ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

TECHNO-ECONOMIC ANALYSIS OF ONSHORE AND OFFSHORE WIND FARMS IN TÜRKİYE

M.Sc. THESIS

Samet ERGİŞİ

Department of Energy Science and Technology

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TÜRKİYE'DEKİ KARASAL VE DENİZÜSTÜ RÜZGAR SANTRALLERİNİN TEKNO-EKONOMİK ANALİZİ

YÜKSEK LİSANS TEZİ

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Samet ERGİŞİ, a M.Sc. student of ITU Graduate School student ID 301201039, successfully defended the thesis/dissertation entitled "TECHNO-ECONOMIC ANALYSIS OF ONSHORE AND OFFSHORE WIND FARMS IN TÜRKİYE, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family,

FOREWORD

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(Mechanical Engineer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

BOS	**:** Balance of System
CAGR	**:** Compound Annual Growth Rate
CapEx	**:** Capital Expenditure
DPBP	**:** Discounted Payback Period
DÜRED	**:** Turkish Offshore Wind Energy Association (Denizüstü Rüzgar Enerjisi Derneği)
EPİAŞ	**:** Energy Markets Operation Corporation (Enerji Piyasaları İşletme A.Ş)
ERA5	**:** European Centre for Medium-Range Weather Forecasts Reanalysis Version 5
EUR	**:** EURO
FiT	**:** Feed-in Tariff
GW	**:** GigaWatt
GWEC	**:** Global Wind Energy Council
HH	**:** Hub Height
IEA	**:** International Energy Agency
IRR	**:** Internal Rate of Return
kW	**:** kiloWatt
LCoE	**:** Levelised Cost of Energy
MCDA	**:** Multi-Criteria Design Analysis
MW	**:** MegaWatt
NPV	**:** Net Present Value
NREL	**:** National Renewable Energy Laboratory
OpEx	**:** Operational Expenditure
O&M	**:** Operation and Maintenance
PTF	**:** Piyasa Takas Fiyatı (Market Clearing Price)
P2X	**:** Power-to-X
SRTM	**:** Shuttle Radar Topography Mission
TCC	**:** Turbine Capital Cost
TRY	**:** Turkish Lira
TÜREB	**:** Türkiye Rüzgar Enerjisi Birliği (Turkish Wind Energy Association)

UK **:** United Kingdom

USD **:** United States Dollar

WTG **:** Wind Turbine Generator

YEKA **:** Yenilenebilir Enerji Kaynak Alanları (Renewable Energy Resource Area)

YEKDEM **:** Yenilenebilir Enerji Kaynakları Destekleme Mekanizması (Renewable Energy Resources Support Mechanism)

SYMBOLS

C_{capex}	: Capital Expenditure
C_{opex}	: Operational Expenditure
D	: Rotor Diameter
m	: Meter
P_{50}	: 50% Exceedence Probability of the Energy Yield
r	: Discount Rate
T	: Lifespan of the Power Plant
V	: Wind Speed
°C	: Degree Celcius
$	: U.S. Dollar
€	: Euro
£	: Sterling

LIST OF TABLES

Page

LIST OF FIGURES

Page

TECHNO-ECONOMIC ANALYSIS OF ONSHORE AND OFFSHORE WIND FARMS IN TÜRKİYE

SUMMARY

In recent years, the global capacity of wind energy has been experiencing a rapid growth, with onshore wind farms accounting for the majority of the growth. As of 2022, the global installed capacity of wind energy reached 906 GW, of which around 93% is onshore and 7% is offshore. China, the United States, and Germany are currently the top three countries in terms of installed wind energy capacity. In Türkiye, the installed capacity of wind energy has also been steadily increasing. As of January 2023, the total installed wind energy capacity in Türkiye is over 11.9 GW. Despite Türkiye being bordered by the sea on three sides, the country is yet to establish an offshore wind farm. However, the Turkish government has set ambitious targets for increasing the share of renewable energy in the country's electricity mix, including a goal of reaching 5 GW of installed offshore wind energy capacity by 2035.

In this study, a thorough techno-economic analysis of onshore and offshore wind farms in Türkiye is presented.The study utilizes simulations with different wind turbine models to optimize energy production and calculate key economic metrics such as net present value (NPV), levelized cost of electricity (LCoE), and internal rate of return (IRR). With a specific focus on one onshore and one offshore wind farm location, the research facilitates a comparative assessment of different turbine models to identify the most efficient and cost-effective options for wind energy generation.

After conducting a comprehensive analysis and extensive review of relevant literature, the Northern site of Bozcaada Island has been meticulously chosen as the optimal location for the offshore wind farm. Additionally, considering the necessary capacity allocation and technical permits obtained, the Ezine Substation has been identified as the optimal grid connection point for the offshore wind farm. To ensure a fair comparison with the offshore wind farm's distance to the grid connection point, a site between the villages of Derbentbaşı and Çamlıca in Ezine has been selected for the onshore wind farm by taking into consideration the wind atlas of the region. This selection aims to maintain a similar proximity to the grid connection point, allowing for equitable evaluation and comparison of both onshore and offshore wind farm projects. By choosing the Bozcaada Island's Northern site for the offshore wind farm and the Derbentbaşı - Çamlıca area for the onshore wind farm, this study ensures that both projects are located in optimal positions for efficient energy production and effective grid connection.

In order to conduct accurate energy yield assessments for both onshore and offshore wind farms, WindFarmer Analyst 1.5.0 software and ERA5 data has been used. WindFarmer Analyst software is a widely used and specialized tool in the field of wind energy analysis. It is a software application that enables detailed assessments and simulations of wind farm projects. Developed by DNV specifically for wind energy professionals. WindFarmer Analyst provides advanced features and functionalities to analyze the performance, feasibility, and economic viability of wind farms. On the

other hand, ERA5 is a widely recognized and reliable dataset, provides comprehensive meteorological information necessary for evaluating wind resources and estimating energy production. By utilizing ERA5 data, this study ensures a robust and consistent approach to the energy calculations for both wind farm projects. The utilization of ERA5 data enhances the accuracy and reliability of the energy assessments, enabling a comprehensive analysis of the wind farms' potential energy output. For onshore wind farm, a comprehensive selection of 7 distinct wind turbine models was utilized, representing 4 reputable manufacturers: Enercon, Vestas, Nordex, and GE. This diverse range of turbine models enabled a comprehensive evaluation of their performance and efficiency in maximizing energy production for the onshore wind farm site. In the case of the offshore wind farm, a Siemens Gamesa offshore wind turbine model with two different hub heights were utilized. WindFarmer Analyst software provides conceptual wind turbine models with varying unit power and hub heights. To calculate the annual energy production for the offshore site, three additional conceptual models were incorporated, resulting in a total of five turbines allowing for a comparative assessment of their performance and suitability for the offshore wind farm site.

This study also incorporates various sensitivity analysis to further enhance the understanding of the offshore wind farm project. Firstly, sensitivity of wind farms to variations in total installed capacity through different layouts using varying numbers of wind turbines were analysed. The initial study involved a layout with 28 wind turbines for the offhore wind farm. To conduct a sensitivity analysis, four additional layout scenarios were investigated, including configurations with 8, 12, 16, and 20 wind turbines. This allowed for a comprehensive assessment of the sensitivity of the wind farm's performance across different turbine layouts and installed power.

In addition, various scenarios were examined, considering different percentages of cost reductions and analyzing financial outcomes under different discount rates. By altering the discount rate, the study provided insights into the financial viability and robustness of the project in different economic scenarios.

Furthermore, this study explores the sensitivity of the offshore project with YEKDEM incentive and the revenues from green energy certificates. The analysis expands the understanding of how changes in market conditions and pricing mechanisms can affect the financial outcomes of offshore wind farms.

The simulations in this study indicate that onshore wind farms are a feasible and economically viable option in Türkiye, with several turbine models producing favorable results in terms of energy production and economic metrics. However, the same cannot be said for offshore wind farms, as the simulations show that the high costs associated with offshore installations outweigh the potential benefits of increased wind speeds and energy production. But sensitivity analyses reveal that with the possible future reductions in CapEx, and a new amplified YEKDAM tariff in parallel with the current market prices offshore wind farms investment would be feasible.

Overall, this study suggests that while onshore wind farms are a viable option for renewable energy production in Türkiye, offshore wind farms are not yet feasible due to the high costs associated with installation and maintenance. The findings of this thesis could provide valuable insights for policymakers, investors, and other stakeholders in the renewable energy sector in Türkiye, as well as contribute to the broader discussion on the feasibility of offshore wind farms in other regions with similar conditions.

TÜRKİYE’DEKİ KARASAL VE DENİZÜSTÜ RÜZGAR SANTRALLERİNİN TEKNO-EKONOMİK ANALİZİ

ÖZET

Küresel olarak sürekli artış gösteren enerji talebi doğrultusunda, fosil yakıt rezervlerinin sınırlı olması nedeniyle ülkeler enerji ihtiyaçlarını karşılayabilmek adına yenilenebilir enerji kaynaklarına yönelmiştir. Alternatif yenilenebilir enerji kaynaklarından birisi de rüzgar enerjisidir. Küresel anlamda rüzgar kurulu gücü son yıllarda hızla artmaktadır ve bu büyümenin çoğunluğunu karasal rüzgar enerji santralleri oluşturmaktadır. 2022 yılı sonu itibariyle, rüzgar enerjisinin küresel kurulu gücü 906 GW'a ulaşmıştır. Bu kurulu gücün yaklaşık %93'ünü karasal rüzgar enerji santralleri oluştururken sadece %7'si denizüstü rüzgar enerji santrali olarak karşımıza çıkmaktadır.

Ülkeler karbonsuz enerji üretim dönüşümlerini tamamlayabilmek adına rüzgar kapasitelerini artırabilme çabası içindedir. Özellikle Çin, yıllardır rüzgar enerji pazarının lideri olarak yatırımlarına devam etmektedir. 2022 yılında küresel anlamda 66.8 GW olarak açıklanan ilave karasal rüzgar kurulu gücünün %52’si Çin tarafından gerçekleştirilmiştir. Karasal rüzgar enerjisine benzer şekilde, denizüstü rüzgar enerji pazarının da lideri Çin’dir. Amerika Birleşik Devletleri ve Almanya kurulu rüzgar enerjisi kapasitesi açısından Çin’i takip eden diğer iki ülkedir.

Türkiye'de rüzgar enerjisi kurulu gücü de son yıllarda istikrarlı bir şekilde artmaktadır. İlk rüzgar enerji santrali 1998 yılında kurulmuş olup, Ocak 2023 itibarıyla Türkiye'deki toplam kurulu rüzgar enerjisi kapasitesi 11,9 GW'ın üzerine çıkmıştır. Verilen teşvikler ve stratejik kalkınma planları dahilinde yenilenebilir enerji yatırımlarının Türkiye’de artarak devam etmesi beklenmektedir. Üç tarafı denizlerle çevrili olmasına ve 69 GW denizüstü rüzgar enerji kapasitesi olmasına rağmen, Türkiye’de henüz bir denizüstü rüzgar enerji santrali kurulamamıştır. Bununla birlikte, ülkenin yenilenebilir enerji potansiyeli dikkate alınarak hazırlanan Türkiye Ulusal Enerji Planı kapsamında 2035 yılına kadar 5 GW denizüstü olmak üzere toplam 29.6 GW toplam rüzgar enerjisi kapasitesine ulaşma hedefi vardır. Türkiye elektrik üretim kapasitesinde yenilenebilir enerjinin payını artırmak için iddialı hedefler belirlemiştir.

Bu çalışma, Türkiye'deki kara ve deniz rüzgar santrallerinin kapsamlı bir tekno-ekonomik analizini sunmaktadır. Çalışma, enerji üretimini optimize etmek ve net bugünkü değer (NPV), seviyelendirilmiş elektrik maliyeti (LCoE) ve iç karlılık oranı (IRR) gibi temel ekonomik ölçütleri hesaplamak için farklı rüzgar türbini modelleriyle hazırlanmış simülasyonlardan yararlanmaktadır. Bir karasal ve bir denizüstü rüzgar santraline odaklanan araştırma, rüzgar enerjisi üretimi için en verimli ve uygun maliyetli seçenekleri belirlemek için farklı türbin modellerinin karşılaştırmalı değerlendirmesini sunmaktadır.

Kapsamlı bir literatür araştırmasının ardından, ülkemizde denizüstü rüzgar santrali için ideal konum olarak Bozcaada'nın kuzey bölgesi seçilmiştir. Ayrıca, gerekli kapasite tahsisi ve diğer tüm teknik izinlerin alındığı varsayımı ile, Ezine Trafo Merkezi,

denizüstü rüzgar santrali için en uygun şebeke bağlantı noktası olarak belirlenmiştir. Denizüstü rüzgar santralinin şebeke bağlantı noktasına olan uzaklığı ile muadil bir mesafede olacak şekilde, bölgenin rüzgar atlası da dikkate alınarak karasal rüzgar santrali için Ezine'nin Derbentbaşı ve Çamlıca köyleri arası uygun bulunmuştur. Bu seçim, hem karasal hem de denizüstü rüzgar santrali projelerinin sağlıklı bir şekilde değerlendirilmesine ve karşılaştırılmasına izin vererek, şebeke bağlantı noktasına benzer bir yakınlığı korumayı amaçlamaktadır. Aday bölge olarak denizüstü rüzgar santrali için Bozcaada'nın Kuzey bölgesini ve karasal rüzgar santrali için Derbentbaşı-Çamlıca bölgesininin ele alındığı bu çalışma, her iki projenin de verimli enerji üretimi ve etkin şebeke bağlantısı için en uygun şekilde konumlandırılmasını sağlamaktadır.

Hem karasal hem de denizüstü rüzgar santrallerine ait enerji üretim analiz ve değerlendirmeleri yapabilmek adına WindFarmer Analyst 1.5.0 programı ve ERA5 verileri kullanılmıştır. WindFarmer Analyst, rüzgar projelerinin detaylı değerlendirmelerini ve simülasyonlarını sağlayan bir yazılım uygulamasıdır. DNV tarafından özellikle rüzgar enerjisi profesyonelleri için geliştirilmiştir. WindFarmer Analyst, rüzgar çiftliklerinin performansını, fizibilitesini ve ekonomik uygulanabilirliğini analiz etmek için gelişmiş özellikler ve işlevler sağlar. Bu çalışmada WindFarmer Analyst programının optimizasyon özelliği kullanılarak her iki saha için de simetrik saha yerleşimi esas alınmıştır. ERA5 veri seti ise, rüzgar kaynaklarının değerlendirilmesi ve enerji üretiminin tahmin edilmesi için gerekli olan kapsamlı meteorolojik bilgileri sağlayan, rüzgar enerjisi alanında yaygın olarak kullanılan güvenilir bir veri setidir. ERA5 seti 100m yükseklik için rüzgar hız verilerine sahiptir. Modellemede kullanılan farklı göbek yüksekliklerine sahip farklı türbin modelleri için rüzgar hızı ekstrapolasyon ile elde edilmiştir. Kullanılan program ve veri seti, her iki rüzgar santrali projesi için enerji hesaplamalarına yüksek kalite ile birlikte tutarlı bir yaklaşım sağlamıştır. ERA5 verilerinin kullanılması, enerji değerlendirmelerinin doğruluğunu ve güvenilirliğini artırarak rüzgar santrallerinin potansiyel enerji çıktılarının kapsamlı bir analizini mümkün kılmıştır. Karasal rüzgar santralleri için, 4 saygın türbin üreticisine (Enercon, Vestas, Nordex ve GE) ait 7 farklı rüzgar türbini kullanılmıştır. Denizüstü rüzgar santrali analizlerinde ise, Siemens Gamesa'nın iki farklı göbek yüksekliğine sahip rüzgar türbini modeli kullanılmıştır. Bununla birlikte WindFarmer Analyst programının sunduğu farklı güç ve göbek yüksekliklerine sahip üç konsept türbin modeli de dahil olacak şekilde toplamda beş türbin yerleşim çalışması yapılmıştır.

Elde edilen üretim sonuçları doğrultusunda her iki saha için de en verimli senaryo sonuçları kullanılarak, finansal parametreler hesaplanmıştır. Ekonomik yönden değerlendirme kriterleri olarak Net Bugünkü Değer (NPV), İç Karlılık Oranı (IRR) ve Seviyelendirilmiş Enerji Maliyeti (LCoE) parametreleri dikkate alınmıştır. Net Bugünkü Değer, yatırımın ekonomik ömrü boyunca sağlayacağı getirinin bugünkü değerinden yatırım giderlerinin bugünkü değerinin düşülmesi ile elde edilen farkı ifade eder. Net Bugünkü Değer parametresinin negatif çıkması projenin yatırıma uygun olmadığını ortaya koymaktadır. İç Karlılık Oranı ise net bugünkü değeri sıfırlayan kazanç oranıdır. Projenin yatırıma elverişli olabilmesi için iç karlılık oranının öngörülen iskonto oranından yüksek olması gerekmektedir. Seviyelendirilmiş Enerji Maliyeti ise planlanan santralin üreteceği enerjinin birim maliyetidir.

Bu çalışma kapsamında, offshore rüzgar santrali projesi için yapılan hassasiyet analizleri de yapışmıştır. Analizler, projenin farklı bileşenlerinin ve değişkenlerin projenin uygulanabilirliği üzerindeki etkilerini değerlendirmeyi amaçlamaktadır.

İlk olarak rüzgar türbini yerleşimi hassasiyeti incelenmiştir. Başlangıçta 28 rüzgar türbini içeren bir yerleşim modeline ilave olarak, 8, 12, 16 ve 20 rüzgar türbinini içeren dört farklı senaryo üzerinde çalışılmıştır. Bu analizler, farklı türbin yerleşimlerinin ve kurulu güçlerin, projenin performansına ve finansal sonuçlarına olan etkisini ortaya koymayı amaçlamaktadır.

Bunlara ek olarak yatırım maliyetinde olası düşüş senaryoları da incelenmiştir. Ayrıca, farklı iskonto oranları altında projenin finansal uygunluğu ve kârlılığı değerlendirilmiştir. Bu analizler, projenin maliyet yapısının ve iskonto oranının kârlılık üzerindeki etkisini anlamak için değerli fikirler sunmaktadır.

Son olarak, YEKDEM destek mekanizması ve yeşil enerji sertifikalarının hassasiyet analizi yapılmıştır. Bu analizler ile, farklı elektrik satış fiyatı senaryolarının ve yeşil enerji sertifikalarından gelecek gelirlerin projenin finansal çıktıları üzerindeki etkisi incelenmiştir. Hassasiyet analizleri, projenin farklı değişkenler ve senaryolar altındaki potansiyelini anlamak için önemli bir araçtır. Bu analizler, projenin finansal performansını daha kapsamlı bir şekilde değerlendirmek için yapılmıştır.

İncelenen senaryolar ve geliştirilen analizler, enerji üretimi ve ekonomik ölçümler açısından karasal rüzgar santrallerinin Türkiye'de ekonomik olarak uygun ve uygulanabilir seçenek olduğunu göstermektedir. Bununla birlikte, simülasyonlar, denizüstü rüzgar santrali kurulumlarıyla ilişkili yüksek maliyetlerin, deniz üstünde artan rüzgar hızlarının ve enerji üretiminin potansiyel faydalarından daha ağır bastığını gösterdiğinden, ekonomik olarak denizüstü rüzgar santrallerinin mevcut şartlar kapsamında uygun ve uygulanabilir seçenek olmadığını ortaya koymaktadır. Ancak gelişen altyapı ve teknoloji gelişmeleri neticesinde yatırım maliyetlerindeki olası düşüşlerin ve piyasa şartları ile paralellik gösteren yenilenmiş bir YEKDEM tarifesi sayesinde deniz üstü rüzgar santrali yatırımları uygulanabilir bir seçenek olabilecektir.

Bu çalışmanın bulguları, Türkiye'deki yenilenebilir enerji sektöründeki politika yapıcılar, yatırımcılar ve diğer paydaşlar için değerli bilgiler sağlamanın yanı sıra, benzer koşullara sahip diğer bölgelerde açık denizüstü rüzgar santrallerinin fizibilitesine ilişkin ileri seviye çalışmalara katkıda bulunabilir.

1. INTRODUCTION

Offshore wind possesses remarkable potential as a scalable, cost-effective, and readily available energy technology capable of generating enormous power. This clean energy source holds the promise of displacing fossil fuels swiftly, contributing to economic growth, and enhancing energy security. Additionally, offshore wind presents opportunities for scaling up the production of green hydrogen and P2X (Power-to-X) technologies, which play a crucial role in decarbonizing energy-intensive sectors.

The global offshore wind industry had its best year ever in 2021 with record breaking 21 GW of additional capacity. It should also be noted that new offshore installations in 2020 was only 6.1 GW. As the end of 2021, cumulative offshore wind capacity has reached to 56 GW across the world, bringing offshore's share of new wind installations to 7% [1-2].

The International Energy Agency (IEA) is urging for a significant expansion of offshore wind energy, aiming to increase its proportion within the overall wind power sector. In 2020, offshore wind accounted for just 7% of total wind deployment. However, the IEA's roadmap sets a target for offshore wind to surpass 20% of total wind deployment starting from 2021 onwards. To achieve this goal, annual installations of offshore wind power must increase by a substantial factor of 13. This means scaling up from the 6.1 GW of offshore wind capacity installed in 2020 to a remarkable 80 GW by the year 2030 [3].

Türkiye has taken swift action in advancing its efforts towards offshore wind energy. In 2018, a tender known as YEKA was initiated with the intention of allocating 1,200 MW of offshore wind capacity across three potential zones: Gelibolu, Saroz, and Kıyıköy. The ceiling price set for the auction was stated as 80 USD/MWh, and the auction methodology was underbidding. However, due to the absence of participants, the auction had to be canceled. The primary reason for companies refraining from participating in the auction was the lack of comprehensive technical studies and inadequate infrastructure in place.

To further promote the development of offshore wind energy, the Turkish Offshore Wind Energy Association (DÜRED) was established on March 5, 2021. According to DÜRED, Türkiye possesses an immense offshore wind energy potential of 75 GW [4].

On the other hand, a study provided under a World Bank Group (WBG) initiative on offshore wind that is funded and led by the Energy Sector Management Assistance Program (ESMAP), the combined technical potential for offshore wind energy is estimated to be 69 GW [5] . Aligning with the national energy plans, it becomes evident that Türkiye must initiate investments in its offshore wind energy capacity. This strategic move will not only facilitate the adoption of cutting-edge energy transformation technologies but also create opportunities for advancements like green hydrogen and Power-to-X. By embarking on offshore capacity investments, Türkiye can unlock the potential for integrating the latest energy solutions, thus driving progress towards a sustainable and technologically advanced future.

This study examines the techno-economic analysis of offshore wind energy in Türkiye. It evaluates the feasibility of an offshore wind farm in comparison to an onshore counterpart within the current market conditions in Türkiye. The study begins with a literature survey, followed by an overview of the global and Turkish wind energy landscape, supported by relevant data. The methodology employed in the study is then explained, leading to a comprehensive technical and economic assessment. Subsequently, a detailed sensitivity analysis is conducted to explore various scenarios. Finally, results and conclusions derived from the study is presented.

2. LITERATURE REVIEW

2.1 Offshore Wind Studies

By the end of 2021, the cumulative global offshore wind energy capacity had reached an impressive 56 GW. Over the past decade, it is evident that the average annual growth rate of the market has been approximately 22%. This sustained growth trajectory highlights the increasing significance and potential of wind energy, encompassing both offshore and onshore installations. Projections indicate that by 2050, wind energy, in combination with offshore and onshore sources, could contribute as much as 25-30% towards global electricity consumption, underlining its crucial role in the transition to a sustainable energy future [1,6-7].

The prevalence of offshore wind farms is steadily growing, and the potential energy production from offshore wind surpasses that of onshore counterparts. However, there are numerous challenges impeding the development and implementation of offshore wind farms. Among these obstacles, economic conditions emerge as the most crucial factor determining the feasibility of offshore power plants within the current market.

A recurring theme across various research articles is that the costs associated with offshore power plants exhibit considerable variation based on factors such as location, water depth, and proximity to the shore. Furthermore, support mechanisms and state policies also play pivotal roles as economic factors influencing the viability of offshore wind energy projects. Numerous countries worldwide are actively formulating policies and strategies to advance their offshore wind energy sector. For instance, the United Kingdom (UK) has set ambitious goals to reduce offshore wind costs by £100 per MW, aligning with its 2020 targets. Notably, in 2017, UK offshore projects made significant progress, achieving a levelized cost of energy (LCoE) below 100£/MWh. Building upon their success, the UK conducted offshore tenders in 2019, similar to Türkiye's YEKA tenders, which had remarkable outcomes. The awarded tenders resulted in an impressive 5.5 gigawatts of offshore wind capacity, surpassing the initial targets. Furthermore, the prices reached a record low of £39.65 (~$49) per MWh, underscoring the substantial cost reductions achieved within the sector. China, positioning as the global leader in cumulative offshore wind deployment, has witnessed a remarkable decline in average total installation costs over the period of 2010 to 2020. The costs decreased by 32%, from 4.476 $/kW to 2.968 $/kW. Denmark, on the other hand, took measures to reduce transmission line costs during its offshore wind tenders in 2017 by incorporating nearshore areas into the bidding process. As a result, Denmark achieved an average total installation cost of 2.963 $/kW in 2020, indicative of their effective cost optimization strategies. The Netherlands, which ranked as the second-largest driver of offshore wind capacity growth in 2020 (1.5 GW), had the most competitive weighted average total installation cost compared to other markets.With only 2.745 $/kW, the Netherlands demonstrated their ability to achieve cost efficiency in offshore wind projects. An evaluation concentrating on the Levelized Cost of Electricity (LCoE) for offshore wind energy across European Atlantic countries reveals notable variations. The assessment indicates that the most favorable areas, including the UK, Ireland, Netherlands, Germany, and Denmark, have the lowest cost of electricity, approximately 95€/MWh. Conversely, areas characterized by limited wind resources, such as the Gulf of Biscay and the southern region of the Iberian Peninsula, experience the highest LCoE, exceeding 160€/MWh. The scarcity of wind resources in these regions presents challenges for offshore wind projects, leading to increased costs for electricity generation. Portugal is also an example of higher LCoE values for offshore wind energy with 125 €/MWh. In the United States, LCoE for offshore wind farms was recorded at 123.4 $/MWh in 2018. This value indicates that the LCoE in the USA is considerably higher compared to its European counterparts. In Brazil’s case, it is notable that the Northeast region boasts the highest wind potential in the country. The LCoE in this region is approximately 69.9 $/MWh, showcasing its favorable conditions for offshore wind energy. In contrast, the Southeast region of Brazil has an LCoE of around 95 $/MWh, indicating a slightly higher cost compared to the Northeast region. From a global perspective, the weighted-average total installation costs have witnessed a significant decline. From 2010 to 2020, there was a 32% decrease in the global average total installation costs, with the cost per kilowatt (kW) falling from 4.706 $/kW to 3.185 $/kW. This highlights the positive trend of decreasing costs in the offshore wind industry on a global scale. Studies show that, costs reductions may reach 50% between 2020 and 2026. Should the ongoing trend of cost reduction persist beyond 2026, offshore wind has the potential to achieve cost competitiveness by 2030.

Based on auction and tender results, it is indicated that starting from 2023, the cost of electricity is projected to decrease to a range between 0.05$/kWh and 0.10$/kWh. These levels of cost reduction are attainable even in relatively new markets such as Türkiye [8-15]. Figure 2.1 provides an overview of the total installed costs, capacity factors, and LCoE of offshore wind energy on a yearly basis.

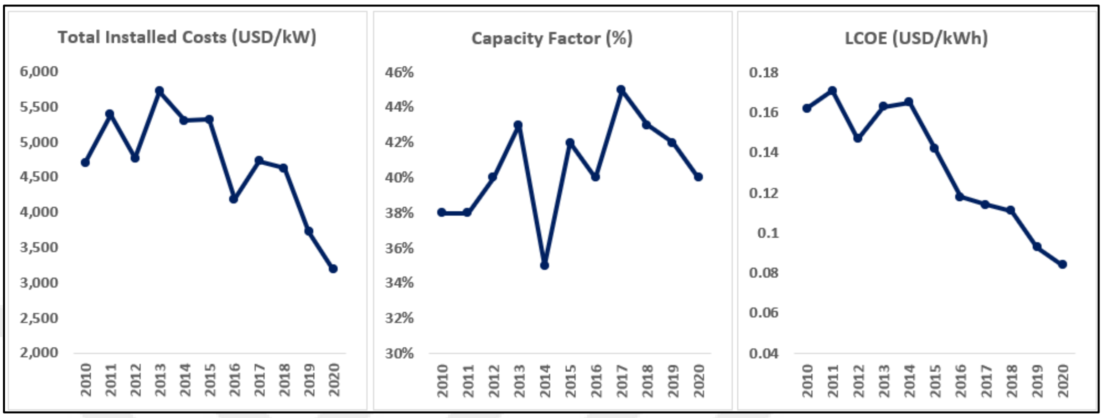


Figure 2.1 : Global weighted average total installed costs, capacity factors and LCoE, 2010-2020 [16].

The support mechanism plays a crucial role in influencing offshore investments. When comparing Feed-in Tariffs (FiT) and Feed-in Premium, it is emphasized that the Feed-in Premium is the most suitable support mechanism for offshore wind investments. This preference stems from the recognition that offshore wind power plants are highly sensitive to the unique conditions specific to each site [8].

Despite the greater energy production potential of offshore wind farms, they tend to exhibit lower internal rates of return (IRR) and higher levelized cost of energy (LCoE) compared to their onshore counterparts. In 2018, the LCoE for offshore wind farms averaged 92$/MWh, whereas onshore wind farms ranged from 29-56$/MWh. However, it is worth noting that there has been a significant decline in the global weighted-average LCoE for offshore wind over the years. Between 2010 and 2020, the LCOE dropped by 48%, from 0.162 to 0.084 USD/kWh. Furthermore, there was a 9% year-on-year decrease in the levelized cost of electricity (LCoE) in 2020. It is important to recognize that the LCoE value alone should not be the sole determinant when conducting economic analyses of offshore wind farms. LCoE primarily comprises the capital expenditures (CapEx) and operational expenditures (OpEx) of projects, while excluding other significant factors such as residual costs, decommissioning expenses, support mechanisms, and balancing costs. Additionally, the choice of discount rates used in LCoE calculations may vary among countries. To illustrate, different countries propose distinct discount rates. For instance, the British government suggests a discount rate of 10%, whereas Denmark recommends a discount rate of 4%. And general assumption of using an 8% discount rate for LCoE calculations may not be suitable or applicable for all countries. It is important to acknowledge that different regions may have significant variations in their economic viability, influenced by factors such as regional incentives and contract frameworks. The public's perception, as well as willingness and ability of people to pay a premium for electricity generated from low CO_2 sources, significantly influences long-term wholesale electricity prices. It is important to note that public opinion and perception can undergo sudden and significant changes over time. However, it is worth mentioning that while public perception is an essential consideration in the energy landscape, it is typically not used into LCoE calculations [11-12,17-18].

The supply chain of wind turbine manufacturers has a notable impact on the economic viability of offshore wind farms. While China has played a significant role in the offshore wind market, it is currently facing challenges in terms of infrastructure and logistics, which puts it behind Europe in this regard [7]. In the case of Türkiye, it would be beneficial to consider European examples as a benchmark to guide the development of its offshore wind industry.

Design of offshore platforms may face undergo changes in the future. Currently there are two main structures: fixed and floating platforms. The majority (74%) of offshore wind platforms are of the fixed type, specifically the monopile design. Monopile constructions are suitable for water depths of up to 140 meters. However, for greater depths, alternative techniques and designs, such as floating platforms, become necessary. Such design shifts and possible future changes will have a significant impact on turbine prices. Potential cost-saving advantages and efficiency improvements can be realized by embracing larger capacities in both turbines and overall plant design. It is important to highlight that the CapEx associated with offshore wind turbines are projected to decrease by approximately 10-40% by 2030 and potentially up to 20-50% by 2050. Moreover, LCoE for offshore wind turbines is anticipated to decrease by around 20% by 2030 and potentially up to 35% by 2050 [19-23].

Regarding the progress of offshore wind energy projects in Türkiye, the Ministry of Energy had planned an offshore wind tender in October 2018 with a capacity of 1.2 GW. The ceiling price for the tender was set at 80$/MW, and the candidate zones included Edirne, Kırklareli, and Tekirdağ. However, due to the absence of sufficient technical data, no investors participated in the tender. According to the findings of the literature survey, Bozcaada stands out as the area with the highest potential based on techno-economic analysis, attracting attention for future offshore wind development in Türkiye [24-27].

The lack of economic analysis studies on offshore and onshore wind farms in Türkiye presents numerous opportunities for further research in this area. Conducting a comprehensive study with data obtained from turbine manufacturers operating in the Turkish wind market can provide valuable insights and a detailed understanding of the economic aspects of wind energy projects in the country.

3. METHODOLOGY

3.1 Methodology Review

In the studies of the reviewed literature, it is revealed that LCoE is chosen as the economic cost evaluation method as most. But as also mentioned before, It is crucial to exercise caution when utilizing LCoE results to compare projects, particularly when comparing projects situated in different countries. Although the LCoE units are consistent, there is no universally defined standard for the inclusion of costs in the calculation of this metric. It was stated in the literature survey that different countries use different discount rates. In the paper authored by Jacobsen, Hecia-Koch and Wolter [12], it is stated that British Government suggests a discount rate of 10% for economic analysis while the Denmark suggests 4%. In the paper of Gernaat et al. [21], discount rate was taken as 10% into account regarding the global perspective.

The work of D.G. Caglayan et al. [17], simulation was made and production analysis was performed using online Merra2 data along with the different locations and turbine characteristics. These simulations were modeled in NREL's TCC&BOS model and the investment costs were revealed. Ocean eligibility was demonstrated using the design with the lowest LCoE value. National Renewable Energy Laboratory (NREL) releases cost breakdowns of wind turbines in US as three groups: turbine capital cost (TCC), balance of system cost (BOS) and financial cost (FIN). NREL’s models are stated as most up-to-date models for cost estimations.

In the publication of U. Cali et al. [24], technical analysis were performed by using Virtual Wind Farm model and annual energy production estimations were revealed for different locations in Türkiye. According to the technical analysis outputs, a comprehensive economic feasibility analysis is performed utilizing a discounted cash flow economic model including the support schemes and different discount rates. NPV, LCoE, DPBP and IRR parameters were used for comparition of different locations.

Similar to publication of U.Cali et al., in the paper of M.Satir et al. [25], economic cost evalueation tools for feasibility study were LCoE and NPV. For the technical analysis, windPro software was used in their studies.

It is seen that another method used for the economic analysis was the life cycle cost (LCC) analysis method. In the paper of Mytilinou and Kolios [8], The LCC analysis was mentioned to be capable of assessing costs and recommending cost reductions over the entire lifespan of a project. In the paper of L.Castro-Santos et al. [19], LCC analysis was used as the method to calculate the installation costs of offshore wind farms in deep waters. But it can be seen that, calculation of the LCC for a wind farm, particularly an offshore wind project, can present significant challenges. It encompasses multiple cost stages spanning from pre-development to decommissioning, and there is no universally recognized resignation applicable to all wind projects. LCC analysis might be more useful in making an investment decision regarding the construction of an offshore power plant rather than comparing the offshore wind farm with an onshore counterpart.

As a result of this analysis, it is concluded that it would be more appropriate to use the LCoE, NPV and IRR parameters as the economic comparison tools. A model will be created by obtaining information through market and literature research for capital expenditure, operational expenditures and related costs. Other methods such as NREL’s TCC&BOP model could be included in the study as the needs and wants of this project become more apparent. The study begins with data collection, including market and literature research to gather information on capital expenditure (CAPEX), operating expenditure (OPEX), and other related costs. Additionally, long-term ERA5 data spanning approximately 26 years will be obtained using the WindFarmer Analyst software. Next, a technical analysis will be conducted to obtain annual energy production calculated by simulating various wind turbine configurations. The outputs from the technical assessment will be utilized to calculate economic metrics. To explore the sensitivity of the results to different parameters, sensitivity analyses will be performed. Various parameters will be systematically altered to assess their impact on the overall findings. Finally, the results obtained from the technical and economic analyses, along with the sensitivity analyses, will be compiled and presented. The methodology and study framework are illustrated in Figure 3.1.

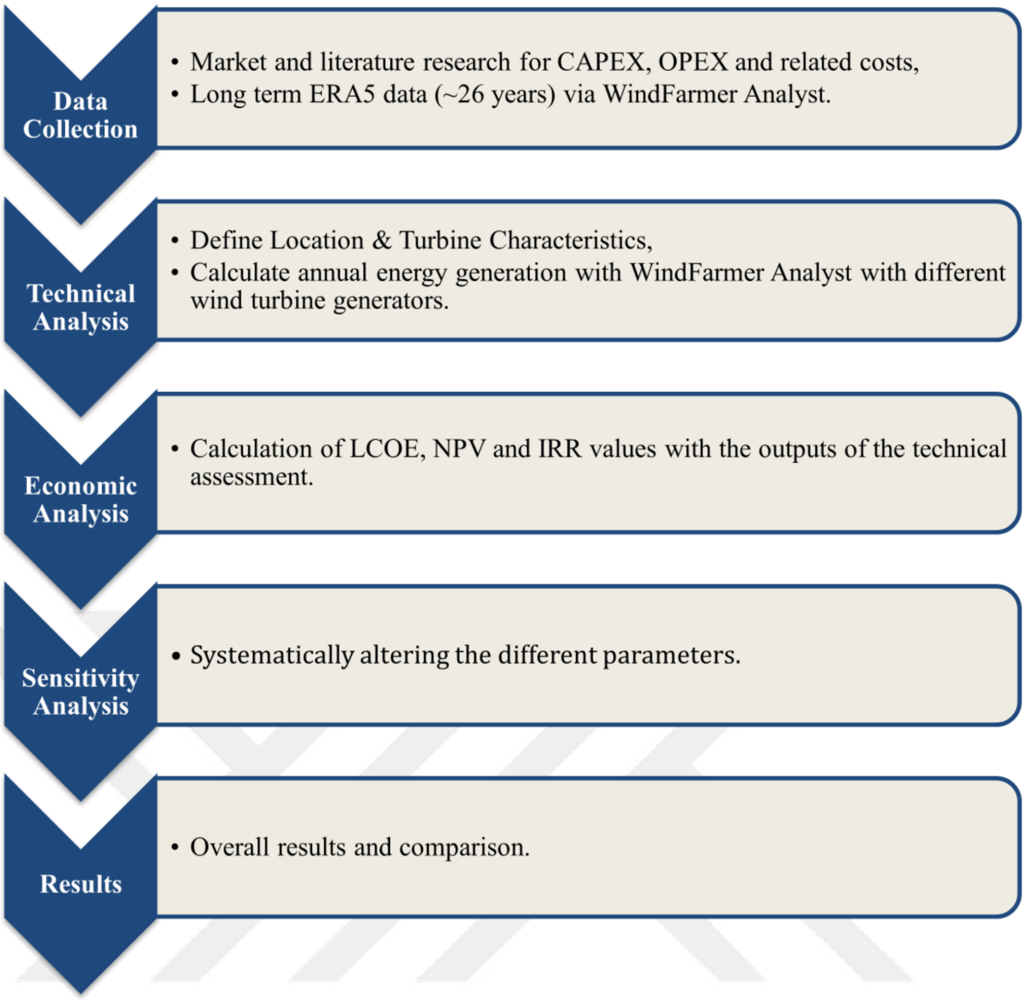


Figure 3.1 : Representation of the methodology and study framework.

4. WIND ENERGY MARKET OVERVIEW

4.1 Global Wind Energy Overview

As of 2022, the global wind energy capacity reached a significant milestone of 906 GW, with 842 GW onshore and 64 GW offshore, reflecting the remarkable growth and adoption of wind power around the world. Annual cumulative installations are shown in Figure 4.1. During 2022, an impressive 77.6 GW of new wind power capacity was added (68.8 GW onshore, 8.8 GW offshore), further bolstering the renewable energy sector. This substantial increase in wind power installations highlights the ongoing commitment of countries and industries to transition towards cleaner and more sustainable energy sources. The continued expansion of wind energy capacity demonstrates the positive momentum and potential for a greener and more carbon-neutral future [2].

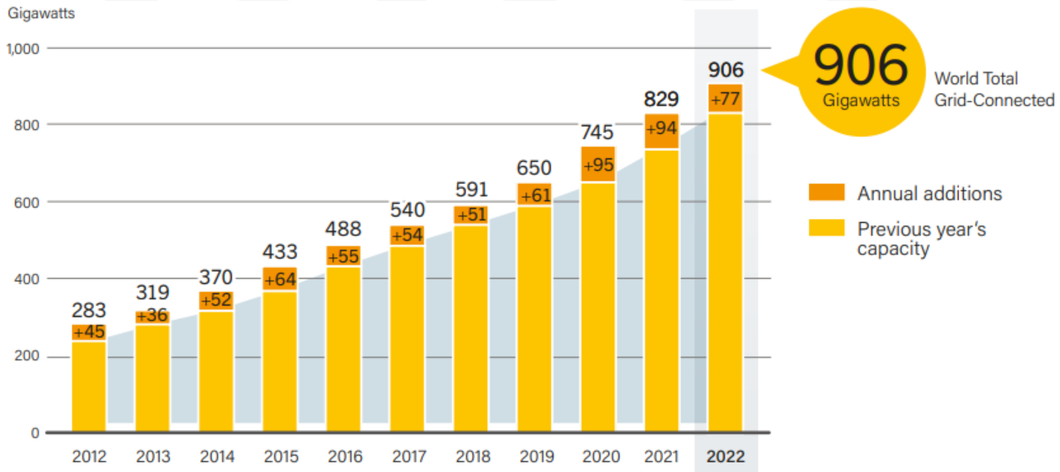


Figure 4.1 : Wind power global capacity and annual additions, 2012-2022 [28].

China is the global leader in wind energy capacity and installations. China has been heavily investing in renewable energy, including wind power, to address its growing energy demands and reduce reliance on fossil fuels. The country's commitment to wind energy is evident in its significant installed capacity and ambitious targets for further expansion. In 2022, China, the United States, Brazil, Germany, and Sweden emerged as the top five markets for new wind power installations. In 2022, the top five countries for new wind power installations—China, the United States, Brazil, Germany, and

Sweden—played a crucial role, collectively representing a remarkable 72% of the global installations. Among them, China emerged as the frontrunner, contributing significantly to this global achievement with an impressive 49% share of the new wind power installations, as shown in Figure 4.2.

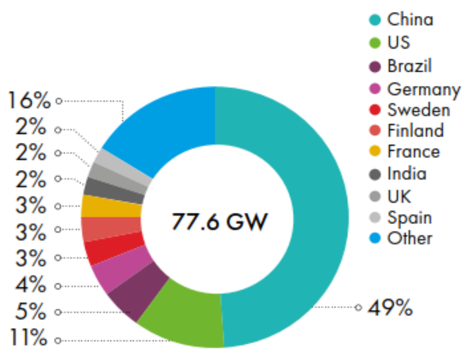


Figure 4.2 : New wind power capacity by countries in 2022 [2].

Projections indicate that the cumulative installed capacity for onshore wind energy is anticipated to reach 5,044 GW globally, while offshore wind energy is expected to reach 1,000 GW. These figures demonstrate the significant growth and potential of both onshore and offshore wind power as key contributors to the global renewable energy landscape. The projections highlight the continued expansion and deployment of wind energy technologies to meet the increasing global demand for clean and sustainable electricity generation [29].

Between 2010 and 2020, the global weighted average total installed costs for offshore wind experienced a significant decline of 32%, dropping from 4,706 USD /kW to 3,185 USD /kW. Notably, the peak for the global weighted average total installed cost occurred in 2011 at 5,390 USD/kW, representing a substantial 41% higher value compared to its 2020 level. In the case of onshore wind, the global weighted average total installed cost witnessed a decline of 31%, reducing from 1,971 USD /kW in 2010 to 1,355 USD/kW in 2020. In 2020, it was down by 9% compared to the 2019 value of 1,491 USD/kW. The average turbine prices ranged between 700 USD/kW and 910 USD/kW in 2020. Except for China, prices in most regions decreased by approximately 49% to 59% from their peaks in 2008 and 2009. Chinese wind turbine prices experienced a significant drop of 78% since their peak in 1998, declining from 2,520 USD/kW to 540 USD/kW.

The offshore wind sector has witnessed notable technological advancements, such as the utilization of larger turbines, longer blades, and higher hub heights, along with the expansion of wind farms farther from the shore to access better wind resources. These developments have contributed to an increase in the global weighted-average capacity factor for offshore wind. From 2010 to 2017, the capacity factor rose from 38% to 45%. However, it experienced a slight decline to 40% in 2020, primarily due to China's growing share in the global deployment of offshore wind projects. In the case of onshore wind, technological improvements have also played a significant role. The global weighted-average capacity factor for onshore wind has shown a notable improvement of almost one-third, increasing from 27% in 2010 to 36% in 2020 [11].

These trends highlight the ongoing affordability of wind energy technologies, making them more competitive in the global energy market. Figure 4.3 presents a comparison of the global weighted averages of total installation costs, capacity factors, and LCoE values for onshore and offshore wind farms between 2010 and 2020.

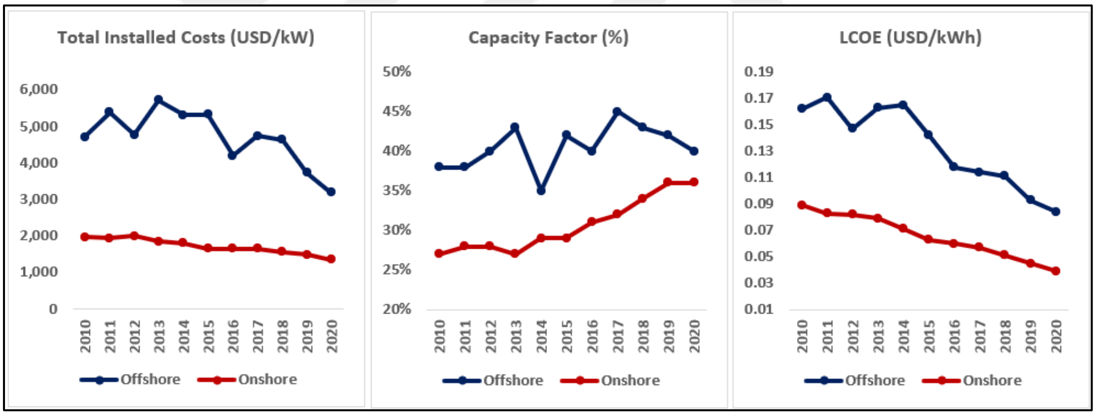


Figure 4.3 : Global weighted average total installed costs, capacity factors and LCoE for offshore and onshore wind farms, 2010-2020 [16].

4.2 Turkish Wind Energy Overview

4.2.1 Cumulative installations

Türkiye's journey in wind power generation began in 1998 with a wind power plant in Izmir, having an initial installed capacity of 1.5 MW [30]. However, the momentum of wind power development has significantly increased in recent years, driven by the incentives for renewable energy power plants. As of January 2023, cumulative installed wind energy capacity has reached 11.9 GW, as shown in Figure 4.4. It should also be noted that nearly 921 MW of wind power plants are under construction.

According to the TEİAŞ's December-Installed Capacity Report, Türkiye's overall installed capacity has reached 103.8 GW and wind energy corresponds to 11.4% of the total installed power [32].

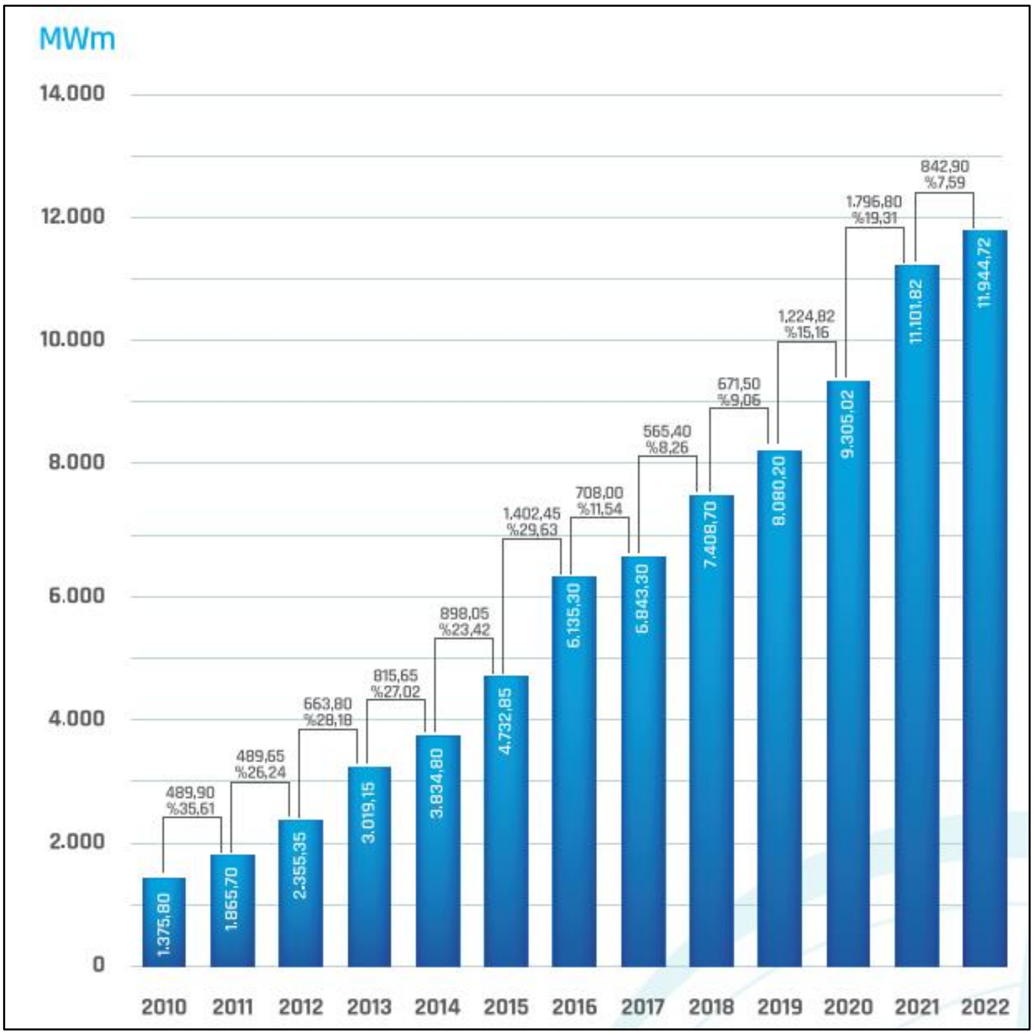


Figure 4.4 : Wind energy cumulative installations in Türkiye [31].

4.2.2 Wind energy potential

Türkiye has a significant potential for onshore wind energy. According to various estimates and studies, the total onshore wind energy potential in Türkiye is believed to be substantial. The exact figure may vary depending on different sources and methodologies used for assessment. According to the Ministry of Energy, Türkiye has a technical potential of around 48,000 MW for onshore wind energy [33]. Onshore wind atlas for Türkiye, depicting wind speeds at a height of 100 meters, can be observed in Figure 4.5.

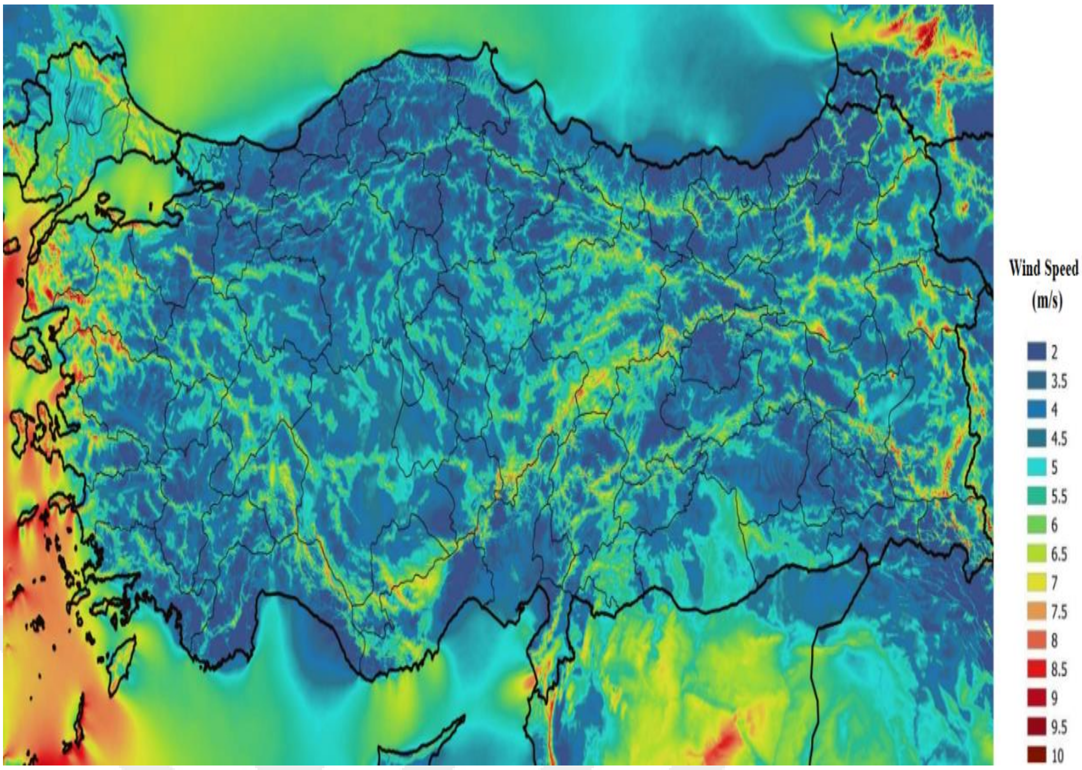


Figure 4.5 : Onshore wind atlas for Türkiye [34].

In addition to wind resource assessment, the seabed topography, including bathymetric features, is also a crucial factor in determining suitable locations for offshore wind potential. Understanding the underwater terrain, water depths, and geological characteristics of the seabed helps identify areas that are conducive to offshore wind development. The higher wind speeds experienced at sea compared to land offer the advantage of generating more energy from offshore wind farms. According to DÜRED, Türkiye possesses an immense offshore wind energy potential of 75 GW. On the other hand, a study provided under a World Bank Group (WBG) initiative on offshore wind that is funded and led by the Energy Sector Management Assistance Program (ESMAP), the combined technical potential for offshore wind energy is estimated to be 69 GW, considering both fixed bottom turbines in areas with water depths less than 50 meters, amounting to 12 GW, and the utilization of floating turbine concepts in areas with water depths up to 1,000 meters, adding a further 57 GW. According to the study, the most favorable regions for offshore wind development are located in the northwest part of the Aegean Sea, as shown in Figure 4.6. The specific figures regarding Türkiye's offshore wind potential may vary depending on the sources and methodologies used in the assessments. However studies consistently highlight the country as having substantial capacity for offshore wind projects.

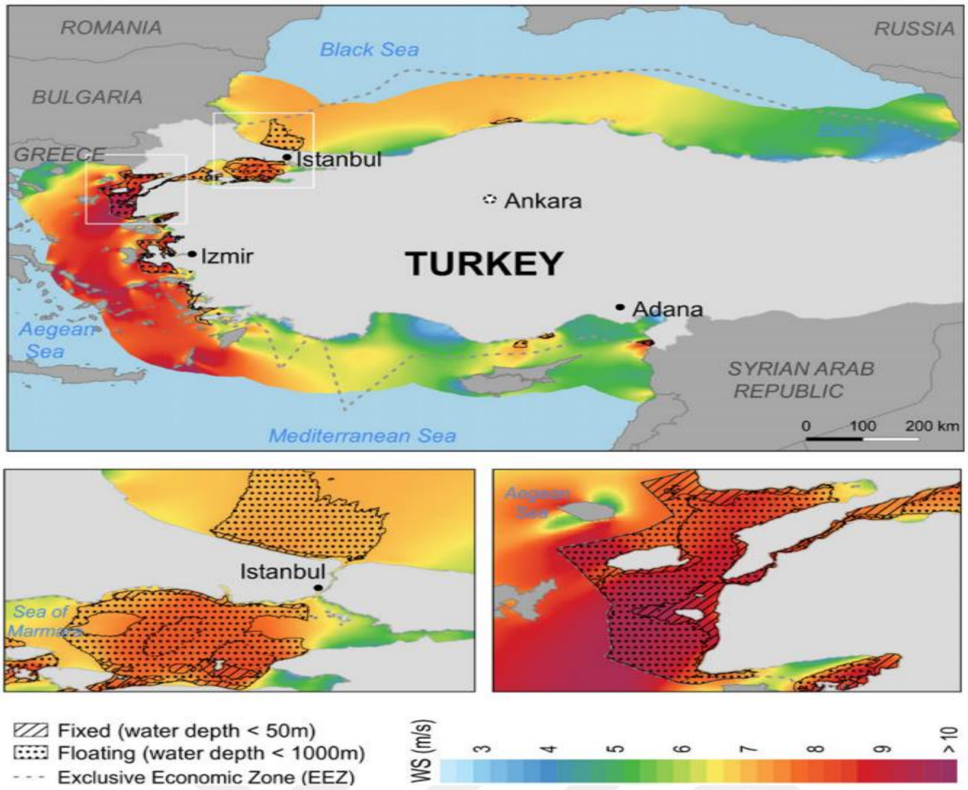


Figure 4.6 : Offshore wind atlas for Türkiye [5].

4.2.3 YEKA tenders

YEKA, which stands for "Yenilenebilir Enerji Kaynak Alanları" in Turkish, refers to Renewable Energy Resource Zones in Turkiye. YEKA tenders are a part of the Turkish government's efforts to promote renewable energy development in the country. These tenders involve the allocation of specific areas or zones for renewable energy projects, including wind and solar power. Under the YEKA tenders, the government offers long-term contracts to investors for the development, construction, and operation of renewable energy projects in designated areas.

First onshore wind YEKA tender took place on August 3, 2017. A consortium comprising Siemens, Türkerler and Kalyon Enerji Holdings emerged as the winning bidder, offering the lowest power purchasing price to the Government. Their winning bid stood at 3.48 USDcents/kWh, demonstrating their competitive pricing in the tender process. This landmark tender marked a significant milestone in Turkiye's wind energy sector.

In May 2019, the Ministry of Energy and Natural Resources concluded second tender for 1 GW of wind energy projects. The capacity was divided into four different connection regions: Balıkesir, Çanakkale, Aydın, and Muğla, each with a capacity of

250 MW. Through competitive bidding, Enercon secured projects in Muğla with a bid of 4.00 USDcents/kWh and in Balıkesir with a bid of 3.53 USDcents/kWh. Enerjisa successfully offered USD 4.56 USDcents/kWh for the Aydın region and 3.67 USDcents/kWh for the Çanakkale region. As a result, these companies were awarded 15-year power purchase contracts.

The Ministry of Energy concluded the third YEKA tender by awarding 850 MW of wind capacity to a total of 9 companies and 20 projects. Among the winning bids, Eksim Enerji AS emerged as both the lowest and highest bidder. For a 70 MW wind project located in the provinces of Karaman and Mersin, Eksim Enerji offered the lowest bid at 0.408 TRY/kWh. Conversely, they made the highest bid of TRY 0.778 TRY/kWh for a 30 MW project in the provinces of Siirt, Şırnak, and Hakkari. Overall, Eksim Enerji secured success with six projects, collectively totaling 260 MW in capacity [35-37].

Following the first YEKA tender in 2017, 1200 MW offshore wind tender was announced in June 2018. The tender, which had to be completed by October 23, was postponed due to the lack of demand. It has been planned to be realized by dutch auction method, starting from the ceiling price of 80 USD/MWh. In addition, a minimum 60% domestic manufacturing contribution share has been determined in the offshore YEKA and 80% of the people who will work on the project must be Turkish nationals. Gelibolu, Saros and Kıyıköy in the sea of Marmara have been determined as candidate regions for the offshore developments [38]. Candidate zones are shown in Figure 4.7. The lack of demand for the offshore YEKA tender in 2018 can be attributed to several potential factors, including market conditions/uncertainty, regulatory framework, and technical challenges. The market conditions or uncertainty at the time might have made the offshore wind market less attractive to potential participants, leading to a lack of interest in the tender. Additionally, the regulatory framework established for the tender may not have aligned with the expectations or requirements of potential participants, discouraging their participation. Furthermore, the technical challenges or poor infrastructure associated with offshore wind projects, such as installation and maintenance in marine environments, could have presented significant obstacles and deterred potential participants. These factors collectively contributed to the lack of demand for the offshore YEKA tender in 2018.

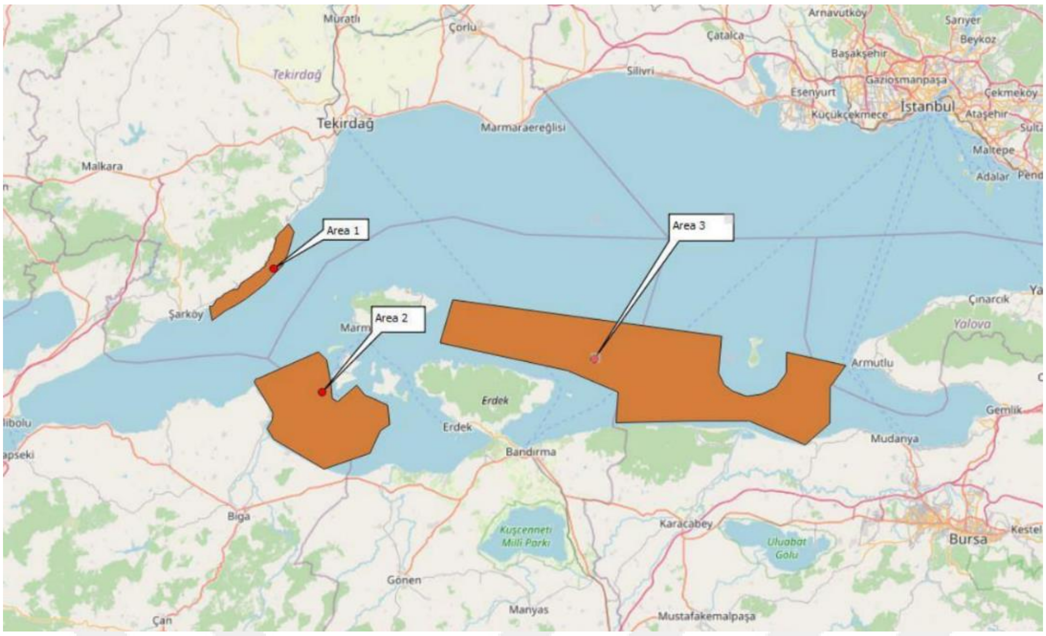


Figure 4.7 : Candidate zones for Offshore YEKA Tender [39].

4.2.4 Future outlook

Türkiye has set ambitious targets for wind energy development. By 2025, the country aims to achieve an installed onshore capacity of 13.1 GW, and by 2030, the target increases to 18.1 GW. Looking further ahead, Türkiye plans to expand its wind energy capacity to 29.6 GW by 2035. Additionally, there is a goal of installing 5 GW of offshore wind energy by 2035. These targets position Türkiye among the top 10 countries in Europe in terms of wind energy ambitions for the year 2030. With a strong focus on these goals, Türkiye is actively working towards the expansion of its wind energy sector, making significant contributions to its renewable energy portfolio. With ongoing efforts to expand renewable energy sources, including wind power, Türkiye aims to further increase its installed wind energy capacity. The country's geographical location, which offers favorable wind resources, presents opportunities for the continued growth of the wind energy sector. The government's commitment to renewable energy targets and supportive policies are expected to attract investments and stimulate the development of new wind projects [40-41].

5. TECHNICAL ASSESSMENT

A thorough technical assessment for a wind farm encompasses multiple essential elements. The process commences with the collection of wind resource data, encompassing prolonged measurements of wind speed and direction, enabling an understanding of the wind potential at the site. Moreover, site-specific details such as geographical coordinates and topography play a vital role in evaluating local conditions. Furthermore, acquiring turbine specifications, encompassing power curves and performance parameters, is crucial for estimating the energy production potential. Within this study, utilization of fixed-bottom offshore wind turbines have been considered for offshore wind farm.

Environmental factors are also taken into account, as well as assessing grid connection requirements and constraints. Subsequently, the wind farm layout is designed, optimizing turbine placement while considering wake effects. Evaluating the necessary electrical infrastructure to transmit the generated electricity to the grid is another critical step. Leveraging the wind resource data and turbine specifications, the annual energy yield of the wind farm can be estimated.

Additionally, conducting a financial analysis helps to evaluate the project's economic viability. Furthermore, identifying and assessing potential risks and uncertainties is essential. Conducting an assessment of environmental and social impacts is undertaken is also important for development phases, while ensuring compliance with regulations and obtaining the necessary permits and clearances. Employing these sequential processes ensures a comprehensive technical assessment of the wind farm, addressing its feasibility and performance.

Within this study, it is assumed that all required permissions, including those related to environmental considerations, grid connection and electrical infrastructure have been obtained and compliance with regulations have been fulfilled. Further details regarding these aspects will not be provided.

5.1 Site Selection

Site selection is of utmost importance in wind energy development as it directly impacts energy production, efficiency, and project viability. A well-chosen site with strong and consistent wind resources maximizes energy output and reduces operational costs. In alignment with the study's objectives, the primary focus of site selection was on offshore locations. Following the identification of a suitable offshore site in the candidate region, the plan was to subsequently select an onshore power plant site within the same or nearby vicinity. Selecting an appropriate site for an offshore wind farm involves considering several crucial factors. Recommendations provided by ORECCA (Offshore Renewable Energy Conversion platforms – Coordination Action) [42] and factors such as wind resource, distance to shore and water depth are taken into account during the site selection process. Based on previous analyses, it has been demonstrated that the optimal location for implementing an offshore wind power plant in Türkiye is Bozcaada-Çanakkale, highlighting its suitability for such a project.

Wind atlas from 2 different sources were examined for the wind regime at 100 meters of the Bozcaada region [43-44]. And also a wind regime has been analysed using the long term ERA5 data for a period of 26 years (1996-2022). Wind regime in project site will be detailed further in following section.

The selected offshore project site has a water depth of less than 50 meters, making it suitable for fixed bottom foundations. These foundations involve securely attaching the wind turbine structure to the seabed using various methods. They are relatively cost-effective and widely used in offshore wind projects, particularly in regions with shallower waters. Fixed bottom foundations provide a stable and secure platform for offshore wind turbines, allowing for efficient power generation while withstanding various environmental conditions. The voltage level of 33.6 kV is taken into account for the collection system and the transmission from the collection system to the onshore substation. 154 kV high voltage overhead line, which is connecting Çamseki WPP to Ezine Substation, is considered as a connection point (it is assumed that the necessary capacity allocation, related permits and all technical requirements are provided). Therefore onshore substation is planned with 33,6/154 kV transformers.

Project boundary and wind speed atlas for offshore project site is given in Figure 5.1.

Figure 5.1 : Offshore project boundary and wind speed atlas [43].

It has been planned that the offshore and onshore wind farms will be connected to the same grid connection point with the same distance. After considering the distance of the offshore power plant from the grid connection point, which is approximately 16 km, and examining the wind atlases, the onshore power plant site was selected to be located between Derbentbaşı and Çamlıca villages. Project boundary and wind speed atlas of the site is given in Figure 5.2.

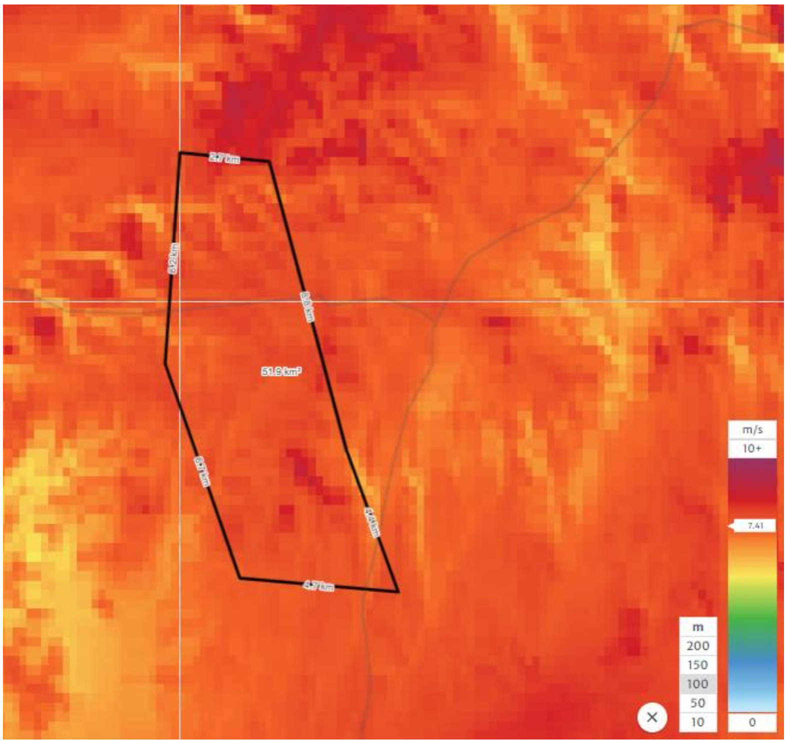


Figure 5.2 : Onshore project boundary and wind speed atlas [43].

5.2 Modelling

For the wind flow and energy modelling, WindFarmer: Analyst 1.5.0 software has been used. Wind farm modelling refers to the process of using mathematical models to simulate the behaviour of a wind farm. The purpose of wind farm modelling is to analyse the performance and efficiency of wind turbines, as well as to optimize the design and layout. The WindFarmer Analyst software utilizes modelling techniques to optimize the arrangement of wind turbines, including their spacing, orientation, and positioning relative to each other.

To ensure accuracy, the software incorporates high-resolution wind resource characteristics, including wind speed, direction, turbulence, and other meteorological parameters. The resolution of the input data is quite high due to the quality. These wind resource characteristics serve as the boundary conditions for the wind flow simulations, enabling the software to generate reliable insights into the expected performance of the wind farm.

There are several aspects that influence the wind flow on site that needs to be considered in the model. The topographical changes, the surface roughness changes and any obstacles near the turbine locations can have an impact on the wind flow experienced by the turbines.

5.2.1 Terrain

The process of working with elevation data on WindFarmer Analyst involves a series of steps. Firstly, the procedure begins with the download of free SRTM (Shuttle Radar Topography Mission) terrain for the desired area. It is worth noting that the SRTM data provided in WindFarmer: Analyst is currently limited to a 3 arc second resolution. Although this resolution may be lower compared to purchased terrain files, it is often adequate for most purposes. After obtaining the gridded elevation file, the next step involves converting it into contours. By performing this conversion, the elevation data is transformed into a visual representation that facilitates analysis and interpretation [45].

5.2.2 Surface roughness

Surface roughness refers to the irregularity and texture of the ground surface over which wind flows. It is an important factor in wind energy as it influences the wind speed and flow characteristics at a specific location. The surface roughness affects the performance of wind turbines by introducing turbulence and friction, which can impact the efficiency and power output of wind farms. The effect of surface roughness on wind energy can be understood in the following way:

- Wind Speed Reduction: As wind encounters rough terrain or obstacles on the ground, such as trees, buildings, or hills, it experiences frictional forces that slow down the wind speed. This reduction in wind speed decreases the available kinetic energy that can be captured by wind turbines, leading to lower power generation.
- Turbulence: Surface roughness introduces turbulence in the wind flow, causing irregular air movements. Turbulence can lead to increased fatigue and stress on wind turbine components, potentially affecting their lifespan and requiring more maintenance. It can also impact the aerodynamic performance of wind turbine blades, reducing their efficiency.
- Wind Direction and Shear: Surface roughness can influence the direction of the wind flow, leading to changes in wind patterns and the distribution of wind resources. Additionally, roughness can create wind shear, which is the change in wind speed and direction with height. Wind shear affects the load distribution on wind turbine blades and can impact their structural integrity [46-48].

Table 5.1 provides the roughness classes and corresponding roughness lengths used in wind energy applications.

Table 5.1 : Roughness classes and roughness lengths [49].

Roughness Class	Roughness Length (m)	Landscape Type
0	0.0002	Water surface
0.5	0.0024	Completely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills.
1.5	0.055	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1250 meters.

Table 5.1 (continued) : Roughness classes and roughness lengths [49].

Roughness Class	Roughness Length (m)	Landscape Type
2	0.1	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters.
2.5	0.2	Agricultural land with many houses, shrubs and plants, or 8 meters tall sheltering hedgerows within a distance of about 250 meters.
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	Larger cities with tall buildings.
4	1.6	Very large cities with tall buildings and sky scrapers.

Onshore wind farms are typically subjected to a range of surface roughness conditions, including rural areas, forests, or urban landscapes. Each terrain type has different roughness characteristics, such as the presence of trees, buildings, or open fields. These variations in surface roughness impact the wind flow, with urban areas typically having higher roughness and more significant wind speed reductions compared to open rural areas.

Offshore wind farms are installed in marine environments, where the surface roughness is primarily determined by the water surface. Compared to onshore wind farms, offshore locations generally have lower surface roughness due to the smoother water surface and absence of obstacles. The smoother conditions result in less turbulence and lower wind speed reductions, allowing for more consistent and higher wind speeds at offshore wind farm sites. In this study, roughness class for offshore project site is Class 0 as expected.

For both wind farms, surface roughness map was obtained through Global Wind Atlas (GWA) Map Warehouse, which considers the various roughness changes. The Global Wind Atlas (GWA) is an online platform that provides access to comprehensive wind resource data and tools for wind energy planning and assessment. It is a collaborative initiative led by the Technical University of Denmark (DTU) Wind Energy and the World Bank Group [50]. Figure 5.3 and

Figure **5.4** illustrate the roughness maps for both offshore and onshore wind farms, respectively.

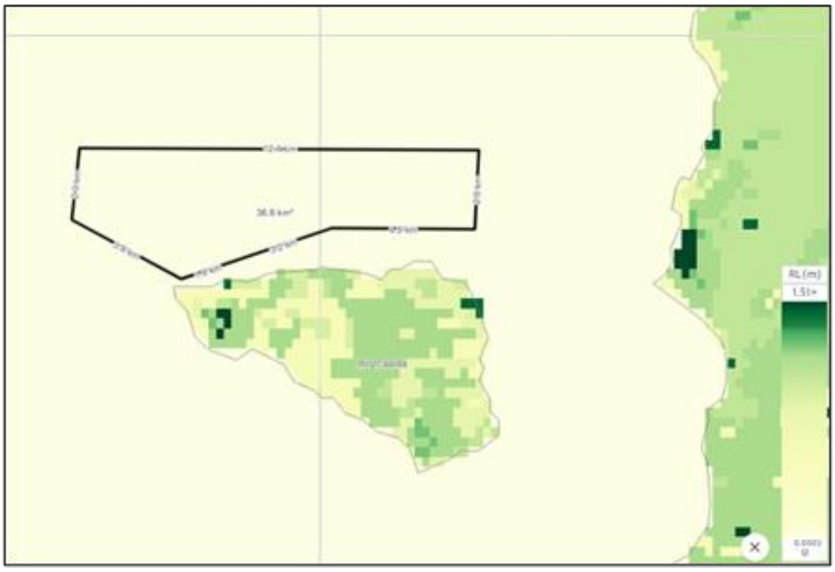


Figure 5.3 : Roughness map of offshore wind farm [51].

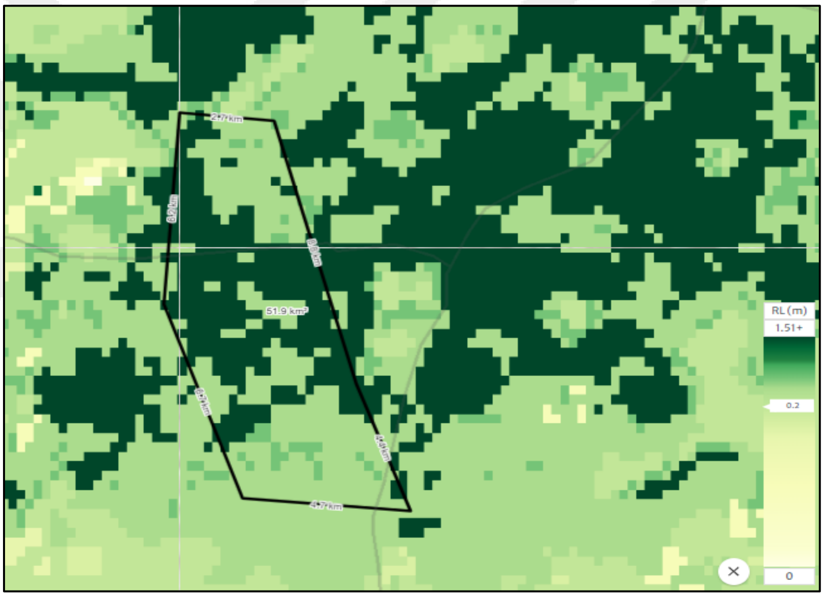


Figure 5.4 : Roughness map of onshore wind farm [51].

5.3 Data Assessment

Data assessment is the process of evaluating the wind energy potential of a specific location or region. It involves gathering and analyzing data on the wind characteristics, such as speed, direction, and frequency, to determine the viability of harnessing wind energy for power generation. Due to the absence of meteorological station data in the region, the wind data analysis for the wind regime was conducted using the ERA5 dataset. This dataset spans a long-term period of approximately 27 years and provides information on wind speed and direction at a height of 100 meters above ground level, as well as pressure and temperature values at a height of 2 meters above ground level.

Table 5. presents the mean wind statistics obtained from the ERA5 data for both onshore and offshore wind farms.

Table 5.2 : Summary of the mean wind statistics for both project site.

	Height	Onshore Project Site	Offshore Project Site
Wind Speed	100m	6.32 m/s	7.60 m/s
Prevailing Wind Direction	100m	Northeast	East-Northeast
Temperature (Max|Min)	2m	15.9 °C (39.3°C|-13.9°C)	16.7 °C (33.9°C|-6.2°C)
Pressure	2m	991.4 mBar	1010.1 mBar

Despite GWA's claim that a wind speed of 9.5 m/s can be achieved at a height of 100m in offshore sites, the analysis of ERA5 data reveals that the average wind speed at that height is 7.6 m/s. Similarly, while GWA asserts that an onshore site can reach 8 m/s, the ERA5 data indicates that the mean wind speed for onshore locations is 6.32 m/s.

To conduct the analysis of annual energy production, various wind turbine models from different manufacturers, each with its own hub height, were utilized. It is important to highlight that the wind speed data obtained from ERA5 corresponds to a height of 100 meters. Thus, in order to estimate the wind data at the turbine hub heights, the wind shear model was used for extrapolation.

The wind shear model serves as a mathematical representation that illustrates the variation of wind speed with height above the ground. It finds frequent application in the realm of wind energy to approximate wind speeds at various elevations, particularly in scenarios where only a limited number of measurements at different heights are accessible. Based on the logarithmic wind profile, the wind shear model assumes that wind speed increases logarithmically with greater height above the ground [52].

5.3.1 Wind climate for onshore

5.3.1.1 Frequency distribution

When examining the region's wind climate, the wind rose depicted in Figure 5.5 becomes a crucial resource for comprehending the distribution of wind directions.

Within its circular format, the wind rose reveals prevailing wind patterns, with the Northeast direction prevailing between 30-60° and occasional winds originating from the South at 180°.

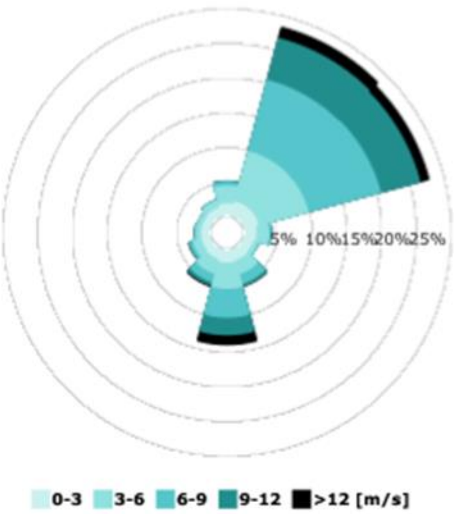


Figure 5.5 : Wind rose of onshore project site.

The wind speed frequency distribution, shown in Figure 5.6, is another essential parameter that expresses the frequency of wind speed at each speed range in 1m/s bins. The ERA5 shows high frequency at moderate wind speeds between 5-8 m/s.

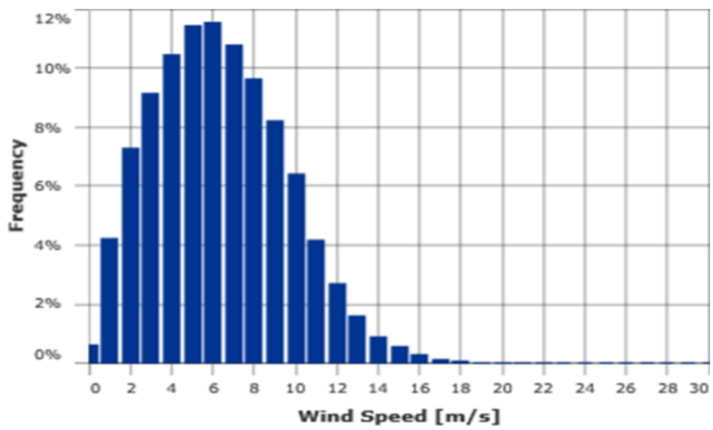


Figure 5.6 : Wind speed frequency distribution for onshore project site.

5.3.1.2 Daily, monthly and yearly distribution

Daily, monthly, and yearly wind speed variations play a crucial role in the context of wind energy for several reasons. Firstly, understanding the daily variations helps in optimizing the operation and maintenance of wind turbines. By identifying peak wind periods and diurnal cycles, wind farm operators can schedule maintenance activities, turbine inspections, and repairs during periods of lower wind speeds, minimizing downtime and maximizing energy production.

Monthly variations in wind speed are important for resource assessment and energy production forecasting. Analyzing the seasonal trends in wind speeds allows for more accurate predictions of energy generation, aiding in energy grid planning and integration. It helps determine the expected output of wind farms during different months, enabling better management of energy supply and demand.

Yearly wind speed variations provide insights into the long-term viability and profitability of wind energy projects. By analyzing the historical data on annual wind speed patterns, developers and investors can assess the potential energy yield over the lifespan of a wind farm. This information is vital for financial planning, project financing, and risk assessment, ensuring that wind energy projects are economically viable and sustainable in the long run [53-54].

The diurnal, or daily, wind speed variations is provided in Table 5. and Figure 5.7. The diurnal wind speed provides an indication as to the variation in wind speed throughout the day. The daily wind profile reveals a consistent and stable wind resource, with speeds ranging from 6.09 to 6.45 m/s and an average of 6.32 m/s. This consistency indicates favorable conditions for wind energy generation in the region. Wind profile holds promise for reliable and consistent energy production.

Table 5.3 : Diurnal wind profile for onshore project site.

Hours	Wind Speed (m/s)
00:00	6.44
01:00	6.18
02:00	6.17
03:00	6.17
04:00	6.21
05:00	6.26
06:00	6.33
07:00	6.39
08:00	6.36
09:00	6.32
10:00	6.33
11:00	6.34
12:00	6.37
13:00	6.09
14:00	6.15
15:00	6.26
16:00	6.36
17:00	6.42

Table 5.3 (continued) : Diurnal wind profile for onshore project site.

Hours	Wind Speed (m/s)
18:00	6.46
19:00	6.43
20:00	6.42
21:00	6.44
22:00	6.45
23:00	6.45
Mean	6.32

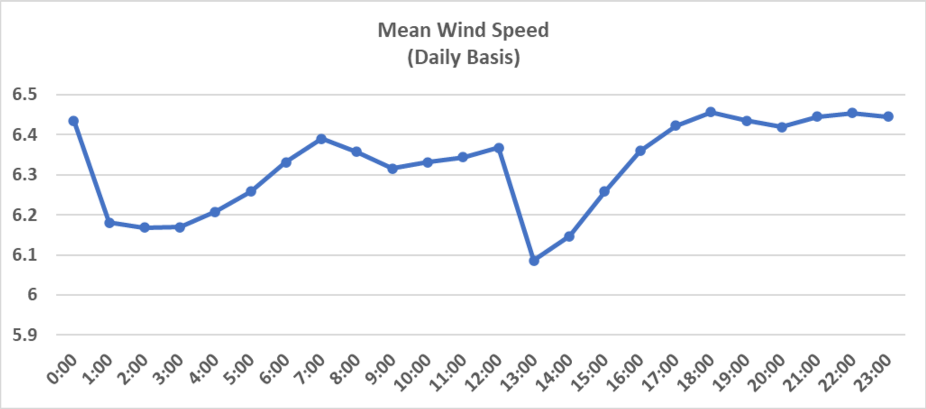


Figure 5.7 : Diurnal wind profile for onshore project site.

Table 5. and Figure 5.8 shows the monthly wind speed profile where seasonal variation can be observed. It can be noted that the wind speed is observed to be lowest in May with 5.25 m/s, and highest in the December with 7 m/s.

Table 5.4 : Monthly wind profile for onshore project site.

Hours	Wind Speed (m/s)
Jan	6.81
Feb	6.99
Mar	6.62
Apr	5.74
May	5.26
Jun	5.38
Jul	6.49
Aug	6.99
Sep	6.07
Oct	6.18
Nov	6.38
Dec	7.00
Mean	6.32

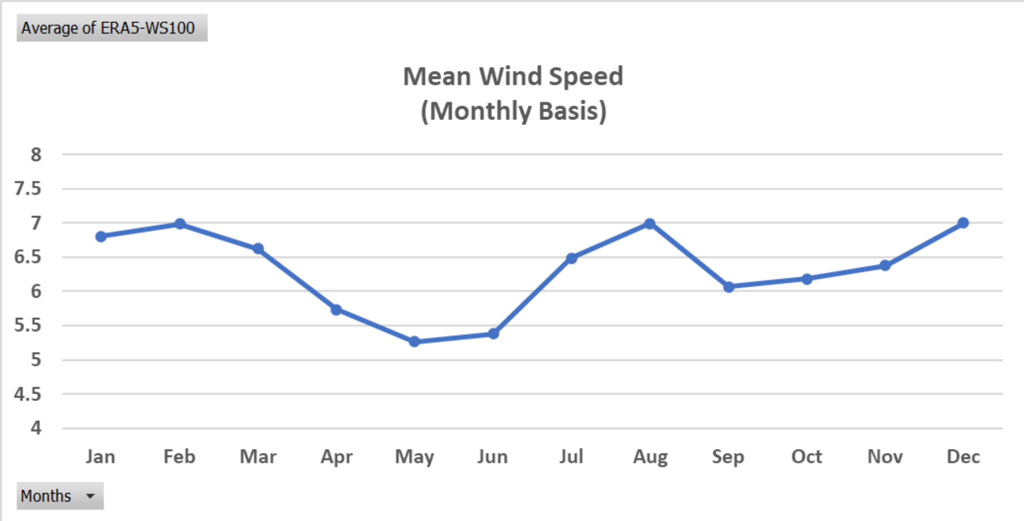


Figure 5.8 : Monthly wind profile for onshore project site.

Figure 5.9 provides the yearly variation, demonstrating that the wind speed range remains relatively stable throughout the years. Notably, over the past 8 years, the wind profile consistently exhibits a reliable and consistent resource, indicating a sustained wind climate.

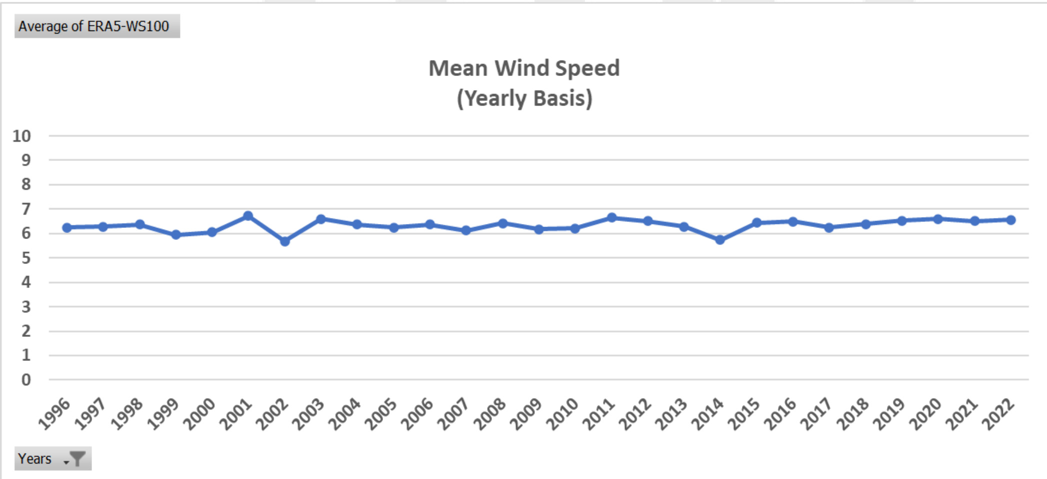


Figure 5.9 : Yearly wind profile for onshore project site.

5.3.2 Wind climate for offshore

5.3.2.1 Frequency distribution

Upon examining the wind rose analysis, it becomes apparent that the North-Northeast direction at 30° stands as the prevailing wind direction, as shown in Figure 5.10. Additionally, a notable proportion of winds originate from the 60° direction. Furthermore, occasional winds are observed to emanate from the South at 180°.

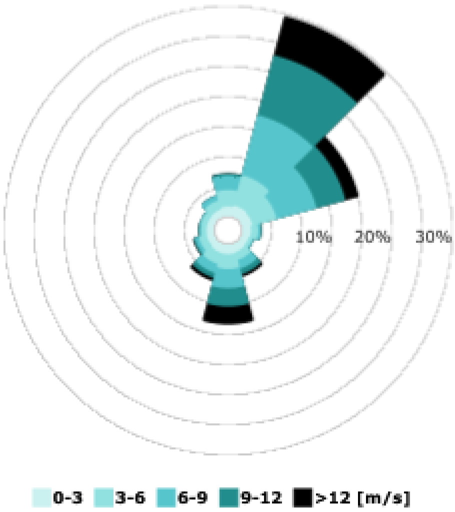


Figure 5.10 : Wind rose of offshore project site.

The wind speed frequency distribution, shown in Figure 5.11, is another essential parameter that expresses the frequency of wind speed at each speed range in 1m/s bins. The ERA5 shows high frequency at relatively high wind speeds between 5-9 m/s.

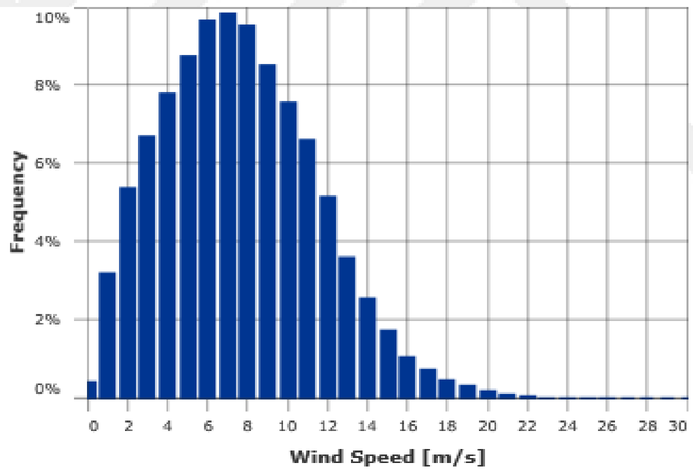


Figure 5.11 : Wind speed frequency distribution for offshore project site.

5.3.2.2 Daily, monthly and yearly distribution

Definitions and significance of diurnal, monthly, and yearly distributions are elaborated in Section 5.3.1.2.

The diurnal wind speed distribution is provided in Table 5. and Figure 5.12. The diurnal wind speed provides an indication as to the variation in wind speed throughout the day. The daily wind profile reveals a consistent and stable wind resource, with speeds ranging from 7.33 to 7.78 m/s and an average of 7.60 m/s. This consistency indicates favorable conditions for wind energy generation in the region. Wind profile holds promise for reliable and consistent energy production.

Table 5.5 : Diurnal wind profile for offshore project site.

Hours	Wind Speed (m/s)
00:00	7.64
01:00	7.35
02:00	7.36
03:00	7.39
04:00	7.46
05:00	7.55
06:00	7.65
07:00	7.73
08:00	7.76
09:00	7.73
10:00	7.68
11:00	7.62
12:00	7.59
13:00	7.33
14:00	7.39
15:00	7.54
16:00	7.67
17:00	7.74
18:00	7.78
19:00	7.76
20:00	7.72
21:00	7.71
22:00	7.69
23:00	7.66
Mean	7.60

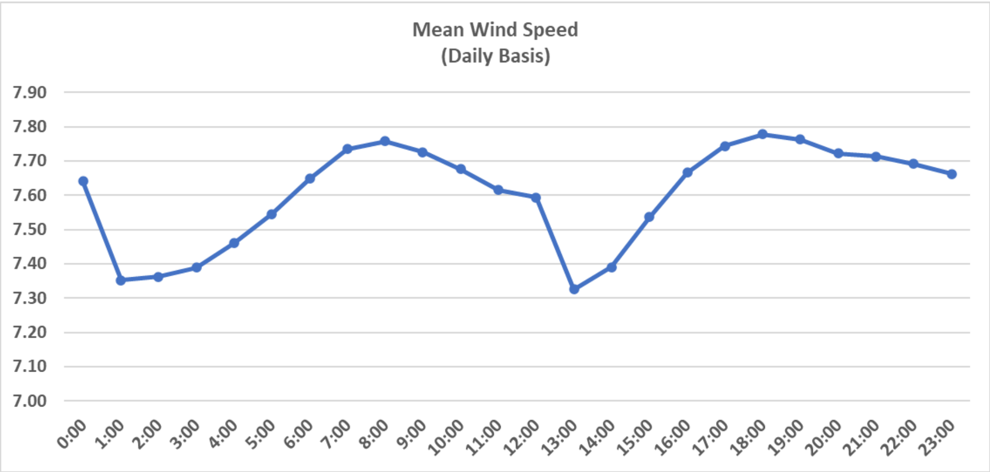


Figure 5.12 : Diurnal wind profile for offshore project site.

Table 5 and Figure 5.13 shows the monthly wind speed profile where seasonal variation can be observed. It can be noted that the wind speed is observed to be lowest in May with 6.34 m/s, and highest in the December with 8.60 m/s.

Table 5.6 : Monthly wind profile for offshore project site.

Hours	Wind Speed (m/s)
Jan	8.32
Feb	8.51
Mar	7.99
Apr	6.91
May	6.34
Jun	6.42
Jul	7.60
Aug	8.13
Sep	7.21
Oct	7.45
Nov	7.75
Dec	8.60
Mean	7.60

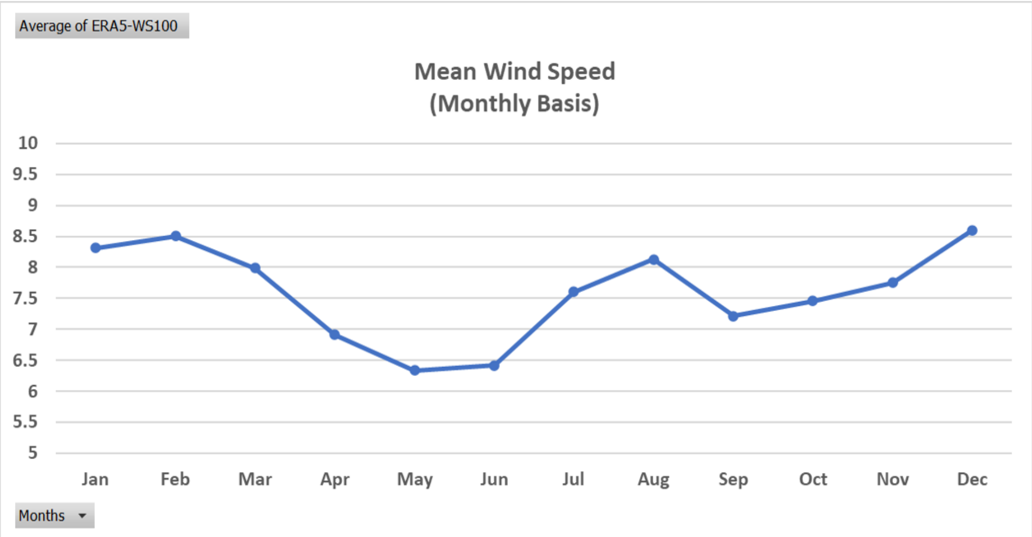


Figure 5.13 : Monthly wind profile for offshore project site.

Figure 5.14 provides the yearly variation, demonstrating that the wind speed range remains relatively stable throughout the years. Notably, over the past 8 years, the wind profile consistently exhibits a reliable and consistent resource, indicating a sustained wind climate.

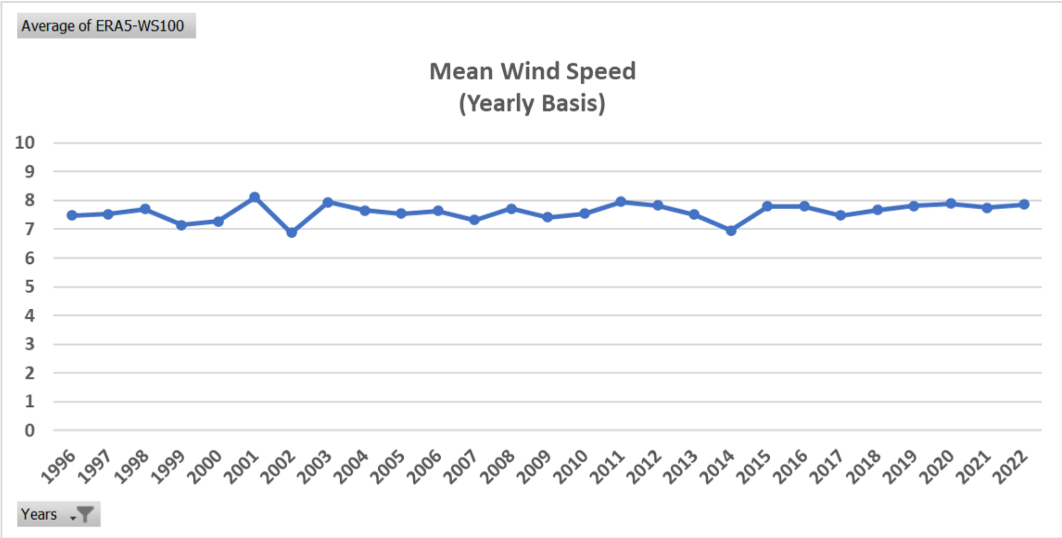


Figure 5.14 : Yearly wind profile for offshore project site.

It is evident that onshore and offshore project sites demonstrate similar patterns in terms of diurnal, monthly, and yearly variations. The consistency observed across these temporal scales suggests a similarity in the fluctuations of wind characteristics between these two types of locations.

5.4 Annual Energy Production

The annual energy production assessment for the onshore wind farm involved the utilization of seven different wind turbines from four manufacturers, namely Nordex, Enercon, Vestas, and GE. To select appropriate wind turbine models, it is crucial to understand the concept of wind turbine classes. These classes are defined in the International Electrotechnical Commission (IEC) standard 61400-1 and are based on the average wind speed at the installation site. They are typically labeled as I, II, III, and S. Each class has its own set of requirements and features, including design criteria for the turbine's structural components, expected turbulence levels, and the specific wind speed ranges in which the turbine is designed to operate optimally and securely. Selecting the correct wind turbine class is essential for wind farms to optimize energy production, ensure cost-effectiveness, and maintain structural integrity and safety. Matching the turbine class to the site's wind conditions maximizes energy generation and reduces upfront costs and payback periods. It also guarantees that the turbines can withstand the expected wind loads and operate reliably throughout their lifespan. These turbine classes for this study were chosen in regards with their compatibility with the wind speed regime at the site, particularly Class III and Class S, were carefully considered when selecting the appropriate turbine models for the onshore wind farm project site. Wind turbine class parameters according to the average wind speeds are given in Table 5.

Table 5.7 : Wind turbine classes with average wind speeds [55].

Wind Turbine Class		I	II	III	S
$V_{average}$	(m/s)	10	8.5	7,5	Values specified by the designer

For the offshore wind farm, Siemens Gamesa offshore wind turbine model with two different hub heights were utilized. Additionally, the WindFarmer Analyst software provided conceptual wind turbine models with varying unit power and hub heights. To calculate the annual energy production for the offshore site, three additional conceptual models were incorporated, resulting in a total of five turbines

Initially, the optimization involved deploying 68 wind turbine generators (WTGs) at the onshore site to determine the optimal wind turbine model scenario in terms of energy production. The target installed power for the offshore scenario was set to match the total capacity achieved by the selected onshore wind farm. The scenario resulting in a 408 MW installed capacity proved to be the most suitable for the onshore wind farm. To achieve or approach the same installed capacity for the offshore scenario, the number of WTGs employed varied between 26 and 51, depending on the unit power of the wind turbine models.

WindFarmer Analyst utilizes a symmetrical layout algorithm that has been used to calculate annual energy production. This algorithm optimizes the arrangement of wind turbines in a symmetric pattern to maximize energy capture while considering factors such as wind speed, turbulence, and wake effects. By employing this algorithm, WindFarmer Analyst ensures that the wind turbines are positioned in an efficient and balanced manner with considering the prevailing wind direction, resulting in enhanced energy production over the course of a year.

Turbine specifications and annual energy production results for onshore wind farm and offshore wind farm are given in Table 5 and Table 5 respectively.

Table 5.8 : Turbine specfications and annual energy production results for Onshore Wind Farm.

Turbine Manufacturer	Enercon	Nordex	Vestas	GE	Enercon	Vestas	Vestas
Turbine Model	E115-EP3-E4	N149	V163	GE-158	E175-EP5	V162	V172
Rotor Diameter	115.7 m	149.1 m	163.0 m	158.0 m	175.0 m	162.0 m	172.0 m
Unit Power	4.26 MW	4.5 MW	4.5 MW	5.5 MW	6.0 MW	6.2 MW	7.2 MW
Hub Height	92 m	120 m	120 m	120 m	132 m	120 m	150 m
Number of Units	68	68	68	68	68	68	68
Total Capacity (MW)	289.68	306	306	374	408	421.6	489.6
P50 - Gross Production	561.98 GWh	885.01 GWh	986.81 GWh	1009.33 GWh	1253.00 GWh	1101.96 GWh	1307.53 GWh
P50 - Net Production	496.72 GWh	775.00 GWh	763.71 GWh	880.81GWh	1090.97 GWh	956.38 GWh	1138.42 GWh
Net Capacity Factor (P50)	19.56%	28.89%	28.47%	26.87%	30.50%	25.88%	26.53%
Production per MW (P50)	1,714.7	2,532.7	2,495.8	2,355.1	2,673.9	2,268.5	2,325.2

Table 5.9 : Turbine specfications and annual energy production results for Offshore Wind Farm.

Turbine Manufacturer	Siemens Gamesa	Siemens Gamesa	Offshore Concept Model	Offshore Concept Model	Offshore Concept Model
Turbine Model	SG14-222 DD	SG14-222 DD	8 MW D-167	10 MW D-178	16 MW D-240
Rotor Diameter	222.0 m	222.0 m	167.0 m	178.0 m	240.0 m
Unit Power	14.7 MW	14.7 MW	8.0 MW	10.0 MW	16.0 MW
Hub Height	143 m	134 m	113 m	119 m	135 m
Number of Units	28	28	51	41	26
Total Capacity (MW)	411.6	411.6	408	410	416
P50 - Gross Production	1619.29 GWh	1598.18 GWh	1499.25 GWh	1433.32 GWh	1625.00 GWh
P50 - Net Production	1463.58 GWh	1443.84 GWh	1353.09 GWh	1296.49 GWh	1478.43 GWh
Net Capacity Factor (P50)	40.56%	40.02%	37.83%	36.07%	40.54%
Production per MW (P50)	3,555.8	3,507.9	3,316.4	3,162.2	3,553.9

When comparing different wind farms and layouts, it is important to consider various parameters. In this study, two significant parameters for legitimate comparison are the capacity factor and production per megawatt (MW). These metrics provide valuable insights into the operational efficiency and productivity of wind farms, enabling a comprehensive evaluation of their performance.

The capacity factor of a wind farm is the ratio of its actual energy output over a specific period to its maximum possible output if it were operating at full capacity during that period. It represents the actual utilization of the installed capacity. A higher capacity factor indicates that the wind farm is operating more efficiently and generating a larger proportion of its maximum potential output [56].

Production per MW refers to the amount of energy generated by a wind farm per unit of installed capacity. It calculates the average energy production per megawatt of installed wind turbine capacity. It provides insights into the relative performance and productivity of different wind farms.

The scenario with a total installed capacity of 408 MW, utilizing the Enercon E175-EP5 6.0 MW turbine models, emerged as the most favorable option for onshore wind farm compared to other scenarios in terms of capacity factor and production per MW. For offshore wind farm, five different scenarios were simulated, each utilizing a different number of wind turbine models. Among these scenarios, the simulation with 28xSiemens Gamesa 14.7 MW wind turbine with a hub height of 143 m demonstrated the most optimal results compared to the other scenarios. All turbine layouts for onshore and offshore wind farm scenarios including substation and ERA5 locations are given in Figure 5.15 and Figure 5.16.

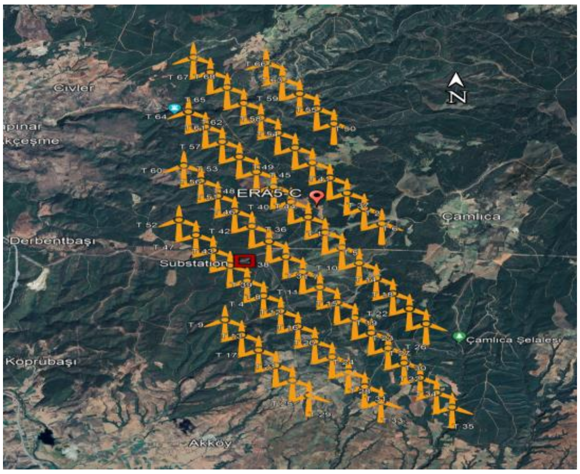


Figure 5.15 : Layout with 68 WTGs for onshore scenarios.

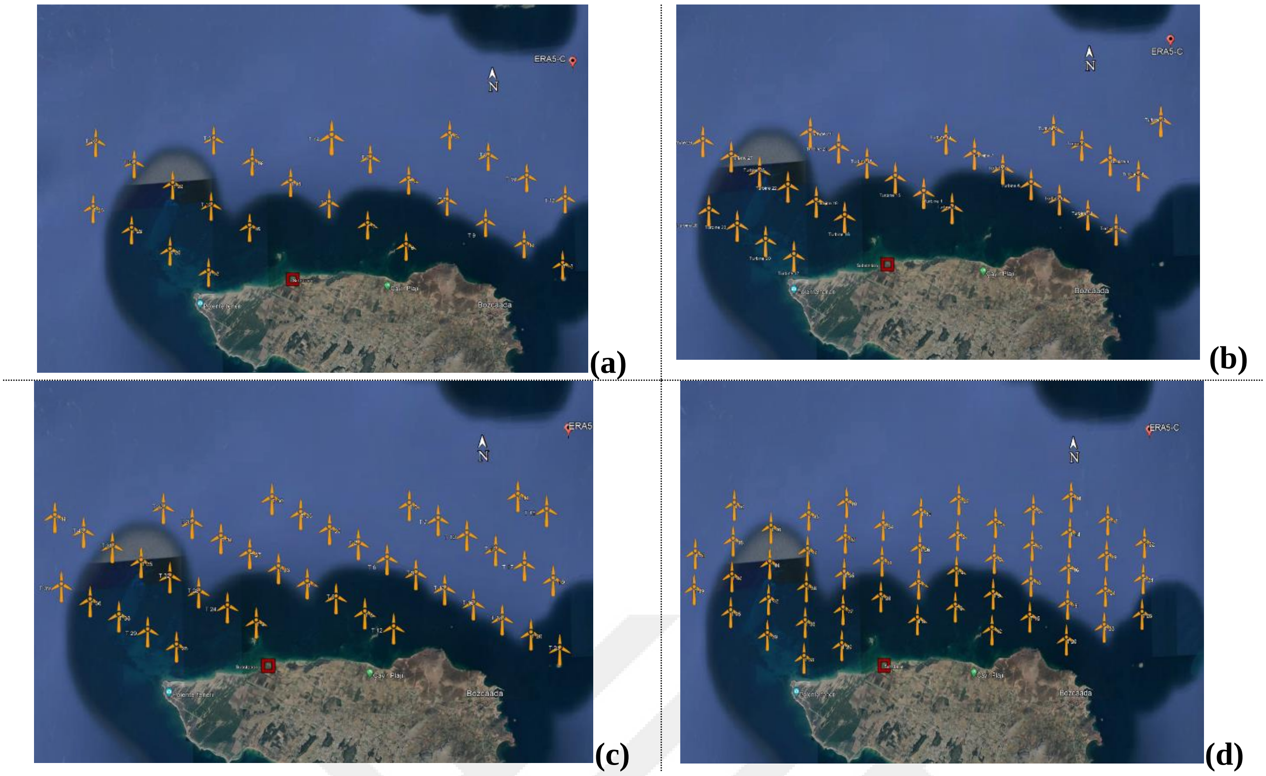


Figure 5.16 : Layouts for offshore scenarios: (a) 26 WTGs. (b) 28 WTGs. (c) 41 WTGs. (51) WTGs.

6. ECONOMIC ANALYSIS

NPV, LCoE, and IRR are the main economic indicators for decision making and helping power plant project developers make their investments. NPV (Net Present Value) is a financial measure utilized for assessing the profitability of an investment. It quantifies the disparity between the present value of cash inflows (revenues or benefits) and the present value of cash outflows (costs or expenditures). Throughout the entire 25-year lifespan of the power plant project, NPV can be expressed by [24]:

$$NPV = -C_{CAPEX} + \sum_{t=1}^{T=25} \frac{netCash\ Flow\ (t)}{(1+r)^t} \tag{6.1}$$

- C_{CAPEX} = capital expenditure
- T = lifespan of the power plant (25 years)
- r = discount rate (considered as 8%)

The LCoE is a unique cost metric per unit that captures the net present value of a power plant throughout its lifetime. It is calculated by [24]:

$$LCOE = \frac{\sum_{t=0}^{T=25} \frac{C_{CAPEX}(t) + C_{OPEX}(t)}{(1+r)^t}}{\sum_{t=0}^{T=25} \frac{netAEP}{(1+r)^t}} \tag{6.2}$$

- C_{OPEX} = operational expenditures for the year of t
- netAEP = Estimated annual energy production

IRR assesses profitability by determining the discount rate at which the NPV of the power plant becomes zero. It is calculated by dividing the net profit by the total cost of the power plant.

The estimated annual revenues for wind farms are calculated based on the feed-in tariffs, alsoknown as YEKDEM mechanism. YEKDEM stands for "Yenilenebilir Enerji Kaynaklarını Destekleme Mekanizması," which translates to "Renewable Energy Resources Support Mechanism" in English. YEKDEM is a feed-in tariff system implemented by the Turkish government to promote and incentivize the development of renewable energy projects in the country.

Under the YEKDEM system, producers of electricity from renewable energy sources, such as wind, solar, hydro, geothermal, and biomass, are eligible to receive a fixed feed-in tariff for a specific period. This tariff is guaranteed by the government and provides long-term price stability for renewable energy producers, ensuring a favorable investment environment. On May 1, 2023, the Turkish Republic Presidency issued Decree No. 7189, introducing the new YEKDEM prices. New mechanism includes 10-year feed-in tariffs and 5-year domestic production incentives for renewable power projects that are commissioned between 01.07.2021 and 31.12.2030 [57]. Cap prices stated in YEKDEM tariffs has taken into account as the sales prices, namely 8.25 USDcents/kWh for offshore wind farm and 6.05 USDcents/kWh for onshore wind farm. Even though the feed-in tariffs are subject to 10 year, it is assumed all during the project life of 25 years.

There is also local content support for domestically manufactured equipment used in the relevant generation facility for the first 5 year of operation. This support is considered for a duration of 5 years, with a rate of 38.45 TRY/kWh for offshore facilities and 28.80 TRY/kWh onshore wind farm. According to the market survey conducted by the Central Bank of Türkiye, the year-end USD/TRY expectation of the participants is 23.09 for 2023, while the next year USD/TRY expectation is determined to be 24.61, with 6.6% increase [58]. The increase in the exchange rate has also be taken into account for the remaining years of the 5-year domestic contribution support period when calculating the new contribution fee.

CapEx of a wind power plant is consists of turbine costs (including transport and installation), electrical and civil works costs (balance of the system) and project development and management costs.

For onshore wind power plant, interviews and negotiations with the turbine manufacturer and market research revealed that CapEx per MW can be taken as 1.250.000$ in current market conditions. OpEx is around 14.500$ per MW per year.

For offshore wind power plant, National Renewable Energy Laboratory’s report regarding the wind energy costs of 2021 has been used. CapEx and OpEx values per kW for an offshore wind power plant with 8 MW turbines, are shown in the Table 6.1. These values used for the SG14 – 222 DD turbines, analyzed in this assessment.

Table 6.1 : CapEx and OpEx values for fixed bottom offshore wind turbines [59].

Parameter	Unit	Utility Scale Fixed-Bottom Offshore Wind Turbine
Wind Turbine Rating	MW	8
CapEx	$/kW	3,871
OpEx/year	$/kW/yr	111

The turbine costs account for approximately 70.4% of the total CapEx cost for onshore wind farms, while for offshore wind farms, they account for around 33.6% [59].

The financial results, obtained with the initial study is shown in the Table 6.2.

Table 6.2 : Financial results.

	Onshore Wind Farm (68xE175-EP5 – 6.0 MW)	Offshore Wind Farm (28xSG14-222 DD – 14.7 MW)
Annual Energy Production	1,090.97 GWh	1,463.58 GWh
CapEx	$510,000,000	$1,593,303,600
OpEx/year	$5,916,000	$45,687,600
Annual Electricity Sales Revenue	$66,003,776	$120,745,647
Discount Rate	8%	
NPV	$135,973,232	-$783,927,048
LCoE	49.22 $/MWh	133.20 $/MWh
IRR	11.01%	1.35%
Result	Feasible	Not Feasible

The findings with the initial study indicate that, based on similar technical parameters, implementing an offshore wind power plant in the Bozcaada region would not be preferable due to the lack of profitability. In the current market conditions, with higher capital expenditure and operational expenditure values, it is unfortunately not feasible to proceed with an offshore wind farm. The results indicate that the offshore scenario has a significantly lower Internal Rate of Return (IRR) compared to the applied discount rate, which demonstrates the lack of profitability for the offshore wind farm. Furthermore, considering the Levelized Cost of Energy (LCoE), it is evident that the sales price should exceed 133.2 USD/MWh. The Net Present Value (NPV) results further confirm that the project is not feasible in its current state.

7. SENSITIVITY ANALYSIS

Sensitivity analysis is a technique used to examine how changes in specific variables or assumptions impact the outcome or results of a particular model, calculation, or decision-making process. It helps identify the sensitivity or responsiveness of a system or model to different inputs and provides insights into the potential effects of varying those inputs.

In this study, different scenarios are created by adjusting different variables while keeping others constant. The purpose is to assess how sensitive the overall results are to changes in those variables. By analyzing the outcomes under different scenarios, it would be better to understand of the key drivers and uncertainties in project.

7.1 Sensitivity Analysis of Total Installed Capacity

The analysis focuses on examining the sensitivity of wind farms to variations in total installed capacity through different layouts using varying numbers of wind turbines. The initial study involved a layout with 28 wind turbines for the offhore wind farm. To conduct a sensitivity analysis, four additional layout scenarios were investigated, including configurations with 8, 12, 16, and 20 wind turbines. This allowed for a comprehensive assessment of the sensitivity of the wind farm's performance across different turbine layouts. Layout configurations are given in Figure 7.2.

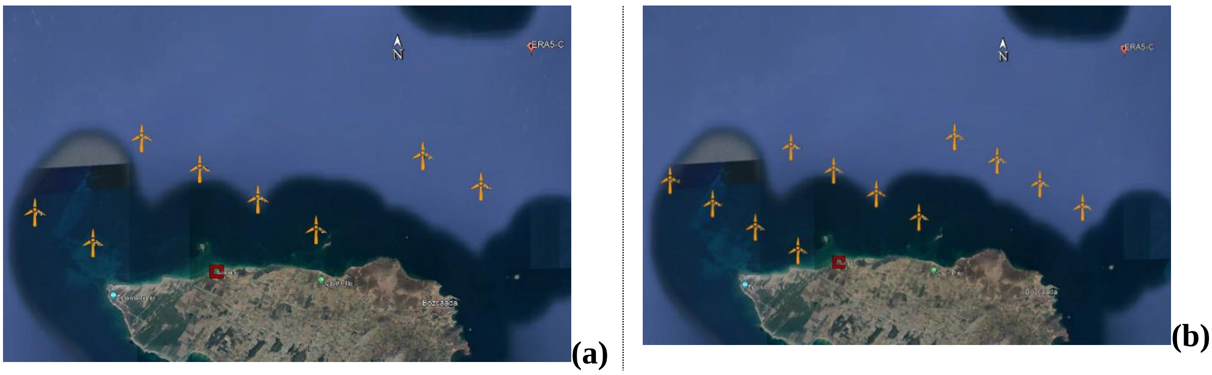
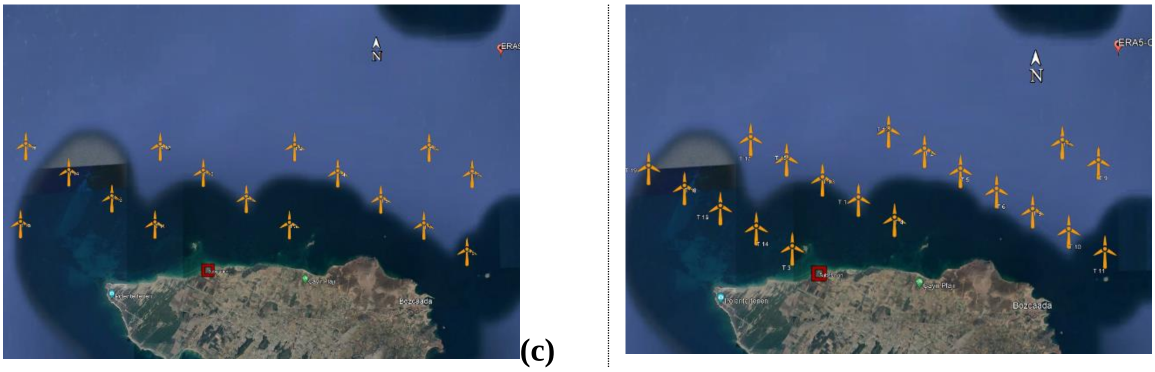


Figure 7.1 : Layouts for offshore alternative scenarios: (a)8 WTGs. (b)12 WTGs.



(c) (d)

Figure 7.2 (continued) : Layouts for offshore alternative scenarios: (c)16 WTGs. (d)20 WTGs.

Technical and financial results of the studied scenarios are given in Table 7.1.

Table 7.1 : Offshore layout results with different configurations.

Parameters	Results				
Turbine Manufacturer	Siemens Gamesa				
Turbine Model	SG14 – 222 DD				
Unit Power	14.7 MW				
Hub Height	143 m				
Number of Units	8	12	16	20	28
Total Capacity	117.6 MW	176.4 MW	235.2 MW	294 MW	411.6 MW
P50 - Gross Production	462.64 GWh/y	693.96 GWh/y	925.28 GWh/y	1156.61 GWh/y	1619.29 GWh/y
P50 - Net Production	426.00 GWh/y	638.68 GWh/y	850.65 GWh/y	1056.71 GWh/y	1463.58 GWh/y
Net Capacity Factor (P50)	41.32%	41.30%	41.26%	41.00%	40.56%
Production per MW (P50)	3,622.4	3,620.6	3,616.7	3,594.3	3,555.8
LCoE	130.75	130.81	130.96	131.77	133.20
IRR	1.60%	1.59%	1.58%	1.49%	1.35%
NPV	-$217,041,468	-$325,838,974	-$435,273,329	-$549,937,101	-$783,927,048

As depicted in Figure 7.3, the relationship between production and LCoE values is examined in relation to the installed power. As anticipated, there is a proportional increase in production with the increasing installed power. Initially, the LCoE value shows a slight increase up to the 250 MW installed power level. However, beyond this threshold, it becomes evident that the LCoE experiences a significant upward trend for higher installed power values.

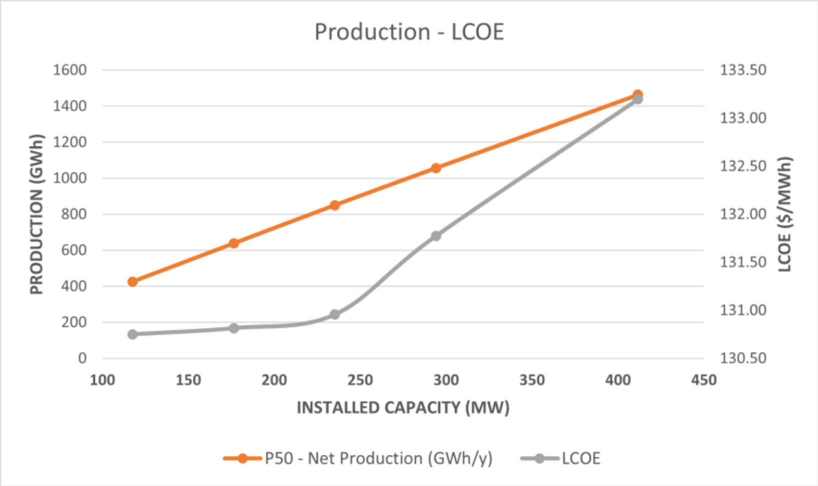


Figure 7.3 : Comparing of annual production against LCoE.

Figure 7.4 illustrates the correlation between production and IRR values. It is notable that the IRR values experience a sharp decline after reaching 250 MW of total installed capacity.

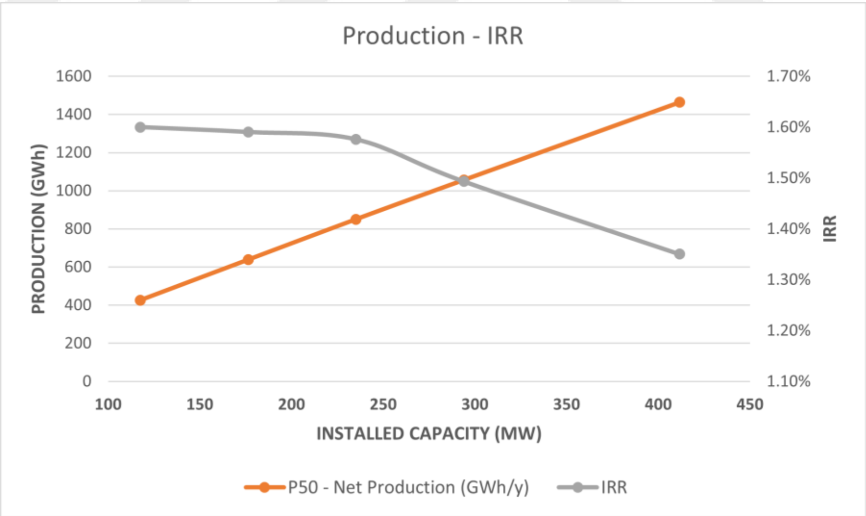


Figure 7.4 : Comparing of annual production against IRR.

Even with conducting a sensitivity study, the results indicate that it was not possible to achieve desirable net present value for any of the scenarios. In all cases, the NPV were negative, indicating that the projected cash outflows exceeded the projected cash inflows for the wind project.

The results of the sensitivity study indicate that there is a critical threshold for total installed capacity. Beyond 250 MW, both the levelized cost of electricity (LCoE) values and internal rate of return (IRR) values exhibit notable changes. The significant ramp-up in LCoE values suggests that the cost of generating each unit of electricity increases substantially as the total installed capacity exceeds 250 MW. Additionally, the sharp decline in IRR values indicates that the project's overall financial performance declines as the total installed capacity surpasses 250 MW. Overall, it can be seen that the profitability of the project diminishes as a result of high investment costs and low revenue generation in the market conditions, specifically the electricity sales price. The findings suggest that the project's financial viability is adversely affected by these factors.

7.2 Sensitivity Analysis of CapEx Reduction

In the calculations for offshore wind farm, 3,871 USD/kW is assumed as CapEx value. This value is more than three folds of onshore counterpart. While the assumed CapEx may appear to be quite high, it can be considered realistic given the current market conditions. In this section, different scenarios are analyzed by considering various percentages of cost reductions in (10%, 20%, 30%, 40%, 50%, 60%). By examining how these variations in CapEx reduction impact the project's financials and overall feasibility, valuable insights can be gained regarding the project's cost sensitivity and potential opportunities for cost savings.

The results are presented in

Table **7.2**, demonstrating the anticipated positive impact of cost reduction on the project's economic parameters. It was observed that feasible levels for the site were only achieved after a 40% reduction, equivalent to 2,322.6 USD/MWh.

Table 7.2 : Results of cost reduction analysis.

Cost Reduction	10%	20%	30%	40%	50%	60%
New CapEx	$3,483,900	$3,096,800	$2,709,700	$2,322,600	$1,935,500	$1,548,400
LCoE	123.00	112.80	102.60	92.41	82.21	72.01
IRR	2.24%	3.29%	4.56%	6.13%	8.19%	11.05%
NPV	-$624,596,688	-$465,266,328	-$305,935,968	-$146,605,608	$12,724,752	$172,055,112

Feasibility Check	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Feasible	Feasible

Figure 7.5 : Onshore wind farm IRR and LCoE trends with cost reduction.

For an onshore power plant, the wind turbine and related costs account for 70.4% of the total CapEx, whereas for an offshore wind farm, this ratio is 33.6%. For offshore, balance of system/plant costs contribute to 48.2% of the CapEx, with soft costs accounting for 18.2%, as shown in Figure 7.6. As evident, balance of system costs bear the majority share of the CapEx. It is clear that, as the infrastructure for electrical works and construction works for offshore power plants continue to develop, it is expected and targeted that costs will decrease in the future. It should also be noted that turbine costs are in a decreasing trend with the developing technology.

Parameter	Value ($/kW)
Turbine	**1,301**
Balance of Plant	**1,866**
Development and project management	91
Substructure and foundation	496
Electrical infrastructure	693
Assembly and installation	408
Lease price	178
Soft Costs	**704**
Plant commissioning	34
Decommissioning	117
Contingency	366
Construction finance	152
Insurance during construction	34
TOTAL CAPEX	**3,871**

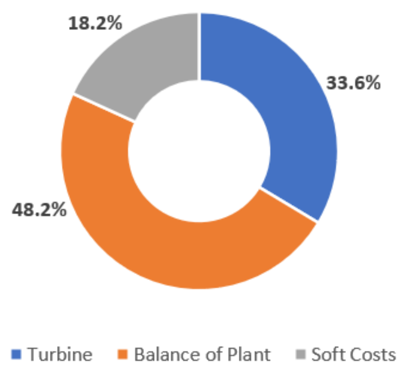


Figure 7.6 : Fixed-bottom offshore wind power plant CapEx cost breakdown [59].

7.3 Sensitivity Analysis of CapEx Reduction with Discount Rate

Additionally, financial outcomes of the project under different discount rates with various cost reductions have also been examined, based on the YEKDEM tariff for electricity sales revenue. The Table 7.3 and Figure 7.6 present the results of economic studies conducted at varying discount rates ranging from 6% to 3%.

Table 7.3 : Results of varying discount rates with cost reduction.

Discount Rates	Cost Reduction	10%	20%	30%	40%	50%	60%
	Reduced CapEx	$ 3,483,900	$ 3,096,800	$ 2,709,700	$ 2,322,600	$ 1,935,500	$ 1,548,400
	IRR	2.24%	3.29%	4.56%	6.13%	8.19%	11.05%
6%	LCOE	107.86	99.34	90.83	82.31	73.80	65.28
	NPV	-$465,902,699	-$306,572,339	-$147,241,979	$12,088,381	$171,418,741	$330,749,101
5%	LCOE	100.73	93.01	85.29	77.56	69.84	62.11
	NPV	-$367,304,582	-$207,974,222	-$48,643,862	$110,686,498	$270,016,858	$429,347,218
4%	LCOE	93.93	86.96	80.00	73.03	66.06	59.09
	NPV	-$252,367,868	-$93,037,508	$66,292,852	$225,623,212	$384,953,572	$544,283,932
3%	LCOE	87.48	81.23	74.98	68.73	62.48	56.22
	NPV	-$117,685,444	$41,644,916	$200,975,276	$360,305,636	$519,635,996	$678,966,356

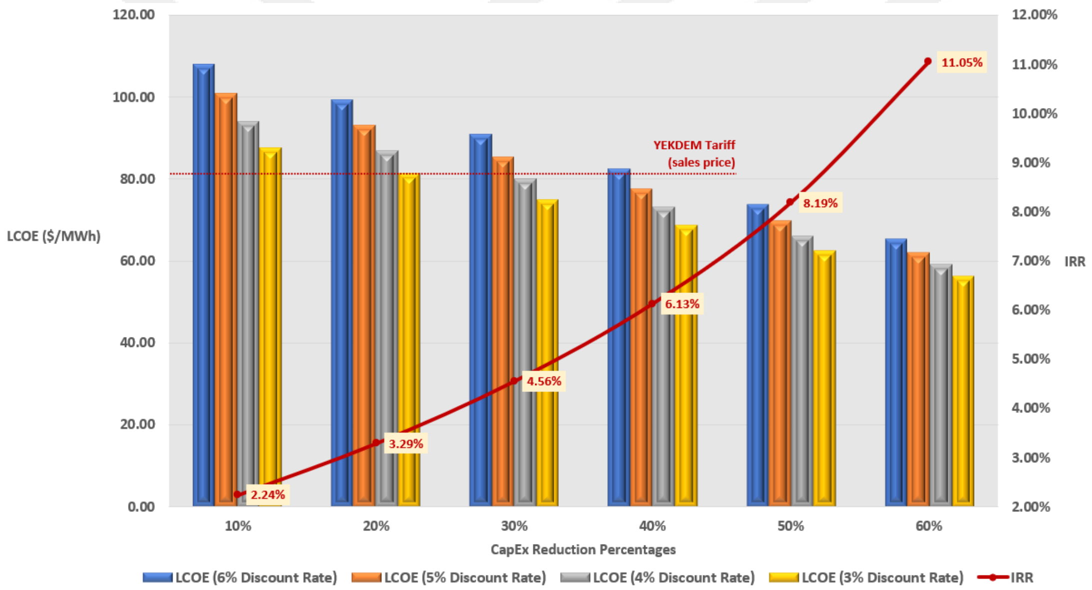


Figure 7.6 : Offshore wind farm IRR and LCoE trends with cost reduction.

A positive trend in the project's feasibility is observed as the cost reduction increases and the discount rate decreases. It is evident that both low discount rate and prioritizing efforts to reduce costs are crucial for the project's success. The discount rates used in financial calculations are influenced by multiple factors and are not standardized globally due to variations in economic conditions, market dynamics, and risk profiles. One such factor is inflation, which gradually diminishes the purchasing power of money over time. Countries with higher inflation rates tend to employ higher discount rates to account for the anticipated devaluation of future cash flows.

Moreover, each country possesses unique political, economic, and regulatory risks that impact the attractiveness of investments. Countries facing greater perceived risks typically employ higher discount rates to mitigate the additional uncertainty [60]. In the case of Türkiye, it is advisable to strive for financial stability to mitigate risk factors and reduce investment uncertainties, ultimately leading to lower discount rates and improved investment profitability.

7.4 Sensitivity Analysis of Incentives and Green Energy Certificates

Incentive refers to a policy or program designed to encourage and promote the growth of wind energy projects. It typically involves financial or non-financial benefits provided to developers, operators, or investors to incentivize the deployment and utilization of wind energy technologies. Incentives play a crucial role in wind energy development. For example YEKDEM provides long-term feed-in tariffs for wind energy projects, ensuring a fixed payment per kWh of electricity generated. Additionally, there is support for utilizing locally manufactured equipment and components in wind energy projects, aiming to boost local manufacturing and employment opportunities. Based on the initial study, it was determined that utilizing the cap prices for YEKDEM tariffs and taking advantage of the local content support alone were insufficient to make an offshore wind power plant economically feasible.

Upon analyzing the PTF (Piyasa Takas Fiyatı) which is market clearing price for the Turkish market, it was observed that the average market clearing price stood at 147.5 USD/MWh in 2022 [61]. With using this average market clearing price of 2022 as the electricity sales price, the project demonstrates financial feasibility with an IRR of 9.67% and an approximate net present value of 231.6 million dollars.   .

Average market clearing price observed in 2022 is significantly higher than the offered tariff price in YEKDEM in 2023. It indicates that YEKDEM incentive is far from the current and actual conditions of the free market. Aligning the YEKDEM tariff closer to the electricity trading levels in the free market is not only necessary but also seen as a more appealing factor for project developers and investors.

On the other hand, green energy certificates are also seen as another source of income that is increasingly being used in financial analyses for projects. Green energy certificate, also known as a renewable energy certificate (REC) or a guarantee of origin

(GO), is an instrument that represents the environmental attributes of renewable energy generation. It provides proof that a specific quantity of electricity has been generated from renewable sources [62]. By selling green energy certificates, project owners can generate additional revenue beyond the sale of electricity. These certificates have value in markets where there is demand for renewable energy or where compliance obligations exist for renewable energy usage.

Green energy certificate issuing organizations vary by country and region. Major organizations that issue green energy certificates are International Renewable Energy Certificate System (I-REC), Gold Standard (GS) and Verified Carbon Standard (VCS). Türkiye has also an organization responsible for issuing green energy certificates that is called the YEK-G (stands for Renewable Energy Resource Guarantee System. It operates under the auspices of the Energy Market Regulatory Authority (EPDK) and oversees the certification and tracking of renewable energy generation in the country. The green certificates issued by YEK-G can be traded in the Turkish electricity market, and with this system, Türkiye aims to support the development of renewable energy projects, encourage investment in the sector, and contribute to the country's renewable energy targets and sustainability goals [63].

According to the electricity market summary information report published by Turkish Energy Markets Operation Corporation (EPİAŞ), the weighted average trade price for the wind industry was 0.50 TRY/MWh in 2022 [64]. By utilizing this value in this study, it indeed generates additional income for the project; however, it does not result in any significant differences in the financial parameters.

It is forecasted that green certificate prices will be in the range 5-8 EUR/MWh (5.47-8.76 USD/MWh with using 1.09 exchange rate) between 2023-2030 [65]. When certificate trading utilized in this study with using the CAGR (6.05%) between 2023 and 2030 and applying to the 25 years lifespan of the project, it has seen that project has absolutely significant yearly revenue from green certificate trade with approximately 21%, but green certificate trading alone does not make the project feasible for investment since there is only slight improvements in financial parameters.

8. CONCLUSION

This study conducts a comprehensive techno-economic evaluation of both an offshore wind power plant and an onshore wind plant for comparative purposes. The analysis initiates with a thorough wind resource assessment and the calculation of annual energy production. Economic parameters are then derived and utilized to facilitate an appropriate comparison between the two wind farm options. Additionally, a thorough sensitivity analysis is performed, focusing on various parameters, to provide comprehensive insights into the project's viability.

The findings indicate that implementing an offshore wind power plant in the Bozcaada region would not be preferable due to the lack of economic profitability. In the current market conditions, with higher capital expenditure and operational expenditure values, it is unfortunately not feasible to proceed with an offshore wind farm.

The sensitivity studies conducted in this study show that as the reduction in costs increases, there is a promising trend towards improving the feasibility of the project. It is evident that cost reduction is crucial for the project's success. It is also noteworthy that approximately half of the offshore wind power plant's CapEx is allocated to the balance of system, which includes electrical and civil works for installation. Research indicates that turbine costs have been declining in recent years, and it can be anticipated that technological advancements will also impact installation costs. However, aiming for lower installation costs also requires support from advanced supply chain management, effective collaboration with industry peers, utilization of advanced installation techniques, government support, and incentives.

Another output obtained from the analyzes is that the project demonstrates viability at low discount rate levels. The determination of discount rates for financial calculations is influenced by various factors and lacks global standardization due to variations in economic conditions, market dynamics, and risk profiles. Countries with lower discount rates commonly share the objective of stimulating economic growth, addressing inflaion risks, and ensuring price stability. Therefore, it is crucial for Türkiye to pursue financial stability in order to mitigate risks and minimize investment uncertainties. This will ultimately result in lower discount rates and enhanced investment profitability.

In terms of electricity sales revenue, it is evident that the implementation of an amplified new YEKDEM tariff, along with a specialized support mechanism, is crucial for the successful establishment of an offshore wind power plant. The current market conditions, especially the significantly high CapEx amounts, pose challenges for investors and create a sense of intimidation. To boost the investments in offshore wind farms and attract more investors, it is essential to ensure that the YEKDEM price or power purchase agreement guarantee reflects a more realistic and aligned approach with free market values. By adjusting these factors to be in line with market realities, it will help alleviate investor concerns and create a more favorable environment for investments in offshore wind farms.

While Türkiye has achieved growth in onshore wind energy in the past decade, venturing into offshore wind development should not rely solely on onshore wind experience. Therefore, it is essential for Türkiye to invest in technology research specifically tailored to offshore wind power to kickstart the industry's development.

To enhance the sensitivity and obtain clearer results, further research can be conducted to examine the capital expenditure and operational expenditure prices specific to offshore wind farms in Türkiye. As technology advances and the market infrastructure develops, it is conceivable that offshore power plants can become economically viable by reducing installation and operating costs. However, under the current conditions, an offshore wind power plant located in the Bozcaada region, considered the most suitable offshore wind farm location in Türkiye, unfortunately does not present a viable investment opportunity.

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