ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

OFFSHORE WIND FARM SIMULATION ANALYSIS IN TURKISH AEGEAN SEAS, FOÇA REGION

M.Sc. THESIS

Deniz SATILMIŞ

Energy Science and Technology Division

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JULY 2024

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

TÜRK EGE DENİZİ FOÇA BÖLGESİ DENİZ ÜSTÜ RÜZGAR SANTRALİ SİMULASYON ANALİZİ

YÜKSEK LİSANS TEZİ

Deniz SATILMIŞ
(301191043)

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Deniz SATILMIŞ, a M.Sc. student of İTU Graduate School student ID 301191043, successfully defended the thesis entitled "OFFSHORE WIND FARM SIMULATION ANALYSIS IN TURKISH AEGEAN SEAS, FOÇA REGION", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Asst. Prof. Dr. Murat ÇAKAN** Istanbul Technical University	**.....**
Jury Members :	**Prof. Dr. Zehra YUMURTACI** Yıldız Technical University	**.....**
	Asst. Prof. Dr. Burak BARUTÇU Istanbul Technical University	**.....**

Date of Submission : 28 June 2024

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To my beloved family,

FOREWORD

It was just a year before the lifechanging COVID-19 epidemic came into our lives, that I decided to pursue a master's degree in renewable energy field. The journey has lasted longer than expected, but it is with great honor and pride that I am writing these lines.

This thesis represents the determination of my journey in the field of offshore wind energy, specifically focusing on the feasibility and potential of offshore wind power generation in Turkey. Throughout this study, I have explored the technical, economic, and environmental aspects of offshore wind farms, aiming to contribute valuable insights to the growing body of knowledge in this area.

The motivation for this research stems from the urgent need to transition to sustainable energy sources in the face of global climate change. Wind energy, with its vast potential and minimal environmental impact, stands out as a promising solution. Turkey, with its extensive coastline and favorable wind conditions, holds significant potential for harnessing offshore wind power. This thesis delves into the practicalities and challenges of realizing this potential, providing a comprehensive analysis that encompasses both theoretical simulations and real-market considerations.

I would like to extend my deepest gratitude to my supervisor, Asst. Prof. Dr. Murat ÇAKAN, whose guidance, expertise, and encouragement have been invaluable throughout this research. I am also grateful to all my professors in the program for their support and resources that have facilitated the completion of this study.

Also, I would like to thank my family and my dear wife, for their unwavering support and understanding during this demanding journey. Their stubborn belief in my capabilities has been a constant source of motivation and strength. No expression of thanks would suffice to show how grateful I am to their presence.

To end with, this thesis is a testament to the collective efforts and support of many individuals. It is my hope that the findings and insights presented herein will contribute to the advancement of further research and innovation in the field of offshore wind power generation in Turkey.

July 2024

Deniz SATILMIŞ
(Environmental Engineer)

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ABBREVIATIONS

ACER : Agency for the Cooperation of Energy Regulators

AEP : Annual Energy Production

AHP : Analytical Hierarchy Process

CAPEX : Capital Expenditures

CEO : Chief Executive Officer

CFSR : Climate Forecast System Re-Analysis

DRES : Deniz Üstü Rüzgar Elektrik Santrali

ECMWF : European Centre for Medium-Range Weather Forecasts

EEA : European Environment Agency

EIA : Environmental Impact Assessment

EMODnet : European Marine Observation and Data Network

EPDK : Enerji Piyasası Düzenleme Kurumu / Energy Market Regulatory Authority

EPİAŞ : Enerji Piyasaları İşletme Anonim Şirketi / Energy Exchange Istanbul

ERA : ECMWF Re-Analysis

ERA5 : ECMWF Reanalysis v5

EU : European Union

EWEA : European Wind Energy Association

FANGBM : Fractional Nonlinear Grey Bernoulli Model

GIS : Geographical Information Systems

GJ : Gigajoule

GW : Gigawatt

GWEC : Global Wind Energy Council

GWh : Gigawatt hour

HEREMA : Hellenic Hydrocarbons and Energy Resources Management Company

HVOF : High Velocity Oxygen Fuel

IAEA : International Atomic Energy Agency

IEA : International Energy Agency

IEC : International Electrotechnical Commission

IRENA : International Renewable Energy Agency

IRR : Internal Rate of Return

ITA : International Trade Administration

kW : Kilowatt

kWh : Kilowatt hour

LCOE : Levelized Cost of Electricity

MCDM : Multi-Criteria Decision-Making

MCSS : Multi-Criteria Site Selections

MW : Megawatt

MWh : Megawatt hour

NHSSM : Novelty Hybrid Site Selection Method

NPV : Net Present Value

NREAP : National Renewable Energy Action Plan

OPEX : Operating Expenses

OWF : Offshore Wind Farm

PDF : Probability Density Function

PPA : Power Purchase Agreement

REC : Renewable Energy Cooperative

ROI : Return on Investment

SG : Siemens Gamesa

TEİAŞ : Türkiye Elektrik İletim Anonim Şirketi / Turkish Electricity Transmission Corporation

TL : Turkish Lira

TÜREB : Türkiye Rüzgar Enerjisi Birliği / Turkish Wind Energy Association

TW : Terawatt

TWh : Terawatt hour

UK : United Kingdom

US : United States

USA : United States of America

USD : United States Dollar

WAsP : Wind Atlas Analysis and Application Program

YEKA : Yenilenebilir Enerji Kaynak Alanları / Renewable Energy Zones

YEKDEM : Yenilenebilir Enerji Kaynaklarını Destekleme Mekanizması / Renewable Energy Resources Support Scheme

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OFFSHORE WIND FARM SIMULATION ANALYSIS IN TURKISH AEGEAN SEAS, FOÇA REGION

SUMMARY

This study investigates the feasibility of implementing OWFs in Turkish seas, with a focus on harnessing underutilized wind resources to contribute to renewable energy development. Despite the abundant wind potential in the region, there are currently no OWFs in Turkey. This research aims to fill this gap by evaluating the technical, economic, and policy aspects of OWF implementation, providing a comprehensive assessment that could serve as a model for similar initiatives globally.

The primary objectives are to assess the wind energy potential in Turkish seas, analyze global trends in offshore wind energy, identify challenges and barriers to OWF development in Turkey, and explore the economic and environmental benefits of such projects. The methodology involves a thorough review of existing literature, policy documents, and climate data, supported by secondary research techniques to gather reliable information on the economic feasibility of OWFs.

For this study, Turkey's Foça region was selected to run the simulation of the hypothetical OWF. The energy yield calculations are based on the wind characteristics of this region, providing a realistic assessment of potential power generation and economic returns. The technical analysis, encompassing the simulation of Siemens Gamesa 5 MW turbines at varying wind speeds, reveals favorable conditions for power efficiency. The power output calculations, particularly at 10 m/s, support the notion that Turkey's coastline holds significant promise for harnessing wind energy.

Key findings from the study highlight the significant wind energy potential in the Aegean Sea and underscore the financial viability of OWFs in the region. The economic analysis, based on a 25-year operational period, shows promising results with a positive net present value (NPV) of $465 million against an investment value of $319 million, and a cumulative net profit of $981 million, indicating substantial profitability. The study also addresses critical technical considerations, such as turbine efficiency and wind speed variability, and proposes solutions to enhance project performance and sustainability.

Additionally, the study discusses the potential challenges posed by low wind speeds, below the cut-in speed for turbines, and the impact of higher wind speeds on turbine performance and longevity. These considerations are crucial for maintaining both power efficiency and the longevity of the wind turbines, highlighting the importance of selecting optimal wind speed ranges for effective power generation.

This comprehensive feasibility study suggests that Turkey's coastline has the potential to emerge as a significant hub for large-scale power generation. The combination of favorable wind conditions, technical efficiency, and promising economic returns positions Turkey as a viable player in Europe's pursuit of renewable energy sources. The research concludes with recommendations for advancing the Turkish offshore

wind sector, emphasizing the need for advanced turbine technologies, supportive policy frameworks, strategic site selection, public engagement, and workforce development.

This research provides valuable insights for policymakers, industry stakeholders, and environmentalists, offering a framework for evidence-based decision-making in the context of renewable energy initiatives. By addressing the untapped potential of wind resources in Turkish seas, this study aims to promote a shift towards sustainable energy, serving as a call to action for advancing renewable energy infrastructure both domestically and globally.

TÜRK EGE DENİZİ FOÇA BÖLGESİ DENİZ ÜSTÜ RÜZGAR SANTRALİ SİMULASYON ANALİZİ

ÖZET

Bu çalışma, Türkiye denizlerinde deniz üstü rüzgar elektrik santrallerinin (DRES) uygulanabilirliğini kapsamlı bir şekilde inceleyerek, Türkiye'nin büyük ölçüde atıl durumda olan rüzgar enerjisi kaynaklarını nasıl etkin bir şekilde değerlendirebileceğini araştırmaktadır. Türkiye, geniş kıyı şeridi, stratejik coğrafi konumu ve önemli rüzgar potansiyeliyle dikkat çekmesine rağmen, bugüne kadar deniz üstü rüzgar enerjisi projelerine yönelik somut adımlar atılmamıştır. Bu durum, Türkiye'nin yenilenebilir enerji üretiminde sahip olduğu potansiyeli tam anlamıyla kullanamamasına ve fosil yakıtlara olan bağımlılığını azaltma hedefinin gerisinde kalmasına neden olmuştur. Bu araştırma, Türkiye'nin bu eksikliği gidermesi ve deniz üstü rüzgar enerjisinden maksimum verim elde etmesi için gereken teknik, ekonomik ve politik gereksinimleri belirlemeyi amaçlamaktadır.

Çalışmanın ana hedeflerinden biri, Türkiye'nin deniz üstü rüzgar enerjisi potansiyelini detaylı bir şekilde değerlendirerek, bu potansiyelin nasıl kullanılabileceğini ortaya koymaktır. Türkiye, Ege Denizi, Marmara Denizi ve Karadeniz gibi farklı denizlerde çeşitli rüzgar hızları ve iklim koşulları ile karşılaşmaktadır. Bu çeşitlilik, Türkiye'nin deniz üstü rüzgar enerjisi projeleri için farklı bölgelerde farklı stratejiler benimsemesi gerektiğini göstermektedir. Çalışma, bu bölgelerdeki rüzgar enerjisi potansiyelini değerlendirmekle kalmayıp, aynı zamanda bu potansiyelin etkin bir şekilde kullanılması için gerekli olan teknik altyapıyı ve teknolojik gereksinimleri de ortaya koymaktadır.

Bu bağlamda, çalışma küresel deniz üstü rüzgar enerjisi trendlerini analiz ederek, Türkiye'nin bu alandaki uluslararası deneyimlerden nasıl yararlanabileceğini incelemektedir. Özellikle Avrupa ülkeleri, deniz üstü rüzgar enerjisi projelerinde önemli ilerlemeler kaydetmiş olup, Türkiye'nin bu ülkelerde geliştirilmiş ve hayata geçirilmiş projeleri inceleyerek bunlardan katkılar alması büyük önem taşımaktadır. Çalışma, Avrupa'da başarılı olmuş deniz üstü rüzgar enerjisi projelerinin Türkiye'ye nasıl uyarlanabileceğini ve bu projelerin Türkiye'nin özel ihtiyaçlarına göre nasıl modifiye edilebileceğini araştırmaktadır. Bu sayede, Türkiye'nin deniz üstü rüzgar enerjisi projelerinin başarılı bir şekilde hayata geçirilmesi için gerekli olan stratejik planlama, teknoloji transferi ve uluslararası işbirliği fırsatları değerlendirilmiştir.

Çalışmanın bir diğer önemli hedefi, Türkiye'de DRES geliştirilmesine yönelik mevcut zorlukları ve engelleri belirlemektir. Türkiye'de deniz üstü rüzgar enerjisi projelerinin önünde duran en büyük engellerden biri, bu alandaki yasal düzenlemelerin eksikliği ve mevcut mevzuatın yetersizliğidir. Deniz üstü rüzgar enerjisi projelerinin hayata geçirilebilmesi için, Türkiye'nin ulusal enerji politikalarının ve düzenlemelerinin bu projelere uygun hale getirilmesi gerekmektedir. Bu açıdan bakıldığında, çalışma, deniz üstü rüzgar enerjisi projelerinin geliştirilmesi için gerekli olan yasal ve idari düzenlemelerin nasıl oluşturulabileceğini ve bu süreçte karşılaşılabilecek potansiyel engellerin nasıl aşılabileceğini de tartışmaktadır.

Ek olarak, çalışma, DRES projelerinin ekonomik ve çevresel faydalarını da kapsamlı bir şekilde incelemektedir. Türkiye'nin enerji ihtiyacı hızla artmakta olup, bu ihtiyacı karşılamak için sürdürülebilir ve çevre dostu enerji kaynaklarına yönelmek kaçınılmaz hale gelmiştir. Deniz üstü rüzgar enerjisi projeleri, Türkiye'nin hem enerji arz güvenliğini sağlaması hem de sera gazı emisyonlarını azaltması açısından büyük bir potansiyele sahiptir. Çalışma, bu projelerin çevresel etkilerini değerlendirirken, aynı zamanda ekonomik açıdan sağlayacağı avantajları da göz önünde bulundurmaktadır. Özellikle, bu tür projelerin Türkiye ekonomisine yapacağı katkılar, istihdam yaratma potansiyeli ve enerji maliyetlerini düşürme olasılıkları detaylı bir şekilde analiz edilmiştir.

Bu çalışma için, Türkiye'nin Ege Bölgesi'nde yer alan Foça bölgesi, hipotetik bir DRES'nin simülasyonunu gerçekleştirmek üzere seçilmiştir. Foça, coğrafi konumu ve rüzgar potansiyeli ile deniz üstü rüzgar enerjisi projeleri için ideal bir bölge olarak öne çıkmaktadır. Çalışma kapsamında yapılan simülasyonlar, Foça bölgesinin rüzgar enerji üretimi açısından son derece elverişli koşullara sahip olduğunu ortaya koymaktadır. Siemens Gamesa 5 MW türbinlerinin çeşitli rüzgar hızlarında simülasyonları, bu türbinlerin Foça bölgesinde nasıl bir performans sergileyeceğini ve elde edilebilecek enerji verimliliğini ortaya koymaktadır. Özellikle, 10 m/s hızındaki rüzgarlarda elde edilen güç çıkışı, Foça bölgesinin deniz üstü rüzgar enerjisi potansiyelini en iyi şekilde kullanabileceğini göstermektedir.

Çalışmanın en önemli bulgularından biri, Türkiye'nin Ege Denizi kıyılarındaki rüzgar enerjisi potansiyelinin büyüklüğünü ve bu potansiyelin kullanılabilirliği durumunda Türkiye'nin enerji üretiminde dışa bağımlılığını azaltabilecek bir potansiyele sahip olduğunu göstermektedir. Çalışmada yapılan kabullere dayanan ekonomik analizler, deniz üstü rüzgar enerjisi projelerinin uzun vadede son derece karlı olabileceğini ortaya koymaktadır. 25 yıllık bir operasyonel dönemi kapsayan bu analizlerde, $319 milyon dolaylarında bir yatırım miktarıyla, $465.26 milyon pozitif net bugünkü değer (NPV) ve $981 milyon kümülatif net kâr gibi değerler, böylesi bir yatırımın Türkiye için önemli bir getiri sağlayabileceğini ve enerji sektöründe güçlü bir rekabet avantajı yaratabileceğini göstermektedir.

Ayrıca, bu çalışmada türbin verimliliği, rüzgar hızı değişkenliği ve türbin ömrü gibi kritik teknik hususlar detaylı bir şekilde ele alınmıştır. Özellikle, düşük rüzgar hızlarının türbin performansını olumsuz yönde etkileyebileceği ve yüksek rüzgar hızlarının ise türbinlerin ömrünü kısaltabileceği gibi teknik zorluklar, bu tür projelerin başarılı olabilmesi için dikkatle ele alınması gereken önemli faktörler arasında yer almaktadır. Bu nedenle, çalışmada, optimum rüzgar hız aralıklarının belirlenmesi ve bu aralıklara uygun türbin teknolojilerinin seçilmesi için önerilerde bulunulmuştur.

Sonuç olarak, bu kapsamlı fizibilite çalışması, Türkiye'nin deniz üstü rüzgar enerjisi potansiyelini ortaya koymakta ve bu potansiyelin etkin bir şekilde kullanılabilmesi için gerekli olan adımları detaylandırmaktadır. Türkiye'nin sahip olduğu elverişli rüzgar koşulları, güçlü ekonomik potansiyel ve yenilikçi teknolojilerle desteklendiğinde, Türkiye'nin deniz üstü rüzgar enerjisi sektöründe önemli bir küresel oyuncu haline gelebileceğini göstermektedir. Bu çalışma, Türkiye'nin enerji politikaları ve stratejilerinin deniz üstü rüzgar enerjisi projelerini destekleyecek şekilde yeniden yapılandırılması gerektiğini vurgulamaktadır. Ayrıca, araştırma, Türk deniz üstü rüzgar sektörünün gelişimini desteklemek için ileri türbin teknolojileri, destekleyici politika çerçeveleri, stratejik yer seçimi, kamu bilincinin artırılması ve iş gücü geliştirme gibi önemli unsurları da kapsamaktadır.

Bu bağlamda, çalışma, Türkiye'nin yenilenebilir enerji kaynaklarını etkin bir şekilde kullanabilmesi ve enerji üretiminde sürdürülebilirliği sağlaması için önemli bir yol haritası sunmaktadır. Araştırmanın bulguları, Türkiye'nin enerji sektöründe yaptığı dönüşüm çalışmalarına önemli katkılar sağlayabilir ve bu dönüşümün hızlandırılmasına yönelik somut öneriler sunabilir. Sonuç olarak, bu araştırma, Türkiye'nin deniz üstü rüzgar enerjisi potansiyelini ortaya çıkararak, bu alandaki atıl potansiyelin değerlendirilmesine yönelik bir çağrı niteliğindedir ve hem yerel hem de küresel ölçekte yenilenebilir enerji altyapısının geliştirilmesine önemli katkılarda bulunmayı hedeflemektedir.

1. INTRODUCTION

1.1 Introduction

Offshore wind farms, consisting of extensive arrays of wind turbines located in marine environments, are pivotal in the renewable energy sector. They capitalize on oceanic wind resources to generate clean, sustainable electricity (Jiang, 2021). Positioned in oceanic and sea regions, these farms leverage the high and consistent wind speeds found offshore, which often exceed those on land. They convert the kinetic energy from these strong and steady winds into electrical power (Possner & Caldeira, 2017; Reeves & Beck, 2003). Figure 1.1 below (Innovation News Network, 2020) is a picture of an OWF composed of multiple offshore wind turbines.

Figure 1.1: Picture of an OWF.

OWFs are composed of numerous interconnected turbines that feed into an electrical grid, facilitating the transmission of generated electricity to the land for the purposes of distribution and use (Ackermann, 2005; Perveen et al., 2014). Consequently, these installations play a crucial role in decreasing gas emissions and have a role in meeting energy needs by mitigating the environment related impacts linked with power

generation throughs fossil fuels (Esteban et al., 2011; Premalatha et al., 2014; Scolaro & Kittner, 2022).

This introductory section lays the groundwork for the thesis study, provides a thorough understanding of the background of the research, context, and the central issue driving the investigation. It places the research within the larger context of renewable energy and offshore wind development, highlighting the study's importance.

1.2 Contextual Framework and Rationale of the Study

The global drive for clean and sustainable energy solutions has spurred swift progress in renewable energy technologies (Esteban et al., 2011; Premalatha et al., 2014; Scolaro & Kittner, 2022). OWFs have emerged as a crucial element in the global renewable energy landscape. Positioned in marine environments, these farms utilize the strong and consistent wind resources at sea, playing a significant role in reducing greenhouse gas emissions and fulfilling energy demands.

Turkey’s geographical position provides a significant advantage, with extensive coastlines along the Mediterranean, Aegean, and Black Seas offering an excellent wind profile for offshore wind energy production (Talınlı, 2018). However, despite these favorable wind characteristics, Turkey has not yet developed any OWFs. This oversight represents a missed opportunity for diversifying the nation's energy mix and enhancing its contribution to global renewable energy goals.

1.3 Problem Statement

This research is driven by the lack of progress in establishing OWFs in Turkish waters. Despite the country's favorable wind profile and the global trend towards renewable energy, the development of any OWFs has not yet been pursued (Talınlı, 2018). This underutilization of wind potential marks a lost chance for diversifying the energy mix and more significantly contributing to global renewable energy targets.

Recent discussions, as announced by the Energy Minister in August 2023, about possibly establishing offshore wind turbines (OWTs) in Turkey highlight the urgency of this issue (Hurriyet Daily News, 2023). Exploring the feasibility of OWFs is increasingly pressing as these discussions evolve. The lack of OWFs hinders Turkey's

transition pace to renewable energy, posing challenges in achieving sustainable energy and addressing environmental concerns.

This study aims to address the untapped renewable energy potential by exploring the feasibility of designing and implementing OWFs in Turkish waters. It seeks to identify the barriers and opportunities related to this initiative, ultimately aiding decision-making in offshore wind energy development in Turkey and globally. The following sections will explore this issue in greater detail, presenting a roadmap for the future of renewable energy in Turkey, particularly in offshore wind.

1.4 Objective of the Research

This thesis serves both an academic purpose and a call to action for renewable energy development. Its goal is to examine and evaluate the feasibility of establishing OWFs in Turkish waters. While the focus is on Turkey, the implications extend beyond national borders.

The study addresses the crucial issue of underutilized wind resources in Turkish seas, which, if effectively harnessed, could revolutionize the region's energy landscape. Despite optimal wind conditions, the absence of OWFs is striking, especially at a time in during which the renewable energy sources are vital against climate change and improving the security of energy supply.

The primary goals of this study are twofold. Firstly, it aims to explore the viability of implementing OWFs in Turkish seas by investigating offshore wind energy technologies, regulatory frameworks, and environmental factors. Secondly, it seeks to contribute to the expansion of the renewable energy sector both in Turkey and internationally, by providing insights into the difficulties, potential, and best practices associated with offshore wind energy.

In essence, this research aspires to promote a shift towards sustainable energy in Turkey and to act as a benchmark for other countries aiming to utilize their renewable energy resources. The conclusions drawn from this study are intended to inform policymakers, industry stakeholders, and environmentalists, steering them towards a greener, sustainable energy future, and substantially advancing renewable energy infrastructure both locally and globally.

1.5 Aim, Objectives and Questions of Research

This study aims to address some research questions that are defined in this paper. Seeking answers to how feasible is it to establish OWFs in Turkish seas, given the substantial wind available resources, is one of the vital questions that is addressed.

Also, it is crucial to search answers to the questions of what the main challenges and barriers to the development of OWFs in Turkey are, as well as what opportunities and benefits, including economic and environmental aspects, are associated with implementing OWFs in Turkish waters to discuss the results that this paper sets out.

Last but not least, this study examines what particular design requirements and recommendations needed for prospective OWFs in Turkish waters.

The primary goal of the paper is to thoroughly evaluate whether it is feasible to design and set up OWFs in the waters surrounding Turkey. It seeks to understand the various challenges, opportunities, and obstacles related to renewable energy projects. The paper intends to offer very important points of view for decision makers, players in the industry, and environment related bodies to aid in making solid based decisions concerning OWF development in Turkey.

This study pursues several specific goals. It begins by assessing the untapped potential of wind energy in Turkish waters and its importance through achieving renewable energy objectives. It also reviews global trends and advancements in offshore wind energy and their relevance to the Turkish context. Furthermore, the study identifies and examines the particular challenges and barriers to establishing OWFs in Turkish seas. It examines the opportunities and advantages of developing offshore wind infrastructures in Turkish seas, covering financial, environment related, and energy supply security perspectives. Lastly, it proposes a detailed framework and economic concerns for prospective OWFs in Turkish waters.

Together, above mentioned goals aim at unlocking the untapped potential of renewable energy in Turkish waters. They offer a basis for evaluating the possibility of realization, concepts, and establishment of OWFs, thereby enhancing the region’s sustainable energy structure.

1.6 Importance of the Study

This study is highly significant, particularly in the areas of renewable energy development and sustainability. Given the growing concerns about climate change and the need for diverse energy sources, this study is vital.

Firstly, it addresses a major gap in utilizing the unfilled potential of renewable energy, particularly the offshore wind. The wind characteristics in Turkish waters remain largely unutilized, and the absence of OWFs presents a unique chance to enhance the country's energy mix. By assessing the applicability of OWF execution, this study aims to significantly boost clean energy production, thereby reducing carbon related emission values and promoting sustainability in environmental perspective.

The discoveries of this study may also have an impact on how renewable energy is developed in Turkey and in other countries. The knowledge gained from this study will be extremely helpful in navigating the opportunities and difficulties associated with offshore wind energy as efforts around the world to switch from fossil fuels to sustainable energy sources escalate (Premalatha et al., 2014). Lessons from Turkey can be applied to other coastal regions with similar characteristics, impacting investment choices in the renewable energy industry and energy policies.

Furthermore, the establishment of OWFs can drive economic growth by opening new job opportunities, supporting neighboring industries, and inviting investors (Hurriyet Daily News, 2023). Through energy self-sufficiency promotion, fossil fuel dependence reduction, and energy mix diversification, it also enhances energy supply security.

In conclusion, the research's importance rests in its ability to help Turkey and other countries transition to a sustainable and ecologically conscious energy future. It provides a roadmap to harness the potential of renewable energy, mitigate climatic effects, and promote financial development, placing it to be an essential initiative.

1.7 Scope and Constraints of the Study

The study intends to carry out a comprehensive analysis of the possible application of OWFs in Turkish waters. It will do this by examining a number of factors, including the potential for wind energy, worldwide trends, Turkish-specific challenges, opportunities, and design considerations for OWF projects. Recent developments,

including expressions of interest and region determinations by YEKA and the Ministry of Energy and Natural Resources of Turkey, are also taken into account.

Nevertheless, the study has its limitations. One key constraint is the availability of data, particularly when it comes to ongoing conversations and confidential information about offshore wind energy projects. Additionally, the paper is impacted by the dynamic policy and technological frameworks that currently exist. Furthermore, the paper does not delve into advanced engineering and EIAs of certain OWF establishments, but instead offers a wide assessment of applicability and design perspectives.

1.8 Shape of the Study

In order to guarantee a reasonable and consistent progression of study, the thesis is structured into multiple sections, each of which adds to a thorough comprehension of the viability of OWFs in Turkish waters.

Section 2, Literature Review, provides a detailed examination of offshore wind on a worldwide scale and within the Turkish context, exploring its current status, challenges, opportunities, and theoretical foundations.

In Section 3, Methodology, the study design, compiled data sources, their collection strategies, sampling plans, data analysis methods, and ethical perspectives are covered.

Section 4, Results and Discussion, provides a detailed analysis of the data gathered and discusses the implications of the study's observed findings in relation to the larger picture of OWF feasibility in Turkish seas.

Section 5, Conclusion and Recommendations, summarizes the research, emphasizing its significance and eventual influence on the development of renewable energy industry.

The reader will be guided through a thorough investigation of the viability of OWFs in Turkish waters as well as the wider implications for the advancement of renewable energy sources with the help of this framework.

2. LITERATURE REVIEW

2.1 Fundamentals of Offshore Wind Energy

This section explores the fundamental ideas of offshore wind energy, emphasizing the operational procedures and technical aspects of utilizing offshore wind energy. It describes the benefits of offshore wind, such as stronger and steadier wind speeds, and goes over the different technologies employed in OWFs.

2.1.1 Introduction to offshore wind energy

Offshore wind energy, like the wind energy itself, operates on principles that convert wind power into electricity. According to Rivkin and Silk (2013), Denysyuk (2018), Hau (2013), and Weber et al. (2021), these principles include:

- **Conversion of the Energy in the Wind:** Offshore wind turbines capture kinetic energy from the wind using rotor blades. As the wind moves these blades, they rotate.
- **Rotation and Power Generation:** The rotation drives the turbine's mechanical components, converting kinetic energy into electrical energy via a generator.
- **Transmission to the Grid:** Electricity generated is transmitted through underwater cables to an offshore substation, where it is stepped up in voltage for efficient transmission to the onshore grid.
- **Offshore Wind Turbine Components:** Key components include the tower, nacelle (housing the generator), and rotor blades, all designed to withstand harsh marine conditions.
- **Offshore Wind Farm Configurations:** Wind farms consist of multiple turbines arranged to optimize wind capture and minimize interference, designed considering factors like wind direction and speed.
- **Operational and Maintenance Considerations:** Maintenance includes regular inspections and repairs, often requiring specialized vessels.

- **Environmental Impact:** To minimize effects on marine ecosystems, including habitats on the seafloor and marine species, EIAs are carried out.

The collection and transformation of wind energy into a sustainable electrical source is guided by these principles.

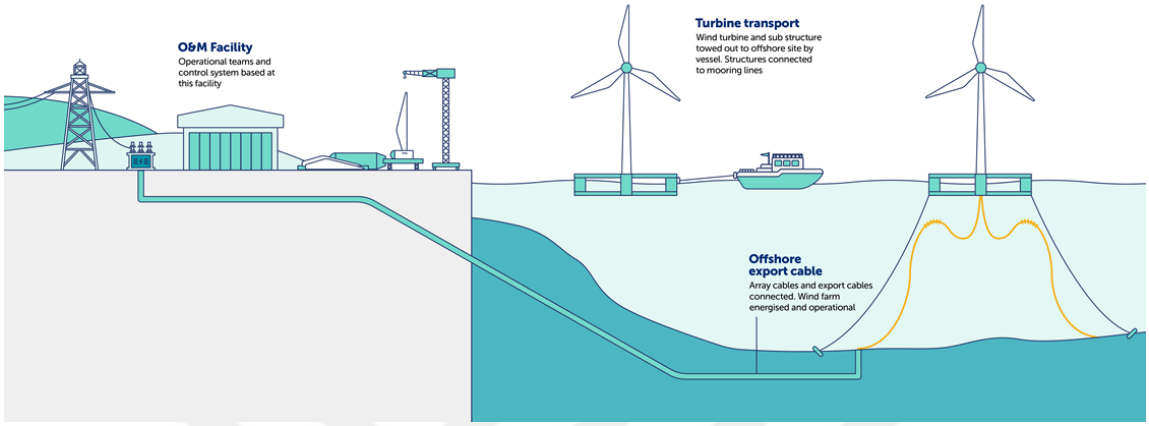

Figure 2.1: General layout of offshore wind energy installations.

Figure 2.1 above (SSE Renewables, n.d.) shows a general layout of offshore wind energy installations. Depending on the water depth and distance to the shore, foundation types might be different.

2.1.2 Benefits of offshore wind

Offshore wind energy establishments offer various benefits, making them an appealing renewable energy source:

1. **Higher and consistent wind speeds:** Compared to onshore**,** offshore sites benefit from higher as well as more consistent wind speeds, resulting in more reliable and efficient electricity generation (Enevoldsen & Valentine, 2016; Volker et al., 2017).
2. **More energy generation potential:** The greater wind speeds in offshore may lead to increased electricity generation per turbine, enhancing the overall efficiency of wind farms (Enevoldsen & Valentine, 2016).
3. **Larger rotors of turbines and greater power capacity:** The environment of offshore supports the deployment of larger turbines, which can capture more wind energy, thereby increasing power capacities (Arshad & O'Kelly, 2013).
4. **Less limitation in land utilization and potential for expansion:** Utilizing sea spaces prevents competition with land use for agriculture or residential

purposes, allowing for optimal space utilization and expansion without impacting terrestrial landscapes (Machado & de Andrés, 2023).

5. **Potential for reduced energy costs:** Technological advancements, economies of scale, and access to stronger winds are expected to reduce costs over time, which is expected to make offshore wind energy economically more viable (Green & Vasilakos, 2011).

These advantages highlight the great potential of offshore wind energy to be considered as a sustainable and reliable power source.

2.1.3 Key elements of offshore wind technology

The technology of offshore wind comprises advanced systems and infrastructure designed for maritime conditions (Asim et al., 2022; Kumar et al., 2016):

- **Turbine Design:** The rotor diameters of offshore turbines are typically larger, and their towers are taller, in order to harness higher wind speeds at higher elevations. They are made of specific materials and coatings for a stronger resistance against corrosion due to sea conditions (Mühlberg, 2010; Quaranta & Davies, 2022).
- **Foundation Types:** Foundation designs vary by water depth, with monopile or jacket foundations used in shallow waters and floating foundations in deeper waters (Bachynski, 2018; Esteban et al., 2019).

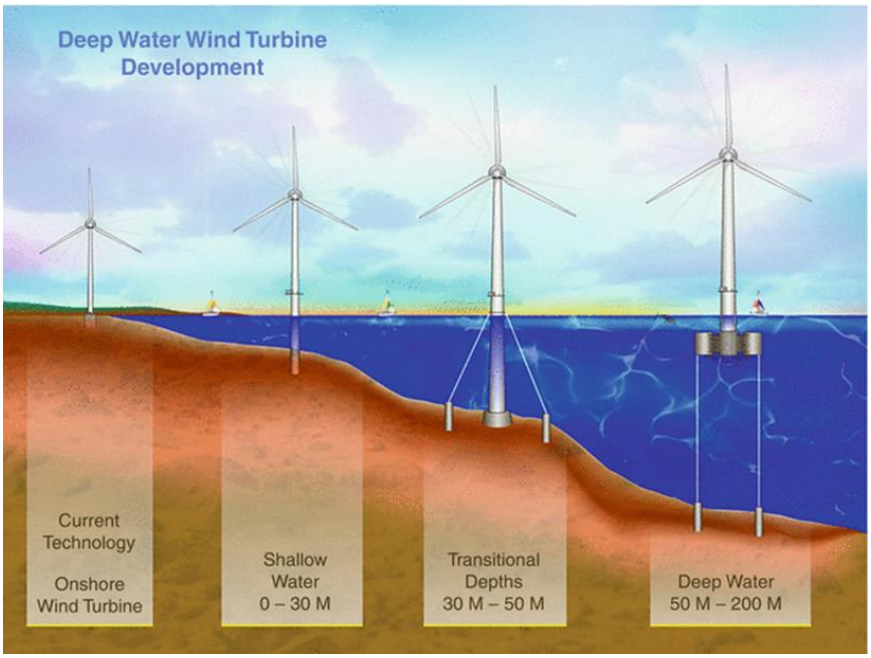

Figure 2.2: Foundation types of offshore wind turbines.

Figure 2.2 above (Dalén, n.d.) shows different types of offshore wind turbine foundations changing based on distance to shore and water depths.

- **Substructures and Installation Techniques:** Installation requires specialized vessels to handle turbine components in challenging offshore conditions (Jiang, 2021).
- **Electrical Infrastructure and Grid Connection:** Extensive infrastructure includes inter-array cables and export cables connecting turbines to offshore substations and then subsequently to onshore grids (Lakshmanan et al., 2021; Pérez-Rúa & Cutululis, 2019; Pillai et al., 2015).

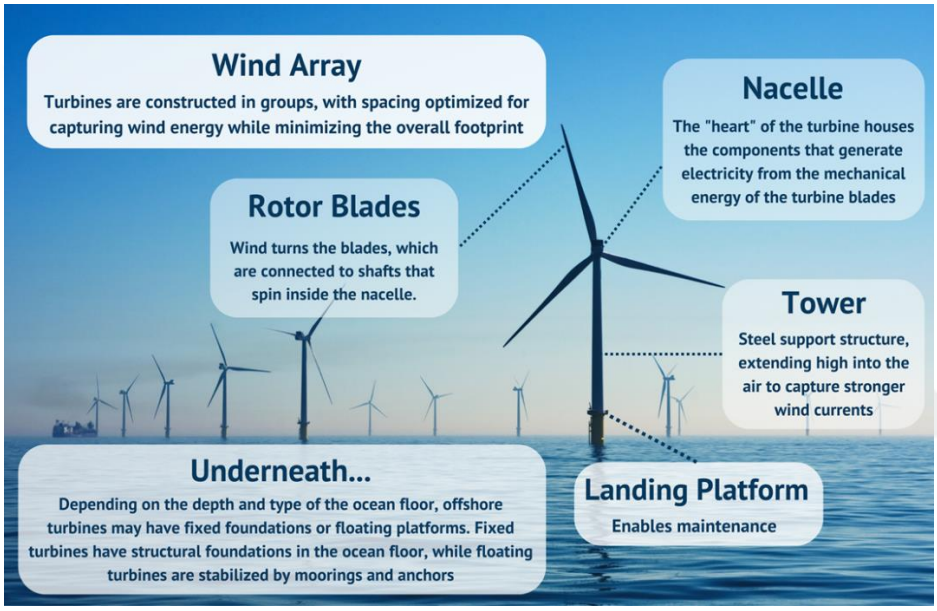

Figure 2.3: Basic elements of an offshore wind turbine.

Above Figure 2.3 (Sea Grant Offshore Wind Energy, n.d.) shows a general layout about the elements of an offshore wind turbine.

2.1.4 Environmental considerations

OWFs are designed with a focus on minimizing environmental impacts on marine ecosystems. Comprehensive assessments are conducted to evaluate the potential effects on seabed habitats, water quality, and marine flora and fauna. Measures are implemented to mitigate risks to marine wildlife, such as reducing collision risks for birds and bats and minimizing underwater noise disturbances to marine species. Activities that temporarily disturb the seabed are managed through monitoring and post-construction habitat restoration efforts. The impact of submarine cables and

infrastructure is minimized by burying the cables and carefully routing them to avoid sensitive habitats. Despite these impacts, OWFs can contribute positively by creating artificial reefs that enhance marine biodiversity over time (Glarou et al., 2020).

2.1.5 Economic viability and cost factors

Offshore wind energy's viability depends on a number of financial and cost factors that affect the growth and sustainability of wind farms in developed nations. According to Gonzalez-Rodriguez (2017), Ioannou et al. (2018), and Shafiee et al. (2016), major upfront investments and capital costs, in addition to operating and maintenance costs, are important economic factors. Significant upfront costs for infrastructure development, grid connection, foundation installation, turbine procurement, and infrastructure development are associated with the establishment of OWFs. Because site surveys, design, engineering, and construction are all included in these capital costs, offshore wind projects are particularly capital-intensive. Furthermore, regular upkeep and repairs, personnel, and inspections are just a few examples of the ongoing operational and maintenance expenses that have a big impact on these wind farms' total lifecycle costs.

However, the LCOE for offshore wind has decreased as a result of technological developments, bigger turbines, better manufacturing techniques, and economies of scale (Bosch et al., 2019; Liang et al., 2021; Shields et al., 2021). Larger turbines generate more electricity, which drives down the price per unit of electricity produced. According to Poulsen and Hasager (2016), innovations, more competition, more efficient supply chains, and improved installation and maintenance efficiency will all contribute to the ongoing decline in the cost of offshore wind energy, making it more affordable than other conventional energy sources.

Government incentives, subsidies, and assistance are essential to the growth of offshore wind. The industry has benefited greatly from early subsidies, and long-term regulations and targets for renewable energy have created an atmosphere that is conducive to investment (Poudineh et al., 2017). Offshore wind projects nevertheless face a number of hazards, such as those related to technology, finances, regulations, and the environment (Karltorp, 2016). In order to get funding, it is frequently necessary to reduce these risks through project finance, consortium-based funding methods, or public-private partnerships.

The primary source of income for OWFs is the selling of electricity, which is backed by renewable energy certificate programs or long-term PPAs (P. Beiter et al., 2020; Poudineh et al., 2017). An important part of figuring out the ROI is assessing these sources of income and projecting financial returns over the course of the project.

The offshore wind industry is becoming more competitive in the energy markets as costs come down and technology advances (Poulsen & Hasager, 2016). Forecasts for the future indicate that cutting-edge technologies will continue to lower costs, making offshore wind a desirable and financially feasible renewable energy source. In order to shape the future and sustainability of these projects, as well as to attract investment and formulate policies in the offshore wind energy industry, it is imperative that decision-makers have a thorough understanding of the economic landscape and cost dynamics.

2.1.6 Emerging trends and innovations in the offshore wind energy industry

The industry of offshore wind energy is always changing due to new regulations, market conditions, and technology developments. New advancements like incorporating energy storage options, such as battery systems and hydrogen generation, in offshore wind projects are complementing recent breakthroughs like floating platforms, larger turbines, and deeper sea deployments (Akdağ, 2023; Wiegner et al., 2024). Energy storage reduces the intermittent nature of wind power and increases system stability and energy delivery reliability.

Furthermore, hybrid projects are beginning to emerge, which combine offshore wind with other reliable sources of renewable energy, such as solar or wave energy (Oliveira-Pinto et al., 2020). These hybrid solutions maximize the potential for coastal areas to produce renewable energy while ensuring more consistent energy output and grid stability (Roy et al., 2018). In order to foster knowledge exchange and joint ventures, cooperation between nations, academic institutions, and industry players is essential (Glowik et al., 2023). The main goals of international cooperation should be to accelerate the growth of offshore wind globally, harmonize laws, and leverage expertise.

Developing decommissioning and repurposing solutions that incorporate circular economy ideas is imperative as offshore wind farms approach the end of their

operational lives (Jadali et al., 2021; Lemasson et al., 2022; Mitchell et al., 2022; Winkler et al., 2022).

For stakeholders in the offshore wind industry to take advantage of opportunities, overcome obstacles, and promote sustainable growth in the sector, they must have a firm grasp of current trends and future directions.

2.1.7 Governance and legislative structures

Regulations, government policies, and actions all have a significant impact on the development and success of offshore wind projects. Nations globally are establishing ambitious targets for renewable energy in order to diminish carbon emissions and combat climate change. Governments around the world are implementing a range of policies and providing incentives, such as subsidiaries, auctions, tax exemptions, and feed-in tariffs, to encourage investment in offshore wind projects. Furthermore, it is imperative to have well-designed zoning regulations to pinpoint optimal sites for wind farm establishment, considering factors such as wind resources, environmental implications, societal aspects, and financial feasibility (Liu et al., 2018).

Securing permissions for the establishment OWFs entails the navigation of intricate regulatory procedures, often involving EIAs and interaction with various parties (Apolonia et al., 2021; Durning & Broderick, 2019; Ryan et al., 2019). These assessments look at ways to reduce risks to marine ecosystems and potentially negative effects on the environment. Ahmed et al. (2020) sets out in their study the significance of effective policies related to grid interconnections and infrastructure advancement for the successful incorporation of offshore wind energy into the onshore grid. This ensures smooth connectivity, establishes transmission corridors, and upholds grid reliability. Moreover, long-term financial sustainability and revenue assurance in implementing offshore wind energy infrastructures are commonly ensured through PPAs or contracts that are secured and supported by governmental bodies (Poudineh et al., 2017). These arrangements offer financial stability, safeguard investors' interests, and improve project viability.

Organizations like the GWEC establish standards and certification protocols to guarantee the safety, reliability, and efficiency of offshore wind installations. Adhering to these standards is vital for project approval and financing. Moreover, involving the public and ensuring inclusivity are crucial to develop offshore wind energy projects.

Public consultation is usually mandated during EIAs, along with encouraging community engagement, addressing concerns raised by the community, and maintaining transparency throughout the project lifecycle. Therefore, for offshore wind energy to advance and sustainable project outcomes to be achieved, a regulative model that strikes a balance between conservation of the environment, economic reliance, and social inclusivity is needed.

This comprehensive review in this section has extensively examined offshore wind, encompassing its fundamentals, benefits, technological progress, environmental impacts, economic factors, prevailing trends, and regulatory structures. The findings of this review provide significant perspectives for parties that are involved in making decisions, policymakers, and financial investors, facilitating and promoting the continuous growth of the offshore wind industry.

2.2 Worldwide Progress and Innovations in OWFs

This section provides a comprehensive analysis of the global progress of OWFs, covering their historical development, technological advancements, and key milestones. It also delves into current trends, innovations that emerge, as well as future projections within the offshore wind industry.

2.2.1 Milestones and innovations in the evolution of offshore wind energy

Technological developments and significant turning points have characterized the development of OWFs. Due to innovative trials and small-scale installations in Denmark and the UK, offshore wind energy initially gained traction in the late 20th century (Ackermann & Söder, 2000). The potential of using wind power in maritime environments was shown by these early projects. Larger installations and economic viability were the focus of the sector by the late 1990s, when commercial-scale OWFs such as Denmark's Vindeby project (Barthelmie et al., 1994) were established. Early in the new millennium, technological advancements produced increasingly efficient turbines, as demonstrated by projects like Denmark's Horns Rev and the UK's North Hoyle, which demonstrated larger capacities and better performance (Thresher et al., 2009). With large investments from nations like Belgium, the Netherlands, and Germany, Europe quickly emerged as a hub for offshore wind development (Brucker,

2020; GWEC, 2020). This led to a notable increase in capacity and the deployment of OWFs in waters far from shore, using creative foundation type designs.

Outside of Europe, offshore wind has become more popular in recent years. According to Dwyer and Bidwell (2019), countries such as China, the US, Taiwan, and South Korea have become significant players in the offshore wind project market as a means of achieving their goals of decreasing carbon emissions and achieving renewable energy targets. Turbines with bigger rotor diameter, floating solutions for the turbine deployment in deeper waters, and improvements in technologies to store the energy are just a few of the ongoing technological advancements that are driving the evolution of offshore wind with the goal of increasing efficiency, cutting costs, and broadening the geographic reach of economically feasible OWFs.

This story highlights how offshore wind energy has grown from experimental beginnings into a rapidly expanding global industry, driving innovation and playing a crucial role in renewable energy solutions.

2.2.2 Global expansion and future prospects of offshore wind

The industry is experiencing substantial growth in installed capacity and is poised for significant global expansion. The installed capacity of OWFs worldwide is estimated by Fernández (2023a) in Statista to be approximately 69,200 MW. With markets in Asia and the Americas growing quickly, this capacity is distributed throughout several regions, with Europe historically setting the standard. To be able to reach their aggressive renewable energy goals, nations like South Korea, Taiwan, and China are investing heavily in OWF projects (Gollakota and Shu, 2023). These nations take advantage of their plentiful wind resources. Developing wind energy projects in offshore along the East Coast is becoming more and more popular in the Americas, especially in the US. In the upcoming years, major projects in states like New Jersey, New York, and Massachusetts, are expected to increase the installed capacity of offshore wind energy (P. C. Beiter et al., 2020; Kempton et al., 2005).

The global outlook for OWF projects indicates robust potential for future expansion. The sector's swift development is underscored by many projects in progress, particularly in the northeastern United States, which are expected to considerably increase capacity within the next decade (P. Beiter et al., 2020). Presently, the offshore wind energy industry features a diverse array of projects worldwide, with Europe at

the forefront in terms of installed capacity and significant growth potential emerging in Asia and the Americas. The industry's strong growth strategies and ongoing projects underscore the strong dedication to achieving an offshore wind-powered sustainable energy future.

2.3 A Glance to Offshore Wind Energy Potential in Turkey

This section examines Turkey's current and future projects in Turkish waters, as well as its policy frameworks and ongoing initiatives related to offshore wind energy. It evaluates the legislative framework and policy measures intended to encourage Turkey's development of offshore wind energy.

2.3.1 Turkey's offshore wind potential and energy evolution

Energy security is ensured by Turkey's energy sector, which uses a variety of sources to meet its needs. Historically, fossil fuels, especially coal and natural gas, have dominated the sector. These sources are essential for producing electricity and meeting industrial needs. (Difiglio et al., 2020; Kaygusuz & Sarı, 2003). Nonetheless, Turkey has been working harder in recent years to promote renewable energy sources in order to diversify its energy mix and lessen its reliance on fossil fuels (Durak, 2023). Figure 2.4 below depicts the evolution of the electricity market reform, which was started with the adoption of the Electricity Market Law in March 2001 (Durak, 2023).

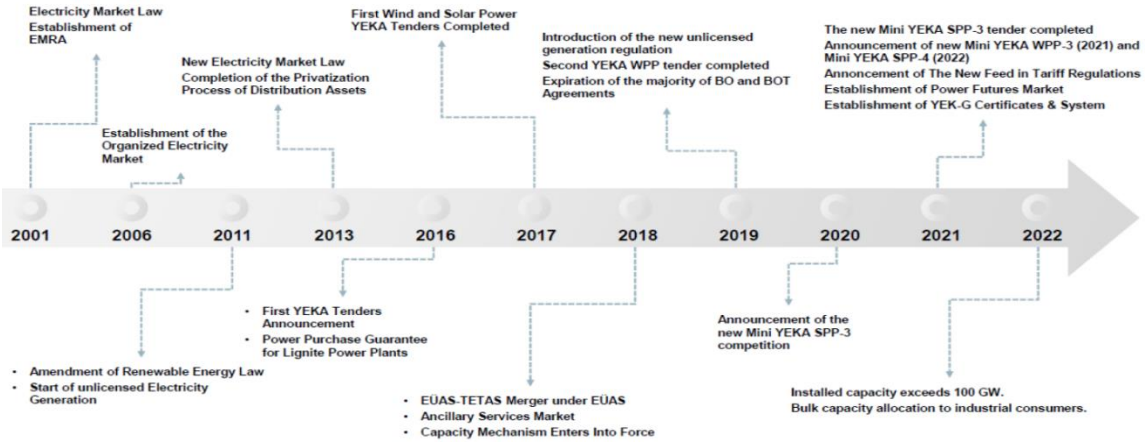

Figure 2.4: Turkish energy market evolution.

Turkey's renewable energy landscape is growing, and renewable energy sources like solar, wind, hydropower, and biomass have become important players (Erdil and Erbıyık, 2015). Of particular importance are onshore wind and hydroelectric stations,

which generate a significant amount of power (Gök, 2013). Despite this progress, offshore wind remains largely unexplored, even though it has the potential to substantially bolster the capacity of renewable energy of the country. Turkey has moderate wind speeds at offshore; these are especially favorable around the western Aegean coast (8.0 - 9.5 m/s) and some areas of the Marmara Sea (7.0 - 8.5 m/s) (Durak, 2023; Mostafaeipour, 2010). The Black Sea has consistently lower wind speeds, averaging between 7.0 and 7.5 m/s or less (Durak, 2023). Yet, it is thought that the wind speeds off the southern coast are insufficient for offshore wind development.

Today, onshore wind turbines in Turkey generate about 12 GW of power (Novak, 2023). Energy demand, nonetheless, has escalated as a result of economic expansion and the growing trend towards urban living. (Raihan & Tuspekova, 2022). According to Durak (2023), the installed total capacity is approximately 105 GW, with a growing need at an annual rate of 4%, driven primarily by industrial activity, which accounted for 44% of total demand in 2021—a 15% increase since 2018. Additionally, the Turkish government subsidizes electricity for about 2 million households, further driving up demand (Durak, 2023). In response, Turkey aims to balance its energy mix sustainably to meet the rising demand and reduce dependency on imported fossil fuels. The government is committed to diversifying the energy portfolio and increasing the share of renewables, in line with global trends towards sustainable energy sources (Durak, 2023; Hurriyet Daily News, 2023).

Turkey's advancements in offshore wind energy are promising, leveraging existing transmission infrastructure to integrate wind power efficiently. The strategy includes reinforcing transmission networks to support large OWFs in high-demand western regions, with TEİAŞ planning significant reinforcement projects over the next decade. Ports like Bandırma, İçtas, Çanakkale, Aliağa, and Çandarlı are being considered for minor enhancements to host offshore wind installations, presenting development opportunities. The shipbuilding industry is pivotal in creating specialized vessels for offshore wind projects, and Turkey's established onshore wind expertise and developed supply chain support this growth.

The National Energy Plan outlines ambitious renewable energy targets, aiming for 5 GW of offshore wind capacity by 2035, contributing to a broader goal of nearly 30 GW total wind energy capacity, alongside solar, hydroelectric, nuclear, and conventional sources. Recent policy initiatives consist of the implementation of fresh

feed-in tariffs and production incentives within the YEKDEM framework, guaranteeing continuous backing for projects related to renewable energy. Additionally, the Ministry of Energy and Natural Resources, with EU funding, is conducting detailed research on meteorological and oceanographic conditions at specific offshore sites to provide essential data for informed decision-making and sustainable development of offshore wind energy.

Turkey's evolving energy landscape, increasingly emphasizing renewables, underscores the pivotal role of offshore wind in forming the nation's sustainable energy future.

2.3.2 Governmental and academic efforts in promoting offshore wind energy

In Turkey, government initiatives and policies are pivotal in advancing renewable energy, including offshore wind. This section explores specific efforts, regulatory frameworks, and policies aimed at promoting offshore wind energy within Turkey. Legislation such as the Renewable Energy Law, along with subsequent amendments, provides feed-in tariffs, incentives, and support mechanisms for renewables, including offshore wind (Bulut & Muratoglu, 2018). Moreover, strategic plans like the NREAP set objectives for renewable energy and outline precise targets for offshore wind capacity (Keskin et al., 2020; Şahin, 2021), guiding its integration into Turkey's energy landscape.

The research initiatives in offshore wind area are also actively supported by research centers, well-qualified universities, and other academic organizations in Turkey. Their projects include environmental impact assessments, technological developments specifically for offshore wind farms, and assessments of wind resources (Erdin & Ozkaya, 2019; Yildirim, 2023). The next section goes into more detail about these initiatives.

2.4 Synthesis of Offshore Wind Farm Research in Turkey

This section provides a critical analysis of the existing literature on OWFs in Turkish seas and comparable global environments. It offers a comprehensive synthesis of methodologies, findings, and conclusions from relevant research.

Satir et al. (2018) emphasize the economic viability and attractiveness of OWFs as a profitable investment in Turkey, drawing parallels with successful projects in European countries. Despite the substantial financial investment and technological complexity involved, OWFs in Europe have demonstrated their feasibility as a sustainable source of energy (Arshad & O'Kelly, 2019; Letcher, 2023; Mani & Dhingra, 2013).

Regarding the suitability of sites, Argin et al. (2019) employed the WAsP in conjunction with statistical modeling to identify optimal locations such as Bozcaada, Bandırma, Gökçeada, İnebolu, and Samandağ. They estimated a combined potential capacity of 1,629 MW. Similarly, Argin and Yerci (2017) highlighted Amasra, emphasizing the need for zoning adjustments to effectively harness its significant offshore wind energy potential.

Genç et al. (2021) utilized GIS and MCDM methodologies to evaluate Turkey's maritime zones, identifying 3,294.8 km2 (1.38%) suitable for OWFs. Their study highlighted the Marmara Sea as the most favorable region, followed by the Aegean, Black, and Mediterranean Seas, emphasizing the importance of supportive legislative frameworks for the expansion of OWFs in Turkey.

Emeksiz and Demirci (2019) introduced the NHSSM incorporating the AHP across thirty-one coastal regions, identifying Bafra, Sinop, and Mersin as top-tier sites with a combined potential capacity of 9,021 MW. Their innovative approach aids in informed decision-making and policy development for renewable energy projects in Turkey.

Deveci et al. (2020) employed an intuitionistic fuzzy sets-based MCDM approach to pinpoint İnebolu, Amasra, and Karasu as optimal locations for OWFs in the Black Sea. They recommended further validation of criteria such as CAPEX costs and tidal influences, suggesting exploration of alternative MCDM methodologies.

Caceoğlu et al. (2022) developed a GIS-based methodology integrating the Analytical Hierarchy Process for the selection of OWF sites in Northwest Turkey, emphasizing Bozcaada and Kıyıköy as prime candidates. Their comprehensive approach establishes a framework for site selection aligned with Turkey's ambitious renewable energy targets.

In conclusion, these studies highlight the significant potential for OWF development in various coastal regions of Turkey. However, the disconnect between academic

research and governmental decisions, particularly regarding YEKA regions (Hurriyet Daily News, 2023), underscores the need to bridge gaps between research insights and policy implementation to effectively harness Turkey's offshore wind resources in alignment with national energy goals. Integrating academic research with strategic governmental initiatives is crucial for maximizing the benefits of renewable energy development in Turkey.

2.5 Theoretical Framework

When exploring the applicability of OWFs in Turkish waters, it is essential to establish a theoretical framework that guides the analysis and interpretation of research findings. This study examines various interdisciplinary aspects of the offshore wind industry through several theoretical lenses:

- **Analysis of Economic Aspects:** This framework examines the cost-effectiveness, financial feasibility, and economic consequences of OWF projects, encompassing investment choices, cost-benefit evaluations, and economic models (Cali et al., 2018).
- **Framework for Environmental Impact Assessment:** By merging environmental theories, this method evaluates the ecological implications, biodiversity effects, and sustainability considerations linked to OWFs (Ryan, Danylchuk, & Jordaan, 2019).
- **Theories on Innovation and Technology Adoption:** Rooted in innovation diffusion and technology adoption theories, this viewpoint delves into the development, adoption, and integration of new technologies within the offshore wind energy sector (Aldersey-Williams, 2020).
- **Perspectives on Policy and Governance:** The theoretical foundation utilized in this study incorporates theories with regards to policy analysis, administrative bodies, and regulatory guidelines to examine the impact of government policies, incentives, and regulations on the advancement of OWF projects in Turkey (Ata, 2015; Partelow et al., 2020).
- **Theory on Social Acceptance and Involved Parties:** By utilizing stakeholder engagement and social acceptance theories, this framework examines local perceptions, community involvement, and strategies promoting engagements of the stakeholders in OWF projects (Partelow et al., 2020).

- **Theories on Risk Assessment:** By integrating risk analysis theories, decision-making processes, and project management, this perspective aids in evaluating and mitigating risks associated with OWF development, thereby supporting strategic decision-making (Liu et al., 2021; Xu et al., 2020).

By using these theoretical frameworks, the study takes a systematic approach to examine the various aspects of OWF implementation in Turkish waters. The integration of these theories enhances comprehension spanning technical, economic, environmental, social, and policy dimensions, facilitating a comprehensive assessment of the potential advantages and obstacles for OWF projects in the area.

2.6 Chapter Summary

This chapter goes into great detail about offshore wind energy, covering its background globally, its current state in Turkey, as well as its opportunities and challenges. It provides a thorough introduction to offshore wind energy, covering its fundamentals, developments in technology, effects on the environment, and place in the world's renewable energy supply.

The talk discusses global trends in offshore wind farms and highlights innovations, challenges, and successes in established markets across the globe. The chapter examines the current energy landscape, with a particular focus on Turkey, emphasizing the growing utilization of renewable energy sources and the dependency on conventional fossil fuels. It addresses the socioeconomic effects, stakeholder engagement tactics, and public perceptions of offshore wind projects in Turkish waters by looking at possible locations, feasibility studies, and regulatory complexities.

In conclusion, the chapter introduces theoretical frameworks relevant to offshore wind feasibility studies, providing insights into economic, environmental, technological, and societal dimensions. It emphasizes the significance of understanding regulatory complexities and theoretical foundations crucial for assessing offshore wind prospects in Turkish seas.

3. METHODOLOGY

3.1 Preliminary Analysis: Renewable Energy Status and Consumption in Europe

This preliminary analysis serves as the foundational groundwork for a deeper exploration of Europe’s offshore wind energy potential and its alignment with global trends.

It encompasses a broad spectrum of factors influencing the energy landscape, from installed capacity in renewables to consumption trends and dependency on external energy sources. It examines forecasts for renewable energy installed capacity, addressing concerns related to hydropower's environmental impact of Europe’s growing reliance on wind energy. This stage evaluates efforts in wind energy, its installed capacity within Europe, highlighting its existing infrastructure and potential for offshore wind power generation. Insights from experts and industry leaders underscore OWF role in shaping Europe's wind energy industry and its capacity to exceed national targets, reinforcing the country's commitment to cleaner energy practices. Overall, this phase serves as a robust foundation, setting the stage for an in-depth exploration of Aegean coastlines and Turkey's offshore wind energy prospects and their global contextualization.

Offshore wind energy has emerged as a pivotal component of Europe's renewable energy landscape, contributing significantly to the region's efforts to transition towards sustainable and low-carbon energy systems. The status of offshore wind energy in Europe can be characterized by several key factors, including technological advancements, policy frameworks, market dynamics, and environmental considerations.

Technological advancements have played a crucial role in driving the growth of offshore wind energy in Europe. Innovations in turbine design, foundation structures, and installation techniques have enabled the development of larger, more efficient, and cost-effective offshore wind farms such as the 1.2 GW Hornsea Project One in UK, and the 2.1 GW HEREMA Project in Greece. According to the EWEA, technological

advancements have led to a substantial increase in the average turbine capacity and overall energy output of offshore wind projects across Europe (IEA, 2019). These advancements have contributed to the region's ability to harness the abundant wind resources available in offshore areas, thereby facilitating the expansion of offshore wind capacity.

Policy frameworks have also been instrumental in shaping the development of offshore wind energy in Europe. Ambitious renewable energy targets, coupled with supportive regulatory mechanisms and financial incentives, have provided a conducive environment for investment in offshore wind projects. The European Union's Renewable Energy Directive and the National Renewable Energy Action Plans of individual member states have set binding targets for the deployment of renewable energy, including offshore wind (IEA, 2020). Additionally, mechanisms such as feed-in tariffs, competitive auctions, and subsidy schemes have facilitated the financing and development of offshore wind projects, driving down costs and enhancing market competitiveness.

Market dynamics have undergone significant transformation, with offshore wind emerging as a mainstream energy source in Europe. According to the International Energy Agency (IEA, 2019), the cumulative installed capacity of offshore wind in Europe exceeded 25 GW by the end of 2020, accounting for the majority of global offshore wind capacity (IEA, 2019). The increasing competitiveness of offshore wind energy, relative to conventional energy sources, has attracted investments from utilities, developers, and financial institutions, leading to a surge in project development and construction activities.

Environmental considerations have also shaped the status of offshore wind energy in Europe, with a growing emphasis on sustainability and climate change mitigation. Offshore wind projects offer several environmental benefits, including reduced greenhouse gas emissions, improved air quality, and protection of biodiversity (Farr et al., 2021). The European Commission's European Green Deal and the Climate Law reinforce the continent's commitment to achieving carbon neutrality by 2050, with offshore wind playing a pivotal role in decarbonizing the energy sector (*European Climate Law*, 2020). Moreover, initiatives such as the Offshore Renewable Energy Strategy (2020) and the EU Biodiversity Strategy (2020) aim to promote the

sustainable development of offshore wind while safeguarding marine ecosystems and biodiversity.

The status of offshore wind energy in Europe reflects a dynamic and rapidly evolving sector driven by technological innovation, supportive policy frameworks, market competitiveness, and environmental imperatives. Continued investment, innovation, and collaboration will be essential to further expand offshore wind capacity, optimize energy production, and address emerging challenges such as grid integration, permitting, and stakeholder engagement. As Europe continues to lead the global transition towards a sustainable energy future, offshore wind stands poised to play a central role in achieving climate objectives and fostering economic growth and prosperity. Key factors influencing the offshore wind energy landscape in Europe are;

- **Installed Capacity in Renewables:** The growth of offshore wind energy in Europe is closely tied to the continent's overall installed capacity in renewable energy sources. According to the EEA, Europe has witnessed a significant expansion in renewable energy capacity in recent years, with renewables accounting for a growing share of the electricity mix (Renewable Energy in Europe). Consequently, Europe is a leader in offshore wind energy. The European Commission expects the EU to produce at least 240 GW of global offshore wind power capacity by 2050 (Offshore wind energy in Europe, 2024). In 2022, renewable energy capacity in Europe amounted to 705.8 GW, as illustrated in below Figure 3.1 (Fernández, 2023b). Also, below Figure 3.2 shows the renewable electricity mix ratio changes in the EU, by energy source, as well as the steady increase in wind power from 2013 to 2021. (Fernàndez, 2024)

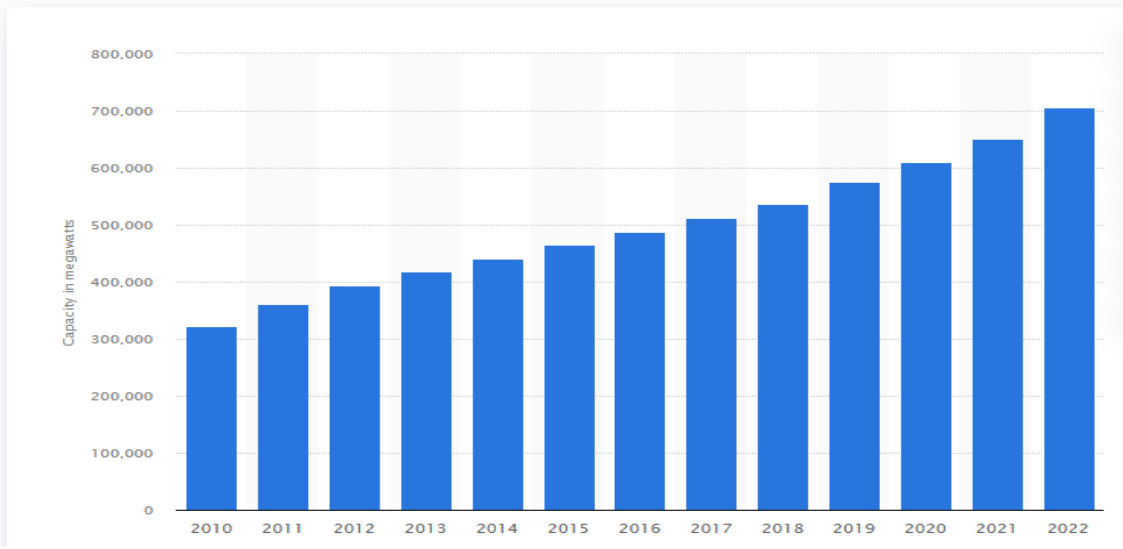

Figure 3.1: Renewable energy capacity in Europe from 2010 to 2022 in MW.

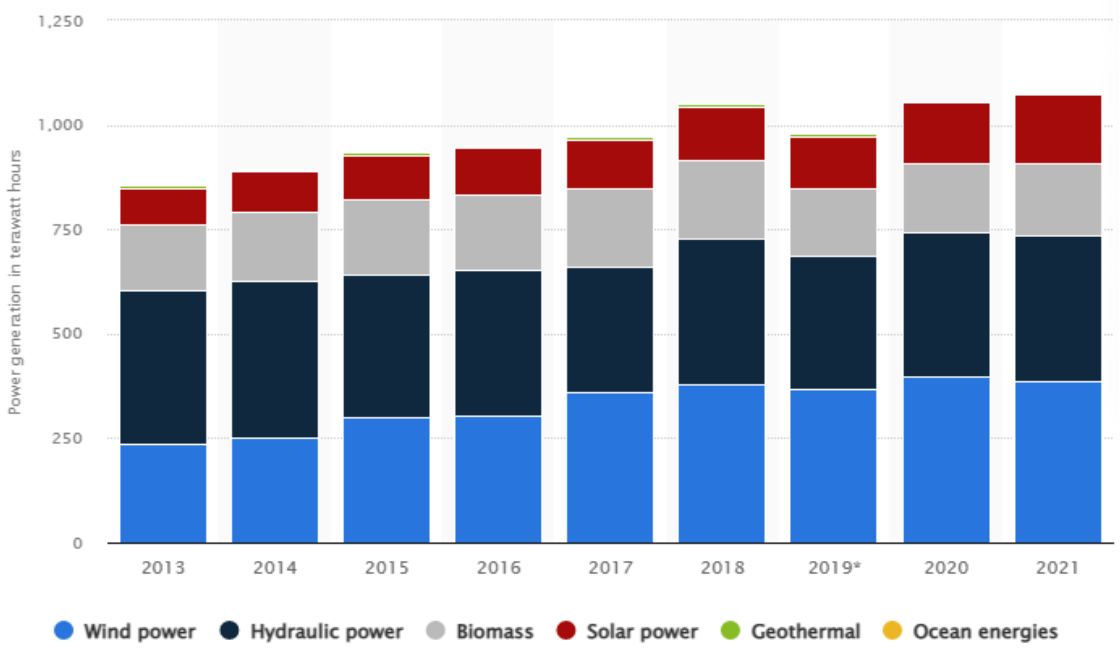

Figure 3.2: Renewable electricity mix in the European Union from 2013 to 2021, by energy source (in TWh).

- **Technological Innovation**: Technological advancements in offshore wind turbine design, foundation structures, and installation techniques drive the efficiency, cost-effectiveness, and scalability of offshore wind projects. The EWEA underscores the role of innovation in reducing the LCOE and enhancing the competitiveness of offshore wind (Technology & Innovation). Floating bases for offshore wind turbines could prove to be a game-changing technology, allowing much wider exploitation of wind resources (Fernández,

2024). Apparently, the leading projects for commercializing these floating technologies are based in Europe (Fernández, 2024).

- **Consumption Trends:** Consumption trends in Europe, including changes in energy demand patterns and consumption habits, influence the deployment and utilization of offshore wind energy. ACER highlights the importance of monitoring energy consumption trends to ensure adequate supply and optimize energy efficiency (Energy Consumption in Europe, 2021). Consequently in 2022, the EU's final energy consumption by end users fell by 1.5% compared to 2021 levels (European Environmental Agency, 2024). Primary energy consumption, which includes all energy uses, notably also fell by 4% from the year 2021 to 2022 (European Environmental Agency, 2024). Nevertheless, it is possible to note a consistent increase in renewable energy share in the gross consumption in the EU, from 2012 to 2021, as illustrated in below Figure 3.3 (Fernàndez, 2024).

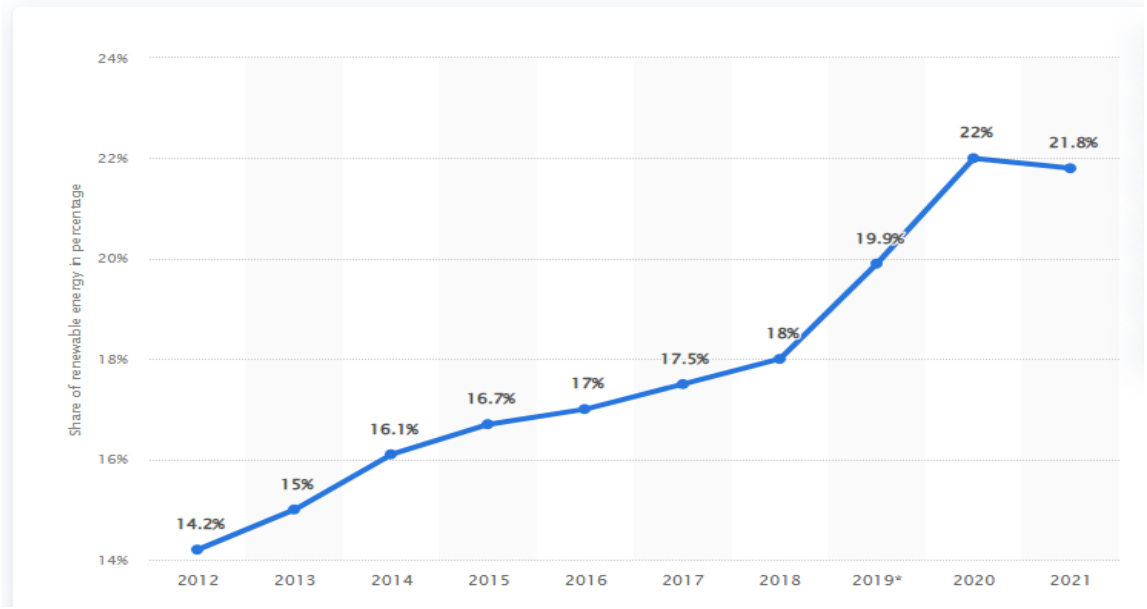

Figure 3.3: Share of renewable energy in the gross consumption of energy in the European Union 2012 to 2021.

- **Dependency on External Energy Sources:** Europe's dependence on external energy sources, particularly fossil fuels, underscores the need to diversify the energy mix and enhance energy independence. The European Commission emphasizes the importance of reducing energy imports and increasing domestic energy production through renewable sources ("Energy Security Strategy"). Offshore wind energy offers a domestic and sustainable alternative,

helping to mitigate geopolitical risks associated with reliance on imported fuels. Europe's energy demand has long exceeded local production capacities, resulting in a dependency on energy imports in the EU reaching as high as 60 percent in recent years (Statista, 2023). In 2017, the dependency rate was equal to 55 %, which means that more than half of the EU's energy needs were met by net imports (Statista, 2023).

- **Policy and Regulatory Frameworks:** Policy and regulatory frameworks at the national, regional, and supranational levels shape the market dynamics, investment climate, and deployment incentives for offshore wind energy. The European Commission's Renewable Energy Directive sets binding targets for renewable energy deployment, including offshore wind, across member states ("Renewable Energy Directive"). The European Parliament has been supportive of offshore wind energy, in particular the potential for a North Sea offshore grid (energy hub) (Fernández, 2024). We observe that some EU Member States have set their own indicative targets for offshore wind deployment by 2030, accompanied by a range of support schemes (Fernández, 2024).

3.2 Overview of Turkish Offshore Wind Energy Potential

The European offshore energy sector is undergoing significant development, driven by efforts to transition towards renewable sources and reduce dependence on fossil fuels. This overview will critically analyze the current status of offshore energy in Europe, comparing the situations in Turkey.

Turkey, during the years, continued its wind energy investments throughout the years to utilize the wind potential of the country. This increase in installed wind power capacity from 2008 to 2023 is shown in below Figure 3.4 (Dierks, 2024). In line with that, Turkey has emerged as a promising market for offshore wind energy development, given its extensive coastline and strong wind resources. The Turkish government has expressed ambitions to harness offshore wind energy to diversify its energy mix and enhance energy security (BloombergNEF, 2021). However, progress has been relatively slow compared to other European countries, with regulatory uncertainties and permitting challenges hindering investment and project implementation (Güngör, 2023). Despite these challenges, Turkey has taken steps to

accelerate offshore wind development, including the announcement of ambitious targets and the initiation of feasibility studies for potential project sites (BloombergNEF, 2021).

Turkey has a significant offshore wind energy potential, estimated at 90 GW (4C Offshore, 2021). The country is expected to take off first due to political commitment to energy transition and an already well-developed local supply chain for onshore wind (4C Offshore, 2021). However, most of Turkey's adequate offshore wind resources are found in deep waters in the Eastern Mediterranean and Black Seas, suited for floating turbines (4C Offshore, 2021).

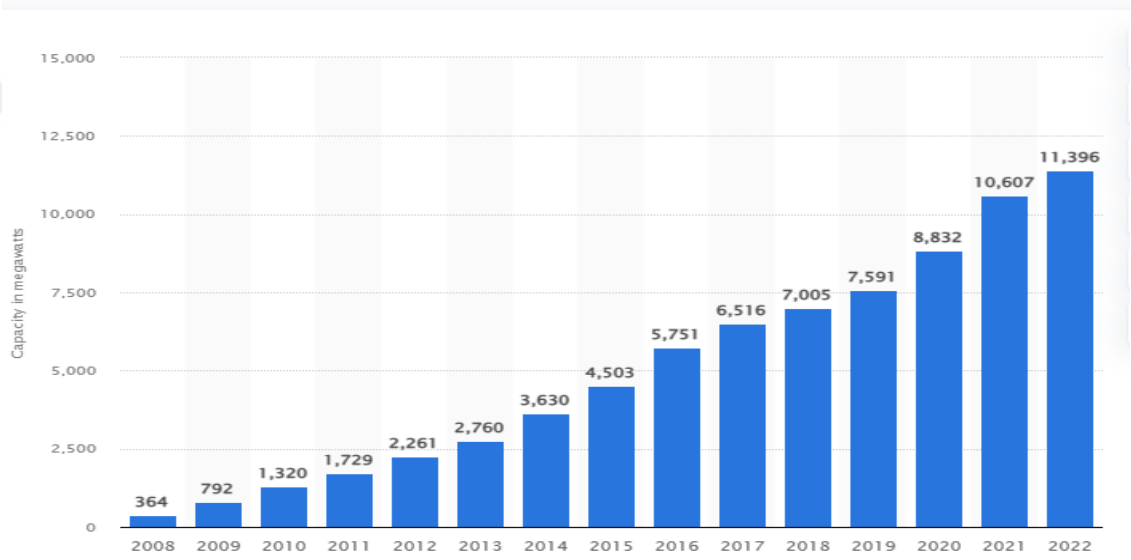

Figure 3.4: Installed wind power capacity in Turkey from 2008 to 2023 (in MW).

We observe that the country has significant potential for offshore wind energy. Turkey seems developed in terms of political commitment and the development of a local supply chain.

In conclusion, the European offshore energy sector is witnessing dynamic growth driven by advancements in offshore wind power and ongoing exploration of wave and tidal energy. While countries like the UK and Germany lead the offshore wind market, emerging markets like Turkey and Greece hold considerable potential for future development. However, challenges related to regulation, permitting, and investment continue to pose barriers to realizing this potential. Overcoming these challenges will require concerted efforts from governments, industry stakeholders, and the wider community to unlock the full benefits of offshore energy in Europe.

The next section is a presentation of current data and an in-depth comparative case study of the economic analysis of Turkey's Aegean Sea offshore potential.

3.3 Data Collection and Methodology Review

This primary step involves a comprehensive review of existing literature, reports, and data sources related to Turkey's energy landscape, specifically focusing on wind energy, renewable energy policies, installed capacities, and forecasts. In this research, the data collection methodology was primarily based on secondary research techniques, leveraging existing sources such as research papers, Turkish government publications, European Union reports, and climate data. The emphasis on secondary research was driven by the need to gather comprehensive and reliable information related to offshore wind farm economic feasibility, drawing insights from existing knowledge, regulations, and empirical studies.

The initial phase involved an extensive literature review, wherein peer-reviewed research papers and industry reports were analyzed to understand the global and regional contexts of offshore wind energy, focusing particularly on Turkey. This approach allowed grasping the historical development, technological advancements, and challenges faced by offshore wind projects. Insights from successful projects, like Hornsea Project One in the North Sea, provided valuable benchmarks for assessing Turkey's potential.

Government sources and policies, especially those from the Turkish government and the European Union, were pivotal in understanding the regulatory landscape and incentives that influence offshore wind development. This secondary data helped in gauging the existing support mechanisms, potential barriers, and the overall policy environment shaping the offshore wind sector in Turkey. Additionally, climate data played a crucial role in evaluating the wind energy potential along the Turkish coastline. Utilizing existing climate studies (Gumuscu et al., 2023; RealGreekExperiences, 2023; TheWindPower, 2024; Vagenas et al., 2017; Veers et al., 2019) and wind resource assessments, we could simulate conditions in the Aegean Sea, providing a foundation for the economic feasibility analysis.

While primary research might offer more direct and specific insights, the reliance on secondary data in this study was justified by the need for a broader understanding of

the offshore wind landscape in Turkey. The limitations of this methodology include potential gaps in data availability, varying data quality across sources, and the inability to capture real-time or site-specific information. However, the thorough validation of sources and a systematic approach to data synthesis ensured a reliable foundation for the economic feasibility study of OWFs in the Turkish Aegean region.

4. RESULTS AND DISCUSSION

4.1 Data Analysis

Turkey's recent advancements in the energy sector signal a transformative shift, positioning the nation as a notable player in the global energy arena (Costu, 2023). At the forefront of these developments is the East-West Energy Corridor Project, a strategic initiative that involves the construction of Trans-Caspian and Trans-Caucasian oil and natural gas pipelines. By expanding its existing seven energy transmission lines, (Costu, 2023) including both oil and natural gas pipelines, Turkey aims to significantly enhance its energy transfer capabilities. The Iğdır-Nahçıvan Natural Gas Pipeline, among other key projects, has been instrumental in connecting Asia to Europe, thereby solidifying Turkey's role in shaping Europe's energy landscape.

Crucially, Turkey recognizes the importance of renewable energy in ensuring a sustainable future. The country's focus on renewable energy production aligns with its growing population and economy, fostering a rapid expansion of the energy system. This dual commitment to both conventional fossil fuels and renewable sources underscores Turkey's comprehensive approach to energy security and sustainability. Turkey's emergence as a significant player in the global energy landscape is evident in its multifaceted efforts. The nation's strategic investments in energy transfer, exemplified by the East-West Energy Corridor Project and the Istanbul Energy Center, coupled with its emphasis on renewable energy, showcase a comprehensive approach to shaping its energy future. As Turkey works towards its 'Energy Century' vision, its increasing role in the global energy market is poised to have far-reaching implications for both regional and international energy dynamics (Costu, 2023).

The information provided by the ITA (ITA, 2023) outline the Turkish government's strategic approach to address the current account deficit by prioritizing renewable energy investments. The focus on domestic resources, particularly in wind, solar, hydro, geothermal, and biomass energy, reflects a concerted effort to reduce the hefty $40 billion spent on energy resource imports like oil, natural gas, and coal. Notably,

renewable energy projects up to 5 MW benefit from simplified regulations, exempting them from the power generation license requirement from the EPDK, and net-metering is permitted.

The Turkish government's initiative to issue YEKA tenders for large-scale solar and wind projects underscores its commitment to renewable energy development. However, challenges arose in attracting investors for larger YEKA projects, leading to the decision to break down future tenders into smaller capacities, such as 10 MW, 15 MW, and 20 MW. This move aims to address financing concerns and stimulate broader investor participation (ITA, 2023).

The ITA (2023) report highlights the impact of the COVID-19 pandemic on renewable energy demand, but anticipates a resurgence as economic conditions have improved in the latter part of 2021 and beyond. Projections suggest that Turkey's installed capacity will double by 2050, with 50% of power generation coming from renewable sources. This aligns with the government's goal to prioritize renewable energy, not only for economic reasons but also to reduce reliance on energy imports.

In terms of recent market trends, while progress on large YEKA projects has been gradual, the unlicensed solar sector (less than 1 MW) has shown substantial growth, reaching an output of 6.3 GW. Wind energy, geothermal, and biomass energy also contribute significantly to the renewable energy landscape, collectively meeting 44.2% of total demand as of September 2020. The government's focus on decreasing the current account deficit, largely driven by energy imports, reinforces its commitment to fostering a favorable environment for renewable energy investments.

The competitive landscape in Turkey involves major competition from international players such as German, Chinese, Korean, and Italian companies, alongside local companies. The selection criteria for equipment and technology suppliers include considerations of price, quality, and financing. Incentives for localization are acknowledged as a significant financial barrier, and the fixed feed-in tariffs for YEKA projects with long-term power purchase guarantees indicate the government's commitment to supporting and stabilizing the renewable energy market (ITA, 2023).

The statistics from Statista (2023) paint a dynamic picture of Turkey's energy landscape, showcasing a noteworthy shift in the country's energy mix over the years. Turkey has historically capitalized on its hydroelectric potential, with the first hydro

plants dating back to the early 20th century. However, the environmental concerns associated with large hydro plants have prompted a diversification strategy, leading to a significant increase in the share of solar and wind energy.

The remarkable growth in renewable energy generation is a key highlight. This growth reflects Turkey's commitment to embracing cleaner energy sources. Wind energy, in particular, has witnessed impressive expansion, contributing over 35 TWh in 2022 - a remarkable surge from 2008's 0.8 TWh. The country has also made strides in solar power, with generation escalating from 0.2 GWh in 2015 to nearly 16 TWh in 2022. However, concerns arise about potential delays in future wind and solar investments, particularly in the aftermath of the COVID-19 pandemic. Experts stress the need for government intervention to address these challenges, emphasizing the importance of extending deadlines and enhancing network infrastructure.

Hydropower remains a significant player in Turkey's energy portfolio, constituting nearly one-fifth of the country's energy production. Despite a decrease from the 2019 peak of 89 TWh to 67.2 TWh in 2022, hydropower maintains its status as the largest renewable source of electricity. The decline in hydropower generation may however be influenced by factors such as changing precipitation patterns or variations in water availability. In contrast, bioenergy capacity has experienced substantial growth, expanding over tenfold since 2008 and reaching over 1.9 GW in 2022. Additionally, geothermal cumulative installed capacity amounted to approximately 1.7 GW in 2021. While these Figures represent significant progress, it's noteworthy that geothermal and biomass sources still contribute relatively modestly to overall energy generation compared to other renewables.

According to data from Statista (2023), Turkey's energy landscape reflects a commendable effort to diversify its energy sources and increase reliance on renewables. Below Figure 4.1 shows the wind power generation in Turkey from 2008 to 2022. The substantial growth in wind, solar, and bioenergy capacities demonstrates a commitment to cleaner and more sustainable energy practices. However, challenges related to the impact of the COVID-19 pandemic and the need for supportive government policies highlight the importance of continued efforts to secure the country's energy transition.

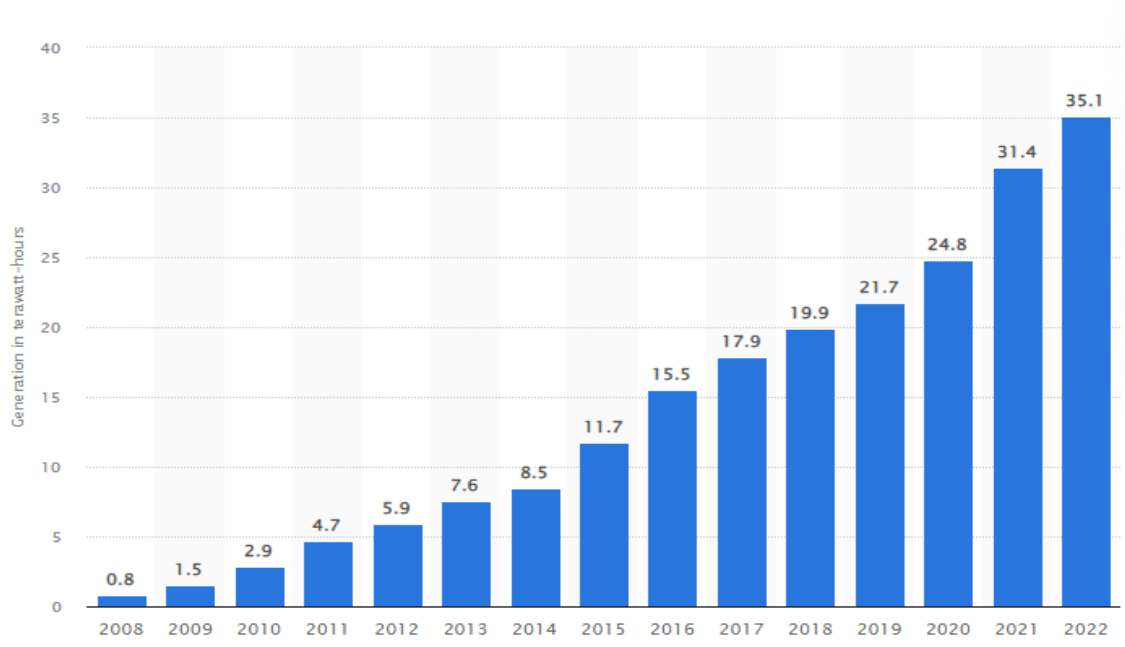

Figure 4.1: Wind power generation in Turkey from 2008 to 2022 (in TWh).

IAEA (2022), confirms the growing trends of energy consumption in Turkey depicting an ever-increasing demand of renewable energy drawing interests in wind energy. Available data project that the estimated available energy sources in Turkey are fossil fuels, nuclear and renewables (including wind power at 48,000 MW, hydropower at 160 TWh/y and solar power at 1,572 kWh-m^2 /y) as illustrated in Table 4.1 (IAEA, 2022).

Table 4.1: Estimated available energy sources in Turkey.

	Fossil Fuels			Nuclear			Renewables		
	Solid	Liquid	Gas	Uranium	Thorium	Hydro	Geothermal	Wind	Solar
Units	Mt	Mt	Bm^3	metric tonnes	metric tonnes	TWh/y	MWe	MW	kWh-m^2/y
Total	21 660	49.6	2.9	53 562	387 724	160	4 500	48 000	1 572

Electricity production data projected from 2000 to 2020 demonstrate varied compound annual growth rates for varied sources as highlighted in Table 4.2 below. It is apparent that the total energy production has been on the rise from 124 TWh in 2000 to 306

TWh in 2020. This represents an annual growth of 4.59%, with wind power registering the highest rates at 39.26% annual growth rate (IAEA, 2022).

Table 4.2: Electricity Production in Turkey in TWh since 2000.

Electricity Production (TWh)	2000	2005	2010	2015	2020	Compound annual growth rate 2000-2020 (%)
Total	124	161	211	261	306	4.59
Coal, Lignate and Peat	38	43	55	76	105	5.23
Oil	9	5	2	2	0.3	-15.47
Natural Gas	46	73	98	99	70	2.17
Bioenergy and Waste	0	0	0	1	4	17.61
Hydro	30	39	51	67	78	4.75
Nuclear	0	0	0	0	0	0.00
Wind	0	0	2	11	24	39.26
Solar	0	0	0	0	11	0.00
Geothermal	0	0	0	3	10	27.65
Other	0	0	0	0	1	18.08

Additionally, the power consumption data reflections from 1980 to 2020 show a consistent increase in energy and electricity consumption per capita demonstrating a trend representing future demand. Electricity consumption increased from 554 kWh/capita (gross) in 1980 to 3,661 kWh/capita in 2020. Consequently, electricity production increased from 11.5% in 1980 to 59.85% in 2020. A considerable 48% increase in a span of 40 years. The dependency on external sources is notably on the rise however, there are notable variations of dependency. The year 2017, Turkey registered the lowest dependency percentage while 2015 the country had the highest dependency as illustrated in Table 4.3 (IAEA, 2022).

Table 4.3: Energy related ratios in Turkey.

	1990	2000	2005	2008	2010	2015	2016	2017	2018	2019	2020
Energy consumption per capita (GJ/capita)	39.94	49.86	51.51	61.04	59.91	68.66	71.47	75.28	73.31	72.68	73.69
Electricity consumption per capita (kWh/capita) (gross)	1012	1903	2231	2770	2854	3375	3499	3672	3709	3648	3661
Electricity production / Energy production (%)	19.7	40.6	57.47	59.33	57.55	72.77	66.71	72.31	66.07	58.31	59.85
Nuclear/Total electricity (%)	-	-	-	-	-	-	-	-	-	-	-
Ratio of external dependency (%)	52.1	66.7	72.67	72.03	70.20	76.04	74.03	5.67	72.38	68.92	70.05

The research conducted by Şahin (2020) focuses on forecasting Turkey's total renewable and hydro energy installed capacity and electricity generation from 2019 to 2030 using the fractional nonlinear grey Bernoulli model (FANGBM(1,1)) and its reduced forms. The study addresses the dearth of projections for Turkey's renewable energy in the literature and employs fractional grey models, a relatively novel forecasting method, in contrast to other studies that rely on traditional forecasting techniques.

The study's findings highlight that hydro energy has consistently held the largest share in Turkey's total renewable electricity generation and installed capacity, but the models project a decrease in its contribution from 2019 to 2030. This decrease raises environmental concerns and prompts a recommendation to the Turkish government to decrease the share of hydropower in total renewable electricity generation. This suggestion is made in light of Turkey being considered an extremely water-stressed country in the coming years, indicating a sensitivity to the environmental implications of energy choices.

The information provided by Firdevs and Alhan (2023) underscores the significant potential for wind energy in Turkey to surpass the country's targeted capacity of 29,600

MW by 2035, as outlined in the national energy plan. The head of the TÜREB, Ibrahim Erden, expressed confidence in Turkey's ability to exceed this target, citing the nation's remarkable progress in reducing dependence on fossil fuels and imported resources over the past two decades (Firdevs & Alhan, 2023). The growth of Turkey's wind energy sector, especially since TÜREB's establishment in 1992, has been notable, with the current installed capacity reaching 106,000 MW, making Turkey the sixth largest in Europe and 12th globally. Erden suggests that, considering the existing capacity and offshore wind potential, Turkey's total wind energy potential could reach 45,000 MW, significantly surpassing the initial target.

The acknowledgment of Turkey's pivotal role in Europe's wind energy ambitions is another key aspect of the information. Giles Dickson, CEO of WindEurope, highlighted the European Union's goal to increase wind power generation from the current 17% to a level where wind energy constitutes a majority of the continent's electricity (Firdevs & Alhan, 2023). European leaders, as articulated by European Commission President Ursula von der Leyen, are actively supporting wind energy through initiatives such as the European Wind Energy Action Plan. Dickson emphasized the desire for a European wind energy manufacturing base, positioning Turkey as a potential contributor due to its advantageous position to provide raw materials for wind turbine production. This alignment presents an opportunity for Turkey to play a crucial role in Europe's efforts to reduce dependency on China and boost its wind energy industry.

Dickson, highlighting the potential for significant economic activity within Europe, emphasized the financial and economic implications of having wind turbines “made in Europe”. The call to keep economic benefits within Europe aligns with the broader goal of fostering regional economic growth and reducing external dependencies. The European Union's reliance on Turkey to assist in expanding its wind energy capabilities signifies a recognition of Turkey's contributions to the sector, and Dickson expressed gratitude for Turkey's notable efforts in wind energy development.

The analysis of Turkey's energy landscape presents a promising outlook for offshore wind power generation in the country. Turkey has made significant strides in the energy sector, particularly in wind energy, as evidenced by the country's impressive progress in onshore wind capacity. The TÜREB reports that Turkey currently ranks sixth in Europe and 12th globally in terms of installed wind power capacity,

highlighting the nation's substantial experience and infrastructure in the wind energy sector. This foundation suggests that Turkey has the potential to leverage its existing knowledge and capabilities to tap into offshore wind power generation.

Offshore wind power in Turkey could be a game-changer, with the country's coastal geography providing an advantageous environment for harnessing wind energy from the sea. The potential capacity of OWFs is notably higher, and Turkey's coastal areas offer vast untapped potential for offshore installations. As mentioned, Turkey's current installed total capacity is 106,000 MW, and considering the offshore potential, the total wind energy capacity could reach 45,000 MW, significantly exceeding the national targets. The strategic geographical location of Turkey, with extensive coastlines along the Black, Aegean and Mediterranean Seas, positions the country favorably for harnessing offshore wind resources.

The demand for increased power consumption and production in Turkey could serve as a driving force for the growth of offshore wind energy. As the country's population and economy continue to expand, there is a rising need for sustainable and reliable energy sources. Offshore wind, with its higher potential capacity compared to onshore wind, could play a crucial role in meeting this escalating demand. Moreover, the enabling factors for offshore wind growth include the global push towards renewable energy, decreasing costs of offshore wind technologies, and Turkey's commitment to enhancing energy security and reducing dependence on fossil fuels.

In conclusion, Turkey's potential in offshore wind power generation is substantial, driven by its coastal geography and established onshore wind capacity. The preliminary analysis suggests a positive trajectory. The increasing demand for power, coupled with favorable factors supporting renewable energy growth, positions Turkey as a potentially viable player in offshore wind production. Further detailed studies and strategic initiatives are required to unlock the full potential and ensure the sustainable development of offshore wind energy in Turkey. However, despite the potential, offshore wind farms in Turkey, like in many regions, face notable challenges and competition. The preliminary analysis does not delve deeply into the specific challenges, but globally, offshore wind projects encounter obstacles related to high upfront costs, technological complexities, and regulatory hurdles. Competition in the offshore wind sector is intense, with various countries vying for leadership and investment.

4.2 Site Analysis for OWFs in the Aegean Sea of Turkish Region

In this section, the paper will carry out a site analysis of OWFs in the Turkish Aegean Sea region and assess the feasibility of the untapped Aegean Sea coast regions.

4.2.1 Site selection: Foça region, Aegean Sea

Offshore wind remains an untapped resource despite its potential to significantly augment Turkey’s renewable energy capacity. It was previously stated in this study that, Turkey's offshore wind speeds are moderate, with the most favorable resources located along the western Aegean coast (usually ranging from 8.0 to 9.5 m/s), followed by sections of the Marmara Sea (typically 7.0 to 8.5 m/s) (Durak, 2023; Mostafaeipour, 2010). Wind speeds across the Black Sea are relatively consistent but lower, averaging around 7.0 to 7.5 m/s or less (Durak, 2023). However, the wind speeds along the southern coast are insufficient for offshore wind development.

Yildirim (2022) insights into the site selection for offshore wind farms in Turkey provide a comprehensive understanding of the considerations and methodologies involved in determining suitable locations. Turkey's geographical advantage, with its extensive coastline along the Aegean, Mediterranean, and Black Seas, as well as the Marmara Sea within its borders, offers rich offshore potential. However, this potential must be carefully assessed to account for various factors that could impact the feasibility and efficiency of offshore wind energy projects.

The investigation emphasizes the need for a detailed analysis of restricted regions, taking into account diverse factors such as military exercise areas, navigation routes, environmental restrictions, and the presence of gas and oil extraction activities according to Yildirim (2022). This approach reflects the multidimensional nature of offshore site selection, where considerations extend beyond wind conditions to encompass safety, environmental impact, regulatory compliance, and social implications. The careful evaluation of these factors is crucial for minimizing risks and ensuring the sustainable development of offshore wind projects.

The literature reveals a multifaceted approach, with studies like Argin and Yerci (2016) and Argin et al. (2019) emphasizing the significance of location selection criteria through MCSS techniques. These criteria incorporate considerations such as technical power capacities, geographical features, social aspects, and environmental constraints.

Such comprehensive evaluations are essential for identifying the most suitable regions for offshore wind farm development, ensuring long-term sustainability and minimal environmental impact.

Cali et al. (2018) in-depth technical and economic feasibility study of offshore wind farm projects in three promising wind regions in Turkey highlights the importance of meeting specific techno-economic conditions for project viability. This underscores the complexity of factors influencing the economic success of offshore wind initiatives, including the LCOE and the need for strategic investments.

4.2.2 Wind speed trends in the Aegean Sea regions

Considering the selected regions suitable for offshore wind power generation in the Aegean Sea, with optimum wind speeds ranging from 8.0 to 9.5 m/s, it is apparent that this paper anticipates running a comparative economic analysis to determine the workability of the OWF projects in Turkey, against those in Europe with similar environmental conditions. The information provided by S&P Global (Lenoir & Larson, 2023) offers valuable insights into the offshore wind landscape across Western Europe, with a focus on Germany, Belgium, the Netherlands, the U.K., and the Nordics.

Below Figure 4.2 shows the Turkey's wind speed profile at 50 m of height (Çalışkan, 2011). Following detailed research with regards to site selection subject to this study, Foça region is identified mainly due to its significant wind speed profile, reaching around 8 m/s of average.

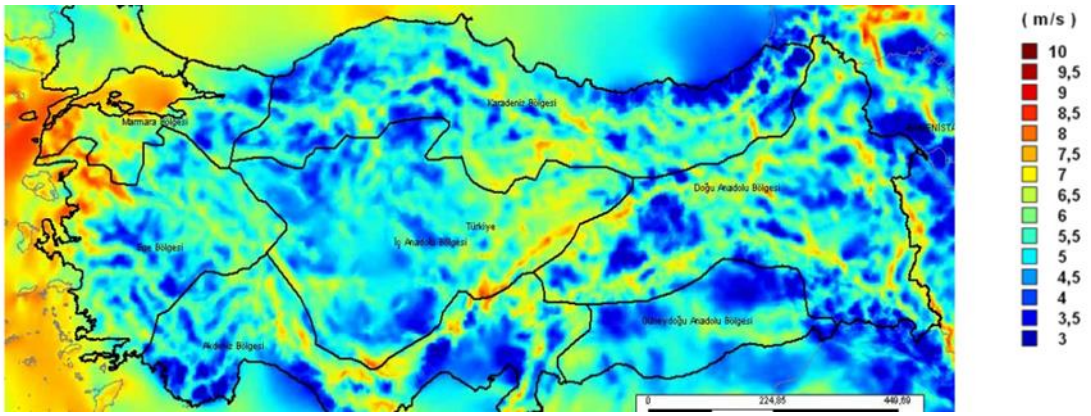

Figure 4.2: Turkey's yearly average wind speed distribution at 50 m height (m/s).

It can be observed that especially Aegean Coast of Turkey represents a strong wind potential that can be subject to potential offshore wind farm locations. The research

conducted by Duzcan and Kara (2023) reveals Foça region's wind rose and wind speed frequency at 84 m of height. Findings are similar with what has been shown in **Hata! Başvuru kaynağı bulunamadı.**. The research revealed that the average wind speed at 84 m height is 10.29 m/s, which is very significant for annual energy production calculations. Also, Figure 4.3 shows that the highest wind speeds are sourced from northeast. This research will further consider this wind speed in the feasibility calculations.

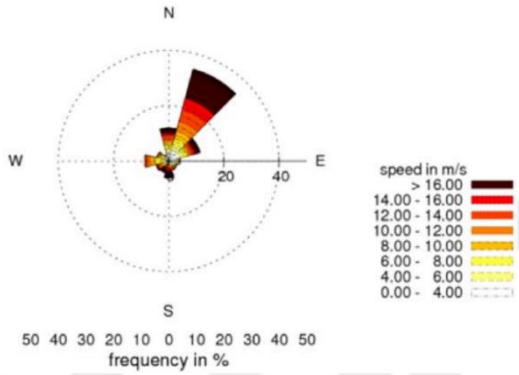

Figure 4.3: Wind rose at 84 m of height in Foça region.

The research article by Poupkou et al. (2011) provides a comprehensive analysis of the wind speed trends in the Aegean Sea between 1979 and 2009, focusing on the Etesian winds during the summer and early autumn months. The study utilized Reanalysis-1 data from the National Centers for Environmental Prediction/National Center for Atmospheric Research to investigate changes in the frequency and intensity of the Etesians. The findings reveal a negative trend in both the frequency and wind speed of the Etesian winds during the 31-year period. The total number of Etesian days from June to September decreased by about 4.6 days, with a monthly maximum intensity reduction of almost 1 m/s. This negative trend is consistent with similar results obtained from observational wind data in the central Aegean for the years 1955 to 2002.

The authors (Poupkou et al., 2011) suggest that the observed decline in Etesian frequency and wind speed may be attributed to a decreasing trend in the pressure gradient between the central and southern Europe high-pressure center and the Middle East low-pressure center, which govern the Etesians system. Additionally, the study explores a possible association between the Southern Oscillation and the Etesian winds, indicating a complex interplay between climate patterns.

The current projections of wind speeds in the Aegean Sea provide this research a basis for comparison to determine the future trends and expectations of wind velocity changes (highs and lows). However, it's important to note that while the above considerations provide a useful benchmark, there will be unique challenges and considerations for OWF projects in the Turkish Aegean Seas. These could include different sea depths, seabed conditions, protected marine areas, port suitabilities and local regulations. Therefore, while the base study can provide a starting point, a detailed site-specific assessment of the Turkish Aegean Sea environment is necessary.

4.2.3 Aegean Sea's hypothetical 100 MW OWF, Foça, Turkey

The Aegean Sea in Turkey holds substantial promise for offshore wind energy development, and assessing the feasibility of offshore wind farms in this region is crucial for sustainable energy planning. Several factors contribute to the favorable conditions for offshore wind in the Aegean Sea. Firstly, the Aegean Sea is known for its consistent and strong winds, particularly in the northern Aegean region, as highlighted by Gumuscu et al. (2023). This region's powerful and sustained winds provide a reliable source of energy, making it conducive for the establishment of offshore wind farms.

Secondly, the ongoing advancements in offshore wind turbine technology have significantly improved efficiency and reduced costs (IEA Wind TCP, 2021). Modern offshore turbines are capable of harnessing energy from stronger and more variable winds, aligning well with the diverse wind characteristics identified in the study. According to the (World Bank Group, 2021), The economic viability of Turkish offshore wind projects is increasingly favorable. Falling costs of equipment and construction, coupled with supportive government policies and incentives, contribute to the attractiveness of investing in offshore wind farms.

The Aegean Sea in Turkey presents a compelling case for the development of offshore wind farms. With abundant wind resources, technological advancements, improving economic viability, careful environmental assessments, and a focus on grid connection, the Aegean Sea has the potential to emerge as a key hub for sustainable offshore wind energy. The magnitude of Aegean OWFs stands out in comparison to familiar OWFs in the global scene based on its wind power potential.

The selection of turbines for this site, considering the technical feasibility of the equipment to support full power potential of the installed wind farm, is concluded with the Siemens Gamesa 5 MW offshore wind turbine. One notable fact is that a single rotation of a similar size of turbine can power a UK home for over a day as argued by (Ørsted, 2022) emphasizing the efficiency and productivity of these offshore installations. (Siemens Gamesa, 2023). The turbines demonstrate flexibility in power output, ranging from 3.6 MW to 5.0 MW, and are designed for optimal efficiency in coastal weather conditions. Notably, the turbines' cut-in speed starts at a wind speed of 3 m/s, and the cut-out speed is estimated at 25 m/s, ensuring effective operation within specified wind ranges (Siemens Gamesa, 2023).

The assessment of turbine efficiency considers the wind speed conditions in the Aegean coastal regions. The study acknowledges that winds below 5 m/s may not generate power effectively, emphasizing the need to evaluate whether the turbine locations align with wind speeds exceeding this threshold. Historical wind speed data from the European regions indicates averages ranging from 8 m/s to over 11 m/s (Sterl et al., 2015) while in the Aegean Sea it ranges between 8.0 and 9.5 m/s (Durak, 2023; Mostafaeipour, 2010), supporting the suitability of the Siemens Gamesa 5 MW turbines for the chosen location. The power velocity curve and wind speed projections from the research provide a basis for simulating turbine operational conditions, considering factors such as cut-in and cut-out speeds.

The theoretical observation of turbine viability involves calculations of power generation hourly and yearly, taking into account Siemens 5 MW turbine specifications and meteorological data. This comprehensive analysis aims to project expected operational standards based on observed weather patterns and data for the Turkish Aegean off-coast region. The consideration of factors such as climate change impact on wind patterns ensures a holistic understanding of the turbines' performance over time. Overall, the critical discussion underscores the meticulous evaluation and planning involved in maximizing the efficiency of offshore wind projects, with the Turkish Aegean OWFs serving as a prominent example of cutting-edge technology and strategic energy infrastructure development.

4.3 Aegean OWFs Power Generation

To calculate the power generated by Aegean OWF, it is imperative to consider the turbine specification and wind speed data to be used in the projections. Considering the application of G128-5.0 MW offshore wind turbines in the OWFs, the specifications by Siemens Gamesa (2024) are crucial to understand how much power is generated since its commissioning.

The Siemens Gamesa G128-5.0 MW is an offshore wind turbine that plays a pivotal role, contributing to the impressive renewable energy generation in the UK North Sea and Northern Japan (Colthorpe, 2022). With a substantial rated power of 5.0 MW, this turbine reflects the cutting-edge technology employed by Siemens Gamesa Renewable Energy, a prominent Spanish manufacturer that has been in operation since 2017 (Siemens Gamesa, 2023). The Siemens Gamesa G128-5.0 MW has the following specifications:

- Wind class: IEC, Ia
- Nominal power: 5,000 kW
- Rotor diameter: 128 m
- Blade length: 64 m
- Swept area: 12,868 m²
- Hub height: Site specific (Siemens Gamesa, 2024). 84 m is considered in the study.

One of the key features of the G128-5.0 MW is its ability to commence operation at a relatively low wind speed of 3 m/s, making it efficient in harnessing wind energy. The turbine's rotor diameter of 128 m and the rotor area of 12,868 m² enable it to capture substantial wind energy, optimizing power generation (Siemens Gamesa, 2024). The use of three rotor blades and a direct-drive gearbox further enhances the turbine's reliability and efficiency. The Siemens Gamesa G128-5.0 MW is designed with a cut-out wind speed of 25 m/s, emphasizing safety during extreme weather conditions.

In terms of construction, the tower is built with steel tube construction, emphasizing durability (Siemens Gamesa, 2023). Siemens Gamesa employs a corrosion protection strategy by using painted coatings on the tower, ensuring longevity in the harsh offshore environment of the North Sea. Since its listing in 2018, the Siemens Gamesa G128-5.0 MW has been a prominent player in the wind energy landscape (Siemens

Gamesa, 2023). The Siemens Gamesa G128-5.0 MW wind turbine, with its advanced features and robust design, is a crucial component of the Aegean OWFs. Its impressive power rating, efficiency, and safety features align with the objectives of large-scale offshore wind farms, contributing significantly to the renewable energy capacity in the northern and western Aegean Sea.

The proceeding sections will provide a projection of the estimated power generation for the identified Aegean Sea case study in Foça coastal region to ascertain its economic viability. This technical and economic simulation is relevant to offer insights into the viability of the expected large-scale offshore wind turbine installation in the Aegean Sea region.

To understand the power generation patterns of OWF projects, identifying the potential of the power plant in numbers is relevant to ascertain its economic viability against its setup costs. Using the principals of aerodynamics of wind turbines, the power generation data provided by the manufacturer (Siemens Gamesa, 2023) is crucial to draw viable conclusions.

The Aegean OWF power generation simulation chosen in this research will be estimated for a period of twenty-five (25) years to ascertain its long-term efficiency in terms of power and revenues. To be exact on the costs of the OWFs, this research will base its estimations on a previous study. Díaz and Soares, in their study, created a dataset comprising information about all operative offshore wind power plants worldwide for the goal of analysing the economics of offshore wind, and more specifically, their cost development. Their study sets out that, based on a number of investments in European countries that reach beyond 10 GW of installed capacity, the investment cost for an offshore wind power capacity is around 2.9M€ per MW (Díaz & Soares, 2020). This figure will be a basis for further calculations in this paper.

Offshore wind projects are highly capital cost intensive. The initial financial investment makes up approximately three-fourths of the total project lifetime cost. This value is extremely high in comparison to conventional power stations, where investment costs typically represent 40% of the project lifetime cost (Díaz & Soares, 2020).

4.3.1 Specifications of the selected turbine

The power generation of each turbine, assessed on an hourly basis to determine its potential, extending on a monthly and yearly timeline basis reflects on the varied environmental patterns (wind velocity) in the specific climate timeline. An ideal power generation would meet the expected outcome in terms of power generation and revenue generation. Assessing the existing case study and simulating them in the Foça region will help inform on the future expectations of the Turkish OWFs and amid climate challenges. To establish an assessment of Turkish Aegean OWF Project, and to calculate turbine efficiency, the research will consider the following information available by the Siemens G128-5.0 MW turbine manufacturer and the global & Turkish meteorological office department data.

- Rated Capacity: 5,000 kW (Siemens Gamesa, 2023)
- Swept Area: 12,868 m² (Siemens Gamesa, 2023)
- Rotor Diameter: 128 m (Siemens Gamesa, 2023)
- Number of blades: 3
- Hub height: 84 m
- Air Density (ρ): 1.225 kg/m³ (standard value adjustable according to sea levels & temps) (UBC ATSC 113, 2019; Wen et al., 2018)
- Power Coefficient (C_p) ranging from 0.4 to 0.5 (optimum average) (Wen et al., 2018)
- Cut-in speed: 3.0 m/s (Siemens Gamesa, 2023)
- Cut-out speed: 25.0 m/s (Siemens Gamesa, 2023)

The critical evaluation of wind turbine power generation involves a thorough understanding of the underlying principles and calculations, as outlined in the provided information. The equation 4.1 below is a fundamental expression in wind energy physics, representing the power available in the wind based on air density (ρ), swept area (A), and wind velocity (v) (Sarkar & Behera, 2012).

$$Power\ (W) = \frac{1}{2} \times\ \rho\ \times\ A\ \times v^3 \qquad (4.1)$$

Where;

- Power in Watts
- ρ = density of the air in kg/m3

- A = cross-sectional (swept) area of the wind in m^2
- v = velocity of the wind in m/s (Sarkar & Behera, 2012)

Considering the above, available power in the wind may vary significantly at different wind speeds. The calculations of the power in the wind at different wind speeds may offer a valuable insight into the power generation capabilities of the Siemens Gamesa G128-5.0 MW offshore wind turbine under different wind speeds, considering its maximum output of 5 MW. The following Table 4.4 shows the power in the wind at varied speeds from 1 m/s to 25 m/s.

Table 4.4: Available power in the wind for the swept area and cut-in & cut-out speeds of the selected turbine.

Wind speed (m/s)	Power (kW)	Wind speed (m/s)	Power (kW)	Wind speed (m/s)	Power (kW)
3.0	213	11.0	10,490	19.0	54,060
4.0	504	12.0	13,619	20.0	63,053
5.0	985	13.0	17,316	21.0	72,992
6.0	1,702	14.0	21,627	22.0	83,924
7.0	2,703	15.0	26,600	23.0	95,896
8.0	4,035	16.0	32,283	24.0	108,956
9.0	5,746	17.0	38,722	25.0	123,150
10.0	7,882	18.0	45,966		

This research did observe that our power calculations in the wind did vary from the company specifications considering the power in the turbine at varied and rated wind speeds. It is derived from our power calculation results, the Siemens Gamesa G128-5.0 MW turbine at the wind speed of 8.59 m/s without considering the power capacity factor (between the standard efficiency of 30% and 40%) (PennState College of Earth and Mineral Sciences, 2024), will produce its maximum capacity as shown from the power table. This is however different when we consider the manufacturer standard specifications.

The provided power curve of Siemens Gamesa G128-5.0 MW according to the wind turbine model database, (Bauer, 2024) project that this turbine generates power efficiently between 11.5 m/s and 14.5 m/s. Consequently, we observe that the turbine will start producing power at low speeds of 3 m/s at 59 kW, to 14 m/s where it generates a consistent maximum output of 5,000 kW. Considering this power in the turbine, we can compare the values against those of the power in the wind keeping in mind that the power generated includes power losses and other technical factors; the results provide an interesting observation. It is clear that the power in the wind at varied speeds is sufficient to generate power though at different rates depending on the wind velocity and sea conditions.

Consequently, we observe that the manufacturer's standard power curve sets the rated speed at its standard capacity factor between 13.5 m/s and 14 m/s wind speeds according to the wind power. Therefore, while the power in the wind at the turbine's rated wind speed is much higher than the turbine's rated power, the turbine can only convert a fraction of this power into electrical power. The Figure 4.4 below shows the power curve of the selected turbine. The rated power is typically at wind speeds between 12 and 25 m/s. At wind speeds above the rated wind speed, the power output is limited to the rated power (Bauer, 2024).

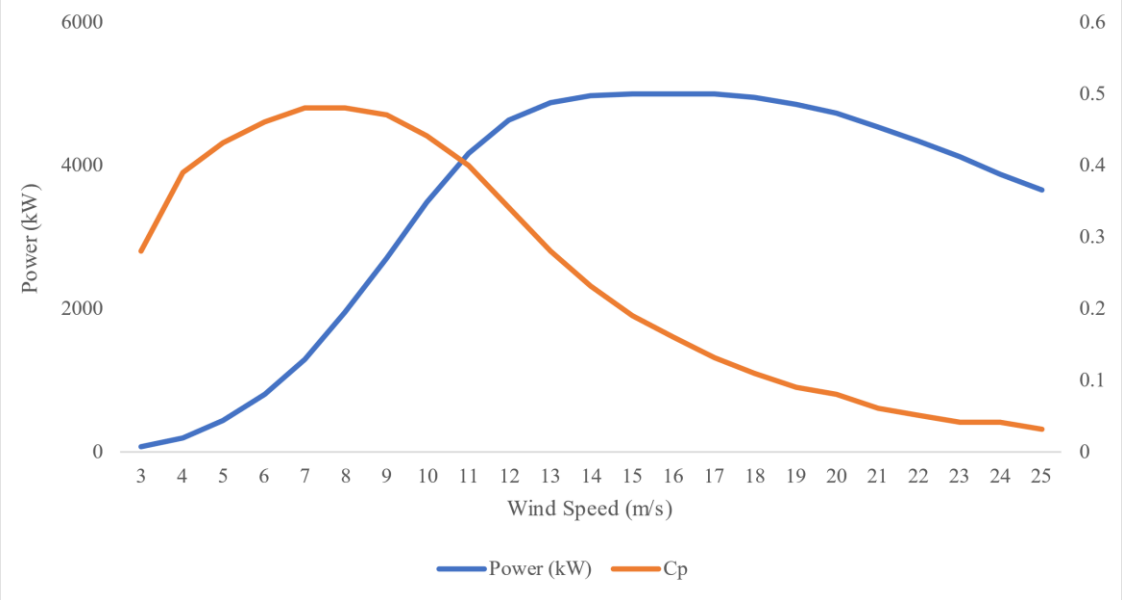

Figure 4.4: Siemens Gamesa G128-5.0 MW power curve and capacity factor.

Based on the Figure 4.4 above, at wind speeds of 4 m/s, the power specified by the manufacturer's power curve, in the turbine is approximately 195 kW, at 8 m/s the

power is 1,943 kW, and at 13 m/s the power is 4,875 kW. The rated power 5,000 kW is registered at wind speeds between 14 m/s and 16 m/s according to the Siemens Gamesa G128-5.0 MW power curve.

On the other hand, at 10 m/s, which is closest to wind speed around Foça region, the turbine's power curve shows 3,487 kW of power. It is also to note that the power that can be generated through the turbine starts to decrease once the wind speed reaches beyond the 16-17 m/s of wind speed levels. This is due to the protection system of the turbine, while approaching to cut-out speed.

The power generation data of the Siemens Gamesa G128-5.0 MW wind turbine and the power available in the wind at various wind speeds provide an interesting comparison, in the light of above Table 4.4 and Figure 4.4.

At Average Wind Speed (4 m/s): The power in the wind is 504 kW, while the turbine generates 195 kW. This suggests that the turbine is operating efficiently, but it's not yet at its rated power output. This is likely below the rated power output of the turbine, as wind turbines typically start generating power at wind speeds of around 3-4 m/s (the cut-in wind speed).

At Average Wind Speed (8 m/s): The power in the wind is 4,035 kW, while the turbine generates 1,943 kW. This suggests that the turbine is operating efficiently, but it's not yet at its rated power output.

At Average Wind Speed (13 m/s): The power in the wind is 17,316 kW, and the turbine generates 4,875 kW. This is close to the rated power output of the turbine, suggesting that the turbine is operating near its maximum efficiency.

At Rated Wind Speed (14+ m/s): The turbine generates its rated power output of 5,000 kW. The power in the wind at 14 m/s is 21,627 kW, which is significantly higher than the power output of the turbine. This is expected, as the turbine cannot capture all the power in the wind due to the Betz Limit and other factors.

From this analysis, it's clear that the power output of the turbine increases with wind speed, but it does not capture all the power available in the wind. This is due to a variety of factors, including the Betz Limit, mechanical and electrical losses, and operational considerations. The turbine reaches its rated power output at wind speeds of around 13 m/s. However, it is to be noted that higher wind speeds don't always

result in higher output, as the turbine may face a derating at speeds higher than optimum level. The power curve of the turbine depicts that the power output of the turbine begins to decrease beyond a wind speed of around 17 m/s, as operating with its full capacity at very high wind speeds may be dangerous for the wind turbine.

This case study highlights the importance of understanding the power curve of a wind turbine, which shows the relationship between wind speed and power output. It also emphasizes the fact that the rated power output of a turbine is not the maximum power available in the wind, but rather the maximum power that the turbine can reliably, and efficiently produce. For the Siemens Gamesa 5 MW, this is 5,000 kW (Bauer, 2024).

The calculations at an average wind speed of around 10 m/s show that the turbine continues to generate substantial power, yet at levels below its maximum capacity.

The capacity factor indicates the amount of energy that is generated by a source relative to the maximum energy rating for the identified turbine, expressed as a percentage. If the percentage is close to 59%, the more we note the energy available throughout the year.

It is important to note that the capacity factor is not the same as efficiency. The capacity factor is a measure of how much power the turbine produces on average compared to its rated power output (Sarkar et. al., 2012). On the other hand, efficiency is a measure of how much of the power available in the wind is converted into electrical power by the turbine. The efficiency of a wind turbine is subject to the Betz Limit, which states that no wind turbine can capture more than 59.3% of the kinetic energy in the wind (Sarkar et. al., 2012).

Albert Betz, a German physicist, set out the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. Based on the conservation of mass and momentum of the flowing air stream, this finding is supported with an ideal actuator disc theory. Below Figure 4.5 shows the schematic of the actuator disc theory, considering the swept area of the wind turbine.

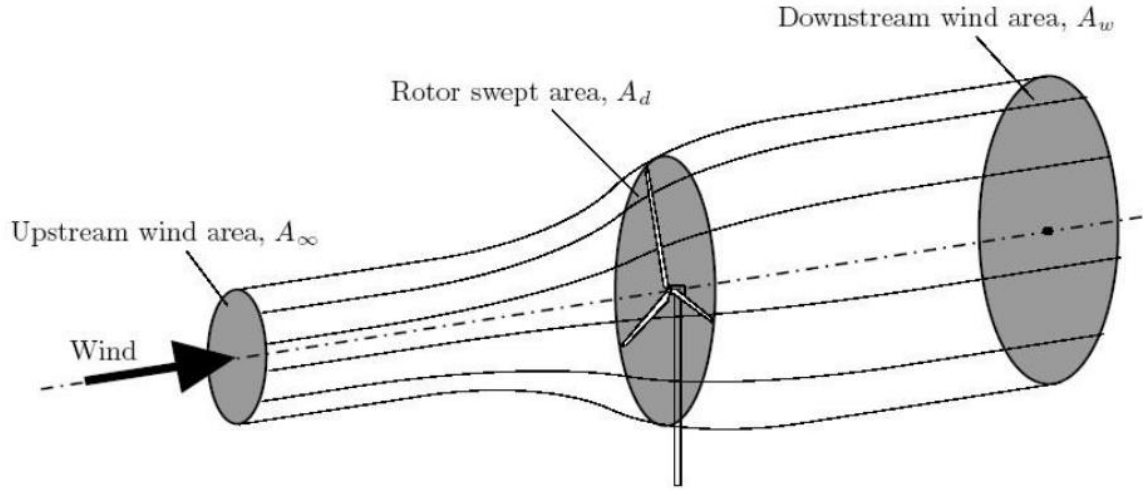

Figure 4.5: Schematic of the air flow through a rotor of a wind turbine.

According to (Pellegri), and based on the simple approach of kinetic energy, the actual power extracted by the blades of the wind turbine is the difference between the upstream and downstream wind powers, shown in below equation 4.2.

$$P_0 = \frac{1}{2}\, m\, (v^2 - v_0^2) \tag{4.2}$$

Where;

P_0 : mechanical power extracted by the rotor,

v : upstream wind velocity at the entrance of the blades

v_0 : downstream wind velocity at the exit of the blades

The air velocity is not continuous from v to v_0 at the location of the blades. The air mass flow rate through the rotating blades of the wind turbine is derived by multiplying the density with the average velocity, as shown in below equation 4.3.

$$m = \rho\, A\, \frac{(v + v_0)}{2} \tag{4.3}$$

Where, ρ and A were previously defined as air density and swept area of the rotor blades.

Substituting equations 4.2 into 4.3, mechanical power that can be extracted from the rotor blades can be expressed:

$$P_0 = \frac{1}{2}\,\rho\,A\,v^3\,\frac{(1+\frac{v_0}{v})\left[1-(\frac{v_0}{v})^2\right]}{2} \tag{4.4}$$

Considering $\frac{(1+\frac{v_0}{v})\left[1-(\frac{v_0}{v})^2\right]}{2}$ as the power coefficient of the rotor (C_p), or its efficiency, the equation 4.4 above can be simply expressed:

$$P_0 = \frac{1}{2}\,\rho\,A\,v^3 C_p \tag{4.5}$$

With regards to the value of the C_p, considering a given upstream wind speed, it depends on the ratio of the downstream wind velocity to upstream wind velocity, which is $\frac{v_0}{v}$. Depicted from below Figure 4.6, power coefficient (C_p) is a single, maximum-value function, reaching its maximum value of $\frac{16}{27}$ (0.593) when the $\frac{v_0}{v}$ ratio is equal to $\frac{1}{3}$. This value can simply be expressed as Betz limit. It is also to note that this value of 0.593 indicates the theoretical maximum value of the power coefficient. This peak is shown in below Figure 4.6. In practice, the maximum achievable C_p is below 0.5.

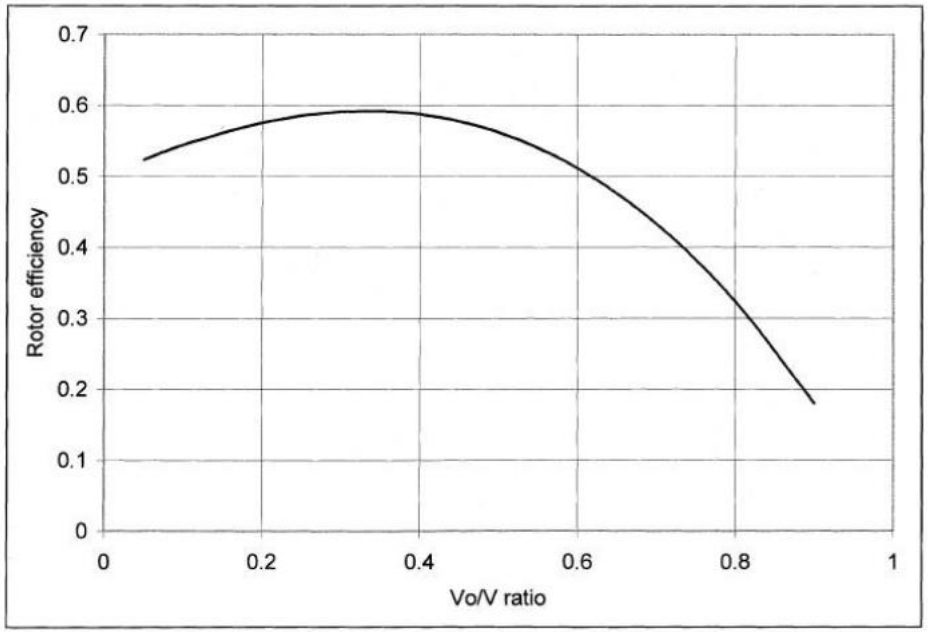

Figure 4.6: Power coefficient change to wind velocities ratio.

This case study highlights the importance of understanding the power curve of a wind turbine, which shows the relationship between wind speed and power output. It also emphasizes the fact that the actual power output of a turbine can vary significantly

from its rated power output due to a variety of factors, including wind speed and direction, air density, and turbine performance.

Observationally, these results highlight the robustness of the Siemens Gamesa G128-5 MW turbine, displaying its ability to harness wind energy efficiently across a spectrum of wind speeds. The turbine's performance aligns well with its design specifications, offering reliable and consistent power generation. The variations and close correlation between calculated and rated power outputs at different wind speeds instills confidence in the turbine's predictability and adherence to design standards.

4.3.1.1 Observations and critical discussions

The Siemens Gamesa G128-5 MW turbine demonstrates a strong performance at various wind speeds, as calculated power output aligned with the company's rated power outputs.

The projected lifetime power production of the Siemens Gamesa G128-5 MW offshore turbine is significant depending on wind speed conditions. At its rated wind speed of 14+ m/s, the turbine is expected to generate a substantial amount of electricity, whereas at lower wind speeds such as 4 m/s, the power production is considerably lower (Bauer, 2024). This highlights the importance of wind resource assessment and site selection to maximize the turbine's energy output over its lifetime.

Assuming a standard and generic efficiency of 32%, (United States EPA, 2013) the projected total power production over 25 years aligns with the expected energy output of the turbine. This indicates that the turbine is operating efficiently and is capable of delivering the anticipated amount of electricity over its operational lifespan. However, it's crucial to continuously monitor and optimize the turbine's performance to ensure it meets or exceeds these expectations.

The disparity in power production between high and low wind speeds underscores the influence of environmental conditions on turbine performance. While the turbine can generate substantial electricity at optimal wind speeds, its output is significantly reduced under less favourable conditions. This highlights the need for comprehensive wind resource assessments and adaptive strategies to mitigate the impact of fluctuating wind speeds on energy production.

Over the turbine's lifetime, operational challenges such as maintenance requirements, component degradation, and downtime due to repairs may arise. Ensuring the

reliability and longevity of the turbine necessitates proactive maintenance practices, effective monitoring systems, and prompt troubleshooting protocols. By addressing these challenges, operators can maximize the turbine's uptime and overall energy production.

The Siemens Gamesa G128-5 MW offshore turbine plays a crucial role in advancing the transition to renewable energy by harnessing wind power to generate electricity. Its significant energy production potential contributes to reducing greenhouse gas emissions, mitigating climate change, and enhancing energy security. Investing in renewable energy infrastructure such as offshore wind farms can further accelerate the transition to a sustainable and low-carbon future.

In summary, the projected lifetime power production of the Siemens Gamesa G128-5 MW offshore turbine reflects its capability to generate substantial amounts of electricity over its operational lifespan. By addressing operational challenges, optimizing performance, and leveraging renewable energy resources, the turbine can play a pivotal role in achieving long-term sustainability goals and fostering a clean energy future.

4.3.2 AEP calculation of the selected offshore turbine

The efficiency results for the G128-5 MW wind turbine at various wind speeds provide valuable insights into its performance across different operating conditions. The turbine demonstrates efficiency generating adequate power; however, we observe variations due to the wind velocity.

The Annual Energy Production (AEP) is a critical metric in evaluating the feasibility and performance of an OWF. This section outlines the detailed steps undertaken to calculate the AEP for a hypothetical OWF in the Foça region of Turkey, using the selected wind turbine model. The methodology incorporates the variability in wind speeds, turbine power output characteristics, and losses due to wake effects, ensuring a robust estimation aligned with realistic operating conditions.

To accurately model the wind speed distribution at the site, we employed the Weibull distribution, a widely used statistical method in wind energy analysis. The Weibull distribution is characterized by two parameters: the shape factor (k) and the scale factor (c). The shape factor describes the spread of the wind speed data, with lower values indicating a broader distribution and higher values indicating a more peaked

distribution. For this study, a shape factor of $k=1.72$ was chosen based on wind data analysis for the Foça region (Duzcan & Kara, 2023). The scale factor was calculated using the average wind speed ($\bar{v}=10$ m/s), ensuring the distribution accurately reflects local wind conditions.

The scale factor (c) is crucial for determining the PDF of the Weibull distribution, which in turn influences the AEP calculation. The scale factor was derived from the average wind speed and the calculated scale factor was approximately 10.84 m/s, ensuring the distribution parameters align with the wind regime of the site.

The selected turbine's power curve, which details the power output at various wind speeds, was provided and analyzed. This curve is essential for integrating with the Weibull PDF to compute the AEP. Due to the non-linear nature of the power curve, cubic spline interpolation was utilized. This method allows for a smooth and accurate representation of the turbine's power output across different wind speeds, avoiding the inaccuracies that might arise from linear interpolation.

The AEP was calculated by integrating the product of the turbine's power curve and the Weibull PDF over the range of wind speeds from 0 to 25 m/s.

In real-world conditions, turbines in an OWF are affected by wake losses, which occur due to the interference of airflow between turbines. These losses reduce the overall efficiency of the wind farm. For this study, a wake loss factor of 0.3% was applied to the AEP (Duzcan & Kara, 2023). The wake loss factor adjusts the AEP to more accurately reflect the expected operational performance of the OWF. The adjusted AEP calculation thus incorporates this minor yet significant reduction in energy production.

The availability of the wind turbine, which accounts for the percentage of time the turbine is operational and capable of generating electricity, is a crucial factor in the AEP calculation. For this study, an availability factor of 95% was assumed. This reflects the typical operational efficiency of well-maintained turbines, accounting for downtime due to maintenance and repairs.

The calculated AEP based on the above assumptions, without considering wake losses, was approximately 18,350,132 kWh/year. After accounting for wake losses, the adjusted AEP was approximately 18,295,082 kWh/year. These results reflect the expected annual energy output of the selected turbine under the specified wind

conditions and operational environment. The capacity factor, representing the ratio of actual output to the maximum possible output, was inherently considered through the Weibull-based AEP calculation process. The results of the calculations, as well as the considerations are summarised in below Table 4.5.

Table 4.5: AEP summary of the selected turbine, capacity factor, shape factor, scale factor, wake losses at 10 m/s wind speed.

Wind Speed (m/s)	Power of the turbine (kW)	Capacity Factor	Shape factor	Scale factor (m/s)	Availability (%)	AEP without wake losses (kWh/year)	Wake losses (%)	AEP with wake losses (kWh/year)
10	3,487	0.44	1.72	10.73	95	18,350,132	0.3	18,295,082

This comprehensive AEP calculation provides a robust estimate of the energy production potential for the hypothetical OWF in the Foça region. By incorporating the Weibull distribution with accurately determined shape and scale factors, using cubic spline interpolation for the turbine power curve, availability and accounting for wake losses, the methodology ensures a realistic and reliable assessment of the turbine's performance. These calculations are vital for the feasibility study, aiding in decision-making processes regarding the development and investment in the offshore wind farm.

In conclusion, these results highlight the challenges faced by the G128-5 MW wind turbine in converting wind energy into usable electrical power across varying wind speeds. While the turbine's theoretical rated power serves as a benchmark, real-world factors such as mechanical losses, electrical losses, and downtime significantly influence its actual performance. The discrepancies between rated power and actual power output underscore the importance of continued research and development efforts to improve turbine efficiency and maximize power production across a range of wind conditions. By addressing inefficiencies and optimizing design and operational practices, wind turbine technology can play a more significant role in

meeting global energy demands and advancing the transition towards sustainable renewable energy sources.

4.4 Feasibility of the Aegean OWF, Foça

Simulating these conditions in the northeast Aegean Sea with a threshold between 14 m/s and 15 m/s, the southwest and southeast region in the Aegean Sea exceeding a threshold of 16 m/s (Vagenas et. al., 2017), and the lowest threshold in the northwest Aegean Sea not exceeding 12.5 m/s (with wind speeds ranging from 6 m/s to 10 m/s (Duzcan & Kara, 2023)) for 25 years; the Aegean OWF simulation, based on the results that represent the Aegean wind velocity variations, could be feasible for producing the maximum expected power.

Comparative observation with notable large scale OWF's in UK North Sea's bearing the wind power results from the simulation, particularly between 8 m/s and 13 m/s, bear similarities to the conditions experienced in the Aegean OWFs making it viable at the rated speeds exceeding 13 m/s. The simulations reflecting similar wind speeds in the Turkish Aegean Sea, suggest that the conditions are conducive to offshore wind power generation, analogous to the large-scale wind power production.

The OWF in Turkey demonstrates a commendable level of power efficiency, particularly at higher wind speed. The substantial cumulative power outputs over the simulated 25-year lifetime underscore the effectiveness of harnessing wind energy in the selected regions. However, it is crucial to consider various factors, including maintenance, environmental conditions, and grid integration, to evaluate the economic and operational feasibility of the OWF. Further studies and simulations accounting for these factors will contribute to a more thorough understanding of the OWF's potential and overall efficiency in generating its maximum power output.

4.4.1 Economic feasibility

Running an economic analysis to understand the performance of the simulated OWF in Foça region, Turkish Aegean Sea is imperative for several reasons. Primarily, an economic analysis provides a comprehensive evaluation of the financial viability and ROI of the Turkish Aegean OWF, considering factors such as initial costs, revenue generation, and operational & other expenses. This analysis becomes particularly

relevant when dealing with substantial initial investments, as in the case of the simulated Aegean OWF along the Foça coastline.

In this study, we have selected to hypothetically install twenty (20) of the selected offshore wind turbines, taking also into account the technical considerations for micro-siting. Thus, Aegean OWF reaches 100 MW of total installed capacity. Based on the 2.9M€ per MW (≈3.19M$ with a €/$ exchange rate of 1.1) figure that we have considered in this study, the total investment cost for the 100 MW OWF will further be considered as 319 million USD. Below Figure 4.7 shows the hypothetical micro-siting of the selected wind turbines, based on an approximation of 7D rotor diameter on the prevailing wind direction, and 4D rotor diameter on the perpendicular to it.

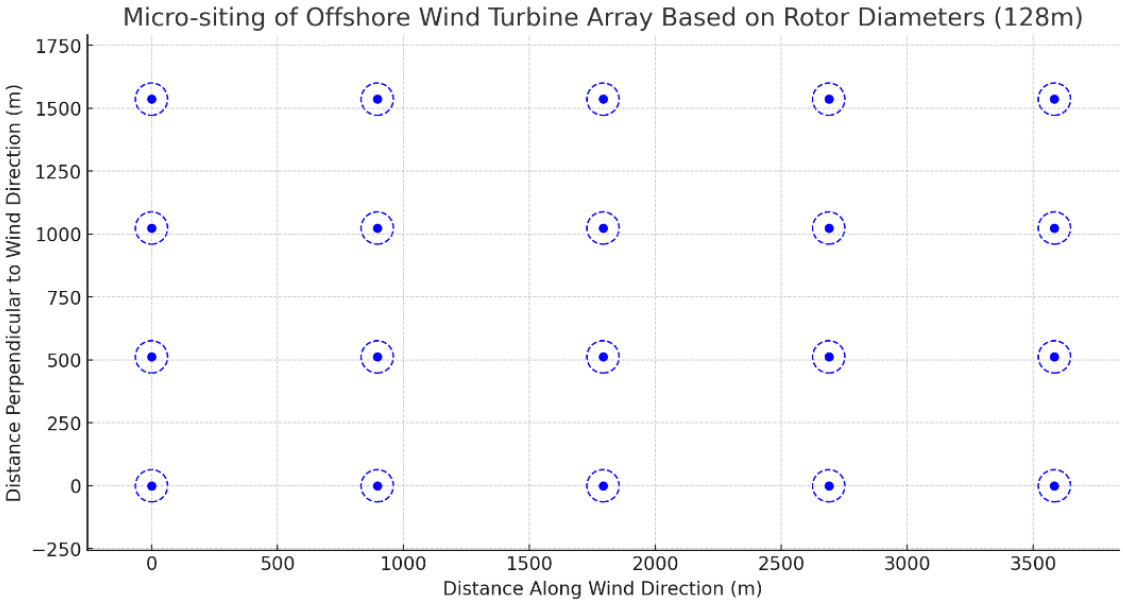

Figure 4.7: Hypothetical OWF array.

The economic analysis allows for a thorough examination of the revenue streams generated by the project simulated in Turkish Aegean OWF over an operational lifespan of 25 years. The calculated revenues, based on the power generation estimates at $83 per megawatt-hour (MWh) (GlobalPetrolPrices, 2024; IRENA Report, 2019) equivalent to $0.0825 per kWh, provide insights into the project's potential profitability. However, as the OWF will operate in Turkish seas, the latest regulations and tariffs must be considered for the unit price, thus the revenue stream calculations. As announced by EPİAŞ, this paper considers the presidential decree which regulates the YEKDEM prices for licensed offshore wind energy generations for the unit prices (EPİAŞ, 2024). Applicable as of 01-Mar-2024, the sales unit price is considered as

2.81 TL/kWh (≈0.0815$/kWh with a $/TL exchange rate of 34.5). This figure is also in line with the considerations in similar previous academic studies.

The operation and maintenance costs for OWF (OPEX) per kWh is taken as 75,000 £/MW in a similar study by BVG Associates (Associates, 2024). For a 100 MW capacity of OWF, this figure is landed in this paper to 0.026$/kWh (with a £/$ exchange rate of 1.25).

This assessment of one of the largest floating OWF in Europe, situated in the Aegean Sea, region, is valuable in understanding how the Turkish Aegean OWFs would fare under varied wind conditions.

Considering the power generation calculations with the SG 5 MW turbine, the likelihood of positive results in the economic analysis is relatively high. The adaptability of the turbine to varying wind speeds, as demonstrated in the Aegean Sea simulation, bodes well for the Turkish Aegean OWF's performance. The consistent wind conditions in the Aegean regions, as indicated by the power calculations, suggest a reliable and stable power output, essential for revenue generation.

Moreover, the economic analysis enables a comparison of the Turkish Aegean OWF with existing OWFs in Europe in terms of operational efficiency, revenue potential and overall financial feasibility. Lessons learned from the well-established and ongoing projects, which has proven successful in their revenue generation and ROI, can inform the expectations and projections for the Turkish Aegean OWF. It allows stakeholders to assess whether similar conditions can lead to a positive economic outcome, taking into account differences in initial costs, market dynamics, and regulatory environments. A thorough economic analysis will provide a more pronounced understanding of the specific economic landscape and potential challenges unique to the Turkish Aegean OWF, ultimately guiding informed decisions on the project's feasibility.

We can further estimate the total revenues generated by the twenty (20) SG 5 MW offshore wind turbines. In order to establish the revenue generated by the project in a year and in its 25-year timeline against the approximated set up cost of **$**319 million, we will also consider some other parameters such as inflation rate, price escalation and other costs.

- Unit Price of Sales

  As explained above, 0.0815 USD/kWh is taken as the basis of revenue generation, in line with the announcement of EPİAŞ. However, it is to note that this price shall be applied until 2030. Consequently, this paper will come out with a different mechanism of sales price for the 25-year period of the hypothetical OWF.

- Unit Price of O&M

  Based on some similar research as explained above, the unit price for operation and maintenance is taken as 0.026 USD/kWh.

- Inflation Rate

  Inflation is the rate of increase in prices over a given period of time. Inflation is typically a broad measure, such as the overall increase in prices or the increase in the cost of living in a country (Oner, 2024). For a 25-year of assessment, it would be unrealistic to consider that the accepted costs will remain the same. Therefore, an inflation rate of 5.0% for each year shall be considered in the revenue stream calculations.

- Price Escalation

  With the assumption of the operating expenses will increase on a yearly basis in line with the considered inflation rate through the life span of the OWF, and taking into account that the sales price will remain the same until 2030 as described in YEKDEM regulations, a price escalation rate of "inflation rate + 3%" with respect to sales price is considered in this study, which is reasonable in long term power purchase agreements with the governmental bodies.

- Other Costs

  Besides the operating costs of the OWF, there will be also some additional costs associated with the governmental bodies and banks, such as tax and finance related costs. This study prefers to have a general approach instead of delving into all of them, considers some major tax exemptions would be provided to the investor, and accepts a percentage rate of 2.0% as other costs based on the streamed revenue.

Following Table 4.6 below summarizes the value assumptions for the feasibility study.

Table 4.6: Considered values for the feasibility study.

Sales Unit Price	O&M Unit Price	Inflation Rate	Other Costs	Price Escalation Rate
0.0815 USD/kWh	0.026 USD/kWh	5.0%	2.0%	Inflation Rate + 3.0%

4.4.2 A 25-year economic analysis of the OWF

Based on the above assumptions and considerations, a revenue stream generation and profit calculation simulation are run. The analysis spans a 25-year operational period and integrates various financial and operational assumptions to provide a comprehensive understanding of the project's potential profitability. Key parameters include the sales unit price of electricity, operational and maintenance (O&M) costs, inflation rate, price escalation rate, and other associated costs. This section also explores underlying economic dynamics and less apparent factors that contribute to the overall financial performance.

The baseline of the calculation in Table 4.7 is the AEP of the turbine, which is calculated as around 18.3 GWh per year for a single offshore wind turbine.

Table 4.7: Turkish hypothetical OWF 2026 -2050 (25 years) revenue and profit generation simulation.

		Generated amount of energy (x20 turbines)	Sales Unit Price	Gross Revenue	O&M (OPEX) Unit Price	O&M (OPEX) Costs	Other Costs (tax, financing, etc.)	Net Profit
		MWh/year	USD/kWh	(M USD)	USD/kWh	(M USD)	(M USD)	(M USD)
2026	Year-1	365,902	$ 0.0815	$ 29.84	$ 0.026	$ 9.38	$ 0.60	$ 19.86
2027	Year-2	365,902	$ 0.0815	$ 29.84	$ 0.027	$ 9.84	$ 0.60	$ 19.39
2028	Year-3	365,902	$ 0.0815	$ 29.84	$ 0.028	$ 10.34	$ 0.60	$ 18.90
2029	Year-4	365,902	$ 0.0815	$ 29.84	$ 0.030	$ 10.85	$ 0.60	$ 18.39
2030	Year-5	365,902	$ 0.0815	$ 29.84	$ 0.031	$ 11.40	$ 0.60	$ 17.84
2031 (*)	Year-6	365,902	$ 0.0872	$ 31.92	$ 0.033	$ 11.97	$ 0.64	$ 19.32
2032	Year-7	365,902	$ 0.0934	$ 34.16	$ 0.034	$ 12.56	$ 0.68	$ 20.91
2033	Year-8	365,902	$ 0.0999	$ 36.55	$ 0.036	$ 13.19	$ 0.73	$ 22.63
2034	Year-9	365,902	$ 0.1069	$ 39.11	$ 0.038	$ 13.85	$ 0.78	$ 24.47
2035	Year-10	365,902	$ 0.1144	$ 41.85	$ 0.040	$ 14.54	$ 0.84	$ 26.46
2036	Year-11	365,902	$ 0.1224	$ 44.77	$ 0.042	$ 15.27	$ 0.90	$ 28.61

Table 4.7 (continued): Turkish hypothetical OWF 2026 -2050 (25 years) revenue and profit generation simulation.

		Generated amount of energy (x20 turbines)	Sales Unit Price	Gross Revenue	O&M (OPEX) Unit Price	O&M (OPEX) Costs	Other Costs (tax, financing, etc.)	Net Profit
		MWh/year	USD/kWh	(M USD)	USD/kWh	(M USD)	(M USD)	(M USD)
2037	Year-12	365,902	$ 0.1309	$ 47.91	$ 0.044	$ 16.03	$ 0.96	$ 30.92
2038	Year-13	365,902	$ 0.1401	$ 51.26	$ 0.046	$ 16.84	$ 1.03	$ 33.40
2039	Year-14	365,902	$ 0.1499	$ 54.85	$ 0.048	$ 17.68	$ 1.10	$ 36.08
2040	Year-15	365,902	$ 0.1604	$ 58.69	$ 0.051	$ 18.56	$ 1.17	$ 38.95
2041	Year-16	365,902	$ 0.1716	$ 62.80	$ 0.053	$ 19.49	$ 1.26	$ 42.05
2042	Year-17	365,902	$ 0.1836	$ 67.19	$ 0.056	$ 20.46	$ 1.34	$ 45.39
2043	Year-18	365,902	$ 0.1965	$ 71.90	$ 0.059	$ 21.49	$ 1.44	$ 48.97
2044	Year-19	365,902	$ 0.2103	$ 76.93	$ 0.062	$ 22.56	$ 1.54	$ 52.83
2045	Year-20	365,902	$ 0.2250	$ 82.32	$ 0.065	$ 23.69	$ 1.65	$ 56.98
2046	Year-21	365,902	$ 0.2407	$ 88.08	$ 0.068	$ 24.87	$ 1.76	$ 61.44
2047	Year-22	365,902	$ 0.2576	$ 94.24	$ 0.071	$ 26.12	$ 1.88	$ 66.24
2048	Year-23	365,902	$ 0.2756	$ 100.84	$ 0.075	$ 27.42	$ 2.02	$ 71.40

Table 4.7 (continued): Turkish hypothetical OWF 2026 -2050 (25 years) revenue and profit generation simulation.

		Generated amount of energy (x20 turbines)	Sales Unit Price	Gross Revenue	O&M (OPEX) Unit Price	O&M (OPEX) Costs	Other Costs (tax, financing, etc.)	Net Profit
		MWh/year	USD/kWh	(M USD)	USD/kWh	(M USD)	(M USD)	(M USD)
2049	Year-24	365,902	$ 0.2949	$ 107.90	$ 0.079	$ 28.80	$ 2.16	$ 76.95
2050	Year-25	365,902	$ 0.3155	$ 115.45	$ 0.083	$ 30.24	$ 2.31	$ 82.91
		9,147,541						$ 981

(*) The sales unit price is considered the same until 2030, in line with the announced prices by EPİAŞ with regards to offshore wind energy generation.

The gross revenue for the wind farm is primarily driven by the amount of energy generated and the sales unit price of electricity. The energy generation remains constant at 365,902 MWh per year. The initial sales unit price is set at $0.0815 per kWh and remains unchanged until 2030. From 2031 onwards, the sales unit price escalates annually at a rate of inflation plus 3%.

In the first year (2026), the gross revenue is calculated as 29.84M USD and it remains constant until 2030, providing a stable income stream in the initial years. Starting in 2031, the price escalation reflects market dynamics and inflationary pressures, ensuring revenue growth. By the 25th year (2050), the escalated sales unit price significantly enhances the gross revenue to a level of 115.45M USD.

Operational and maintenance (O&M) costs are critical for the long-term sustainability of the wind farm. The O&M unit price begins at $0.026 per kWh and escalates annually with an inflation rate of 5%. The initial O&M cost in 2026 is 9.38M USD. By 2050, with the annual escalation due to the inflation rate, the it rises to 30.24M USD. This gradual increase highlights the impact of inflation on operational expenditures, underscoring the importance of efficient maintenance practices to control costs.

Additional costs, including taxes, financing, and other associated expenses, are estimated at 2% of the gross revenue. These costs are calculated each year based on the gross revenue. These costs reflect financial obligations and regulatory expenses, which, though minor, cumulatively impact profitability.

The net profit for each year is determined by subtracting the O&M costs and other costs from the gross revenue. For example, in the first year, the net profit is 19.86M USD, where as in the final year, the net profit, considering price escalation and cost inflation, reaches 82.91M USD. Over the 25-year period, the cumulative net profit sums to approximately $981 million. This substantial profit indicates the economic viability of the OWF project, assuming the underlying assumptions hold true.

4.4.2.1 Analysis of the Key Factors

The initial sales unit price remaining constant until 2030 provides a stable revenue base, mitigating early financial risks. From 2031, the application of an annual price escalation rate (inflation plus 3%) ensures that revenue growth keeps pace with inflationary pressures and potential increases in market electricity prices. This approach balances early stability with long-term profitability.

The O&M cost escalation is reflective of the real-world scenario where maintenance expenses rise with inflation. This factor is critical, as maintenance efficiency and cost management directly influence net profitability. Advanced predictive maintenance technologies and economies of scale can potentially mitigate these rising costs, enhancing financial outcomes.

Considering both an inflation rate and a price escalation rate provides a realistic projection of future financial conditions. This dual consideration ensures that the analysis captures both cost inflation and revenue growth, offering a balanced and comprehensive view of the project's economic viability.

Although relatively minor, the 2% additional costs on gross revenue encompass a range of financial obligations, including taxes and regulatory compliance. These costs, while fixed as a percentage, increase in absolute terms as revenue grows, highlighting the importance of efficient financial planning and regulatory compliance strategies.

This section concludes that this economic feasibility analysis demonstrates the potential profitability of the hypothetical offshore wind farm in the Foça region. With detailed consideration of energy generation, cost structures, and economic factors over a 25-year period, the study highlights the project's viability. The cumulative net profit of $981 million underscores the financial attractiveness of investing in offshore wind energy, supporting the case for further development and implementation of such renewable energy projects in Turkey. Advanced financial modeling and sensitivity analysis further bolster the project's robustness, ensuring it remains a viable investment under varying economic conditions.

4.4.2.2 Financial analysis of the results

The objective of this simulation was to evaluate the profit over the lifetime of the OWF with respect to the financial parameters such as IRR and discounted ROI in consideration of the NPV of money. These metrics provide a comprehensive understanding of the project's potential profitability over its 25-year operational period.

- Internal Rate of Return (IRR)

  IRR is a financial metric used to gauge the profitability of investments. It is defined as the discount rate that equates the Net Present Value (NPV) of all cash flows to zero in a discounted cash flow analysis. Typically, a higher IRR

indicates a more attractive investment opportunity, allowing for the comparison of different investment options based on their profitability. For instance, in capital planning, IRR helps in decisions like choosing between establishing new operations or expanding existing ones. (Fernando, 2024)

- Return on Investment (ROI)

  ROI is a profitability ratio that measures the gain or loss generated from an investment relative to its cost. It offers insights into the profitability of potential projects by indicating how effectively invested money generates returns. ROI is crucial in assessing investment performance; however, for long-term investments, it may be less accurate due to its inability to consider the time value of money. Discounted ROI, which adjusts for the time value of money, is more suitable for long-term investment evaluations. (Debitoor, 2024)

- Net Present Value (NPV)

  NPV is a financial metric that calculates the total value of an investment by considering all future cash inflows and outflows, discounted to their present value. A positive NPV signifies that projected earnings exceed costs, indicating a profitable investment opportunity. Conversely, a negative NPV suggests potential financial losses. NPV is instrumental in evaluating investment opportunities to maximize profitability and long-term value.

With the discount rate assumption of 5.0%, the NPV of each year's net profit is calculated. The result led to a total NPV of 465.26M USD, which is higher than the initial 319M USD investment cost and which shows a positive trend. Figure 4.8 below shows the positive NPV trend for each year, as well as the cumulative values throughout 25-year.

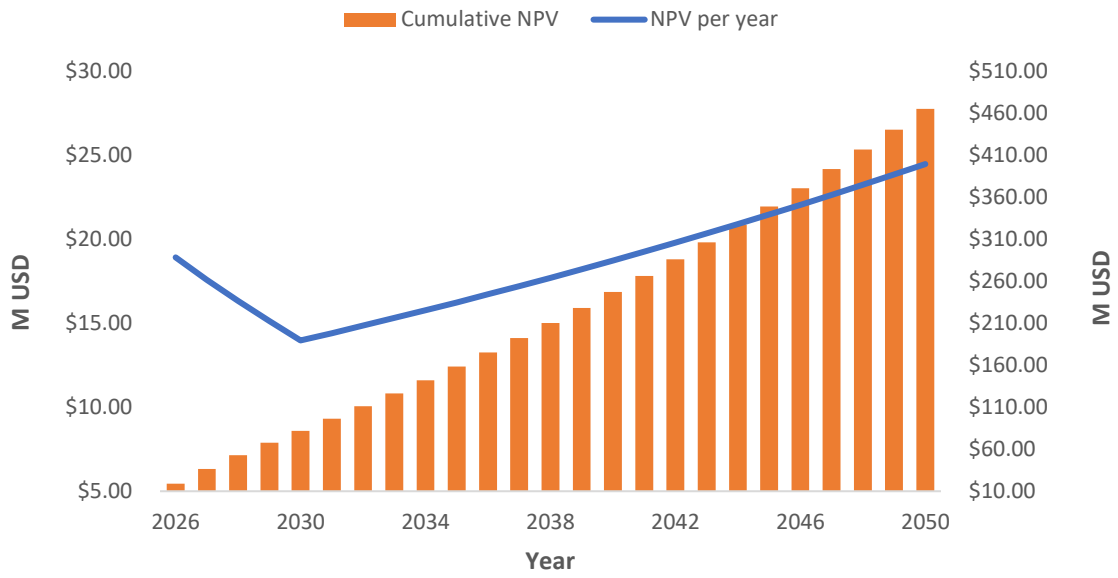

Figure 4.8: NPV for each year and NPV on cumulative basis from 2026 to 2050.

The positive NPV values observed throughout the projected period suggest that the OWF project is anticipated to generate returns exceeding the initial investment. According to (Brigham & Houston, 2013), a positive NPV indicates that the project's cash inflows are greater than the outflows, implying profitability and value creation over time.

The decreasing trend in NPV values over the first 5-6 year period as noted by Akhavan et al. (2021) is observed due to varied factors. OPEX costs that we observe are increasing by the rate of inflation whereas the electricity sales price remains the same. Since after five-six years, electricity sales price begins to increase more than the rate of inflation, we identify that the trend turns into a positive as seen with the behaviour of the NPV curve.

Despite the decreasing trend in NPV during the first quarter, there's a continued positive trend where we observe that this OWF project not only generates considerable profit, but contribute to long-term sustainability as well as decarbonisation efforts. This could lead to governments and investors to increasingly prioritize renewable energy projects due to their environmental benefits, potentially leading to additional support or incentives, as suggested by Inderberg (2017).

The IRR of the OWF project is calculated as 8.0%, reflects the discount rate at which the NPV of all cash flows equals zero and indicating the project's strong potential for

generating returns above the cost of capital. This calculated rate seems to be in line and even above the global offshore wind investment benchmark, which is around 5-6% according to (Guillet, 2022).

The discounted ROI of the economic simulation is calculated as 45.85%. This reflects a substantial return on the invested capital, highlighting the investment's efficiency and potential for generating significant profits.

In conclusion, the financial analysis of the proposed OWF in Foça, Turkey, using NPV, IRR, and ROI metrics, demonstrates strong economic viability. With a positive total NPV of $465.26 million and an ROI of 45.85%, the project promises substantial returns, making it an attractive investment opportunity. The IRR of 8.0% further supports the project's profitability potential. Sensitivity analysis and risk mitigation strategies can enhance the project's robustness, ensuring sustained profitability under varying economic conditions.

It is also worth noting that these calculations assume a consistent annual inflation rate of 5%. Economic conditions and inflation rates can fluctuate over time, and these projections provide a baseline scenario. Nevertheless, the overall trend suggests that the simulated OWF in the Aegean Sea holds promise for long-term financial viability, aligning with the goals of sustainable energy production and economic return.

4.5 Identification of Key Stakeholders and Government Policies in Turkey

In Turkey's energy sector, several key stakeholders hold significant sway in shaping the nation's energy landscape. At the forefront stands the Ministry of Energy and Natural Resources, a pivotal governmental body wielding considerable influence (Power, 2022). This ministry serves as the architect behind Turkey's energy policies, steering initiatives, and laying the groundwork for the country's renewable energy trajectory, including the strategic development of offshore wind projects. Working in tandem, EPDK assumes a crucial role in the energy ecosystem, ensuring regulatory compliance, licensing procedures, and fostering a competitive and transparent energy marketplace (Turk, 2012).

Also, major energy players like Turkish Petroleum, Enerjisa, and Zorlu Energy wield substantial influence. These entities stand as significant investors spearheading renewable energy ventures, notably including investments in the establishment and

expansion of offshore wind farms (Akca Prill, 2020; Mills & House, 2014). Complementing the efforts of these companies, industry associations like the TÜREB and the TEİAŞ play pivotal roles. TÜREB, renowned for its expertise and advocacy, champions the cause of wind energy, fostering collaboration, knowledge sharing, and policy advocacy within the renewable energy sector (Tuncer, 2012). Meanwhile, TEİAŞ contributes to the orchestration and coordination of electricity transmission, a critical aspect in the integration of renewable energy sources into the national grid (Arizu et al., 2006).

Collectively, these stakeholders constitute Turkey's energy sphere, each entity playing a distinct and essential role in advancing the nation's energy agenda. Their collaborative efforts, policy advocacy, and strategic investments underscore Turkey's commitment to renewable energy development, particularly in the domain of offshore wind, heralding a transformative shift towards a more sustainable and diversified energy future.

Furthermore, the exploration of governmental policies and energy strategies provides a lens into Turkey's concerted efforts toward advancing renewable energy and offshore wind development. Notably, initiatives like YEKA tenders exemplify the government's resolute commitment to nurturing the growth of renewable energy (Hurriyet Daily News, 2023). Despite initial challenges in enticing investors for larger-scale YEKA projects, the government's responsive approach is evident in restructuring tenders into smaller capacities, showcasing adaptability to market dynamics and fostering broader investor participation.

According to the review of Tanil (2023), Turkey's energy landscape reflects a significant reliance on fossil fuels, with 83% of its total primary energy supply derived from fossil fuels, a Figure comparable to some EU member states. However, the country has made substantial strides in renewable energy, doubling its production since 2009 and achieving 54% of total energy from renewable sources in 2019, primarily through hydro, wind, and solar energy. The government's objectives aim to reduce import dependency on oil and gas, promoting renewable energy and even considering the introduction of nuclear power to diversify the energy mix. This strategic shift seeks not only energy security but also economic growth, aligning with both national priorities and EU policy objectives.

Additionally, RECs have emerged, facilitated by supportive energy policies and the Renewable Energies Act, contributing to local energy production, employment, and sustainable economic growth (Özgül et al., 2020). The study of Özgül et al. (2020) delves into the dynamics of these cooperatives, investigating their organization, financing, and barriers through a questionnaire, interviews, and website analysis. These RECs could serve as a model for utilizing local renewable resources, aligning with both energy transition goals and sustainable economic growth.

Wind energy, particularly offshore wind, holds tremendous potential to diversify Turkey's energy sources. Despite its coastal proximity, offshore wind energy remains largely untapped. A methodological framework by Argin et al. (2019) was used to identify suitable offshore wind farm locations, evaluating wind energy potential across 55 coastal regions. The analysis identifies Bozcaada, Bandirma, Gokceada, Inebolu, and Samandag coastlines as prime locations for offshore wind farms, estimating a total capacity of 1,629 MW. Emphasizing the potential of offshore wind, this study underlines its role in reducing reliance on imported energy resources and enhancing domestic energy production. These findings pave the way for policymakers to support the growth of renewable energy, particularly offshore wind, contributing to Turkey's energy independence and sustainable economic development.

Moreover, the introduction of net-metering regulations, exempting smaller-scale renewable energy projects from the rigorous power generation licensing requirements, stands as a testament to Turkey's proactive measures aimed at incentivizing decentralized energy production (Bölük & Kaplan, 2022). This move not only empowers smaller renewable energy ventures but also encourages diverse energy participation across the nation. The country's comprehensive National Energy Plan, spanning the period from 2020 to 2035, sets ambitious benchmarks for various renewable energy sources, including offshore wind, with a bold target of achieving 5 GW of installed offshore wind capacity by 2035 (Durak, 2023).

These governmental policies underscore Turkey's strategic focus on diversifying its energy portfolio and diminishing reliance on energy imports. Aligning with global trends that prioritize cleaner and sustainable energy solutions, Turkey's initiatives signal a resolute commitment toward fostering a robust, self-sustaining energy landscape. The emphasis on renewable energy, including offshore wind, within its

long-term energy vision reaffirms Turkey's progressive stance in steering its energy trajectory toward a more sustainable and environmentally conscious future.

4.6 Quantitative Analysis of Energy Production and Consumption.

Quantitative assessments will be performed to analyze historical energy production and consumption trends in Turkey, especially focusing on wind, solar, hydro, and other renewable sources. This analysis will involve evaluation of growth rates, installed capacities, and trends over the past two decades.

Turkey's energy landscape, as outlined in the preliminary analysis, showcases a multifaceted approach to power production and consumption, encompassing both traditional and renewable sources. The country has undertaken significant initiatives, such as the East-West Energy Corridor Project, to enhance its energy infrastructure. The focus on Trans-Caspian and Trans-Caucasian pipelines reflects Turkey's strategic positioning in facilitating energy transfer between Asia and Europe. The Iğdır-Nahçıvan Natural Gas Pipeline, part of these efforts, strengthens Turkey's role in shaping Europe's energy dynamics.

Renewable energy has emerged as a pivotal component of Turkey's energy strategy. The commitment to renewables aligns with the country's growing population and economy, resulting in a rapid expansion of the energy system. The Turkish government's emphasis on domestic resources, particularly wind, solar, hydro, geothermal, and biomass energy, aims to reduce the substantial expenditure on energy imports. Policies such as simplified regulations for projects up to 5 MW and the issuance of Renewable Energy Resource Zone (YEKA) tenders underscore the government's dedication to fostering renewable energy development. The government's goal to double installed capacity by 2050, with 50% coming from renewables, underscores a long-term commitment to reducing reliance on energy imports. Market trends reveal significant growth in the unlicensed solar sector and substantial contributions from wind, geothermal, and biomass energy, collectively meeting a substantial portion of total demand.

Quantitative analysis of energy production and consumption in Turkey, as presented by the IAEA, underscores the country's dependence on varied energy sources. The estimated available energy sources include fossil fuels, nuclear, and renewables, with

wind power projected at 48,000 MW. Electricity production data from 2000 to 2020 exhibit varied compound annual growth rates, with wind power registering the highest at 39.26%. The increasing energy and electricity consumption per capita reflect a rising demand, raising concerns about potential dependency on external sources.

Sahin's (2020) research forecasts Turkey's total renewable and hydro energy installed capacity and electricity generation until 2030, utilizing fractional nonlinear grey Bernoulli models. The study highlights a consistent contribution of hydro energy but projects a decrease, prompting environmental concerns and a recommendation to reduce hydropower's share. This aligns with Turkey being deemed water-stressed, emphasizing the need for environmentally conscious energy choices.

The information provided by Firdevs and Alhan (2023) underscores the significant potential for wind energy in Turkey, surpassing the targeted capacity by 2035. Turkey's current sixth position in Europe for installed wind capacity and its advantageous position for offshore wind contribute to the nation's pivotal role in Europe's wind energy ambitions. The call for keeping economic benefits within Europe aligns with the broader goal of regional economic growth.

4.7 Evaluation of Offshore Wind Potential in Turkey

The evaluation of offshore wind potential in Turkey, considering the literature and preliminary analysis, underscores the promising outlook for harnessing wind energy from the country's extensive coastal regions. Turkey's geographic positioning, with coastlines along the Black, Aegean, and Mediterranean Seas, provides a favorable environment for offshore wind power generation. According to information provided by Firdevs and Alhan (2023), Turkey's existing onshore wind capacity lays a strong foundation for the expansion of offshore wind projects. The TÜREB reports that the current installed total capacity is 106,000 MW, and the nation's total wind energy potential could reach an impressive 45,000 MW, surpassing initial targets. The preliminary analysis also highlights that Turkey's wind power generation witnessed a substantial increase from 2008 to 2022, with offshore wind farms becoming a game-changer due to their higher potential capacity.

In line with these findings, the discussion on the evaluation of offshore wind potential in Turkey emphasizes the need for detailed studies and strategic initiatives to unlock

the full capabilities of offshore wind energy. The graph depicting wind power generation in Turkey from 2008 to 2022 (Statista, 2023) further illustrates the significant growth in onshore wind capacity and suggests the untapped potential of offshore wind resources. However, while the preliminary analysis presents a positive trajectory, challenges such as high upfront costs, technological complexities, and regulatory hurdles for offshore wind projects are recognized globally. Despite the potential, the specific challenges and competition in the Turkish context require thorough consideration.

Turkey's coastal geography, as evidenced by its extensive shorelines, is a critical factor in the evaluation of offshore wind potential. The coastal areas provide an advantageous environment for harnessing wind energy from the sea, where wind resources are typically stronger and more consistent than onshore locations. This aligns with Turkey's increasing power consumption and production needs, driven by a growing population and expanding economy. As emphasized by the International Atomic Energy Agency (IAEA, 2022), the estimated available energy sources in Turkey, including wind power at 48,000 MW, highlight the nation's recognition of the importance of renewable energy, particularly wind, in meeting its energy demands.

To further support the evaluation of offshore wind potential, it's essential to consider the economic and environmental implications. The acknowledgment of Turkey's pivotal role in Europe's wind energy ambitions, as highlighted by Giles Dickson, CEO of WindEurope, adds another layer to the discussion. The European Union's goal to increase wind power generation aligns with Turkey's advantageous position to contribute to Europe's wind energy manufacturing base, potentially reducing external dependencies and fostering regional economic growth. This aligns with Turkey's broader efforts, as outlined in the preliminary analysis, to position itself as a significant player in the global energy market, with a comprehensive approach to shaping its energy future.

The evaluation of offshore wind potential in Turkey reveals a confluence of geographic advantages, existing onshore wind capacity, and strategic positioning in the broader context of Europe's renewable energy goals. The literature and preliminary analysis provide a foundation for understanding Turkey's potential to become a major player in offshore wind power generation.

4.8 Forecasting and Scenario Analysis

Forecasting models and scenario analyses will be employed to project Turkey's future energy landscape, focusing specifically on offshore wind energy's role, potential growth, and its contribution to the national energy mix.

The information provided by (Kesikli, 2023) on the energy sector in Turkey presents a comprehensive overview of the country's ambitious goals and strategies in the realm of electricity generation. The Turkish government's objective to have renewable energy account for 30% of overall electricity generation by 2023 reflects a commitment to sustainability and reducing dependence on imported energy sources. According to this research, the targeted overall power generation of 120 GWh by 2023 necessitated a substantial investment of approximately $110 billion, underscoring the scale of the country's energy ambitions. The driving forces behind these investments include rapid population growth, increasing energy demands, and the pursuit of energy supply security.

The liberalization of the energy market, facilitated by the Electricity Market Law of 2001, has been a pivotal factor in transforming Turkey's energy landscape. Prior to this legislation, private sector involvement in electricity production was limited, primarily relying on concession frameworks. The subsequent privatization initiatives, starting in 2004, aimed to create a more competitive marketplace. Notably, the 2013 privatization of the electricity distribution network marked a significant milestone.

Importantly, Kesikli's information sheds light on Turkey's evolving energy mix. While the 2010 gross electricity consumption was 210,434 GWh, a 21% increase to 255,545 GWh was observed in 2014, highlighting the expanding energy market. The diversification of the energy mix is emphasized, with targets indicating that by 2019, Turkey's energy composition is projected to comprise 40% natural gas, 25% hydro power, 25% coal, and 10% renewables. This strategic balance aims to enhance energy security, reduce dependence on imported sources, and improve overall energy efficiency.

In the realm of renewables, Turkey is acknowledged to have significant potential for power generation. However, the current reliance on imported natural gas has led to a trade deficit, prompting the government's multifaceted energy strategy. This strategy not only prioritizes energy security and efficiency but also seeks to create an attractive

investment climate for foreign investors. The implementation of feed-in tariffs and incentive programs, particularly for renewable energy projects utilizing locally manufactured equipment, is a notable aspect. These incentives are designed to encourage global suppliers to establish manufacturing facilities in Turkey, fostering both economic growth and energy sustainability.

The comprehensive investment incentive plan outlined by Kesikli (2023) encompasses value-added tax and customs duty exemptions for renewable energy projects, further incentivizing investment in this sector. Regional investments, aimed at addressing energy imbalances within the country, and the encouragement of research and development activities contribute to a holistic approach toward achieving Turkey's energy goals.

In conclusion, Turkey's energy sector, as portrayed in Kesikli's analysis, reflects a dynamic landscape marked by substantial investments, liberalization efforts, and a strategic focus on renewables. The government's ambitious targets and incentive programs underscore a commitment to sustainable and diversified energy sources, positioning Turkey as a significant player in the global energy arena. However, ongoing vigilance and effective policy implementation will be crucial to overcoming challenges and realizing the outlined energy objectives.

4.9 Risk Assessment and Mitigation Strategies

Offshore wind projects, particularly in the Turkish Aegean Sea, are subject to various risks that necessitate a comprehensive risk assessment and effective mitigation strategies. The research identified key risks and proposed mitigation measures to ensure the successful and sustainable operation of offshore wind farms.

4.9.1 Variability in wind speeds

One of the prominent challenges identified is the variability in wind speeds in the Turkish Aegean Sea, which can impact the overall efficiency and reliability of offshore wind energy generation. According to Gumuscu et al. (2023), wind speed variations were observed, with instances of lows as 2 m/s, indicating potential periods of low efficiency. To mitigate this risk, the implementation of advanced turbine technologies designed for lower wind speeds (Gumuscu et al., 2023) is recommended. Additionally, energy storage solutions and hybrid energy systems can help compensate for

fluctuations in wind velocity, providing a more stable power output (Gumuscu et al., 2023; Veers et al., 2019).

The Aegean Sea experiences significant variability in wind speeds throughout the year due to the changing seasons. The Meltemi winds in the summer can reach these high speeds, occasionally exceeding 100 km/h (approximately 27.8 m/s). Similarly, the north winds in the winter can also reach high speeds, up to 8-9 on the Beaufort scale (Real Greek Experience, 2024; Windy.App, 2024). The Beaufort scale is a measure that is used to estimate wind speeds based on empirical observations. The scale ranges from 0 (calm) to 12 (hurricane).

Wind speed is a critical factor in wind power generation. The power output of a wind turbine is proportional to the cube of the wind speed (Energy Education n.d). Therefore, higher wind speeds result in significantly more power generation. However, it's important to note that wind turbines have a cut-out wind speed, typically around 25 m/s (Siemens Gamesa, 2024), above which the turbine will shut down to avoid damage.

Given these wind speeds, the Aegean Sea, particularly in the summer and winter months, has significant potential for wind power generation. The high wind speeds can result in high power outputs from the wind turbines. However, if the wind speeds frequently exceed the cut-out wind speed of the turbines, this could lead to frequent shutdowns and potentially damage the turbines. Considering the Siemens Gamesa 5.0 MW turbines, their efficiency would be influenced by these seasonal wind variations. The turbines would generate more power during periods of higher wind speeds, and less power during periods of lower wind speeds. Therefore, the net power output of the turbines over the course of a year would be a result of these seasonal variations in wind speed.

These variations in wind speeds have significant implications for wind power generation in the Aegean Sea. Higher wind speeds, particularly those observed in the summer and winter, could lead to increased power output from wind turbines. However, the variability in wind speeds, especially the lower speeds in spring and certain areas in summer, could affect the consistency of power generation. This underscores the importance of considering seasonal wind speed variations when planning wind energy projects in the Aegean Sea.

4.9.2 Technological risks

Technological risks associated with offshore wind turbines, such as equipment failures or malfunctions were observed in our research. To address this, routine maintenance and monitoring protocols should be established (Veers et al., 2019). Additionally, continuous advancements in turbine technologies are monitored and adopted to enhance reliability, and efficiency (Gumuscu et al., 2023).

4.9.3 Environmental and regulatory risks

Environmental and regulatory risks, including potential impacts on marine ecosystems and changing governmental policies, were recognized. Proper site selection, thorough environmental impact assessments, and collaboration with regulatory bodies are crucial risk mitigation strategies (European Commission, 2019). Governments can play a key role by providing stable regulatory frameworks and incentives to support offshore wind projects (Gumuscu et al., 2023).

4.9.4 Financial risks

Financial risks, encompassing capital expenditure overruns and fluctuating energy prices are inherent in offshore wind projects. A well-structured financial plan, risk-sharing mechanisms, and partnerships with financial institutions are essential for mitigating financial uncertainties (GWEC, 2020).

The installation of OWFs in the Aegean Sea, particularly in Turkey, involves several financial risks. These risks are influenced by various factors including the choice of wind turbines, such as the SG 5 MW.

Capital Intensity: Wind turbines, including the SG 5 MW, are capital-intensive investments (EWEA, 2024). The initial costs include the turbine itself, installation, connection to the grid, and potentially, the construction of new infrastructure. These upfront costs can be substantial and pose a financial risk if the revenue generated by the turbine does not cover these costs over its operational lifetime (EWEA, 2024).

Operational and Maintenance Costs: Once installed, wind turbines incur ongoing operational and maintenance costs. These costs can be significant and vary depending on the specific turbine model, local environmental conditions, and the availability of skilled maintenance crews (PWC, 2024). If these costs are higher than anticipated, they can negatively impact the profitability of the wind farm (PWC, 2024).

Revenue Uncertainty: The revenue generated by a wind turbine is highly dependent on wind speeds, which can be variable and unpredictable (PWC, 2024). Seasonal variations in wind speeds in the Aegean Sea, as discussed earlier, can lead to fluctuations in power output and hence, revenue. This uncertainty can pose a financial risk (PWC, 2024).

Regulatory and Policy Risks: Changes in government policies or regulations can also pose a financial risk. For example, changes in renewable energy subsidies, tax incentives, or electricity pricing can directly impact the revenue of wind farms (PWC, 2024).

Market Risks: The global wind turbine market is projected to grow at a compound annual growth rate of 6.3% from 2020 to 2030 (Allied Market Research, 2024). However, market risks such as changes in technology, competition, and demand can impact the financial viability of wind farms (Global Market Insights, 2024).

In conclusion, while the installation of OWFs in the Aegean Sea has the potential for significant renewable energy generation, it's crucial to consider these financial risks. A detailed financial analysis and risk assessment should be conducted for each specific project to ensure its financial viability.

5. CONCLUSION AND RECOMMENDATIONS

In conclusion, our feasibility study on offshore wind power generation in Turkey, particularly in Foça region of the Aegean Sea, presents a compelling case for its potential as a hub for large-scale power generation. The technical analysis, encompassing the simulation of Siemens Gamesa 5 MW turbines at varying wind speeds, reveals favorable conditions for power efficiency. The calculated power output at 10 m/s with the impact of several technical considerations, combined with the evaluation of Turkish OWF's power potential, support the notion that Turkey's coastline holds significant promise for harnessing wind energy.

The technical analysis of the simulated Aegean conditions case study demonstrates comparable and, in some scenarios, superior power efficiency in the Turkish offshore setting. The power output calculations for the total of twenty (20) turbines further align with the estimated maximum power, reinforcing the feasibility of large-scale power generation in the Turkish seas. Regarding the efficiency of the Siemens Gamesa SG 5.0 MW turbines, it’s important to note that while the actual power produced is lower than the rated maximum, this is a common occurrence in wind energy projects due to the variable and unpredictable nature of wind. The efficiency of a wind turbine is typically evaluated based on its performance at different wind speeds, its reliability, and its lifespan.

Economically, the revenue returns and analysis based on ROI, IRR and NPV underscore the financial viability of offshore wind projects in the Aegean region. The robust net returns and impressive annualized ROI percentages at varying wind speeds substantiate the economic feasibility of such ventures, making them attractive investments with substantial profit margins.

This comprehensive feasibility study suggests that Turkey's coastline has the potential to emerge as a significant hub for large-scale power generation. The combination of favorable wind conditions, technical efficiency, and promising economic returns positions Turkey as a viable player in Europe's pursuit of renewable energy sources. If the right investments are made and supportive policies are implemented, Turkey's

offshore wind sector could contribute substantially to the country's energy portfolio and the broader European renewable energy landscape.

According to the literature findings, the Aegean Sea experiences wind speeds as low as 2 m/s, highlighting periods of low wind activity. Such low wind speeds are critical as they fall below the typical cut-in speed for many modern wind turbines, limiting their ability to generate power efficiently.

Modern wind turbines, including the SG 5 MW turbine simulated in this research, are typically designed to start producing power at a certain cut-in speed, which is around 3 to 4 m/s for many models. Below this threshold, the turbine remains inactive, resulting in decreased power efficiency during periods of low wind. Therefore, low wind speeds would likely contribute to decreased overall power efficiency and output, especially if sustained for extended durations.

Conversely, examining the effects of higher wind speeds between, encompassing the rated wind speed of 14 m/s, is crucial for understanding the optimal operating range of the simulated Turkish Aegean OWF. The rated wind speed represents the point at which the turbine achieves its maximum efficiency, and the power output expected to be at its peak. In this range, the simulated OWF is likely to perform most efficiently, generating electricity close to its capacity. However, it is essential to consider the potential impacts of wind speeds exceeding the rated speed, as discussed in the literature. The simulated turbine may face challenges such as over speeding and increased loads, which could affect its long-term reliability and efficiency at speeds exceeding 25 m/s. Thus, striking a balance within the optimal wind speed range is critical to maintaining both power efficiency and the longevity of the wind turbines.

Winds below 8 m/s in the Turkish Aegean Sea may pose challenges to the power efficiency of the simulated OWF due to the turbines' metrics. Additionally, while wind speeds between 8 and 14 m/s are expected to contribute to optimal power efficiency, exceeding the rated wind speed 14 m/s to 24 m/s maintains the turbines power output at its maximum however speeds above 25 m/s might introduce concerns about turbine performance and longevity. A comprehensive analysis, considering various wind speed scenarios and their impact on turbine performance, is crucial for accurately assessing the feasibility and sustainability of the proposed offshore wind project at varied conditions.

The research on OWFs in Turkey has further shed light on potential challenges and opportunities. In light of the findings, the research proposes six key recommendations aimed at helping Turkey unlock its maximum potential in offshore wind energy. With the variations in wind power posing a challenge of efficiency, addressing the challenge of wind velocity variations in the Turkish Aegean Sea requires a combination of technological, strategic, and policy-driven approaches. Here are recommendations based on the research findings and broader insights into offshore wind energy:

Advanced Turbine Technologies:

Invest in turbines with advanced technologies designed to capture energy efficiently even at lower wind speeds. Innovations in turbine design, such as larger rotor diameters and improved aerodynamics, can enhance performance during periods of variable wind speeds (European Commission, 2019; GWEC, 2020).

To capitalize on its offshore wind potential, Turkey should prioritize substantial investments in cutting-edge technology and infrastructure. Upgrading and expanding the grid infrastructure to accommodate the intermittent nature of wind energy and adopting the latest turbine technologies will enhance efficiency. Drawing lessons from similar existing projects, Turkey can benefit significantly from embracing state-of-the-art equipment and ensuring a resilient and interconnected grid.

Policy Framework and Regulatory Support:

Establishing a clear and supportive policy framework is essential for fostering a conducive environment for offshore wind projects. The Turkish government should work towards creating stable regulatory frameworks, offering long-term incentives, and streamlining permitting processes. Learning from similar projects realized, where a supportive regulatory environment played a crucial role, Turkey can attract more investments and ensure sustained growth in its offshore wind sector.

Collaboration and Knowledge Sharing:

Encouraging collaboration among industry stakeholders, research institutions, and international partners is crucial. Turkey can benefit from the exchange of knowledge, experiences, and best practices in offshore wind development. Adopting a collaborative approach, which involves partnerships with local communities, suppliers, and global organizations, Turkey can create a vibrant ecosystem that accelerates the learning curve and minimizes challenges.

Site Selection and Planning:

Conduct thorough site assessments and choose locations with more consistent wind patterns (International Energy Agency (IEA), (2019)). Comprehensive analyses of wind patterns, atmospheric conditions, and other meteorological factors can guide the selection of sites that minimize the impact of wind velocity variations.

Public Awareness and Engagement:

Increasing public awareness and fostering community engagement are integral to the success of offshore wind projects. Turkey should prioritize comprehensive public awareness campaigns to educate communities about the benefits of offshore wind energy. Proactive engagement with local communities, coupled with transparent communication, provides a model for Turkey to follow, ensuring social acceptance and minimizing potential opposition.

Capacity Building and Workforce Development:

Developing a skilled workforce is essential for the sustainable growth of Turkey's offshore wind industry. The country should invest in education and training programs focused on the specific needs of the offshore wind sector. Emphasis on workforce development and local job creation serves as an excellent example. By nurturing a skilled workforce, Turkey can enhance project efficiency, reduce dependence on foreign expertise, and contribute to job creation in the renewable energy sector.

In conclusion, these recommendations, grounded in the insights gained from Turkish Aegean OWFs and the broader literature on offshore wind energy, offer a roadmap for Turkey to unlock its offshore wind potential. Addressing technological, regulatory, collaborative, social, and human capital aspects will position Turkey as a leading player in Europe's transition to sustainable and renewable energy sources.

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CURRICULUM VITAE

Name Surname **:** Deniz SATILMIŞ

EDUCATION **:**

- **B.Sc.** **:** 2013, Yildiz Technical University, Faculty of Civil Engineering, Environmental Engineering

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2023-To Date, Nordex Finland Oy
- 2020-2023, Karadeniz Holding (Karpowership)
- 2016-2020, ILTEKNO İleri Teknoloji Mühendislik

PUBLICATIONS/PRESENTATIONS ON THE THESIS:

- **Çakan, M., & Satılmış, D.** (2024). Offshore Wind Farm Simulation Analysis in Turkish Aegean Seas, Foça Region. *12th International Congress on Advanced Scientific Studies and Interdisciplinary Research* (p. 79). Paris: Atlas.