OFFSHORE WIND FARM SITE SELECTION FOR AEGEAN AND MEDITERRANEAN SEA, TURKEY

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submitted by **HATİCE KÜBRA YILDIZ** in partial fulfillment of the requirements for the degree of **Master of Science** i**n Civil Engineering, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Ahmer Türer
Head of the Department, **Civil Engineering**

Assoc.Prof.Dr Elif Oğuz
Supervisor, **Civil Engineering, METU**

Assoc. Prof. Dr. Nejan Huvaj Sarıhan
Co-Supervisor, **Civil Engineering, METU**

Examining Committee Members:

Prof. Dr. Burcu Altan Sakarya
Civil Engineering, METU

Assoc.Prof.Dr. Elif Oğuz
Civil Engineering, METU

Prof.Dr. Elçin Kentel Erdoğan
Civil Engineering, METU

Assoc.Prof.Dr. Nilay Sezer Uzol
Aerospace Engineering, METU

Assoc.Prof.Dr.Tahsin Tezdoğan
Naval Architecture, Ocean and Marine Eng., University of Strathcyde

Date: 26.08.2021

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name: Yıldız,Hatice Kübra

Signature:

ABSTRACT

OFFSHORE WIND FARM SITE SELECTION FOR AEGEAN AND MEDITERRANEAN SEA, TURKEY

Yıldız, Hatice Kübra
Master of Science, Civil Engineering
Supervisor: Assoc. Prof. Dr. Elif Oğuz
Co-Supervisor: Assoc. Prof. Dr. Nejan Huvaj Sarıhan

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This thesis was focused on investigating potential sites in the Aegean and Mediterranean Sea for offshore wind turbines considering a number of criteria such as water depth, wind speed, grid connectivity, etc. Prior to that, all major floating offshore wind turbine installations in Europe and across the World were reviewed. The current status of the offshore wind industry in terms of technology and supporting mechanisms were summarized. Following this, potential sites were mapped using collected data from a wide range of sources and analyzed using the Geographical Information System (GIS) program. For potential sites, a detailed GIS analyses were carried out considering buffer zones and restricted areas. Among the potential sites, the most suitable sites were selected. Then, turbine layout was prepared for the most suitable sites, and potential of wind power plants was roughly estimated. Lastly, grid connection was prepared for the most suitable sites; then, onshore and offshore cable lengths were calculated.

Keywords: Offshore Wind Power Plant, Site Selection, Wind Energy in Turkey, Grid Connection, Offshore Wind Turbines

ÖZ

EGE DENİZİ VE AKDENİZ’DE(TÜRKİYE) AÇIK DENİZ RÜZGAR ÇİFTLİĞİ İÇİN UYGUN ALAN SEÇİMİ

Yıldız, Hatice Kübra
Yüksek Lisans, İnşaat Mühendisliği
Tez Yöneticisi: Doç. Dr. Elif Oğuz
Ortak Tez Yöneticisi: Doç. Dr. Nejan Huvaj Sarıhan

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Bu tez, su derinliği, rüzgâr hızı, şebeke bağlantısı vb. gibi bir dizi kriter göz önünde bulundurularak açık deniz rüzgâr türbinleri için Ege Denizi ve Akdeniz’de uygun alan seçimine odaklanmıştır. Bundan önce, Avrupa'daki ve dünyadaki tüm açık deniz yüzer rüzgâr türbini kurulumları gözden geçirilmiş, açık deniz rüzgâr endüstrisinin teknoloji ve destekleyici unsurlar açısından mevcut durumu özetlenmiştir. Sonrasında, çeşitli kaynaklardan toplanan veriler kullanılarak potansiyel alanlar haritalanmış ve Coğrafi Bilgi Sistemi (CBS) programı kullanılarak bu potansiyel alanlar analiz edilmiştir. Tampon bölgeler ve kısıtlanmış bölgeler göz önüne alınarak potansiyel alanlar için bir dizi detaylı CBS analizi yapılmıştır. Sonrasında, potansiyel alanlar arasından en uygun alan seçimi yapılmıştır. Bu aşamadan sonra uygun alan için türbin yerleşimi yapılıp yaklaşık bir rüzgâr potansiyel hesabı yapılmıştır. Son olarak elektrik iletim şebekesi rotaları belirlenmiş, bu rotalara yerleştirilen elektrik iletim kabloları için uzunluk hesaplamaları yapılmıştır.

Anahtar Kelimeler: Açık Deniz Rüzgâr Çiftliği, Alan Seçimi, Türkiye’de Rüzgâr Enerjisi, Şebeke Bağlantısı, Açık Deniz Rüzgâr Türbinleri

To my mother…

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ABBREVIATIONS

AFAD	Disaster and Emergency Management Presidency
AHP	Analytic Hierarchy Process
BOEM	Bureau of Ocean Energy Management
BOTAŞ	Petroleum Pipeline Company
DOE	Department of Energy
EIA	Energy Information Administration
EMODNet	The European Marine Observation and Data Network
GEBCO	The General Bathymetric Chart of the Oceans
FIT	Feed-in Tariff
FBOWT	Fixed-bottom offshore wind turbines
FOWT	Floating offshore wind turbine
GHG	Greenhouse gas
GIS	Geographical Information Systems
GPS	Global Positioning System
GWA	Global Wind Atlas
HDO	Horizantal directional drilling
HGM	The General Directorate of Maps
IAC	Inter-array cable
IEA	The International Energy Agency
IEC	The International Electrotechnical Commission
IRENA	The International Renewable Energy Agency
KOERI	Kandilli Observatory and Earthquake Research Institute
MCDM	Multi-Criteria Decision Making
MMS	The Minerals Management Service
MTA	General Directorate of Mineral Research and Exploration
NEA	The National Energy Administration

NREL	National Renewable Energy Laboratory
OECD	The Organisation for Economic Co-operation and Development
OEC	Offshore export cable
OHL	Overhead line
OnEC	Onshore export cable
ONS	Onshore substation
OSM	Open Street Map
OWPP	Offshore wind power plant
OWT	Offshore wind technology
PGA	Peak ground acceleration
PPA	Power purchase agreement
SHARE	Seismic Hazard Harmonization in Europe
SHGM	The General Directorate of Civil Aviation
SOA	The State Ocean Administration
TEİAŞ	Turkish Electricity Transmission Corporation
TLP	Tension leg platform
TUDES	Turkey's National Sea Level Monitoring System
TWEA	Turkey Wind Energy Association
UNCLOS	United Nations Convention on the Law of the Sea
USGS	The United States Geological Survey
WAsP	Wind Atlas Analysis and Application Program
WDPA	The World Database on Protected Areas

CHAPTER 1

INTRODUCTION

Interest in offshore wind power plants (OWPPs) is increasing worldwide due to their advantages over onshore wind power plants (see details in Chapter 2). Turkey has had one of the fastest-growing energy demands among the Organization for Economic Co-operation and Development (OECD) countries for over 20 years (Ministry of Foreign Affairs of Turkey, 2021). After China, Turkey takes second place due to its increasing demand for electricity and natural gas globally. Despite increasing energy need, imported energy sources dependency reaches approximately 74 percent for Turkey in 2021 (Ministry of Foreign Affairs of Turkey, 2021). In order to reduce imported energy resources amount, shifting energy policies to renewable energy resources is needed. Turkey is a country covered with seas on three sides and rich in wind sources, so the country has high offshore wind potential. In order to benefit from this offshore wind potential and reduce imported energy amounts, OWPP installations can be recommended by experts. Therefore, the focus of this thesis is to select suitable sites for a potential OWPP installation in Agean and the Mediterranean Sea in Turkey. For this reason, potential sites have been investigated after a series of elimination by considering some site selection criteria (will be explained in the next Chapters).

The Turkish Ministry of Energy and Natural Resources announced an OWPP tender for three potential areas (Saros, Kıyıköy, and Gelibolu) with 1200 MW capacity in 2018 (Anadolu Agency, 2018); this auction was canceled since no bids were received. Today, there is no OWPP project (installed or under construction) in Turkey; however, it is aimed to implement this technology in the coming years. Today, according to Turkey Wind Energy Association (TWEA), cumulative installed onshore wind turbine installed capacity has reached 9305 MW by 2021 (Turkish Wind Energy Association, 2021).

As abovementioned, this thesis mainly focuses on a suitable site selection for a potential OWPP in Agean and Mediterranean Sea in Turkey. Prior to this, in Chapter 2, the development of OWPP, common foundation types, leading countries in offshore wind industry are explained in a comprehensive literature review. Also, floating offshore wind turbines (FOWTs) around the world are presented.

In Chapter 3, another literature review is carried out for previous site selection studies for both in world and Turkey. In this chapter, it is aimed to obtain generally considered site selection criteria from the previous site selection studies.

Also, in Chapter 4, followed methodology is explained; then, modelling and analyzing in GIS environment is presented. In this thesis, ArcGIS Pro software is used to carry out mapping and analyses.

For a potential OWPP, one of the important steps is suitable site selection. To determine site selection criteria, comprehensive literature reviews were carried out. Data is collected to prepare maps of each criterion for Turkey. Analyses are carried out and presented in Chapter 5.

In Chapter 6, potential sites and their compliance with the criteria are discussed to determine the most suitable area. While evaluating sites, buffer zones and limited/resricted areas are also considered. After the selection of the most suitable area, turbine layout and grid connection is prepared in Chapter 7. A grid connection is a critical step since it directly affects project costs. Therefore, an appropriate cable route is selected to minimize cable laying costs. Before measuring this distance, a suitable 380-400 kV(kilovolt) Turkish substation (point of interconnection) is decided. Then, offshore export cables (OEC), onshore export cables (OnEC), overhead line lengths (OHL) are calculated or measured by taking profile lengths (surface lengths) for determined cable routes.

The contribution of this thesis is that :

i. A great number of site selection criteria are discussed in detail (wind speed, territorial waters, water depth, military zones, ports, offshore seismic activity, shipping routes, environmentally protected areas, fishery, distance to shore for grid connection, shipwrecks, civil aviation, existing pipelines, underwater cables, offshore observation wells, and seabed soil) compared to previous studies which are carried out for Turkey (see details in Chapter 3).

ii. Earthquake data is taken from three different sources (General Directorate of Mineral Research and Exploration (MTA), Seismic Hazard Harmonization in Europe (SHARE Project), and Kandilli Observatory and Earthquake Research Institute (KOERI). A buffer distance is added around fault lines to eliminate risky earthquake areas. The earthquake has not been considered in much detail. Note that earthquake has been disregarded in most studies for Turkey.

iii. OWPP turbine layout is prepared for selected site, and grid connection process is described. As a result, preliminary cable lengths are calculated as abovementioned. In previous studies, such a detailed grid connection study was not carried out. This part is important in terms of introducing the offshore wind grid connection concept and its components.

iv. Again, differently from previous studies, shipwrecks, offshore observation wells, civil aviation and sea-bed soil conditions were also examined in more detail. These criteria also have been disregarded in most studies.

v. Also, in this thesis, it is stated that Turkish waters are more suitable for floating offshore wind turbines (FOWTs) than fixed-bottom offshore wind turbines (FBOWTs). This is because water depth exceeds 50 m limit at a small distance from the coastline. Note that 50 m is a recommended value between FOWTs and FBOWTS by World Bank Report, 2019. It is worth noting that previous studies carried out in Turkey assumed the implementation of FBOWTs. This is most probably because of the prevalence of those foundations in Europe.

vi. It is expected that, this study will be useful for the first OWPP deployment in Turkey in future since this thesis presents a comprehensive site selection study, which is a starting point on OWPP development.

CHAPTER 2

LITERATURE REVIEW ON OFFSHORE WIND ENERGY DEVELOPMENT AROUND THE WORLD

With the increasing population of the World, energy consumption is also increasing. Between 2010 and 2040, energy consumption has risen by 56% (U.S Energy Information Administration, 2021). Fossil fuels such as oil, natural gas, and coal are significant energy sources worldwide (Kumar et al., 2016; Timmons et al., 2014). Economic foreign dependency on energy sources, insufficient energy sources, and climate change requires a transition from fossil fuel to renewable energy sources. Nuclear energy, which uses non-fossil fuel sources, leads to less greenhouse gas (GHG) emissions. Even though it has completed its development process and is very effective in energy production, it does not fully meet the desired clean and healthy energy solution. The cause of this is the adverse effects of radioactive waste and the high radiation (Kumar et al., 2016).

On the other hand, utilizing renewable and sustainable resources (wind, wave, tidal, solar, geothermal, and biomass etc.) to generate energy and making widespread use of these sources is considered to be an effective solution to energy problems (J. Chen, 2011; Da et al., 2011; Vis & Ursavas, 2016). Wind, a mature resource with a history of 3500 years, might be an alternative resource used to meet the energy consumption in the World. Also, it does not emit GHGs during energy production, and modestly small spaces are sufficient for installation (Kumar et al., 2016).

Wind turbines, which are the most common and effective wind energy systems, were developed for the first time in the early 1900s (Kumar et al., 2016). According to the statistics published by the International Renewable Energy Agency (IRENA), wind energy potential has quadrupled in the last decade (IRENA, 2019). In the 1990s, the amount of energy produced by onshore wind turbines in some regions, such as

Denmark, Schleswig-Holstein in Germany, and Gotland in Sweden, has reached 10% of the total energy requirement of the region (Henderson et al., 2003). It can be stated that onshore wind turbines dominated the market. However, this growth in the onshore wind has brought along some problems such as the difficulty of transporting the large components of a wind turbine (i.e., blades, hub, etc.), restrictions about negative visual effects, and noise impacts. As a solution to these problems, the tendency and research towards offshore wind energy have increased.

Thus, the technological advancements in the last decades have led the market to move towards offshore wind energy due to its significant advantages. On the other hand, offshore wind farms have some drawbacks such as high operational and maintenance costs, load magnitude, extreme weather conditions, complexity, and uncertainty related to the support structure's design process (Henderson et al., 2003; O’Kelly & Arshad, 2016). Offshore costs are 2-3 times higher than onshore counterparts. It requires much greater supporting structures, underwater cables to set up an electrical network with land, and unique vessels to deploy and maintain an offshore wind farm (Bilgili et al., 2011).

For offshore wind turbines, bottom-fixed types (gravity, monopile, tripod, jacket) and floating types (spar-buoy, barge, tension leg platform (TLP), semi-submersible, etc.) have been offered as supporting structures. Some of these with their typical installation depth ranges are shown in Figure 2.1.

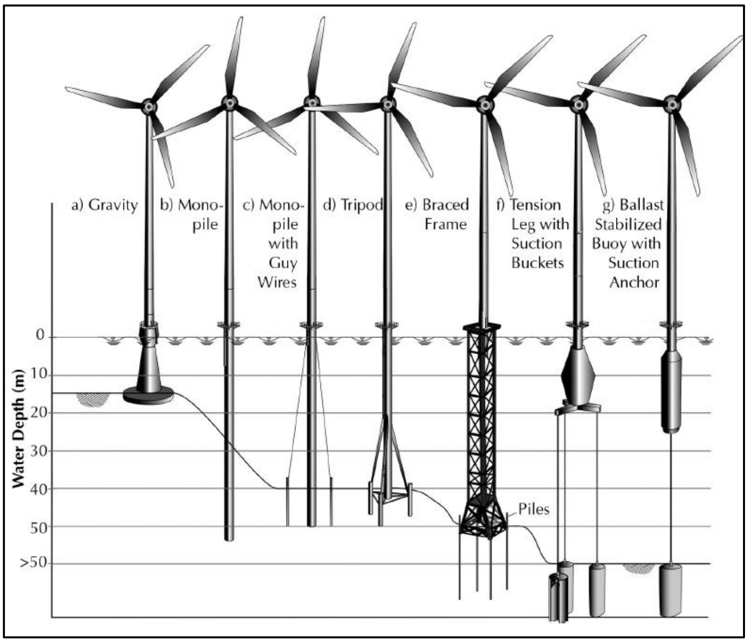

Figure 2.1. Different types of supporting structures, foundation type changes with water depth (Malhotra, 2011).

Water depth is a significant factor affecting the type of wind turbine foundation. For near-the-shore OWPPs, fixed-bottom types (see Figure 2.2) have been used as support structures until the depth of 50 m, recommended by the World Bank Report (2019). However, installations are increasingly moving away from the shore for more significant wind potential and an abundance of suitable areas in the open sea (World Bank, 2019).

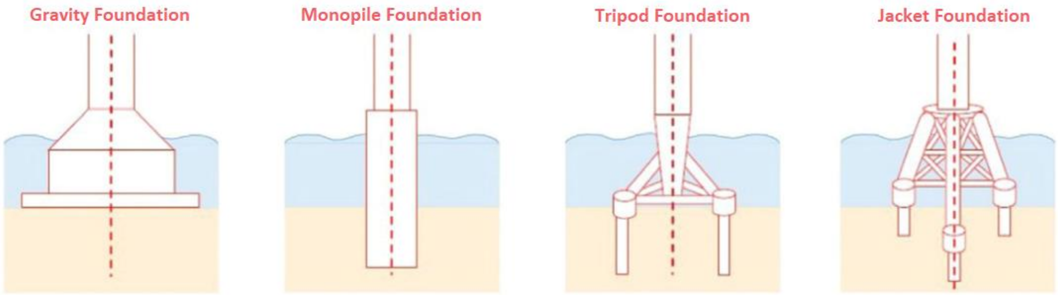

Figure 2.2. Illustration of fixed-bottom offshore wind turbine foundation (Micelli, 2012)

Nevertheless, fixed-bottom types after 50 m water depth are challenging and not economically suitable (World Bank, 2019). Therefore, floating types have been preferred as an alternative support structure for water depth exceeding 50 m (Lefebvre & Collu, 2012). So, floating offshore wind turbines (FOWTs) are preferable for the water depth exceeding 50 m, in general. Also, when sea-bed soil is soft, they become attractive. Hansen (2006) states that floating wind turbines might be installed until the 700 m sea depth (Hansen, 2006). The floating foundations are spar-buoy, tension leg platform, semi-submersible, and barge types as most common (Butterfield et al., 2005; Wang et al., 2010).

Figure 2.3 shows the stability triangle, which presents the way of achieving stability of different floating platform concepts. The stability of floating platforms is provided in mainly three systems, as seen from the figure: ballasts, mooring lines, and buoyancy. Besides these three main systems, hybrid systems also exist inside the triangle (Butterfield et al., 2005).

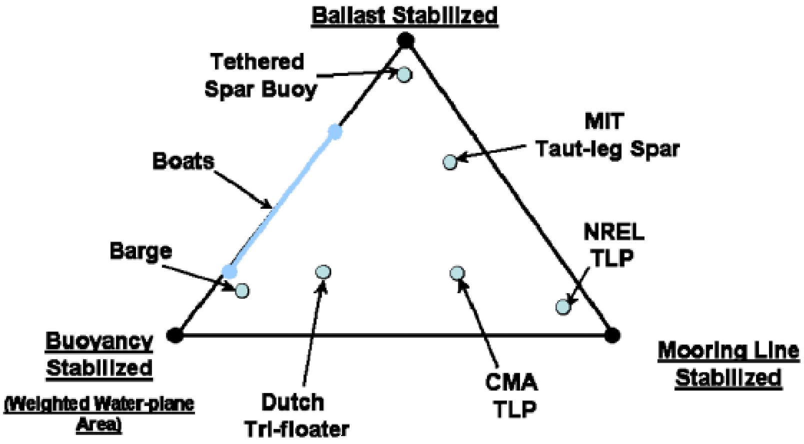

Figure 2.3. Stability triangle (Butterfield et al., 2005)

Mooring lines, suction caissons stabilize the cylinder tubes and the turbine system for spar types (see Figure 2.4). The center of buoyancy is higher than the center of gravity in water for this type of foundation. This situation is beneficial for heeling to right system behavior. Mooring lines and suction caissons provide keeping the position of the turbine system in balance. The design of spar buoy is simple, and it requires lower mooring costs (Quest Floating Wind Energy, 2021). However, heavy lift vessels are needed to carry or transfer turbines to the field.

Tension leg platform (TLP) system includes a center column, and this center column is connected to tendons, carrying tension force (see Figure 2.4). The gravity anchors are used to provide the balance of the system. TLP structures can be used for the water depth around 60 m, and the turbine system can be mounted onshore, then carried to the construction site. The mass of the system is generally lower than other FOWT types. However, it required effort to provide stability of the turbine system during transportation and installation. The mooring cost of this system is high, and sometimes, the system might require a specially designed vessel (Quest Floating Wind Energy, 2021)

Another type is a semi-submersible turbine system shown in Figure 2.4. The design of a semi-submersible foundation consists of a large column connected to a semi-submersible platform, as seen in the Figure. The column is commissioned to provide hydrostatic stability to the system. The upper part of the turbine is connected seabed by drag anchors and mooring lines. The cost of mooring lines is low in contrast to TLP systems. However, like TLPs, semi-submersible systems might be mounted onshore. However, these foundations are required heavy pieces and complex fabrication processes (Quest Floating Wind Energy, 2021).

Barge systems consist of a hull. This hull can be steel or concrete and anchored to the seabed with mooring lines, as seen in Figure 2.4. Barge systems might support multiple wind turbines by stabilizing the system with a large waterplane area and distributed buoyancy (COWI, 2021). Table 2.1 shows the advantages/priorities and disadvantages/limitations of the typical floating turbines.

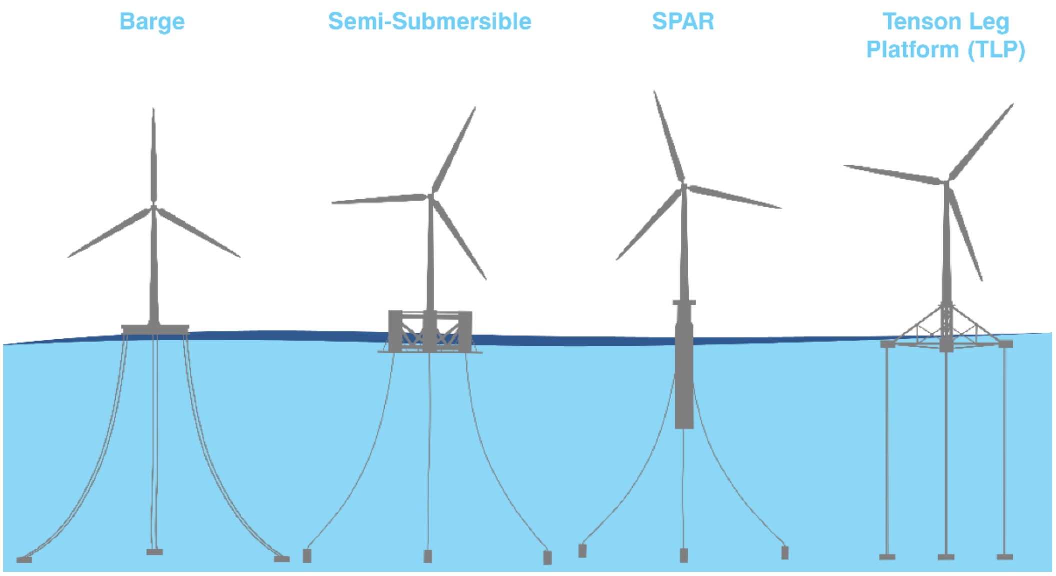

Figure 2.4. Illustration of different FOWTs (Quest Floating Wind Energy, 2021)

Table 2.1. Advantages and disadvantages of substructures for FOWTs (Butterfield et al., 2005; IRENA, 2016)

FOWT Types	**ADVANTAGES/PRIORITIES**	**DISADVANTAGES/ LIMITATIONS**
Spar Buoy	• A propensity for smaller wave-induced motions • Requires simpler design • Low mooring cost	• Requires heavy-lift vessels and offshore mounting • Usable deeper water than semi-submersible or TLP foundations (exceeding 100 m)
Semi-Submersible	• Mounted onshore • Transport to the site with tugboats • Usable water depths around 40 m • Low mooring costs like spar buoy systems	• A tendency for higher critical wave-induced motions • Needs more material and larger structural components • Complex fabrication c

Table 2.1 (continued)

TLP	• A propensity for smaller wave-induced motions • Low mass • Assembly onshore • Usable for water depths around 50-60 m	• Difficult to keep the system stable while carrying construction site • Requires specially designed vessels • Uncertainty about the effect of potential high-frequency dynamic impact on the system • High mooring cost
Barge	• Sensitivity to sea bottom condition • Lower anchor cost than other FOWT • Less depth dependency than other FOWT	• Under high wave loading • Complex design and material • Heavy structure (due to dependency on waterplane area to provide ballast)

Further, offshore wind energy technologies are well-developed in some countries and regions, especially in Europe, the US, Japan, and China, constituting the vast majority of all installed offshore wind power capacity in the World. Moreover, the world's leading countries in offshore developments, such as UK, Denmark, Germany, the US, and China, improved policies and regulations over time to reach their goals. Besides these countries, Japan also has a large electricity market and is in the earthquake zone, challenging wind energy deployments. Therefore, it is critical to enhance knowledge and prepare necessary legislation by taking advantage of their experience before developing an offshore wind turbine for newcomers like Turkey. Offshore development of Europe and some offshore wind technology (OWT) leading countries are presented in the following sections.

2.1 Offshore Wind Energy Development in Europe

Offshore wind turbines were proposed for the first time in the 1930s (Bilgili et al., 2011). This proposal was to place the turbine above the sea on a pylon tower. However, for the first time, offshore wind turbine platforms were introduced by Dr. William Heronemus from MIT. The first offshore wind turbine in Europe was Nogersund, built in Sweden in 1990. This turbine was built 250 meters from the shore at a depth of 7 meters in water. The first wind farm was Vindeby, made in Denmark, and consisted of 11 wind turbines (Bilgili et al., 2011). Currently, Europe is the world leader in OWT for floating and fixed-bottom wind types. It has a 25 GW grid-connected capacity, 5402 connected wind turbines (produces energy-fully commissioned), 116 offshore wind farms in 12 EU countries. The UK, Denmark, and Germany are the leading countries of Europe in terms of OWT (see Figure 2.5) (WindEurope, 2021a).

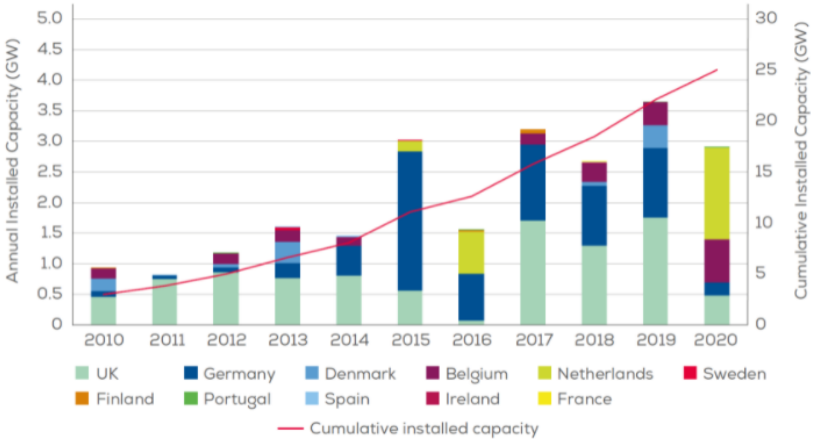

Figure 2.5. Cumulative and annual offshore wind installations in 2010-2020 (WindEurope, 2021a)

2.1.1 Regulations and Policies for Offshore Wind Energy in Europe

As stated in Section 2.1, Denmark was the first country to step into OWT. However, with the withdrawal of government support in the 2000s, there were stagnations in this area, as in Denmark. No offshore turbines were installed between 2004-2008 years in the country, but the government started to maintain the development of this area again after 2009. However, in the meantime, The UK took the position of the world's leading country in offshore wind power at the end of 2008. Especially in the years when the recession was seen in Denmark, The UK took its place in this field with the government's support, and in 2009, The UK left Denmark behind in terms of installed offshore turbines (DeCastro et al., 2019; Zaaijer & Henderson, 2004).

By 2020, the UK's cumulative installed offshore wind capacity has reached 10428 MW, while the same capacity of Denmark has reached 6180 MW (WindEurope, 2021c). The UK has many wind projects in the long term to reduce GHGs. The government supports these projects; the trend in European countries has been to monopolize management and control structure by reducing the number of relevant agencies and required licenses (DeCastro et al., 2019; Zaaijer & Henderson, 2004).

2.1.2 Offshore Wind Power Potential and Installed Capacity in Europe

WindEurope Report (2020) states that 2918 MW offshore wind turbines were built in Europe by the end of 2020. This rate shows a decrease of approximately 20% compared to 2019 due to the Covid-19 pandemic. The capacity of this 2918 MW by country: Netherlands 1493 MW, Belgium 706 MW, The UK 483 MW, Germany 219 MW, and Portugal 17 MW (WindEurope, 2021b). Europe aims to meet %25 of its electricity demand from offshore wind power by 2050. WindEurope states that Northern Seas, the Atlantic, and the Mediterranean have 330 MW offshore floating potential by 2022, and 7 GW offshore floating potential by 2030 can be implemented (WindEurope, 2021b). Table 2.2 shows offshore floating wind turbines to be commissioned in the following years in Europe.

Table 2.2. Floating wind turbines to be commissioned in the next years (WindEurope, 2021b)

Country	**Wind Farm**	**Capacity (MW)**	**Floater Type**	**Number of Turbines**	**Expected Commissioning Date**
France	Éoliennes Flottantes de Groix	28.5	Semi-sub	3	2022
France	EFGL	30	Semi-sub	3	2023
France	EolMed	30	Barge	3	2023

Table 2.2 (continued)

France	Provence Grand Large	25	TLP	3	2023
Norway	Hywind Tampen	88	Spar	11	2022
The UK	Kinkardine	50	Semi-sub	5	2021

In addition, Table 2.3 shows floating type OWPP or demonstration projects in Europe. Some properties such as distance to shore, water depth, installed sea information is also given in the same table.

Table 2.3. Floating offshore wind turbine projects and their properties in Europe (4C Offshore, 2021)

Project Name	**Country**	**Distance from shore (km)**	**Depth (m)**	**Sea Name**	**Development Status**	**Project Capacity (MW)**	**Turbine Capacity (MW)**	**Foundation**	**Homes Powered Annually (tons)**	**CO_2 reduced per year (tons)**
Poseidon P60 Mermaid	Belgium	50	42	North	Concept/Early Planning	2.3	2.3	Semi-Sub	1629	3292
Poseidon P37	Denmark	-	-	Kattegat	Decommissioned	0.03	0.011	Semi-Sub	21	43
Hywind Scotland Pilot Park	UK	25	95-120	North	Fully Commissioned	30	5	Spar Floater	21248	42942
Wave Hub	UK	16	48-58	Celtic	Fully Commissioned	30	-	TLP	21248	42942
SeaTwirl P3	Sweden	-	-	Kattegat	Decommissioned	0.002	0.002	Spar Floater	1	2
SeaTwirl S1	Sweden	-	-	Gullmarn	Fully Commissioned	0.03	0.03	Spar Floater	21	43
FREIA I	Sweden	-	-	Baltic	Cancelled	18	3	Semi-Sub	12749	25765
FREIA II	Sweden	-	-	Baltic	Cancelled	576	6	Semi-Sub	407955	824477
HEXICON	Sweden	-	-	Baltic	Cancelled	44	-	Semi-Sub	31163	62981
Brindisi	Italy	21.3	-	Adriatic	Decommissioned	0.08	0.08	TLP	57	115
Afefa	Italy	90		Mediterranean	Cancelled	700	-	TLP	495779	1001969
Aida	Italy	22	-	Mediterranean	Cancelled	308		TLP	218143	440866
Atair	Italy	-	-	Mediterranean	Cancelled	-	-	TLP	-	-
Bari	Italy	22	-	Adriatic Sea	Cancelled	441	-	TLP	312341	631240

Table 2.3 (continued)

Bella	Italy	16	-	Mediterranean	Cancelled	280	-	TLP	198311	400788
DemoSath-BIMEP	Spain	2	85-90	Bay of Biscay	Consent Authorised	2	2	TLP	1417	2863
X1 Wind Prototype	Spain	-	-	Atlantic	Consent Authorised	-	-	TLP	-	-
FLOCAN 5	Spain	2	50-120	Atlantic	Consent Application Submitted	40	8	TLP	17706	35785
Balea	Spain	-	-	Bay of Biscay	Concept/Early Planning	26	2 x 5 -2x 8	-	18415	37216
Canary Island Test Area	Spain	-	60-200	Atlantic	Concept/Early Planning	310	-	-	219559	443779
EOLINK 1/10 Scale Prototype	France	-	-	North Atlantic	Fully Commissioned	-	-	Semi-Sub	-	-
Floatgen Project	France	22	33	Atlantic	Fully Commissioned	2	2	Semi-Sub	1417	2863
Sem-Rev Site D' Experimentat Ion En Mer	France	24	34	Atlantic	Fully Commissioned	8	-	Semi-Sub	5666	11451
Nenuphar Test Site	France	5	60-70	Mediterranean	Consent Authorised	10	5	Semi-Sub	7083	14314
Les eoliennes flottantes de Groix&Belle-İle	France	13	57-71	Atlantic	Consent Application Submitted	24	6	Semi-Sub	16988	34353
EolMed	France	15	50-74	Mediterranean	Concept/Early Planning	18.45	6.15	Semi-Sub	17423	35212

Table 2.3 (continued)

Les eoliennes flottantes du Golfe du Lion	France	17	65-80	Mediterranean	Concept/Early Planning	24	6	Semi-Sub	16998	34353
Spinfloat Demonstrator	France	-	-	Mediterranean	Concept/Early Planning	6	6	Semi-Sub	4250	8588
InFLOW	France	50	52-63	Mediterranean	Cancelled	1.2	1.2	Semi-Sub	850	1718
Nenuphar-large scale prototype	France	-	-	-	Cancelled	5	5	Semi-Sub	3541	7157
Nenuphar twin float	France	-	-	Mediterranean	Cancelled	20	5	Semi-Sub	14165	28628
Bilice	Crotia	40	-	Adriatic	Cancelled	448	-	TLP	317928	641260
Dubrovnik	Crotia	26	-	Adriatic	Cancelled	392		TLP	277636	561103
Galway Bay Marine and Renewable Energy Test site	Ireland	1.3	20-23	Galway Bay	-	-	-	-	-	-
Floating Power Plant - Ireland	Ireland	-	-	-	Concept/Early Planning	224	8	Semi-Sub	158649	320630
Windfloat 1 Prototype (WF1)	Portugal	5	-	Atlantic	Decommissioned	2	2	Semi-Sub	1417	2863
Windfloat Atlantic (WFA)	Portugal	20	85-100	Atlantic	Pre-Construction	25	8.4	Semi-Sub	17706	35785

Table 2.3 (continued)

Windfloat Atlantic (WFA) Phase 2	Portugal	-	-	Atlantic	Concept/Early Planning	125	8	Semi-Sub	88532	178923
Branca	Portugal	17	-	Atlantic	Cancelled	301	3.5	TLP	213185	430847

2.2 Offshore Wind Energy Development in China

With the rapidly increasing population and resulting economic growth in China, energy has become an important issue due to the increasing energy demand (J. Chen, 2011). China is the biggest energy-consuming country in the World (International Energy Agency, 2019), and according to the IEA, by 2030, China's energy demand is predicted to be doubled compared to 2005 (Da et al., 2011). China has produced energy from fossil fuels, especially coal, for many year (Chen, 2011). However, despite the large fossil resource reserves in China, the Chinese per capita fossil reserve is relatively low since it has the largest population in the World (Yu & Qu, 2010), and yet China's energy dependence on foreign countries is growing day by day (Da et al., 2011). Therefore, taking into consideration the energy security concern and the global problems such as sustainability, climate change, and increasing environmental pollution with the use of fossil fuels, China has turned to the use of renewable and sustainable energy resources (Chen, 2011).

2.2.1 Regulations and Policies for Offshore Wind Energy in China

The first two critical political steps of the tendency towards renewable and sustainable energy are the Renewable Energy Law (2006) and the Medium-Long Term Development Plan for Renewable Energy (2007). By 2020, the Chinese government aims to produce 15% of its energy needs from non-fossil energy sources and reduce its carbon dioxide emissions by 40-45% compared to 2005 (Qin et al., 2010).

At the very first stage of the development of the offshore wind energy systems, in China, demonstration projects have been implemented with caution since it does not seem very practical to implement large-scale projects. Thus, it aims to establish management systems and construction standards to guide the development of offshore wind energy through experience gained in the design, construction, operation, and maintenance of offshore wind farm demonstration projects.

In the first years of its offshore wind power, China faced three main challenges (Chen, 2011):

First, more research and development were needed to develop large-scale projects because the technology was not sufficiently developed. Second, due to the intermittence and instability of the energy produced from the wind, all the generated energy was not expected to be demanded by the power grid companies. This situation limited the integration of wind energy into the power grid. However, improving the non-grid-connected wind power generation theory and using energy storage systems such as batteries may be solutions to this problem. Third, although cost-effective improvements, such as optimization of design, layout, and installation, were planned, it was not economically suitable to make significant investments in the short term since the cost of offshore wind energy was twice as expensive as onshore.

There are very few regulations regarding offshore wind power in China. Moreover, these regulations, which are limited by planning and policies, are expressed in invalid and uncertain worded terms (DeCastro et al., 2019). According to Chang et al. (2017), although procedures can be implemented more quickly in a short time, these policies need to be replaced by laws since they do not have long-term persistence and have no legal validity (Chang & Wang, 2017). On the other hand, Leary et al. (2011) argue that policies such as five-year plans and legalized norms such as "The Renewable Energy Law" include offshore wind energy development (Leary & Esteban, 2011).

Renewable energy resources in China are managed by many ministries and agencies. The main reason for delays in the development of OWPP is the lack of coordination between these government agencies. While the National Energy Administration (NEA) was in favor of installing OWPPs as close to the shore as possible to reduce costs and minimize technical difficulties, The State Ocean Administration (SOA) favored further away offshore installations to minimize the restriction of other user areas like fisheries, tourism, and military. However, in 2010, NEA and SOA began joint regulations to eliminate such contradictions between them. With the joint rules established by NEA and SOA, the areas where OWPP cannot be installed have become clear. According to these regulations, and OWPP cannot be installed in waters up to 10 km from the shore, in water depths up to 10 m, and in areas reserved for commercial or military use (DeCastro et al., 2019).

According to He et al. (2016), offshore wind energy incentives policies such as reductions in VAT and income tax on additional loans in China are considered to be insufficient in the long term. The reason for this, more complex and riskier offshore installations are subject to the same tax incentives as onshore. To eliminate this unsatisfactory situation, the current policies need to be amended for the benefit of offshore installations, or a separate tax incentive policy for offshore needs to be implemented (He et al., 2016).

Wind energy is usually used by connecting to the thermal power grid. However, because the wind is a discontinuous and unstable energy source, negative impacts on the grid and thus resulting reduction in the quality of electricity may occur. Therefore, the non-grid-connected wind power theory proposed by the dean of the Macro-economic institute in Jiangsu, Gu Weidong, may be an alternative option for the use of wind energy. This theory is based on the direct use of wind-generated energy and was applied to the seawater desalination industry in 2011, considering the current industrial development of Jiangsu. When the freshwater obtained in this demonstration project was tested, it was found to be at the national pure water standards, and the hydrogen obtained was 99.99% purity (Chen, 2011). The hydrogen obtained by wind power can be stored in fuel cells to be used as fuel in transportation (Weidong, 2016). In the light of these experimental practices, the government has decided that the use of non-grid wind energy will be industrialized, and its application in different areas such as non-grid connected wind-coal multi-energy systems (Weidong, 2016) will be promoted (Chen, 2011). This system will both contribute to the environment by reducing the carbon emission rate by integrating non-grid-connected wind energy to traditional energy production methods and will provide economic and social benefits by increasing the efficiency of traditional methods (Weidong, 2016).

More than half of the wind power installed until 2009 is not connected to the grid. In the light of this experience, the Chinese government has chosen to pay particular attention to grid connection (Da et al., 2011). By amending the Renewable Energy Law in 2009, grid companies were given a guarantee to purchase energy generated from renewable energy sources. In addition, the "Renewable Energy Fund" was established to compensate for extra costs which may be derived from the purchase of renewable energy (IRENA, 2014; Trust, 2014).

2.2.2 Offshore Wind Power Potential and Installed Capacity in China

Between 2006 and 2009, China doubled its onshore wind power installations each year, and in 2009, it reached an installed onshore capacity of 26 GW. However, most of these installations are concentrated in the north and northwest of China. Wind power installations, which are far away from coastal areas where population density and thus energy demand are high, require a long electricity transmission line (Qin et al., 2010). Therefore, there has been a trend towards offshore in recent years since it has long shores with many suitable areas for offshore installation (see Figure 2.6) (Chen, 2011; Da et al., 2011). Many studies, research, and analysis have been carried out to determine the potential of offshore wind power in China. Even though the studies conclude different results such as 750 GW, 600 GW, or 200 GW, the reality is that there is a high amount of offshore wind energy potential in China that can be a significant part of the response to concerns about its increasing energy demand (Da et al., 2011). In eastern China, where economic growth is faster than in the west part of the country, there are long shorelines suitable for the installation of an offshore wind farm with a water depth of 5-20 m (Chen, 2011), but the number of suitable areas for offshore wind farm developments is restricted for reasons such as lack of experience about offshore, severe climate conditions like frequent typhoon and floating ice, and military use of a large amount of China coasts due to political fluctuations in Northern Asia (Da et al., 2011). However, utilizing offshore wind power in areas close to the main energy demand areas such as Fujian, Jiangsu, Guangdong, and Shandong will provide the advantage that long-distance electricity transmission extending from west to east does not need to be used anymore (Chen, 2011). Also, developing offshore wind energy in China has some advantages such as low labour cost, relatively shallow waters in the coasts, unlike in Europe, and low transmission costs thanks to short distances between potentially suitable areas for offshore wind energy installations and regions with high energy demand (Da et al., 2011).

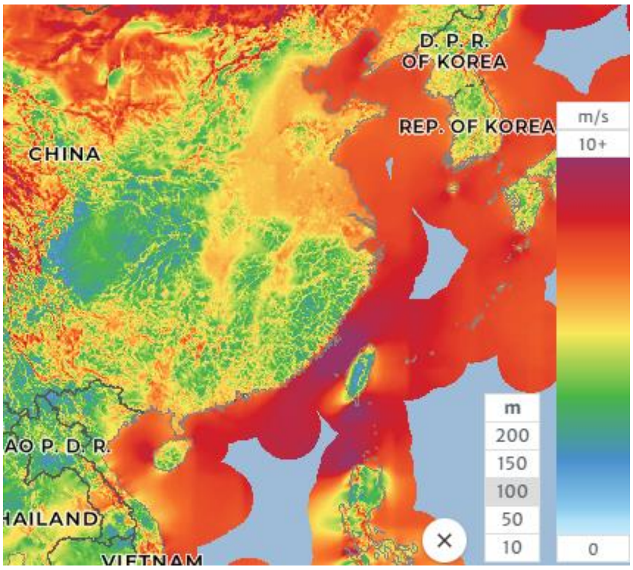

Figure 2.6. Wind speed map of China coasts, at 100 m height (Global Wind Atlas, 2021)

In order to contribute to the target of obtaining 15% of the energy need from non-fossil sources in 2020, it was aimed to reach installed offshore wind power capacity of 5 GW in 2015 and 30 GW in 2020 (Sun et al., 2012). The first step taken in the field of offshore wind energy in line with the determined policies is the Donghai Bridge wind farm with a capacity of 100 MW, which is a demonstration project, the construction of which was commenced in 2009 and fully commissioned in 2010. The speed of further development and installation was not expected, and the capacity was well below the 2015 targets. Results were accelerated in the following years, and

China reached the total installed offshore wind power capacity of 6838 MW at the end of 2019 and maintained 3rd place in this field in the World (Lee & Zhao, 2020). Although China is one of the major countries on OWT, the progress of floating offshore wind technology is slow and underdeveloped compared to the other prominent countries. MingYang Smart Energy develops the first prototype floating wind turbine of China for the South China Sea. The turbine's capacity is 5.5 MW, and it is designed for severe typhoons and wave environments. It is aimed that the floating turbine will be installed in China Three Gorges' Yangxi Shapa III OWPP (400 MW) for demonstration (offshorewind, 2021).

2.3 Offshore Wind Energy Development in Japan

Among the Organization for Economic Co-operation and Development countries (OECD), Japan has the third-largest economy and the second-largest country in the electricity market that makes the country one of the biggest CO_2 emitters with 1.098 million tons in 2018 (OECD, 2020). In the early 1970s, the primary energy source of the country was oil; however, in the 2010s, coal, natural gas, and nuclear power became the leading sources for Japan, and each of these sources had nearly a 30% share of the generated power (Govindji et al., 2014). In March 2011, an earthquake hit the coast of Tohoku, and the Fukushima nuclear disaster occurred, which caused several damages to both the environment and industry; therefore, the country decided to avoid constructing new nuclear reactors. A decreasing trend of nuclear power caused an energy supply gap, and the state increased energy production from coal to close this gap (Govindji et al., 2014; Hanada & Shibata, 2019).In Figure 2.7, showing electricity generation by source in Japan, it is clear that electricity produced from nuclear power reached nearly 290 billion kWh at the end of 2010. After the disaster, the use of nuclear energy for energy production decreased dramatically (IEA, 2020).

Nowadays, the country meets 1/3 of its energy demand from coal and natural gas and develops policies on renewable energy sources to reduce dependency on fossil fuels and close the energy gap which is caused by shutting down of some nuclear power plants after Fukushima (Govindji et al., 2014; Hanada & Shibata, 2019). According to International Energy Agency (IEA) report, the amount of electricity produced from natural gas reached 360.375 billion kWh, and it was followed by coal with 320.298 kWh and oil with 52.455 kWh in 2018 in Japan (see Figure 2.7) (IEA, 2020).

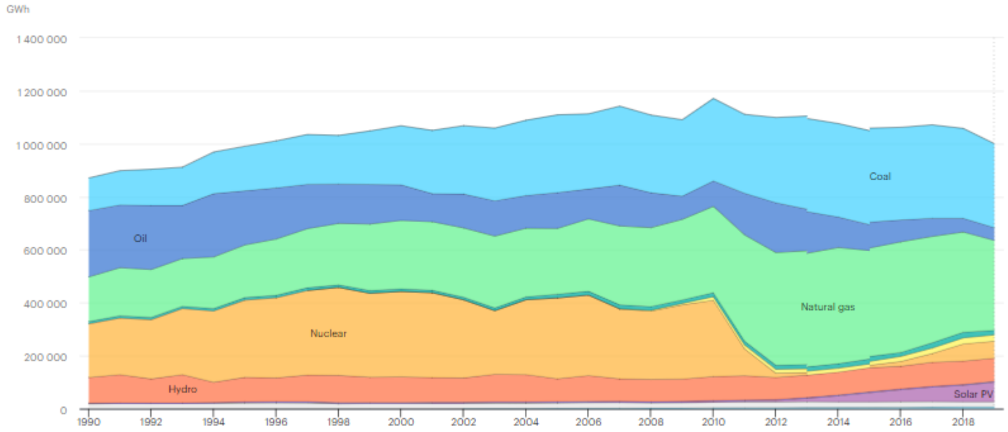

Figure 2.7. Electricity generation by sources in Japan between 1990-2019 years (IEA, 2020)

The ability of Japan to fulfill its own energy need is 7.4%, and the land is scarce in terms of having oil and natural gas; therefore, the country is energy dependent. In order to decrease this dependency, it is crucial to accelerate developments in renewable energy resources for the Japanese government. However, only 6.9% of the electricity demand of the country is met from renewable energy sources (hydropower excluded), and the dominant share of the ratio belongs to solar energy with 83% (67.609 billion kWh) at the end of 2018 (see Figure 2.7) (Agency for Natural Resources and Energy. Ministry of Economy, 2018; IEA, 2020).

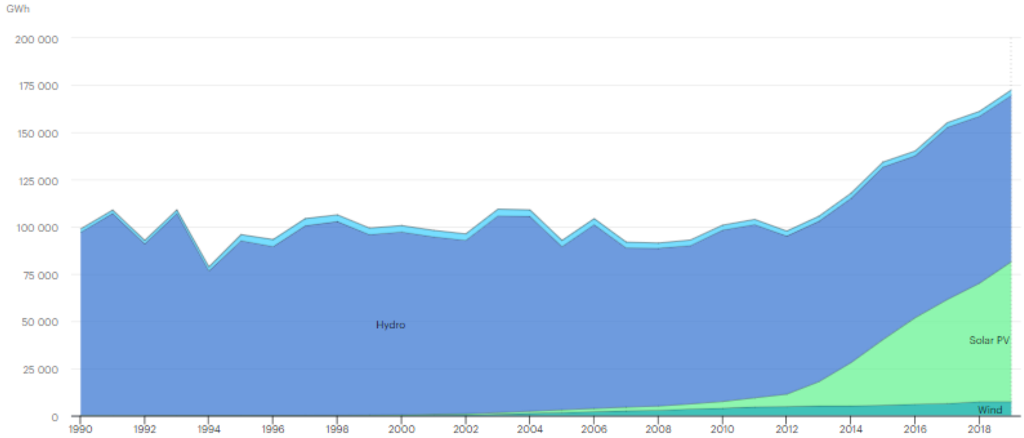

Figure 2.8. Renewable energy generation by sources in Japan between 1990-2019 years (IEA, 2020)

The share of wind power is small (7.632 billion kWh) compared to solar energy (67.609 kWh), and the government aims to increase the projects on wind energy and gives priority to wind power in national development plans. Damage due to typhoons and lightning are some of the factors explaining why wind technology stays behind solar energy in the country. Moreover, the building codes state that the turbines having a height greater than 60 m is classified as a complicated building; therefore, the permission process for turbines more than 60 m takes a long time (Bossler, 2012; IEA, 2020).

According to Figure 2.9, which shows the wind map of Japan at 100 m height, the country has high offshore wind potential; furthermore, it has the 6th largest sea space around the World with the seventh-longest coastline of ~ 30.000 km. Therefore, the wind energy policy of the country focuses on OWT since it allows constructing farms in the open sea and decreases problems due to restricted use on land. However, going to the sea also causes other problems difficulties (Main(e) International Consulting LLC, 2013). Since 80% of the offshore wind is in deep water, which makes the deployment of fixed bottom types of turbines quite limited; therefore, the leading wind strategy of the country concentrates on floating offshore wind turbines.

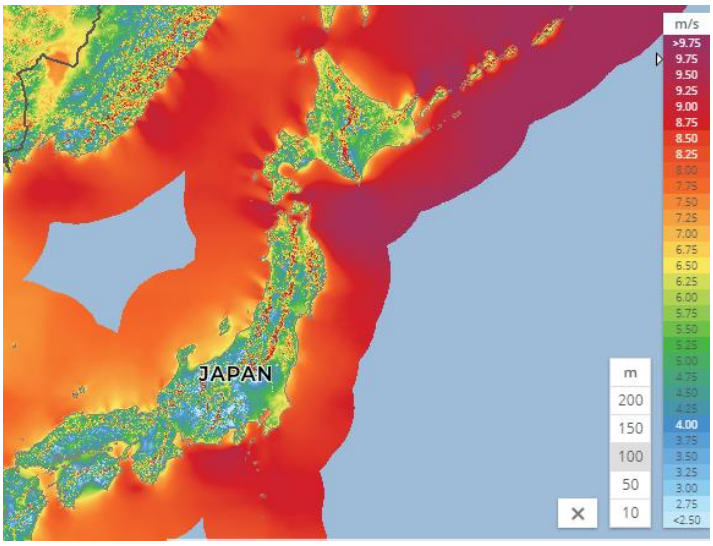

Figure 2.9. Wind speed map in Japan at 100 m height (Global Wind Atlas, 2021)

Japan is an earthquake-prone country; therefore, the load effects due to earthquakes significantly affect offshore wind turbine design. International Electro-Technical Commission (IEC) standards have no specific criteria for the design of turbine resistance to earthquakes. However, the Japanese government stipulates and elaborates earthquake building standards and expands the studies through offshore wind turbine construction under the earthquake effect. Kamisu Phase I, which was completed in 2010, before the Great East Japan Earthquake. In 2011, the offshore wind farm was hit by the earthquake, which is classified as intensity six (magnitude 9.0) on the Japan scale, and more than 5 meters high tsunami waves occurred. Three days later, from the earthquake, the controls on turbine systems showed that there was no damage of the earthquake to the turbines except for the grid system. Although the Great Earthquake did not cause significant damage to the Kamisu Phase I turbine system, the Kamisu Phase II turbine system is designed under the consideration of seismic load and tsunami data measured around the turbine system location during the earthquake (Takashi Matsunobu et al., 2014).

2.3.1 Regulations and Policies for Offshore Wind Energy in Japan

Public confidence in nuclear power has decreased after the Fukushima nuclear disaster; therefore, Japan decided to diversify its energy portfolio. The government of Japan wants to meet high electricity demand from offshore wind since the country has great potential in terms of offshore wind potential and a long coastline. The main challenge for Japan offshore is water depth; however, floating offshore technology is promising since the studies are carried out to reduce the cost of floating offshore technology. Until today, the country did not have any legal regulation on offshore to encourage investors or stakeholders and accelerate the implementation of the technology; nevertheless, the development and cost reduction of the technology is achieved. For the offshore wind market, it is required to have permission regulations, price supports, competitive auctions, and other systems for the market development; accordingly, the prime minister of the country prepared a policy for OWT. The Prime Ministers of Economy, Trade, Industry, Environment, and Transportation (METI&MLIT&ME) decided on five offshore wind areas for the implementation of offshore wind farm projects. While environmental issues about offshore turbines belong to the responsibilities of ME, which aims to reduce CO_2 emissions by the support of OWT, the economic and industrial development of OWT belongs to the responsibilities of METI. Based on the Feed-in Tariff (FIT) program of the country, developers will be supported for suitability and applicability of the proposal projects up to 30 years (BROEHL, 2019; A. Li et al., 2019).

2.3.2 Offshore Wind Power Potential and Installed Capacity in Japan

In Japan, energy generation by the wind started around the 1980s. First, a full capacity wind farm started to work in 1999 with a 1000 kW capacity. Sakata Nearshore Offshore Wind Farm is the first offshore wind farm in the country, under operation since 2004. The foundation type of the turbines is a high-rise pile cap (see Figure 2.10), and the farm consists of 5 turbines with a capacity of 2 MW each.

(Govindji et al., 2014). Rough sea conditions, seabed topography fluctuations, the variation of sediment thickness, and the shallowness of the rock layer require new construction techniques for offshore wind turbines. A high-rise pile cap foundation is a solution for the stated conditions, and it is the most preferred type for the projects in the East China Sea (Li et al., 2017; Qi et al., 2014). According to the International Energy Agency, Japan produced 3.721 MW of energy from wind power. Only 65 MW of the amount is from open sea wind projects at the end of 2019. The offshore wind capacity of the country increased by 15% from the year before. The government aims to increase the amount of energy provided offshore to 4 GW at the end of 2040. IEA states that the offshore energy potential of the country is more significant than 8.080 TWh, and the electricity demand of the country is 994 TWh (IEA, 2020).

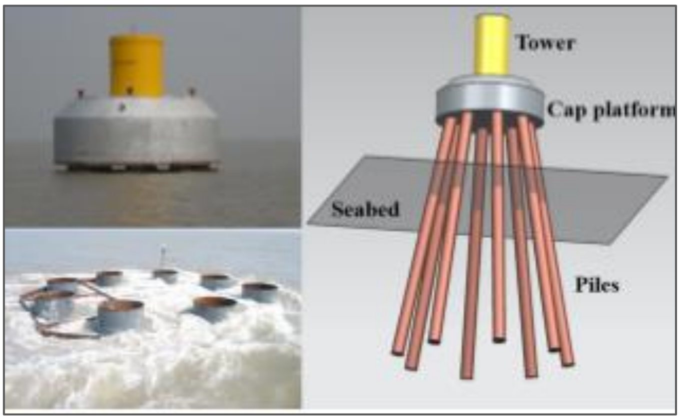

Figure 2.10. High rise pile foundation model (Chen et al., 2018)

Although a more significant percentage of the water depth of the country is suitable for floating offshore wind turbines, the country also has fixed bottom offshore wind turbines which are installed in appropriate places (Main(e) International Consulting LLC, 2013). Table 2.4 shows FOWTs in Japan and their properties.

Table 2.4. Floating offshore wind turbine projects and their properties in Japan (4C Offshore, 2021)

Project Name	**Distance from shore (km)**	**Depth (m)**	**Sea Name**	**Development Status**	**Number of turbines**	**Project Capacity (MW)**	**Turbine Capacity (MW)**	**Foundation type**	**Homes Powered Annually**	**CO_2 reduced per year (tons)**
Fukushima FOWT	20	100-150	Pacific Ocean	Fully Commissioned	1	2	2	Semi-Sub	1417	2863
Kyushi University Wind Lens Prot.	0.7	-	Hakata Bay	Fully Commissioned	2	0.006	0.003	Semi-Sub	4	9
Sakiyama 2 MW FOWT	5	100	Goto-nada sea	Fully Commissioned	1	2	2	Spar Floater	1417	2863
Kitakyushu-NEDO	15	50-100	Sea of Japan (East Sea)	Under Construction	1	3	3	Semi-Sub	2125	4294
Fukushima Phase III	35	100-150	Pacific Ocean	Concept/Early Planning	143	1000	-	Semi-Sub	708255	1431384

2.4 Offshore Wind Energy Development in the US

Over time, the primary energy sources of the United States have changed many times. In the first half of the 1800s, the primary energy source was wood. After 1850, coal production gained an essential place for energy production in the US and became a leading energy source over wood. This situation continued until the 1950s. After the 1950s, petroleum takes the place of coal and has become the primary energy source of the US. In time, new energy sources have been discovered, such as natural gas, nuclear power, renewable energy sources (US Department of Energy, 2015). According to U.S Energy Information Administration (EIA), the amount of produced electricity reached 4.12 trillion kilowatt-hours in 2019. The most significant third place with 23% (966 billion kWh) and 20% (809 billion kWh), respectively. Renewable energy sources have a 17% (720 billion kWh) share of electricity production. As it can be seen from Figure 2.11 , prominent renewable sources are wind power and hydropower, with a share of 42% (300.07 billion kWh) and 38% (273.71 kWh) among the renewable energy sources in 2019, respectively (U.S Energy Information Administration, 2020).

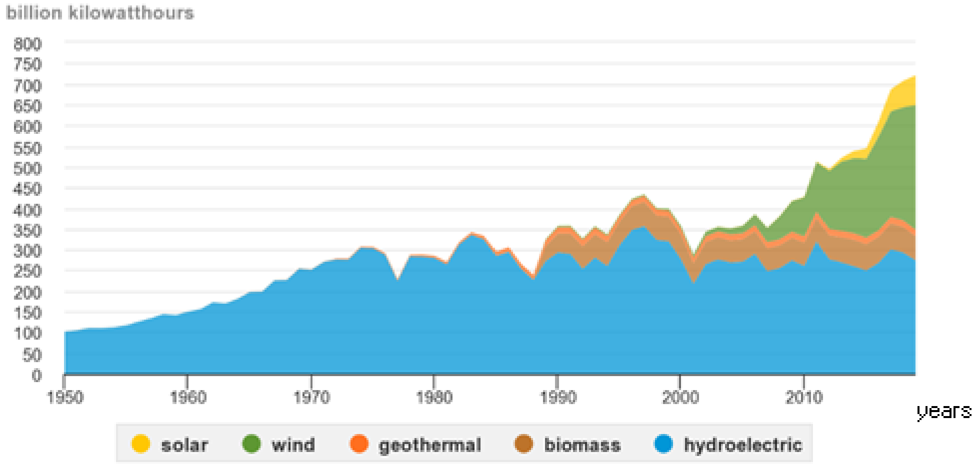

Figure 2.11. U.S electricity generation from renewable energy sources (U.S Energy Information Administration, 2020)

The limited fossil sources, environmental concerns, national energy independence, technological improvements are the main factors that orient the energy policy of the developed countries to renewables (Timmons et al., 2014). In the United States, between 2000 and 2017, renewable energy capacity has increased by 83%, which is the most massive increase among the sources. According to Figure 2.12, in 2007, 110 GW of electricity was produced from renewable resources. In 2017, electricity capacity from renewables had increased to 233 GW, by 112%. The wind energy capacity of the United States has increased by ten times and became the largest renewable source in the nation since 2007. The total installed wind power capacity of the United States reached 97960 MW at the end of 2019, and this amount meets the electricity needs of more than 26 million homes in the country. The foresight of the US Department of Energy (DOE) is that wind power will meet 20% of electricity demand by the end of 2030 (Koebrich et al., 2017; Oteri et al., 2018)

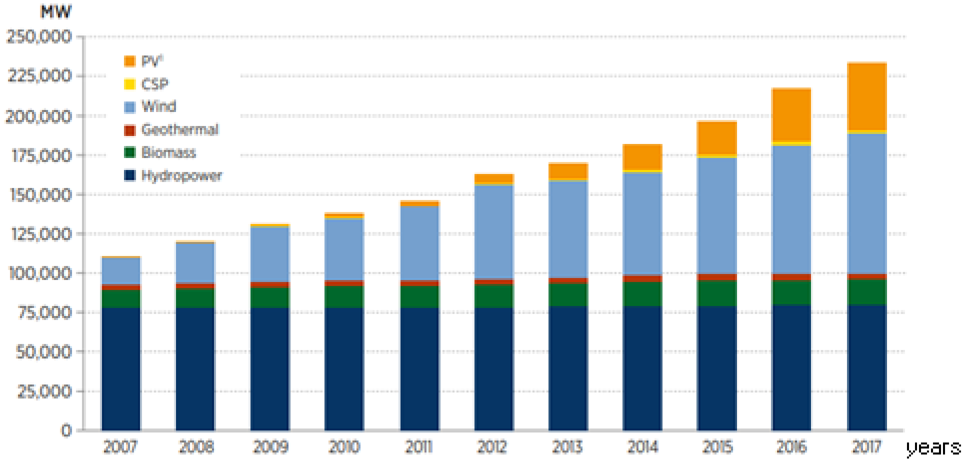

Figure 2.12. Distribution of renewable energy sources of the US by year (Koebrich et al., 2017)

As can be seen in Figure 2.13, South and North Dakota, Texas, and Montana are some of the wealthiest states for wind speed in the US. Windy areas generally are far from natural and artificial obstructions that make these areas suitable for the implementation of wind technology. The west and east coasts of the US also have affluent windy regions (American Wind Energy Association, 2019; Patullo, 2010).The leading state of the nation is Texas, with 25 GW installed wind capacity. And also, a group of projects is on the way by the capacity of 7 GW for the state (Hill, 2019).

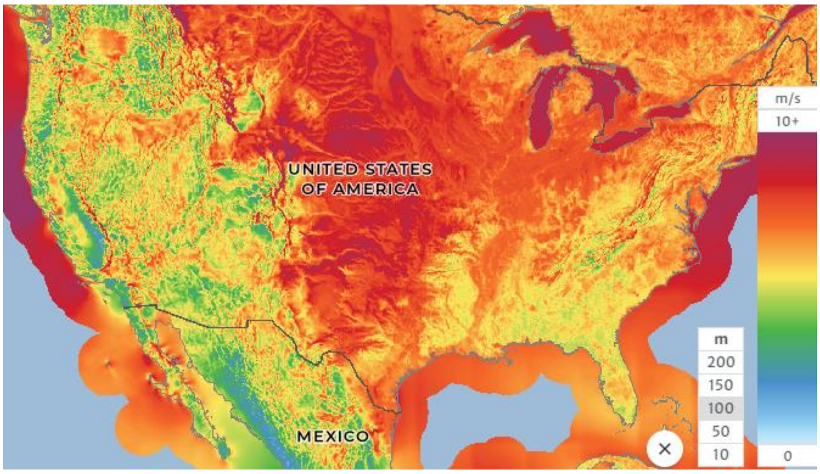

Figure 2.13. Wind speed map of the US at 100 m height (Global Wind Atlas, 2021)

The US ranks second in wind power technology capacity after China (188.4 GW) at the end of 2017 (Koebrich et al., 2017). However, the US stays behind Europe in terms of OWT. To reach the developments in Europe and to benefit from its great offshore wind potential, the US has increased interest in offshore wind energy development.

The US has efficient wind sources with more than 2000 GW (The US Department Of Energy, 2016b) offshore wind potential, which makes two times of current electricity demand of the country. As it is stated earlier, this energy potential is gathered east and west coasts of the US. Thus, the shores of the US are suitable for deploying offshore wind turbines in terms of wind conditions. The highest potential for offshore wind exists in Massachusetts coasts (AWEA, 2018; Oteri et al., 2018). Bathymetry of the region is also a prominent factor for offshore projects as the water depth is one of the main parameters that complicating some stages of the project, such as foundation design, installation costs, and operation efforts. Figure 2.14 shows the bathymetric data for the coast of the US. According to Figure 2.14, it is clear that the Gulf of Mexico and East coasts have shallow waters that create appropriate regions for fixed bottom wind turbine installation for bathymetric conditions (Schwartz et al., 2010). However, the US generally has medium to deep water depth, where the areas have high offshore wind potential.

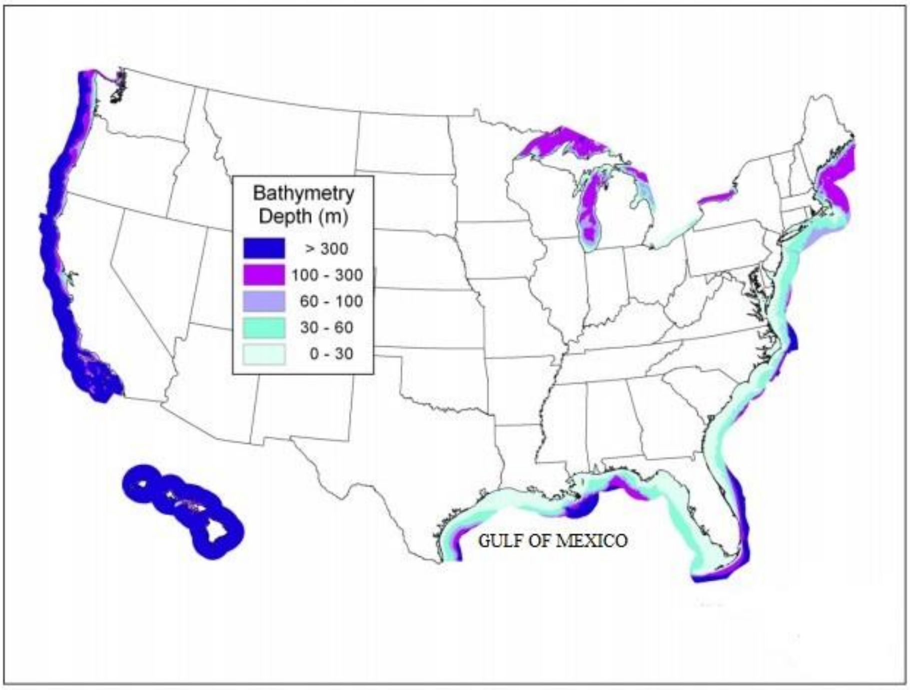

Figure 2.14. Bathymetry data of the US coasts (Schwartz et al., 2010)

According to Figure 2.15, only 17% of the US water having offshore wind potential is suitable for a fixed bottom foundation (Main(e) International Consulting LLC, 2013). Since the highest share of the water depth is belongs to water depth greater than 100 m, floating offshore technology development policies become more critical than fixed bottom technology for the US.

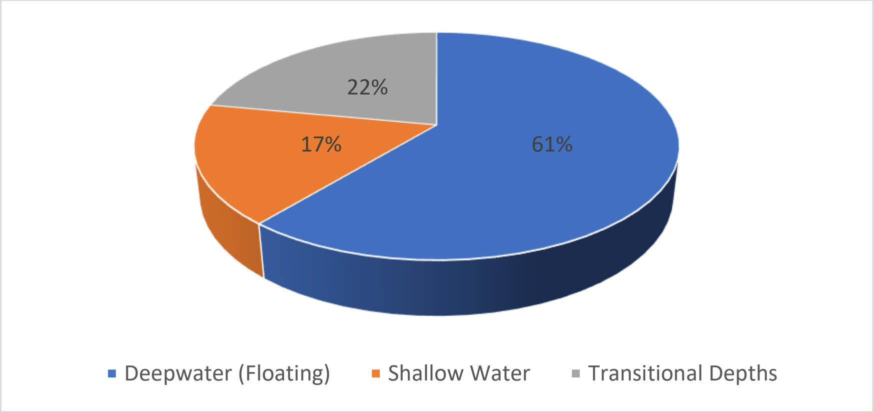

Figure 2.15. Approximate percentage of gross offshore wind resource area for three technology stages (Main(e) International Consulting LLC, 2013)

The distance between the energy demand and installation field is another important issue for wind technology in the US, as in China. For the US, the distances between areas having high offshore wind potential and major cities with high energy demand are close. Thus, transmission costs are reduced. In addition to those factors, a growing population creates land problems for major cities. Therefore, onshore development is limited around the towns. The closeness of high offshore potentials to city centers eliminates land problems and increases the practical usage of wind sources. All explained factors make the US suitable for marine wind technology (Musial & Ram, 2010).

2.4.1 Regulations and Policies for Offshore Wind Energy in the US

The United States released the first strategic plan on OWT in 2011, and it authorized its first offshore farm, Block Island. In this way, the offshore energy portfolio of the US has started. The Block Island Wind Farm has a total capacity of 30 MW and five equal jacket foundation types of wind turbines. The farm installed in Rhode Island is one of the windiest places in the US (AWEA, 2018; The US Department Of Energy, 2016b)

The first offshore project of the State, Cape Wind, proposed in 2001, it would be installed on the coast of Nantucket, Massachusetts. The project consisted of 130 wind turbines with 3.6 MW power capacity each, and the total size of the Cape Wind was 468 MW. The type of foundation was selected as a monopile for these turbines (4C Offshore, 2019). The authority aims to put Cape Wind under operation at the end of 2005; however, the permission process and discussions on the project took a long time (Rajesh, 2011). A group of resident people and businesses concerned about electricity cost, marine life, fishing, boating, and tourism showed opposition to the project. The supporter of Cape Wind stated that the project would supply 75% of the electricity needs of Cape Cod and close islands and will provide renewable, non-polluting energy sources (Alessi, 2017; Dennery, 2015; Timmons et al., 2014). Cape Wind would be built in federal waters; therefore, regulations and decisions on the project would be under the federal government. In 2002, the US Army Corp started to carry out studies and built towers to get wind measurements to the construction field. Their findings stated that there were not any harmful effects of the turbines on marine life and the environment. The projects would be beneficial for the health and the local economy in terms of reducing CO_2 emission and creating job opportunities for local people (Dennery, 2015).

Even though the Minerals Management Service (MMS) published a report which stated that Cape Wind had negligible adverse effects on marine life and military radar systems in 2008 (Dennery, 2015), the objections on the project continued by blocking the progress for a long time. Therefore, a conflict occurred between power purchase agreements (PPAs) due to increasing inflation. All of the stated factors and conflicts of PPAs complicated the contract process and resulted in the cancellation of the Cape Wind Offshore Project in February 2015 (4C Offshore, 2019; Dennery, 2015).

‘The Turning Point for Atlantic Offshore Wind Energy,’ which states the importance of offshore development for the Atlantic Coast published by the National Wildlife Federation in 2012 (U.S. Department of Energy (DOE), 2014). Forty other environmental organizations supported the publication. Besides universities and environmental organizations, federal governments such as The US Department of Energy (DOE) and The US Department of Interior (DOI) also carried out projects and studies on offshore wind energy. In 2011, DOE aimed to give fund nearly $250 million for research and agreements within the Offshore Wind Strategic Plan framework, which aims to develop demonstration projects by 2017 (U.S. Department of Energy (DOE), 2014).

The first installed offshore project of the US, Block Island costs $360 million; thus, its cost is higher than most of the projects which are carried out in Europe. Therefore, the Bureau of Ocean Energy Management (BOEM) takes a step to decrease costs and risks and improve the fixed bottom offshore market by attracting different industry groups like Shell from UK and Statoil from Norway. BOEM organized a competition for future maritime projects in line with the US offshore wind development. In 2017, twelve commercial and five demonstration projects won the competition (see Table 2.5) (The US Department Of Energy, 2016a). Figure 2.16 shows processes for the winning projects, and it is clear that offshore wind projects are concentrated around the North Atlantic region of the US.

Table 2.5 Winning projects of the competition organized by BOEM (American Wind Energy Association, 2019; The US Department Of Energy, 2016a)

Project Owner (Project Name)	**State**	**Project Pipeline (MW)**	**Area (km^2)**	**Winning Bid ($)**	**Water Depth (m)**	**Average Wind Speed (m/s)**
Cape Wind Associates (Cape Wind)	MA	468	119	-	1-18	8.7
Vineyard Wind	MA	1600	675	150,197	36-58	9.3
DONG Energy & Eversource (Bay State Wind)	MA	2000	759	281,285	39-50	9.3
Deepwater Wind (Block Island Wind Farm)	RI	30	2	-	28-23	9.7
Statoil Wind	NY	1000	321	42,469,725	20-40	9.3

Table 2.5 (continued)

US Wind	MD	750	132	3,841,538	16-29	8.2
Dominion	VA	2000	457	1,600,000	18-33	8.5
Avangrid Renewables	NC	1485	495	9,066,550	31-43	8.5
DONG Energy	NJ	1947	649	880,715	17-34	8.4
Deepwater Wind (Skipjack)	DE	120	390	-	9-33	8.3
US Wind	NJ	2226	742	1,006,240	17-34	8.6
Deepwater Wind (Deepwater One North)	RI	500	395	3,089,461	30-46	9.2
PNE Wind USA (Excelsior Wind Park)	NY	400	166	-	20-40	9.2
Trident Winds (Morro Bay)	CA	765	275	-	-	7.81
AW Hawaii Wind Oahu Northwest	HI	408	46	-	-	8.3
AW Hawaii Wind Oahu South	HI	408	49	-	-	8.4
Progression Hawaii	HI	400	46	-	-	8.4

North Atlantic has suitable conditions for possible projects since it is similar to the North Sea in terms of meteorology, bathymetry, and environment. It allows project developers to benefit from experience gained during the construction of North Sea projects. The other reason is that the implementation of other renewable energy sources is difficult due to limitations on land since North Atlantic regions are densely populated. Thus, this situation makes offshore wind the only suitable renewable energy source for the North Atlantic regions (The US Department Of Energy, 2016a)

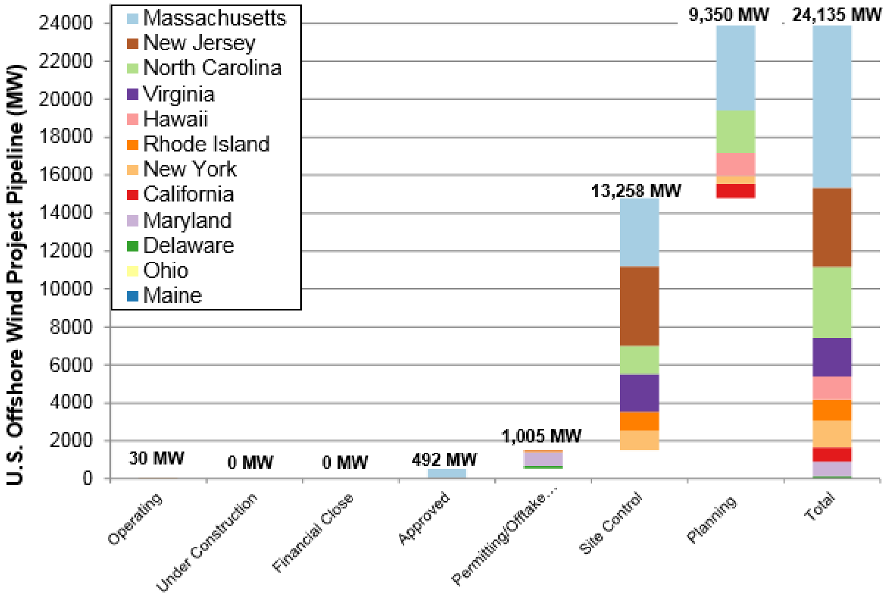

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Figure 2.16. States and status of offshore wind projects in the US (The US Department Of Energy, 2016a)

Studies and research on offshore projects in the US are carried out for more than 20 years; however, the US's fixed bottom offshore wind capacity is not comparable to European fixed bottom capacity. High project costs, uncertain policy supports can be shown as the main challenges for FBOWTs in the US (U.S. Department of Energy (DOE), 2014). According to National Renewable Energy Laboratory (NREL), 61% of offshore wind resource of the US is at water depth greater than 100 m, resulting in the high foundation and installation costs for fixed bottom offshore wind turbines. Therefore, the open sea wind power policy of the US concentrates on FOWTs in the control of NREL, which carries out studies and research on renewables for more than 35 years. The cost of floating offshore is higher than fixed bottom; however, NREL states that floating fees will reduce in the long term due to the absence of foundation and specialized foundation vessels of floating turbines. Today, the general aim is to reduce the cost of floating turbines because of their suitability for US water and to be the future of offshore wind power. In 2012, U.S. Department of Energy, (DOE) announced that it would fund seven demonstration projects with $168 million within the framework of cost reduction for floating offshore wind turbine installation (U.S. Department of Energy (DOE), 2014). The funding aims to select the most suitable three projects of seven and maintain the projects on design, fabrication, and installation stages by 2017. One of the selected projects is carried out by Statoil North America Stamford, which consists of 4 wind turbines with capacities of 3 MW. The type of foundation is selected as spar-buoy, and the water depth at the construction area is deeper than 140 m. The construction region is decided as the Gulf of Maine that has high offshore wind potential. The other project, VolturnUS, is a pilot project having two turbines with capacities of 6 MW carried out by the University of Maine. The foundation type of project is selected as semi-submersible, and the construction field is decided as Mohegan Island. The project is significant since its foundation is different from the traditional semi-submersible foundation in terms of having concrete components instead of steel. The University of Maine maintains VolturnUS under the leadership of DeepCwind Consortium, which focuses on OWT in deep water. The third project, WindFloat Pacific, consists of five semi-submersible turbines (each of them having 6 MW capacity) deployed by Principle Power (Main(e) International Consulting LLC, 2013; U.S. Department of Energy (DOE), 2014).

2.4.2 Offshore Wind Power Potential and Installed Capacity in the US

In the United States, 57,000 wind turbines having 97,960 MW capacity operate in 41 states and two territories by the end of 2019. Texas is a prominent state with greater than 25,000 MW installed wind power capacity; however, nearly all produced energy capacity belongs to onshore wind power in the US (American Wind Energy Association, 2019). Although the US has more than 2000 GW offshore wind power capacity, which makes twice the country's energy demand, only 30.125 MW energy – 30 MW from Block Island Wind Farm and 0.125 MW from Keuka 125 kW

Rim Drive is produced from offshore wind power. However, according to the DOE, 2000 MW new offshore projects will be under operation at the end of 2023, and the offshore wind capacity is expected to reach 22 GW by 2030 and 86 GW by 2050 (AWEA, 2018; The US Department Of Energy, 2016b). Floating offshore wind power projects in the US are shown in the following table.

Table 2.6. Floating offshore wind turbine projects in the US (4C Offshore, 2021)

Project name	**Region**	**Distance from shore (km)**	**Depth (m)**	**Sea Name**	**Development Status**	**Number of turbines**	**Project Capacity (MW)**	**Foundation type**	**Home powered annually**
DeepCwind Consortium	Maine	3.5	-	Atlantic	Decommissioned	1	0.002	Semi-Sub	14
Keuka 1:125 scale	Florida	-	-	St Johns River	Decommissioned	5	0.15	Semi-Sub	106
Keuka 125 kW Rim Drive	-	-	-	-	Fully Commissioned	1	0.125	Semi-Sub	89
New England Aqua Ventus I	Maine	-	-	Atlantic	Consent Application Submitted	2	16	Semi-Sub	8499
Keuka 25 MW Rim Drive	-	-	-	-	Concept/Early Planning	2	25	Semi-Sub	17706
MAKANI Airborne Wind	-	-	-	-	Concept/Early Planning	1	0.6	Spar Floater	-
Nautica Wind Power	-	-	-	-	Concept/Early Planning	1	-	Spar Floater	-
New England Aqua Ventus II	Maine	-	-	Atlantic	Concept/Early Planning	-	480	Semi-Sub	339963

Table 2.6 (continued)

New England Aqua Ventus III	Maine	-	-	Atlantic	Concept/Early Planning	-	4508	Semi-Sub	3192815
Redwood	California	32.2	600-1000	Pacific Ocean	Concept/Early Planning	10	100	Semi-Sub	106238

2.5 Offshore Wind Energy in Other Countries

The floating offshore wind turbine projects are presented in the following table for some other countries.

Table 2.7. Floating offshore wind turbine projects in some other countries (4C Offshore, 2021)

Project name	**Country**	**Distance from shore (km)**	**Depth (m)**	**Sea Name**	**Development Status**	**Number of turbines**	**Project Capacity (MW)**	**Foundation type**	**Homes Powered Annually**
Ulsan 750 kW Floating Dem.	South Korea	5	30	Sea of Japan (East Sea)	Pre-Construction	1	0.75	Semi-Sub	531
Donghae Gas Field Floating D.	South Korea	-	-	Sea of Japan (East Sea)	Early Planning	-	1200	-	849906

Table 2.7 (continued)

Gyeongju FOWT Phase I	South Korea	50	200-500	Korea Strait	Early Planning	-	500	-	754128
KRISO	South Korea	-	-	Korea Strait	Early Planning	4	12	Semi-Sub	8499
Saemangeum 1 GW	South Korea	-	-	Yellow Sea	Early Planning	100	500	-	354128
Sin Chang	South Korea	1	20-50	Korea Strait	Early Planning	20	100	-	70826
Taean	South Korea	-	-	West Korean Pennisular	Early Planning	-	100	-	70826
Ulsan-Floating	South Korea	-	-	Sea of Japan (East Sea)	Early Planning	-	-	Semi-Sub	-
Ulsan 5MW Floating Prototype	South Korea	-	-	Sea of Japan (East Sea)	Early Planning	-	5	Semi-Sub	3541
Ulsan Donghae 1000 MW	South Korea	-	-	Sea of Japan (East Sea)	Early Planning	-	1000	-	708255
Ulsan Donghae 200 MW Floating	South Korea	-	-	Sea of Japan (East Sea)	Early Planning	50	200	-	141651
Ulsan Port	South Korea	-	-	Korea Strait	Early Planning	-	100	-	70826
Yokjido	South Korea	-	-	Sea of Japan (East Sea)	Early Planning	-	500	-	354128
Durrazzo	Albenia	36	18-40	Adriatic	Cancelled	154	539	-	381750
HEXICON-Larnaca	Cyprus			Mediterranean	Cancelled	72	44	Semi-Sub	31163

Table 2.7 (continued)

Gujarat-FLOWOCEAN AB	India		-	Arabian	Concept/Early Planning	-	-	-	-
Aicha	Tunisia	-	-	Mediterranean	Cancelled	-	-	TLP	-

2.6 Summary

Like offshore wind energy leading countries, Turkey has an important offshore wind potential. Although no tangible step has been taken in Turkey for this technology, it is expected to make investments in the coming years. The aim of Chapter 2 is to collect information on the development of OWT around the World. In this way, the experiences and policies of OWT leading countries are mentioned. These experiences might be significantly beneficial for newcomers like Turkey. It is clear in this chapter that the foremost factor for OWT development is financial support. For example, there was a great stagnation in OWT due to a lack of financial support in Denmark between 2004 – 2008. However, in 2009, the industry started to gain momentum again with new financial support. Also, in 2000s, UK has made significantly accelerated progress in this industry on projects and research and development. The reason for progress was increasing governmental financial support. Likewise, the development of OWT in Germany has become possible thanks to government financial support. The German government took Denmark as an example in terms of the feed-in tariff concept for OWT. In this regard, the most critical step in Turkey's progress towards OWT might be financial support provision.

In addition, unlike many European countries, Turkey is located in an active earthquake zone. In this direction, the country can take seismically active countries such as Japan as an example in the implementation and design of OWT.

CHAPTER 3

LITERATURE REVIEW ON PREVIOUS SITE SELECTION STUDIES

In this Chapter, firstly, site selection studies around the world are presented, then, site selection studies for Turkey are explained. The aim of this chapter is to investigate generally used criteria around the world for a potential OWPP site selection.

3.1 Previous Site Selection Studies for a Potential OWPP Around World

In this section, previous site selection studies are mentioned around the world. Table 3.1 presents different site selection studies and considered site selection criteria for each study. By taking into account these studies, a list of criteria is determined for this thesis. As shown in Table 3.1, wind speed is the most considered criterion among site selection criteria from different studies. However, as it is clear from Table 3.1, different studies consider different criteria for site selection.

Table 3.1. Criteria used in this thesis (first column), and previous site selection studies for an OWPP around the world

Criteria	(Vagiona & Karanikolas, 2012)	(Vagiona & Kamilakis, 2018)	(Abdel-Basset et al., 2021)	(Díaz & Soares, 2021)	(Mayaki et al., 2018)	(Wu et al., 2020)	(Mahdy & Bahaj, 2018)
Wind speed (m/s)	+	+	+	+	+	+	+
Territorial waters	-	-	-	+	-	-	-
Water depth (m)	-	-	+	+	-	-	+
Military zone	-	-	-	+	-	-	+

Table 3.1 (continued)

Ports	-	-	-	+	-	-	-
Offshore seismic activity	-	-	-	-	-	-	-
Shipping	-	+	+	+	+	+	+
Environmentally protected areas	+	+	-	+	-	+	+
Bird areas	-	-	-	+	-	+	-
Bird migration routes	-	-	-	+	-	+	-
Distance to shore for grid connection	+	-	+	+	-	-	+
Distance to shore	+	-	-	+	-	-	+
Shipwrecks	-	-	-	-	-	-	-
Civil aviation	-	-	-	+	+	-	-
Underwater pipelines	-	-	-	+	-	-	-
Underwater cables	-	-	-	+	-	-	+
Offshore observation wells	-	-	-	-	-	-	+
Seabed soil	-	-	+	+	-	+	+
Fishery	-	-	-	+	-	-	+

While + indicates considered criteria, - indicates not considered.

In their study, Vagiona and Karanikolas (2012) investigated potential OWPP sites in Greece considering mean wind speed, distance to environmentally protected areas, distance to main ship routes, distance to the shore, and distance to shore for grid connection.

Vagiona and Kamilakis (2018) aimed to investigate sustainable site selection around South Aegean Sea, Greece. Wind velocity, shipping activities, distance to environmentally protected areas and served population were evaluation criteria of their study.

Diaz and Soares (2021) considered a variety of criteria as seen from Table 3.1. They classified their site selection criteria as exclusion criteria (military zones, fishery areas, shipping routes, underwater cables and pipelines, seabed soil (sand and gravel eliminated, etc.,) and evaluation criteria (wind speed, water depth, distance to grid connection, distance to airports, etc.,).

3.2 Previous Site Selection Studies for a Potential OWPP in Turkey

Developing countries like Turkey follow trends of changing energy sources from fossil fuels to renewables; the country caught the trend in 1998 by installing the first onshore wind power plant in İzmir, Alaçatı. Following this, research on wind power started to increase, and the number of wind power plants increased over the years. Figure 3.1 shows the cumulative capacity increase generated from wind energy over the years. According to (TWEA), Turkey generates 9305 MW, 8.44% of its total electricity from wind energy sources as of 2021 (Turkish Wind Energy Association, 2021).

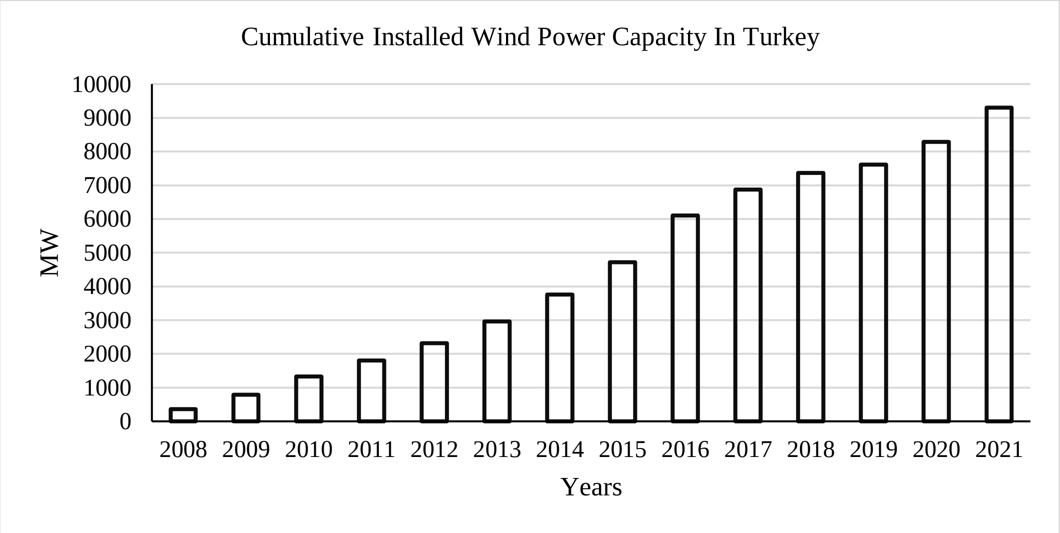


Figure 3.1. Cumulative installations for wind power plants in Turkey (Turkish Wind Energy Association, 2021)

Due to its geographical location and surrounded by seas on three sides, Turkey is rich in wind energy. In the western part of the country, the wind blows at a higher speed (>9 m/s) at 100 m. Also, more than 70 percent of the country's onshore wind farms are installed in the Aegean (37.74 %) and the Marmara regions (34.044 %), which are in the country's western part (Turkish Wind Energy Association, 2021).

Turkey has been making efforts to solve the energy sector's problems using clean and sustainable solutions over the last decade. For this purpose, various research and development activities started to be supported. However, currently, all the country's wind power plants are located in onshore, and the country does not have any OWPP. By this way, with the increasing interest in OWPP in world, studies on OWT are increasing in Turkey. Table 3.2 shows criteria considered in this thesis in first column. Six OWPP site selection studies carried out for Turkey are reviewed and tabulated in Table 3.2. Consideration of criteria varies from study to study; however, as the table shows, in previous studies, site selection criteria are not considered as comprehensively as in this thesis.

Table 3.2. Criteria used in this thesis (first column), and previous site selection studies for a potential OWPP in Turkey

Criteria	Study 1 (Güzel, 2012)	Study 2 (Akalın, 2018)	Study 3 (Özdilim, 2017)	Study 4 (Yerci, 2015)	Study 5 (Emeksiz & Demirci, 2019)	Study 6 (Deveci et al., 2020)
Wind speed (m/s)	+	(≥ 6.5 m/s at 100 m)	+(≥ 7 m/s at 100 m)	(≥ 3 m/s at 50 m)	+	+
Territorial waters	+	-	+	+	+	-
Water depth (m)	<45	15-30	~30	<45	+	+
Military zone	+	-	+	+	+	+
Ports	-	-	-	-	-	+
Offshore seismic activity	-	+	-	-	-	-
Shipping	+	+	+	+	+	-
Environmentally protected areas	-	+	-	-	+	+
Bird areas	-	-	-	-	-	-

Table 3.2 (continued)

Bird migration routes	+	-	-	-	+	-
Distance to shore for grid connection	+	+	-	-	-	+
Shipwrecks	+	-	-	-	-	-
Civil aviation	-	-	-	+	-	-
Underwater pipelines	-	-	-	+	+	-
Underwater cables	-	-	-	+	+	-
Offshore observation wells	-	-	-	-	-	-
Seabed soil	-	-	-	-	-	-
Fishery	-	-	-	-	-	-

While + indicates considered criteria, - indicates not considered.

In his thesis, Güzel (2012) states site selection criteria as wind, bathymetry, military zones, shipping routes, environmental protected areas, bird migration routes, shipwrecks, tourism sites. However, in his study, these criteria are not discussed in detail to select potential sites. He studied Bozcaada and Gökçeada as potential sites. Also, Güzel (2012) carried out a WAsP (Wind Atlas Analysis and Application Program) analysis to investigate the offshore wind feasibility of Bozcaada and Gökçeada.

Akalın (2018) accepted site selection criteria as wind speed, bathymetry, shipping routes, grid connection distance, distance to earthquake fault lines. Çanakkale, Bozcaada and Gökçeada were study areas for thesis of Akalın. To investigate the suitability of sites, Akalın used the Analytic Hierarchy Process (AHP) in her study.

Özdilim (2017) carried out a study for Bozcaada vicinity by using a WAsP analysis like Güzel (2012). Wind speed, bathymetry, protected areas, bird migration routes, military zones, territorial waters, and shipping were mentioned as site selection criteria.

Yerci (2015) took wind speed, water depth, military zones, territorial waters, shipping routes, civil aviation, underwater pipelines- cables as site selection criteria for the study. Yerci also carried out a WAsP analysis to investigate feasibility studies for Bozcaada, Bandırma, Gökçeada, İnebolu, Samandağ.

Emeksiz and Demirci (2019) investigated wind speed, water depth, military zones, shipping routes, protected areas, bird migration routes, underwater cables-pipelines as site selection criteria in their study. They used AHP to investigate suitable sites; they select nine suitable areas out of thirty-one potential sites. These nine suitable areas were Karasu, Bafra, İnebolu, Sinop, Gökçeada, Bozcaada, Bandırma, Antalya and Mersin)

Similar to Akalın (2018) and Emeksiz & Demirci (2019), Deveci et al. (2020) carried out Multi-Criteria Decision Making (MCDM) (in this case, fuzzy logic) to determine the most suitable site for a potential OWPP in Black Sea. İnebolu was selected as the most suitable site in Black Sea. The site selection criteria in their study were that wind speed, water depth, military zones, ports, protected areas, and distance to grid connection.

3.3 Results for Site Selection Criteria Literature Review

In Section 3.1 and Section 3.2, some of previous site selection studies are presented. By considering these studies, a list of criteria is obtained. Thus, the aim of this previous site selection literature review is to obtain a comprehensive list of site selection criteria. Accordingly, several criteria are decided and compared to previous studies. In this thesis, considered criteria are wind speed, territorial waters, water depth, military zones, ports, offshore seismic activity, shipping routes, environmentally protected areas, bird areas, bird migration routes, fishery, distance to shore for grid connection, tourism sites and visual impact (distance to shore), shipwrecks, civil aviation, existing pipelines, underwater cables, offshore observation wells, and seabed soil. These criteria are a set of criteria collections considered in previous site selection studies.

CHAPTER 4

METHODOLOGY AND GIS TOOL

In this Chapter, followed methodology used in this thesis are explained. Following this, for the suitable site selection, GIS tool (ArcGIS Pro) is used. Therefore, GIS tool and ArcGIS Pro is also presented in this Chapter.

4.1 Methodology

In this section, the applied methodology for suitable selection is explained. In the previous Chapter, Chapter 3, several site selection criteria were decided by carrying out a literature review. During the data collection stage (see Figure 4.1), required data is collected from the relevant database for the specified site selection criteria. The database is in various forms such as excel, figure, shapefile, text, etc., so that they are converted to a suitable format to use the required data in the GIS program; this process is called data processing. For data processing, ArcGIS Pro was used in this thesis.

Following data processing, the next step is preliminary suitable site selection. In this part, the first criteria are minimum mean wind speed (6.5 m/s at 100 m reference height) and maximum water depth (150 m). Areas with these criteria (a maximum water depth of 150 meters and a minimum wind speed of 6.5 m/s) are investigated, and sites that do not meet are excluded. Again, ArcGIS Pro is used to identify these areas. After that investigation, it is examined whether there is a reverse turbulence effect in these sites. If high turbulence coming from land exists, these areas are also excluded. In order to investigate this situation, wind roses and wind data of sites are considered (via Global Wind Atlas database).

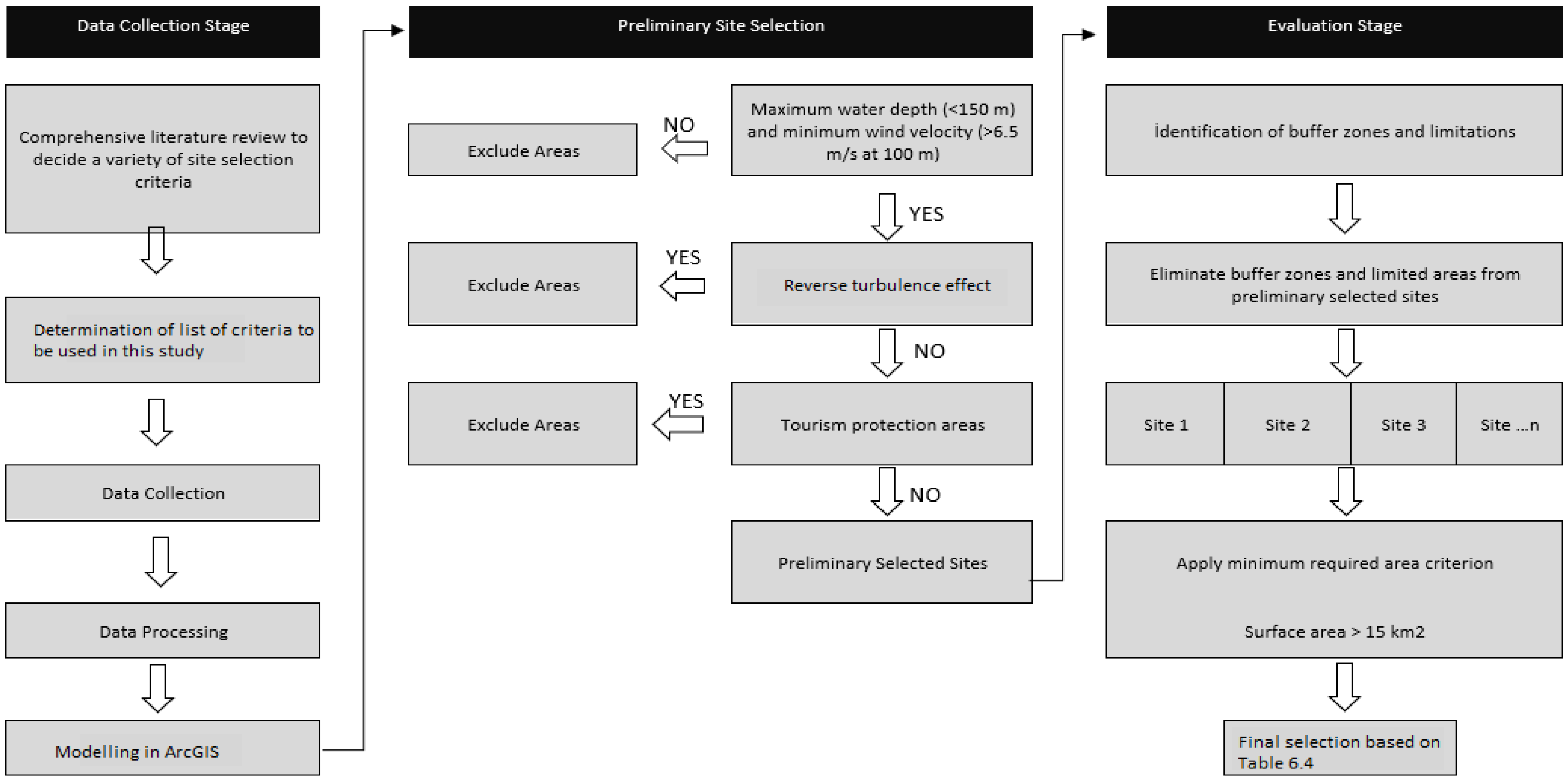


Figure 4.1. Applied site selection methodology in this thesis

Areas having reverse turbulence effects are also excluded. The reason for that is areas with high turbulence coming from land negatively affect wind stability, which is an undesirable situation for a potential OWPP.

After excluding areas having turbulence problems, tourism-protected areas are considered. The fact that presence of tourism activities in a site is not a reason for elimination in itself at this stage. However, some areas are very dense in terms of tourism and are under protection in general. Not the existence of tourism activity but being under tourism protection is a reason for elimination.

After preliminary site selection, the next step is the evaluation step. In this part, preliminary suitable sites are considered in terms of a variety of site selection criteria. Buffer zones and limited areas are excluded in preliminary sites. After that, some suitable sites are recommended. The last criterion of this step is to apply the minimum required area criterion. For this one, recommended sites having an area of smaller than 15 km^2 are excluded. The aim of applying the minimum required criterion is to increase efficiency. Minimum area criterion limits changes study to study, i.e., COWI recommends considering the areas having a minimum area of 25 km^2. However, in this thesis, a minimum of 15 km^2 is considered.

4.2 GIS-ArcGIS Pro

GIS is defined by The United States Geological Survey (USGS) as a hardware and software system in order to display, analyze, manage and collect data, which is geographically or spatially referenced data (USGS, 2021).

ESRI definition states that GIS captures, stores, updates, manipulates, analyzes, and displays data. Also, GIS aims to connect data (such as an attribute table) to a map by integrating data pieces in different ways. This situation makes the GIS tool a foundation for mapping and analysis used in almost every industry and science (ESRI, 2021).

The data types in GIS are classified as spatial and tabular. There are four main methods in GIS tools: data input, data management, data analysis, and data output. Also, there are two main layers in GIS, namely vector and raster layer, as seen in Figure 4.2. While polygons, lines, points are vector layers components, images or pixels are raster layer components.

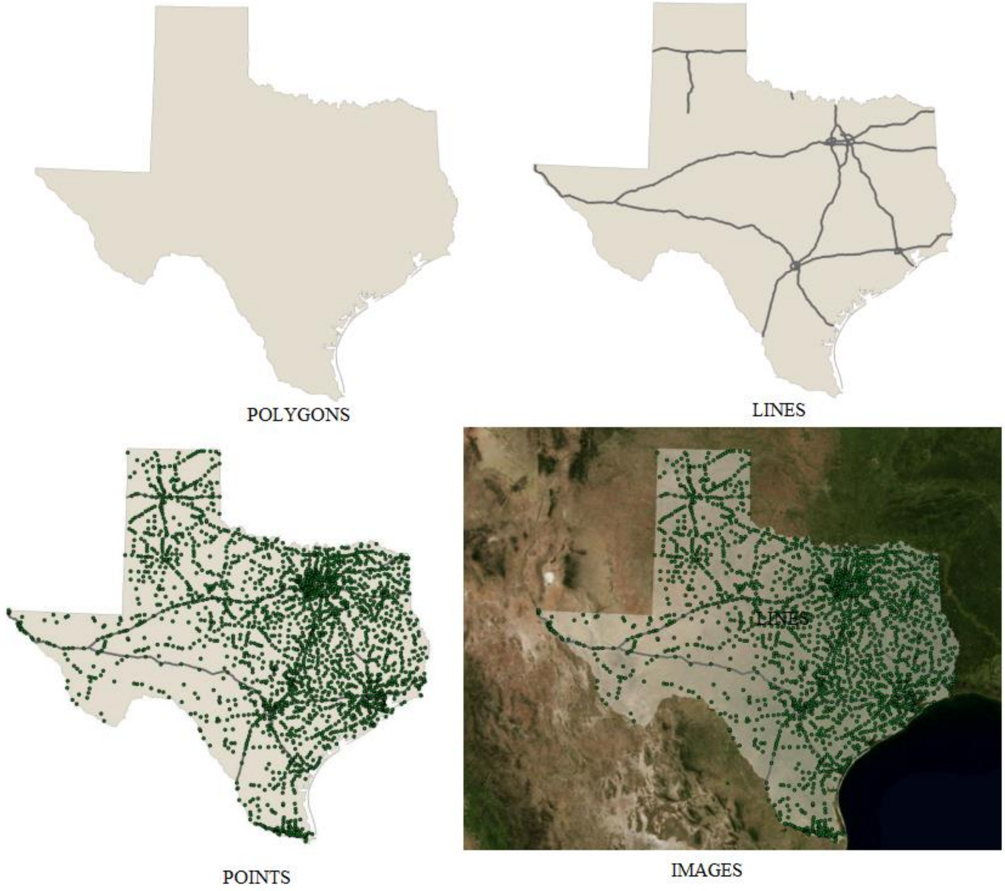


Figure 4.2. Geographic object types in GIS, polygons, lines, points, and images (pixels) (MIT, 1994)

In the GIS environment, polygons are generally used for areas like administrative areas, hazard areas, country boundaries, etc. Lines are usually used to represent rivers, water systems, roads, and the like. Point features are used for control points, hill points, houses, turbines, etc. Images or pixels are raster layers, and raster pieces of information are stored by grids or pixels. Satellite images, google photos are some of the examples of raster features. There exist attribute tables to contain data for vector layers. However, for raster layers, no attribute table exists. Instead, each pixel or grid has information on the related raster layer. Also, it is possible to convert a raster layer to a vector layer or vice versa. In this thesis, from different GIS tools, ArcGIS Pro is used. The main page of ArcGIS Pro can be seen in Figure 4.3.

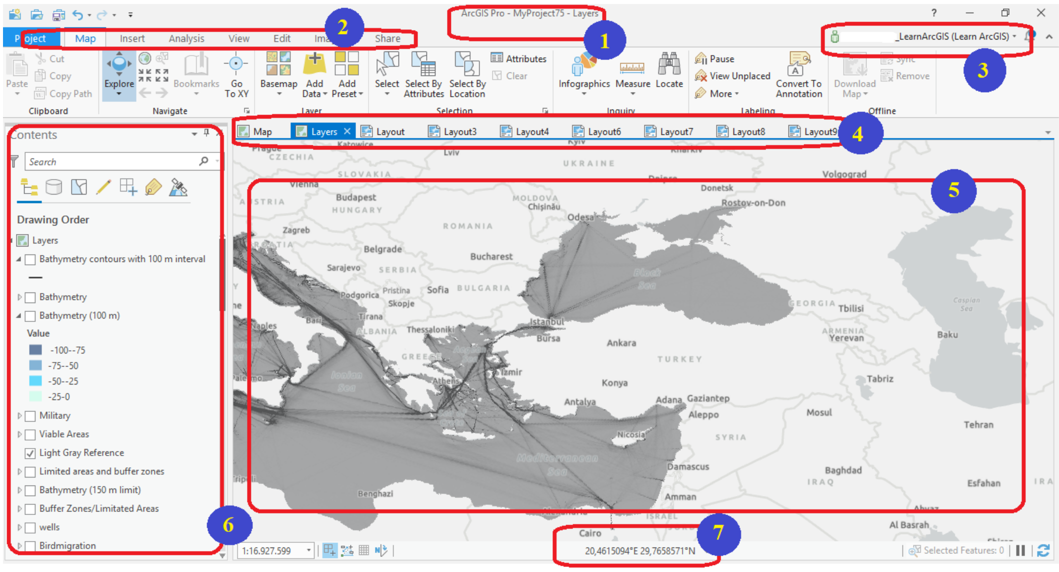


Figure 4.3. ArcGIS Pro main page

Based on Figure 4.3, Number 1 shows the name of the project. Number 2 is a menu bar, including “Map”, “Insert”, “Analysis”, “View”, “Edit”, “Image”, and “Share” options. Below this menu bar, a toolbar exists. Toolbars help to access additional tools in the ArcGIS Pro environment. As an example, in Figure 4.3, some additional tools can be seen under the “Map” menu, like “Explore”, “Base map”, “Add data”, etc. In the same figure, Number 3 shows the name of the user account. Number 4 shows layers and layout windows. While in the layer window, a user can create a project; in the layout window, a layout for the prepared project can be created in the form of a figure, pdf, report, and the like. Number 5 shows the display window. By using this window, users can see the features they carried out. Number 6 shows “Table of contents/Map legend”. I Table of content window; prepared layers can be turned on or turned off. Layer properties such as symbology, legend, attribute symbols can be followed in this window. Additionally, Number 7 shows coordinate systems (longitude and latitude of a point).

For this thesis, GIS modeling and analyzing start with gathering data from relevant database. Table 4.1shows some of the site selection criteria used in this thesis with their database forms and converted forms (indicates GIS forms to conduct analyses). As also explained above, raster data expresses spatial data in cellular squares, while vector data consists of points, lines, and polygons stored in geographic databases with (x,y) coordinates.

Table 4.1.Site selection criteria and their forms in ArcGIS

Criteria	**Database form**	**Converted Form**
Wind speed	Raster data	Raster data
Territorial water borders	Vector data	Vector data
Water depth	Raster data	Raster data
Military zones	Figure (.jpg)	Vector data
Ports	Excel (.xls)	Vector data
Offshore seismic activity	Figure (.jpg) (MTA data)	Vector data
	Text (.txt) (KOERI data)	
	Vector data (The SHARE)	
Shipping routes	Raster data	Raster data
Environmentally protected areas	Vector data	Vector data
Bird areas	Vector data	Vector data
Fishery	Raster data	Raster data
Distance to shore for grid connection	Excel (.xls)	Vector data
Shipwrecks	Vector data	Vector data
Civil aviation	Excel (.xls)	Vector data
Existing pipelines	Figure (jpg.)	Vector data
Underwater cables	Vector data	Vector data

Table 4.1 (continued)

Offshore observation wells	Figure (.jpg)	Vector data

To select suitable sites and to implement collected data, different ArcGIS Pro analyses are carried out to evaluate spatial suitability for OWPP installations. For example, while defining limitations like maximum water depth, minimum wind speed, etc., complex ArcGIS analyses are required. For example, wind speed data is downloaded from Global Wind Atlas (GWA) in the form of raster data (see Table 4.1). In order to extract a minimum wind speed of 6.5 m/s from all source data, an "*extract analysis*" is needed. Also, to introduce a maximum bathymetry (150 m), "*an extract data by attribute analysis"* is carried out to remove bathymetry data above 150 m. To define a buffer zone around some criteria, "*buffer analyses"* are needed. And these analyses are carried out one by one for each related criterion. Then, to create limitations or suitability maps, all layers (buffer zones and restricted areas) are combined together by carrying out "*merge analysis*" and "*intersect analysis"*.

Moreover, database of each criterion differs from each other in terms of data forms, as presented in Table 4.1. For example, the General Directorate of Mineral Research and Exploration (MTA) earthquake data are presented as figure (.jpg) form in its original database. So, converting MTA figure data to a vector layer is needed to use data in GIS environment. For this reason, georeferencing is needed to convert figure data to vector data. KOERI earthquake locations data is a .xml file. So, some modifications are needed to convert .xml data to vector data. Also, WGS1984 coordinate system is used in this thesis.

Moreover, an image from ArcGIS Pro is presented in Figure 4.4. Blue rectangular shows the analysis window on the far left of the figure. Analyzes are carried out using this window (*geoprocessing*). The red rectangular in Figure 4.4 shows layers (*table of contents*) prepared in ArcGIS. These layers show site selection criteria, which will be explained in the following chapter, Chapter 5. On the top of Figure 4.4, a green rectangular is shown, "Toolbar" of "Analysis" menu. Using this toolbar window, it is possible to carry out complex analysis, i.e., writing a python code, composing raster functions, etc.

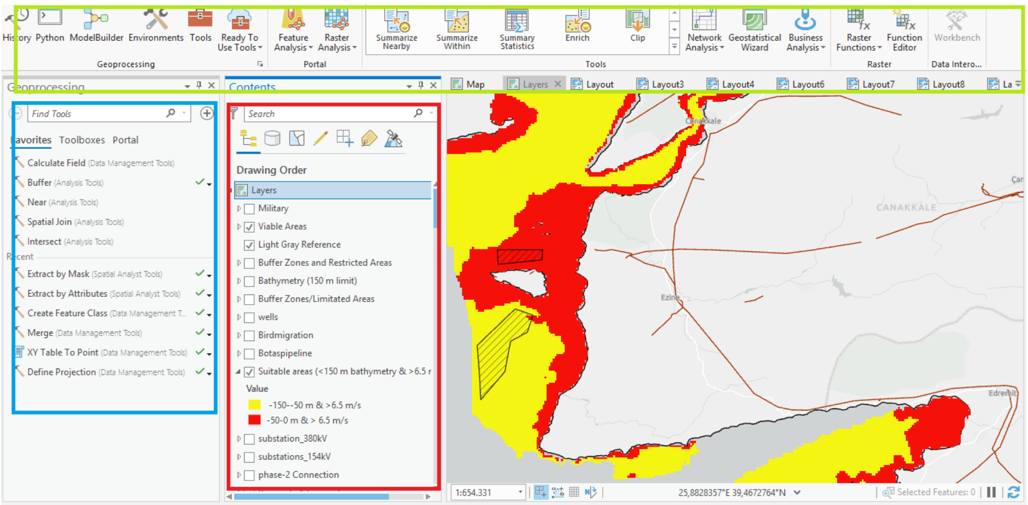


Figure 4.4. A view from ArcGIS Pro

Another sample image from ArcGIS is shown in Figure 4.5. In this figure, "*profile analysis*" is shown. An input line is drawn for a route to extract its profile. The aim of presenting this profile analysis is to show how to measure surface profile length (see details in Chapter 7, grid connection length measurement of sea bottom and topographic surfaces).

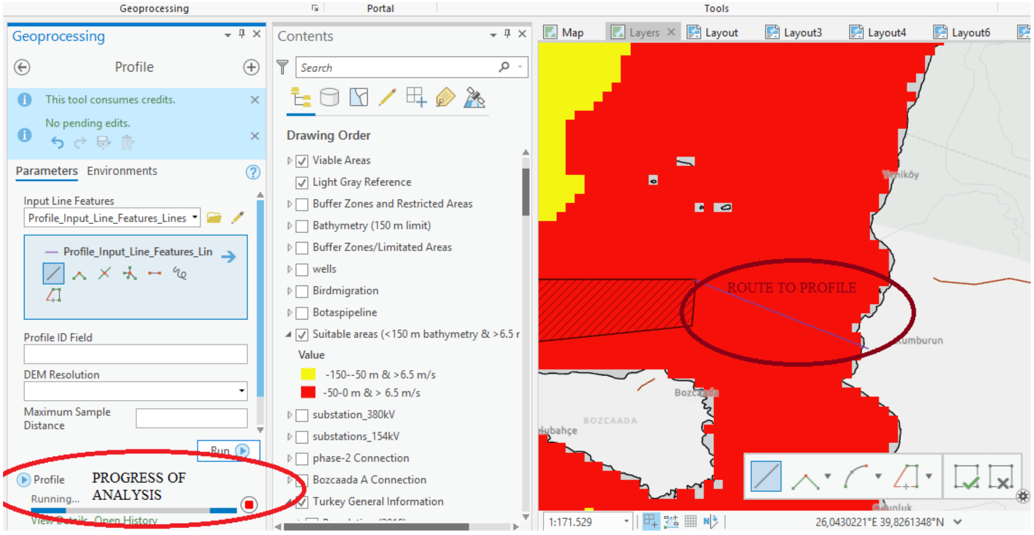


Figure 4.5. Analysis to measure cross-sectional profile surface of a route

After entering the required units and parameters to ArcGIS profile analysis, the resulting cross-sectional profile along the route is shown in Figure 4.6. Based on this profile (Figure 4.6), it is possible to calculate the length of a surface.

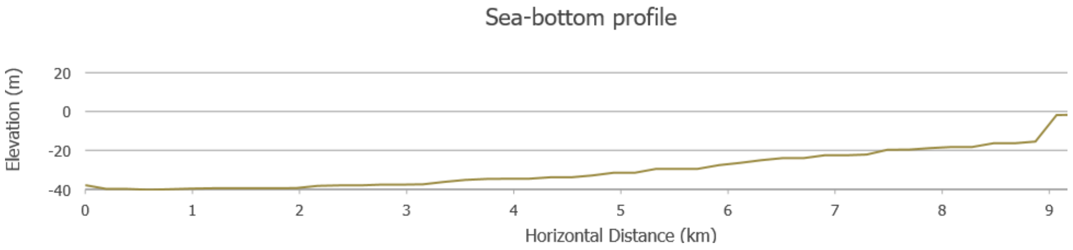


Figure 4.6. The cross-sectional profile of the given route

Profile extraction is shown here as an exemplary analysis. As mentioned above, cable lengths calculated for a selected route, using this analysis, are presented in Chapter 7. The other analyses carried out in this thesis are that i. overlay analysis, ii. proximity analysis, iii. density analysis, iv. geocoding.

CHAPTER 5

SITE SELECTION CRITERIA FOR A POTENTIAL OWPP AND THE CRITERIA EVALUATION FOR TURKEY

The use of wind energy in the World dates back to ancient times, and the mechanical power of wind energy has been used in different geographies for centuries, as stated in Chapter 2. In history, the first known wind turbine to produce electricity was created by Prof. James Blyth of Anderson's College, Glasgow (now known as Strathclyde University) in 1887 (Price, 2005) . Then, the first modern onshore wind power plant was built up in Denmark, 1918. After this date, the development of wind technology continued on land. However, over time, some problems arising from onshore technology have led to the idea of moving offshore. The noise of the wind turbines, the negative reactions of people living around the wind farms, and the lack of space became the basis of moving the turbines offshore. The first offshore wind turbine was installed in Denmark in 1991 (Bilgili et al., 2011; Brennan et al., 2012).

As mentioned in Chapter 2, offshore wind turbine applications have advantages over onshore ones, like having a stronger, stable, and predictable wind speed. Moreover, onshore wind farm construction might be complicated due to the site's topology, and the transportation of turbine components. In contrast, turbine components are easier to set up in offshore because of the comfortable, easy ship and vessel transportation. Additionally, wind turbines' noise might be disturbing for residential people living around onshore wind power plants, in contrast to OWPPs, which are located far from urban areas. Besides, offshore wind is a more stable source than onshore wind since friction force losses are less offshore (American Geosciences Institute, 2021).

For an OWPP project, there are many essential steps to follow prior to deployment. The first step of an OWPP project is the determination of suitable sites for an OWPP considering criteria and limits. For an appropriate site selection, many factors must be considered.

In Section 5.1, site selection criteria are explained in this chapter, and their evaluations and maps are presented. In Section 5.2, buffer distances and restricted areas used in previous studies and in this thesis are presented.

5.1 Site selection criteria

This section discusses the importance of site selection criteria and their evaluation for Turkey in detail. A number of the database is used for assessment of the suitable site selection criteria; then, the required data are mapped and analyzed using ArcGIS Pro (see Chapter 4 for details). Site selection criteria (wind speed, territorial waters, water depth, military zones, ports, offshore seismic activity, shipping routes, environmentally protected areas, bird areas, bird migration routes, fishery, distance to shore for grid connection, tourism sites, visual impact, shipwrecks, civil aviation, existing pipelines, underwater cables, offshore observation wells, and seabed soil) are presented in the following sections. These criteria are decided by considering previous site selection studies, as explained in Chapter 3.

Wind

The efficiency of a potential OWPP is related to wind speed since produced energy is directly proportional to the cube of wind velocity. Therefore, selecting areas having high wind speed is important for suitable site selection. Wind speed varies from region to region based on different geographical conditions like vegetation, topography, etc. As stated above, wind speed is higher and is more stable in offshore than on land. Friction loss is less in offshore compared to onshore (Esteban et al., 2011). Figure 5.1 shows onshore and offshore wind velocity map in Europe at 100 m reference height. The height of wind turbines can be higher or shorter than 100 m; however, this figure has been added this thesis to show how the wind speed differs onshore and offshore in general.

Moreover, mean wind speed is more uniform in offshore, which results in less turbulence effect for the turbine system (Esteban et al., 2011). Less turbulence effect means the life of the generator gets longer.

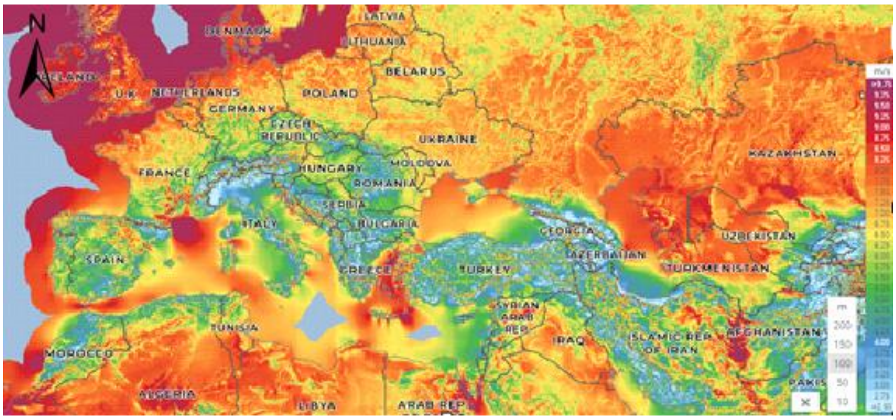


Figure 5.1. Onshore and offshore wind speeds in Europe at 100 m height (Global Wind Atlas, 2021)

While the produced electricity increases by up to 150 %, the wind farm's capacity factor increases up to 25-40 % by steadier offshore wind speed compared to onshore. Therefore, determining lower wind limits to obtain a good efficiency is also important. World Bank states that the minimum limit for an offshore wind farm should be 7 m/s wind speed at 100 m height to get high efficiency (World Bank, 2019); however, Tricoli et al. (2006) suggest the lower limit should be 6 m/s for 60 m height (Tricoli et al., 2006).

In this thesis, the minimum limit for wind speed is taken as 6.5 m/s at 100 m reference height to obtain high efficiency. If World Bank suggestion would be applied as a limit in this thesis, the number of areas that might be selected for Turkey will be reduced. Therefore, the minimum wind speed limit is chosen as 6.5 m/s at 100 m of reference height.

As a wind speed database, GWA 3.0 (Global Wind Atlas, 2021) is used. GWA provides open-source GIS data as a raster. This data is available for each country separately at different reference heights. The mean annual wind speed, power capacity, or dominant wind direction (wind rose) data is also available on GWA.

Nevertheless, wind speed is not the only criteria that should be evaluated for site selection. There are other criteria that should be considered in site selection after identifying high windy areas.

Figure 5.2 shows the windiest sites of Turkey for the limitation of 6.5 m/s at 100 m height. For this minimum limitation, GWA raster data is masked (extract analysis) by using ArcGIS tool.

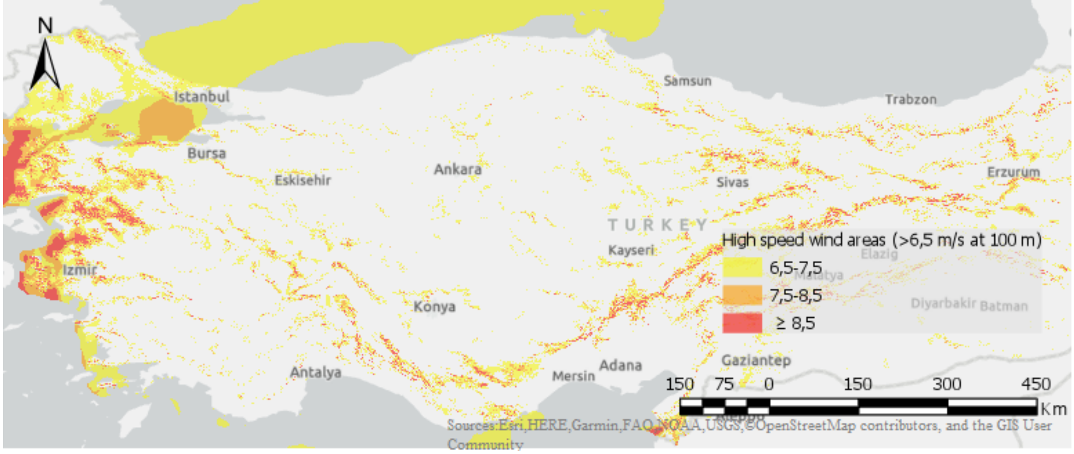


Figure 5.2. High windy areas (>6.5 m/s) in Turkey at 100 m height

Disclaimer: This map is taken from the GWA 3.0 database (Global Wind Atlas, 2021) and does not aim to create any discussion or political issues in terms of the territorial water problem between Turkey and neighboring countries.

In Figure 5.2, it can be clearly seen that the west coastal area of the country is abundant in terms of windy sites. There are regions that might be suitable in terms of high wind speed in coast of Black Sea and Marmara Sea. However, within the scope of this thesis, Aegean and Mediterranean Sea are studied in order to determine suitable sites for a potential OWPP.

Territorial Waters

Territorial water is another crucial factor that should be considered for a suitable site selection process. By international laws, territorial water distance is defined as 22 km, nearly 12 nautical miles from the shore (United Nations, 2021). While selecting a suitable site, these territorial water borders should be defined clearly since disputed borders might create problems between countries. In addition, the radar system of the countries might take the rotor motions as aviation signals. This situation also might create problems between countries. Therefore, the farm site should be in a safe place to prevent potential issues between countries (Güzel, 2012; UN, 1958; World Bank, 2019)

The territorial waters problem is an ongoing problem between Turkey and Greece. The Turkish and Greek islands are very close to each other. Also, in the regions where the number of islands is high, the distance between the islands of the two countries decreases even to 2 km. Therefore, a suitable site selection for an OWPP that might be implemented in the Aegean Sea should be carried out very carefully. Territorial waters do not present any potential problem for the rest of the seas of Turkey. (Güzel, 2012). Note that there exist Economic Exclusive Zone disputes in the Mediterranean Sea.

When wind data is downloaded from GWA database, it includes boundaries of territorial water for each country. Thus, wind map also includes territorial water boundaries, also. For this reason, a disclaimer has been added to the figure (Figure 5.2) given above. So, the territorial water data is also taken from GWA.

Water Depth

Water depth is another important parameter for site selection since it is directly related to the cost of the project. Bathymetry affects the selection of foundation type, connection, and construction costs directly. For water depths between 0-30 m, in general, a gravity-based or monopile foundation is used. For water depth of 30-60 m, tripods, jackets, or truss type foundation is used. Although a few studies, such as Vasileiou et al. (2017), state that 60-70 m is the limit for fixed bottom foundations (Vasileiou et al., 2017), some other studies consider 50 m as a threshold boundary for applying floating and fixed bottom systems. World Bank Report (2019) also recommends 50 m as a limit between fixed-bottom and floating systems. Considering this, 50 m is chosen as the boundary for the application of fixed bottom or floating systems in this thesis (Díaz & Soares, 2021; World Bank, 2019; X. Wu et al., 2019). 150 m is selected as an upper limit of floating systems due to technical and economic concerns. Thus, for 0-50 m water depth is taken as suitable for fixed-bottom systems, 50-150 m water depth is accepted as suitable for floating systems in this thesis. Since OWT is a on development and new technology, deployment of a possible OWPP requires state-of-the-art methods apart from traditional ones. The floating turbine concept is also a new technology. Therefore, upper water depth limit is chosen as 150 m in this thesis. For deeper water (>150 m), the cost of implementation of an OWPP might be high. Also, In this section, The General Bathymetric Chart of the Oceans (GEBCO) is used as a water depth database (GEBCO, 2021).

Figure 5.3 shows the bathymetry map of Turkey with 150 m maximum depth limitation. In Figure 5.3 it can be clearly seen that at small distances from shore, water depth gets deeper rapidly in Turkey. Turkish seas seem suitable for FOWTs rather than FBOWTs in general. The shallow waters are very limited in Turkey.

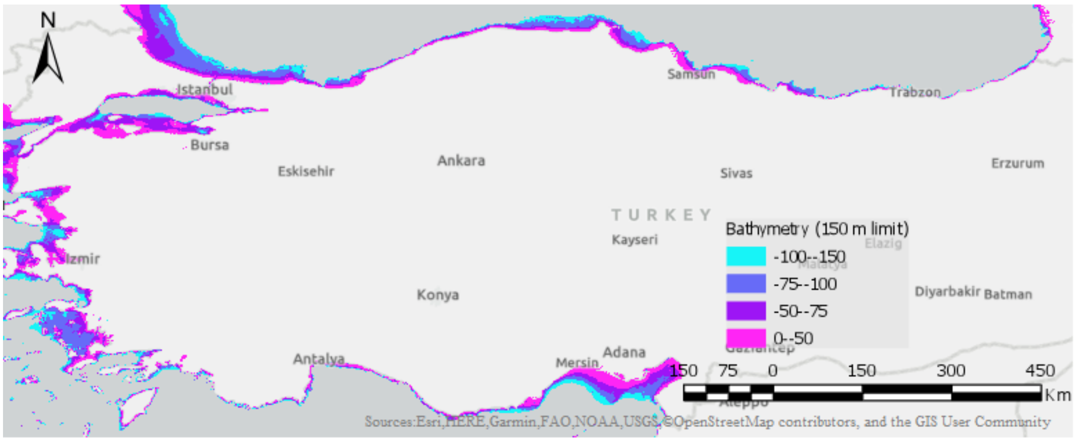


Figure 5.3. Bathymetry of Turkey's seas up to 150 m depth

Military Zones

Military zones and training areas might be identified for a site selection process. The offshore wind turbines might be damaged during military training. Training areas should be determined before the project, and the necessary meetings should be held with the authorities. In some cases, it has also been observed that the boundaries of military areas change according to the projects when permissions are obtained from the authorities. There are two classes of military zones in Turkey: i.Forbidden and security zones: No vessel is allowed in those areas unless they have permission ii. Practice zones: Not always utilized by the military but announced to mariners beforehand on weekly basis announcements if they are going to be in the sea. Those areas are considered to be negotiable after discussions with the Ministry of Energy and Natural Resources.

In this study, military zones are considered but these areas are not excluded, nor buffer added around them. However, when selecting suitable sites, it is clearly stated whether the area is under military restrictions or not since these areas are negotiable as stated above.

Due to confidentiality, the border of these areas is not given in maps. Military zone data is taken from Turkish Naval Forces Office of Navigation Hydrography and Oceanography (2018).

Ports

Investigation of existing ports is important for suitable site selection. It is essential for a potential OWPP site to have a close, large and high load-bearing capacities port. Actually, being close to an existing large port does not indicate the complete handling of offshore logistics throughout the project life. Sometimes, large ports work with a full capacity, which might not provide a contribution to an OWPP for installation or maintenance works. However, existing port capacity might be increased, or an additional port might be constructed around existing large port. In general, OWPPs require highly modified and industrialized ports with special kinds of cranes or logistic equipment (Akbari et al., 2017).

Note that using different ports for construction and Operation-Maintainance (O&M) works are common around the world. In order to minimize project cost, close ports are desirable; however, there exist examples of far ports (i.e., Veja Mate OWPP in Germany are 146 km away from O&M port,114 km away from construction port).

Figure 5.4 shows the main ports (high quay length and highly capacitied) of Turkey. Marmara region has advantages in terms of the abundance existence of large ports due to high industrialization. In general, potential sites that are not located in the Marmara Sea would require significant port developments (searates, 2021).

Figure 5.4. High-capacity ports of Turkey

Offshore Seismic Activity

Seismic activity is another important concern for a suitable site selection study due to the safety of turbines. High seismic activity or being close to subduction zones might cause damage to offshore turbine systems, offshore cables, or offshore substations. Earthquake sometimes causes liquefaction submarine landslides, which result in damaged turbine foundations, or cables (De Risi et al., 2018). Figure 5.5 presents a map showing countries having OWPP with red boundaries. Blue boundaries indicate the subduction zones producing a severe earthquake. It can be clearly seen that some countries having OWPP are also at risk of high seismic activity. The figure also shows peak ground acceleration (PGA) with a probability exceedance of 10% by 50 years. Turkey is a seismically active country, which will be detailed in the following paragraphs, and therefore, earthquake is a critical issue for Turkey. Figure 5.5 shows that especially Asian countries like Japan are developed in OWT. Japan is also at a high risk of earthquakes (De Risi et al., 2018). Thus, Turkey might benefit from the experience of Japan in this field.

Moreover, reliable design and comprehensive assessment methods for turbine structures are required for the seismically risky areas. However, there exist no specifications or guidelines for soil-wave-turbine structure interaction for an OWPP under earthquake risk apart from IEC 61400-1 (Annex D- Only additional seismic load).

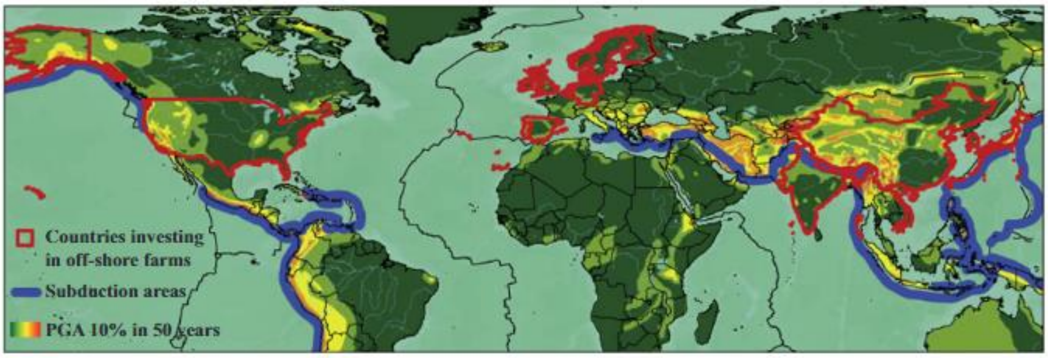
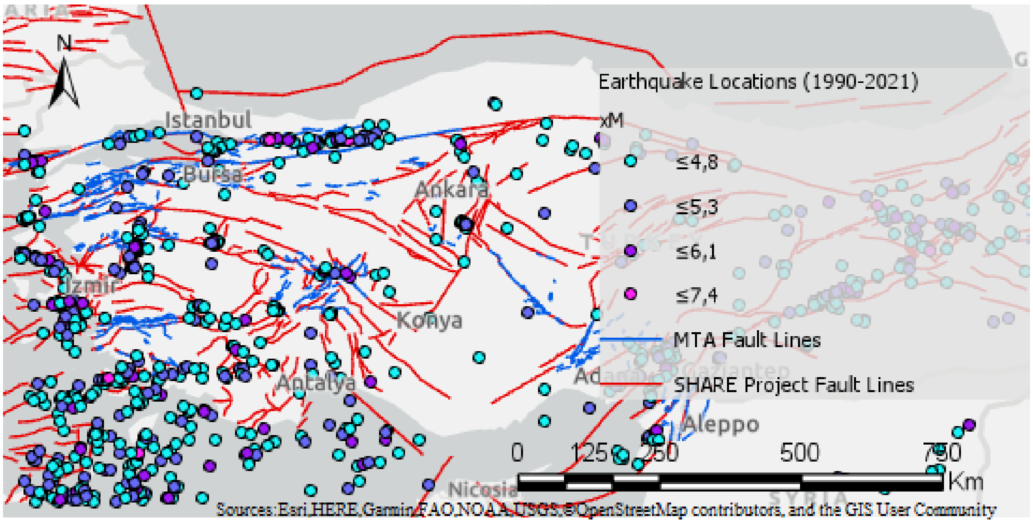


Figure 5.5. Map of countries having OWPP, subduction zones, and global seismic hazard map (De Risi et al., 2018)

The earthquake-triggered tsunamis also damage to offshore wind turbine structures, especially turbines located in shallow waters or shoreland.

In contrast to Europe, seismic activity in Turkey is very high. Figure 5.6 shows the seismic properties of Turkey. Red fault lines are taken from the SHARE project database, and blue fault lines are obtained from MTA (MTA, 2013; SHARE, 2021). The figure also shows the earthquake locations between 1900-2021 for earthquakes having a higher magnitude than 4.5 based on KOERI (KOERI, 2021). In Figure 5.6, it can be clearly seen that Turkey is an active earthquake country, and the fault lines should be detected in detail during the site selection process. Comparing MTA and The SHARE Project fault lines, it might be understood that there exists consistency through the North Anatolian Fault in Northern Marmara. Although MTA does not provide more information on offshore fault lines for the Central, Southern Marmara

Sea, and the Aegean Sea, The SHARE Project has information on those regions. For a suitable site selection, it is recommended that a buffer zone might be defined around these lines. For this study, 2 km buffer distance is defined both side of earthquake fault lines.



Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 5.6. Fault lines and earthquake locations of Turkey

Note that earthquake locations show good consistency with active earthquake fault lines. Comparing only the number of earthquakes may be misleading to demonstrate the critical seismic conditions. For example, the most devastating earthquakes in Turkish history occurred along North Anatolian fault zone; however, a high number of earthquakes does not indicate devastating earthquakes. Therefore, earthquake magnitude maps may be more representative, which is considered in the Turkish seismic hazard map in Figure 5.7 in PGA. North Anatolian Fault Line can be noticed easily covering the whole country in the east-west direction. Also, Northwest Turkey, around Marmara Sea, is represented by red color, meaning higher seismic activity with PGA value exceeding *0.5g*. Although Figure 5.7 shows onshore earthquake data, it is important in terms of giving an idea about areas where the fault lines can continue from the coast.

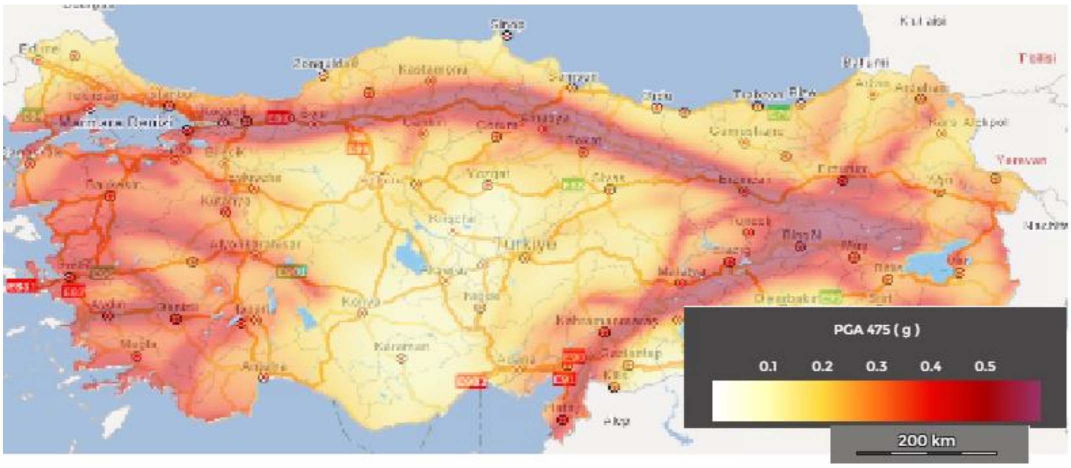


Figure 5.7. PGA map of Turkey (AFAD, 2021)

Shipping Routes

Another critical factor for a suitable site selection is shipping routes since a potential collision may damage turbine structures, ships, or the environment. A potential collision of ship and turbine might cause significant damage in vessels, turbine upper-structure or foundation damages, and might result in environmental pollution such as spilling of oil or chemicals around OWPP. Nevertheless, collision reports are very few in the offshore wind industry since collision data is not appropriately recorded (Presencia & Shafiee, 2018). Ship collisions can be caused by inspection and maintenance vessels, commercial or passenger ships coming from the traffic lines (Rigo, 2015).

Jay (2009) suggests 3.6 km of buffer distance around the shipping route in order to reduce the risk of collisions for offshore wind turbines (Jay, 2009). Also, Hong and Möller (2011) state that 1, 3, and 3.6 km buffers for low, medium, and crowded traffic routes, respectively (Hong & Möller, 2011). The United Nations Convention on the Law of the Sea (UNCLOS) suggests a minimum 500 m buffer distance around shipping routes to prevent collisions or damages between ship traffic and turbines.

In this thesis, the database of shipping routes is taken from European Marine Observation and Data Network (EMODnet), which is a project funded by the European Union (EMODnet, 2021e).

Figure 5.8 shows the international shipping routes around Turkey based on number of shipping routes per km^2. Turkey is a bridge between Europe and Asia, which makes its shipping traffic dense. These routes are international routes; therefore, changing these routes is very complicated and challenging. To select suitable sites, the crowded shipping paths should be detected, and a buffer zone should be chosen to prevent potential damages around the routes.

Figure 5.8. International shipping routes and shipping density around Turkey

In this thesis, crowded shipping routes are eliminated while selecting a suitable site. And a buffer distance is defined (for details, see Section 5.2).

Environmentally Protected Areas, Bird Breeding Areas, and Bird Migration Routes

Although wind energy is clean, it still has some negative effects on the environment. The turbines might affect the bird migration routes, bird habitats, and protected areas. Thus, some environmental areas are excluded with a buffer distance (see Table 5.2) from offshore wind project applications to preserve the ecological, historical and cultural heritage. According to the World Database of Protected Areas (WDPA), there are 243767 protected areas globally, and 17449 of the whole is the marine protected area (Caglayan et al., 2019). Some species are heat-sensitive; therefore, they might be affected by the heat of underwater cables, which provide electricity transmission. The magnetic effect of turbines and electrical systems is also one of the significant factors affecting the environment. Besides, wind turbine substructures might give a home to some other species like reefs (Kirkegaard, 2020).

Hong and Möller (2011) suggest 3 km of buffer zones around environmentally protected areas to protect animals and the environment for a potential OWPP. If a bird area exists around this environmental area, an additional 2 km is also recommended (Hong & Möller, 2011). Tercan et al. (2020) define no buffer zones but eliminate the protected environmental area or bird area (Tercan et al., 2020).

Figure 5.9 shows key biodiversity areas and bird areas in Turkey. Key biodiversity areas are divided into two categories as recommended protected areas and completely protected areas. While selecting suitable sites, these areas should be considered in detail. However, these two categories are given under one field as key biodiversity areas.

Bird breeding areas data, key biodiversity areas data, and bird migration routes data are obtained from the BirdLife database (BirdLife International, 2020), Key biodiversity areas partnership (KBA Partnership, 2021), Birdmap (Birdmap, 2021), and Hacioglu et al.,(2017).

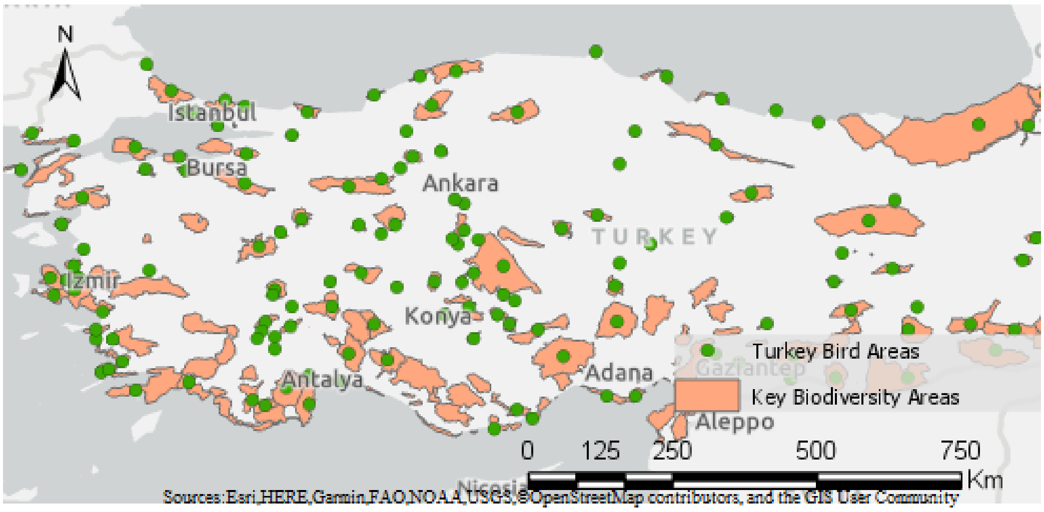
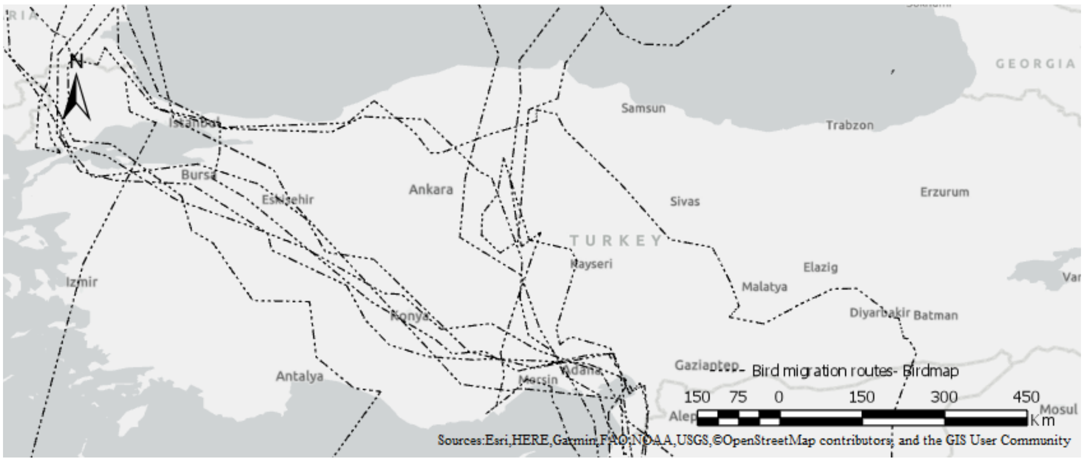
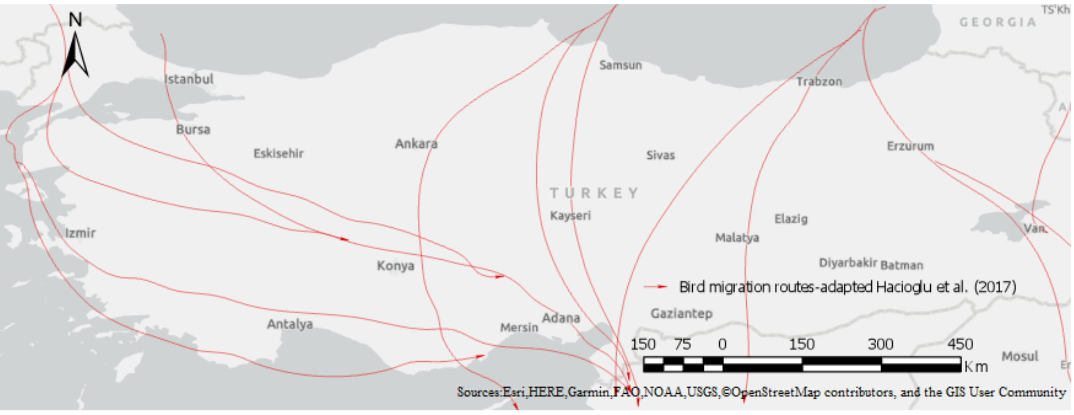


Figure 5.9. Key biodiversity areas and bird areas in Turkey

Birds are the most affected species from wind turbines because their migration routes or breeding areas might be affected. To prevent this, bird migration routes should be carefully identified. Observation of bird migration routes, especially offshore, is a challenging task. This is why bird migration routes are usually tracked by placing Global Positioning System (GPS) devices on the limited number of individual birds. Obtained routes do not represent all bird migration routes but give a good idea about general patterns, which may help in preliminary site selection. Since there is no comprehensive study on bird migration routes in Turkey, detailed bird migration routes data cannot be presented. However, during a suitable site selection process in this thesis, major bird migration routes are considered based on Figure 5.10. Thus, bird migration routes are also investigated and considered for appropriate site selection steps based on Figure 5.10 *(a)* and *(b).*



(a) transferred GIS environment from Birdmap, 2021



(b) transferred GIS environment from a figure in Hacioglu et al. (2017)

Figure 5.10.Major bird migration routes

Fishery Areas

The trend toward OWT increases day by day around the world. However, there exists a conflict between OWPP sites and fishery. Turbine construction, maintenance, and repairing operations might disturb species and fishery activities around the OWPP. Therefore, economically active regions due to fishery might be carefully detected and eliminated. Current and future fishery activities around the sites should be investigated, and active or potentially active sites should be removed from the potential sites. Thus, minimizing conflicts between offshore wind turbines and fishery has significant importance in offshore deployment in terms of economic, cultural, and environmental aspects. (Fayram & de Risi, 2007).

In this thesis, dense fishery areas are excluded without a buffer zone while determining potential sites. The fishery data is obtained from EMODnet and presented in Figure 5.11 (EMODnet, 2021b). Normally, vessels having a minimum length of 15 m are registered to Automatic Identification Systems. EMODnet tracks the fishery activity of these registered vessels. Thus, smaller than 15 m length of vessels are not included in this data.

The density of fishing hours is shown in the following figure as fishing hours per km^2 per month. In Figure 5.11, it is clearly seen that the west part of Turkey is active in terms of a fishery. Middle Black Sea, Mersin, and Hatay regions are also very dense in terms of fishing activities. In this thesis, any areas having 1-1.5 fishing hours per km^2 per month is eliminated without defining any buffer zone.

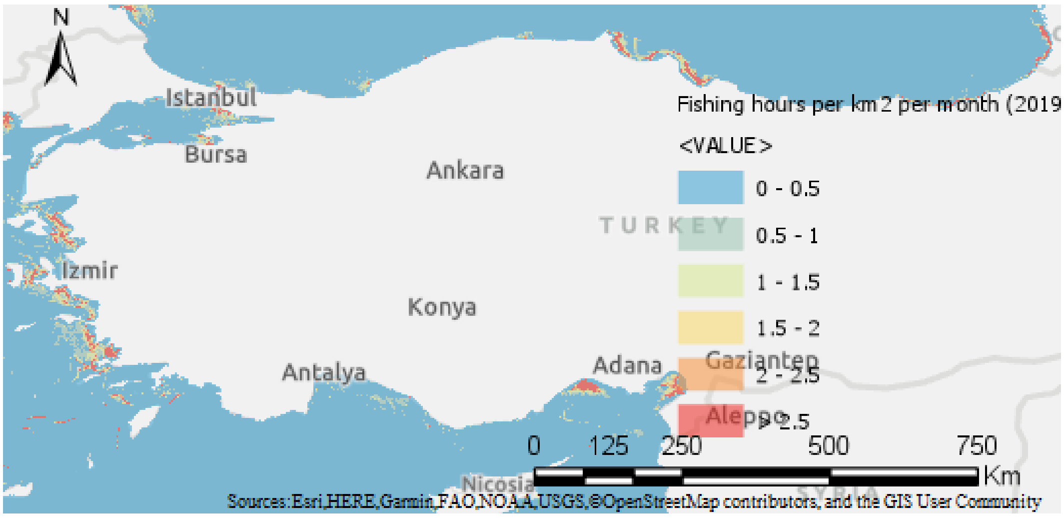


Figure 5.11. Fishing density map of Turkey

Distance to Shore for Grid Connection

The electrical connection is also a critical issue to be considered in selecting a suitable site for an OWPP because electrical connection (offshore, onshore cable lengths, constructing offshore substation) might directly affect the project's cost. OWPPs produce high-capacity electricity; therefore, the substations that need to be connected must also have a high capacity since the amount of produced energy in OWPP is generally high, which may create challenges such as extreme weak-grid situations, islanding conditions, and large harmonics and resonances. So, it is recommended by the Turkish Electricity Transmission Corporation (TEİAŞ) to have a high-capacity substation (380 - 400 kV for Turkey) close to the selected area.

In this thesis, the cable connections and 380-400 kV capacity substations are investigated using Open Street Map (OSM) database. The grid connection mechanism and elements are presented in Chapter 7.

Tourism Sites and Visual Impact of Turbines

Deployment of OWPPs near tourism sites might disturb the local economy and reduce tourism activities. Therefore, during a suitable site selection study, tourism potential of the site should be investigated in detail, and turbines should be built as far as possible from places where tourism activities are high.

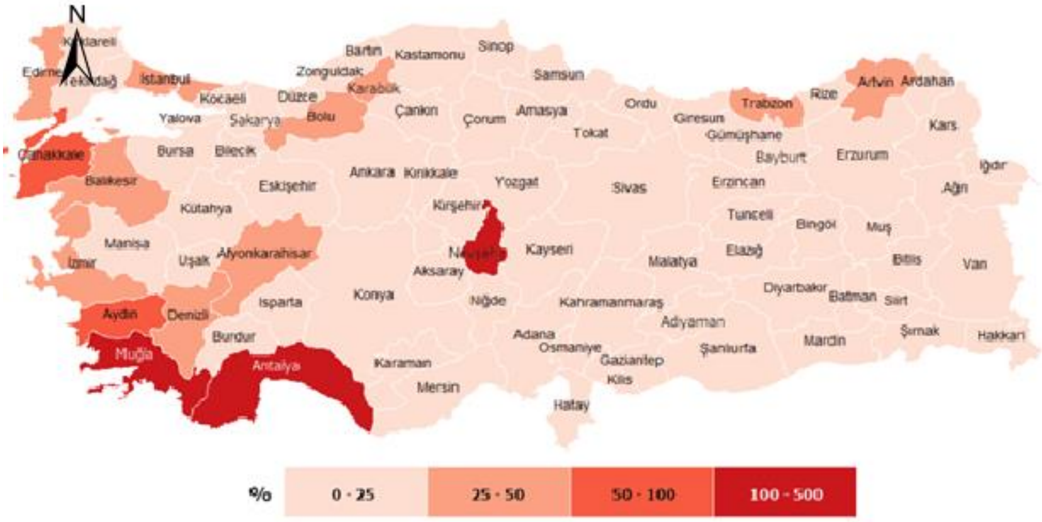


Figure 5.12. Map of tourist density (number of tourists /city population) in summer (thoooth, 2021)

Figure 5.12 shows tourist density percent by city population in 2018 for the summer season. In Figure 5.12, it is clearly seen that the west of Turkey is denser in terms of tourism; in addition, the same region also has high wind speed (see Figure 5.2). Thus, for an OWPP installation, tourism should be investigated in detail.

Moreover, OWPP location should be selected carefully; it should not be too close to coastal areas to disturb local tourism and residents. Also, the location should not be too far from the shore to further increase the cost. Mahdy and Bahaj (2018) state that the minimum distance to the coast must be 1.5 km from the shore to prevent residential and tourism impacts. And the maximum distance to shore should not exceed 25 km to minimize cost. However, reactions of residential to an OWPP changes from region to region, i.e., in some of the projects, visual impact might not be a concern for residents. Therefore, in this thesis, any buffer distance or any minimum distance to coast is not defined for the visual impact factor of an OWPP. Also, most commonly known tourism sites are excluded while selecting suitable sites for OWPP.

Shipwrecks

A shipwreck is another crucial issue for OWPP site selection since it might directly affect turbine safety. Before selecting a suitable site, potential sites should be investigated considering shipwrecks, and necessary investigations should be carried out to determine whether they are explosive or not.

In Turkey, it is known that there are explosive shipwrecks, especially from the 1st World War in Turkey. Shipwrecks are generally concentrated around the Istanbul and Dardanelle Straits.

In this thesis, shipwrecks are examined carefully, and the data are taken from EMODnet and classified based on the type of shipwrecks (EMODnet, 2021c). Coordinates of shipwrecks are excluded with a buffer distance around them.

Civil Aviation

Civil aviation creates concerns in the offshore wind industry due to the probability of wind turbines constituting an obstacle to aircraft and radar systems (Osprey Consulting Services, 2019). Suppose the potential sites are close to civil aviation areas or radar systems. In that case, a buffer distance might be defined around these areas or systems to prevent potential crushing or damages rooted in aviation devices. In this thesis, a buffer distance is defined around civil aviation devices also.

Nguyen (2007) says that at least a 2500 m buffer circle should be defined around airports or radar systems (Nguyen, 2007). There is an obstacle limit surface defined around civil aviation areas. For Turkey, higher than 150 m structures should provide consent from the Directorate General of Civil Aviation (SHGM) confirming that the project would not cause any dangerous obstacles in terms of aircraft activity (The General Directorate of Civil Aviation, 2021). In the direction of runways, 150 m limits changes, i.e., 360 m for 15 km distance. For higher turbines such as 15 MW turbines, the total height reaches around 390 m (240 m rotor diameter+ 150 m hub height). As a result, a buffer distance higher than 15 km might be needed.

In this thesis, the data and coordinates of civil aviation devices and radars are taken from SHGM and WFP GeoNode. A buffer distance of 15 km is applied around the airports to provide safety for both turbines and aircraft. Figure 5.13 shows maps of airports in Turkey (WFP GeoNode, 2021).

Figure 5.13. Map of airports in Turkey

Seabed Soil

The seabed's condition and its substrata are also critical in suitable site selection since soil types significantly affect foundation design. The type of offshore wind turbine foundation and its design is highly correlated with the seabed layers. Rock formations or other hard substrata are not suitable for OWT; other soil formations are generally suitable for both fixed-bottom and floating foundations. For foundation design, a comprehensive seabed profile and substrata investigations are needed. Geotechnical design should be carefully carried out for substrates, which have a relatively weak nature of the seabed soils. In risk assessments for potential sites due to geotechnical design of foundations and underwater electricity transmission cables i.liquefaction, ii. lateral spreading, iii.marine landslides, iv. seabed soil settlement, v. bearing capacity of foundations, etc., should be considered

Nevertheless, there are no detailed and comprehensive publicly available sources focusing on the Turkish seas. Figure 5.14 shows seabed strata in Aegean and Mediterranean Sea. This data is taken from the EMODNet database (EMODnet, 2021a).

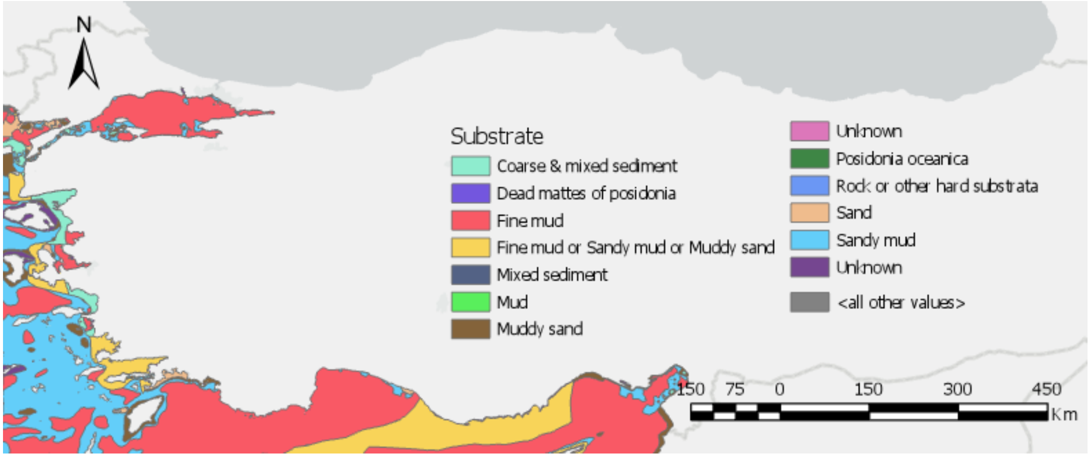


Figure 5.14.Sea-bed substrate for Aegean and Mediterranean Sea

Figure 5.14 indicates that Mediterranean and Marmara Sea are more homogeneous than Aegean Sea. While the dominant formation for Mediterranean and Marmara is fine mud, the dominant formation for Aegean Sea is sandy mud. In the North Sea, soil profile is more uniform (composed mostly of dense sands) to Aegean Sea.

Existing Pipelines and Underwater Cables

Underwater pipelines and cables may be damaged during the construction of turbines, and this situation might lead to unpredictable accidents, interruptions, and economic losses. Therefore, cable lines and pipeline routes should be examined in detail at the site selection stage. In this thesis, cable and pipeline routes were examined during the site selection process; however, it is not possible to reach the exact coordinates of Turkish offshore pipelines due to confidentiality. For Turkish pipelines, a figure (Figure 5.16) prepared by Petroleum Pipeline Company is considered. Since the exact coordinates of pipelines in Turkey are confidential, Figure 5.16 is approximately transferred to GIS tool. If a turbine construction is planned near these lines, it will be important to define a certain buffer zone around the pipes and lines. In this study, a 500 m of buffer distance is defined around underwater cables and pipelines (Tercan et al., 2020) (Díaz & Guedes Soares, 2020), and the underwater cable (telecommunication cable data) is taken from the EMODnet database and transfer to the GIS environment (EMODnet, 2021d)

Figure 5.15 shows underwater telecommunication cables, and Figure 5.16 shows underwater pipelines around Turkey. As stated, underwater telecommunication line data is taken from the EMODNet; however, the pipeline map is taken from BOTAŞ. There are two important offshore pipelines. These are TurkStream and Trans-Anatolian pipelines. Turkstream is a line having 930 km in length that carries natural gas from Russia through the Black Sea. The shore location of the pipeline is around Kırklareli, Kıyıköy. Trans- Anatolian is also crossing Dardanelle Strait (BOTAŞ, 2020).

Figure 5.15.Underwater telecommunication cables around Turkey

Figure 5.16. Underwater pipelines in Turkey (BOTAŞ, 2020).

Offshore Observation Wells

Similar to pipelines and underground cables, existing wells might cause undesired interaction between OWPP and offshore wells. A total of 4910 wells (both gas and petroleum) were drilled in Turkey during the 1934-2018 period. The total number of offshore wells drilled in Turkey so far is 74 (Aydın et al., 2019). While the number of wells drilled in Turkish seas has increased in recent years, it is still low compared to other countries. For this thesis, existent offshore observation wells are included. Buffer zones are identified as 1 km (Mahdy & Bahaj, 2018); this thesis uses a 1 km buffer distance around offshore observation wells.

5.2 Buffer Zones and Restricted Areas

Buffer zones should be defined to ensure security around an OWPP, considering some criteria and preventing potential damage to OWPP or protected things. Table 5.1 shows buffer zone values taken from different studies.

Table 5.1. Buffer zones for OWPP in literature

Criteria	**Excludes**	**Buffer zones from literature**
Distance from shore	Below	1.5 km (Tercan et al., 2020) 8-19 km (Caglayan et al., 2019) 22 km (Caglayan et al., 2019)
Distance from shipping routes	Below	3.6 km (Caglayan et al., 2019) 1 km for low traffic, 3 km for medium, and 3.7 km for dense traffic (Caglayan et al., 2019) 500 m (Díaz & Soares, 2020)
Airports	Below	1.5 km (Caglayan et al., 2019) 2.5 km (Tercan et al., 2020)
Wind speed	Below	6 m/s at 60 m (Tercan et al., 2020) 7 m/s at 100 m (World Bank, 2019)
Distance from environmental protection areas	Below	Boundary (Tercan et al., 2020) 3 km (Caglayan et al., 2019)
Distance from military areas	Below	Boundary (Tercan et al., 2020) 500 m (Tercan et al., 2020)
Water Depth	Above	1000 m (Caglayan et al., 2019) 200 m (Tercan et al., 2020)
Subsea cables and pipelines	Below	250 m (Tercan et al., 2020) 500 m (Díaz & Guedes Soares, 2020; Tercan et al., 2020)
Distance to bird protection areas	Below	Boundary 2 km (Caglayan et al., 2019)

Table 5.1 (continued)

Distance from fishing areas	Below	Boundary (Tercan et al., 2020)
Offshore observation wells	Below	1 km (Mahdy & Bahaj, 2018)

Table 5.2 shows the buffer distances and limitations used in this thesis. To increase energy efficiency, minimum wind speed is taken as 6.5 m/s at 100 m reference height, and maximum water depth is taken as 150 m in this study, as previously mentioned. All commercial fishery areas are excluded to avoid disturbing the local economy. 2 km buffer distance around fault lines, 1 km buffer for key biodiversity areas,15 km buffer for civil aviation ports and devices are defined in this study.

Table 5.2. Buffer zones used in this thesis

Criterion	**Suitable limits**	**Data Source in GIS**
Wind speed at 100 m	≥ 6.5 m/s (100 m reference height)	GWA (Global Wind Atlas, 2021)
Commercial fishery	All	EMODnet Fishing Intensity
Distance to shipping routes	≥ 1 km from densely used corridors	EMODnet (EMODnet, 2021e)
Water depth	≤ 150 m	GEBCO (GEBCO, 2021)
Offshore seismic activity	≥ 2 km from earthquake fault lines	Fault line locations: SHARE Project (SHARE, 2021) General Directorate of Mineral Research and Exploration (MTA, 2013) Earthquake locations (1990 – 2021): KOERI (KOERI, 2021)
Distance to bird migration routes and bird areas	All	BirdLife International (BirdLife International, 2020)
Distance to Key Biodiversity Areas	≥ 1 km	KBA Partnership (KBA Partnership, 2021)
Length of onshore cables	380-400 kV substation locations needed	Open Street Map (Open Street Map, 2021)
Military areas	Military areas are not excluded	Turkish Naval Forces Office of Navigation Hydrography and Oceanography (Turkish Naval Forces Office of Navigation Hydrography and Oceanography, 2018)
Distance to civil aviation devices/airports	≥ 15 km	SHGM (The General Directorate of Civil Aviation, 2021) (WFP GeoNode, 2021)
Shipwrecks	≥ 1 km	EMODnet Shipwrecks (Mayaki et al., 2018)

Table 5.2 (continued)

Offshore petroleum and natural gas wells	≥ 1 km	Menlikli et al. (2009) (Menlikli et al., 2009)
Underwater communication cables	≥ 750 m	EMODNet (EMODnet, 2021d)
Subsea pipelines	≥ 750 m	Petroleum Pipelines Company (BOTAŞ, 2020)
Seabed Soil	All Rock Layers	EMODNet (EMODnet, 2021a)

In this part of the thesis, used buffer distances and limited areas are explained as presented in Table 5.2. These limits and buffers are important since these are considered during suitable site selection. By excluding these limits and buffers from a region, suitable site borders might be determined.

CHAPTER 6

SUITABLE SITE SELECTION IN TURKEY FOR A POTENTIAL OWPP

In this chapter, firstly, preliminary site selection is presented based on minimum wind velocity and maximum water depth criteria (see Figure 4.1) to investigate potential sites. Then, for potential suitable sites, site selection criteria are discussed one by one.

6.1 Preliminary Determination of Potential Sites in Aegean and Mediterranean Sea

In this section, preliminary suitable areas are discussed in Aegean and Mediterranean Sea. Figure 6.1 shows preliminarily suitable areas for a potential OWPP based on limited wind speed and water depth. Red areas indicate 0--50 m water depth and >6.5 m/s wind velocity (suitable for fixed-bottom wind turbines). Yellow areas indicate -50--150 m water depth and >6.5 m/s wind velocity (suitable for floating wind turbines).

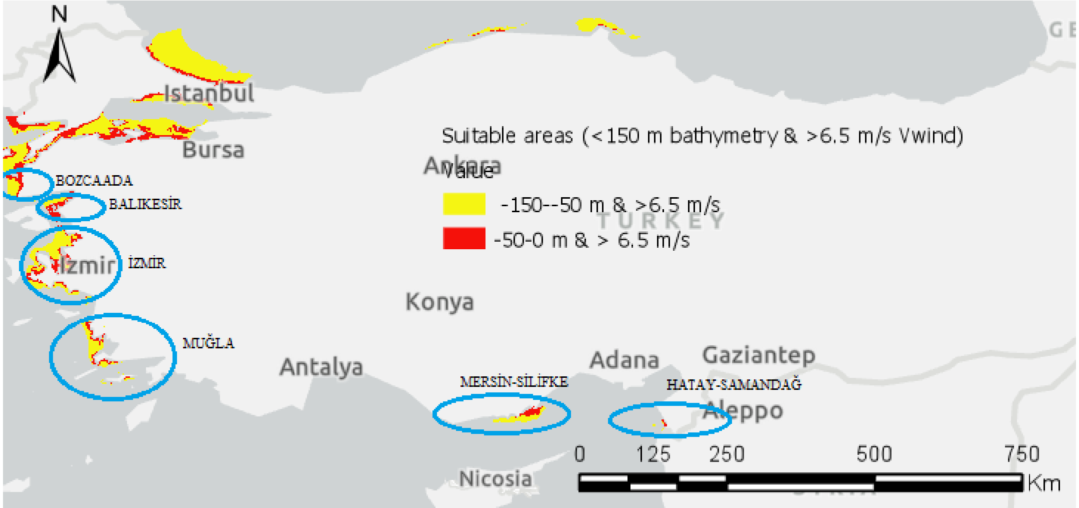


Figure 6.1. Suitable sites in terms of minimum wind speed and maximum water depth

Bozcaada, Balıkesir, İzmir, Muğla, Mersin-Silifke, Hatay-Samandağ are identified as preliminary suitable areas initially. Although the abovementioned six areas seem appropriate for an OWPP in Aegean and Mediterranean Sea, only three of them were studied in detail in the next section (Section 6.2). Balıkesir and Mersin are excluded since they have high turbulence coming from land, which is undesirable. Also, as wind blowing from the land is dispersed in mountains and hills, its stability is also reduced. Also, Balıkesir is quite close to the shore from both sides. Muğla is eliminated since Muğla sites has busiest tourism sites (Bodrum, Milas, Didim, Kuşadası, etc.) of Turkey.

In Table 6.1, the sea areas of Turkey are presented. It should be noted that suitable areas (annual mean wind speed greater than 6.5 m/s at 100 m, and water depth smaller than 150 m) constitute approximately 4.6 % of all Turkish waters. While 3.21 % of these sites are suitable for floating foundations, nearly 1.39% are convenient for fixed bottom foundations. Thus, it is clear that suitable waters for fixed-bottom systems are smaller compared to floating systems.

Table 6.1. Sea areas of Turkey

All sea area (km^2)	462000	
Sea area with water depth of 0-50 m (fixed bottom) and wind velocity ≥6.5 m/s (km^2)	6389.089	21256.610
Sea area with water depth between -50--150 m (floatings systems) and wind velocity ≥6.5 m/s (km^2)	14867.521	

In Section 6.2, Hatay-Samandağ, İzmir, and Bozcaada are discussed as potential sites in detail to investigate suitable sites for an OWPP.

6.2 Evaluation of Potential Sites

In this part of the study, site selection criteria are investigated in detail for the potential sites (Hatay-Samandağ, İzmir, and Bozcaada).

Figure 6.2 shows the energy production of each city of Turkey in GWh, and Figure 6.3 shows the self-sufficiencies of each city by percent. The self-sufficiency percent of İzmir is lower than Hatay and Bozcaada.

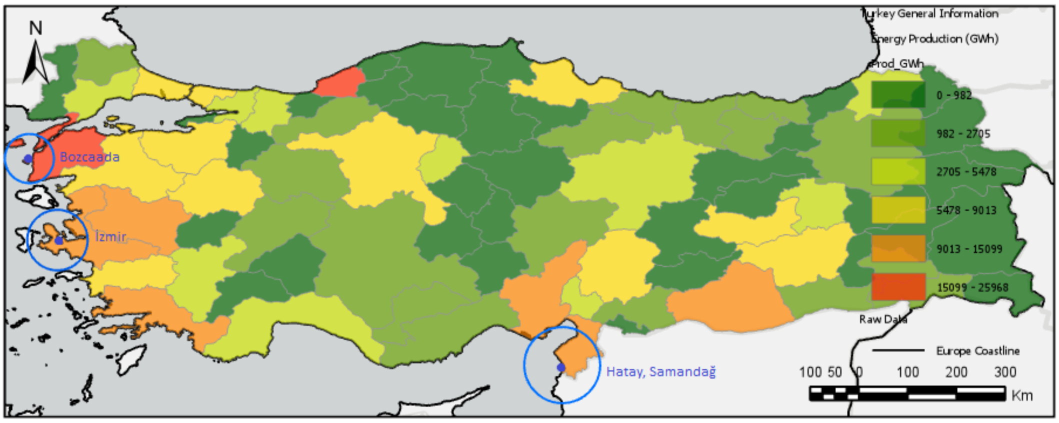


Figure 6.2.Energy production of Turkey city by city

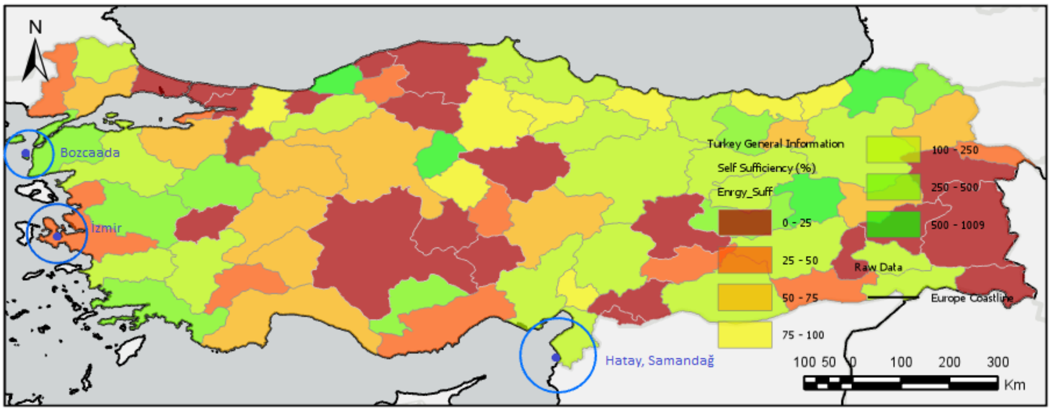


Figure 6.3. Self-sufficiency percent of Turkey’s cities

6.2.1 Hatay, Samandağ

Hatay is in the southeast of Turkey and the East of the Mediterranean Sea, as shown in Figure 6.4.

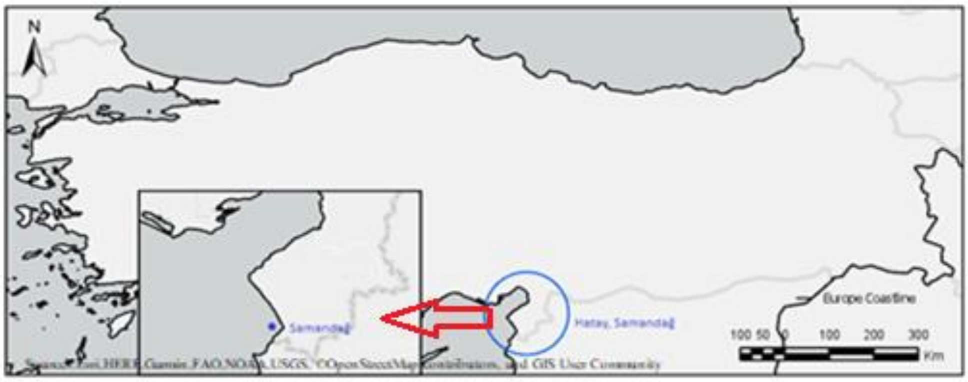


Figure 6.4. Location of Hatay in Turkey

Site Selection Criteria Evaluation for Hatay, Samandağ

Figure 6.5 shows that around Samandağ, mean annual wind speed at 100 m exceeds 9 m/s. This region is one of Turkey's windiest sites, and currently, there are many onshore wind power plants in this area.

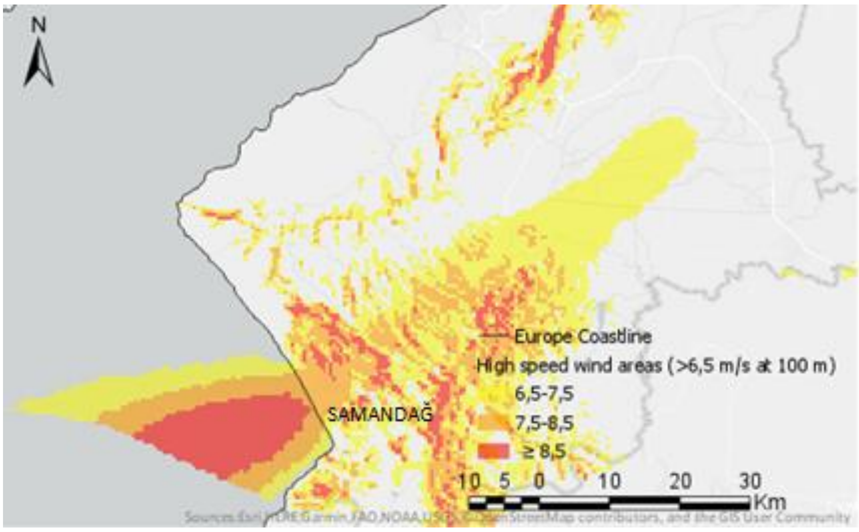


Figure 6.5.Annual mean wind speed map of around Hatay at 100 m reference height

Nevertheless, when water level is considered around Samandağ, it is clear from Figure 6.6 that the water depth changes suddenly to -150 m *at* a small distance. Over this depth (deeper -150 m), a project's cost might be debatable since cost increases dramatically with depth.

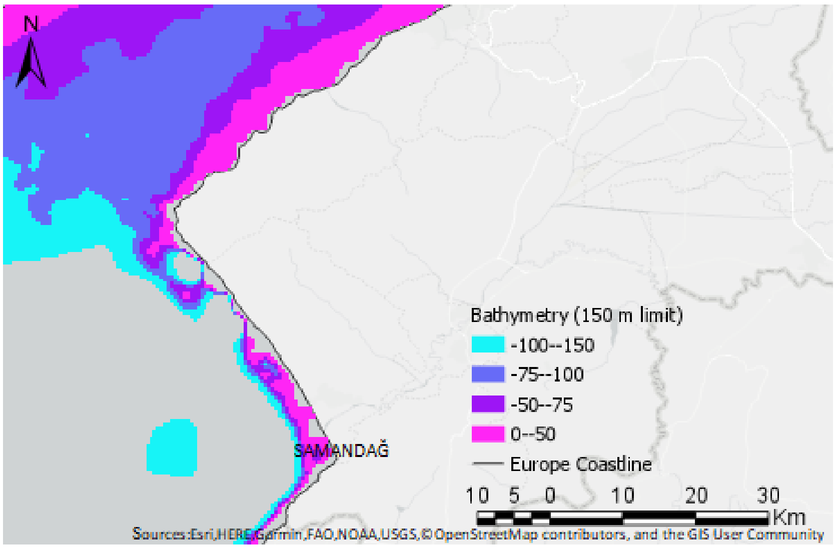


Figure 6.6. Bathymetry map of Hatay to 150 m depth limit

In the future, if FOWTs can be developed with lower project costs in deeper areas (>150m), this area might present wide suitable sites for FOWTs.

Moreover, Figure 6.7 shows the shipping traffic, underwater telecommunication cables, and shipwrecks around Hatay. It is clear that around Samandağ, shipping traffic not too dense to prevent an installation of an OWPP. Also, there are no dangerous shipwrecks around Samandağ region, and there is an underwater telecommunication cable, as presented in Figure 6.7. A buffer distance should be defined around underwater cables or pipelines to protect them from possible damage. Territorial water is not a major concern around Hatay, as in the Aegean sites.

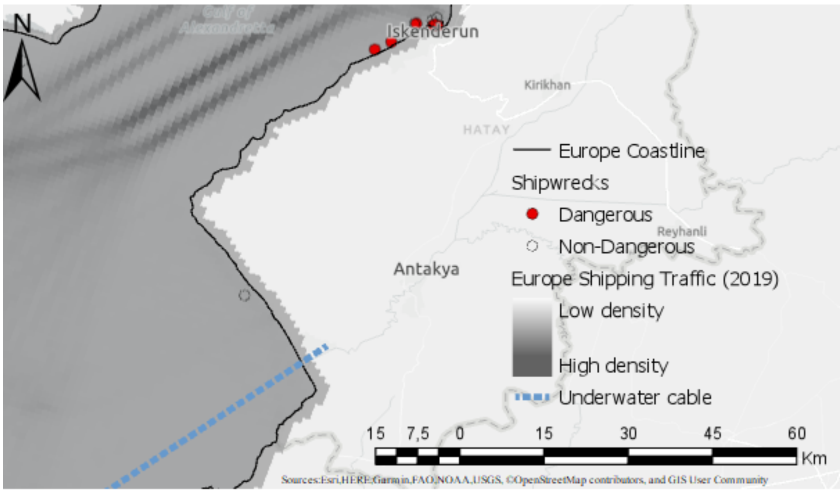


Figure 6.7. Shipping routes, underwater telecommunication cable lines, and shipwrecks (dangerous or nondangerous) map of the vicinity of Hatay

As stated in Section 5.1, seismic activity is an essential concern during the suitable site selection process. Figure 6.8 shows the earthquake fault lines taken from MTA and the SHARE Project. Although the Turkish database does not offer any fault line passing through Samandağ region in offshore, the SHARE Project database shows fault lines around Samandağ (red lines in Figure 6.8). Earthquake locations are also shown in Figure 6.8 (KOERI), with an earthquake magnitude higher than 4.5. The SHARE Project, MTA, and earthquake locations data are consistent in general. Thus, the site is under earthquake risk, a detailed seismic study of the site should be carried out. Thus, the earthquake risk should be considered for the design, installation, and implementation process of an OWPP. In this thesis, to avoid destroying effect of an earthquake, seismicity is considered in site selection process.

Iskenderun port is closest port Hatay-Samandağ region; however, the shipping traffic around the port is dense. For a potential OWPP around Samandağ, a new industrialized port should be constructed, or the capacity of Iskenderun port should be increased.

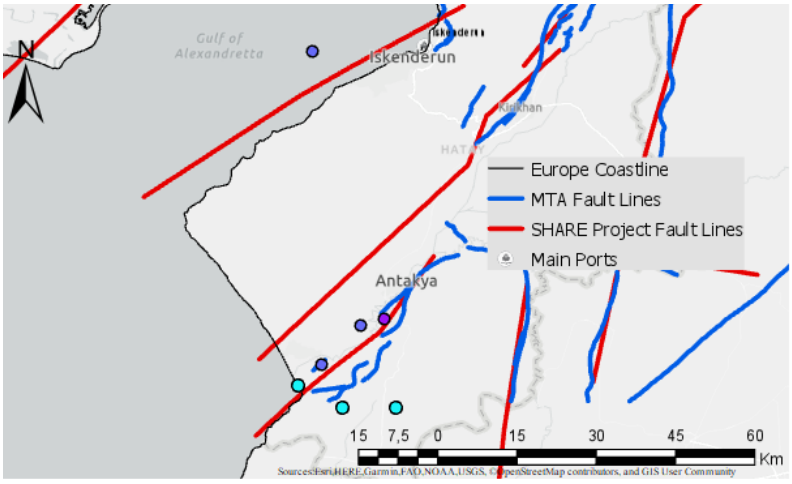


Figure 6.8. Earthquake fault lines, earthquake locations, and main ports around Hatay

The fishery density map is also shown for 2019 year based on the EMODNet data in Figure 6.9, and it is clear that around Samandağ region, the fishery is not too dense. Therefore, for a possible OWPP, the fishery is not a concern affecting the economy.

Key biodiversity areas, bird areas are also shown in Figure 6.9. It is clear that biodiversity areas are very dense around Samandağ. The environmental concern in the region is very high. Although Samandağ provides one of the highest wind potentials in Turkey, environmental protection zones and significant bird migration routes limit the implementation of OWPP significantly (Argin et al., 2019) (see also Figure 5.9 and Figure 5.10). This situation makes the Hatay-Samandağ controversial to select as a suitable site.

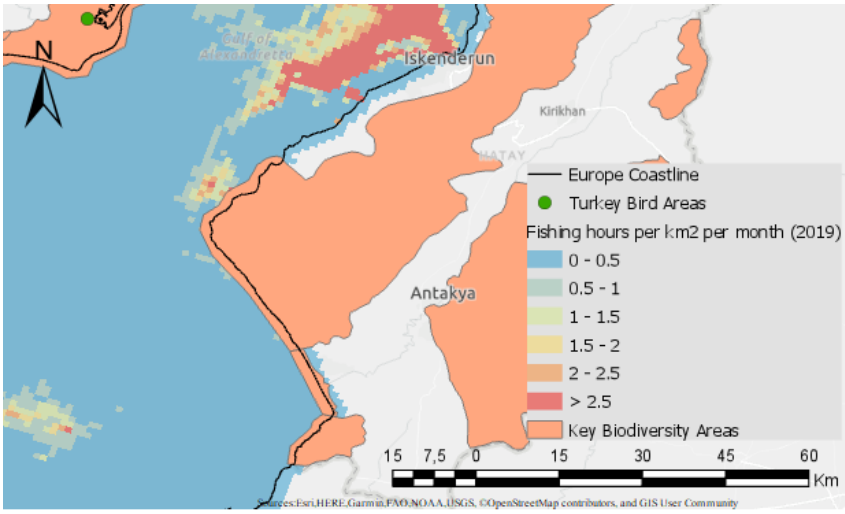


Figure 6.9. Key biodiversity areas, bird areas, and fishery map of Hatay vicinity

As stated in Chapter 5, Section 5.1, rock formation and hard substrata are not suitable for OWPP installation. Figure 6.10 shows substrate around Hatay. According to Figure 6.10, fine mud and sandy mud are dominant soil types around Hatay. It seems that there is no rock layer or hard strata.

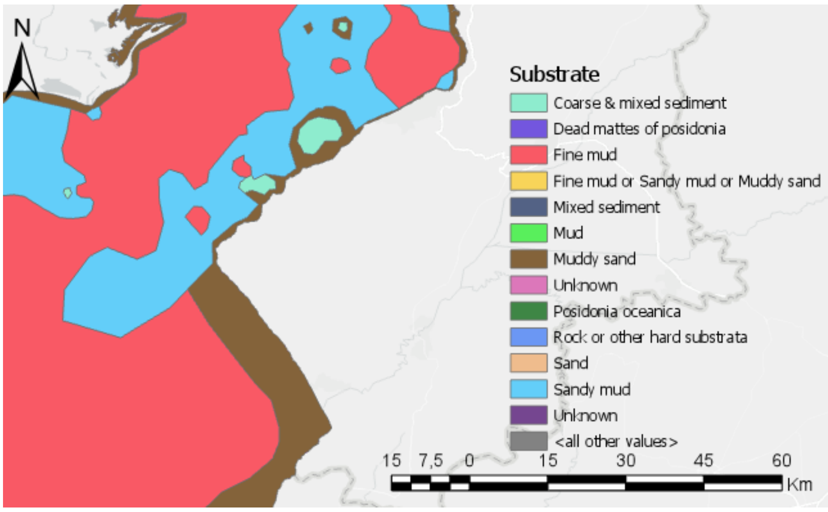
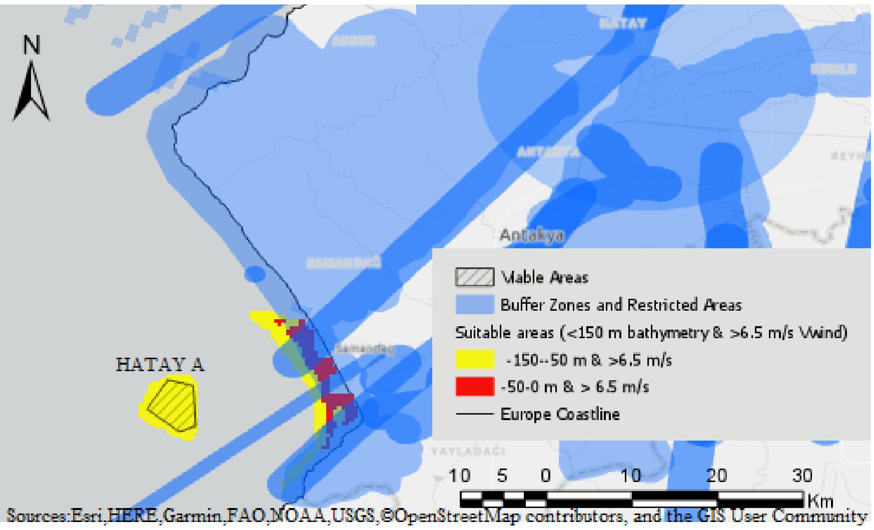


Figure 6.10.Substrate around Hatay



Sources:Esri,HERE,Garmin,FAO,NOAA,USGS,©OpenStreetMap contributors, and the GIS User Community

Figure 6.11. Suitable sites in Hatay-Samandağ

Considering wind speed (exceeding 6.5 m/s) and 150 m water depth limitation, appropriate areas are also shown in Figure 6.11. In Figure 6.11, buffer zones and limited areas (except military areas) are shown as blue areas. After excluding these unsuitable areas (buffer zones and restricted/limited areas), Hatay A site and some areas close to shore remain, as can be seen from the figure. However, it is clearly stated in the methodology section that areas smaller than 15 km^2 are excluded also. The areas close to shore have smaller area than 15 km^2; therefore, these areas are also excluded.

Hatay A site having an area of 19.45 km^2 seems to be suitable when buffer distances and limitations are removed; however, as it is explained, Hatay-Samandağ is located on important bird migration routes (see Figure 5.10), and this site has a great number of environmentally protected areas. For a potential OWPP, this situation should be carefully examined, and environmental and bird migration surveys should be carried out. Hatay A site has serious environmental concerns; therefore, installing an OWPP in there is controversial.

6.2.2 İzmir

İzmir is in the west part of Turkey, near the Aegean Sea, as seen in Figure 6.12.

Figure 6.12. Location of İzmir in Turkey

Site Selection Criteria Evaluation for İzmir

The annual mean wind speed map of the vicinity of İzmir is shown in Figure 6.13 . Especially, the West and north part of İzmir has wind speed more than 9.1 m/s at 100 m. Also, there are many onshore wind power plants in İzmir. In this part of the thesis, the vicinity of İzmir will be examined for a site selection of OWPP.

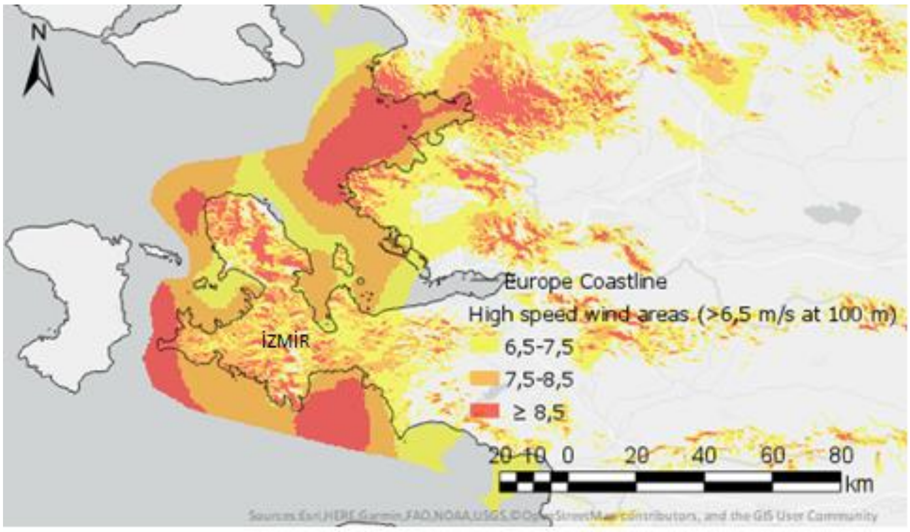


Figure 6.13. Wind map of the vicinity of İzmir at 100 m height

Figure 6.14 shows the bathymetry map around İzmir having a 150 m depth limit. The water level changes suddenly in the south part of the region. For the western part, although the water level is appropriate for a floating OWPP, the territorial water limitation creates problems since this site is very close to the Greek waters.

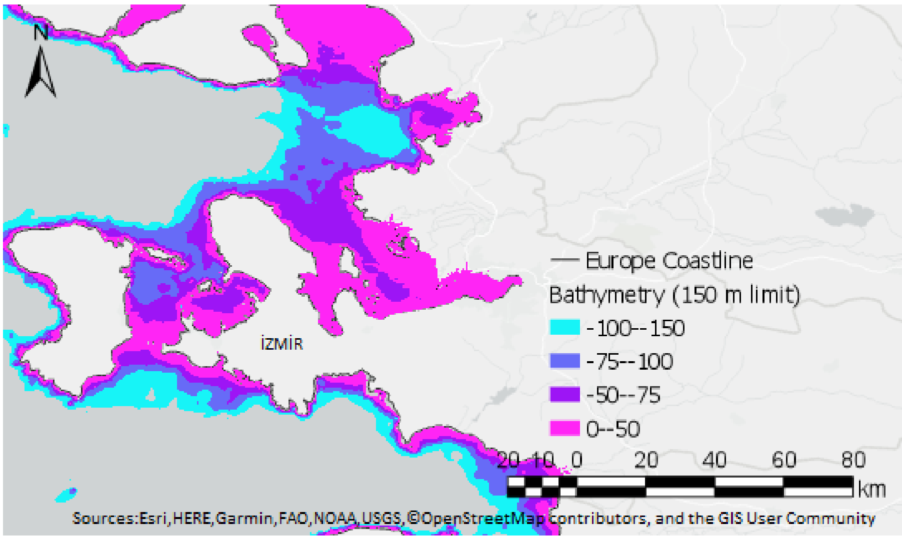


Figure 6.14.Bathymetry around İzmir for 150 m limitation

When the northern part of İzmir (around Çandarlı) is considered, there is another challenge, *shipping routes*. Figure 6.15 shows the international shipping traffic routes in the vicinity of İzmir. It is clear from the figure that a dense traffic route exists in the northern part of İzmir; thus, an installation of an OWPP in this region might not be suitable. In Figure 6.15, dangerous and non-dangerous shipwrecks are also shown. There are a few dangerous shipwrecks in the vicinity of İzmir.

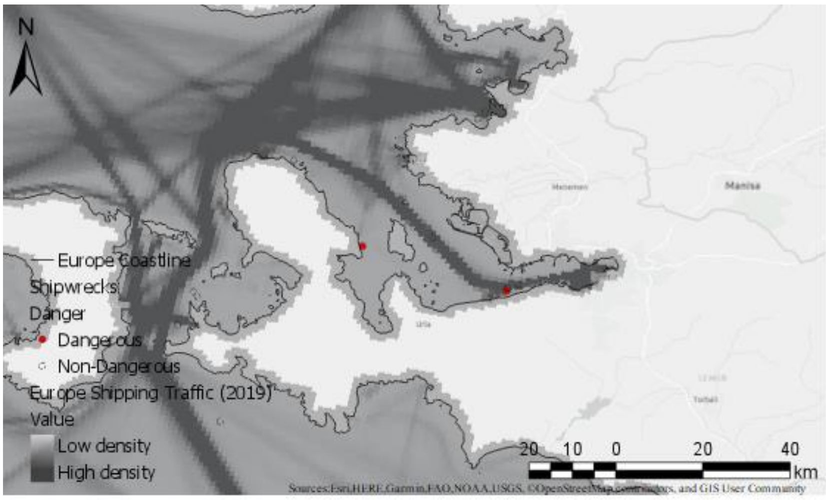


Figure 6.15. Shipping routes and shipwrecks map around Izmir

Notice that many fault lines cross different sites of İzmir region (see Figure 6.16). It can be said that the area is under risk of earthquakes also. Earthquake locations are also shown in Figure 6.16. Çandarlı site is also under the risk of earthquake, an earthquake fault line is crossing it.

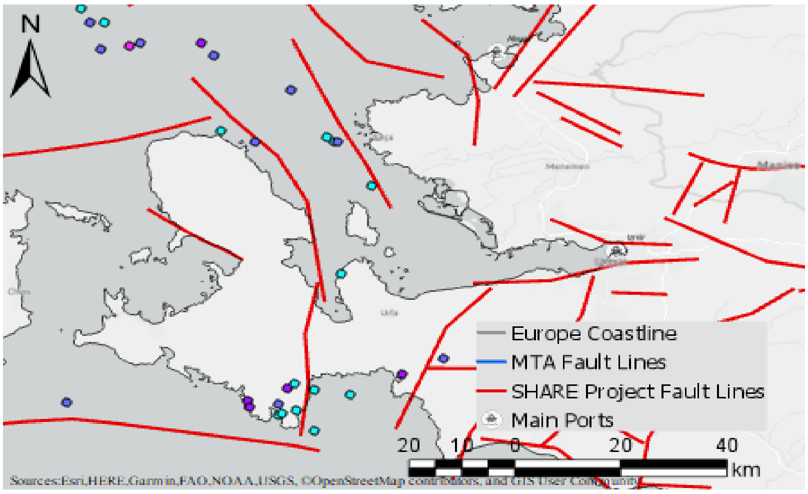


Figure 6.16. Earthquake fault lines, earthquake locations, and main ports around İzmir

As clear from Figure 6.17, fishing activities are very dense around the vicinity of İzmir. It means that fishery might be affected by a possible OWPP, especially in the

South part of the İzmir region. Also, in the northern part, there are some areas where the fishery activities are dense.

Moreover, key biodiversity areas and bird areas are very dense around İzmir. Through the Bay of İzmir, civil aviation activities take a significant place. These factors limit the site from being a suitable option for an OWPP.

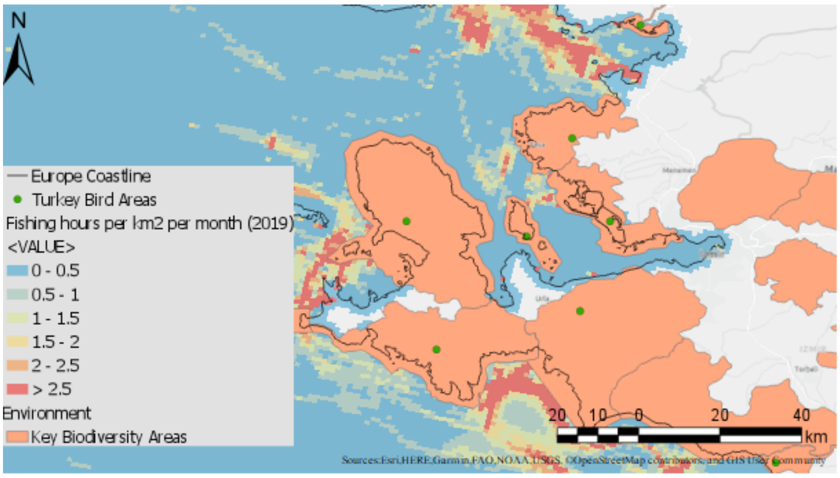


Figure 6.17. Key biodiversity and bird areas, and fishery in the vicinity of İzmir

Military training zones and military forbidden zones are also very widely distributed around the İzmir. There are also high-capacity ports around İzmir; however, these ports' trade traffic is very high and implements full capacity like Iskenderun Port. Therefore, a new industrial port might be required for an OWPP or increasing the capacity of an existing port might be needed. Tourism activities also take place around İzmir, so the deployment of an OWPP may create a negative social and visual impact.

İzmir and its surroundings have very heterogeneous strata as seen from Figure 6.18. Also, there is no rock formation in the vicinity. A detailed geotechnical investigation should be carried out for a potential OWPP to be installed there.

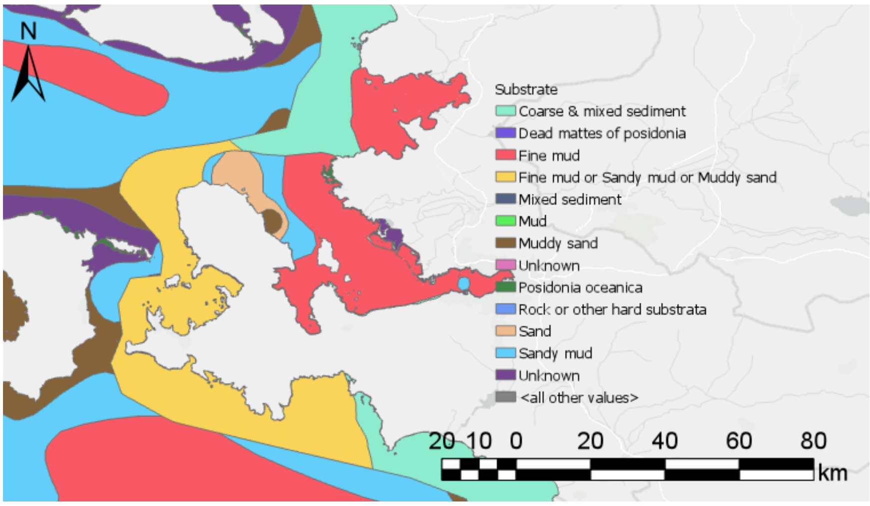
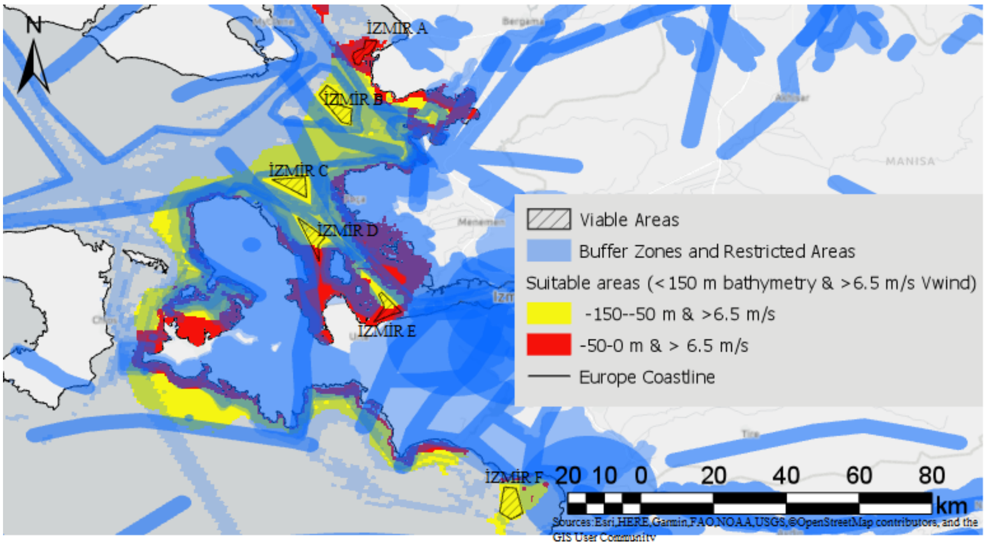


Figure 6.18. Substrata around İzmir

Potential sites in İzmir are shown in Figure 6.19. There are six suitable areas around İzmir considering the abovementioned site selection criteria. Some of these areas are under military restrictions, as presented in Table 6.2. In Figure 6.19. *the west of* İzmir has suitable areas; however, these areas are not included due to very high tourism activities (Alaçatı-Çesme). Also, areas smaller than 15 km^2 are also excluded.



Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, ©OpenStreetMap contributors, and the GIS User Community

Figure 6.19.Suitable sites around İzmir

The suitable sites having a minimum of 15 km^2 area are investigated in this thesis as stated in methodology part (Section 4.1). These suitable areas are presented in Table 6.2.

Table 6.2. Suitable İzmir Sites

Site	Military restriction	Foundation Type	Area (km^2)
İZMİR A	Do not exist	Fixed bottom	16.50
İZMİR B	Partially exist	Floating	30.55
İZMİR C	Exist	Floating	21.00
İZMİR D	Exist	Fixed bottom & Floating	20.00
İZMİR E	Do not Exist	Fixed bottom & Floating	18.00
İZMİR F	Do not Exist	Floating	30.00

6.2.3 Bozcaada

Bozcaada is located in the west part of Turkey, in the Aegean Sea as shown in Figure 6.20.

Figure 6.20. Location of Bozcaada in Turkey

Site Selection Criteria Evaluation for Bozcaada

The average offshore wind speed in the vicinity of Bozcaada exceeds 9.3-9.35 m/s (see Figure 6.21); therefore, the region seems suitable in terms of technical wind potential for an OWPP. The water depth changes gradually around the island. Figure 6.22 shows a bathymetry map around Bozcaada with 150 m depth limit.

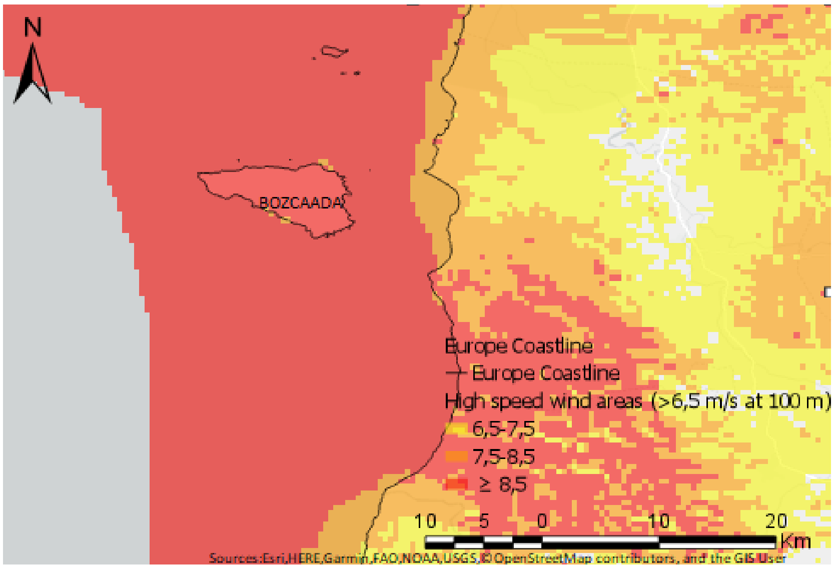


Figure 6.21. The mean wind speed map of Bozcaada region at 100 m height

Especially in the Aegean Sea, Bozcaada is very close to the border of territorial waters, and there is an ongoing territorial water problem between Turkey and Greece. This situation may be a problem for some sites of Bozcaada since the region is close to territorial waters.

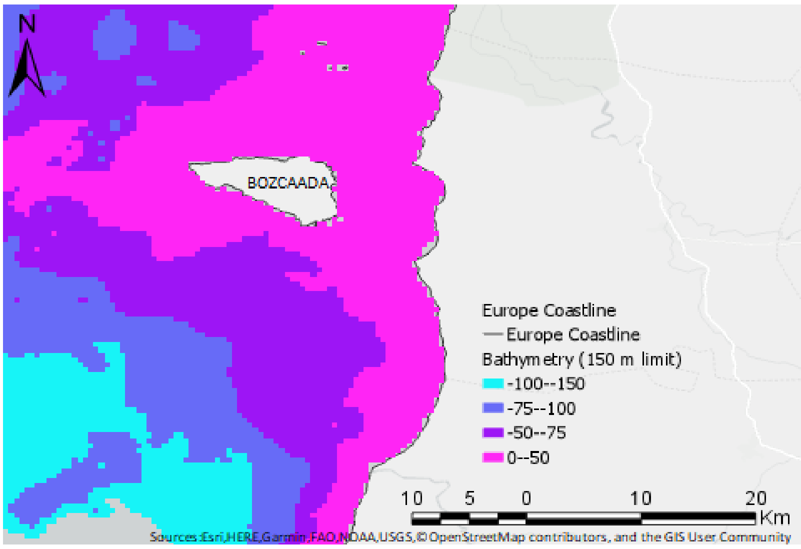


Figure 6.22. Bathymetry around Bozcaada by 150 m limit

Moreover, there is no port through the vicinity of Bozcaada, and the closest port is Kepez Port, where it is in Dardanelle Strait (~47 km away from Bozcaada). Since this situation will directly affect the cost of a construction, a new high-capacity port should be constructed for potential OWPP deployment.

As stated in Section 5.1, shipping routes are another factor for the selection of a suitable OWPP location. Figure 6.23 shows the shipping route around Bozcaada.

Another concern for the OWPP site is the shipwrecks. There are few dangerous or non-dangerous shipwrecks in the vicinity of Bozcaada. While selecting a potential site for an OWPP, the areas having shipwrecks should be excluded. Also, along the northwest Bozcaada, underwater telecommunication cables pass.

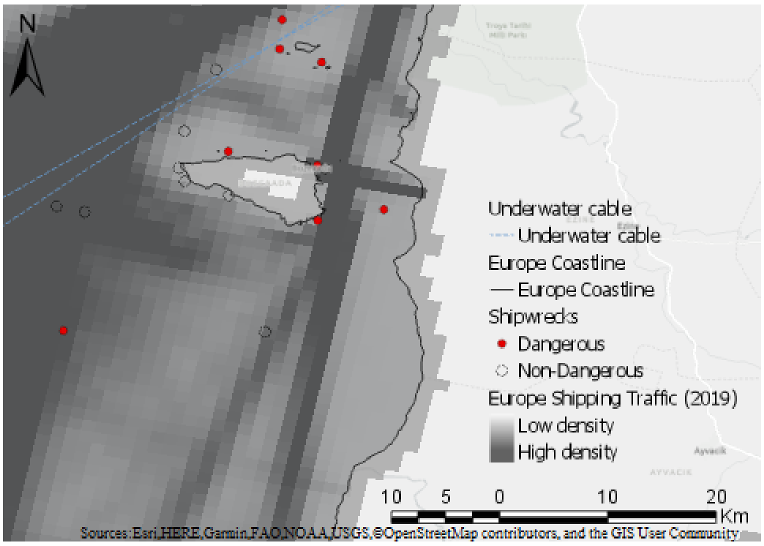


Figure 6.23. Shipping route, underwater telecommunication cable lines, and shipwreck map of Bozcaada site

Earthquake locations and faults are shown in Figure 6.24. Although these faults line extends up to the coastline through Çanakkale, there is a possibility that these fault lines might be crossed along with Bozcaada sites. Therefore, for a possible OWPP, detailed seismic research should be carried out around the vicinity of Bozcaada.

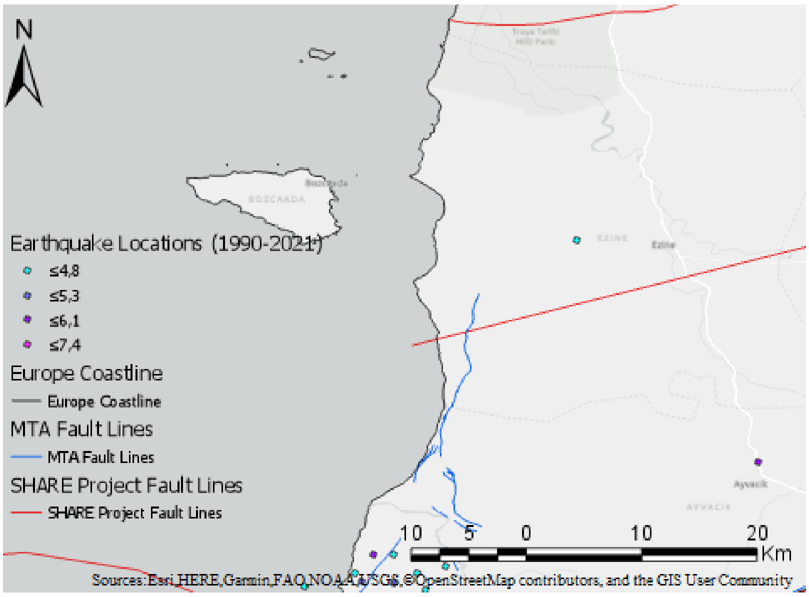


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Figure 6.24. Fault lines and earthquake locations in the vicinity of Bozcaada

Since Aegean Sea sites are very close to the border of territorial waters, fishery activities are limited. Therefore, fishery activities are not the main concern for an OWPP installed around Bozcaada (see Figure 6.25).

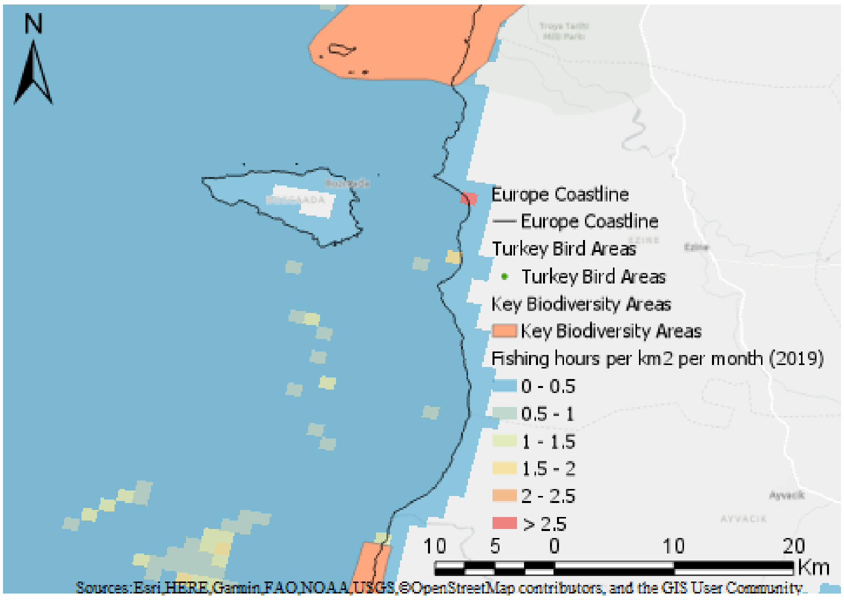

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Figure 6.25. Fishery, key biodiversity, and bird areas around Bozcaada

Substrata around Bozcaada vicinity is shown in Figure 6.26. The formation of soil in here is sandy mud, muddy sand, fine mud, and mixed sediment. For a potential OWPP installation, a detailed geotechnical site investigation should be carried out.

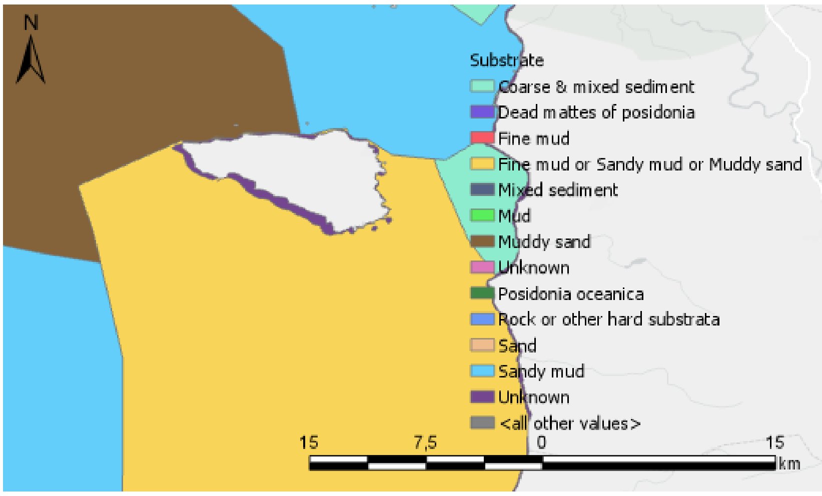

Figure 6.26. Substrate around Bozcaada

After the removal of buffer areas and limited sites, five areas remain as suitable around Bozcaada, as shown in Figure 6.27. The properties of these areas are given in Table 6.3. Except for Bozcaada A, all Bozcaada sites are under military area limitations, so, for a potential OWPP, the required permissions should be taken from the authority. For the conformity of selected areas in Bozcaada, tourism activities should be investigated in detail.

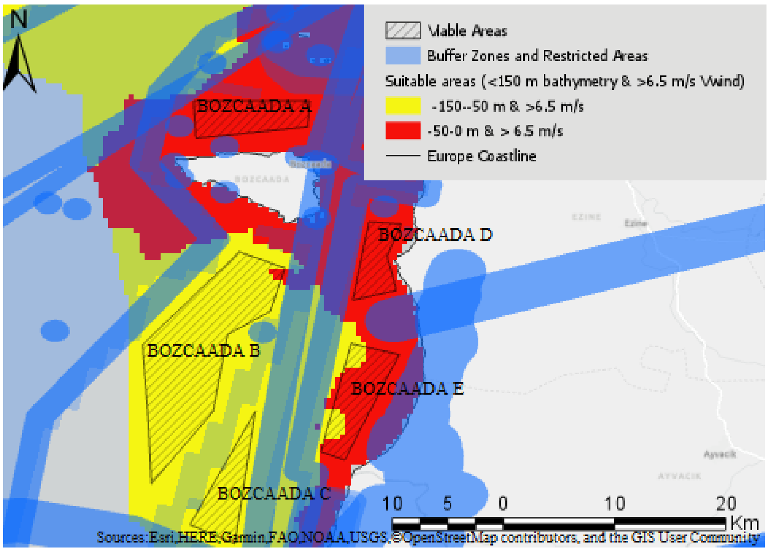

Figure 6.27. Bozcaada sites and buffer zones/limitations in the vicinity of Bozcaada

Table 6.3. Bozcaada sites

Site	**Military restriction**	**Foundation type**	**Area (km^2)**
BOZCAADA A	Do not Exist	Fixed bottom	22.00
BOZCAADA B	Exist	Floating	89.27
BOZCAADA C	Exist	Floating	23.00
BOZCAADA D	Exist	Fixed bottom	16.00
BOZCAADA E	Exist	Fixed bottom/Floating	29.00

6.3 Results on site selection

In previous sections, potential sites were evaluated considering a variety of site selection criteria. Hatay A site is determined as a suitable site around Hatay-Samandağ. However, there are a great number of environmentally protected areas and bird migration routes around Hatay, and these areas might be damaged during or after the construction of an OWPP. Therefore, the installation of an OWPP is very controversial issue around Samandağ. Even if the construction works are not carried out in Samandağ, which should be protected, the turbines might give a damage to migratory birds since this area is located on important bird migration routes (see Figure 5.10).

İzmir site is investigated in Section 6.2.2 to determine whether this region is suitable for a potential OWPP deployment. The narrow continental shelf in the region, the concentration of tourism activities, dense fishing activities, the existence of fault lines, the existence of environmental protection areas, and having a water depth exceeding 150 meters in short distances restrain area selection around İzmir. Six areas are investigated in this thesis for İzmir site.

Bozcaada consists of 5 possible sites, and some of them have a water depth smaller than 50 m. Due to having the highest wind speed, less shipping traffic, less fishing activity compared to İzmir and Hatay, Bozcaada is more suitable than others.

Table 6.4 shows the evaluation of potential OWPP sites. In Table 6.4, it can be clearly seen that Bozcaada is a stronger alternative compared to other sites. İzmir might take the second place among the investigated sites, presented in Figure 6.19. However, as it is stated in Section 5.2, tourism situation and negative visual impact of these areas should be studied in detail for a possible deployment.

Table 6.4. Evaluation of potential OWPP sites

Criteria	**Hatay - Samandağ**	**İzmir Sites**	**Bozcaada Sites**
Wind speed (m/s)	~9	~9.1	~9.3-9.4
Territorial waters problem	No	Partially Yes	Partially Yes
Existence of military zones	No	Partially Yes	Partially Yes
Sea-depth	>50 m	Both <50 m >50 m	Both <50 m >50 m

Table 6.4 (continued)

Foundation type	Floating	Fixed bottom &Floating	Fixed bottom & Floating
Ports	Iskenderun (Exceeds 90 km)	İzmir, Aliağa, Çandarlı (20~30 km)	Kepez (45~65 km)
Seismic activity	Medium-high	High	High
Fishery areas	No significant activity in the vicinity of the site (0-0.5 fishing hours per km^2 per month)	High activity in the vicinity of the site (2-2.5 fishing hours per km^2 per month)	No significant activity in the vicinity of the site (0-0.5 fishing hours per km^2 per month)
Having bird breeding areas and migration routes (see Figure 5.10)	On bird very important migration routes	On bird migration routes	On bird migration routes
Likelihood of having environmental limitation (see Figure 5.9)	Very likely	Likely	Less Likely
Visual impact problems	~20 km	~1-2 km	~1-3 km
Problems due to tourism (see Figure 5.12)	0-25 %	25-50 %	50-100 %
Civil aviation	~50 km to closest airport	~15-60 (changes site to site) km to closest airport	~30-60 km (changes site to site) to closest airport
Existing pipelines	No pipelines around Hatay-Samandağ	No pipelines around İzmir	No pipelines around Bozcaada

Table 6.4 (continued)

Offshore grid connection lengths**	More than 30 km offshore cable line required	Changes for İzmir sites; but less than Hatay A site Soma PoI (5~25 km) Karaburun PoI(1.5~25 km) Aliağa -2 (~19 km)	Changes for Bozcaada sites (9~19 km); but less than Hatay A site

**only bird eye lengths, not surface profile lengths

A preliminary grid connection study for Bozcaada A and Bozcaada B is carried out and presented in Chapter 7.

CHAPTER 7

PRELIMINARY TURBINE LAYOUT AND GRID CONNECTION STUDY

After selecting a suitable site for an OWPP, layout of farm should be determined. Following this, a possible grid connection of the area and the cable length calculations should be carried out. In this chapter, the preliminary turbine layout is determined following traditional preliminary calculations in the offshore industry. After that, a preliminary grid connection study is carried out and presented by taking the profile length of seabed surface (see Chapter 4).

7.1 Turbine Layout

In this thesis, a 5 MW NREL wind turbine is selected for Bozcaada A and Bozcaada B sites. Then, turbine layout is prepared for these two sites. To prepare a layout, the horizontal and vertical distance between the turbine in the wind farm is calculated with respect to turbine rotor diameter. 126 m rotor diameter for NREL 5MW is used in the calculations according to the literature (Jonkman et al., 2009).

The approximate area of Bozcaada A is calculated as 22 km^2, and Bozcaada B is calculated as 89.27 km^2. Also, corner coordinates of Bozcaada A and B sites as are presented in Table 7.1.

Table 7.1.The corner coordinates of Bozcaada A and Bozcaada B

Bozcaada A coordinates	**Bozcaada B coordinates**
i) 25,9667037ºE-39,8523623ºN	i) 26,0141589ºE-39,7657591ºN
ii) 26,0572230ºE-39,8615454ºN	ii) 26,0499620ºE-39,7519887ºN
iii) 26,0593220ºE-39,8827977ºN	iii) 26,0380277ºE-39,7184807ºN
iv) 25,9653918ºE-39,8827977ºN	iv) 26,0036016ºE-39,6969070ºN
	v) 25,9925853ºE-39,6340221ºN
	vi) 25,9430118ºE-39,5771043ºN
	vii) 25,9365856ºE-39,6886447ºN

While placing turbines, the dominant wind direction is critical. The turbines are placed in dominant wind direction (30º with the north for Bozcaada sites), by taking a distance between turbines, seven times rotor diameter in the dominant wind direction. The vertical distance between turbines should be five times the rotor diameter (see Figure 7.1). Thus, 7x126 is 882 m distance exists in the direction of wind between turbines. The perpendicular distance between the turbines is five times the rotor diameter; 5x126 = 630 m spacing. Figure 7.1 shows the layout of turbines and the distance between them with respect to dominant wind direction.

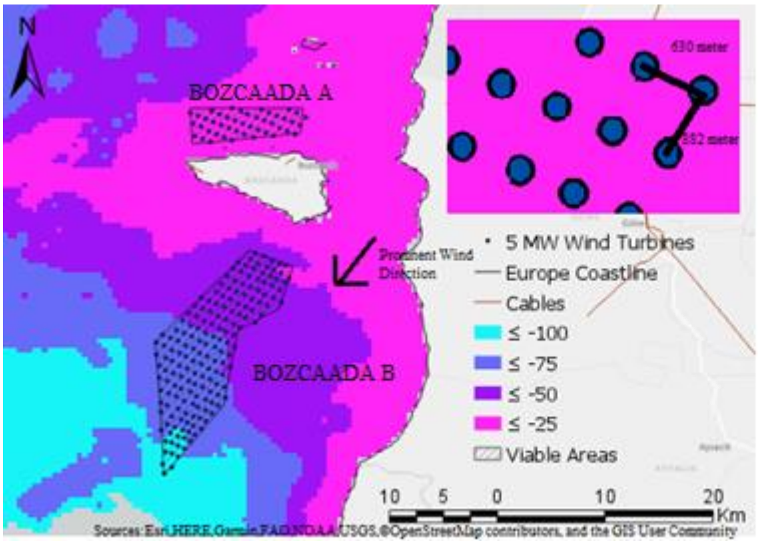

Figure 7.1. Turbine layout of Bozcaada A and Bozcaada B

In addition to 5 MW NREL turbine, the total generation capacity of OWPP using 8 MW, 10 MW, and 15 MW turbines is also calculated and presented in Table 7.2.

Table 7.2. Bozcaada A and Bozcaada B total capacities of sites based on different turbine types

Site	**Area (km^2)**	**Dominant Wind direction (Angle with north)**	**Turbine Rated Power (MW)**	**Number of Turbines**	**Total Installed Capacity (MW)**
Bozcaada A	22.00	30	5	45	225
			8	25	200
			10	21	210
			15	13	195
Bozcaada B	89.27	30	5	175	875
			8	100	800
			10	80	800
			15	43	645

In the case of 5 MW NREL wind turbine usage, the required number of turbines is 45 and 175 for Bozcaada A and Bozcaada B, respectively. The total generation capacity of both sites is 1100 MW for a 5 MW wind turbine. If 0.4 capacity factor used for calculations; then, 1100x0.4, 440 MW capacity is estimated (IEA, 2021).

7.2 Grid Connection

Grid connection is an important factor affecting a suitable OWPP location since it is directly related a project's cost. Table 7.3 shows how cost factor changes with water depth and distance to shore.

Table 7.3. Cost factor with distance to coast and depth (European Environment Agency (EEA), 2009a)

	Distance to Coast (km)							
Depth (m)	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-100**	**100-200**	**>200**
10-20	1.000	1.022	1.043	1.065	1.086	1.183	1.408	1.598
20-30	1.067	1.090	1.113	1.136	1.159	1.262	1.501	1.705
30-40	1.237	1.264	1.290	1.317	1.344	1.464	1.741	1.977
40-50	1.396	1.427	1.457	1.487	1.517	1.653	1.966	2.232

TEİAŞ experts recommend a 380-400 kV capacity point of interconnection (PoI) for a grid connection. PoIs transfer energy from generation to transmission and from transmission to a distribution system. There are two 380-400 kV capacity PoIs (Gelibolu and Çan) around Bozcaada (see Figure 7.2). Gelibolu connection is far away (~100 km bird-eye offshore distance) from Bozcaada sites. To connect the offshore cables to Gelibolu PoI, it is needed to go around Gelibolu Peninsula since south Gelibolu is protected against construction works (due to existence of Gelibolu historical national park). This situation directly increases project cost due to the requirement of high offshore cable laying costs. For this reason, Çan PoI seems a more suitable option compared to Gelibolu PoI to minimize offshore cable laying cost. Figure 7.2 shows the locations of Çan and Gelibolu PoI for 400 kV connection.

Çan PoI is selected in order to show offshore and onshore cable connection layout in this thesis.

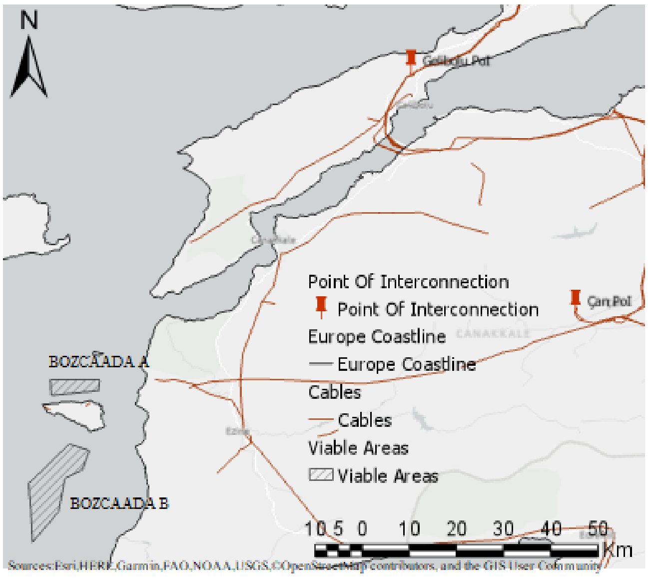

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Figure 7.2. Gelibolu and Çan PoIs

After selection of a suitable PoI, the next step is to determine a possible cable route and measure length of the cables. In the field, a maximum of eighteen turbines is connected with "*inter-array cables (IACs)*". The reason for connecting a maximum of eighteen turbines is capacity limitations. Offshore industry experts state that 90 MW (18 wind turbine times 5 MW capacity) is maximum capacity of transmission cables. Including eighteen connected wind turbines and their IAC connections are called as "*wind turbines (WTs) connection*" in this thesis.

In addition, each WTs connection is connected to shore with buried underwater cables, and these underwater cables are called as "*offshore export cables (OEC)*". There might be some minimum distance between these OECs to provide easy maintenance and repair work when it is necessary. By the recommendation of offshore wind industry experts, minimum distance between OECs should be two times water depth at the shore or field. The minimum distance between OECs is taken as 20 m at shore. Therefore, the cable layout is prepared with respect to these expert recommendations.

Grid connection process includes a number of steps which are summarized in the following (see Figure 7.3) i.calculating lengths of IAC based on average water depth , ii.calculating lengths of OECs considering sea-bed cross-section, iii. calculating lengths of onshore export cable lengths (OnECs) based on TEİAŞ recommandations, iv. Calculating lengths of overhead cable (OHL) between onshore substation (ONS) and suitable PoI.

A concrete structure is buried onshore to collect OECs, called *"transition joint bay (TJB)"*. Horizantal directional drilling (HDD) is made to collect OECs in TJB, see details in Figure 7.3. These collected cables are then transported to ONS if the 400 kV PoI is far from the shore.

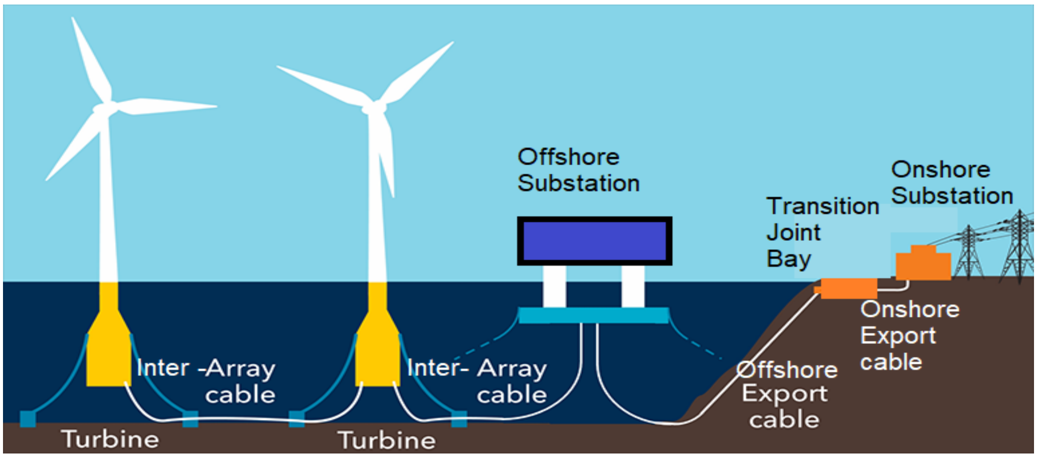

Figure 7.3. The general layout of grid connection for an offshore wind farm adapted from (Det Norske Veritas (DNV), 2021)

Note that offshore substation is is used when OWPP is far from the shore. However, in this thesis, OWPP is not very farm from the shore. Therefore, offshore substation is not used while carrying out grid connection study.

Figure 7.4 shows main connection routes of Bozcaada A and Bozcaada B sites to Çan PoI.

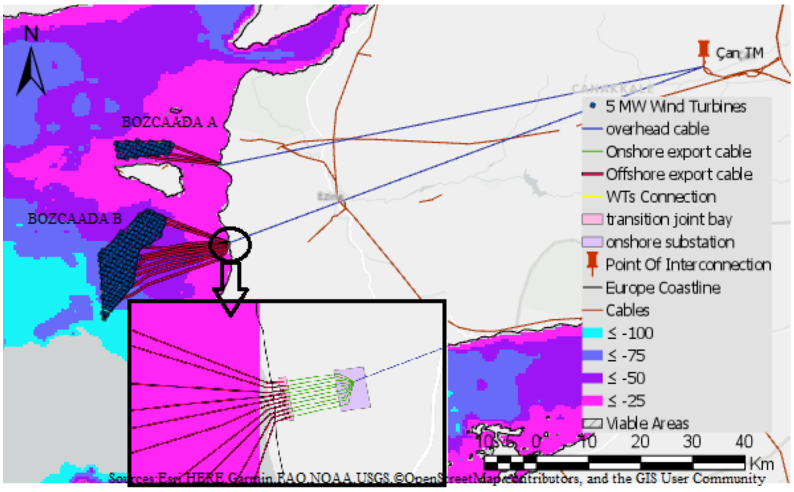

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Figure 7.4. Grid connection routes for Bozcaada A and Bozcaada B

7.2.1 Cable Layout and Cable Length for Bozcaada A

In this part, cable layout and cable lengths for Bozcaada A is calculated and presented.

IAC Lengths for Bozcaada A

As stated in before, a maximum of eighteen wind turbines might be connected to each other due to capacity limitations, by recommendation of offshore wind industry experts. For Bozcaada A, there are three WTs connections; two of them consist of eighteen wind turbines, while one of them consists of 9 connected turbines (see Figure 7.5). Figure 7.5 shows Bozcaada A layout and WTs connection-1 with red triangular polyline.

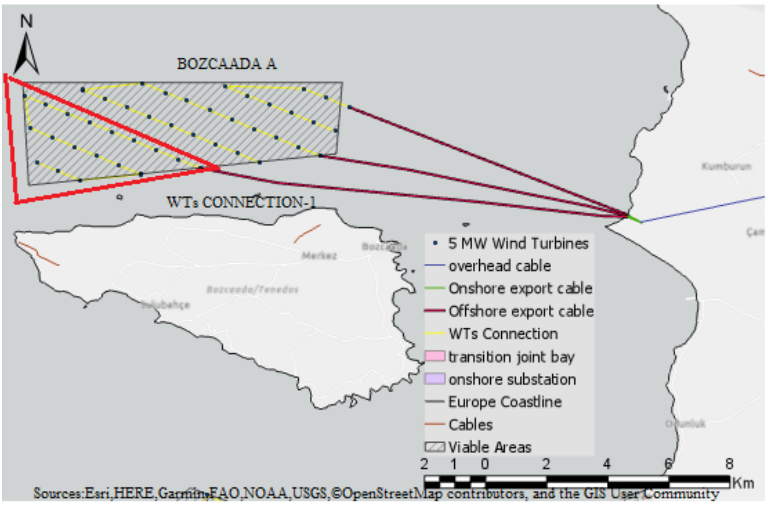

Figure 7.5. WTs Connection-1 in Bozcaada A

IAC length calculation for WT-Connection 1 is summarized as an example in the following.

i. Water depth changes from 8 m to 35 m in Bozcaada A site; water depth of 20 m is taken in calculations as an average value.

ii.There are 18 turbines for WT-Connection 1. Cable length between turbines: 12040 (horizontal distance between turbines along the connection route measured by GIS) + 20 x 35 =12740 m (see Table 7.4), 20 indicates average water depth, 35 indicates the number of turbine cables (number of sagging cables)

iii.Total IAC length for Bozcaada A is 32.08 km.

Table 7.4. Total wind turbine inter-array connection length of Bozcaada A

Connection	**Bird-Eye Distances (km)**	**IAC lengths (km)**
WTs Connection-1	12.04	12.04+0.02x35=12.74
WTs Connection-2	11.70	11.70+0.02x35=12.40
WTs Connection-3	6.60	6.60+0.02x17=6.94
		Bozcaada A $_{\text{CableLengthInWindFarm}}$=32.08 km

OEC Lengths for Bozcaada A

OECs are shown with red lines in Figure 7.6. As abovementioned, OECs are connected from relevant WTs connection to TJB. The location of TJB is selected using OSM (see Figure 7.6). According to OSM, an empty area on land is determined in line with 380-400 kV PoI; then, TJB is placed on this area.

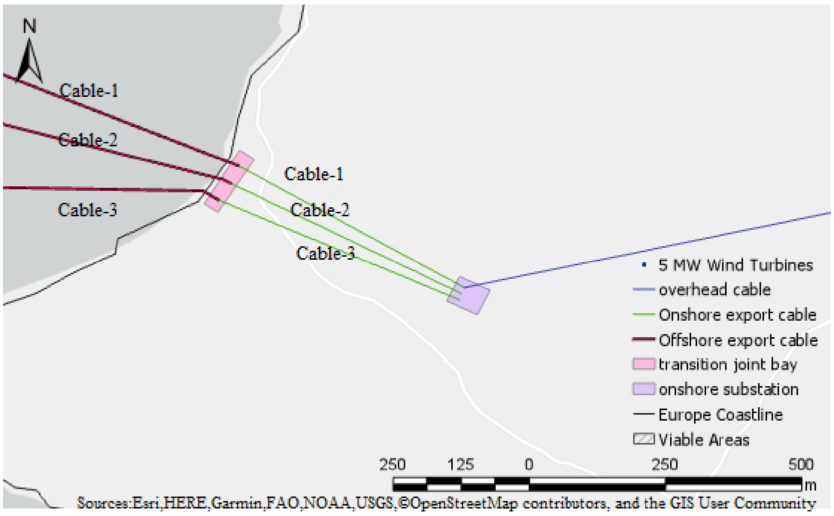

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Figure 7.6. Offshore export cable (OEC) lines coming from each WTs-Connection to transition joint bay (TJB)

OEC lengths are tabulated below in Table 7.5. Cable lengths are measured via GIS tool by taking the sea-beds profile length for each route.

Table 7.5. Offshore export cable lengths

Connection	**Offshore export cable (OEC) length (km)**
Connection-1	9.0
Connection-2	8.0
Connection-3	7.9
Bozcaada A $_{\text{OffshoreExportCableLength}}$=24.9 km	

OnEC Length for Bozcaada A

OnEC lines are connected from TJB to ONS. Similar to IAC and OEC; OnECs are buried. An ONS is constructed to change cable types, with the landing area of 10.000 m^2 per 1 GW. When PoI is close enough to shore, construction of an ONS is not necessary. However, for Bozcaada case, Çan PoI is far from the coast (more than 90 km onshore distance). Therefore, construction of an ONS structure is required. The length of each OnEC is tabulated below in Table 7.6.

Table 7.6. Onshore export cable lengths

Connection	**Onshore export cable (OnEC) lengths (km)**
Cable-1	0.49
Cable-2	0.48
Cable-3	0.49
	Bozcaada A $_{\text{OnshoreExportCableLength}}$=1.46 km

To summarize, for Bozcaada A

i. Total inter-array cable (IAC) length is calculated as 32.08 km

ii.Total offshore export cable (OEC) length is calculated as 24.9 km

iii.Total onshore export cable (OnEC) length is calculated as 1.46 km

iv.Overhead line (OHL) length between the onshore substation (ONS) and Çan PoI (blue line in Figure 7.6) is calculated as 91.8 km. (TEİAŞ recommends that OHL length should be equal to birds-eye distance times 1.25)

7.2.2 Cable Layout and Cable Length for Bozcaada B

In this section, cable layout and cable lengths for Bozcaada B site is calculated and presented.

IAC Length Calculations for Bozcaada B

Figure 7.7 shows turbine layout and cable routes in Bozcaada B. There are ten WTs connections for Bozcaada B site. Nine of them consist of eighteen wind turbines connected to each other. One of them connects only thirteen wind turbines. Also, ten OECs and OnECs exist as shown in Figure 7.7.

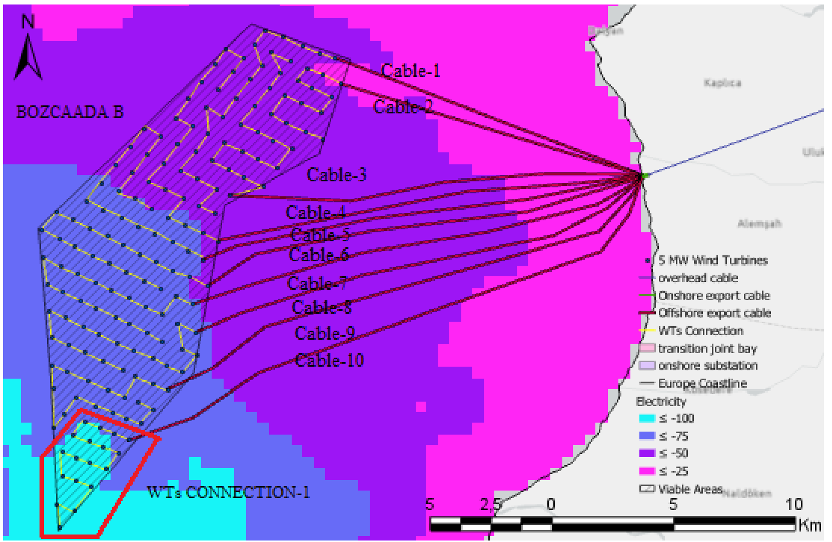

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Figure 7.7. WTs Connection-1 and bathymetry around Bozcaada B

WTs connection-1 is shown in Figure 7.7 with red polyline boundaries. Calculation for WT-Connection-1 IAC cable length is presented as follows:

i.Water depth changes from 69 m to 150 m, average water depth of 110 m is taken in calculations as a preliminary step.

ii.There are eighteen turbines for WT-Connection 1. Cable length between turbines: 12380 m (horizontal distance between turbines measured by GIS) + 110 m (average water depth) x 35 (number of turbine cables) = 16230 m (see Table 7.7).

iii.Total IAC length for Bozcaada B is 157.5 km.

Table 7.7. Total wind turbine inter-array connection length of Bozcaada B

Connection	Bird-Eye Distances (km)	IAC lengths (km)
WTs Connection-1	12.38	12.38+0.11x35=16.23
WTs Connection-2	12.63	12.63+0.11x35=16.48
WTs Connection-3	11.87	11.87+0.11x35=15.72
WTs Connection-4	11.42	11.42+0.11x35=15.27
WTs Connection-5	10.97	10.97+0.11x35=14.82
WTs Connection-6	12.48	12.48+0.11x35=16.33
WTs Connection-7	13.23	13.23+0.11x35=17.08
WTs Connection-8	13.39	13.39+0.11x35=17.24
WTs Connection-9	12.88	12.88+0.11x35=16.73
WTs Connection-10	8.32	8.32+0.11x25=11.07
Bozcaada B $_{\text{CableLengthInWindFarm}}$=157.97 km		

OEC Lengths for Bozcaada B

OECs are shown in red in Figure 7.8. As stated in Section 7.2.1, OECs are connected to related WTs connection to TJB located near to shore.

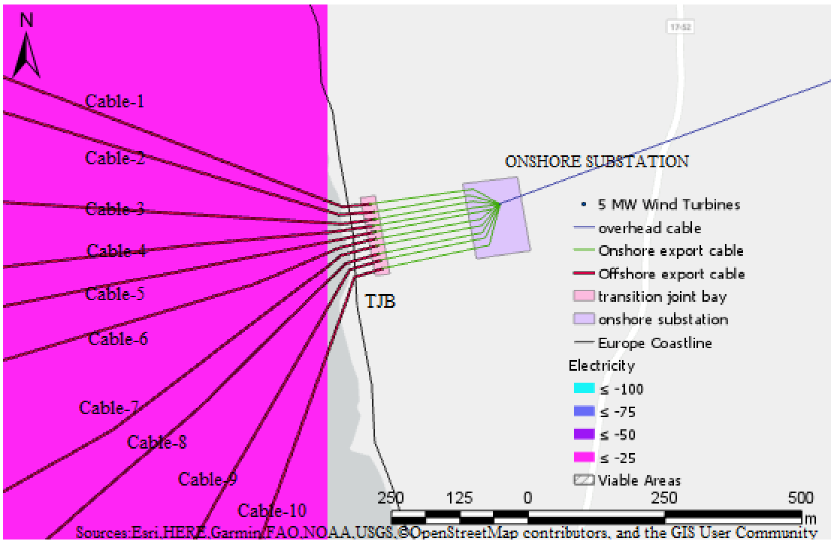

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Figure 7.8. Offshore export cable lines for Bozcaada B

The lengths of ten OECs are presented in Table 7.8. Lengths are measured via GIS tool by taking a cross-sectional length of the seabed (for detail how to take profile length, see Chapter 4).

Table 7.8. Offshore export cable lengths

Connection	OEC lengths (km)
Cable-1	10.88
Cable-2	10.30
Cable-3	13.10
Cable-4	13.78
Cable-5	14.23
Cable-6	14.52
Cable-7	15.34
Cable-8	15.90
Cable-9	17.97
Cable-10	20.70
Bozcaada B $_{\text{OffshoreExportCableLength}}$=146.72 km	

OnEC Lengths for Bozcaada B

OnEC lengths are measured via GIS tool by taking the surface profile of topography. OnECs for Bozcada B presented in Table 7.9.

Table 7.9. Onshore export cable lengths

Connection	OnEC lengths (km)
Cable-1	0.28
Cable-2	0.28
Cable-3	0.24
Cable-4	0.23
Cable-5	0.22
Cable-6	0.20
Cable-7	0.22
Cable-8	0.23
Cable-9	0.23
Cable-10	0.24
Bozcaada B $_{\text{OnshoreExportCableLength}}$=2.37 km	

To summarize, for Bozcaada B

i.Total inter-array connection (IAC) length is calculated as 157.5 km

ii.Total offshore export cable (OEC) length is calculated as 146.75 km iii.Total onshore export cable length (OnEC) is calculated as 2.4 km

iv.Overhead line (OHL) length between the onshore substation (ONS) and Çan PoI is 97.5 km.

CHAPTER 8

CONCLUSION

In this thesis, for suitable site selection, required data were collected from relevant database. For three potential sites (Hatay-Samandağ, İzmir, Bozcaada), suitable site selection criteria were discussed in detail one by one. Finally, one site in Hatay-Samandağ, six sites in İzmir, and five sites in Bozcaada were investigated. By comparing a set of site selection criteria, Bozcaada was selected as the most suitable area among the sites in Aegean and Mediterranean Sea. After Bozcaada, İzmir sites were recommended as second suitable site.

Since Bozcaada was selected as the most suitable site, turbine layout and grid connection calculations are carried out for Bozcaada A and Bozcaada B sites in Chapter 7 following on industrial practice. As a result, 1100 MW capacity was reached totally in Bozcaada A and Bozcaada B without considering any capacity factor. As stated, with 0.4 capacity factor, 440 MW capacity was estimated, totally.In this thesis, it is also emphasized that Turkish waters seem more suitable for floating wind turbines compared to fixed-bottom ones.

ACKNOWLEDGMENT

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