University of Cyprus

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

OFFSHORE WIND ASSESSMENT IN CYPRUS

MASTER'S THESIS

ELENI KANARI

Nicosia, November 2025

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ELENI KANARI

Research Supervisor

Dimitris Stagonas

Professor

"A Thesis submitted for a Master's degree at the University of Cyprus"

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Declaration

Metereological data used for this study (wind speed) were downloaded throught the Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.adbb2d47. The python codes for reading and processing the NetCDF metereological variables were processed in Visual Studio Code.

ABSTRACT

This research explores the offshore wind potential of Cyprus and assesses its viability for establishing offshore wind energy projects. The study evaluates three coastal sites Limassol, Larnaca, and Paphos to analyze their wind characteristics and associated energy capabilities. Utilizing hourly ERA5 reanalysis data, which were extrapolated to hub height, the study estimates the Annual Energy Production (AEP) for a 15 MW offshore wind turbine. The focus of the analysis is to compare the energy outputs from the selected locations to determine those with the greatest offshore wind potential. The findings of this study enhance the understanding of offshore wind resources in Cyprus and serve as a valuable foundation for exploring future offshore wind energy development opportunities within the region.

Keywords: Offshore wind energy, ERA5, Annual Energy Production (AEP), Wind resource assessment, Site comparison.

ΠΕΡΙΛΗΨΗ

Η παρούσα έρευνα εξετάζει το υπεράκτιο αιολικό δυναμικό της Κύπρου και αξιολογεί τη βιωσιμότητά του για την ανάπτυξη υπεράκτιων αιολικών εγκαταστάσεων. Στο πλαίσιο της μελέτης αξιολογούνται τρεις παράκτιες τοποθεσίες Λεμεσός, Λάρνακα και Πάφος με σκοπό την ανάλυση των ανεμολογικών χαρακτηριστικών τους και του αντίστοιχου ενεργειακού δυναμικού. Χρησιμοποιούνται μετεωρολογικά δεδομένα ERA5 σε ωριαία ανάλυση, τα οποία προσαρμόζονται στο ύψος πλήμνης και αξιοποιούνται για τον υπολογισμό της Ετήσιας Ενεργειακής Παραγωγής (AEP) υπεράκτιας ανεμογεννήτριας ισχύος 15 MW. Η ανάλυση επικεντρώνεται στη σύγκριση της αναμενόμενης ενεργειακής απόδοσης των επιλεγμένων τοποθεσιών, με στόχο τον εντοπισμό εκείνων που παρουσιάζουν το υψηλότερο υπεράκτιο αιολικό δυναμικό. Τα αποτελέσματα της έρευνας συμβάλλουν στην καλύτερη κατανόηση των υπεράκτιων αιολικών πόρων της Κύπρου και αποτελούν μια αξιόπιστη βάση για τη διερεύνηση μελλοντικών ευκαιριών ανάπτυξης υπεράκτιων αιολικών έργων στην περιοχή.

Λέξεις κλειδιά: Υπεράκτια αιολική ενέργεια, ERA5, Ετήσια Ενεργειακή Παραγωγή (AEP), Αξιολόγηση αιολικού δυναμικού, Σύγκριση τοποθεσιών.

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Abbreviations

AEP	Annual Energy Production
CAPEX	Capital Expenditure
CF	Capacity Factor
EIA	Environmental Impact Assessment
EU	European Union
ERA5	ECMWF Reanalysis v5 (Global Atmospheric Reanalysis Dataset)
GHG	Greenhouse Gas
GIS	Geographic Information System
LCOE	Levelised Cost of Energy
MWh	Megawatt-hour
MW	Megawatt
O&M	Operation and Maintenance
OPEX	Operational Expenditure
RES	Renewable Energy Sources
Uci	Cut-in Wind Speed
Ur	Rated Wind Speed
Uco	Cut-out Wind Speed
WPD	Wind Power Density
WS	Wind Speed

1. Introduction

Offshore wind energy has swiftly advanced into a cornerstone of worldwide renewable energy strategies because of a pressing demand for lowering Greenhouse gas (GHG) emissions as well as increasing energy security and moving away from traditional fossil fuel modes. When compared to onshore energy installations the offshore wind is more capable in terms of more robust, stable and predictable wind conditions, which will deliver higher energy yields and better operating efficiency (Busby, 2012; Betz, 2013). Significant improvements in turbine design, grid integration and foundation engineering have allowed for increasingly larger offshore turbines to be installed in both deeper waters and more exposed marine environments to enable better deployment of offshore wind as an efficient and renewable source of power at far greater scale compared to onshore energy resources (Bortolini et al., 2019; Cao et al., 2021).

Offshore wind power development is more prominent and long-term plans for investment and long-time policy framework for deployment in Europe are conducive towards this approach. Nations including the UK, Denmark, and Germany have created massive offshore wind deployment, highlighting the viability of the technology and the role it plays in securing offshore resources and aiding in the transition to green technology. These developments are also enabling further examination of the environmental and social impacts associated with offshore wind plants. To illustrate, potential impacts on marine species, seabed ecosystems and underwater noise have been studied, highlighting the importance of environmental impact assessment frameworks and mitigation strategies (Abramic et al., 2022; Bailey et al., 2010; Copping et al., 2020).

Recently, interest has turned to the Mediterranean region as a potential location for offshore wind deployment. While development is orders of magnitude earlier than Northern Europe development, studies indicate large opportunities with wind resources, favourable climatic conditions and increasing interest in renewable energy (Bray et al., 2016). But a number of issues persist, including deeper waters located near the coast, limited infrastructure existing and various regional environmental challenges to overcome that necessitated planning and analysis (Coll et al., 2010).

Cyprus is a fascinating example in contrast. Though well endowed with renewable energy potential, the country still depends to a large extent on imported fossil fuels. Consequently exploring offshore wind links to larger national and EU sustainability goals. However, the development of offshore wind in Cyprus is scarce and the existing literature on site-level offshore wind evaluations is scanty. This lack of understanding is particularly clear when considering the use of the specific coastal regions for offshore wind resource development, and the resulting potential energy generation. That said, there is a crucial need to identify and evaluate suitable coastal sites to determine the feasibility of offshore wind development in Cyprus. A systematic approach for this kind of research has been suggested in recent unpublished academic projects describing analytical procedures for site selection, data analysis and energy assessment.

To fill this gap, this research explores offshore wind potential of three coastal areas in Cyprus: Limassol, Larnaca and Paphos. We use ERA5 reanalysis data and extrapolate it to hub height to investigate wind characteristics in each area and estimate the Annual Energy Production (AEP) of a 15 MW offshore wind turbine (Azad et al., 2014; Beji, 2016). The aim of this study is to identify the hotspots for offshore wind potential and to help evaluate offshore renewable resource in the region through a comparative analysis of the selected locations.

The obtained data contribute greatly in the field of offshore wind project opportunities in Cyprus and lay the technical framework for assessing whether it is feasible to build the offshore wind infrastructure in the future. Furthermore, outcomes are anticipated to assist in future research, policy issues and strategic planning for the integration of offshore wind energy into national energy.

This thesis is structured as follows. First, background information is provided with respect to the offshore wind energy, with focus on the world's offshore wind development trends, literature on recent developments in the Mediterranean, and studies conducted on the evaluation of offshore wind resources within Cyprus. The methodology chapter of this research includes data sources, analytical approaches, turbine specifications and the procedure for estimating the Annual Energy Production (AEP). In the results and discussion chapter, the highest energy yield produced across the three selected coastal locations. Finally, in the last chapter the findings are presented more holistically, some conclusions are made and some suggestions for future research and the possible further development of offshore wind energy in Cyprus are provided.

2. Background and Literature Review

2.1 Growth of Offshore Wind Energy on a Global Scale

Offshore wind energy is one of the most rapidly growing renewable energy resources in the world as countries look to curb greenhouse gas emissions and diversify their fuel and other energy needs. Offshore wind facilities gain more favorable wind conditions that are higher than those found onshore, stable and predictable, with a comparative advantage of high efficiency and capacity factors (Bortolini et al., 2019). Modifications in turbine design, foundation engineering and marine infrastructure have dramatically lowered costs and facilitated widespread applicability in deep waters and harsher marine environments. These breakthroughs have helped make a shift in the offshore wind technology from an additional renewable option to a key element in international energy policy and as a contributor to the industrialization process.

Offshore wind development has also been driven by engineering innovation and improvements in turbine and wind farm configuration, allowing deployment in deeper water and high-energy offshore sites (Figure 1).

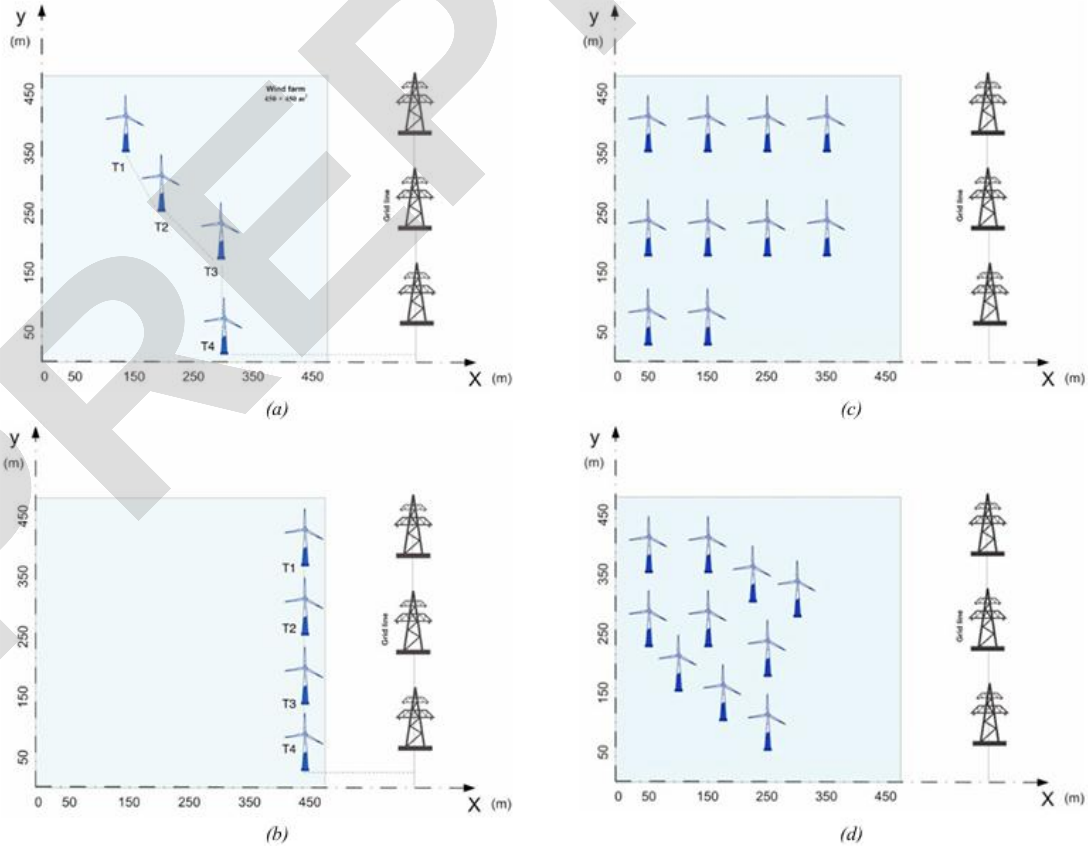

Figure 1: Example configurations of offshore wind farm layouts.

European nations are the pioneers in this regard, deploying large offshore wind farms and having benefited from mature policy structures, long-term goals and specific targets for energy development. The lessons learnt from European deployment demonstrate the importance of infrastructure, public policy and engineering innovation in allowing offshore wind to be strategically positioned within sustainable development planning. This expansion has resulted in more concern about the environmental consequences and social acceptance of offshore wind energy.

2.2 Offshore Wind in the Mediterranean Region

Due to its favourable climatic conditions and increasing renewable energy needs, the Mediterranean region has recently emerged as a target for the deployment of offshore wind. When compared to Northern Europe, the Mediterranean basin has been suggested in many papers to possess suitable wind resources and coastal characteristics that are conducive to offshore wind projects. However, the development is still in its early stages Bray et al. (2016) identify a series of offshore ‘hotspots’ across the Mediterranean where water depths and wind speeds are compatible with offshore wind energy production.

These are coastal areas of Italy, Greece, Tunisia and Malta illustrating that there is considerable potential for utility-scale offshore wind generation in the region (Figure 2).

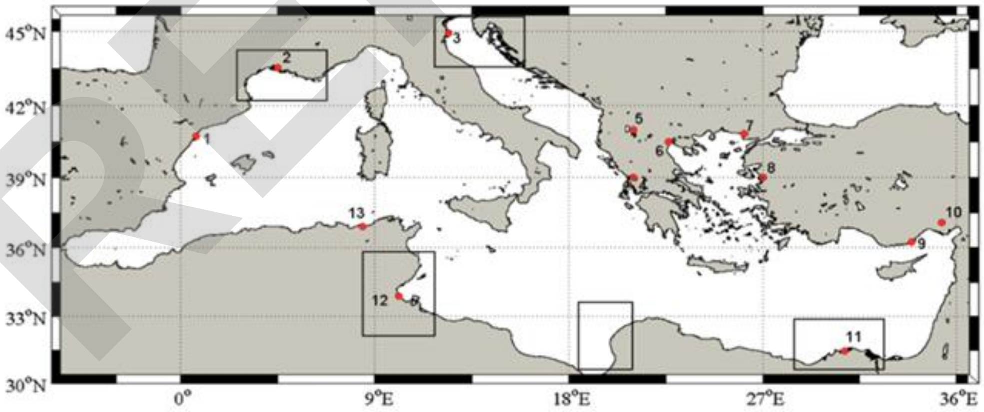

Figure 2: Offshore wind hotspot locations and overlapping wetlands in the Mediterranean region.

Notwithstanding the high resource availability, the Mediterranean has many peculiarities that are in contrast to the more developed Northern European offshore wind regions. A limitation is the fact that the deep-water profile close to the coastline makes it expensive and complex to implement the infrastructure. The issue of the environment is also of great concern given the ecological sensitivity of the Mediterranean Sea with its diverse marine ecosystems and major migratory pathways. As Bray et al. (2016) demonstrate, some of the most promising offshore wind areas overlap with protected environmental areas and marine traffic corridors, so it is essential to use marine spatial planning properly.

In addition, large-scale offshore energy projects in the Mediterranean require coordinated policy and regulatory frameworks that still lag significantly behind more mature offshore wind markets. While interest in offshore wind deployment is growing among the Mediterranean countries, the current energy infrastructure and marine engineering supply chains are still relatively underdeveloped. Hence, the Mediterranean region possesses immense potential and a complex technical and environmental backdrop to offshore wind deployment.

2.3 Offshore wind potential in Cyprus

Cyprus is ripe for offshore wind development because of its geographic advantage and its dependence on imported fossil fuels. Even if its potential for renewable energy is vast, the country remains reliant on hydrocarbon-based electricity generation, raising problems of energy security, environmental performance as well as long-term sustainability. As a result, offshore wind energy has been determined as a unique opportunity for Cyprus to integrate in its energy diversification, lowering carbon emissions and being more closely aligned with European Union renewable energy directives and decarbonisation policies.

Despite the location on Cyprus's relatively deep coast, a number of coastal regions have also reported suitable wind conditions and local spatial characteristics for offshore wind farm activities. Previous research and regional evaluations have revealed that Cypriots along their coastline possess characteristics of wind resources that correspond with other offshore regions in the Eastern Mediterranean, thus suggesting that a large scale offshore wind infrastructure might be viable in Cyprus (Bray et al., 2016). Research conducted in Mediterranean basin models have shown that, in the Mediterranean basin context, coastal environments in the Mediterranean basin can yield mean annual wind speeds above the minimum thresholds typically required for offshore wind deployment, especially at hub heights relevant to modern large-scale turbines.

Yet, despite these favourable conditions, scientific studies that evaluate offshore wind resources available specifically for Cyprus have not yet been performed in depth. Such research gap encompasses the lack of sufficient data availability, little assessment of long-term wind characteristics, and the absence of detailed analysis on specific coastal areas that may be viable for future offshore wind projects. Thus, even though regional studies give broad information about the viability of the Mediterranean Sea for offshore wind development, national-scale offshore resource characterisation for Cyprus remains comparatively underdeveloped.

Thus, this study fills an essential research gap through assessment of offshore wind potential with ERA5 reanalysis wind data extrapolated to hub height with three coastal locations — Limassol, Larnaca and Paphos. This thesis adds to the existing knowledge by evaluating the wind characteristics and expected energy production of a 15 MW turbine operating offshore Cyprus, providing knowledge critical for future planning, policy design and offshore wind development strategies in the region. The results are expected to pave the way for research and feasibility studies on the deployment of offshore renewable energy in Cyprus.

2.4 Literature review and research gap

Existing literature shows this type of wind is a growing field with significant technological and policy backing throughout Northern Europe, and growing potential in the Mediterranean region. It has been established that there exist several places in the Mediterranean basin with wind speeds and water depths appropriate for offshore wind development, although these areas mostly lie near environmentally sensitive regions and therefore need to be planned and implemented carefully for environmental concerns. The practicality of offshore wind technology has been further reinforced by progress in the scale of turbines, farm layout and infrastructure design, which have allowed for more economic and technical potential for offshore installations.

However, in the literature we see that there are very few detailed studies looking only at Cyprus regarding the promise of offshore wind in the Mediterranean region. However, previous research has predominantly been focused on the Mediterranean basin at a macro level and does not cover the comparative offshore wind potential of different coastal areas in Cyprus. In this context, a gap in the scientific understanding regarding long-term wind characteristics, energy production estimates, and site suitability for offshore wind deployment at a national level has emerged.

In order to fill this research gap, this thesis carried out a comparative study by using long-term ERA5 reanalysis wind data from Cyprus to assess three coastal locations in Cyprus (Limassol, Larnaca and Paphos). This study evaluates the offshore wind resource in Cyprus with greater specificity, by calculating the Annual Energy Production (AEP) of a 15 MW offshore wind turbine for each site. The results add to the literature through a more site specific perspective that guides the creation of future offshore wind projects and policies. In addition, the study contributes to the establishment of precedents for further techno-economic and environmental feasibility studies focusing on the deployment of offshore renewable energy resources in Cyprus.

3. Methodology

3.1 Methodology Overview

The present study uses a standardized approach to the evaluation and comparison of the offshore wind power potential in three key coastal sites in Cyprus: Larnaca, Limassol and Paphos. This analysis is conducted over the long-term atmospheric reanalysis and with an offshore wind turbine representative to help identify the expected energy yield and the long-term variability of wind resources over a period of years.

The methodology framework consists of four main phases. A rectangular computational domain from Cyprus was first created and long-term wind data were obtained from the ERA5 reanalysis dataset. ERA5 serves as global atmospheric coverage with hourly resolution and has been extensively used in the study and validation of offshore wind conditions in the Mediterranean area for consistent and reliable climatological analysis. For the period 1970–2024, hourly time series of the zonal and meridional wind components at 100 m height were downloaded, making a 55-year record of offshore wind conditions around Cyprus. The data were subsequently processed with Python to obtain the wind speed at 100 m for the grid points for the selected three offshore locations.

The second step extrapolated the 100 m wind speed time series directly and plotted it at the height of the turbine hub of 150 m as part of power law shear in accordance with the marine environment. These values generated continuous hourly wind speed time series at hub height for each of the selected locations for all the time in the study.

In the third stage, our work proposed modelling a 15 MW offshore wind turbine using the power curve that relates hub height wind speed to electrical power output incorporating cut-in, cut-out and rated wind speeds. The selected turbine rating reflects ongoing trends of offshore wind development, in which higher turbine capacities are being employed to improve energy capture in moderate wind states.

Moreover, annual estimates for the Annual Energy Production (AEP) and the capacity factor were produced for each site, per year, using the power curve as an extrapolated term from the hub height wind speed series and by integrating hourly power generation over the year. This resulted in a long-term (1970–2024) record of the AEP and capacity factor for Larnaca, Limassol and Paphos from which the average and inter-annual variability was derived. Data was processed and analysed using Python (xarray, numpy and pandas) in Visual Studio Code, maintaining computational reproducibility. Therefore, this approach is in line with existing practices in the assessment of offshore wind resources and with recent studies of offshore wind potential in the Mediterranean. The following sections present a detailed description of the methodological framework sections including data acquisition, pre-processing, hub-height extrapolation, turbine modelling and AEP computation.

3.2 Site Selection

Three offshore sites were chosen around Cyprus for analysis: Larnaca, Limassol and Paphos. The chosen sites were selected according to some criteria for offshore wind developments. For one thing, they are different maritime terrains with different weather systems exposure to offshore wind, as well as a difference in regional climatological diversity. Secondly, they sit where prior studies have identified interest in offshore renewables in national energy planning plans. Finally, the sites are geographical along the southern coast of Cyprus, allowing us to compare the variability of offshore wind resources spatially.

The direct coordinates assigned within each location came from the ERA5 grid, and were drawn at a distance of a few kilometers offshore to help reduce the impact of the coast while remaining within commercially deployable areas of offshore wind turbine deployment. By using ERA5 grid points it ensures consistent spatial coverage and avoids interpolation between grid cells.

For data extraction and calculation purposes the wider study domain involved defining a bounding box of latitude–longitude [40°N, 25°E, 25°N, 40°E] which covers Cyprus and Eastern Mediterranean region. All three selected sites are located in this domain.

Table 1 ERA5 grid coordinates of the selected offshore sites.

Site	Latitude (°N)	Longitude (°E)	Distance from coast (approx.)
Larnaca	34.75	33.50	~5 km offshore
Limassol	34.50	33.00	~5 km offshore
Paphos	34.75	32.50	~5 km offshore

The selected locations are representative offshore sites for capturing wind resource variability while remaining suitable for potential future offshore wind development. The geographic positions of the selected sites are shown in Figure 3.

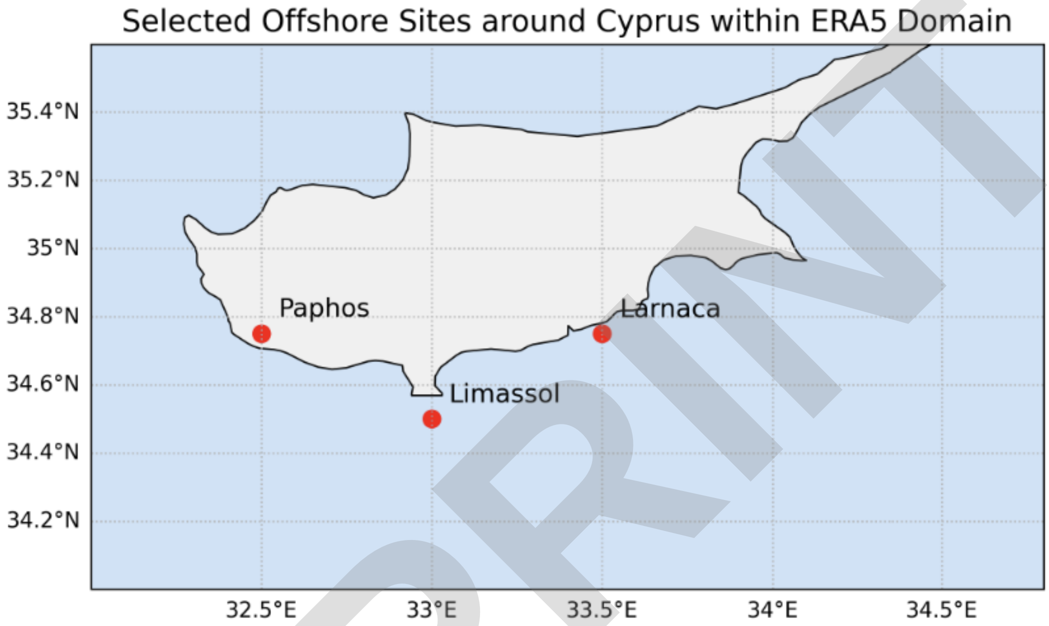

Figure 3: Geographic location of the three selected offshore sites (Larnaca, Limassol and Paphos) within the ERA5 data domain. The locations are positioned a few kilometres offshore and represent realistic zones for potential offshore wind turbine deploy

3.3 ERA5 Data Acquisition and Pre-Processing

This study aims to assess the long-term offshore wind resource at the identified locations with the ERA5 atmospheric reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). For wind energy research, ERA5 is one of the most sophisticated global reanalysis products because it provides a long coverage time frame, high temporal resolution, and validated performance over marine environments. It offers globally consistent hourly information, and is especially useful when in-situ measurements offshore are not available or sparse, as in Cyprus.

ERA5 is available on a regular grid with a 0.25° × 0.25° horizontal resolution, of spatial grid cells ~31 km around Cyprus. The information in the dataset is obtained from different observations such as satellites, buoys, remote-sensing platforms and numerical weather prediction models. It thus ensures reliable and quality meteorological data for all the offshore wind assessments in long cycle.

For this analysis, we downloaded the zonal (u) and meridional (v) wind components at a height of 100 metres above sea level for the entire study domain. These elements are combined into wind speed with:

$$U_{100} = \sqrt{{u_{100}}^2 + {u_{100}}^2} \qquad \textit{(Eq.1)}$$

This height was selected because ERA5 gives direct values at 100 m, closely aligning with offshore turbine hub heights and alleviating the uncertainty associated with vertical extrapolation through it.

Temporal and spatial coverage

The ERA5 data was downloaded for the period 1970–2024, comprising for each site a continuous time series of hourly wind over a time frame of 55 years. Such a long time-period record allows a strong characterisation of wind variability, interannual fluctuations, and long-term trends – all vital to understanding the reliability of offshore wind power generation. The download domain was defined in a bounding box of:

[40° N, 25° E, 25° N, 40° E]

This rectangular area is chosen to cover the whole island of Cyprus and its offshore waters in full context. All of the sites chosen do fall squarely within this analysis area (no spatial interpolation was necessary between ERA5 grid points).

Extraction and sorting of data

Annual NetCDF files have been downloaded using the Copernicus Data Store (CDS) using both the official CDS API and custom Python scripts. We opted for an automated approach to achieve reproducibility and consistency on the downloaded dataset. The NetCDF files for each year contain hourly u- as well as v-components for the wind field over the complete analysis domain.

After this download, the subsequent pre-processing was done:

1. Annual files are merged to form an entire multi-year time series and are thus standardized for analysis.
2. Wind determination at grid locations at individual offshore positions.
3. Conversion of wind elements into scalar wind speed.
4. Elimination of undesirable or absent values that are missing or atypical information and confirmation of dimensional consistency.
5. Allocation of timestamps and geospatial attributes to time-series data.

Then, continuous hourly wind speed time-series for Larnaca, Limassol and Paphos were built using these extracted data. These time-series will serve as the basis of all subsequent analysis such as hub-height extrapolation, turbine modelling and Annual Energy Production computation.

Data reliability and justification

The choice of ERA5 as the primary data source was attributed to the following reasons:

1. Long temporal extent for climatological examination.
2. Data validation in several offshore investigations.
3. High temporal resolution (1 hour).
4. Global consistency, full coverage in all spatial regions.
5. Well-established relevance for offshore wind energy studies.

Due to the absence of a large scale offshore measurement effort in Cyprus, only reanalysis products are considered as an available system of long-term offshore wind information. Thus, ERA5 is widely considered an accurate and scientifically proven dataset for evaluating offshore wind energy resources.

3.4 Wind Speed Extrapolation to Hub Height

The wind speed values determined from ERA5 are at 100 meters above sea level. Of course, in most cases the distance for large offshore projects, especially at high hub heights (greater than 100 m), is more than 100 m. As a result, in the present study, a hub height of 150 m was selected, as this is the height of the present day 15 MW offshore wind turbines, which are popularly installed on large-scale offshore wind farms. Hence, from this point forward, it became important to extend the wind speeds from 100 m to the turbine hub height.

Wind speed variation with height in the lower part of the atmosphere is typically characterised using a power-law vertical profile. The power-law relationship expresses the wind speed at a desired height z in terms of a reference wind speed at height z_r:

$$U(z) = U(z_r)(\frac{z}{z_r})^a \quad \textit{(Eq.2)}$$

- U(z) is the wind speed at height z (150 m),
- U(zr) is the wind speed at the reference height (100 m),
- Zr=100m
- α is the wind shear exponent.

Choice of wind shear exponent

The parameter α is related to both atmospheric stability and terrain properties. In offshore areas with less surface roughness and air flow relatively smooth, a lower value of α is typically used. Values are recommended between:

$$a = 0.10 \text{ and } 0.16$$

for maritime environments.

In this study, a value of:

$$\alpha=0.12$$

was used for extrapolation, suitable for the widely utilized application of offshore wind where surface roughness is relatively low and atmospheric conditions are moderately stable.

The calculated extrapolated wind speed, at 150 m was:

$$U(150) = U(100)(\frac{150}{100})^{0.12} \quad \textit{(Eq.3)}$$

This transformation was performed for each hourly wind speed value for the entire 1970–2024 time series for each one of the three offshore locations. The use of the power-law method provides uniformity across the entire dataset, allowing for a truly realistic sense of wind speed at turbine hub height.

Rationale for the power-law approach

This power-law implementation was selected on account of its applicability in:

- long term offshore resource assessment,
- studies of the wind based on reanalysis,
- modelling of energy production at large scale.

Other methods such as logarithmic law or stability-corrected profiles can be used, but the required inputs (e.g., offshore roughness length, wave height, humidity and temperature gradients) are not readily available for Cyprus. Therefore the power-law approach is a good and widely-accepted way to estimate hub-height winds using reanalysis data.

Hub-height wind time series

All subsequent turbine performance modelling conducted in this study is driven using the estimated wind speeds at 150 m:

- power curve evaluation,
- Annual Energy Production (AEP),
- apacity factor estimation,
- time-dependence and trends in long-term.

These hub-height wind speed time series are realistic descriptions of how a utility-scale offshore wind turbine placed at these locations would perform.

3.5 Offshore Wind Turbine Model and Power Curve

A representative large-scale offshore wind turbine was modelled to estimate the energy generation potential at each of these selected offshore sites. For this analysis, we chose a turbine of rated capacity 15 MW. Such capacity is typical of the latest generation of commercial offshore wind turbines currently being deployed in major European offshore wind farms and aligns with current industry trends toward larger hub heights and rotor diameters.

The turbine model used in this study takes a configuration of hub height (150 m) and performance characteristics based on generic power curves used in recent offshore wind studies. In this context, a power curve describes the relationship between the wind speed at the height of the hub and the electrical power output of the turbine. The power curve is a crucial input for wind energy modelling, as it determines the energy production corresponding to different wind speed conditions.

Power curve characteristics

The power curve is defined using three critical wind speed thresholds:

- **Cut-in wind speed** (Uci): the wind speed at which the turbine begins generating power.
- **Rated wind speed** (Ur): the lowest wind speed at which the turbine reaches its rated capacity.
- **Cut-out wind speed** (Uco): the wind speed at which the turbine is shut down to prevent structural damage.

For the 15 MW turbine used in this study, the following representative values were adopted:

Table 2 Operational parameters of the 15 MW offshore wind turbine used for power curve modelling.

Parameter	**Value**
Cut-in wind speed (Uci)	3 m/s
Rated wind speed (Ur)	11 m/s
Cut-out wind speed (Uco)	25 m/s
Rated power	15 MW

Between cut-in and rated wind speeds, the power output is assumed to increase with the cube of wind speed, reflecting aerodynamic behaviour. The power curve is described mathematically as:

$$P(U) = \begin{cases} 0 & \mathrm{U < Uci} \\ P_{rated}\,(\frac{U-Uci}{Ur-Uci})^3 & \mathrm{Uci \le U < Ur} \\ P_{rated} & \mathrm{Ur \le U \le Uco} \\ 0 & \mathrm{U > Uco} \end{cases} \qquad \textit{(Eq.4)}$$

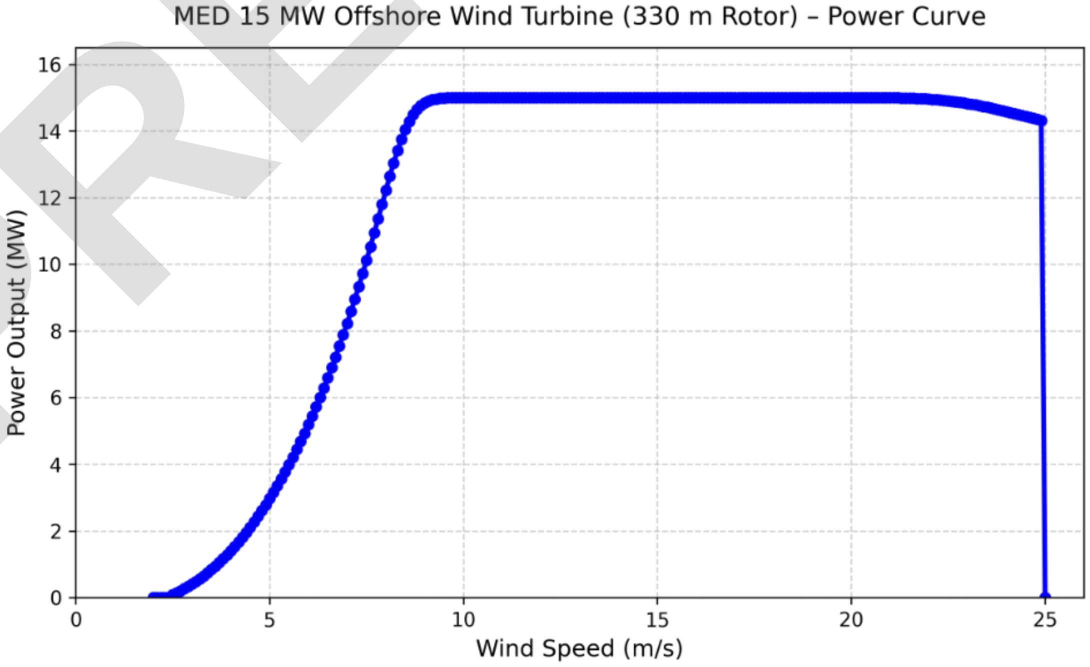

Figure 4: Power curve of the 15 MW offshore wind turbine (330 m rotor diameter) used in this study. The turbine begins generating at 3 m/s, reaches its rated power of 15 MW around 9–11 m/s, and shuts down above 25 m/s for structural protection.

The power curve depicting turbine performance showcases the standard aerodynamic characteristics of large offshore wind turbines. It reveals a cubic escalation in power generation from cut-in to rated wind speeds, eventually leveling off at a constant rated output plateau. This established power curve was utilized with the hourly hub-height wind speed data for each location, producing a continuous time series of power output. This series serves as the foundation for the Annual Energy Production (AEP) and capacity factor calculations discussed in Chapter 4.

3.6 Annual Energy Production (AEP) and Capacity Factor Calculation

Annual Energy Production (AEP) forms the primary quantitative output for evaluating the wind energy potential at each of the selected offshore sites. The AEP represents the total amount of electrical energy generated by a single 15 MW offshore wind turbine operating under the long-term wind conditions at each site. The calculation is performed by integrating the hourly power output time series derived from the turbine power curve during each year of the study period (1970–2024). The AEP for each year is expressed as:

$$AEP = \sum_{t=1}^{8760} P\big(V(t)\big) * \Delta t \quad \textit{(Eq.5)}$$

where P (V(t)) is the turbine power output as a function of hourly wind speed V(t) and Δt = 1 hour. Only the wind speeds within the turbine operational limits contribute to the annual energy generation, whereas wind speeds below the cut-in and above the cut-out are assigned zero output.

The AEP calculation is implemented in Python by combining the hub-height hourly wind speed time series with the turbine power curve, resulting in a continuous time series of power output for each year and each site. The procedure is aligned with standard offshore wind resource assessment methodologies and similar to modelling approaches applied in recent offshore wind studies in the Mediterranean (Onea et al., 2022; Hadjipetrou et al., 2021).

In addition to AEP, the capacity factor is calculated as a measure of the efficiency of the wind resource utilisation over each year. The capacity factor is defined as:

$$CF = \frac{AEP}{P_{rated} * 8760} \qquad \textit{(Eq.6)}$$

where P_{rated} = 15 MW.

This metric provides an indication of the average utilisation of the turbine's generation potential at each site. Both AEP and capacity factor are calculated annually from 1970 to 2024, allowing for long-term performance assessment and comparison between Limassol, Larnaca and Paphos. The long-term time-series approach enables the quantification of interannual variability and trends in offshore wind potential, which represents an essential step for developing realistic offshore wind resource assessments for Cyprus.

The results of these calculations are presented in Chapter 4, where annual and long-term average AEP and capacity factor are reported and compared across the three locations.

3.7 Long-Term Trend and Variability Analysis

To assess the temporal variability of the offshore wind resource, the Annual Energy Production (AEP) and capacity factor were calculated for every year between 1970 and 2024 for each of the three study sites. This produced 55-year time series of annual wind energy production, enabling the evaluation of long-term fluctuations as well as the comparison of interannual performance across the sites.

For each annual dataset, the following statistical indicators were computed:

- annual AEP and capacity factor,
- long-term multi-year means,
- standard deviation,
- minimum and maximum values,
- annual anomaly relative to the long-term average.

To identify long-term evolution in the wind resource, a linear regression model was applied to the 55-year AEP and capacity factor time series. The trend is represented by the slope of the fitted regression line, which indicates whether the wind energy potential has increased, decreased or remained stable over time at each location.

This analysis provides a quantitative measure of the temporal variability of the offshore wind resource and allows for direct comparison of long-term performance across the three coastal sites. The outcomes of this analysis are presented in Chapter 4, where differences between Limassol, Larnaca and Paphos are evaluated and discussed.

4. Results and Discussion

4.1 Wind Resource Characteristics at Hub Height (150 m)

The offshore wind resource evaluation carried out in this analysis offers an in-depth insight into the long-term wind conditions at a height of 150 m above sea level for three designated coastal areas: Limassol, Larnaca, and Paphos. The wind speed time series extracted from the ERA5 dataset illustrates considerable spatial variability along the southern coastline of the island, which has significant implications for the potential development of offshore wind energy.

Over the 55-year assessment period (1970–2024), the long-term average wind speeds indicate that Limassol presents the most advantageous wind conditions, with an average speed of approximately 5.69 m/s. This is followed by Larnaca at 5.14 m/s, while Paphos shows considerably lower average wind speeds of 4.45 m/s at hub height. These findings imply that the central southern coastline enjoys stronger and more stable offshore winds, likely due to local topographic factors and prevailing synoptic flow patterns in the Eastern Mediterranean.

Table 3 Long-term wind resource and energy performance statistics (1970–2024).

Site	Mean Wind @150m (m/s)	Mean AEP (MWh/year)	Std. AEP (MWh/year)	Mean CF (%)	Std. CF (%)	Years
Larnaca	5.14	42,520	2,678	32.4	2.0	55
Limassol	5.69	51,041	3,071	38.8	2.3	55
Paphos	4.45	29,012	2,656	22.1	2.0	55

Alongside the mean wind profile, temporal fluctuations were noted across all locations. Annual variations in wind speeds are influenced by regional climatic factors such as seasonal pressure differences, variability in Etesian wind intensity during summer months, and positioning of winter storm tracks. Despite these natural fluctuations, Limassol consistently records higher wind speeds compared to other regions, reinforcing its potential for offshore wind energy development.

The comparative analysis of hub-height wind characteristics reveals significant disparities even within a small geographical area like Cyprus. This spatial variation underscores the necessity for site-specific resource evaluations since applying a uniform national assumption could result in suboptimal turbine placements and decreased energy production efficiency. The subsequent sections will delve into how these wind characteristics impact Annual Energy Production (AEP) and turbine performance.

4.2 Annual Energy Production (AEP) Results

The Annual Energy Production (AEP) was computed for each of the three offshore locations by applying the 15 MW turbine power curve to the hourly hub-height wind speed time series obtained from ERA5 over a 55-year period (1970–2024). The results highlight substantial spatial variability in offshore wind energy potential around Cyprus.

The long-term mean AEP values indicate that Limassol is the highest-performing site, generating on average 51,041 MWh/year, followed by Larnaca at 42,520 MWh/year, while Paphos yields significantly lower production of 29,012 MWh/year. These summary statistics are presented in Table 4.

Table 4 Summary of long-term AEP and capacity factor performance (1970–2024).

Site	Mean AEP (MWh/yr)	Std. Dev. (MWh/yr)	Mean CF (%)	Std. Dev. CF (%)	Years
Larnaca	42,520	2,678	32.4	2.0	55
Limassol	51,041	3,071	38.8	2.3	55
Paphos	29,012	2,656	22.1	2.0	55

Statistically, this means:

- **Limassol** produces ~20% more energy than Larnaca.
- **Limassol** produces ~76% more energy than Paphos.
- **Paphos** shows consistently weaker potential, reflecting the lower wind speeds presented earlier in Section 4.1.
- Interannual variability remains low across all sites (standard deviation ≈ 5–6% of the mean), demonstrating stable long-term offshore wind conditions — an essential factor for investment reliability

The temporal evolution of AEP is illustrated in Figure 5, showing clear annual fluctuations driven by regional atmospheric variability, yet also featuring distinct long-term trends.

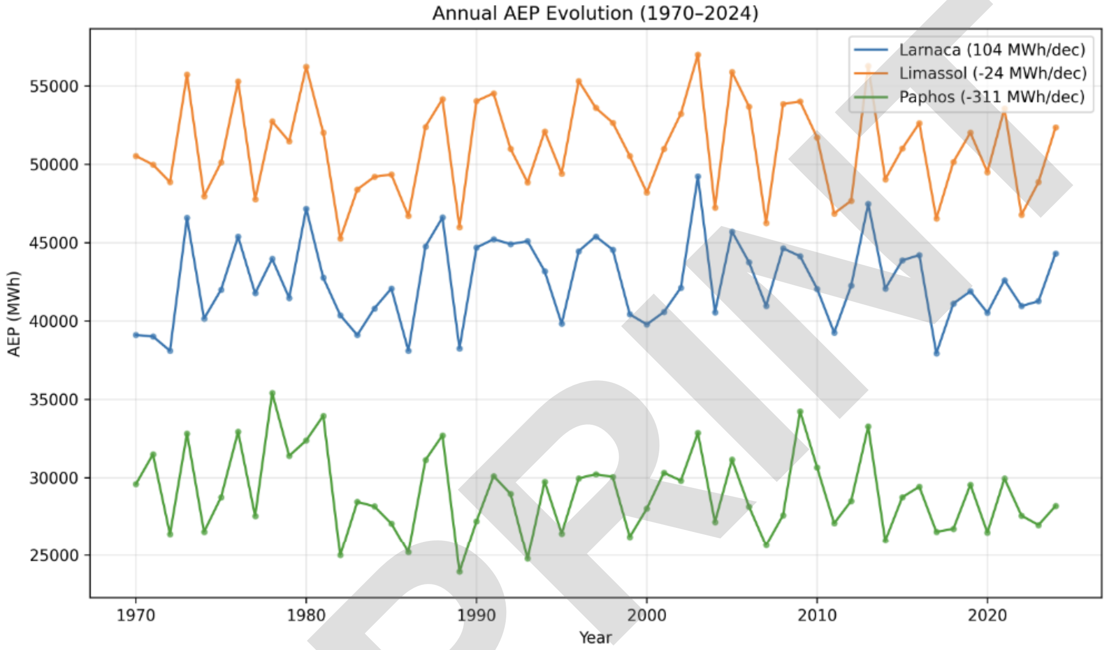

Figure 5: Annual AEP evolution for Larnaca, Limassol and Paphos (1970–2024), including linear trend lines and estimated rates of change (MWh/decade)

The plotted trends show:

- **Larnaca:** a very slight long-term increase in AEP (+104 MWh/decade)
- **Limassol:** relatively stable generation (−24 MWh/decade)
- **Paphos:** a noticeable long-term decline (−311 MWh/decade)

To further investigate possible climate-related impacts, mean AEP was also evaluated over three climatological periods (1970–1990, 1991–2010, 2011–2024), as shown in Figure 6.

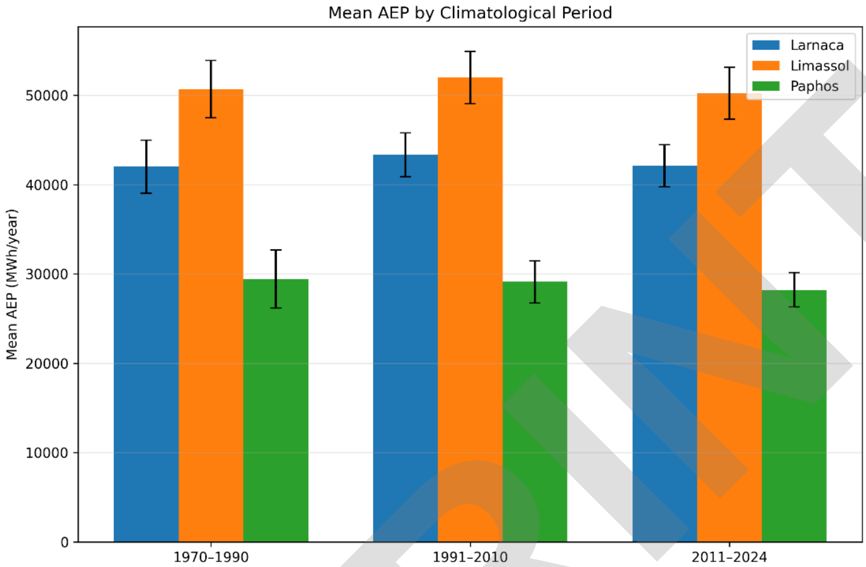

Figure 6: Mean AEP values divided into three climatological periods, with variability expressed via standard-deviation error bars.

Although some multi-decadal variability exists, Limassol consistently maintains its position as the highest-performing site, reinforcing its suitability for future offshore wind development. Larnaca shows stable performance across time, whereas Paphos exhibits a slight decline in the most recent climatological period.

4.3 Capacity Factor Results

The capacity factor (CF) provides a measure of the turbine's efficiency in harnessing the available wind resource by expressing the ratio of actual energy generated to the theoretical maximum production at continuous rated output. Similar to AEP, capacity factor calculations were performed for each year of the 55-year study period (1970–2024), using the same turbine power curve and hub-height wind speed dataset.

The long-term mean CF values follow the same performance hierarchy observed in AEP results:

- **Limassol** achieves the highest mean capacity factor (38.8%).
- **Larnaca** performs moderately (32.4%).
- **Paphos** exhibits the lowest efficiency (22.1%).

These findings are fully consistent with the wind speed climatology described in Section 4.1 and the AEP comparison presented in Section 4.2.

To examine temporal performance stability, CF time series were analysed across the entire period. Figure 7 displays the annual fluctuations and linear trends observed at each site.

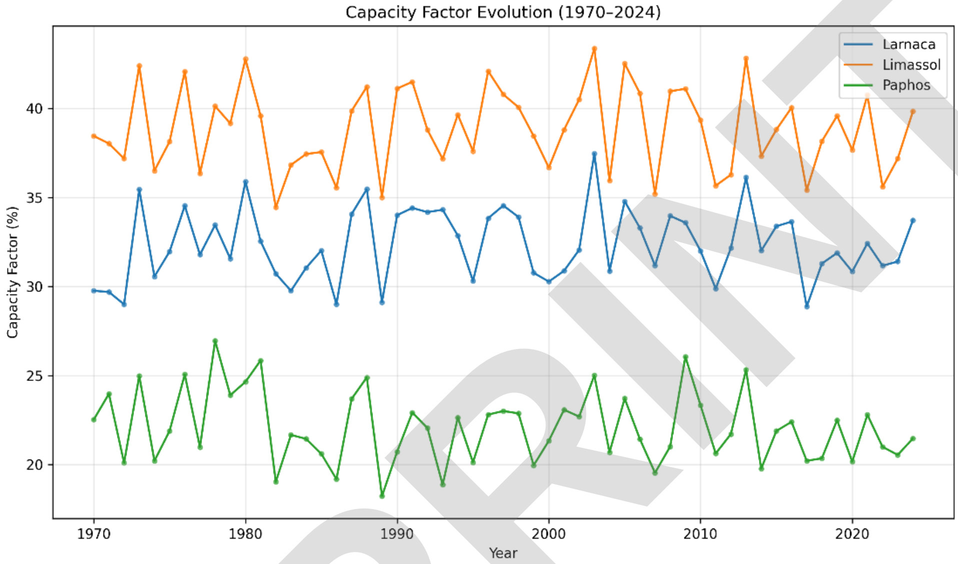

Figure 7: Annual capacity factor evolution for Larnaca, Limassol and Paphos (1970–2024), including linear regression trend estimates.

The results show:

- **Limassol**: consistently high CF with minimal drift over time
- **Larnaca**: stable performance and low variability
- **Paphos**: lower overall CF and a gradual declining trend

To evaluate multi-decadal changes possibly linked to climate variability or evolving synoptic wind conditions, mean CF values were additionally aggregated into three climatological periods (1970–1990, 1991–2010, 2011–2024), as shown in Figure 8.

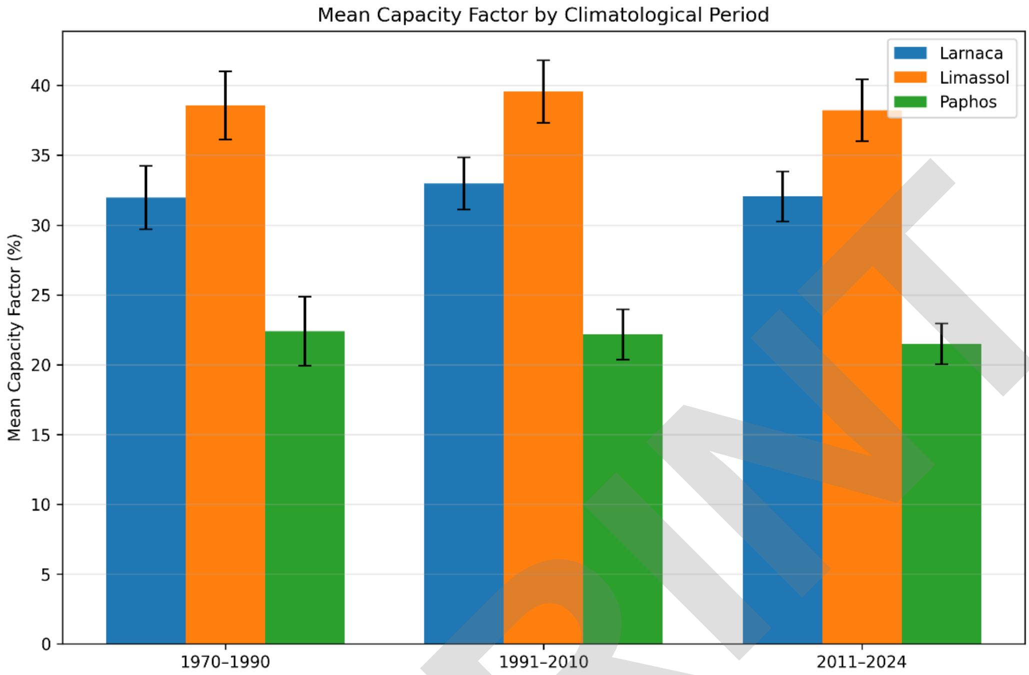

Figure 8: Mean capacity factor during three climatological periods for each study site. Error bars represent ±1 standard deviation.

The analysis reveals that:

- **Limassol** remains consistently superior throughout all periods.
- **Larnaca** shows minor fluctuations but no long-term decline.
- **Paphos** records a small drop in the most recent period, aligning with decreased wind speeds identified in earlier analyses.

4.4 Wind Speed Distribution Analysis

A comprehensive evaluation of the offshore wind conditions necessitates more than just long-term averages; the complete statistical characteristics of the wind field play a crucial role in determining energy output and operational efficiency. To illustrate this, probability distributions for wind speed were created utilizing a 55-year hourly dataset (1970–2024) from all three research locations. Histograms depicting wind speed at the turbine hub height (150 m) were modeled using a Weibull probability density function, which is recognized as the standard statistical approach in offshore wind resource assessment because of its effectiveness in capturing variations in environmental wind conditions.

Figures 9 to 11 depict the distribution of wind speeds across each study site. Each illustration features a best-fit Weibull curve, which visually represents the occurrence of various wind speed conditions that the turbine is likely to encounter.

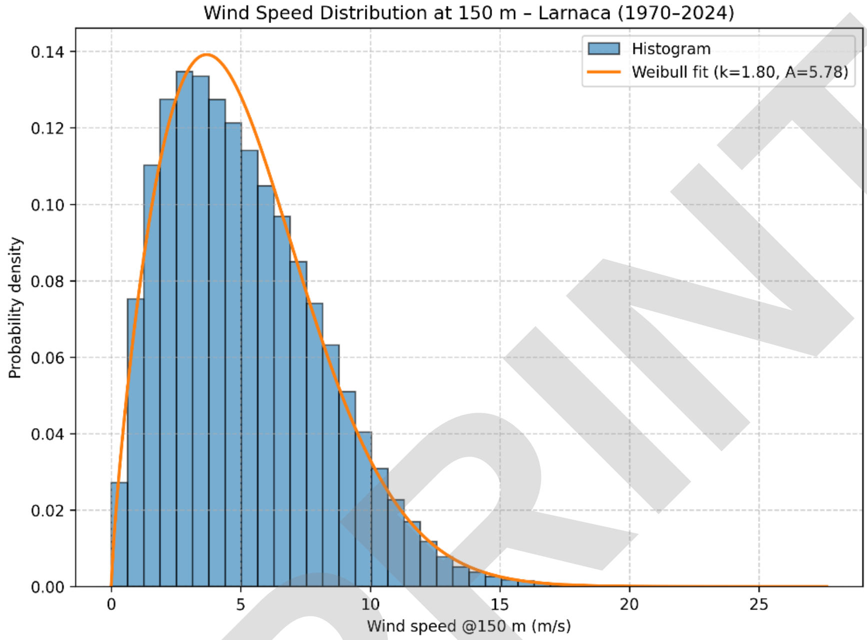

Figure 9: Wind speed distribution at 150 m with Weibull fit for Larnaca (1970–2024).

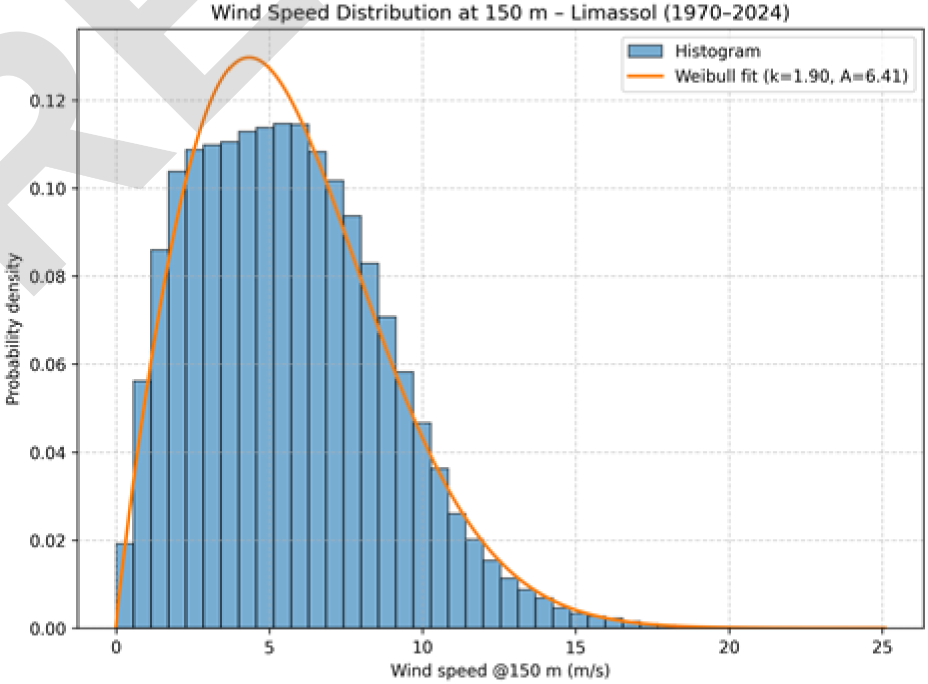

Figure 10: Wind speed distribution at 150 m with Weibull fit for Limassol (1970–2024).

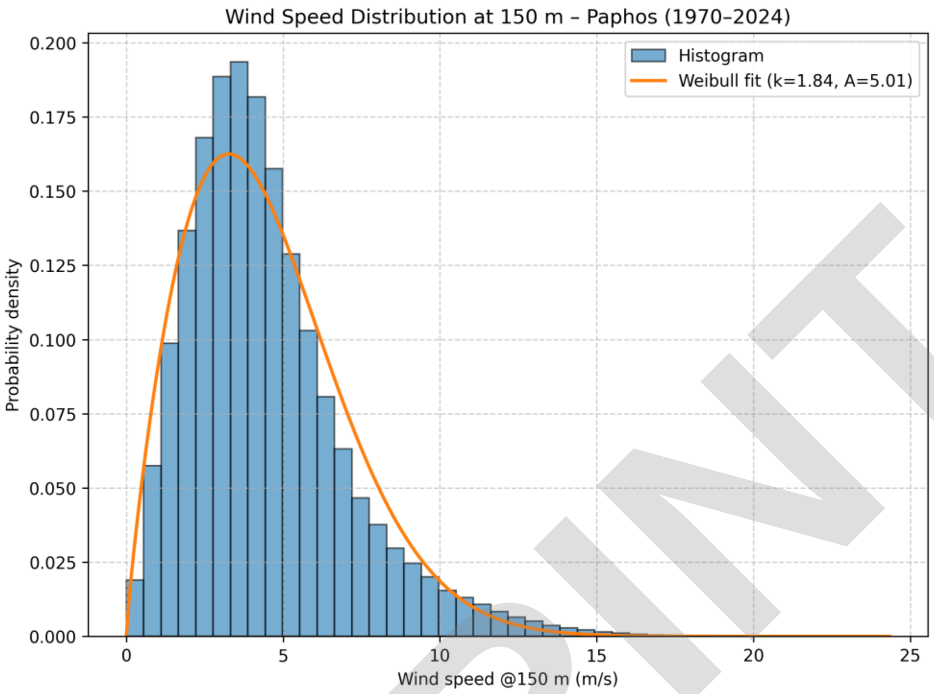

Figure 11: Wind speed distribution at 150 m with Weibull fit for Paphos (1970–2024).

Interpretation of Results

Limassol exhibits the most advantageous wind conditions, characterized by a wider range and greater frequency of wind speeds that fall within the optimal operational range for turbines (6–10 m/s). This finding directly correlates with the superior Annual Energy Production (AEP) and Capacity Factor (CF) values discussed previously.

In contrast, Larnaca presents a robust wind profile but is slightly biased toward lower wind speeds when compared to Limassol.

Paphos displays a narrow distribution that leans to the left, suggesting a significant prevalence of low-wind occurrences (<6 m/s), which constrains its potential for energy generation.

Moreover, all three regions exhibit a distinct long tail in their distributions, indicating sporadic high-wind events. However, these events contribute minimally to overall energy output due to the leveling off of the power curve.

In summary, the analysis of wind speed distributions elucidates the notable differences in power performance across Cyprus's offshore zones. Limassol stands out as the most promising site for future offshore wind projects, whereas Paphos presents conditions that may necessitate additional considerations, such as selective turbine optimization or hybrid energy solutions.

5. Conclusions

5.1 Thesis Outcomes

This thesis provides an extensive assessment of offshore wind resources over the long term for three southern coastal areas of Cyprus: Limassol, Larnaca, and Paphos. This analysis utilizes ERA5 reanalysis data extrapolated to a hub height of 150 meters and is evaluated through a representative model of a 15 MW offshore wind turbine. The findings indicate notable spatial variations in wind conditions across Cyprus, with Limassol recording the highest wind speeds and energy production, followed by Larnaca, while Paphos exhibits the lowest figures.

Over the complete period of 55 years (1970–2024), Limassol showcases both the most vigorous and productive wind regime, achieving an average Annual Energy Production (AEP) of approximately 51 GWh per turbine and a capacity factor nearing 39%. Larnaca shows favorable but somewhat diminished generation potential, whereas Paphos is marked by significantly weaker winds resulting in considerably lower energy output. Notably, the standard deviation in AEP remains relatively low across all locations, suggesting a consistent and predictable wind climate that enhances long-term project feasibility and mitigates financial risks for upcoming offshore initiatives.

The analysis of wind speed distribution further indicates that Limassol and Larnaca exhibit Weibull characteristics that are conducive to large-scale offshore wind development; conversely, Paphos does not meet the economic viability thresholds typically required. Collectively, these results underscore that despite Cyprus's comparatively limited coastline when juxtaposed with major offshore markets, the south-central marine region holds realistic potential for integrating utility-scale offshore wind projects. This aligns with national energy transition goals as well as EU renewable energy objectives.

In conclusion, this study establishes essential baseline knowledge regarding offshore wind availability in Cyprus and identifies Limassol as the most promising site for future offshore wind deployment. The results offer a solid groundwork for advancing into more sophisticated stages of project development encompassing engineering design, grid integration strategies, cost evaluations, and environmental permitting processes.

5.2 Recommendations for Future Work

Though this study forms a solid foundation for appraising Cyprus' chances of offshore wind, there are still certain areas requiring further investigation before it can be turned into realistic implementation planning. Among the future research work recommended:

- Techno-economic feasibility studies encompassing installation, operation, maintenance and grid link costs; the provisioning of offshore infrastructures; electricity pricing; and potential revenue streams.
- Marine spatial planning and environmental impact assessments concentrating on conservation of biodiversity, the routes taken by marine traffic, fishing operations in this area, and conflicts with potential tourist scenic assets.
- Advanced offshore wind technology appraisal, including floating installation platforms and turbines for deeper waters—such as those envisaged around Cyprus—producing 18–20MW.
- Higher-resolution mesoscale and microscale simulations done to provide fuller details of local wind flow dynamics, wake interactions in a future wind farm configuration, and optimizing where turbines are placed.
- Stability and interconnection grid studies, identifying electrical infrastructure improvements, how future energy storage technologies relate with both – and well as potential for Cyprus to contribute to wider interregional power exchanges via networks.
- Modelling of climate change sensitivity, exploring how predicted meteorological changes in the eastern Mediterranean could affect long-term wind availability offshore infrastructure strength.

With these future research priorities addressed, Cyprus can move from resource discovery to practical offshore wind development planning -- while ensuring that economic, environmental and societal factors are balanced. In this way, offshore wind power will become an essential part of our national transition toward an independent and resilient energy future that is sustainable.

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