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Offshore wind farm site suitability and assessment along Tamil Nadu coast using RISAT-1 SAR and synergetic scatterometer data

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Abstract: The possibility of expanding the wind power production to the offshore regions is viable especially in the regions where winds tend to be higher and consistent. Out of all the coastal states of India, Tamil Nadu coastal region is having higher and persistent winds throughout the year. This study focusses on the utilisation of satellite remote sensing in identifying most suitable sites favourable for installing offshore wind farms. Four years (2012-16) of Radar Imaging Satellite (RISAT)-1 Synthetic Aperture Radar (SAR) and long-term synergetic scatterometer (Quick Scatterometer - QuikSCAT, Oceansat Scatterometer - OSCAT, Advanced Scatterometer -ASCAT-A and ASCAT-B) data for 16 years have been processed to generate mean wind speed maps at 80 m hub height. A Geospatial Information System (GIS) based methodology was developed to characterize the offshore wind power potential along the study region within the Exclusive Economic Zone (EEZ) by using ten site suitability parameters – mean wind speed, bathymetry, distance from the ports, electrical transmission lines, cyclone risk, seismic risk, avian exclusion, visual exclusion, ecosystem exclusion, potential shipping lane exclusion. After assigning suitable relative weightages to each parameter, the offshore wind power potential sites of Tamil Nadu (TN) coast have been evaluated, using heat maps with ranking score between 1 and 10, where 10 denotes the most suitable site. Based on the analysis, it has been observed that the offshore region between Kolachel and Tuticorn, TN has good potential for wind power generation. The overall electrical power generation in the most suitable sites have been estimated using Vestas 3MW and Gamesa 5MW offshore turbine curves. Similar methodology can be adopted for identifying potential sites of wind farms for the entire Indian coast.

Key words: offshore winds, site suitability, RISAT, scatterometer, India

1. Introduction

With the exhaustion of fossil fuels and increasing awareness on environmental issues, harnessing energy from available resources has become a prime focus in the developing countries (Yan et al., 2010). Among the renewable resources, wind power is a very large energy source, with proven commercial technology and very low or negligible CO_2 emissions (Archer and Jacobson, 2005). In comparison to land wind, offshore winds are strong and steady because of the absence of physical barriers (Xin, 2010). Currently, United Kingdom is the leading nation having installed offshore wind power capacity of 6836 MW, followed by Germany (5355 MW), China (2788 MW), Denmark (1271 MW), and Netherlands (1118 MW), totalling over 18,814 MW (Global Wind Energy Council, 2014). India has no offshore wind farms as on today.

Now the Government of the India is focusing to harness the offshore wind resources within the Indian Exclusive Economic Zone (EEZ) with the “National Offshore Wind Energy Policy 2015” by encouraging the development of offshore wind farms. The First Offshore Wind Project of India (FOWPI) with the capacity of 1 GW is initiated in the coastal waters off Gujarat. With the utilization of onshore and the upcoming more offshore wind farms, the government of India has set a target to achieve 60 GW power generation capacities by 2022 and reduction in carbon emissions by 33-35% of its Gross Domestic Product (GDP) by 2030. Hence, there is an immense requirement of assessing the suitable shelf areas along the coastal region. Indian coastal ecosystem comprising of mudflats, sandy beaches, estuaries, creeks, mangroves coral reef, marshes, lagoon, sea grass beds and sandy and rocky beaches extended up to 42,000 sq. km (approx. 12 nm), so this region should be avoided for any developments (Kumar et al., 2006; Venkataraman and Wafar 2005). Therefore, finding suitable sites beyond of this region within the Exclusive Economic Zone (EEZ) remains a scientific and technical challenge for the engineers and investors.

It has been observed from the work done by Arun Kumar et al. (2016) that Tamil Nadu coastal region has higher and persistent wind speed all throughout the year. Hence, in this study we have attempted to utilise satellite remote sensing data to identify favorable sites for installing offshore wind farms using Geospatial Techniques (GIS).

2. Data and Methods

2.1 Satellite data

2.1.1 Scatterometer data

Scatterometers are the missions with specific goal of observing the equivalent-neutral surface ocean-vector winds across the world. Orbit-wise scatterometer wind products at 12.5 km spatial resolution from Quick Scatterometer - QuikSCAT (L2B version 3), Oceansat Scatterometer - OSCAT (L2B version 2) for the whole mission period 2000-2009 and 2010-2014 respectively and Advanced Scatterometer - ASCAT (L2B version 2 coastal winds) for 2012-2016 have been processed to generate long-term synoptic mean in the Indian region (Lat.0-25ºN; Long. 65-95ºE). The mission targeted wind vector precision and accuracy are, respectively, 3.0 m s^{-1} for ASCAT, 0.5 m s^{-1} for QuikSCAT (Vogelzang et al., 2011) and OSCAT. A combined wind speed product generated from the four scatterometers have been extracted for the Tamil Nadu coastal region and used in this work. The method of combining the scatterometer data is described in Arun Kumar et al. (2016).

2.1.2 SAR data

Around 3000 Radar Imaging Satellite (RISAT)-1 images in HH polarization of Coarse Resolution ScanSAR (CRS) and Medium Resolution ScanSAR (MRS) modes with 36 × 36 m and 18 × 18 m spatial resolution respectively have been obtained from National Remote Sensing Centre (NRSC) over Indian region for the period 2012-2016. The SAR images are processed from L2 to 10 m wind speed using C-band Geophysical Model Function (GMF) CMOD-5N (Hersbach, 2010). The data has been averaged to around 1 km × 1 km to reduce the inherent speckle noise, a random phenomenon in radar, and eliminate effects of tilt and modulation error from longer waves, before wind inversion. SAR-based ocean surface wind retrieval is described in Dagestad et al. (2013) and references therein. Space Applications Centre (SAC) developed a reprocessing chain to massively process RISAT-1 images. For HH data, the polarization ratio with both incidence angle and wind direction relative to the radar look angle is used. The wind directions were obtained from European Centre for Medium-range Weather Forecasts (ECMWF) atmospheric model at spatial grid of 0.125°. The data closest to the time of RISAT- 1 pass are interpolated in space before wind inversion. Validation of RISAT-1 SAR derived wind speed is described in Jagdish et al. (2018). For wind power assessment, this volume of the data may be in sufficient, but there were no studies so far to assess the validity of SAR data for wind resource assessment in India. An average wind speed dataset derived from the RISAT-1 SAR has been cropped to the study area for further analysis.

2.1.3 Wind computation methodology

Scatterometer and SAR derived wind data are available at 10 m above m.s.l. In order to estimate the speed at the hub height over the water, log-law applied by assuming the neutral stability of the atmosphere and an oceanic surface roughness z_0 = 0.2 mm (Manwell et al., 2010). The data were extrapolated to the required height (h=80 m in this case) using this logarithmic approach. The log-law states that a wind speed at a given hub height.

$$v_h = v_0 \left(\frac{\log(h/z_0)}{\log(10/z_0)}\right) \qquad (1)$$

where, v_0 is the wind speed (ms^{-1}) at the 10 m above the sea level and v_h wind speed (ms^{-1}) at a hub height respectively. In this paper, two offshore wind turbines from different manufacturers: Vestas V112 3MW and Gamesa G128 5MW have been used to derive the electrical power production. The power curves of the two turbines are shown in figure 1.

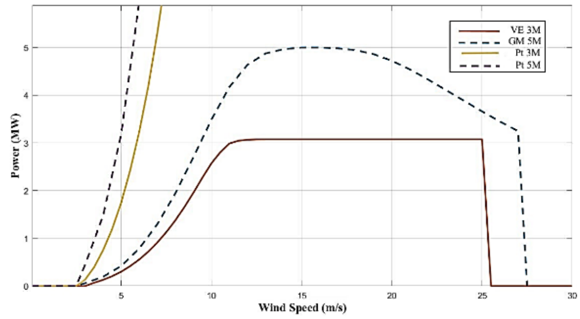

Figure 1: The Power characteristics curve for Vestas V112 offshore 3 MW (VE 3M) and Gamesa G128 5MW (GM 5M) Turbines

The individual effective footprint (i.e. Array spacing) on the seabed was calculated using the equation (Sheridan et al., 2012).

$$\text{Array spacing} = \mathrm{D}^2 \times \mathrm{v_{df}} \times \mathrm{v_{cf}} \qquad (2)$$

where, D is the rotor diameter (m); $\mathrm{v_{df}}$, $\mathrm{v_{cf}}$ are downwind and crosswind spacing factor 10 and 5 respectively. Thus, the corresponding array spacing for the VM 3M and GM 5M turbines are 0.63 and 0.82 km^2 respectively. The number of turbines commissioned within the area was determined using

$$\text{Number of turbines} = \frac{\text{Total area available}}{\text{Array spacing}} \qquad (3)$$

The nameplate wind power capacity (i.e. total installed capacity) was computed by multiplying the rated power of single turbine with the number of installed turbines. However, this is not achievable for any turbine due to several losses such as availability, schedule maintenance, unplanned shutdown, wake effect, turbine efficiency. Hence, the practical power estimates were also computed using the manufacturer's power curve. In decision-making contexts, it is often necessary to compare renewable energy resources such as offshore wind to traditional generation sources (i.e. coal, nuclear, natural gas). In such a comparison, it is more useful to use the 'average output' than the installed nameplate capacity (Sheridan et al., 2012).

2.2 Site suitability criteria

Ten preliminary site suitability criteria viz., mean wind speed (potential), bathymetry, ports, electric transmission lines, cyclone risk, seismic risk, avian exclusion, visual exclusion, ecosystem exclusion, potential shipping lane exclusion have been calculated using data from different sources. Arc GIS (version 10.4) software has been used to create an "*Offshore Wind Farm Suitability model*". Different site suitability criteria were combined by assigning an appropriate weightage and computed the overall suitability map following (FOWIND, 2015). The detailed modelling steps are shown in the self-explanatory flowchart shown in figure 2. The final suitability scores in the study area were determined by reclassifying the scores derived from the weighted overlay.

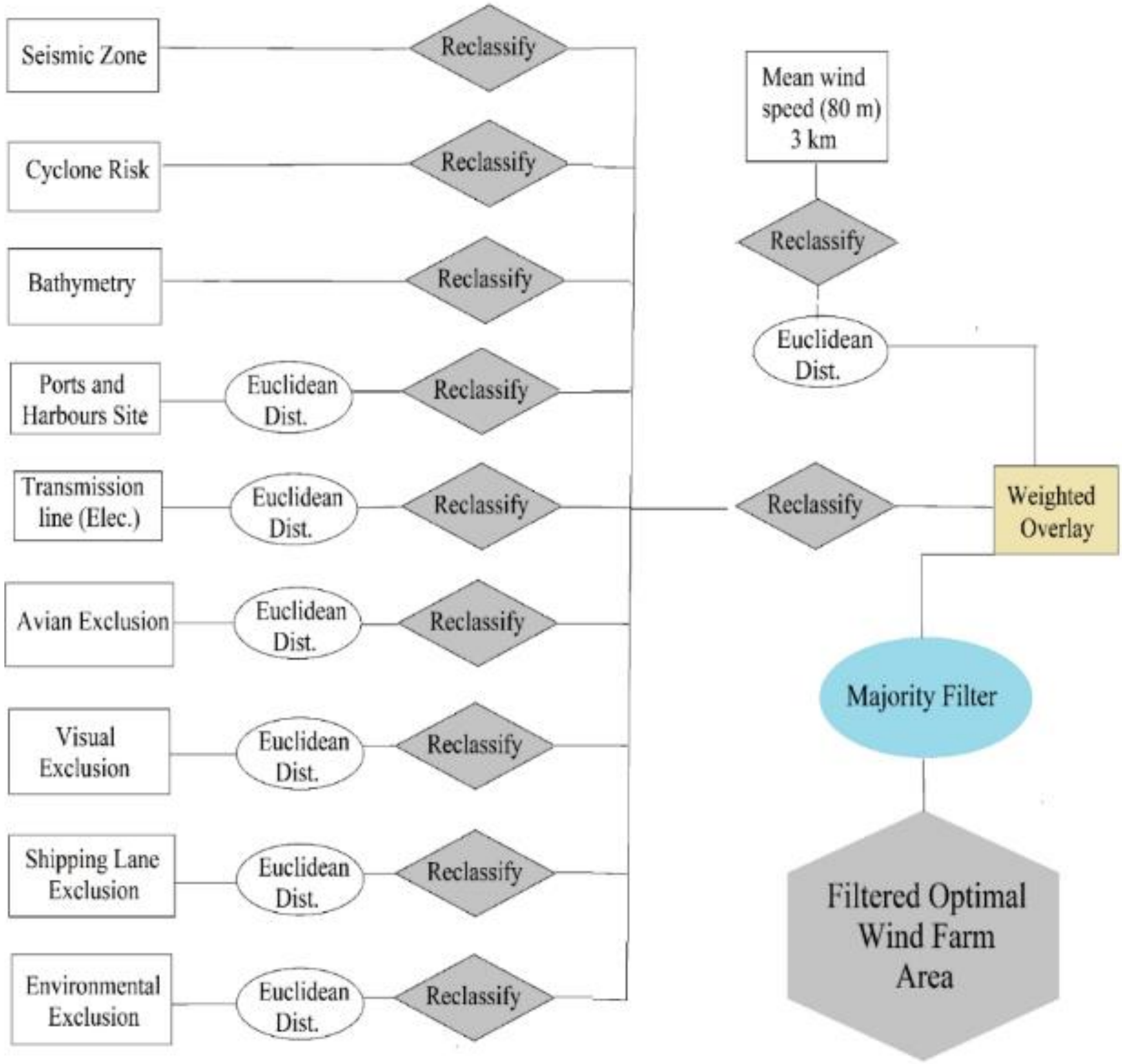

Figure 2: Flowchart for modelling suitability of offshore wind farm development

3. Results and discussion

The data from various resources have been processed in ArcMap and created rasters of 1 × 1 km spatial grid to maintain uniformity. Entire analysis is confined to the Tamil Nadu coastal region between the longitudes 76ºE – 81ºE and 7ºN – 14ºN within the EEZ. A suitable score from 1-10 have been assigned with the 10 for the most suitable criteria (Table 1). Following are the details of each parameter used in the study.

a) Potential Wind Speed at hub height (80 m)

The average mean wind speed distribution at 80 m hub height derived from RISAT-1 SAR (Figure 3a) and synergetic combined scatterometer data (Figure 3b) within the study area has been used separately for the wind farm site suitability analysis. It has been observed that the wind speed is high in the offshore waters between Tuticorn and Kolachel in the south Tamil Nadu. The spatial variation in the wind is high in the SAR data as compared to the scatterometer data. It is because few SAR images available for temporal averaging.

Whereas in the case of scatterometer data, huge volume of each pass data was processed, which makes the synergetic scatterometer data reliable. The benefit of the SAR data is the high resolution (1 km grid) as compared to the scatterometer data (12.5 km).

Table 1: Weighting of spatial influences

Parameter	Criteria	Description	Relative Weightage (%)	Ranking Score	
				Class	Score
Potential Wind Speed at hub height	> 6 m/s	Best practices for economic sustainability	40	<5 m/s – 6.0 m/s	1-3
				6.0 – 7.0 m/s	4-5
				7.0 - 8.0m/s	6-7
				8.0 – 9.5 m/s	8-10
Bathymetry	> -5 m and < -500 m	Best practices for economic sustainability and technology	30	> -200 m	1-3
				-200 - -100 m	4-5
				-100 - -50 m	6-7
				-50 - - 5 m	8-10
Port and Harbours consideration	Nearest	Best practices for economic	8	> 300 km	1-3
				200 – 300 km	4-5
				100 – 200 km	6-7
				0 – 100 km	8-10
Cyclone Risks	Within EEZ	Best practices to minimize impacts	1	0.0205 – 0.0122	1-3
				0.0122-0.0068	4-5
				0.0068-0.0028	6-7
				0.0028-0	8-10
Electric Transmission Line	Nearest	Best practices for economic	10	> 800 km	1-3
				300 – 800 km	4-5
				100 – 300 km	6-7
				0-100 km	8-10
Seismic Risk	Within EEZ	Best practices to minimize impacts	1	65 – 530	1-3
				17 - 65	4-5
				3 – 17	6-7
				0 – 3	8-10
Avian Exclusions	< 2 km	Best practices to minimize impacts	1	0 – 5 km	1-3
				5 – 10 km	4-5
				10 – 100 km	6-7
				> 100 km	8-10
Visual Exclusions	< 10 km	Best practices to minimize impacts	2	0 – 50 km	1-3
				50 – 100 km	4-5
				100 – 200 km	6-7
				> 200 km	8-10
Potential Shipping lanes Exclusions	< 1 km	Best practices to minimize impacts	2	0 – 5 km	1-3
				5 – 10 km	4-5
				10 – 50 km	6-7
				> 50 km	8-10
Ecosystem Site Exclusion	< 10 km	Best practices to minimize impacts	5	0 – 50 km	1-3
				50 – 100 km	4-5
				100 – 200 km	6-7
				> 200 km	8-10
Total			100		

b) Bathymetry

It is very important to determine water depth at any potential offshore wind development site for appropriate foundation technology. On this basis, we can choose the foundation technology and estimate installation cost. In this study, bathymetric data for the Indian EEZ (ocean area up to 200 nm from the baseline) was obtained from the General Bathymetric Chart of the Oceans (GEBCO) (Becker et al., 2009) with a resolution of one arc-minute. Entire bathymetric data was processed and classified into four-water depth ranges see in figure 4. Later the bathymetry data was reclassified from 1-10 considering the depths between -5 and -500 m only. The score with 1 being most unsuitable and with 10 being most suitable for the wind farm sites. It has been observed that the study region is having steep continental shelf within the EEZ region. Generally, wide and shallow continental shelf is preferred for the wind farms. In addition, the EEZ is very narrow of ~ 20 nautical miles with the presence of international waters sharing with Sri Lanka region. Very shallow waters are existing surrounding Gulf of Mannar up to Nagapattinam coast. A gradual change in the depth is observed southwards from Kolachel.

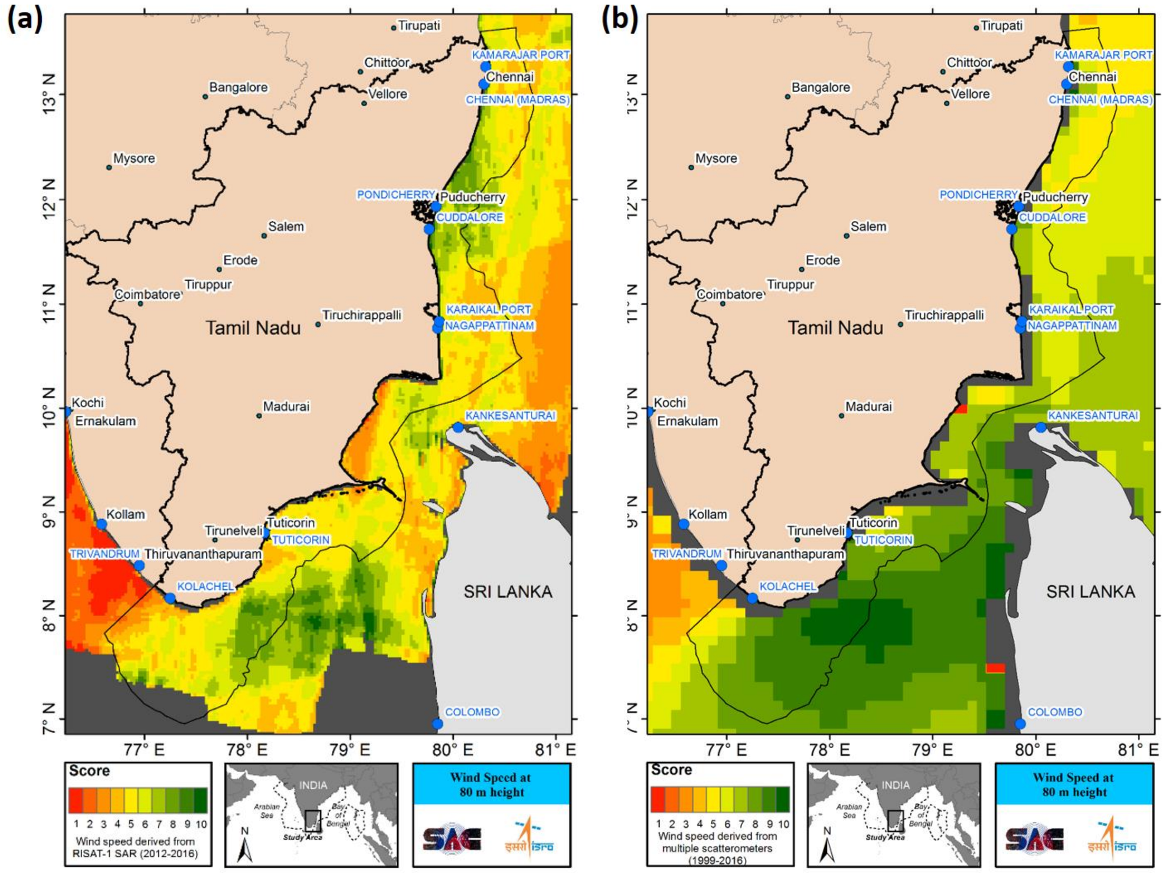

Figure 3: Offshore Wind Speed Heat Map of Tamil Nadu derived from (a) RISAT-1 SAR and (b) multiple scatterometers.

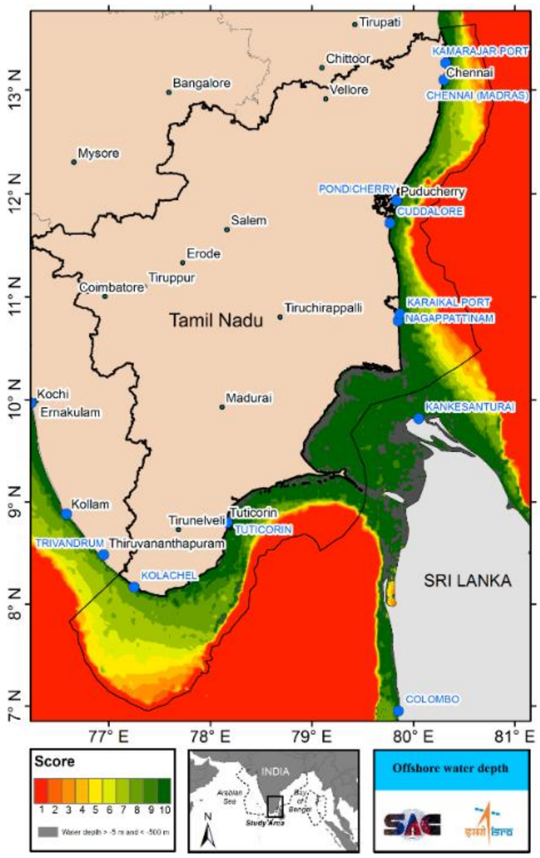

Figure 4: Offshore Water Depth Heat Map

c) *Port and Harbours consideration*

The port is one of the most important components in offshore wind farm construction. Ports handle manufacturing, storage and transportation of wind farm components. In general, all manufacturing facilities would be located on the coast, within the port closest to the offshore wind farm. Overall, this parameter having a goal to reduce the logistic costs. In this study, major port data (in the form of shape file) has been obtained from the World Port Index database. As the distance from the port increases, the region would become unfavourable for the wind farms (Figure 5). Although there are major and minor ports existing along the Tamil Nadu coast, the minor ports were not considered in this study due to unavailability of the data.

d) Cyclone Risks

Consideration of tropical cyclones in the design of offshore wind turbine farm is very important. In order to understand the impact of cyclones, the cyclone track data for the period of 1900 – 2016 has been obtained from International Best Track Archive for Climate Stewardship IBTrACS (source: https://www.ncdc.noaa.gov/ibtracs). A density map of cyclones over North Indian Ocean has been generated (Figure 6). There were few number of cyclones crossed the region. Especially, the southern Tamil Nadu coast is rarely affected by any cyclone during the past 116 years' period. Hence, that region is suitable in terms of cyclonic activity.

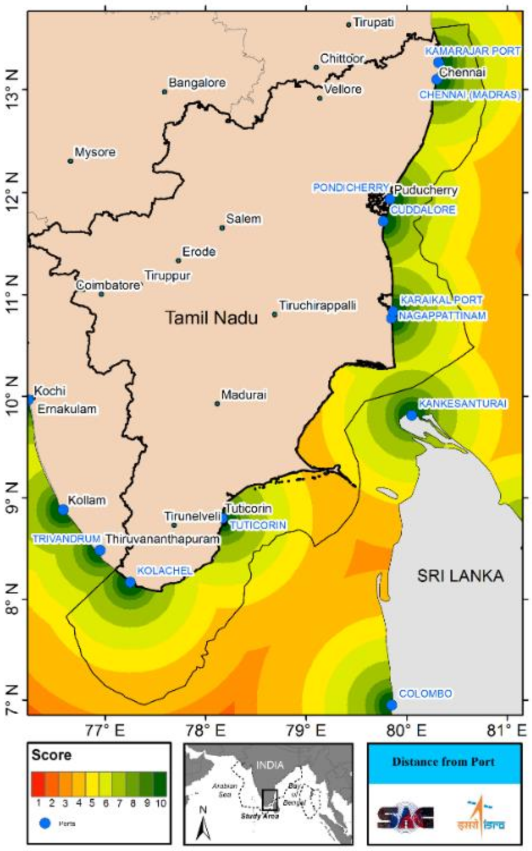

Figure 5: Offshore ports Heat Map

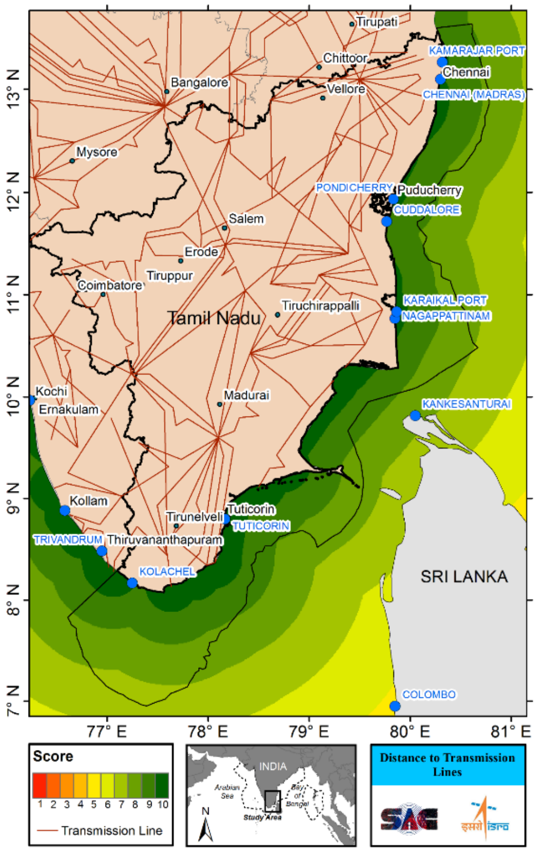

Figure 7: Offshore electric transmission line heat map

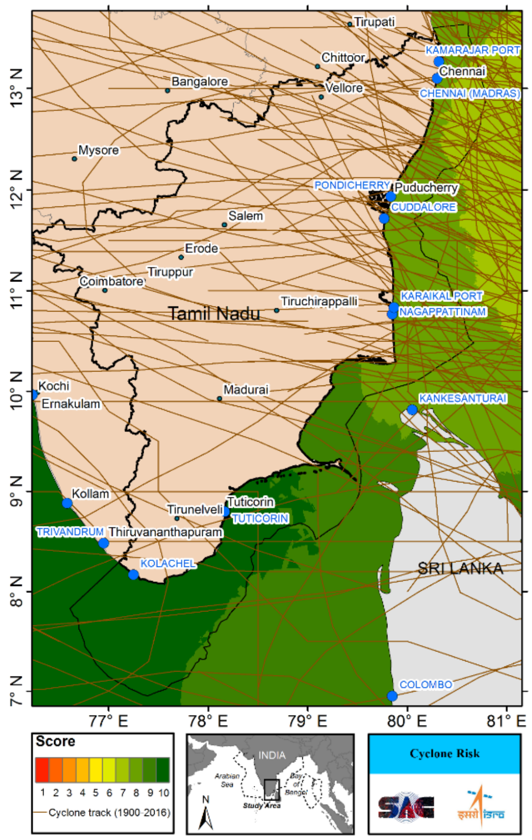

Figure 6: Offshore cyclone risk map

e) *Electric Transmission Line:*

In order to transmit power from the offshore wind farm to the onshore grid system, a dedicated electrical transmission network is required. The wind farm situated far away from the onshore electric transmission lines/grid is less economically viable. Hence, generally wind farm installations are preferred as near as possible to the electrical grids. The data on electrical transmission lines obtained from the Central Electric Authority (CEA) has been processed to estimate the feasibility. It has been observed that the regions closer to the coast are favourable with good score (Figure 7). Submarine electrical transmission lines are preferred for the offshore wind farms. However, lack of data availability restricted the present analysis to the onshore electric transmission lines.

f) *Seismic Zone Exclusion:*

Earthquake is a design concern in seismic areas such as East Asia and Western United states. Global seismic data containing earthquake epi centres have been downloaded (source: http://earthquake.usgs.gov) and prepared a detailed seismic risk map for the study region. However, to date there were no past records of seismic events in the coastal waters of Tamil Nadu. Hence, the entire coastal region is suitable with respect to the seismic hazard is concerned (Figure 8).

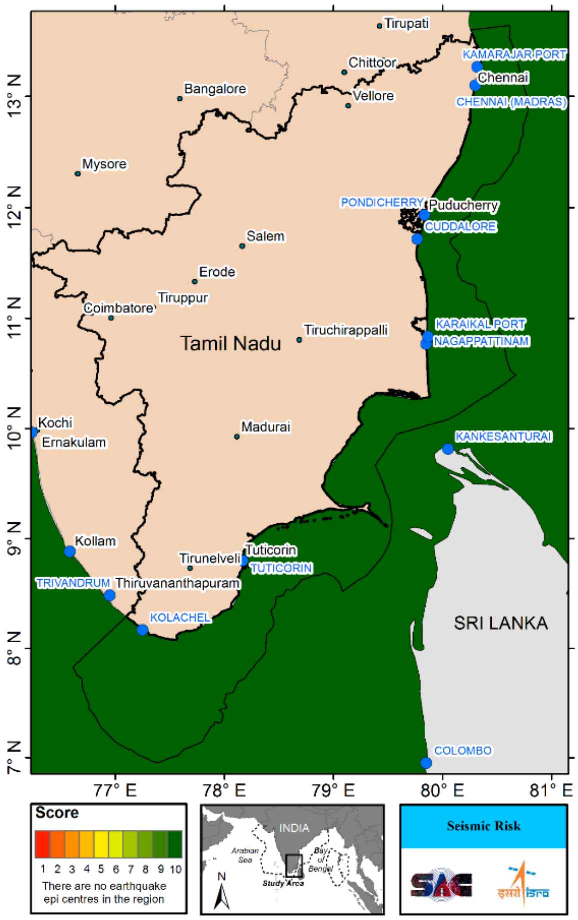

Figure 8: Offshore seismic risk Heat Map

g) Avian Exclusions:

It is very important to study the effects of the offshore wind farms (before construction and during operation) on the Environment. The Potential impacts considering avian mortality is to be included in the study for best practices. In this study, we have considered potential avian impacts within 1 nm from the coast (Figure 9) by excluding the zone parallel to the coastline to avoid interference with the migratory birds (Sheridan et al., 2012). Euclidean distance was computed from the coastline and excluded the region within 1 nm from the analysis (score = 1).

h) Visual Exclusions:

Visual impacts could potentially decrease tourism revenue if people choose to stop visiting a beach when turbines are visible. By considering impact on the coastal residents and tourist sites, offshore wind farms are to be implemented over the several nautical miles away from the shore. Some studies found that even coastal residents, the group with the highest valuation of uninterrupted views, reported very little additional willingness-to-pay for moving turbines beyond 9 miles (8 nautical miles) offshore (Sheridan et al., 2012). In this paper, the visual exclusion of 8 nm away from the coast has been considered (Figure 10).

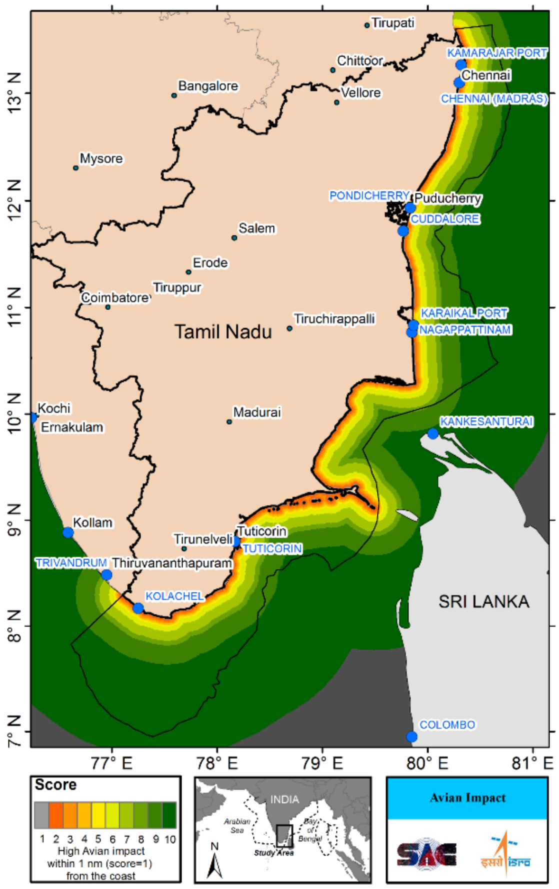

Figure 9: Offshore avian exclusion Heat Map

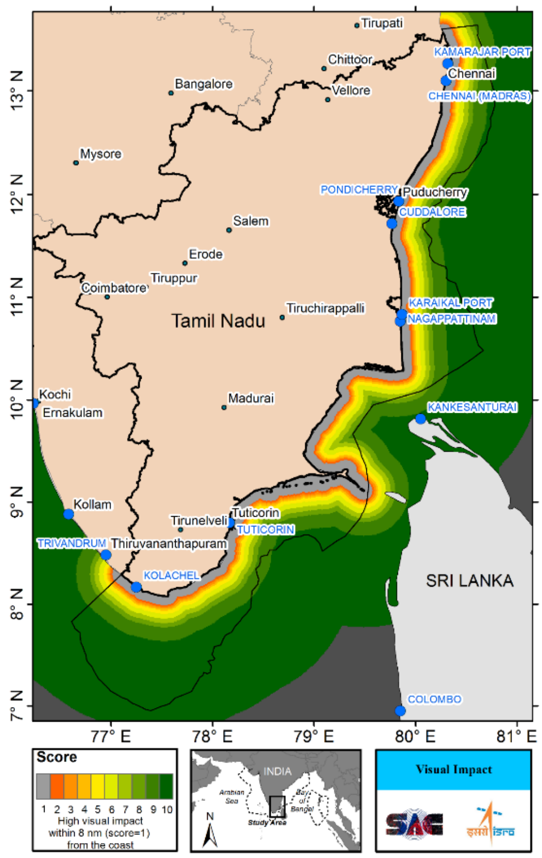

Figure 10: Offshore visual impact Heat Map

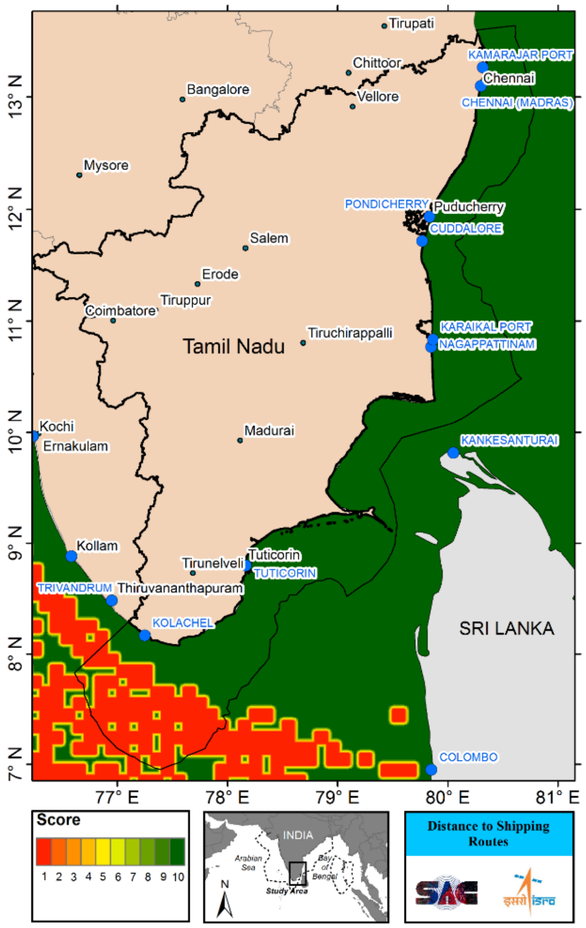

Figure 11: Offshore shipping lane exclusion Heat Map

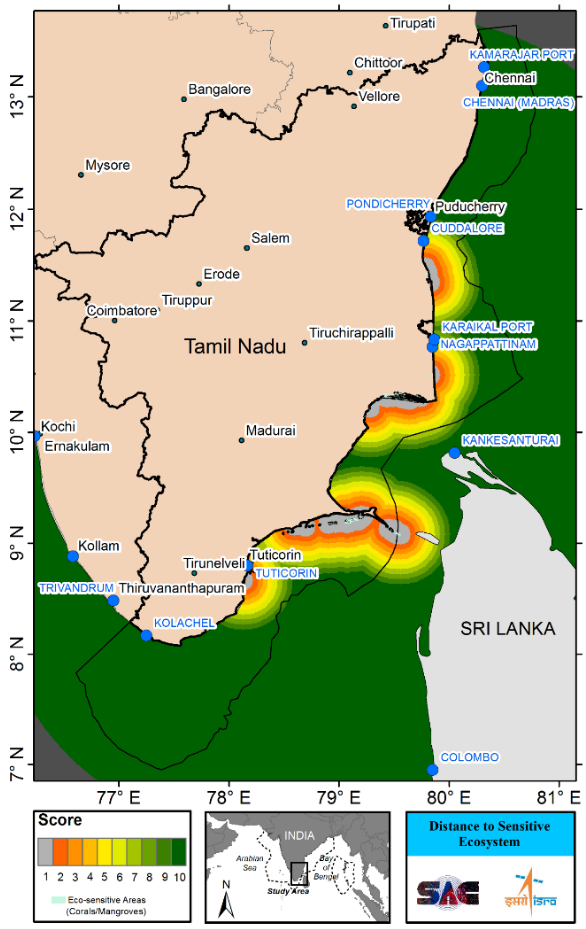

Figure 12: Offshore ecosystem exclusion Heat Map

i) Potential Shipping lanes Exclusions:

In order to understand the potential shipping traffic in the ocean, the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) dataset has been considered. ICOADS is a data set of global marine surface conditions and locations collected and reported by a fleet of about 3700 ships known as the Voluntary Observing Ships (VOS) which shown in the $0.1^0 \times 0.1^0$ grids size. In this paper, a setback of approximately 1 km away from the shipping lanes has been considered in order to avoid collision with the ships plying around that area. It has been observed that major ship traffic is existing along the southern region in relatively deeper waters (Figure 11). The planned *Sethusamudram shipping canal project* may also affect the wind farm development along Rameswaram region, which needs to be further studied and considered.

j) Ecosystem Site Exclusion:

Tamil Nadu coastline contains an abundant variety of ecosystems for example beach, mangrove, coral reef, estuary, island, coastal wetland, etc. Erecting offshore wind turbines will affect their habitats. Therefore, LULC (Land Use Land Cover) data (source: Coastal Zone Information System CZIS, SAC) has been used for preparing a general coastal sensitive ecosystem maps (corals and mangroves) (Figure 12). As the wind turbine foundations are hard structures, it is suggested to exclude these areas by considering marine protection reasons.

In order to aid the selection of zones a scoring mechanism has been derived which takes into account the key technical and consenting factors considered.

Based on the site suitability criteria and wind potential, the most feasible areas suitable for wind farm installation in the study is obtained. The available shelf area, number of installable turbines, name plate capacity and the total expected power generation from the VE 3M and GM 5M turbines are given in table 2 and table 3 respectively. Due to variations in the wind speed inputs, the statistics and optimal sites are found different for SAR and scatterometer based winds (Figure 13). It has been observed that the study region is having more shelf area between 0 and 35 m. Around 1500 – 2000 VE 3M turbines can be installed in < 35 m depth, whereas around 500 – 1990 GM 5M turbines can only be installed in the same shelf region due to its vast turbine area. However, more power can be generated by 5 MW turbines as compared to the 3 MW turbines. On an average, around 1300 kW of power can be generated using the former turbines and with the latter turbines, around 1900 kW is possible. An overall output of 1300 MW or 1900 MW is possible from both the turbines in the optimal region, which converts in to an average annual production of 11966 GWh/year (VE 3M) or 16907 GWh/year (GM 5M) for 0 – 35 m depth range obtained from scatterometer data. The wind production at other two depths are shown in the tables.

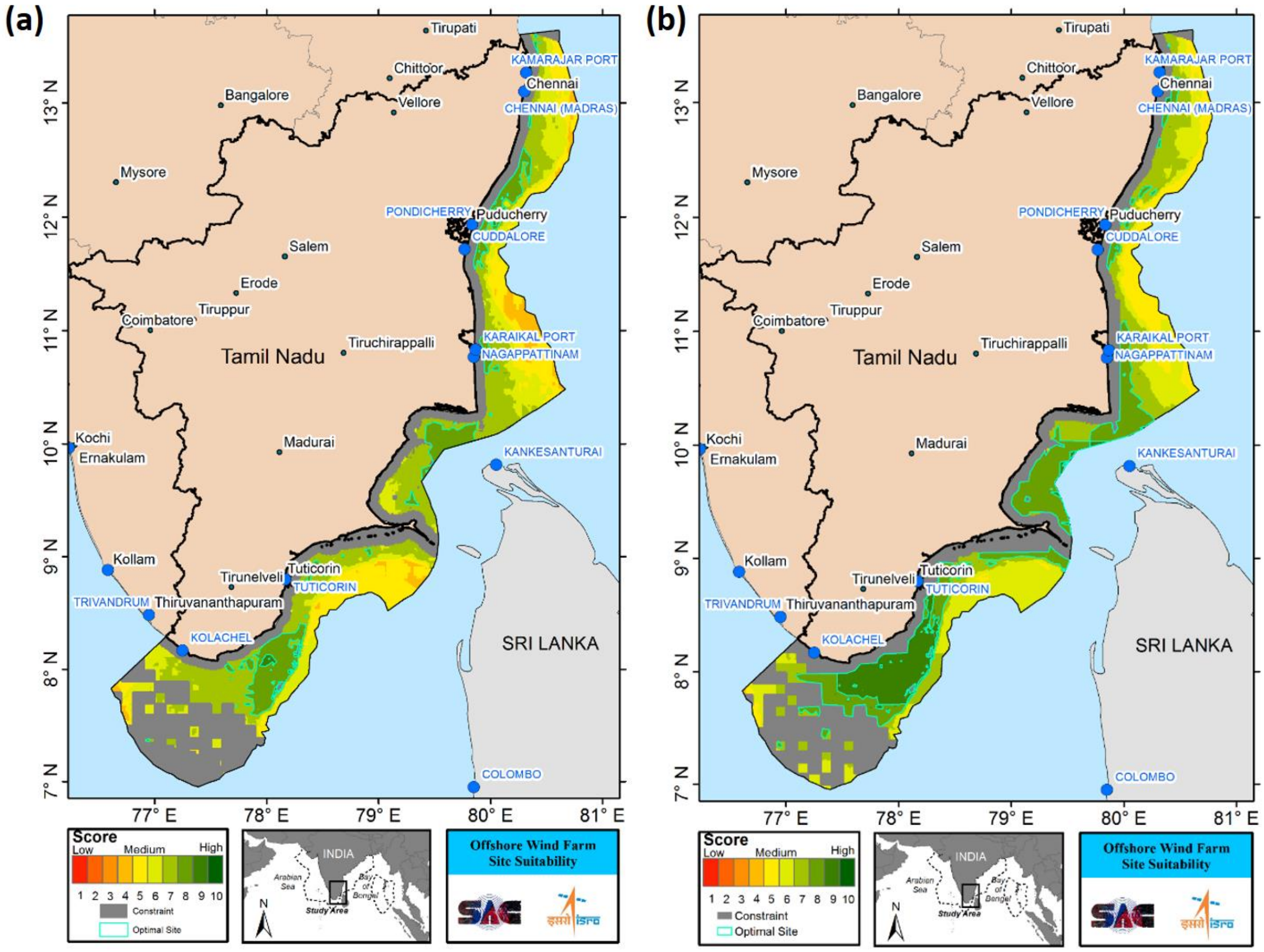

Figure 13: Offshore heat map with potential development zones of Tamil Nadu derived from (a) RISAT-1 SAR data and (b) synergetic scatterometer data

Table 2: Statistics of wind power potential obtained from VE 3M turbine derived from SAR and scatterometer

Parameters	Satellite	Monopile	Jacket	Advanced Jacket	Total
		0-35 m	35-50 m	50-100 m	
Available Shelf Area (km^2)	SAR	425	173	55	653
	SCAT	981	286	202	1469
Number of Turbines	SAR	675	275	87	1037
	SCAT	1557	454	321	2332
Name Plate capacity (MW)	SAR	2025	825	261	3111
	SCAT	4671	1362	962	6995
Range (kW)	SAR	771-1893	847-1753	1017-1725	-
	SCAT	1058-1817	1152-1817	1137-1808	
Mean (kW)	SAR	1187	1364	1416	3965
	SCAT	1393	1588	1533	4514
Total output (MW)	SAR	505	236	78	819
	SCAT	1366	454	309	2129
Total Average Power generation (GWh/year) (EPG)	SAR	4424	2067	683	7174
	SCAT	11966	3977	2707	18650

Table 3: Statistics of wind power potential obtained from GM 5M turbine derived from SAR and scatterometer

Parameters	Satellite	Monopile	Jacket	Advanced Jacket	Total
		0-35 m	35-50 m	50-100 m	
Available Shelf Area (km^2)	SAR	425	173	55	653
	SCAT	981	286	202	1469
Number of Turbines	SAR	518	211	67	796
	SCAT	1196	349	246	1791
Name Plate capacity (MW)	SAR	2590	1055	335	3980
	SCAT	5982	1744	1232	8957
Range (kW)	SAR	1185-2707	1306-2509	1557-2483	-
	SCAT	1495-2569	1629-2569	1608-2556	-
Mean (kW)	SAR	1733	1979	2043	5755
	SCAT	1967	2245	2166	6378
Total output (MW)	SAR	737	342	112	1191
	SCAT	1930	642	437	3009
Total Average Power generation (GWh/year) (EPG)	SAR	6456	2996	981	10433
	SCAT	16907	5624	3828	26359

4. Conclusions

The study provides detailed analysis of potential offshore wind power in the Tamil Nadu EEZ using RISAT-1 SAR and synergetic scatterometer data. Geospatial suitability model has been developed using ten important criteria for the suitable site identification. The southern parts of Tamil Nadu have been identified as one of the potential regions for installing offshore wind farms. In particular, the regions surrounding Tuticorn and Kolachel exhibited the highest suitability. As India is rapidly growing in the economy and population leading to a continuous increase in electricity demand, the offshore wind farms could suffice an excellent alternative energy source because of its negligible greenhouse gas emissions, utilization of offshore surface, cost competitiveness, price stability, and energy security. The methodology can be adopted for identifying potential sites of wind energy for the entire Indian coast. The analysis of production cost and the actual availability of a selected area can be further studied for detailed site suitability.

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