. Oceans are one of the most powerful renewable energy sources available, potentially providing a more sustainable energy supply in the future. The energy generated by waves, tides, and temperature changes is referred to as ocean energy.

As a maritime nation overlooking the South China Sea (SCS) and the Strait of Malacca, Malaysia has the potential to tap into Ocean Renewable Energy (ORE). Despite all the advantages of ORE

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sources compared to conventional sources, all potential concerns of ORE must be investigated and assessed to ensure that it is a safe alternative for the environment compared to traditional power generation [1]. Several studies have been carried out to assess the ORE resources in Malaysia. However, most of these studies are mainly focused on the theoretical and, in a few cases, technical assessments of these resources. Both theoretical and technical resource assessment may not necessarily indicate the viability and suitability of ocean resources to be exploited [2]. Thus, analyzing the theoretical or technical resources alone may not be preferable for determining ORE viability. Instead, it is the practical resource assessment that will determine the suitability of ORE and how it can contribute to electricity generation. This paper presents the current status of ORE in Malaysia with the main focus on wave energy, tidal energy, and OTEC. It also highlights the key technical and practical constraints limiting or excluding ORE utilization.

Energy derived from the oceans has an advantage over conventional energy sources in providing an abundant, inexhaustible, non-polluting source containing vast amounts of energy. Waves, tidal range, ocean currents, OTEC, and salinity gradients are all ORE sources with varied origins requiring different conversion technologies as illustrated in Figure 1 [3].

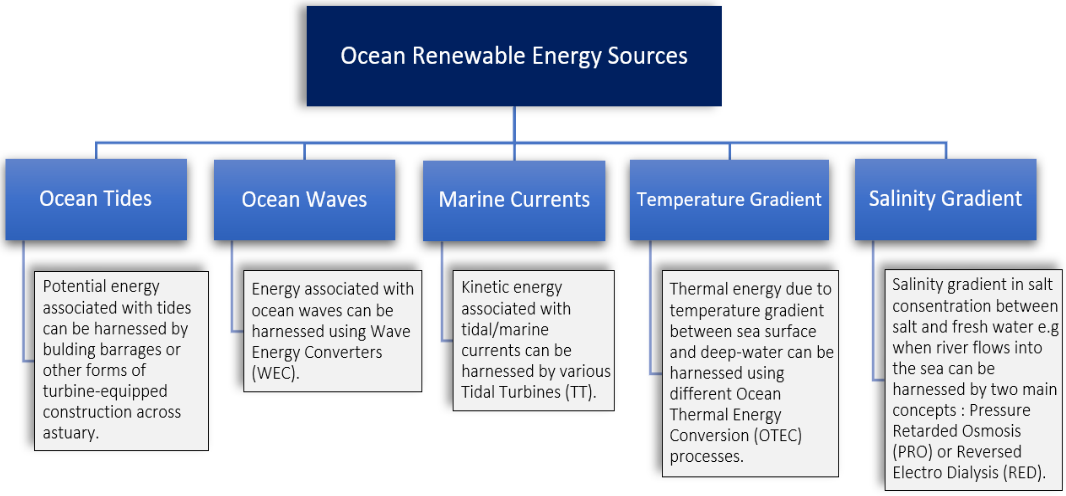


Fig. 1. Ocean renewable energy sources [4]

2. ORE Resource Assessment

ORE resource assessment plays a key role throughout project development, from initial site selection to operation [5]. At the most fundamental level, the purpose of ORE resource assessment is to identify sites suitable for deployment and select the appropriate energy conversion technology for a site [6,7]. However, the level of the required details will vary with the stage of the project development [8]. ORE estimates can be split into three assessment levels; theoretical, technical, and practical as shown in Figure 2 [2].

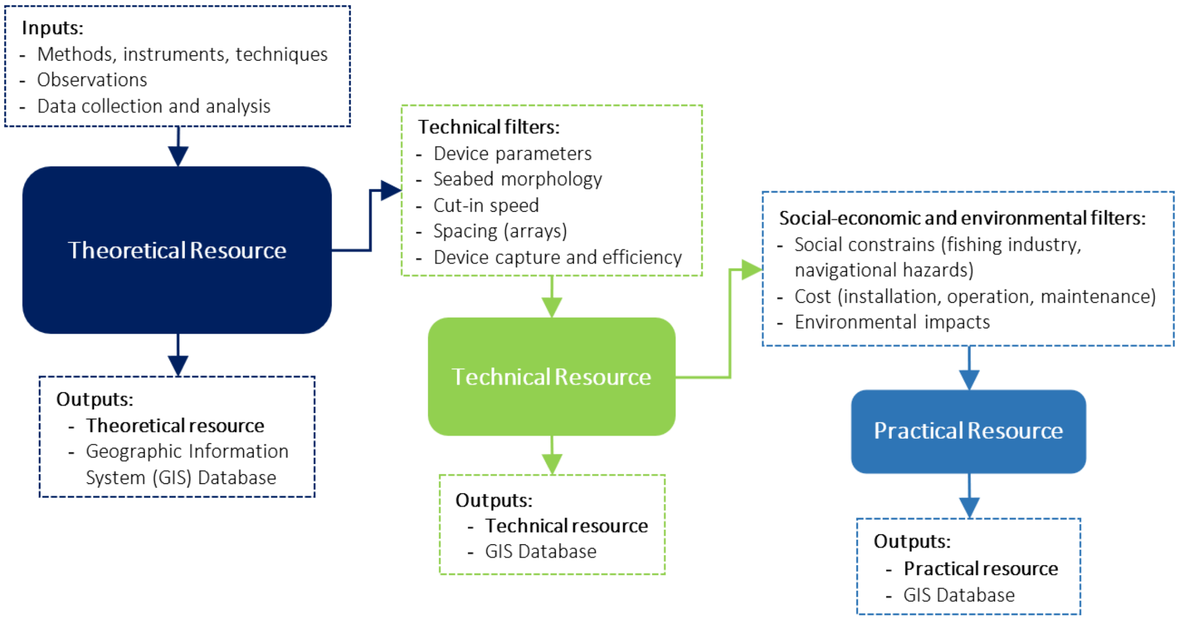


Fig. 2. Levels of ORE resource assessment [2]

3. Wave Energy

Waves are caused by ocean winds that transfer and store some of their energy in water as potential and kinetic energy [3,9]. The amount of wave energy available for extraction from the surface wave in the ocean is defined as the wave energy resource [5]. As with other renewable energy sources, wave energy harvesting depends on reliable assessment and resource mapping, which may vary depending upon the stages of the development of wave energy [10,11].

Wave data sources such as high-resolution observations and measurements of wave conditions, as well as precise and validated numerical models, are essential for assessing wave energy resources at a specific [12]. In situ measurements are direct ways of measuring waves, whereas Doppler and satellites are considered remote approaches. Surface following buoys, seabed pressure sensors, Acoustic Doppler Current Profiler (ADCP), and land-based and satellite radars are some of the available wave measurement devices [13].

Each wave data source type is subject to certain limitations; however, all provide information about different resource scales. Surface following buoys are widely used instruments for long-term deployment and provide continuous and accurate measurements of wave conditions. Yet, their accuracy is affected by currents and steep waves. Furthermore, they are expensive and vulnerable to loss [13,14]. One such alternative to surface following buoys is seabed pressure sensors deployed in shallow water depths (10m-20m) and measure variations in pressure to obtain the wave height and period. However, the accuracy of wave measurement is strongly affected by attenuation effects [14]. ADCP measures the shift in frequency caused by the Doppler effect. ADCP provides precise measurement but is relatively expensive and limited to shallow water applications. ADCP stores data onboard; as a result, the recovery of the instrument is required to extract data [13]. Land-based radars are deployed away from the aggressive environment; however, they require calibration and are limited to the wave height measurement. Despite the low temporal resolution of resource data, satellite remote sensing offers data on significant wave heights across a vast area [13].

Employing numerical wave models for wave resource assessment has become cost-effective, reliable, and time-saving due to advances in numerical technology and enhanced computing platforms [15]. Beyond direct or remote measurements, numerical wave models provide detailed knowledge of wave resource and can generate long-term data over large domains unfeasible to achieve using a measuring instrument [13]. Third-generation Wave Action Models (WAM) or Wave Watch III are commonly used in global-scale simulations of wave conditions over vast spatial domains. However, local-scale models; (SWAN), (TOMAWAC), and MIKE-21 SW are typically utilized in relatively small areas (~ 100 Km) [12]. The primary issue with wave models is that they either underestimate or overestimate wave conditions [12]. Data from numerical wave models are estimates rather than measurements and are interpreted as averages over an area and time [13,16]. As a result, any wave model used to assess wave resource should be validated using calibrated in situ measurements and satellite observations before being employed [12,17].

3.1 Wave Energy Conversion

The energy of the waves is converted into usable energy using wave energy converters (WECs). A wide range of WECs is being designed, developed, and tested today. Despite the considerable variation in Design, WECs are usually classified according to location, orientation to wave direction, operating principle, and power take-off systems [18].

Based on the distance to shore or water depth at which the device or array is deployed, WECs are classified as onshore, nearshore, or offshore [19]. Onshore WECs are fixed or placed on the shoreline to facilitate installation and maintenance. The most advanced class of onshore devices is the Oscillating Water Column (OWC). Nearshore WECs are usually mounted on the seabed (avoiding moorings), but they can sometimes be floating structures. They have nearly the same advantages as onshore devices, simultaneously exposed to higher wave power levels than shoreline converters. Offshore WECs are embedded in floating or submerged constructions moored to the ocean floor and situated in deep water far from the land. Due to their location, they might use the enormous wave power levels of the open sea.

WECs can also be categorized into three predominant types based on their orientation to the incident wave: point absorbers, attenuators, and terminators. In comparison to wavelength, point absorbers are usually smaller in diameter. A buoy that oscillates with waves and is typically axisymmetric is called a point absorber. Power absorption is obtained by the relative motion between the buoy and the reference via a Power Take-Off (PTO) system simultaneously as it responds against a reference (seabed). A buoy can be triggered to oscillate in three degrees of freedom: surge, heave, and pitch by a unidirectional wave. Attenuators are structures that are long in comparison to the wavelength and placed parallel to the wave direction. In essence, they attenuate the amplitude of the wave [19]. Attenuators are made up of individual cylindrical parts that can spin in relation to one another and are connected by flexible hinged joints. Terminators are oriented orthogonally to the direction of wave propagation in contrast to attenuators in order to intercept the waves.

Another classification of WECs is based on their operating principle as OWC, oscillating bodies, and overtopping devices (Figure 3) [20,21]. WECs may also be classified by their PTO systems. PTO system is a mechanism to convert the energy absorbed from the ocean waves by WEC into usable electricity. The most common PTOs are based on pneumatic, hydraulic, mechanical systems, and direct electrical drive [22].

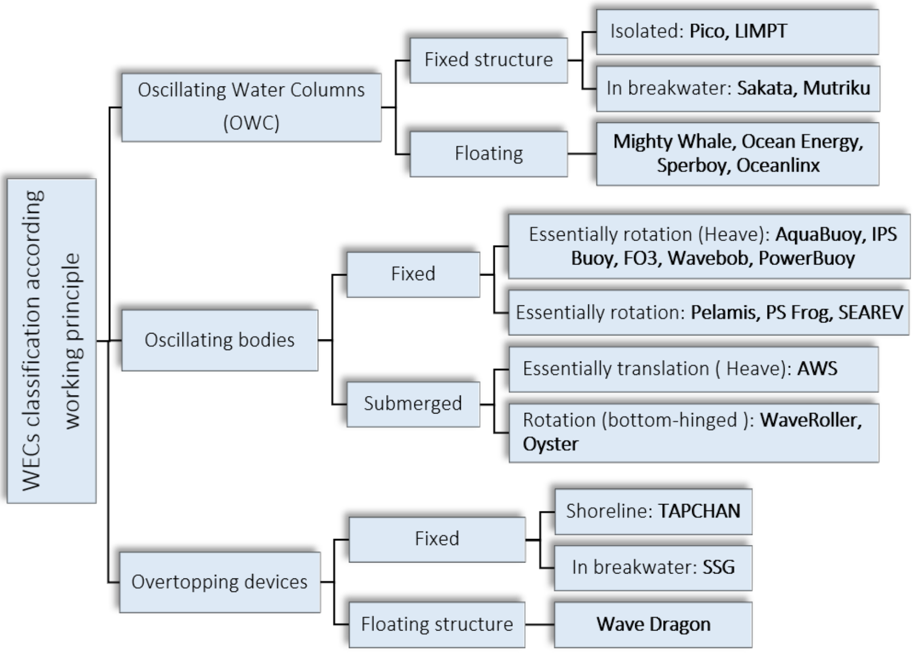


Fig. 3. WEC working principle [20]

3.2 Wave Resource Assessment

The wave energy assessment process should begin with the theoretical resource assessment that defines the yearly average energy available from the wave energy source and takes into account only data on climate characteristics [2,23,24]. The wave energy flux "wave power density" is usually characterized as a power per wave crest length. For deep-water locations wave energy flux in kW/m is calculated using the Eq. (1) [25,26]

$$P = \frac{\rho g^2}{64\pi} T_e H_s^2 \tag{1}$$

where seawater density ρ, acceleration due to gravity g, significant wave height H_s, wave energy period T_e.

In practice, only a small portion of the entire theoretical resource can be exploited. Therefore, the technical resource should be considered [27]. The technical resource is the actual fraction obtained utilizing conversion technology while taking into account the technology's limitations [2,28]. This estimate explicitly considers technological constraints associated with wave energy devices such as water depths, device spacing (in array formation), and device capture and conversion efficiency [2]. The most common approach for estimating technical resource is to employ a power matrix. It is a powerful infographic tool for assessing wave resource and shows the response of the WEC in terms of average power production as a function of two sea state parameters: (H_s) and (T_e) [29]. WEC developers create power matrices for their devices, which depict the device's performance in each (H_s) and (T_e) condition [30,31]. An example of the power matrix of the Pelamis WEC is shown in Figure 4.

Pelamis H_s (m) \ T_e (s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5		270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0			462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5			544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0				739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5				750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0					750	750	750	750	750	750	711	633	619	558	512	470	415
6.5					750	750	750	750	750	750	750	743	658	621	579	512	481
7.0						750	750	750	750	750	750	750	750	676	613	584	525
7.5							750	750	750	750	750	750	750	750	686	622	593
8.0								750	750	750	750	750	750	750	750	690	625

Fig. 4. Pelamis power matrix (in kW) [31]

Power matrices are extracted from numerical simulations and then validated against wave tank model tests or sea trials prototype devices [31]. As a result, they indicate the device's extractable power at any particular sea state, usually in (kW) [32]. Once the location of interest has been selected, the scatter diagram is used to characterize the wave climate Figure 5. It is a long-term wave statistic that describes the probability of occurrence of sea states determined by significant wave height (H_s) and wave period, typically peak period (T_p), energy period (T_e) or zero-crossing period (T_z). The shading illustrates the most common sea states. Wave energy absorption of a specific device at the selected area (assuming no constraints to installing WEC) is obtained by multiplying the scatter diagram with the power matrix [29,33]. The simplicity of this method makes it attractive in power performance estimation. However, uncertainty in the power estimation may arise due to variations in the power capture across the scatter diagram representing the wave climate [33].

Hs \ Tz	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
0.25	0.0066	0.0056	0.0030	0.0023	0.0011	0.0007	0.0003	0.00005				
1	0.0453	0.1650	0.0906	0.0347	0.0131	0.0047	0.0019	0.00069	0.0001	0.00004	0.00007	0.00005
2	0.0018	0.0368	0.1604	0.0650	0.0229	0.0099	0.0032	0.00121	0.00009	0.00005	0.00005	
3		0.0003	0.0187	0.1084	0.0335	0.0071	0.0033	0.00171	0.0004	0.00007		0.00002
4			0	0.01021	0.05565	0.01163	0.00209	0.00052	0.00034	0.00021	0.00005	
5				0.00002	0.00729	0.02391	0.00301	0.00069	0.00031	0.00014	0.00005	0.00005
6					0.00012	0.00603	0.00691	0.00052	0.00007			
7				0.00002	0.00009	0.00026	0.00352	0.00152	0.00016	0.00005		
8							0.00062	0.00288	0.00017			
9								0.00086	0.00073	0.00002		
10								0.00002	0.00043	0.00016		
11									0.00011	0.00014		
12										0.00004		

Fig. 5. Example of a scatter diagram [13]

3.3 Wave Energy Resource in Malaysia

Wave energy development in Malaysia is still in its infancy. According to Yaakob *et al.,* [34], wave energy has less potential to be utilized in Malaysia unless developing WECs operate in low-wave conditions. The climate of the SCS has been investigated by Muzathik *et al.,* [35] over the period between (1998-2009). It was concluded that the average power was between 0.15 and 6.49 kW/m. A research study carried out by Samrat *et al.,* [36] investigated the potential of wave energy locations across the Malaysian coastline using ADCP data obtained from the Malaysian Meteorological

Department Labuan (MMDL) from 2005 to 2012. The annual wave power is estimated to be around 8.5 kW/m, with Perhentian Island being the most energetic site with a yearly average of 15.9 kW/m. Researchers also proposed using an oscillating water column (OWC) as a wave energy harvesting device. Results from a study conducted by Mirzaei *et al.,* [37] to estimate the wave energy resource along the Malaysian coast facing SCS relying on wave data throughout 1979-2009 found that the annual average wave power in the northern section of the coast is higher than the southern section. It ranges between 2.6 and 4.6 kW/m. The power was contributed by H_s between 1m and 3m and a T_e of 6-9 s. In the research study by Yaakob *et al.,* [38], wave energy resource in Malaysia has been investigated in fifteen Exclusive Economic Zones (EEZ) using satellite altimetry wave data, Figure 6. The research revealed that the estimated average wave energy along the Malaysian coast overlooking the SCS is between 1.41 kW/m and 7.92 kW/m. As an extension to the work conducted by Yaakob *et al.,* [38], a study by Hashim *et al.,* [39] evaluated the theoretical, technical, and practical wave power potential in three locations within the EEZ of Malaysia in the SCS using satellite altimeter data. It was demonstrated that only 0.01 % of the theoretical wave power could be harvested if taking into consideration the performance and efficiency of the WEC. To assess the practical resource, several constraints were considered in the study such as submarine cables, underwater pipelines, gas and oil fields, and fishing activities. The study concluded that wave energy resource is too small when considering the technical and practical issues. Table 1 summarizes research studies on Malaysian wave resource assessment.

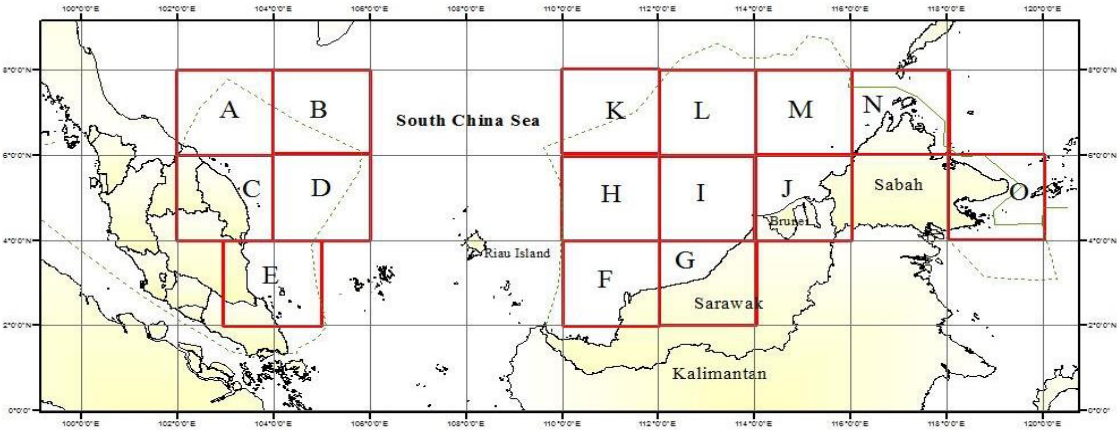


Fig. 6. Investigated areas for wave potential in EEZ Malaysia [38]

Mask analyses on Malaysian territorial waters, including Sabah and Sarawak, were conducted in the study by Nasir and Maulud [40]. These analyses considered several factors limiting or excluding an area to be exploited, such as marine borders, ports, bathymetry in territorial waters, oil and gas pipelines, and marine cables. The results of this study proposed Terengganu and Sarawak as the most potential locations for wave energy exploitation with an average of 2.8 and 8.6 kW/m respectively. The research study by Idris [41] assessed wave energy resources in fourteen zones along the Malaysian coastline using improved coastal altimetry data from Jason-2/PISTACH and AltiKa/PEACHI. It was concluded that the wave energy is between 8 to 20 kW/m and 4-5 kW/m during Southeast- and Southwest- monsoons, respectively. The bulk of this power is generated by H_s = 0.5 m - 1 m and the T_e = 4s - 5.5s. Although the analysis identified 10 of the 14 zones as high-energy zones, with energy storage of more than 40 MW h/m, the Strait of Malacca has a lower wave potential of < 2 kW/m.

Table 1
Summary of research for wave energy potential in Malaysia

Author	Study area	Data / Technology	Wave energy potential
Idris [41]	Malaysian Coastline: - South China Sea - Malacca strait - East Malaysia (Sabah & Sarawak basin)	Improved coastal altimetry data from Jason - 2/PISTACH and AltiKa/PEACHI	- Northeast monsoon 8-20 kW/m - Southwest monsoon 4-5 kW/m. - 10 of 14 zones recorded as high energy zones producing the energy storage of $>$ 40 MW h/m. - Strait of Malacca $<$ 2 kW/m.
Nasir and Maulud [40]	Malaysian territorial waters, including Sabah & Sarawak	Malaysia Meteorology Department (MET Malaysia), Satellite imaginary from National Aeronautics and Space Administration (NASA) & Malaysia Remote Sensing Agency (ARSM) 1992 - 2007	- Average wave power: 2.8 kW/m - 8.6 kW/m
Hashim *et al.,* [39]	Malaysian EEZ in SCS: - zone C - Sarawak waters - zone F - Labuan Island - zone J - along the upper coastline of Sabah	- Satellite Measurement (Altimeter) - Geographical Information System- (ArcGIS) tool	- Only 0.01 of the theoretical power can be harvested. - The practical resource is low when practical constraints are considered
Yaakob *et al.,* [38]	(15) zones in Malaysian Exclusive Economic Zones (EEZ)	Satellite Measurement (Altimeter)	- Average wave power: 1.41 kW/m - 7.92 kW/m - Annual wave energy: 7.10 - 69.41 MWh/m
Mirzaei *et al.,* [37]	East Coast of Peninsular Malaysia (SCS)	Numerical wave model simulation outputs: NOAA WWIII 1979 - 2009	Annual average of wave power: - Northern section 2.6 - 4.6 kW/m - Southern section 0.5 -1.5 kW/m
Samrat *et al.,* [36]	Locations around the Malaysian coastline: - Sarawak - Kota Kinabalu - Mabul Island - Mentagor Island - Perhentian Island	Acoustic Doppler Current Profiler (ADCP) 2005 - 2012	Average power output: - Sarawak 5 kW /m - Kota Kinabalu 6.5 kW /m - Mabul Island 7.91 kW /m - Mentagor Island 7 kW /m - Perhentian Island 15.9 kW /m Annual wave power in the Malaysian sea: 8.5 kW/m
Maulud *et al.,* [42]	Malaysian territorial waters, including Sabah & Sarawak	Geographic Information System (GIS)	- Kelantan & Terengganu are proposed locations for wave energy exploitation
Muzathik *et al.,* [35]	East coast of Malaysia: - Latitude 3.5° N 6.5° N - Longitude 102.0° E, 104.0° E	Wave Measurement Stations	- Average wave power: 0.15 - 6.49 kW/m - Annual wave energy: 17.69 MWh/m
Muzathik *et al.,* [43]	East coast of Malaysia: - Latitude 3.5° N 6.5° N - Longitude 102.0° E, 104.0° E	Wave Measurement Stations	- Average wave power: $<$ 6500 W/m - Annual wave energy:1.8 $\times$ 10.7 Wh/m

According to the above research, most of these studies were primarily focused on assessing the theoretical wave energy resource and identifying the most energetic sites along the Malaysian coastline. However, theoretical resource alone does not imply the suitability and availability of the wave energy resource without taking into account additional constraints that may limit or restrict resource usage. Technical constraints associated with the proposed conversion technique or practical limits that interfere with environmental, socio-economic, or other activities are examples of these constraints.

4. Tidal Energy

Tidal energy is the energy obtained from tides. In oceanography, tides are commonly defined as the periodic variations in sea level that occur due to the gravitational forces of the Sun and the moon. Tides contain potential energy associated with the vertical variations in sea level (tidal range) and kinetic energy, related to the horizontal motion of the tidal stream, and it is extracted by tidal current turbines [44,45].

Tidal range power is produced by creating a head difference between the two bodies of water. In this design, a dam-like structure (barrage) is built across an estuary in a region with an extensive tidal range [46]. Power can be generated using three different operational cycles in this technology: ebb, flood, and two-way generation [45]. In the ebb mode Figure 7, while the valve to the turbine is kept shut, the tides fill the basin through open sluices (a) until the high tide is reached. When the sea level out of the basin is sufficiently low (b), the turbine valve opens, allowing water back to the sea through the turbine to generate power [47]. To generate energy during the flood phase of the tidal cycle, the process is reversed for flood generation. Ebb and flood cycles are combined with pumping to reduce variability in two-way generation.

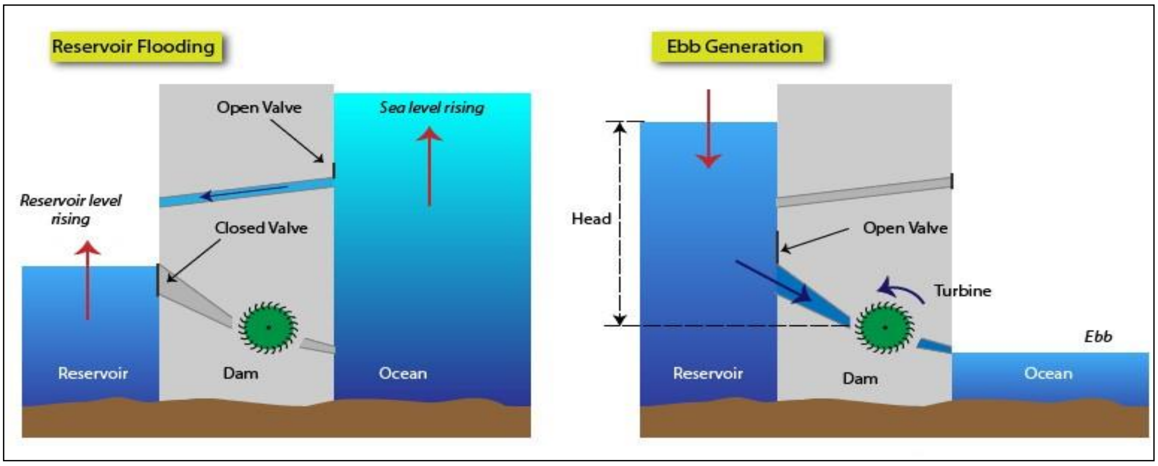


Fig. 7. Ebb regime of tidal range [47]

4.1 Tidal Resource Assessment

The amount of energy produced by a barrage depends on both the tidal range and the capacity of the basin [45,48]. A tidal range of at least 5m of is needed for the minimum viable power generation [9].

$$E = \frac{1}{2} A \rho g h^2 \quad (2)$$

where area of the barrage basin *A*, acceleration gravity g, water density ρ, the difference in head between the basin and sea h.

Unlike the tidal range approach which makes use of potential energy, tidal current turbines (TCT) are placed in the path of the tidal stream (channels or straits) to harness the kinetic energy of the tides and generate electricity. Based on the characteristics of the turbines, TCTs can be categorized into six classes as shown in Figure 8 [49].

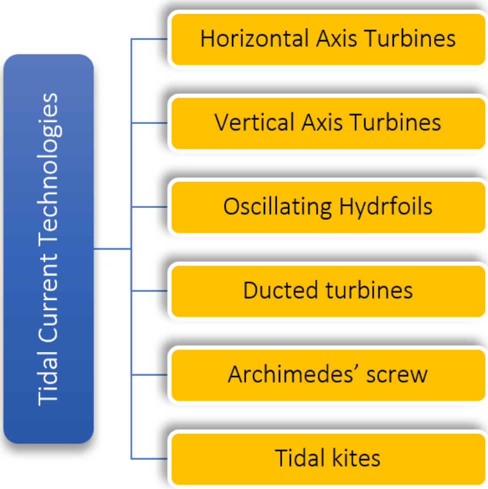


Fig. 8. Tidal current technologies [49]

Horizontal-axis turbines (HATCT): convert the kinetic energy of free-flowing water into rotational energy, which is then converted into electricity.

i. Vertical-axis turbine (VATCT): The primary operating principle of the (VATCT) is identical to that of (HATCT), with the exception that the tidal current rotates the rotors around the vertical axis to generate power.
ii. Oscillating hydrofoil: a hydrofoil is attached to an oscillating arm. The marine current moving on either side of the hydrofoil generates a lift. The tidal current flowing on either side of a wing results in a lift. This motion then drives fluid in a hydraulic system to be converted into electricity.
iii. Ducted turbine or enclosed tips: In some designs, ducts (Venturi effect) may be applied to either horizontal or vertical axis turbines to enhance the power capture by increasing the velocity passing through turbine blades [50].
iv. Archimedes' screw: is a helical system that is driven by flowing water causing the screw to rotate. The mechanical rotation is then converted to electricity [51].
v. Tidal kites: are comprised of a hydrodynamic wing, with a turbine connected, tethered by a cable to a fixed point that leverages flow to lift the wing. As the kite 'flies' loops through the water, the speed increases around the turbine, allowing more energy extraction for slower currents.

In the case of using the tidal current approach, according to Bahaj [30], the power output of the marine current turbines can be calculated as a function of the density of the fluid, swept area of rotor blades and flow velocity Eq. (3) [44]

$$P = \frac{1}{2}\rho A C_P V^3 \quad (3)$$

where flow velocity *V*, swept area of rotor blades *A*, power coefficient C_P, related to the percentage of power extracted from the tidal current by taking into account losses due to Betz's law and those assigned to the internal mechanisms within the converter or turbine. C_P for a tidal current turbine is between 0.35-0.5 [52].

The viability of a site for tidal stream device deployment is dependent on the available tidal velocity in that site as it reflects kinetic energy flux [53]. The higher the tidal velocity, the better. In general, tidal current turbines require a minimum cut-in speed in the range of (0.5 to 1 m/s) to start operating [54]. Another requirement for the tidal stream turbines is a depth that allows allocating the device with enough top and bottom clearance. In array deployment, longitudinal spacing, latitudinal spacing, and the area under high tidal speed are significant to determine the total number of TCTs at the selected site [55].

4.2 Tidal Energy Resource in Malaysia

Malaysia has the potential to harness tidal current energy. Few and limited studies have been carried out on ocean-based energy sources in Malaysia, and most of these studies are assessment studies, Table 2. Based on a study conducted by Lim and Koh [56], it was found that Sibu, Kota Belud, and Pulau Jambongan are promising sites for tidal energy generation with an estimated 8.604 GWh/year of electricity using TCT as shown in Figure 9. The impact of tidal stream energy on the Sarawak coastline was investigated by Rigit *et al.,* [57]. It was found that the Pulau Triso is the only most practicable site for tidal stream energy extraction in terms of tidal stream speed (2.06 m/s) and clearance of shallow-draft oceangoing vessels. Tidal stream resources in the Malacca strait were investigated by Maulud *et al.,* [42] using ADCP. They proposed Mentagor in Pangkor Island, a potential site for exploiting the tidal stream energy. This study also considered the seabed topology of the selected location regarding flow velocity, water depths, and seabed roughness. Other environmental issues such as effects on marine habitats, noise pollution, leakage, and magnetic field that may appear from TCT installation were discussed. In a study conducted by Yusoff *et al.,* [58] to assess the tidal energy in Malaysia based on the analysis of the tides table in 2014, it was found that Klang Port has a good potential for harnessing tidal energy with an average tidal range between 0.4 m and 5.3 m. Nazri *et al.,* [59] investigated sixteen locations across the Malaysian coastline to determine the potential of using the tidal range for power generation. Klang Port in Peninsular Malaysia meets the minimum height requirement (3m), while Sejingkat in Sabah and Sarawak exceeds this limit. Samo *et al.,* [60] have studied the potential of using tidal barrage for power generation in Malaysia. The results identified two locations: Pending in Sarawak and Tawau in Sabah with an estimated power of 115.4 kW and 67 kW, respectively. A research study conducted by Bonar *et al.,* [61] used an upper-bound approach to assess the maximum power available in five sites along the Malacca strait revealing that stream energy in Malaysia is insufficient to make a significant contribution to the mix, as shown in Figure 10. Yet, opportunities to use low-speed tidal turbines on a small scale and off-grid electricity schemes. The results also showed that Port Dickson is the most promising location of all sites in the study. A preliminary study by Musa *et al.,* [62] proposed a small-scale hydro turbine for power generation at two locations: Kg. Tual, Raub, Pahang and Gunung Ledang, Tangkak, of estimated power of 266.99 kW and 4.75 kW, respectively.

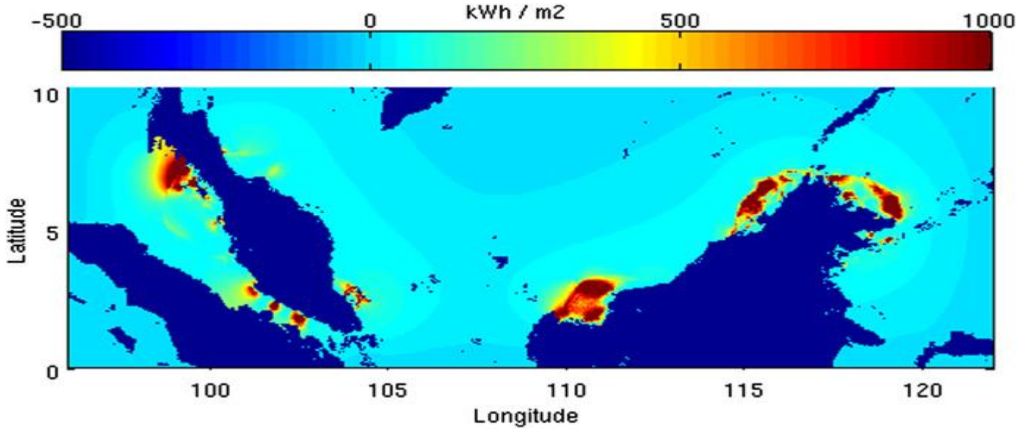


Fig. 9. Energy density profile of tidal current across Malaysia [56]

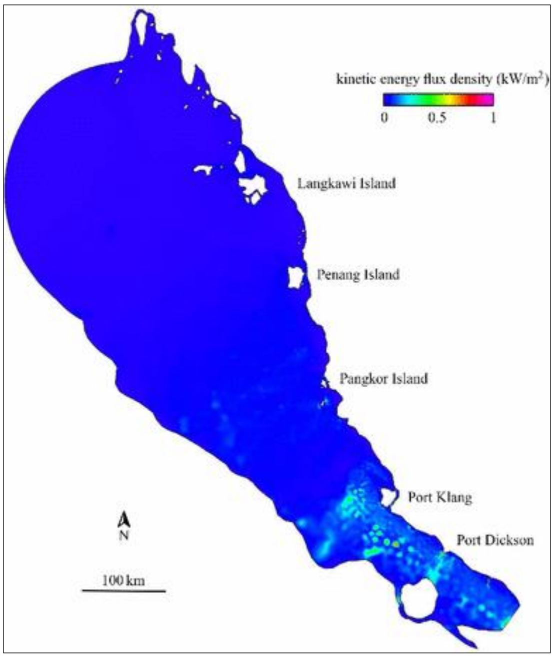


Fig. 10. Potential areas for tidal stream energy at the Straits of Malacca [61]

Table 2
Summary of research for tidal energy resource in Malaysian

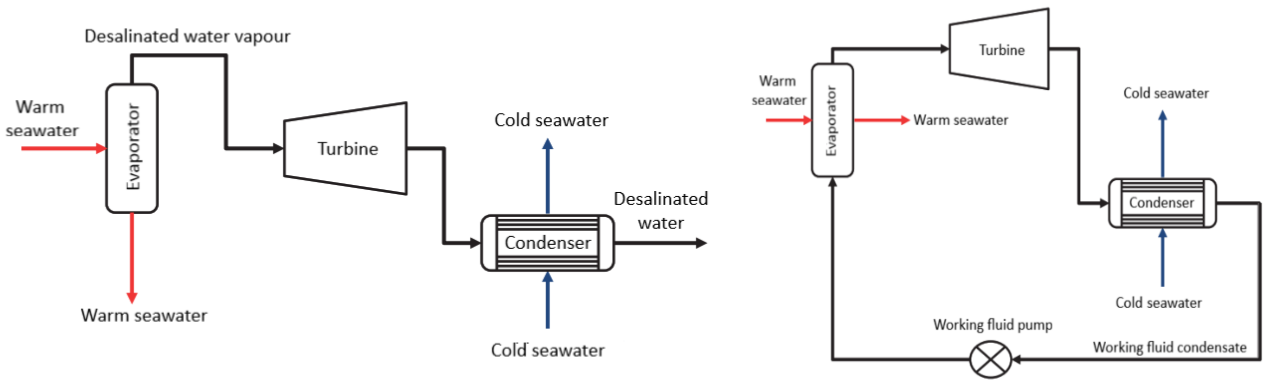
Author	Study area	Data/Technology	Tidal energy potential
Musa *et al.,* [62]	- Kg. Tual, Raub, Pahang - Gunung Ledang, Tangkak, Johor	Altimeter and water velocity probe	Suitable locations for small hydro turbines: - Kg. Tual site 266.99 kW - Gunung Ledang site 4.75 kW
Bonar *et al.,* [61]	Malacca strait: - Langkawi island - Penang island - Pangkor island - Port Klang - Port Dickson	Hydrodynamic Numerical model (DG ADCIRC) Upper Bound Approach Bathymetry data are obtained from the GEBCO (General Bathymetric Chart of the Oceans)	Port Dickson's available power per swept area is > double that at the following best site, Port Klang - Port Klang 20.03 (kW/m^2) - Port Dickson 53.27 (kW/m^2)
Samo *et al.,* [60]	The coastline of Sabah & Sarawak	Table tides obtained from the Sarawak marine department & analyzed by Arc GIS	Two potential areas for tidal barrage: - Pending in Sarawak 115.4 kW (6.2 m) - Tawau in Sabah 67 kW.
Nazri *et al.,* [59]	(16) locations across the Malaysian coastline	Tidal stations measurements from Malaysia Metrology Department (MMD) 2007 - 2011	Potential areas for tidal barrage: - Lumut: (basin area 3.0 km^2) 74.3 GWh - Pelabuhan Kelang: (0.2 km^2) 17.49 GWh - Tanjung Keling: (0.8 km2) 12.89 GWh - Kukup: (0.3 km2) 10.94 GWh - Johor Bahru: (0.5 km2) 17.05 GWh - Sejingkat: (0.3 km2) 24.86 GWh
Yusoff *et al.,* [58]	Malaysian coastline	Tides Tables Malaysia (2014)	- Tidal range in Selangor (Pelabuhan Klang): 0.4 m - 5.3 m
Sakmani *et al.,* [63]	Strait of Malacca (Mentagor - Pangkor Island)	Acoustic Doppler Current Profiler (ADCP)	- Available tidal streams around Pangkor island 1 - 2 m/s
Rigit *et al.,* [57]	(8) sites along of Sarawak coastline	- Tidal stream tables - On-site measurement in Triso Island	- Tidal stream speed at Triso Island 2.06 m/s
Lim and Koh [56]	Malaysian coastline: - Sibu, - Kota Belud - Pulau Jambongan	- Tidal Observation Records (2005) - TPXO Software Output Princeton Ocean Model (POM)	For tidal stream approach: - The total amount of electricity can be generated by MCT in these (3) locations: 14.5 GWh/year
Lee and Seng [64]	(6) Sites across East and West Malaysia	Tidal Observation Records (2005)	For barrage approach: - with a tidal range of 4.38 m (Sejingkat), a single turbine of (5 m) blade length can generate 14.970 kWh monthly.

Lim and Koh [56] in their study, have considered various technical constraints affecting the deployment of Horizontal Tidal Current Turbines (HTCTs), such as water depth and cut-in speed. In the result, they excluded unsuitable sites where water depths ($<$ 20m) and flow velocity $<$ 1m/s. At the same time, other aspects of the array configuration in terms of the number of HTCTs, longitudinal and latitudinal spacing between HTCT and total area were also considered. On the other hand, they did not study the suitability of the selected regions in terms of environmental issues and interference with other activities. The investigation study by Sakmani *et al.,* [63] revealed that Mentagor Island is suitable for tidal stream energy. In this study, several factors, mostly related to environmental issues, have been investigated. However, since the purpose of this study was limited to determining the suitable location, no theoretical resource has been estimated or conversion technology was proposed.

5. Ocean Thermal Energy Conversion (OTEC)

OTEC is a renewable energy source that generates electricity by exploiting the temperature difference between the warm surface waters of the oceans, heated by the Sun, and the deep cold waters. OTEC power systems are basically divided into three categories

i. Open cycle OTEC systems: utilize warm surface water as a working fluid. The surface water is pumped into a chamber where a vacuum pump reduces the pressure to allow the water to boil at a low temperature to produce vapour. The vapour drives a turbine coupled to a generator and then is condensed using deep cold seawater pumped to the surface. Desalinated water is being generated through this process as shown in Figure 11(a) [65].
ii. Closed cycle OTEC systems: use a working fluid with a low boiling point. The vapour drives a turbine coupled to a generator that produces electricity. The vapor is then condensed in another heat exchanger (condenser) using cold seawater pumped from the ocean's depths through a cold-water pipe. The condensed working fluid is pumped back to the evaporator to repeat the cycle (Figure 11(b)). In general, refrigerants or ammonia can be used as the working fluid, but water-ammonia mixtures are also used.
iii. Hybrid cycle OTEC system: it combines both closed and open cycle characteristics. A vacuum chamber quickly evaporates warm seawater. In this way, water steam causes a working fluid to reach its boiling point. Electricity is generated by expanding the refrigerant in the turbine, followed by the vaporized fluid condensing inside a heat exchanger, thus generating desalinated water. Ammonia, fluorinated carbons, and hydrocarbons can be used as working fluids.



(a) (b)

Fig. 11. OTEC flow diagram: a) open-cycle b) closed-cycle [66]

5.1 Ocean Thermal Energy Conversion (OTEC) Resource Assessment

OTEC resource viability is proportional to the square of the temperature difference between warm surface water and cold deep water [67]. Therefore, for proper site selection, climate

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characteristics that may affect throughout the year should be assessed. Generally, regions with ΔT ≥ 20°C are considered a potential interest resource [68]. The OTEC net power density can be determined from Eq. (6) [69]. The pumping power density defined in Eq. (5) corresponds to 30% of the gross power density (power generated by the heat engine) at standard conditions ΔT = 20°C and T = 300 K [70].

$$P_{gross} = w_{cw} \frac{3\,\rho\, c_p\, \varepsilon_{tg}\, \gamma\, (\Delta T)^2}{16\,(1+\gamma)\, T} \tag{4}$$

$$P_{pump} = w_{cw} 0.30 \frac{\rho\, c_p\, \varepsilon_{tg}\, \gamma}{4\,(1+\gamma)} \tag{5}$$

$$P_{net} = P_{gross} - P_{pump} \tag{6}$$

$$P_{net} = w_{cw} \frac{3\,\rho\, c_p\, \varepsilon_{tg}\, \gamma}{16\,(1+\gamma)} \frac{(\Delta T)^2}{T} - P_{pump} \tag{7}$$

where OTEC net power P_{net}, OTEC equivalent deep seawater vertical velocity w_{cw}, seawater density ρ, seawater specific enthalpy C_p, ratio of OTEC surface seawater flow rate over OTEC deep seawater flow rate, combined OTEC turbo-generator efficiency ε_{tg}, available temperature difference ΔT, absolute temperature of OTEC warm seawater T, OTEC seawater pumping power P_{pump}.

5.2 OTEC Resource in Malaysia

In Malaysia, particularly in the Sabah Troughas shown in Figure 12, the possibility to generate electricity from ocean thermal energy has attracted interest (Table 3). Results from the marine survey at SCS from 2006 to 2008 (MyMRS) revealed the temperature difference (3°C at 2900 m water depth compared with 29°C at the surface) at *Sabah* Trough makes OTEC viable to be harnessed in Malaysia.

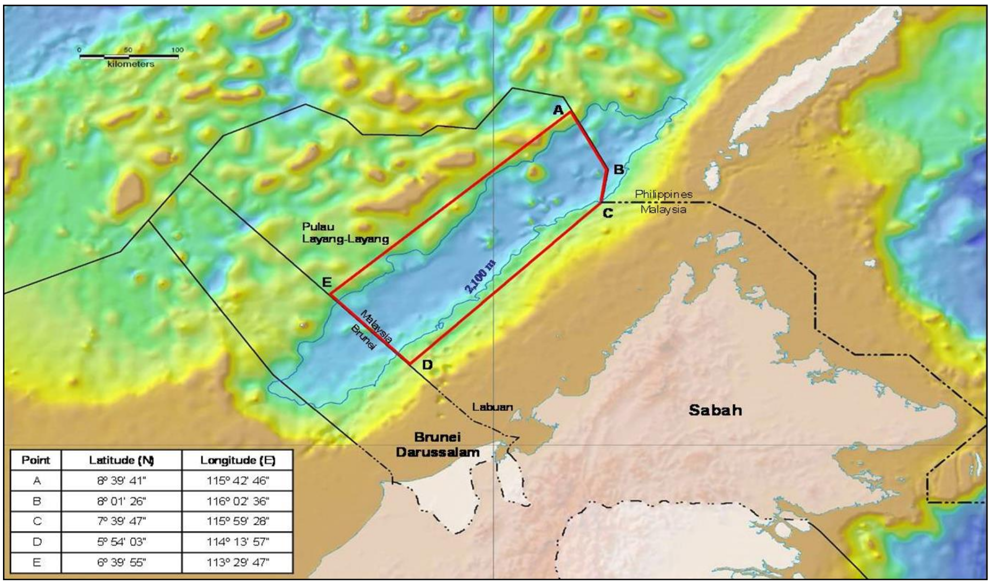

Fig. 12. Location of Sabah Trough [71]

Table 3
Summary of research for OTEC resource in Malaysia

Author	Study area	Data / Technology	OTEC potential
Thirugnana *et al.,* [74]	East Malaysia - Sabah coast: - Semporna - Tawau - Kudat - Pulau Layang-Layang - Pulau Kalumpang	Oceanographic data from Japan Oceanographic Data Center JODC Hybrid OTEC	Estimated power generated by an OTEC system within the Malaysian EEZ, similar to or four times greater than the current government target (3.14x106) for ORE power generation by 2025
Idrus *et al.,* [73]	Malaysian Sea (Shallow water)	Geothermal waste energy & OTEC (Ge-OTEC)	- Max estimated net power: 32.593 MW
Idris *et al.,* [72]	Sabah Trough	Temperature/depth profile obtained from a marine survey (MyMRS 2006-2008)	- Net power: 133.8162 MW
Jaafar [71]	Sabah Trough	T_S 29°C & T_D 3° at 2900 m water depth (MyMRS 2006-2008)	- Estimated generated power: 50 MW

According to Jaafar [71], the power generated from Sabah Trough may exceed 50 MW. The temperature/depth profile obtained from MyMRS 2008 in the research by Idris *et al.,* [72] was used to calculate the net power produced at Sabah Trough. This research used a previously proposed model by Lockheed Martin to estimate OTEC potential [67]. It has been concluded that the net power at Sabah Trough is around 133.8 MW. In a study conducted by Idrus *et al.,* [73], a new concept was proposed called (Geo-OTEC). Both OTEC systems and offshore geothermal waste energy are combined with increasing temperatures. The researchers concluded that the maximum net power from Ge-OTEC is estimated to be 32.5 MW. In a study by Thirugnana *et al.,* [74], the power generated by a hybrid OTEC system suggested for deployment in the Malaysian EEZ near Sabah's coast was estimated. The results conclude that the system can generate power equal to or four times higher than the Malaysian government's target set in 2025.

6. Challenges and Constraints to ORE Development

Despite the promising potential for ORE to contribute significantly to energy needs, assessing the theoretical or technical resources alone may not be preferable for determining ORE viability. The practical resource assessment, on the other hand, will determine the suitability of ORE and how it can contribute to electricity generation since it defines the remaining portion of the technical resource produced once all other constraints, such as socio-economic and environmental, have been accounted for [2,75]. Some of these constraints will directly prevent resource exploitation, while others will impose limitations or make the area less suitable. These constraints may include:

6.1 Socio-economic Constraints

The factors affecting public opinion on ocean energy development are known as socio-economic constraints [7]. The benefits of ORE development will affect public perception [76]. These benefits may include job creation and economic growth, providing a new and assimilated grid and reducing emissions of green gases [77]. However, the ORE project has its negative impacts that involve reducing access to space and environmental issues. The high capital cost required to develop ORE projects is the major challenge. The current unit cost of energy generated is much lower than that of existing marine energy technologies when compared to other renewable energy generation technologies [65].

6.2 Technical Constraints

One of the main challenges to ORE project deployment is the technical issues related to the installation phase. Only a few full-scale devices have been installed so far, limiting practical experience. The successful installation of ORE infrastructures requires knowledge and technical expertise to overcome installation problems [78]. The technical issues are connected to the costs of deployment and maintenance of the ORE device [78]. ORE devices will operate in a harsh environment which imposes extra effort and capital, ensuring the subsystems can withstand the underwater conditions over a long period. Bottom-mounted tidal devices, on the other hand, require significant foundations [7]. The most common issues ocean energy devices will face; are biofouling (moorings, floating or submerged parts of the device) and corrosion.

6.3 Environmental Constraints

The exploitation of ocean energy, as with any energy source, is not without its downsides. Deployment of ocean energy technology in a surrounding marine environment is generally associated with unknown environmental impacts, mainly due to the lack of experience in deploying and operating ocean technologies [7]. For this reason, the Environmental Impact Assessment (EIA) of ORE is implemented (although for small-scale projects, a full EIA may not be required) to ascertain the potential impacts of ORE deployment in the environment [79]. In contrast, Life Cycle Assessment (LCA) is necessary to evaluate the environmental impacts of ocean energy devices throughout their entire life cycle [80]. The LCA covers all life cycle stages associated with manufacturing, operation, maintenance and decommissioning) and in some cases, also involve the mooring and foundation stages and the cable connection to the grid [81]. The possible environmental impacts of the ocean devices will depend on characteristics such as the energy source, construction materials, and device operation principle [82]. Environmental issues with WEC are challenging to assess. Still, they may include competition for space, noise and vibration, electromagnetic fields, disruption to biota and habitats, water quality changes and possible pollution [3]. Excessive environmental loads have detrimental effects on offshore structures, such as compromising their structural integrity. Advanced control mechanisms have been investigated to improve the reliability of offshore structures during operations [83-85].

Similar to WECs, benthic habitats will be affected by TCT and arrays due to the change in water flows, the composition of the substrate, and sediment dynamics [7]. Other potential effects include the mortality of fish passing through turbines (blade strike) and the collision risk of marine mammals with tidal stream farms [86,87]. Due to tidal stream farms, noise disruption in turbulent waters affects marine mammals, which is another critical issue related to tidal energy converters.

While it is unavoidable that physical, chemical, and biological impacts would occur during the construction and operation of an OTEC facility, the precise magnitude and extent of these impacts are still unknown [88]. The effects of OTEC plants such as temperature, salinity, dissolved oxygen; pH; trace metals; and abundance, diversity, mortality, and behavioural changes in plankton, fish, marine mammals, and other biotas should be monitored [89]. The OTEC plant’s cold water discharge may alter benthic ecosystems and impact coral reefs [86]. In the case of closed-cycle OTEC power systems, additional concerns may arise from ammonia which is highly toxic to marine life and could be subject to leaks and spills [90].

6.4 Policies and Regulations

Governments encourage the search for alternative renewable energy sources such as ocean energy to reduce reliance on fossil fuels and diversify energy supply. However, there is a lack of both concrete actions relevant to policies and legal framework and detailed supporting initiatives to accelerate the development of the ocean energy sector [7]. Policy and regulatory frameworks have been long claimed as being among the most significant non-technical barrier affecting the growth of the ocean energy industry [91]. It is thus crucial to determine the current legal framework's strengths and weaknesses to identify the best approaches and conflicting regulations. Furthermore, more financial support assigned for ongoing research should be provided through the establishment of new funding mechanisms dedicated to the ocean energy sector [10].

7. Conclusions

Despite the perspectives associated with the ORE worldwide, the role of ORE in Malaysia remains negligible. This paper has highlighted the levels of ORE resource assessment that would help obtain a detailed characterization of the resource specifically for wave, tidal, and OTEC, focusing on the factors that constrain or limit the utilization of such resources. Finally, several conclusions can be made

i. Most ORE assessment studies in Malaysia are directed to theoretical resource assessment, which may not reflect the viability and suitability of the resource.
ii. ORE exploitation requires a robust assessment methodology to determine the restrictions, constraints, and challenges that need to be overcome for utilizing ORE sources, especially those related to socio-economic and environmental issues or non-technical barriers related to policies and regulations.
iii. Proper technology selection, techniques, and methods for ORE resources would help in its utilization.
iv. Malaysian wave energy resource is less energetic compared to other resources but still can be harvested (suppose no limiting constraints in the selected location) with the focus on technologies operating in low wave conditions.
v. The tidal stream approach is economically viable to be implemented in Malaysia compared to the less favourable tidal range due to the high construction cost.
vi. OTEC is a promising resource, primarily in the Sabah Trough, with a capacity of more than 50 MW; however, an Environmental Impact Assessment (EIA) has yet to be implemented.

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