# A Use Case of Exclusive Economic Zone of Pakistan for Wave Power Potential Estimation

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## Abstract

The demand for energy is constantly rising in developing countries. Ocean waves with continuous energy flux can contribute to universal energy production. The wave energy has its advantages of renewable, non-polluting and large storage, however, the technological solution to extract energy from oceans is still at early stages. In this paper, a strategy is devised to estimate wave power potential for a developing country. Pakistan is considered as a use case on the basis of less renewable energy share and facing energy crises. In this study, wave energy potential is estimated for power generation by excluding the sensitive areas from the exclusive economic zone. The year long significant wave height and mean wave period data set is used for the purpose. A GIS based multi-criteria overlay analysis model is implemented using different restriction and weighted factors such as ocean bathymetry, distance to ports and shoreline. The results show that average wave power is peaked at 9.15 kW/m in the summer season and 85% of Pakistan economic zone is suitable for wave farm development. The wave energy potential assessment is coupled by extractable power estimation that is worked out by assessing the performance of commercial wave energy converters in regional context.

**Keywords:** Wave power, exclusive economic zone, wave potential, wave height, wave period

## 1. Introduction

The demand for energy has risen quite significantly over the past few years. The growth of a developing nation depends on meeting energy demand. As economies grow, increasing population demands more energy. According to the World Bank survey, the world population has increased by 36 % in the last two decades, whereas worldwide energy demand increased up to 54 % [1]. This rising demand for energy results in a push for the countries to generate energy from untapped energy sources [2]. Renewable energy sources are sustainable and have minimal carbon emission [3]. Renewable energy sources including solar, wind and geothermal have remained the focus of research and technology whereas, ocean's wave energy is still widely untapped renewable source and has the potential to influence global energy production. Wave energy from oceans can be used for electricity production as it is a resource potential of up to 2TW globally, which is around one-fifth of the current global energy production [4]. The wave energy ensures continuous supply up to 90% of the time [5], with the added benefit of environmental friendly production [6].

It is estimated [4] that the contribution of global renewable energy will increase to 29% of the total energy resource used for electricity generation by 2040 and wave and tidal energy sector will be fast growing. Ocean waves are more continuous and predictable than wind and sunlight [7], which makes wave energy more reliable in electricity production [8]. Many developed countries such as Sweden, USA, UK, Australia and Portugal have already explored ocean potential along their coastlines and are now implementing the wave energy converters (WEC) for electricity generation [9]. Wave energy also offers much higher energy densities which indicate that devices can extract more power from a smaller volume of the ocean at a consequently lower cost [10]. Researchers [11]–[13] proposed different techniques to assess ocean wave energy potential. The assessment of the wave energy resources include identification of the areas with higher energy densities, quantification of average energy resources annually by using parameters such as significant wave height (SWH), wave energy period and mean wave direction [14]. These parameters are significantly higher at particular spots both in the upper and lower hemisphere. Ocean waters close to Europe, North America, Australia and Pacific rim countries have clearly a huge potential for tapping ocean wave energy, where the wave disturbances exist all year round in significant heights [15]. There is another aspect of high variation of high energy locations in the seas which is often neglected in resource assessments, as long-term wave resource variations can have an impact on designing of wave energy converter farms and extraction technologies. [16]

In order to observe ocean wave energy potential, the major challenge is to identify high energy density locations. Geographic Information Systems (GIS) is used to identify these types of locations. Maulud et al., [17] conducted geo-spatial multi-criteria analysis in GIS to determine the suitable area for wave energy farm in Malaysian territorial waters. Similarly, temporal trends of the wave power depending upon wave height and wave period were analyzed along the Atlantic coast of the USA with the help of GIS [18]. Mork et al. [19] used ArcGIS to compute the regional theoretical wave power worldwide while excluding the areas having a low level of power ($P \leq 5kW/m$). It is concluded that the total theoretical resource of the Asia region, in deep waters, is 547GW [19]. Similarly, the theoretical global wave power potential is estimated and it is found that around 4.6% of the overall worldwide wave energy could be extracted [20]. The average energy flux for Sweden has been calculated using WAM and SWAN wave models by collecting eight years of wave data from 13 different sites. The findings indicate that Swedish coast has an approximate energy power of 2.4 kW/m in the Kattegat, 2.8 kW/m in the nearshore Skagerrak and 5.2 kW/m in the offshore Skagerrak [21]. While emphasizing on the Asian region, it is observed that Malaysian territorial water have a potential power of 2.8kW/m to 8.6kW/m which can be utilized in wave power generation [22].

The broader perspective of this work is to find wave power potential for developing countries where significant power shortages exists. A possible sustainable solution for the economies of such countries is envisaged where in any given country, the national energy mix are still devised around fossil fuels and energy demands are sharply on the rise. Though the South Asian coastlines are not known for rough sea situation for significant amount of time in a calender year, therefore, the average potential is estimated far less than the gloabal average (See Fig. 1).

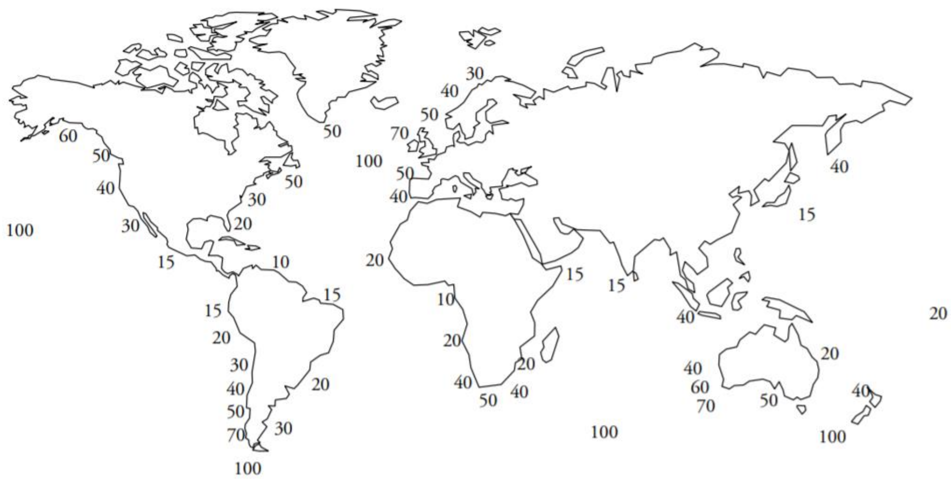



Figure 1: Approximate global distribution of wave power levels in kW/ m [23]

Building on an already weak notion, where the growing demand is set to meet through renewable, the aim of this paper is to devise a methodology to estimate the ocean wave power potential by making a use case of an exclusive economic zone (EEZ) of a developing country located in and around Indian Ocean water. In section 2, a methodology is adopted that is followed in this work to identify the suitable areas in the EEZ of a developing country. An overlay technique is used to systematically avoid the preserved sanctuaries, International communication lines and other logistically active zones. Section 3 reveals the detailed information of the use case. In section 4, the technique is implemented to select potential deep water portions in the marine economic zone. Section 5 of the paper is dealt with the calculations of ocean's wave power at one given site using the year round data set. This has allowed us to estimate the extractable power potential of the economic zone using wave parameters that is useful in the selection of technologies best suited for local conditions (Section 6). Note that these weather conditions prevail in most of the Indian Ocean water countries and the proposed methodology can be generalized for most of the countries located around the region. The paper is concluded in section 7.

## 2. Methodology

The methodology used in this paper consists of different stages to estimate wave power potential in the marine EEZ of a representative developing country. In the first stage, a developing country is taken as the use case after observing its renewable energy share in overall energy mix. In the next stage, suitable areas in the EEZ were identified for wave power extraction by using GIS.

Sensitive areas such as commercial ports, submarine cable routes and oil and gas routes are excluded from the EEZ using this system. In the next stage, the temporal variations in the wave data have been studied and the ocean wave power potential has been estimated in the EEZ of the use case. The annual average energy potential is quantified by using SWH and wave period. In the last stage, the estimated power pattern knowledge is transformed in to the design of buoy farms suited for energy extraction in local conditions and utilizing available wave energy potential.

The use case study is employing the GIS and the ovelay technique has a potential to be generalized in terms of further technology selection. This technique can be impactful for the developing countries in the selected International region where a unique set of power extraction technology can be pursued based on the analysis in the temporal variations of use case wave height and time periods. Planners in these countries can get benefit of the adopted strategy and develop their future energy mix national plans accordingly.

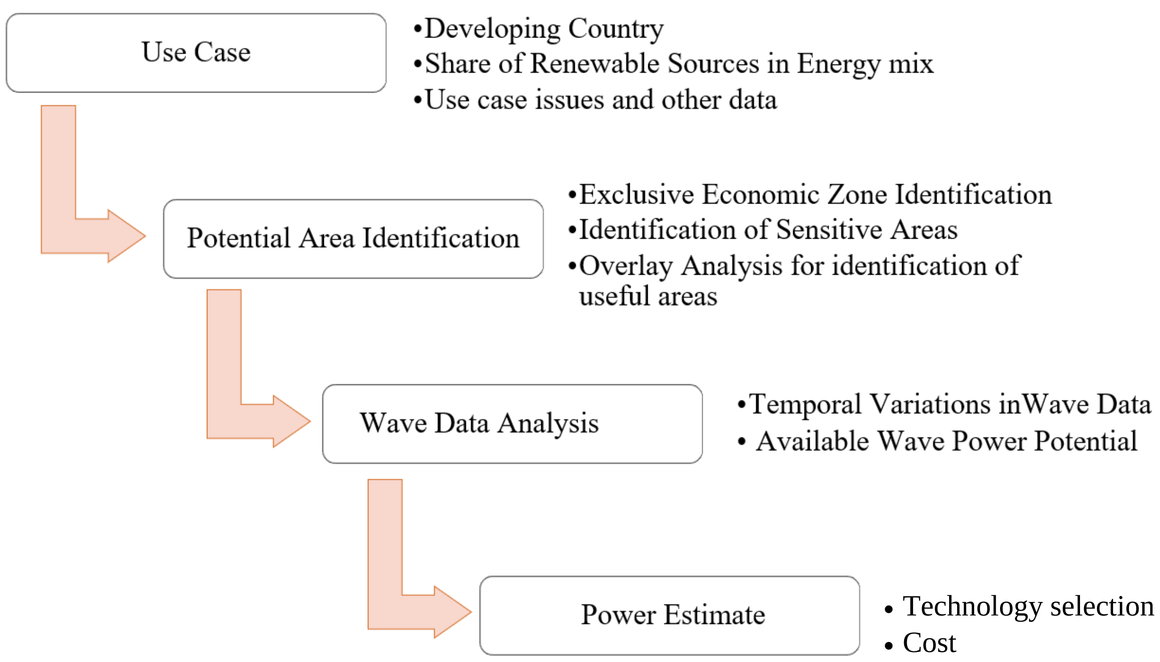



Figure 2: Schematic of Methodology

## 3. Use Case

Energy shortfall is a common problem for emerging economies of South Asia and Africa [24]. For the purpose of generality, the middle income, large population density, fast growing developing potential and existance of large gaps in energy demand and supply are significant contributors in gearing this study to select a North Indian Ocean region, which overwhelmingly comprised of major portion of South Asia. This use case is focusing on developing countries of South Asia that are generating 17% of electricity from renewable energy sources to meet their energy demands [25]. These renewable energy sources include hydro, solar, wind, biofuels and waste, whereas it is observed that 63.6% of renewable electricity is generated only from hydro energy [25]. However, hydropower plant projects face many geographical, logistical, and environmental challenges such as water conflict among countries [26]. The construction of dams is highly expensive due to its huge area, high capital cost, operational challenges, and longtime completion process. Local people living near the dam sites are also susceptible to floods and high water currents as so the survey conducted by World Commission in 2000 indicates that 40 to 80 million people are physically displaced to facilitate the construction of dams [27]. Similarly, dams have harmful impacts on the ecosystem as it is contributing to global warming. There is a demand to utilize renewable energy sources other than hydro in electricity generation, and explore untapped energy sources to meet energy requirements. [28]

Wave energy potential in the Indian Ocean is mostly untapped. For this study, a South Asian country is considered for its wave energy potential estimation based on low non-hydro renewable energy share. The study region has many developing countries which share the majority of the North Indian Ocean shoreline. The three countries having longest coastline in the region are India (7,516 km), Srilanka (1340 km) and Pakistan (990 km). The long shoreline of these countries can be utilized for electricity production using wave energy. Figure 3 shows, the share of non-hydro renewable energy sources in total electricity production of Pakistan, India and Sri Lanka from the year 2010 to 2016. The figure shows that India is utilizing more renewable energy sources other than hydro in its electricity production. In 2016, India has peaked its electricity from non-hydro renewable energy sources to 6.83%. Furthermore, its share of renewable energy has increased by 3.69% overall, from 2010 to 2016. Sri Lanka is also increasing its renewable energy share in electricity production since 2010. During 2010-2016, Sri Lanka has increased its non-hydro renewable share from 0.95% to 3.08%, showing an overall increase of 2.13%. Pakistan has the lowest share of renewable energy in electricity generation among these countries during this period. Pakistan peaked its renewable energy share to 1.44% in 2016. These figures show that Pakistan has a dire need to increase its renewable energy share and well suited as a representative country for use case due to large population size, high energy demand, sizeable shoreline and moderate developing growth rate over the past two decades.

Pakistan has an average electricity shortfall of 6000 MW with an increasing trend in summer [28]. The electricity generation and demand gap of Pakistan are shown in Figure 4 from 2010 to 2018. The average electricity generation and demand gap is about 1000 MW from the year 2010 to 2013, increased to 5000MW in 2016. With this increasing trend, the gap between generation and demand is expected to reach further high, if timely actions have not been taken. This is coupled by distribution system capacity problem and circular debt in the power sector. The renewable energy generation is a sustainable alternative for the current energy scenario of Pakistan. In this study, we will estimate ocean's wave power potential for electricity generation of Pakistan coast line as a use case country. We will find suitable areas having maximum wave power potential in the EEZ of Pakistan and also estimate wave power potential throughout the year, using acquired wave data in the next sections. Overall, Pakistan as a representative use case is characterized with large population, emerging economy status, large shore line and EEZ, many deep water areas in the marine zone, International connectiveity to trade routes and geostrategic location, huge differences in demand and supply, power break down history, untapped wave power and renewable potential and seemingly mild weather conditions of the marine zone.

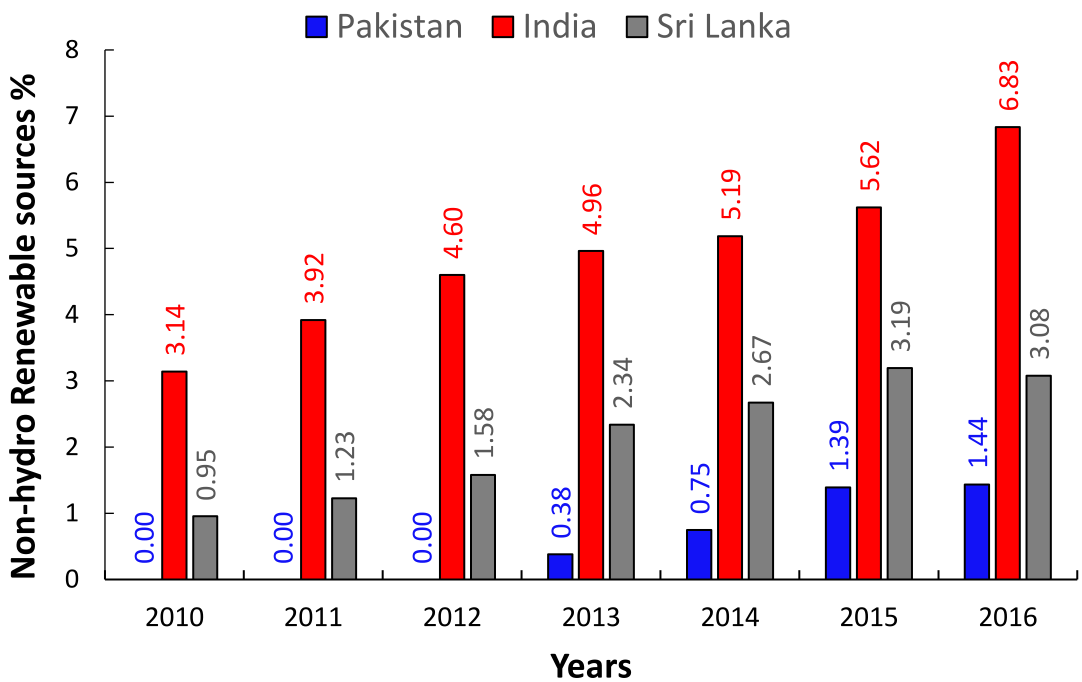



Figure 3: Percentages of non-hydro renewables sources in total electricity production [25]

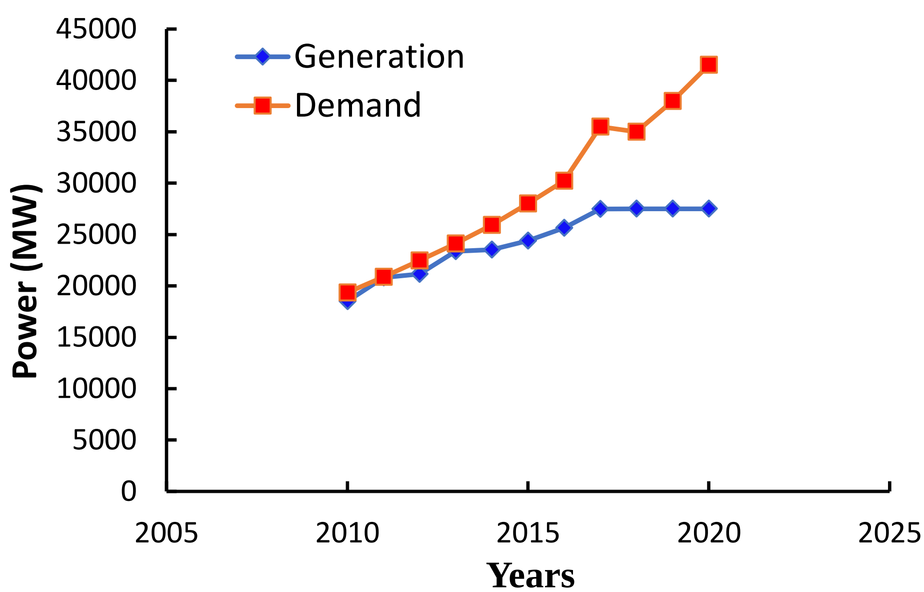



Figure 4: Power generation and demand in Pakistan [29]

## 4. Potential Area Identification

The potential areas for wave energy extraction in Pakistan's ocean waters are identified by using an overlay technique. Potential areas are those which offer favorable wave conditions at different ocean depths. The analysis identifies all the protected and sensitive zones and creates a filter to find the most suitable locations for generating electricity from ocean wave energy. These protected areas include ports, marine parks, oil and gas routes, and submarine cables. After applying the overlay analysis on sensitive and protected areas, the remaining useful areas can be found.

### 4.1 Exclusive Economic Zone Identification

Any country in the world having a sea shoreline, has its own EEZ that has importance in transport, food, tourism, logistics, and energy sectors. It is an area over which countries have specific privileges, such as the use of marine resources and utilization for energy generation [30]. Pakistan, a South Asian country, stretches from 61°E to 76°E longitudes and 24°N to 37°N latitudes comprises of a long shoreline of about 1000 km [31] with the Arabian Sea in the South region. Its EEZ stretches from the baseline out to 350 nautical miles from its coast [30]. ArcGIS is used to identify the EEZ of Pakistan. ArcGIS is a GIS, which works with maps and topographical data. This system helps the users in visualizing, enquiring and analyzing the geospatial data [32]. The vector data set for the EEZ of Pakistan has been extracted as a KML file from the World Marine Regions list. This input dataset is used to map and visualize the results in both vector and raster formats in GIS. Figure 5 shows the EEZ that has an area of approximately 224,387 square km.

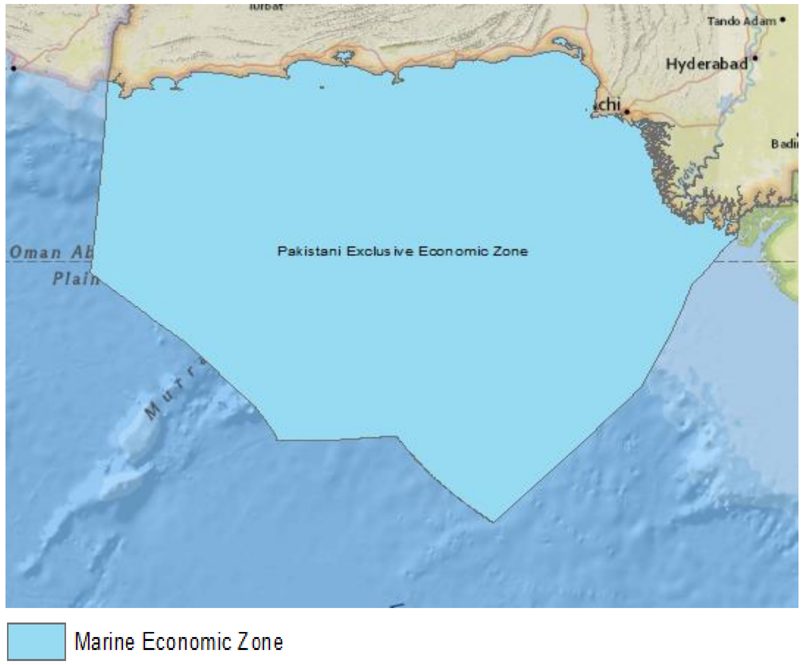



Figure 5: Exclusive Economic Zone

### 4.2 Identification of Sensitive Areas

The EEZ of a country is always busy in executing different coastal activities related to transport, food, tourism, logistics, and energy sectors. Therefore, a complete area of the economic zone cannot be utilized for generating wave energy. The submarines cables passing from EEZ of Pakistan are considered as sensitive areas because problems can arise during the routine maintenance of cables if wave power extraction farms are developed near the running cables. There are six big ports in Pakistan, where Karachi port is the busiest port of Pakistan while Gwadar port is deepest across the world, which are also sensitive areas [33]. Similarly, marine protected zones are sensitive areas reserved by law for the protection of species and other natural and cultural resources enclosed by oceans. Pakistan has one such area named as Astola Island, the largest island along the coast of Pakistan, which is recently declared as marine protected area [34]. It is in Balochistan province, near 39 kilometers East of Pasni. It is home to several species of marine and terrestrial animals and plants. The shoreline is also home to the activities related to fisheries that occur in the continental shelf, i.e., within 100 nautical miles from the coastline. Karachi fish harbour is the biggest in the country that handles about 90% of seafood catch of the country. Moreover, water depths variation inside the zone is also considered as this study finds only deep water wave power potential. The geospatial coordinates of all these variables are extracted from different sources given in Figure 6 and processed in ArcGIS shown in Figure 7.

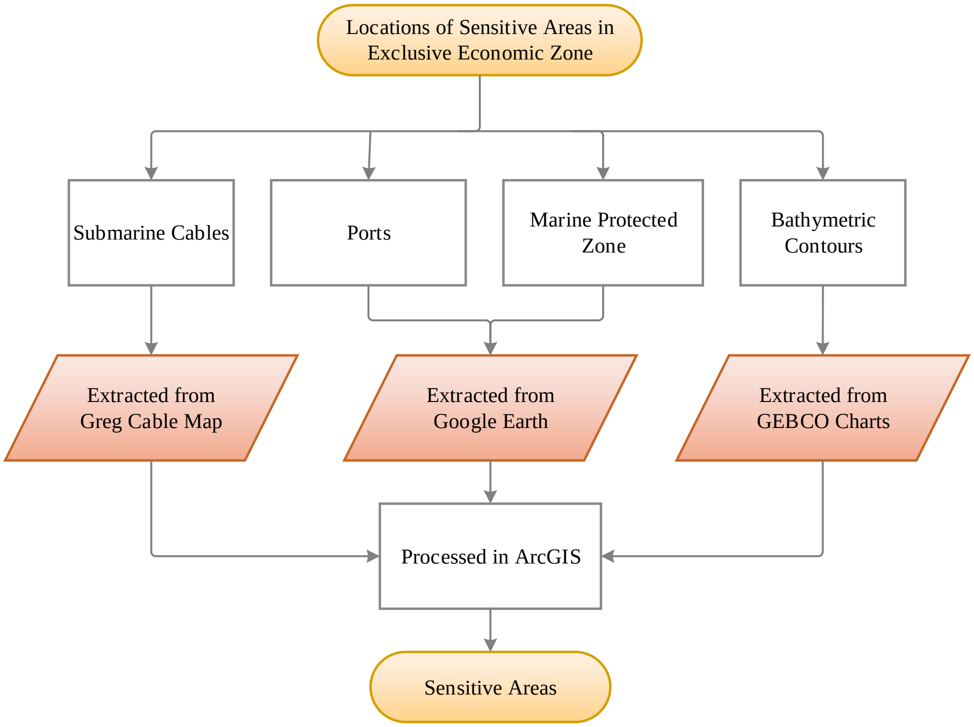



Figure 6: Location of Sensitive Areas

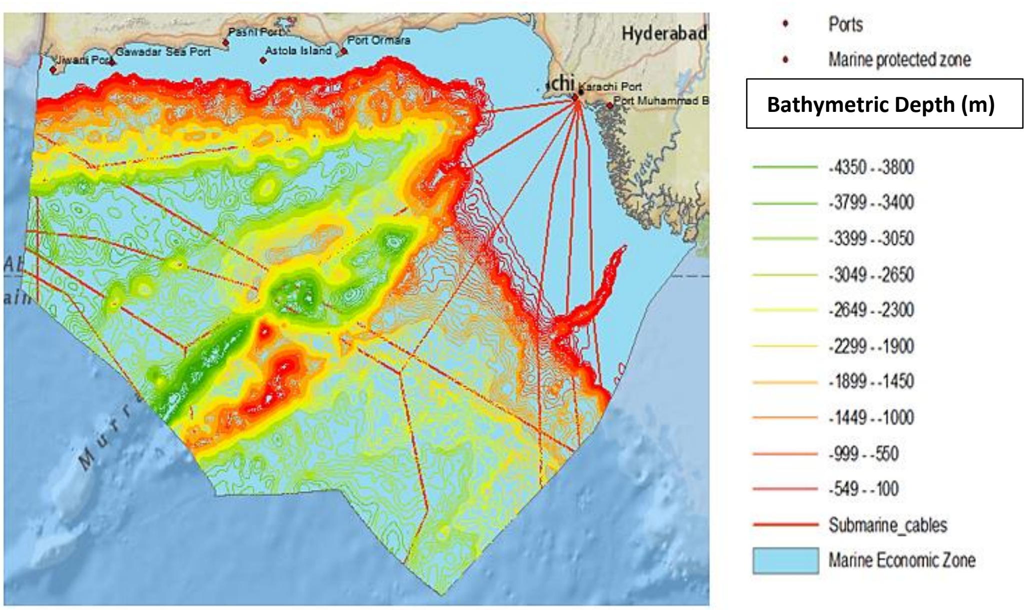



Figure 7: Sensitive Areas

### 4.3 Overlay analysis for identification of useful areas

GIS based overlay analysis eliminates all the protected and sensitive areas by creating a filter to create a new suitability mask which is used for finding maximum wave energy potential. The non-implementing areas were identified by considering the following factors; distance from the coastline, distance from ports, distance from marine protected areas, distance from submarine cables and insignificant water depths.

According to Nobre et al., [35] it is preferred that all systems must be installed at least 12 nautical miles away from shorelines. Therefore, a 12 nautical miles buffer was created around the shoreline as shown in Figure 8. As all the ports of Pakistan are onshore, the shoreline buffer also covers these ports. If a port is offshore, then a buffer distance must be applied for the safety of port activities. Similarly, a buffer distance of 2 nautical miles [35] must be assigned to a marine protected area as shown in Figure 9 to protect the marine environment. A buffer distance of 500 meters in Figure 10 is set around the cables for security purpose. Ocean depths should be considered for the installation of offshore wave energy devices. For most systems, it is suggested [35] that the sea bottom must be deeper than threshold 30 meters. The ocean depths greater than 100 meters are considered in this analysis. Figure 11 shows a useful area for wave energy generation in deep waters. This final useful area is found by performing an overlay analysis in ArcGIS shown in Figure 12. After this analysis has been carried out, the total area of potential wave farm development (non-protected and insensitive areas) is approx. 190,707 square km. It shows that 85% of Pakistan waters are suitable for wave energy generation.

The overlay model in Fig. 12 has a lot of potential to be used as a generalized model for any country. The use case model shows the buffering areas for coastline activities, marine protected areas and submarine cables. These are general activities, part of every country's coast line and EEZ. These individual buffers form a union of buffers (known as sensitive area union in this model) to gather avaoidable areas from the useful areas at the end of the model. The model also involves depth study and excludes any areas less than the implemented depth limit which in this use case is 100 meters. The study can be extended further in which the depth limit can be reduced to 30 meters as specified by Nobre et. al. It will significantly improve the estimated power generation capacity in the proposed area of EEZ. Depth contours are an important data using bathymetric sonar and LIDAR based survey data and can impact on the accuracy of the depth based wave power potential estimation and to confront and plan wave farm deployment and operational challenges. Insignificant depth data, together with sensitive area union forms a spatial join to be part of the EEZ area that needs to be subtracted. The study area signifies the accuracy involved excluding all important activities of the EEZ. It can become an important measure of any country's economic asset or a potential GDP contributor just like assets declared as oil reserves or mineral resources. We will call it EEZ power index that can be measured digitally and has a potential to be used for comparative purposes.

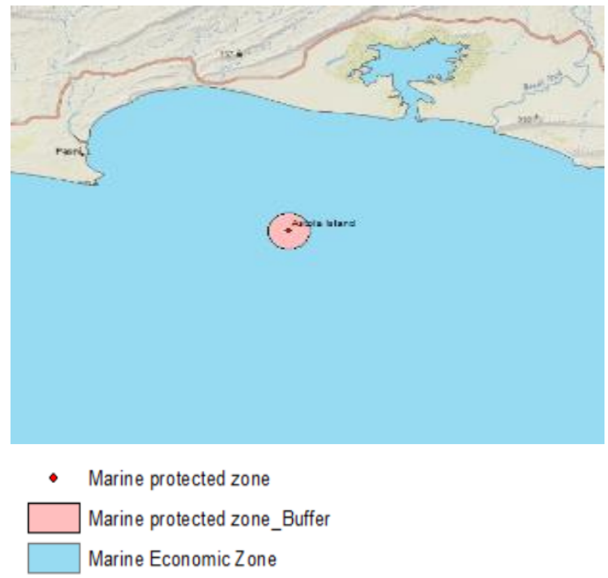
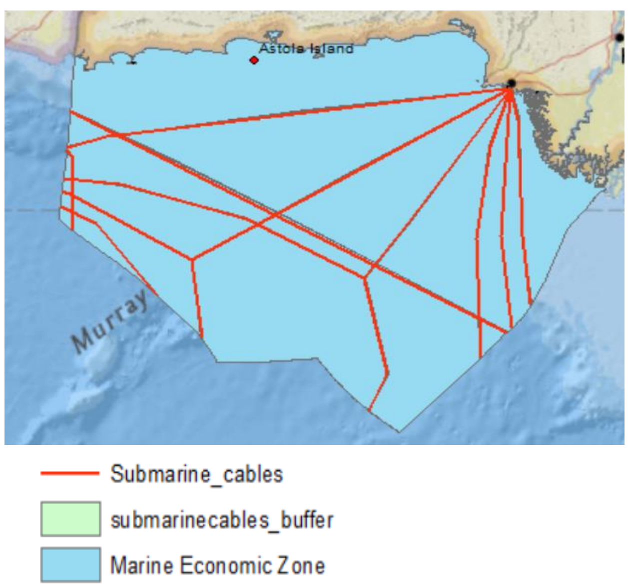




Figure 8: Buffer distance 12 nautical miles from the coastline

Figure 9: Buffer distance 2 nautical miles from the marine protected area



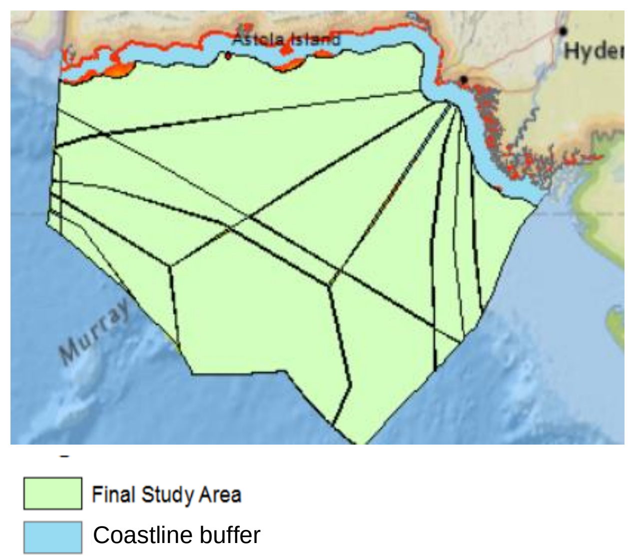




Figure 10: Buffer distance 500 meters submarine cables

Figure 11: Useful Area

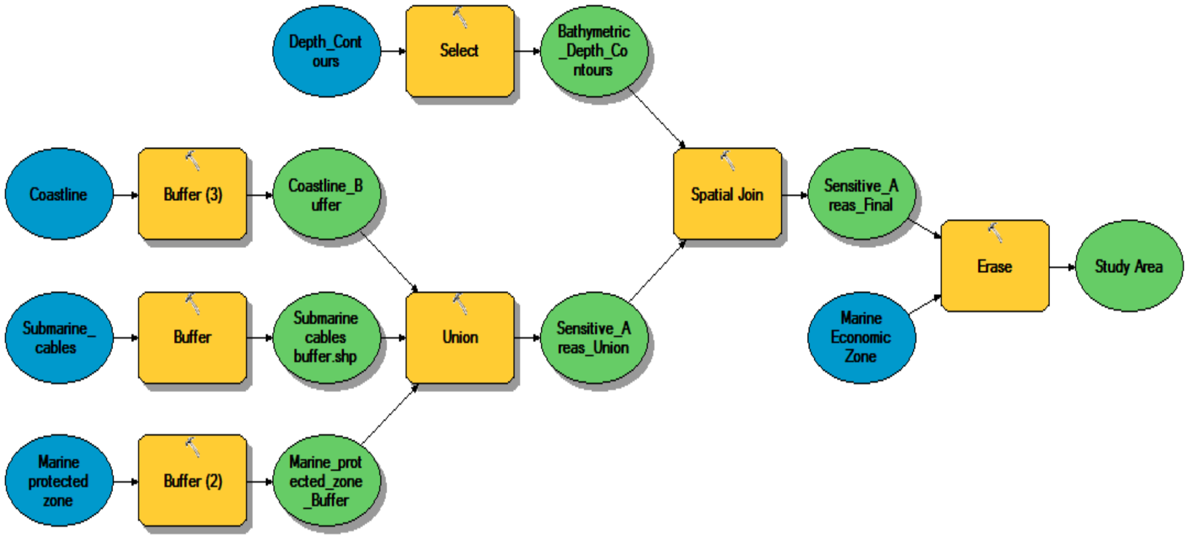



Figure 12: Overlay Analysis Model

## 5. Wave Data Results & Analysis

Different methods can be used to assess wave energy resource [35][36]. Contestabile et al., [38] used hindcast data with a combination of numerical models to assess offshore and nearshore wave energy resource of Brazil coastline. The numerical models mainly use wind and bathymetry data of oceans as input variables and give SWH, wave period and wave direction as output results. Gonçalves et al. [39] compare results of wave buoys and numerical models to find wave energy distribution for the western French coast and find that both methods provide almost same results. A more reliable approach is to use weather forecasting data for longer periods of time. European Centre for Medium-Range Weather Forecasts (ECMWF) [40] and Copernicus Marine Environment Monitoring Service (CMEMS) [41] are European projects for archiving global datasets for multiple physical, biological and other variables in addition to multiple other national and commercial entities. These sources use altimeter based SWH data from multiple satellites like ERS-1, ERS-2, ENVISAT and Jason. Further, their wave models which calculates wave spectrum including, the distribution of sea state and other physical variables are refined through reanalysis that assimilates SWH data observed from historical altimetry missions. The new addition is the synthetic aperture radar (SAR) based satellite like Sentinel 1 SAR and ENVISAT ASAR for covering large footprint of ocean with increased accuracy [15].

In this study, we estimated the wave energy potential for Pakistan by using wave characteristics measurement points at 25 different locations in the EEZ of Pakistan. The nearest shoreline distance is 160 nautical miles. The observation points (shown in Figure 13) cover an area of approximately 3,600 km$^2$ and this particular area is chosen for wave data due to the large depths available. This wave data set includes SWH and mean wave period for 12 months. In this work, the dataset named WAVERYS (CMEMS) is used as it is a wave model that takes into account oceanic currents from the physical ocean reanalysis and assimilates SWH observed from altimetry missions and directional wave spectra from Sentinel 1 SAR processed on a global level considering a spatial resolution of 0.2°×0.2°.

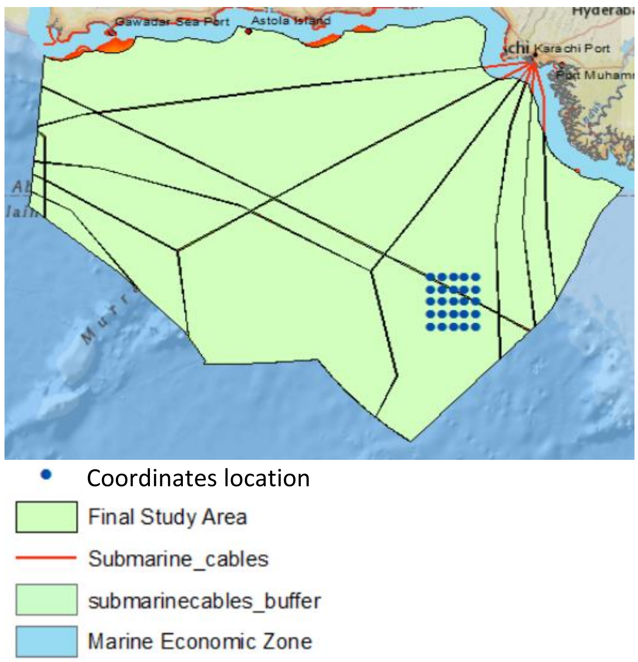
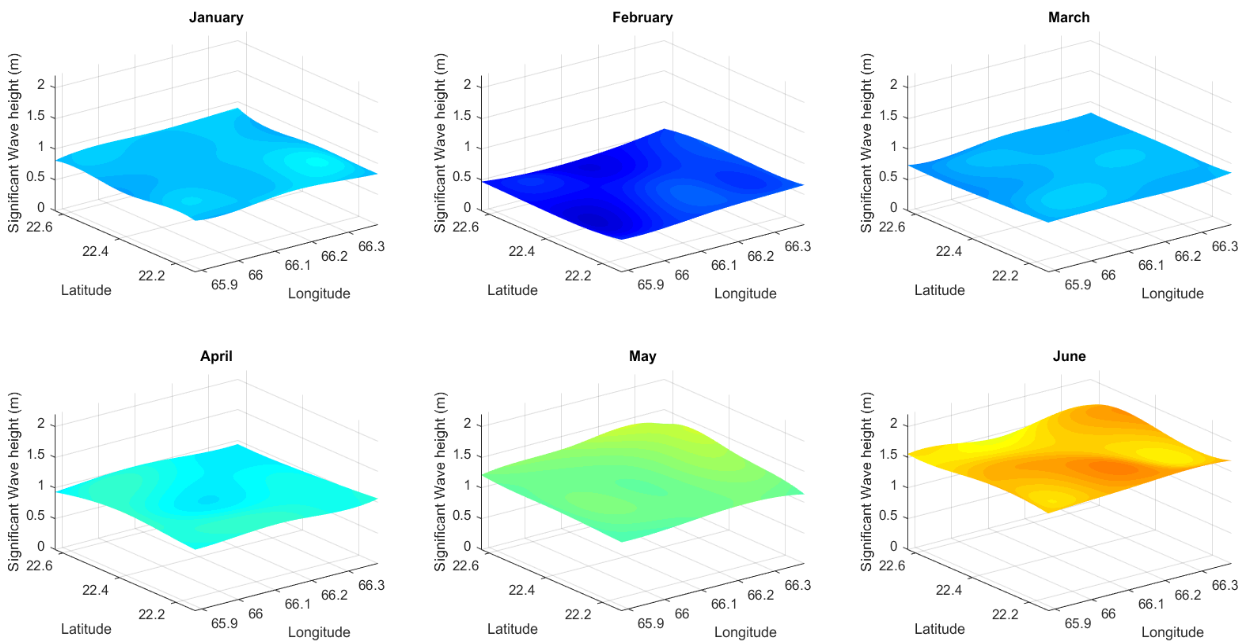



Figure 13: GIS marks for data coordinates

### 5.1 Temporal variations in wave data

The ocean depth and weather conditions have a significant effect on the variation of wave height and wave period. These parameters are used for assessment of ocean wave energy in a certain region. The size of the waves depend on different factors such as the distance and the time the wind travel, wind speed, ocean temperature, wave direction, and sea depth. In the next section, SWH is used to assess the variation in wave power in one full year, whereas, average SWH contour plots are shown in Figure 14 for every individual month.

In the months of January to March, a maximum wave height of 0.9 meters is attained. From April to June wave height is recorded between 0.93 and 1.76 meters. July has the highest waves peaked at 2.13 meters high. From August to October, wave height decreases and reaches up to 0.36 meters. In November and December, wave height remains between 0.78 and 1.21 meters. These results indicate that SWH are maximum in the summer months of Pakistan, whereas, wave heights are comparatively low in remaining months.



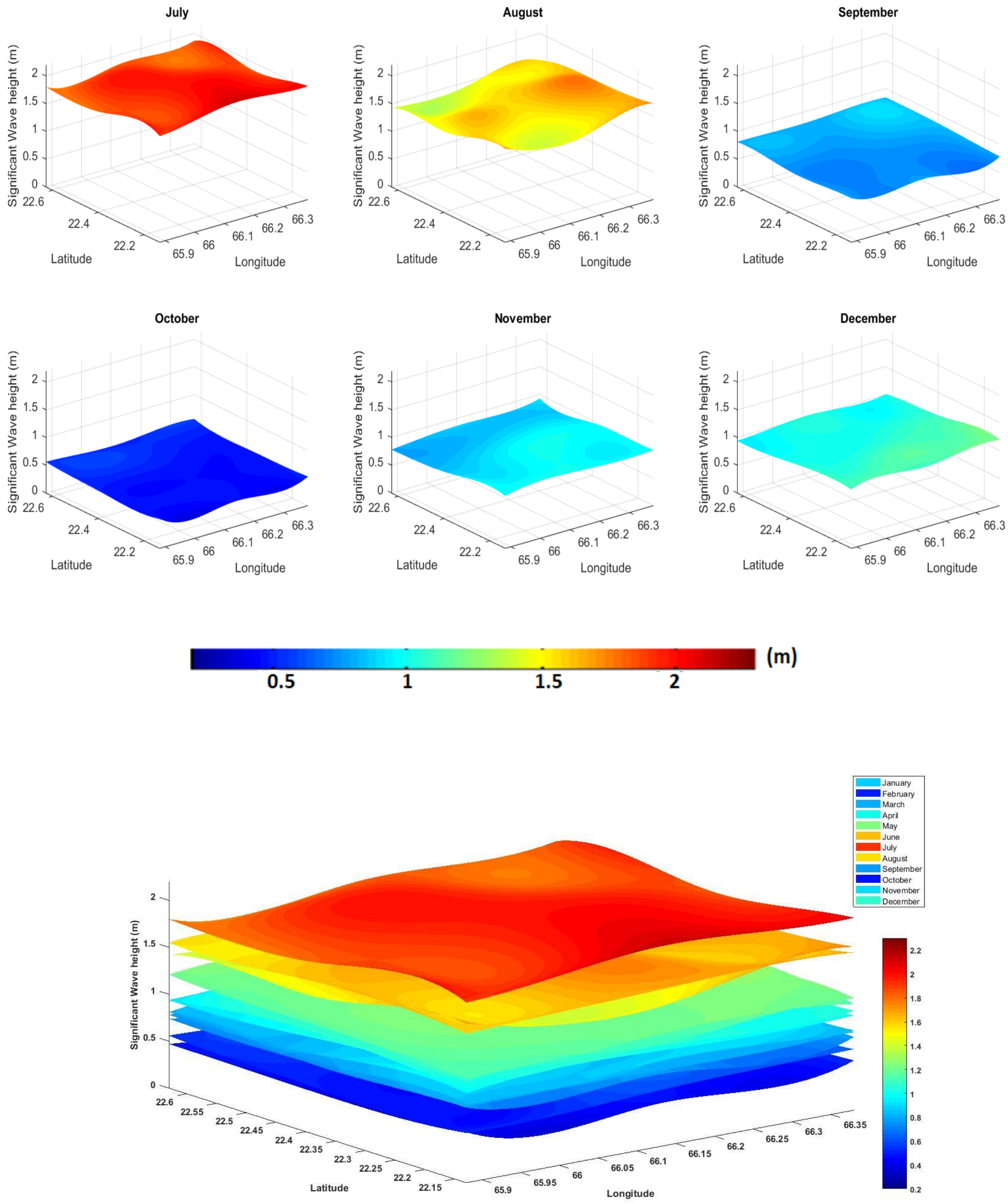
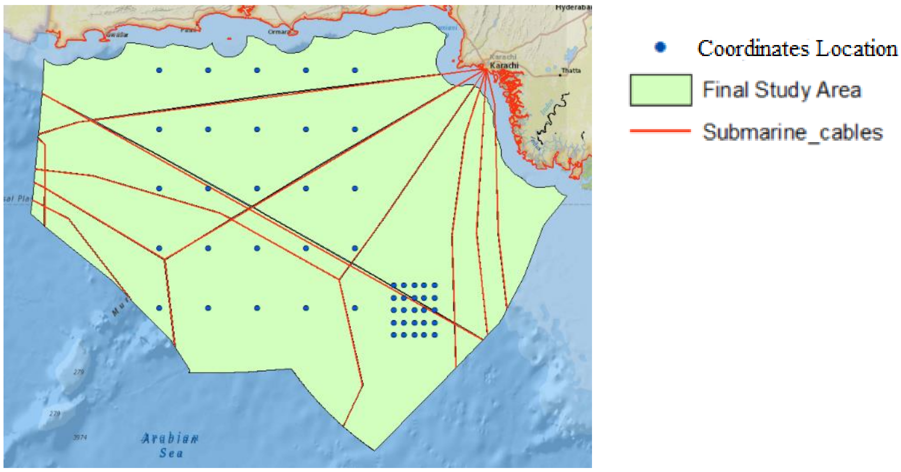



Figure 14: SWH variation for 12 individual months followed by a stacked view.

Some months show a large variation in peak wave height within the observed area, showing localized weather phenomena, whereas other months can be seen as potentially low and are more evenly predictable from the power estimation point of view. To see a wider perspective of the SWH pattern and the resulting wave power estimation, a large scale grid covering the whole EEZ is selected with the data points as shown in Figure 15(a). Monthly temporal variation in SWH as shown in Figure 15(b) is reflecting a similar pattern as obtained for the smaller area. The summer months are showing a significant sea activity as compared to the rest of the year.

a

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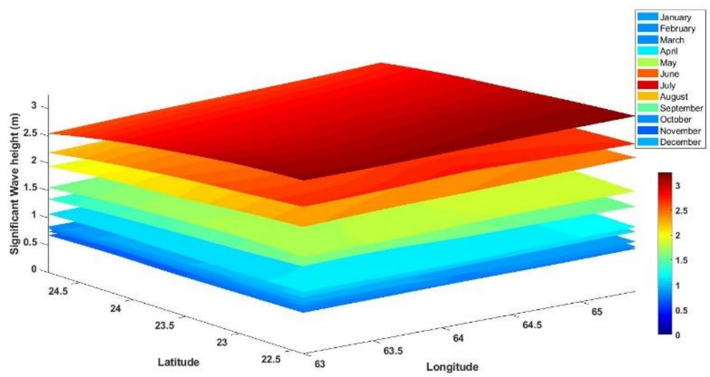


Figure 15: Large scale study at the EEZ level. **a** Coordinates location covering the EEZ in comparison with the selected area, **b** Stacked view for temporal variation in SWH at the EEZ level

### 5.2 Available wave power potential

In this study, all the wave parameters are measured using SWH and wave period data from the points in deep waters where the waves are random and regular. The monthly average wave power for all observation points under a crest of one-meter length in kW/m is calculated using equation (1) [21], [22], [42].

$$P = \frac{\rho g^2}{64\pi} {H_{mo}}^2 T_e \quad (1)$$

In the above expression, $\rho$ is the density of sea water and $g$ is the gravitational acceleration. The value of density depends on temperature and salinity of seawater which varies temporarily and spatially, howerver, it is considered as 1025 kg/m$^3$ for this analysis and the value of gravitational acceleration is 9.81 m/sec$^2$. The wave heights are random in the real sea which is the reason different spectral parameters are used. The spectral wave height $H_{mo}$ used in equation (1) is

$$H_{mo} = 4\sqrt{\mathrm{m_o}} \quad (2)$$

$$T_e = \frac{m_n}{m_0} \quad (3)$$

where $m_n$ is the spectral moment of order $n$ and $m_o$ is zero order spectral moment. The wave peak period $T_e$ is defined as a period of the regular wave. The results of average wave power calculated monthly and yearly using the equation (1) are shown in Figure 16(a). It shows that yearly average wave power is about 4kW/m which is represented by a dotted line. From January to April, wave power is below the average value which is 4kW/m showing that wave power is less because waves are less energetic in these months. In May, wave power reaches up to 4.30 kW/m, whereas, it starts increasing and peaked at 13.25 kW/m in July which indicates that waves are highly energetic in this month. After July, average power reaches up to 7.84 kW/m in August and then it again drops below yearly average wave power. The average monthly wave power below yearly average shows that oceans are calm in these months. For an extended area study covering the whole EEZ, the results are shown in Figure 16(b) in which the annual average wave power comes as 7.89 kW/m, almost double from the smaller selected area. The average monthly wave power peaks in summer to 29.6 kW/m, showing a considerable potential. The larger area shows some higher amplitudes in SWH and time period as compared to the smaller study area that may be due to the localized weather phenomena of smaller grid.

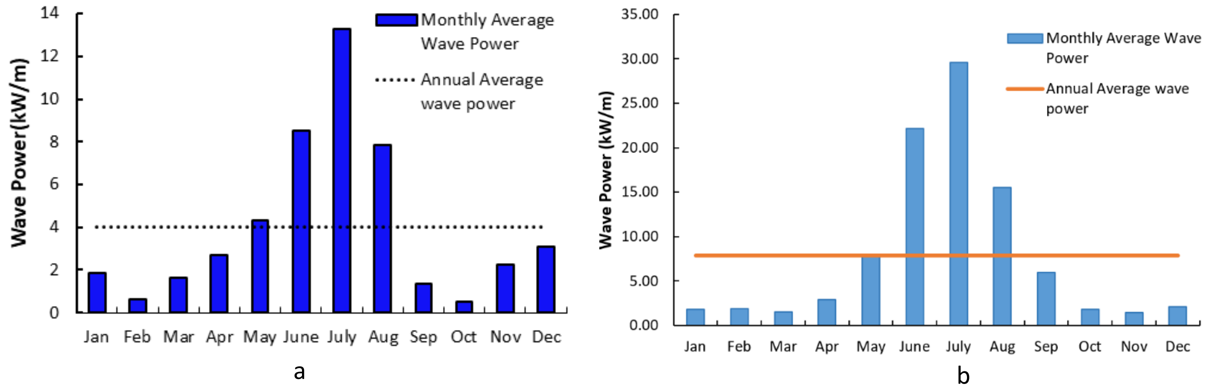


Figure 16: Average Wave Power. **a** For a smaller selected area, **b** For a large scale area covering the EEZ.

The seasonal variation in wave power is also studied because Pakistan has four different seasons in twelve months. Figure 17 shows the contour plots of normalized wave power for different seasons. In winter season (December to February), average wave power is 70% of maximum wave power at 65.9° longitude and 22.6° latitude whereas while moving towards 66.3° longitude and 22.2° latitude in the study area, average wave power reaches to 100% of maximum wave power of 2.34kW/m. The average wave power is 80% of maximum wave power at 65.9° longitude and 22.2° latitude in the spring season (March through May), it increases onwards and reaches to 98% of maximum wave power at 66.3° longitude and 22.6° latitude. In the summer season (June to September), average wave power is again 70% of maximum wave power at 65.9° longitude and 22.6° latitude whereas it reaches to 95% of maximum wave power while traveling towards 66.3° longitude and 22.2° latitude.

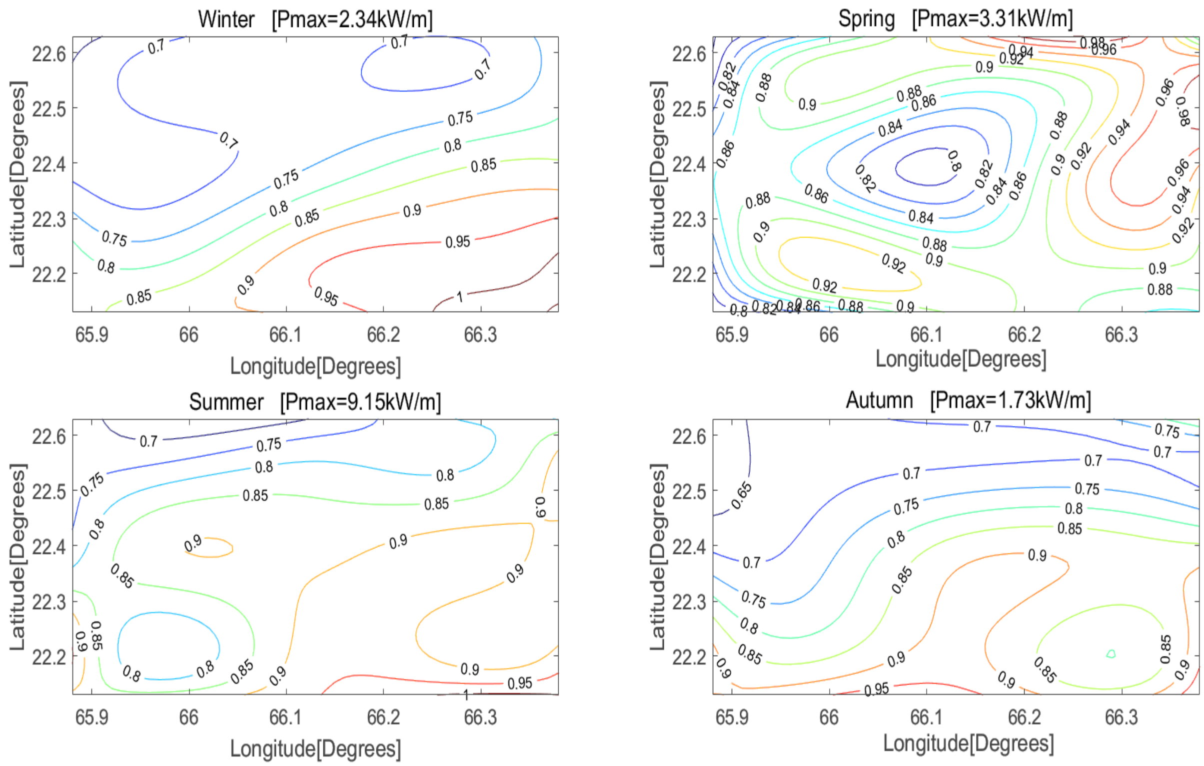


Figure 17: Seasonal Variation in Wave Power

The contour plots of autumn season (October to November) shows the almost same pattern of winter and summer season where average wave power reaches to maximum wave power when moving from the north to south in the Arabian Sea. All these contour plots show that average wave power in the study area is almost 70% close to maximum wave power whereas summer season has maximum wave power of 9.15 kW/m. North to South wave power potential increase is relevant as the depth patterns in further south towards Indian Ocean are significantly large and reflect the requirement to develop power plan accordingly. A design change of buoy farms from low depth to high may have a potential to implement as large sea activity develops potentially in deep waters, therefore, a significant size change for deep water buoys has the case.

## 6. Power Estimates

Wave energy farms deployment are not yet commercialized at large scale, even in developed countries, though Europe has started developing grid connected wave farms on shorelines [43]–[45]. For developing countries, there is a complete lack of investment for this type of renewable sector, so far. For the WEC technology to effectively work in the marine environment, both potential and kinetic energy factors are important. Wave heights characterize the potential energy whereas the wave speed fluctuates the kinetic energy aspect. Other important issues in the design of such devices are the selection of sustainable materials in the corrosive marine environment as well as the structural rigidity of the devices against the ocean storms and long term, maintenance free operational requirement of the devices, involved. By observing Figure 1, it is clear that South Asia has one of the lowest potential of wave power (approx. 15 kW/m), but it points to the underlying factors that a system with less maintenance requirement due to low potency of waves and a high efficiency extracting device has a case.

### 6.1 Technology selection

There are various technologies to extract power from ocean waves [46]. The technologies include WEC which are generally categorized based on installation location and the Power Take-Off (PTO) system. There are many types of devices working on the PTO working principle and can be classified into different types such as attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping device, submerged pressure differential etc. [46]. The design of WEC require a precise description of available wave energy resource at high spatial and temporal resolution. It is important to match the working conditions with the selected WEC capacity and device efficiency [14]. The principle of wave power extraction in a single-unit WEC is based on matching its impedance with the incoming incident waves. The size of a wave energy converter must be large enough to resonate at the peak frequency of incident waves when placed in real seas where high swells are present to achieve maximum efficiency. Research shows that the compact array of buoys is potentially more efficient in natural seas as compared with a single large buoy built with the same amount of material [47].

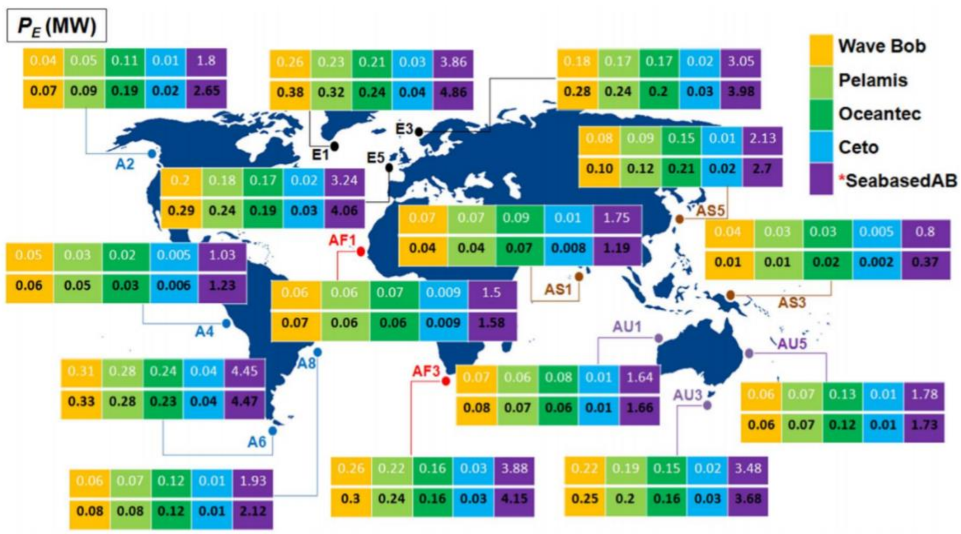


Figure 18: Power output of five commercial WEC systems. The output of the *SeabasedAB system is expressed in kW [15]

There are many commercial WEC systems available and this can be the natural choice to select the most suitable for the wave conditions in the region of interest. Rusu et. al [15] have reviewed the high potential sites in every region of the world, based on the 15 year data (2000-2014) and assessed Power outputs (MW) of 5 commercial WEC. The closest point to the region of interst is AS1 as shown in Figure 18, where the upper and lower lines show mean power output ($P_E$) for the total and winter time, respectively. Out of the five commercial WEC listed, power output and performance efficiency from Oceantec is highest as compared to other devices (See Table 1). It is a normal practice for WEC equipment manufacturers to create power matrix based on the bivariate distribution data of specific wave height and time period. True sea state is the key information and therefore location based power matrix can give an overall picture of device efficiencies available at a particular location.

Table 1: Specifications and performance efficiency of commercial WEC systems at AS1

| **Commercial Devices** | **Category** | **Dimensions (m)** | **Rated Power $P_R$(kW)** | **Regional WEC performance $P_E$(kW)** | | **Performance Efficiency ($P_E/P_R$).100** | |
|---|---|---|---|---|---|---|---|
| | | | | Total | Winter | Total | Winter |
| **Wavebob** [48] | Point absorber | 20 | 1000 | 70 | 40 | 7% | 4% |
| **Pelamis** [49] | Attenuator | 150 | 750 | 70 | 40 | 9.33% | 5.33% |
| **Oceantec** [50] | Attenuator | 52 | 500 | 90 | 70 | 18% | 14% |
| **Ceto**[51] | Point absorber | 7 | 260 | 10 | 8 | 3.84% | 3.08% |
| **SeabasedAB**[52] | Point absorber | 3 | 15 | 1.75 | 1.19 | 11.66% | 7.93% |

### 6.2 Cost

There are many WEC based proposed rig designs [53], [54] in which cost effectiveness is prioritized by inclusion of multiple buoys. For example, Olsen's design [54] comprises of multiple buoys installed in a rig of 36 by 36 m$^2$ area, where each buoy has a diameter of 3.5 m. The power estimation is carried out using the Norwegian sea conditions of SWH and period, resulted in power genartion of 2 MW (See Table 2). In this study, if a single buoy of the same diameter as used in [54], is installed in deep water where mean wave height is 1.06 meters and mean wave period is 5.57 seconds, it can extract wave power of 21.32 kW using the equation (4) [54] whereas, a similar rig of 15 such buoys can extract 319.8 kW wave power.

$$E = 4.5D^{2.4}.H_s^{1.7}.T_p^{-0.9} \tag{4}$$

where $E$ is the power output (kW), $D$ is the diameter of floating body (m), $H_s$ is the SWH (m) and $T_p$ is the wave period (sec). It is based on a floating body having an oblong shape with rounded ends that can follow the wave motion. In our study the potential area consists of 190,707 km$^2$ that can be utilized to develop buoy farms at multiple coordinates. By installing 50 such rigs in useful area, an approx. 16 MW plant can be developed. By looking at the generating power of Olsen's 15 array in both conditions, i.e., 2.025MW in Norwegian waters and 0.32MW in Pakistan waters, there seems to be 6.3 fold ratio. In order to reach to the same power level, 6 to 7 time increase in the number of buoys can be proposed. So, an array of 90 to 100 buoys will transform similar amount of energy what the Olsen's 15 array is doing in Norwegian conditions.

Table 2: Comparison of power output: A conservative estimate for Pakistan

| | SWH (m) | Wave period(s) | Power (kW) - Single buoy | Power (MW) - 15 buoy rig |
|---|---|---|---|---|
| **Norwegion Sea condition** | 4 | 8 | 135 | 2.025 |
| **Pakistan Sea condition (mean)** | 1.06 | 5.57 | 21.32 | 0.319 |

The number of rigs is important in order to conduct the breakeven analysis in economic terms after knowing the capital and operational cost estimates. The estimated cost breakdown for the WEC power plant installation and operation [55] suggests 34.68% for capital equipment and installation, 40.19% for O&M and 24.81% for part replacement and spares. A per unit cost of electricity production would be much higher initially, but can be reduced significantly with the development of this technology. A levelized cost of energy (LCOE) estimate for installation of 50 rigs (one power plant where each rig consists of Olsens's 15 buoys) with a combined generation capacity of 16 MW revealed a varied per unit cost (0.2 $/kWh – 0.8 $/kWh) based on the location of the WEC farm. The capital and operational cost varies a lot for onshore and offshore rigs due to the fact that onshore rig has several cost saving features where structure, mooring, transmission, installation and vessel hire costs can be avoided. WEC are also not subject to aggressive marine environment in the onshore and nearshore areas, therefore, bear less maintenance, operational and parts replacement cost. In terms of energy consumption, it can be expected that with 60 such plants, nearly 1000 MW can be generated that will make up 4~5% of Pakistan's current electricity consumption.

A solution to cut the costs involved for installation of off-shore WEC plants is to design hybrid wind-wave farms in which the same civil work, mooring and grid connectivity be used for both type of renewables. Other cost saving factors include plant installations on coastlines, harbours or near shore as compared to off-shore systems. Other factors particularly relevant to South Asian region is the expectedly low maintenance and replacement requirement of equipment due to sea condition and the availablility of cheap labour.

a b c

Figure 19: WEC technology. **a** Commercial Mutriku wave power plant [45], [56] **b** Grid connected on-shore wave plant [43]. **c** Wind wave hybrid floating plant [57]

Mutriku wave power plant [45], [56] in Figure 19(a) is the World's first grid connected commercial wave farm, using a civil structure developed for dual functionality of wave breaking for port safety as well as waves entry to the air chambers to run air turbines. The design is well suited to the corrosive sea environment as the turbines never touch salty sea water. Figure 19(b) shows the latest technology advancement in WEC, in which the grid connected wave farm has the latest feature of floater lift in an upward position during the storm and restart of functioning again in the normal situation. These state of the art features in these two examples will reduce the replacement and O&M cost significantly, thus making it viable for developing countries to adopt wave power farms. Figure 19(c) is a hybrid wind wave floating power plant. This is developed to collect energy from two sources simultaneously in order to save installation and operational costs.

The study reveals that there is a significant wave power potential in Pakistan's EEZ which can be utilized to eradicate power shortage crisis. Moreover, the investment in the renewable energy sector would also help developing countries like Pakistan to reduce enviormental problems. Due to climate change, Pakistan's coastline may be effected due to raised sea level. It is expected that due to the faster glacier's melting in the Himalayas, can cause severe flooding in the South Asian rivers that will cause abrupt changes in the coastline, uncertain and sometimes extreme weather patterns. This may create a resource potential, as far as the tapping of wave energy is concerned in onshore and near shore areas. There are also depth variation effects on the possible wave power generation, where continuous large wave activity patterns are significant. Large size compact array buoys for deep waters are more suitable as compared to the low depth buoys with limited vertical buoy displacemnet ranges.

## 7. Conclusion

Wave energy is a renewable and environmentally friendly energy resource that can contribute in fulfilling the need for electricity generation in developing countries. The wave power potential of a developing country in South Asia is investigated in the use case. A methodology is devised for the estimation of wave power in the EEZ of Pakistan and finding its wave power potential for the future development of buoy farms. The useful areas in Pakistan's EEZ having wave power potential are found by using an overlay analysis in ArcGIS. For this purpose, sensitive factors such as ports, marine parks, submarine cables, and low ocean depths are identified and subtracted from the total area. The study shows that remaining useful area in Pakistan ocean water is 85% of the total area. A study area is selected from this useful area for estimating wave power potential of Pakistan using SWH dataset of 12 months.

The monthly variations in average wave power are calculated in the study area. These variations show that wave power is maximum at 13.25kW/m in July and minimum at 0.5 kW/m in October. The seasonal variations in average wave power are also calculated for a better understanding of wave power potential. The seasonal variations indicate that average wave power is maximum at 9.15 kW/m at study area in summer season, followed by the spring and winter seasons which show moderate values of average wave power. A large study area is selected to cover the whole economic zone showing an almost double wave power estimate for annual average as compared to the smaller selected study grid. This also indicates that Pakistan ocean water has the seasonal potential for wave energy generation. An estimate using the existing wave power extraction technologies shows that if a compact arrays of buoys are used, the system has the ability to extract considerable amount of power. This can support in reducing the energy demand and supply gap. These results show that Pakistan has higher wave power potential in the summer season as compared to winter, which are hottest months in Pakistan where energy shortages are at peak. It will be beneficial for Pakistan to utilize this renewable energy resource in its power generation for coastal areas.

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