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# ΤΕΧΝΟΟΙΚΟΝΟΜΙΚΗ ΑΝΑΛΥΣΗ ΑΝΑΠΤΥΞΗΣ ΥΠΕΡΑΚΤΙΟΥ ΑΙΟΛΙΚΟΥ ΠΑΡΚΟΥ ΣΤΙΣ ΕΛΛΗΝΙΚΕΣ ΘΑΛΑΣΣΕΣ

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ΑΝΤΖΕΛΑ ΜΟΥΤΣΑΛΑΡΙ

Επιβλέπων: Τάκβορ Σουκισιάν

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# TECHNO-ECONOMIC ANALYSIS FOR THE DETERMINATION OF SUSTAINABILITY AND POSITIONING OF OFFSHORE WIND PARK IN GREEK SEAS

ΜΕΤΑΠΤΥΧΙΑΚΗ ΕΡΓΑΣΙΑ

ΑΝΤΖΕΛΑ ΜΟΥΤΣΛΛΑΡΙ

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# Περίληψη

Η παρούσα διπλωματική εργασία έχει ως αντικείμενο την μελέτη εγκατάστασης υπεράκτιου αιολικού πάρκου σε 5 περιοχές της Ελλάδας και την αξιολόγησή του σαν επενδυτικό σχέδιο. Πιο συγκεκριμένα, γίνεται αρχικά μια σύντομη αναφορά στις ανανεώσιμες πηγές ενέργειας γενικότερα, και την αναγκαιότητα της ύπαρξής τους. Παρατίθενται και αναλύονται σημαντικά χαρακτηριστικά της αιολικής ενέργειας όπως η αιολική ισχύς, η μεταβλητότητά της, οι χαρακτηριστικοί συντελεστές και άλλες βασικές έννοιες της αεροδυναμικής των ανεμογεννητριών. Στη συνέχεια παρουσιάζονται τα τεχνικά χαρακτηριστικά 5 διαφορετικών μοντέλων ανεμογεννητριών, κάθε ένα από τα οποία θα χρησιμοποιηθεί στην εκάστοτε περιοχή για την ανάπτυξη των αιολικών πάρκων. Τα στοιχεία αυτά παρέχονται από τη κατασκευάστρια εταιρία και επίσης γίνεται μια περιγραφή των επιμέρους τμημάτων και του τρόπου λειτουργίας τους. Ο καθορισμός του συνδυασμού μοντέλου-περιοχής αξιολογείται και εξαρτάται από ορισμένα κριτήρια τα οποία πρέπει να πληρούνται, ώστε να γίνει προσέγγιση βέλτιστου αποτελέσματος και από τεχνική αλλά και από οικονομική κυρίως άποψη. Στη πορεία αναφέρονται οι λόγοι για τους οποίους καθίσταται αναγκαία η δημιουργία αιολικών πάρκων, γίνεται μια αναφορά στους περιορισμούς που εμφανίζονται κατά τη χωροθέτηση των ανεμογεννητριών, και αυτοί συνδέονται κυρίως με περιοχές που βρίσκονται υπό προστασία και απαγορεύουν οποιαδήποτε επέμβαση στο συγκεκριμένο περιβάλλον καθώς και με τη μορφολογία και τη σύσταση του πυθμένα. Σημαντικό επίσης, θεωρείται το ανάγλυφο του πυθμένα και το βάθος, καθώς καθορίζουν το τρόπο θεμελίωσης των ανεμογεννητριών . Στη συνέχεια γίνεται η παρουσίαση των υποψήφιων περιοχών στον ελλαδικό χώρο, ο ακριβής εντοπισμός για την εγκατάσταση των 5 αιολικών πάρκων με βασικό κριτήριο το αιολικό δυναμικό αλλά και τους περιορισμούς που προαναφέρθηκαν. Ακόμα, αναπτύσσεται η μεθοδολογία για την επεξεργασία των χαρακτηριστικών των ανεμογεννητριών, αλλά και των δεδομένων που έχουν καταγραφεί τα τελευταία χρόνια και σχετίζονται με τις ανεμολογικές συνθήκες. Η ανάλυση αυτή επιτυγχάνεται με τη χρήση εργαλείων σε προγραμματιστικό περιβάλλον στη Matlab, προκειμένου να προσδιοριστούν σημαντικοί δείκτες. Για τη καλύτερη αξιολόγηση των περιοχών σε συνδυασμό με την απόδοση των ανεμογεννητριών εισάγονται και τα οικονομικά στοιχεία ώστε να καθοριστεί το κόστος της ηλεκτρικής παραγόμενης ενέργειας. Ένα σημαντικό κομμάτι το οποίο δεν παραλείπεται είναι και οι απώλειες ενέργειας που συμβαίνουν κατά τη μετατροπή της παραγόμενης ισχύος σε καθαρή, υπο τη μορφή ηλεκτρικού ρεύματος. Εν συνεχεία υπολογίζεται με αναλυτικές μεθόδους και το συνολικό κόστος που απαιτείται για μια τέτοια επένδυση, το κόστος εγκατάστασης, λειτουργίας και συντήρησης. Τέλος, αξίζει να σημειωθεί ότι ο υπολογισμός του κόστους της ενέργειας εκτελείται και για τα 4 μοντέλα ανεμογεννητριών σε συνδυασμό με τις 4 περιοχές εγκατάστασης για την επίτευξη ακριβέστερης σύγκρισης και αξιολόγησης του κόστους.

# Abstract

Main purpose of this dissertation is the study of installation of an offshore wind farm in 5 Greek areas and its evaluation as an investment project. More specifically, a brief reference is made to renewable energy sources in general, and the necessity of their existence. Important features of wind energy, such as wind power, variability, characteristic factors and other basic concepts of wind turbine aerodynamics are presented and analyzed. Afterwards the technical characteristics of 4 different turbine models are introduced, each one of them will be used the individual areas for the development of offshore wind parks. These data and also a brief description of the individual parts and how they operate are provided by the manufacturer. The determination of the model-area combination is evaluated and it depends on certain criteria that must be met, in order to approach an optimal result both from a technical and principally from an economic point of view. Afterwards they are mentioned the reasons of necessity in creating wind farms, a reference also is made to the restrictions that appear during the location of wind turbines, which are associated with regions that are protected and is prohibited any intervention in this environment, also are related to morphology and composition of the bottom. Important also is considered the relief of the bottom and the depth, as they determine the method of wind turbines' foundation installation. Consequently the 5 Greek prospective areas in are presented with exact location for the installation of the 5 offshore wind parks with basic standard the wind potential but also taking into consideration the restrictions mentioned above. In addition, appropriate principles are developed for data processing of the wind turbines features in combination with the values were recorded in recent years and are related to the wind conditions. This analysis is achieved by using tools in a programming environment called Matlab 2019a, in order to identify important indicators. For accurate evaluation of the areas in combination with the efficiency of the wind turbines, the economic data are introduced in order to determine the cost of the electricity produced. An important part that should not be omitted is the energy losses that occur during the conversion of the gross power production into net, in the form of electricity. The total cost required for such an investment, the cost of installation, operation and maintenance is then calculated by analytical methods. Finally, it is worth mentioning that the estimation of energy costs is performed for each wind turbine model in combination with the five installation areas with main target to achieve a more accurate comparison and cost evaluation**.**

# Introduction

Main purpose of this thesis is evaluating the sustainability of an offshore wind park in Greek seas. The excessive development of technology has contributed in order complex systems such as power production can be produced by exploitation of wind energy through turbines. This project combines wind turbines technical data provided from manufactures with data aggregation of 20 years, especially wind speeds with an interval of an hour, measurements with high frequency so as to minimize deviations and achieve more precise results of power production. The specific data of each turbine that were extracted is power production at each corresponded wind speed. There are five areas that have been already reviewed and concluded that the development of an offshore park is feasible in each one of them. In addition economic elements are estimated in order to provide a more accurate interpretation of each wind parks. In combination with wind speeds values of 20 years collection the turbine that prevails in each prospective areas in connection with wind turbine features each power density of available areas and the financial elements

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# 1. Fundamental Features of Wind & Wind Power

## 1.1 Definition of Wind

The wind is defined as the result caused by the motion of air because of the atmospheric pressure gradients. Wind moves from zones of higher pressure to zones of lower pressure. The higher the atmospheric pressure gradient, the higher the wind speed. So this natural occurrence entails greater values of wind power that can be collected from a turbine an energy-converting machinery.

Wind energy depicts a dominant and innovative source of new power generation and a vital aspect in the world's energy market, is the most completely developed renewable energy generating electricity through wind. Due to the wind kinetic energy which is caused as a consequence of air currents, a propeller is turned and through a mechanical system, it rotates the rotor of a generator that produces electricity.

## 1.2 Wind Power

When an object of a given mass is in motion with a trans-rational or rotational speed, then wind power Kinetic energy appears. When it is observed air movement, then the kinetic energy in be determined as:

$$E_k = \frac{1}{2} m u^2 \tag{1}$$

where **m** is the air mass and **u** – is the mean wind speed over a period. The wind power can be obtained by differentiating the kinetic energy in wind with respect to time, i.e.:

$$P_w = \frac{dEt}{dt} = \frac{1}{2} m u^2 \tag{2}$$

Despite this, only a minor part of wind power can be converted into electrical power. When wind get through a wind turbine and turns blades to rotate, the equivalent wind mass flowrate is:

$$m = \rho A u \tag{3}$$

Where **A** is the swept area of blades, as shown in Figure. 2 and **ρ** the air density**.** Substituting (3) into (2), then the available wind power $P_w$ can be expressed as:

$$P_w = \frac{1}{2} \rho A u^3 \tag{4}$$

Where:

p=wind density (1,2kg/$m^3$)

A: Swept Area

u: wind velocity

A thorough testing of equation (4) reveals that in order to acquire a higher value of wind power, it is required a higher wind speed, a longer length of blades for gaining larger swept area, and a higher air density. The wind power output is related to the cubic power of the mean wind speed, so a minor variation in wind speed lead to large change in wind power.

## 1.3 Wind Variability

It is commonly accepted that the output of wind power is highly variable and from a single area cannot be a reliable source of electricity. Taking into consideration the wind speeds distribution at a site, is important in order to estimate the capacity factor and energy production of a wind turbine.

It has been observed a wind power variation over time, especially under the effect of meteorological fluctuations. The variations exist on all time scales: years, months, days etc. Taking into consideration the variations and the predictability, it is well known that they are important parameters for the integration and optimal utilization of wind in the power system. Electric power systems are variable both in demand and in supply, but they are designed to overcome effectively these fluctuations through their configuration, control systems and interconnection.

## 1.4 Micro-meteorological Range: Turbulence

A principal characteristic of wind, is the high temporal variations. Wind speeds can double or triple within seconds, leading to power rise 8 - 27 times! In addition several obstacles such as tress or Steep Mountain tops and buildings, can also result in Turbulence intensity increase. Regions with high mean wind speeds tend to undergo less turbulence

*Turbulence is negative for wind turbines for below reasons:*

- Increase dynamic loads on blades
- Mitigates energy production
- Reduce operational years of the turbine

*Indications of high turbulence:*

- Areas with many obstacles
- Landscapes with lack of homogeneity
- Existence of  mountain tops

## 1.5 Aerodynamics Of Wind Turbines

In contrast with Dutch windmills design, which depend on the wind's force in order to push the blades into motion, contemporary turbines use more sophisticated aerodynamic basic rules in order to capture wind energy in a more efficient way. *Lift* which has an impact perpendicularly to the direction of wind flow and *drag* which acts parallel to the wind flow direction, are the two fundamental aerodynamic forces in wind-turbine rotors.

Airplane wings can be compared with turbine blades as they use an airfoil design. In an airfoil, one surface of the blade is flat, while the other is relatively rounded. Although lift is a complicated issue, it can be simplified and mentioned that when wind moves over the rounded, downwind face of the blade has to move faster in order to reach the end of the blade and coincide with the direction from which the wind is blowing. Based on the fact that faster moving air tends to rise in the atmosphere, the downwind, curved surface ends up with a low-pressure (and high speed wind) pocket just above it. The low-pressure area sucks the blade in the downwind direction, an effect known as "lift." On the upwind side of the blade, the wind is moving with lower speed creating an area of higher pressure that pushes on the blade, trying to slow it down. Turbine blades present an angle that takes advantage of the ideal lift-to-drag force ratio. Except for aerodynamics, also the size can contribute in creating an effective wind turbine, because the longer the blades (and therefore the greater the diameter of the rotor), the more energy a turbine can capture from the wind and then greater electricity-can be generated. In addition a considerable factor in production capacity is the tower height. The higher the turbine, the more energy it can be captured based on the fact that wind speeds increase with elevation. Also the flow of the wind can be disrupted from ground friction and ground-level objects. There is a scientific estimation which concludes that a 12 % increase in wind speed derives from each doubling of elevation.

In order to determine the wind turbine power generation, power coefficient should be calculated. The power coefficient of the turbine is a function of tip speed ratio $\lambda$ and the pitch angle β. In this case Cp coefficient describes the power extraction efficiency of a wind turbine. The tip speed ratio of a wind turbine is the ratio between the peripheral tip blade speed and the wind speed, and it is expressed as:

$$\lambda = \frac{R\omega}{V} \tag{5}$$

Where:

R: wind turbine radius,

ω: angular velocity of the wind turbine

V: wind velocity.

The pitch angle β is defined as the angle between the airfoil chord and the rotor plane of rotation measured at the blade root. In case the pitch angle of a turbine blade is modified, then the angle of attack and thus, the wind power capability of the blade alters too.

### 1.5.1 Momentum Theory Analysis for a Wind Turbine

Flow is the factor from which a wind turbine extract energy, therefore velocity is reduced and slipstream expands downstream

Conservation of mass:

$$m = \rho A(V - v_i) \tag{6}$$

Alteration in momentum can be related to thrust:

$$T = mV - mV(v - \omega) \tag{7}$$

Expanding:

$$T = mV - mV + m\omega = m\omega \tag{8}$$

Work done on the air by the turbine per unit time is:

$$W = \frac{1}{2}m(V-\omega)^2 - \frac{1}{2}mV^2 = \frac{1}{2}m\omega(\omega - 2V) = 1/2m\omega(2V - \omega) \tag{9}$$

Turbine does negative work (windmill state)

Power:

$$P = T(V - vi) = \frac{1}{2}m\omega(2V - \omega) \tag{10}$$

By substituting:

$$T = (V - vi) = \frac{1}{2} m\omega( 2V - \omega) = m\omega(V - vi) \quad (11)$$

Thus w=2 → w=2υi (or υi=w/2); same as in helicopter rotors

For model validity: V∞-w>0; thus V∞ > w= 2υi

If thrust is not known, induction ratio definition, as indicated below:

$a = \frac{ui}{V}$ or $ui = aV$ Larger $a$ → more flow is slowed as it passes the turbine

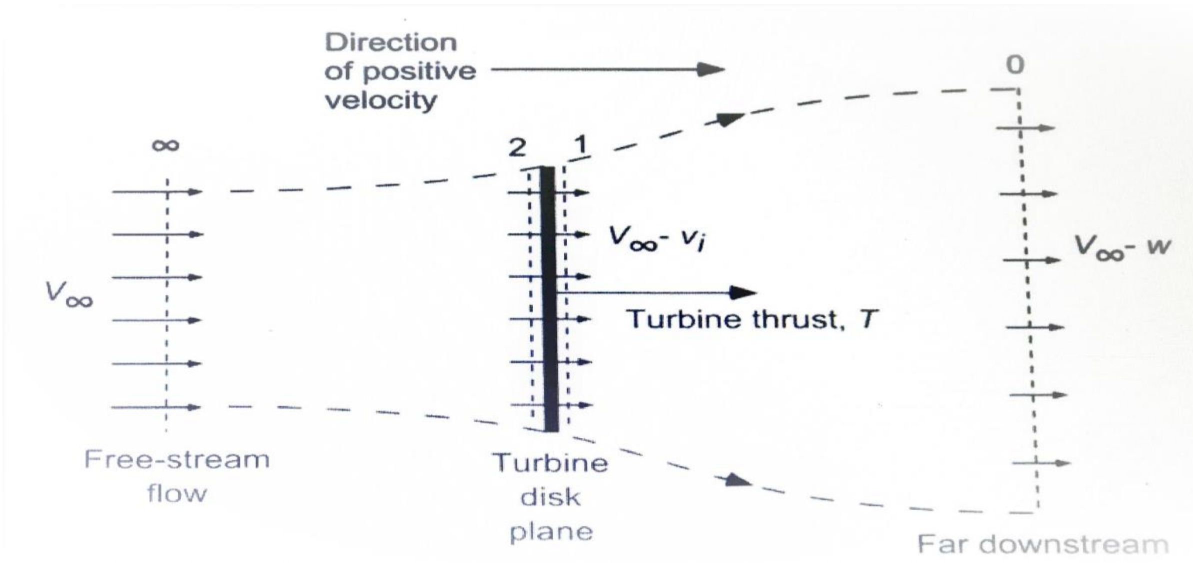


Figure 1. Function of actuator disc

### 1.5.2 Power Coefficients: Cp

Wind turbine efficiency measurement is related to the Power Coefficient (Cp), especially is the ratio of actual electric power produced by a wind turbine divided by the total wind power flowing into the turbine blades at specific wind speed. Describes also the combined efficiency of the various wind power system components which include the generator and power electronics the turbine blades, the shaft bearings and gear train. The manufacturer of each turbine is responsible for the turbines' Cp measurement or calculation, and in most cases is provided at various wind speeds. In case that Cp is known at a given wind speed for a specific turbine, then it can be used in order to estimate the electrical power output.

Wind speed, turbine blade angle, and turbine rotation speed, are operating parameters that can lead to variation of Cp for a specific turbine. It is a measure of a particular wind turbine's overall system efficiency.

$$c_p = \frac{P}{Pwind} \quad (12)$$

**P**: Actual Electrical Power Produced

$P_{wind}$: Wind Power into Turbine, $$P_w = \frac{1}{2}\rho A u^3 \quad (13)$$

### 1.5.3 Thrust Coefficients: - Ct

High levels of wind speed and the expansion of swept can contribute in the increase of electric power production of a wind turbine in a specific area. So in order to achieve higher values of power, in the recent years the diameter of rotor has been widen. The diminish of the pressure is the reason of tension in the disk of the motion and appears non dimensional**,** from which derives a thrust coefficient Ct

$$c_T = \frac{T}{\frac{1}{2}\rho A u^2} \quad (14)$$

### 1.5.4 Speed Ratio

The governing equation for power extraction is:

$$P = Fu \quad (15)$$

Where:

*P:* power,

*F:* force vector

$u$: velocity of the moving wind turbine part.

Interaction of blade with the wind generates the force F. The most vaguely recognizable type of aerodynamic force is drag. As it was already mentioned in pervious section that the direction of the drag force is parallel to the relative wind. Typically, the wind turbine parts are moving, altering the flow around the part.

The above equation shows two important dependents. The first is the speed (*U*) of the machine. The speed at the tip of the blade is usually used for this purpose, and is written as the product of the blade radius *r* and the rotational speed of the wind: U=ωr , where ω is the rotational velocity in radians/second. This variable is non-dimensionalized by the wind speed, to obtain the speed ratio:

$$\lambda = \frac{U}{V} \tag{16}$$

### 1.5.5 Lift and Drag

As stated earlier there are two types of aerodynamic forces, lift and drag. Accordingly, there are two non-dimensional parameters. The formula for lift and drag is expressed below:

$$C_L = \frac{L}{\frac{1}{2}\rho A W^2} \tag{17}$$

$$C_D = \frac{D}{\frac{1}{2}\rho A W^2} \tag{18}$$

Where $C_L$ is the lift coefficient, $C_D$ is the drag coefficient, *W* is the relative wind as experienced by the wind turbine blade, and *A* is the area. It should be clarified that *A* may not be the same area used in the power non-dimensionalization of power

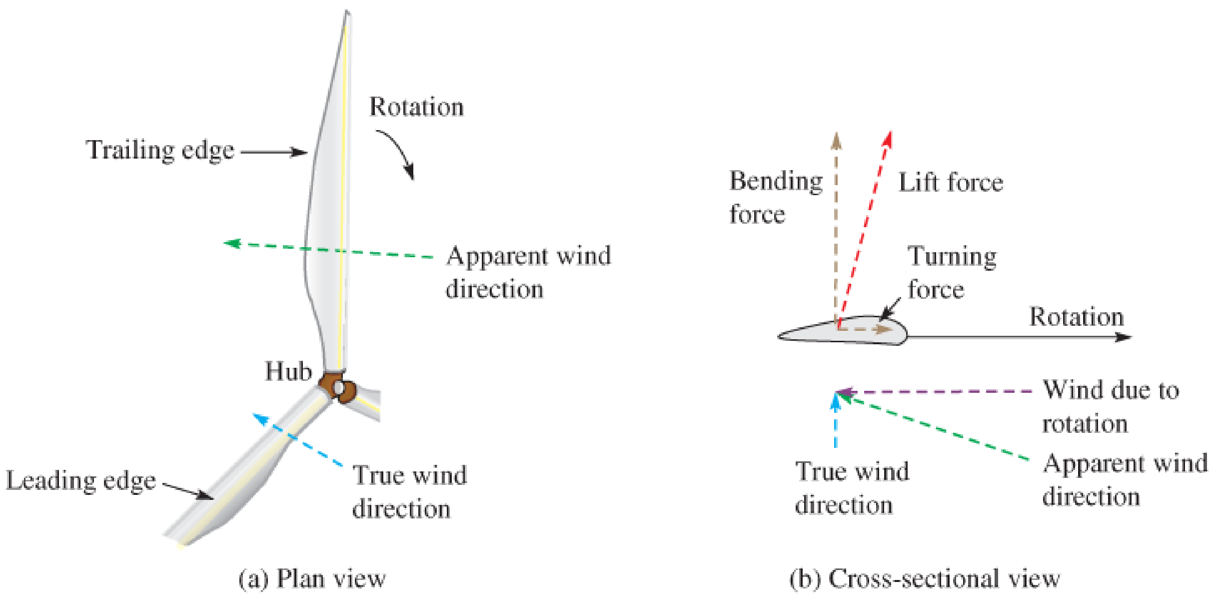


Figure 2. Wind Turbine Blade Aerodynamic

### 1.5.6 Betz's coefficient and turbine efficiency

According to Betz's law (Rauh and Seelert, 1984), a turbine cannot capture more than (59.3%) of the wind kinetic energy. In case of higher wind speeds, the turbine has been designed in a manner that limits the power to the rated level and there is no further increase in the output power. This can be achieved by adjusting the blade angles so as to keep the power at constant levels. In addition, when the turbine operates close to the rated speed then the turbine performance is reduced

# 2. Wind Turbine & Technology

## 2.1 Systems for Aerodynamic Power and Load Regulation

The system for aerodynamic power and load regulation (APLR) has the following main functions:

- Decrease the structural loads on wind turbine through autonomous, aerodynamic control devices or collective actuations of blades.
- Control torque on drive train during normal power production above rated power
- Control rotational speed through blade pitch during normal power production above rated power
- Reduce rotor speed during normal and emergency stop situations
- Control torque during low voltage ride through
- 3D modeling technology which allows computer simulations before manufacturing
- duct that would wrap around a turbine's rotor to increase the rotor's performance

The aim is to develop an APLR system that shall give 25% more annual energy production within the same load envelope as todays' wind turbine technology.

*Current Solutions*

Nowadays the prevailing technology is pitch regulated variable speed, with turbines that can control the loads and power in a manner where there is a primarily laminar air flow around the blade, and where there is a full-length blade pitching activated by electrical motors or by hydraulic pistons in the rotor hub. There are several turbine designs that are still combining the full length pitching with aerodynamic stall, as this can lead in low weak loads and simple power electronics. However due to the excessive loads and prerequisites for additional power compensation equipment in order to comply with some grid requirements, this solution is losing competitiveness.

*Emerging Technologies*

Modifying the aerodynamic lift and drag coefficients of the blade structure, instead of just changing the angle of attack is the main purpose of  Emerging technologies, which includes below:

- Turbines with 2 blades and  partial length pitch
- Controllable flow around blade with micro tab system
- Control mechanism same with aero planes with fast moving flap
- Morphing structures where the blade structure itself alters shape

## 2.2 Wind Turbines Components

Wind turbines varies as per their sizes but all types consist of main components as expressed below

- **Rotor Blades** - The rotor blades of a wind turbine operate in similar way with aircraft wings. One side of the blade is flat, while the other is curved. The wind flows more quickly along the curved edge, creating a difference in pressure on both sides of the blade. In order for the pressure to be equalized the blades are thrusted by the air, causing their turning.
- **Nacelle** – The generator and a set of gears are located inside the nacelle. The generator is connected with the turning blades by the gears. The slow blade rotation is adapted by the gears to the generator rotation speed of approximately 1500 rpm and converts the rotational energy from the blades into electrical energy.
- **Tower** – The tower is constructed in order to support the rotor blades off the ground and at an ideal wind speed. On the top of a tower, are mounted the nacelle and the blades. Also towers are usually between 50-100 m above the surface of the water.

An important element of a wind turbine is the drive train, which connects aerodynamic rotor and electrical output terminals. Based on their structures can be separated into four different types:

- Conventional: High speed generator with few pole pairs and gearbox
- Direct drive: Drive train without a gearbox and low speed generator with many pole pairs.
- Hybrid: Drive train with a gearbox and the generator speed between the above two types.
- Multiple generators: any drive train with more than one generator.

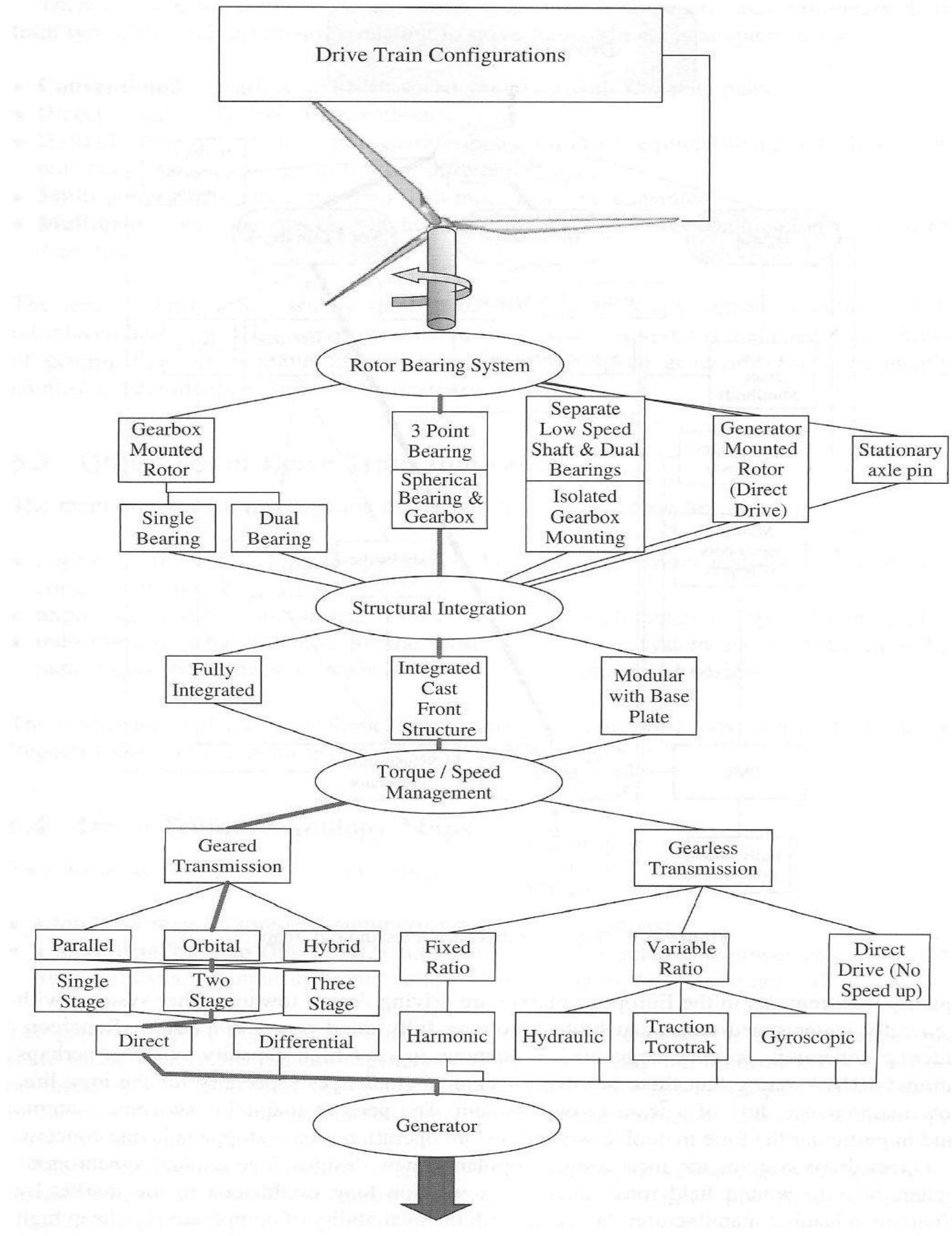


Figure 3. Operational Diagram of a Wind Turbine

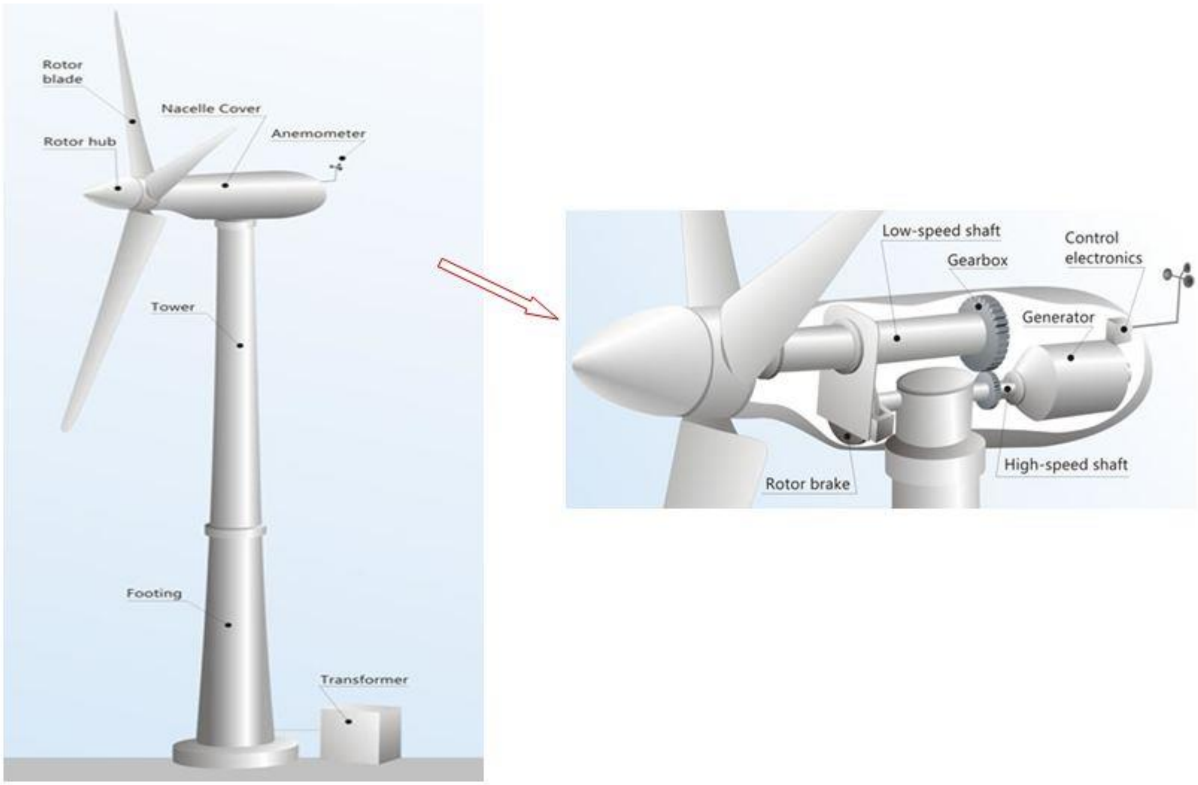


Figure 4. Nacelle Components

# 3. Offshore Wind Parks

## 3.1 Introduction of OWPs

Offshore wind turbines were first revealed in Germany in 1930s and initially installed in Denmark in 1991. By July 2010, there were 2.4 GW of offshore wind turbines installed in Europe. Evaluating the differences of the onshore wind energy with offshore, it is worth mentioning that the last has some appealing attributes such as lower inherent turbulence intensity and lower wind sheer, higher wind speeds and availability of greater areas for installation. But the disadvantages are related to the harsh working states, such as excessive installation and maintenance costs. Especially for the offshore operation, major parts should be enhanced with additional anti-corrosion measures and de-humidification capacity so as to improve their performance, reliability and extend their lifetime too.

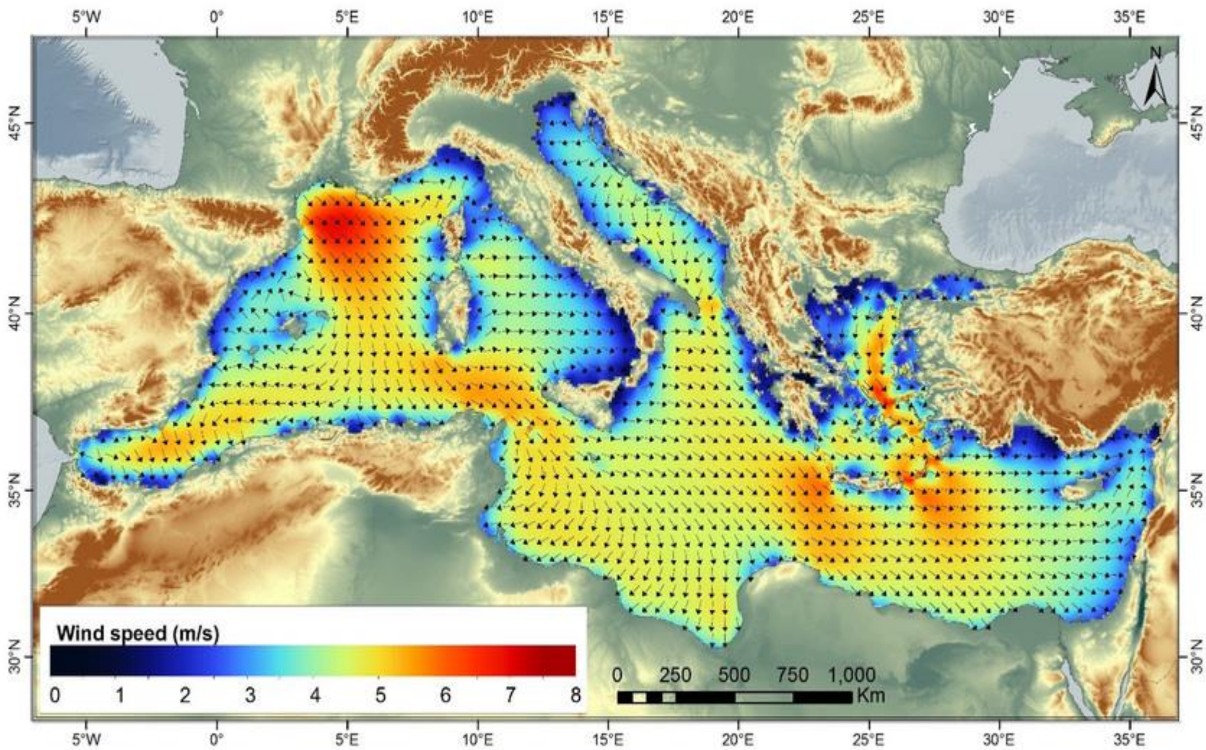

Figure 5. Allocation of wind speed 10m above the sea

## 3.2 Advantages and Drawbacks of Offshore Wind Farms

Advantages:

- Offshore wind speeds tend to be much higher in contrast with lands with greater expansion at a site. Even minor rises in wind speed lead to large increases in energy yield: a turbine in a 15-mph wind can generate twice as much energy as a turbine in a 12-mph wind.
- Offshore wind speeds are more stable in contrast with wind speed on land. In case there is a more constant supply of wind it means that the source of energy is more reliable.
- There are several coastal areas with high energy requirements. In the United States' 50 %

## 3.3 European Advances in Offshore Wind Energy

Europe is the main continent that has devoted time and capital in offshore wind park developments, including the United Kingdom, Denmark, Netherlands, Germany and Belgium placed as five of the top six countries in relation to installed capacity. Almost 90% of the installed global capacity for offshore wind are located in regions of the Atlantic Ocean and in the North. Advances in the technological sector have raised capacity factors (CFs) for offshore wind systems diminishing both variable and fixed costs, combined with installation of greater turbines that contribute to energy output increase.

## 3.4 Offshore Wind Parks in Greece

Prevailing areas in Greece are the Aegean Sea islands and mountain ridges on the mainland, so Greece benefits from a noteworthy wind resource at specific areas preserving mean wind speeds (at hub height) usually surpassing the value of 8–10 m/s. Greece has made remarkable progress in fostering and supporting renewable energy. Having commissioned the first commercial on shore windpark in Europe (built in 1983 on the Cycladic island of Kythnos). However despite the fact that Greece has 58 offshore wind farm project, currently none of them has been implemented and operating in Greek seas

## 3.5 Strategic Planning of Offshore Wind Parks

***Stage 1*** *—Vision and Mission of Strategic Planning*

This stage takes into consideration the current situation of the examined area, regarding the issue of energy independence, the future demand for the production of a large number of public commodities, such as electricity, with main target to export the electricity and thus improve the country's current economic status.

***Stage 2*** *—Exclusion of Unsuitable Areas*

This particular stage takes into account the exclusion of the areas evaluated as unsuitable for the installation of OWFs. The exclusion criteria are defined based on the special characteristics of the examined region, considering also the relevant provisions of the Greek Specific Framework for the Spatial Planning and Sustainable Development for the Renewable Energy Sources.

Especially these exceptions includes below:

1. Wind Velocity

Wind velocity is a significant criterion for the site selection of an OWF, as it is directly linked to the economic feasibility of the project. Therefore, an accurate and detailed analysis of wind data is crucial for a potential wind energy assessment of the proposed suitable sites.

2. Water Depth

Water depth is one of the key criteria for OWFs' siting, as it significantly contributes to the determination of the investment cost of such projects. Specifically, the water depth affects the selection of the wind turbine's support structure, as well as the CAPEX and OPEX of an OWF project, which increase significantly in deeper waters.

3. Military Zones

These marine areas are officially used by the National Army either for training purposes or as firing fields and therefore cannot be considered for any other use.

4. Seismic Hazard Zones

The seismic hazard factor should be considered generally in the site selection process to reduce construction cost. Greece corresponds to one of the most seismically active countries worldwide. Therefore, all infrastructures should be adequately designed against earthquake. In the case of OWFs, this fact may lead to special designs of the wind turbines' support structure and, therefore, to larger construction costs.

5. Underwater Cables

This exclusion criterion is referred to the cables that already exist on the seafloor and serve either for electricity transmission or for telecommunication purposes

6. Distance from Ports

The distance of an OWF project from a port presents an important factor affecting the total investment cost, since it has a direct impact on the installation costs, the operation and maintenance costs, as well as the decommission costs of the OWF. Specifically, the total investment cost decreases as the location of an OWF is closer to an existing port, while, moreover, the proximity of the installation area to a port simplifies the overall project management (e.g., no need to install a substation within the marine environment).

7. Distance from High Voltage Electricity Grid

The distance of an OWF from the national electricity grid and particularly from a high voltage grid is extremely important for technical and economic reasons. A connection to the high voltage grid is selected, because in the opposite case (connection to a medium or low voltage grid) there might be a serious risk of cable destruction due to overloading of the electricity grid.

8. Landscape Protection/Visual and Acoustic Disturbance

The present criterion is related to the distance of an OWF from the coast and it has been used to ensure landscape protection, avoid visual and acoustic disturbances, and ensure the social acceptance of an OWF.

9. Distance from Marine Protected Areas

Marine protected areas correspond to Sites of Community Importance (SCI) of Natura 2000, national marine environmental parks, coastal bathing waters monitored and assessed in the framework of the Monitoring Programme of Bathing Water Quality according to the provisions of the Directive 2006/7/EC and swimming beaches awarded with the Blue Flag.

***Stage 3*** *—Determination of Technical Specifications and Layout*

This stage deals with technical issues related to such projects, such as the selection of the model type of the wind turbine (rotor-nacelle-assembly), the selection of most suitable type of support structure, etc. The required technical *Specifications* are determined by the following elements:

(i) The specific characteristics of the suitable sites, that is, wind velocity, wind direction, water depth and the available surface area/shape of the proposed sites.

(ii) Studying similar projects that have been completed and are in full or partial operation to this day. In addition, using GIS, the OWFs are sited within the suitable area identified in Stage2

***Stage 4*** *—Costing of OWFs*

This stage includes the estimation of Economic elements such as CAPEX and OPEX of all proposed projects.

# 4. Foundation of Wind Turbines in the Marine Environment

## 4.1 Ways of Foundation Based on Sea Depth

Figure 6. Offshore Wind Turbine Foundation

**Monopile:** This kind of foundation supports the tower of the wind turbine either directly or through a transition piece. In case the pile is driven into the seabed or grounded into the sockets drilled into rock, it is depended on subsurface conditions. The most widespread way of foundation for offshore wind turbines in shallow water depths is the monopile. They have to be rigid in order to avoid large natural periods resulting in large, heavy and expensive structures as per their installation. Are suitable **<u>for 0-30 m depth of water.</u>**

**Tripods:** Can be used in order to mitigate the deflections for the wind towers. The pre-fabricated frame has a triangular shape in and it is constructed from steel pipe members joining each corner. A jacket leg installed at each corner is diagonally and horizontally braced to a transition piece in the center. A significant feature of tripods is that these kind of foundations do not require any seabed preparation and are appropriate **<u>for 25-50 m depth</u>** of water.

**Jacket:** It is a squared network consisted of steel rods. It is anchored at four anchorage points and the whole steel construction can be mounted in one piece which increases the levels of safety when anchoring the towers. Using a three-dimensional truss like the jacket foundation substantially increases rigidity. The top of the jackets feature a transition piece that is connected to the turbine shaft, while the legs (three or four, according to the engineering design) are anchored to the sea bed with piles. Despite the fact that jackets are more expensive than a monopile or gravity base foundation, are suitable for 25-50 m depth of water.

**Floating Structures**

Floating foundations are suitable in harsh operating environments. Platform designs for offshore wind, however, have to be adjusted in order to meet the demands of different dynamic stages and an individual loading design, these kind of structures are classified based on the mechanism that complies with the conditions of the static stability requirements.

There are 3 principal stabilizing mechanisms:

- Ballast stabilized having large ballast deep at the bottom of the floating structure, moves the center of gravity of the total system below the Centre of buoyancy. This has as a result the development of a stabilizing righting moment which counteracts rotational displacements, when an incline of the platform occurs.
- Water plane (or buoyancy) is the main contributor in order to restore moment of the floater. Having a large second moment of area with respect to the rotational axis, either due to a large water plane area or due to smaller cross-sectional areas at some distance

from the system central axis, a stabilizing righting moment it is created in case of rotational displacement.

• Mooring stabilized, high tensioned mooring lines generate the restoring moment when the structure is inclined.

**Main Floating Structures**

1. **TLP:** Is the mooring stabilized structure which retain a central column to support the turbine. Three arms reach out at the floater base where the tendons are connected. In order to ensure that the mooring lines are always under tension, the displaced volume should be high enough to provide excess buoyancy. In addition vertical load anchors are required for the mooring lines going straight down to the seabed. TLP are suitable for depths **greater than 50 m.**
2. **Semi-Submersible:** Same mooring system as TLP is used for semi-submersibles. In order to asquire water plane-based stability, this floater type is made out of three columns placed on the edges of a triangle. The wind turbine is either mounted on one of these columns or supported by a fourth one in the center of the triangle. Braces interconnect the columns. Unlike the multi-cylindrical semi-submersible, the water plane-area stabilized barge is rather a plane structure. This kind of floating structure is suitable for depths **greater than 100 m.**
3. **Spars:** Is a cylinder that floats vertically in the water, often with ballast tanks in parts of the cylinder volume. The ballast stabilized floaters, usually consist of a long cylindrical structure which is filled with ballast at the bottom. For station keeping, the floater is commonly equipped with three catenary mooring lines. Spars are suitable for depths greater than 120 m.

## 4.2 Prerequisites of the Sites for installation

The most important parameters that should be taken into consideration for the installation are mentioned below:

1. Minimum distance of 1.5km from the coastline.

2. Minimize visual nuisance from installations.

3. Exclusion of areas where wind farms are incompatible with other uses (eg military bases, fishing, etc.).

4. Avoid areas with significant environmental impacts (eg. Natura 2000 Areas).

5. Priority of areas closer to the port so as to facilitate transportation of required materials for the installation and also for future purposes in case of maintenance of the whole OWPs.

6. Wind energy potential (mean annual wind velocity, percentage of appearance etc.)

# 5. Implementation & Procedure of Wind Park Determination

## 5.1 Basic Technical Characteristics of Nominated Wind Turbines

This chapter describes in detail the models of wind turbines used in this thesis. Four different models were used, together with their power curve and characteristic table with detailed speed-power values. These models are suitable for offshore wind farms and the main features are mentioned below:

1. **<u>Vestas V164 - 7.0 MW</u>**

The new Vestas V164 - 7 Megawatt wind turbine contains 3 blades each of them has a length of 80 m. The total diameter of the rotor is 164 m. maximizing the amount of energy capture, not only with the huge rotor diameter, but also through an optimal rotor to generator ratio. Reducing operations and maintenance costs by enabling to run fewer and larger turbines, Reducing the scale and risk of investment required, as fewer turbines also means fewer foundations and less cabling. Maximizing the return on investment thanks to the 25 year structural life of the turbine power that a turbine ca

**TECHNICAL SPECIFICATIONS**

Rated power: 7,000.0 kW
Cut-in wind speed: 4.0 m/s
Rated wind speed: 13.0 m/s
Cut-out wind speed: 25.0 m/s
Survival wind speed: 50.0 m/s

**Rotor**
Diameter: 164.0 m
Swept area: 21,124.0 m²
Number of blades: 3
Rotor speed, max: 12.1 U/min
Tip speed: 104 m/s
Type: 80

Power density 1: 378.7 W/m²
Power density 2: 2.6 m²/kW

Single blade: 35.0 t
Nacelle: 375.0 t

Hub Height :105 m

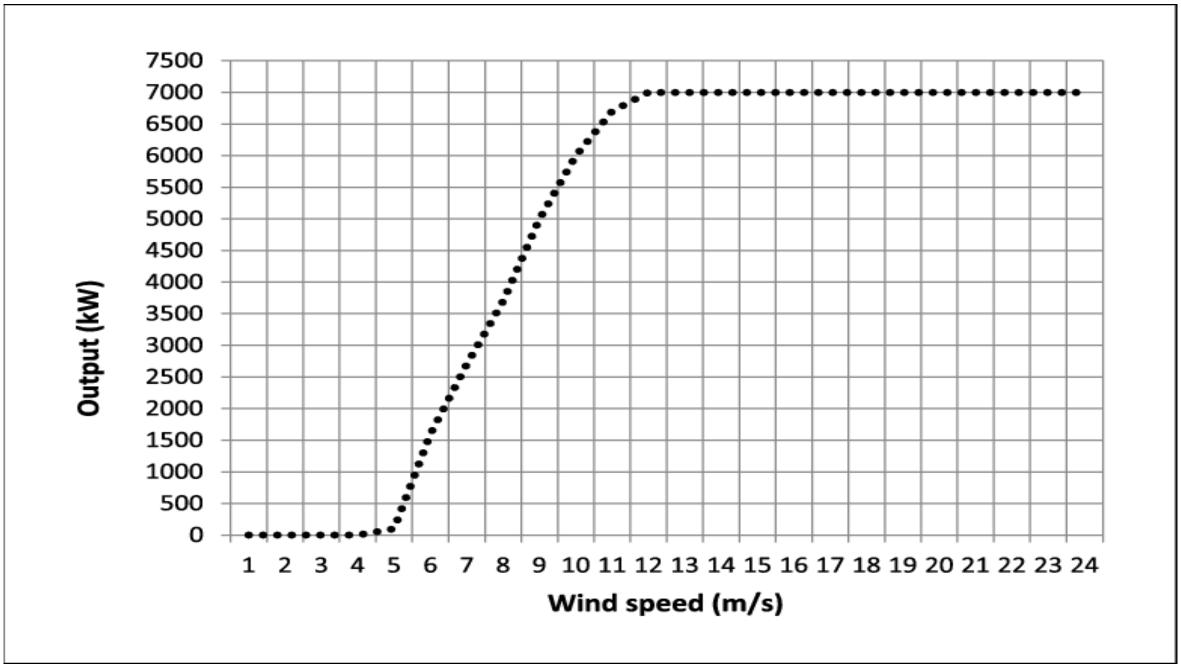


Figure 7. Vestas V164 - 7.0 Turbine Power Curve

2. **Vestas V164-9.5 MW**

The V164-9.5 MW™ continues the legacy of the proven V164-8.0MW®. With minimal design changes, such as a redesigned gearbox and cooling system upgrades, the 9.5 MW provides market-leading output levels, low operational costs, cost-efficient installation and built-in reliability. A proven turbine that can minimize your total cost of energy and maximize the return on investment

**TECHNICAL SPECIFICATIONS**

Flanged connected drive train with easy-access key-components
Main bearings, coupling, gearbox and generator is possible to lift out separately for service
Permanent magnet generator
Nacelle dimensions: 9.3 m x 20.7 m x 8.8 m (H x L x W)
Rotor diameter: 164 m
Helihoist platform available
Named Best Offshore Turbine 2017 by Wind power Monthly Magazine
Built on the proven and trusted V164 turbine platform
Gearbox improvements
Cooling system adjustments
Power production system upgrades

Full scale converter 50/60 Hz at 33-35 or 66 kV nominal voltage
Swept area: 21124 m$^2$

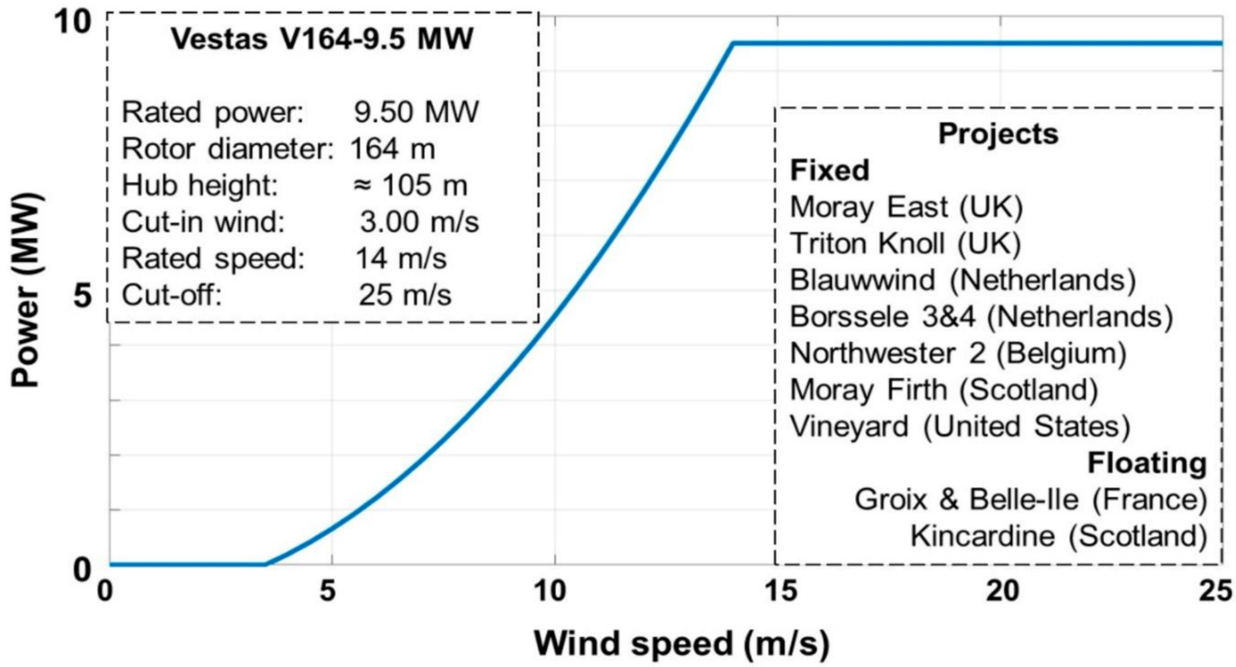


Figure 8. Vestas V164-9.5 Turbine Power Curve

### 3. Vestas V164- 8,00

## TECHNICAL SPECIFICATIONS

**Operating Data**
Cut-in wind speed: 4.0 m/s
Rated wind speed: 13.0 m/s
Cut-out wind speed: 25.0 m/s
Survival wind speed:50m/s
Rotor speed, max: 4.8-12.1 rpm
Nominal rotor speed 10.5 rpm
Operation temperature range: -10- +25o C
Extreme temperature range:-15-+ 35o C

**Design Parameters**
Nacelle: 390.0 t
Hub Height: 105 m
Wind Class IECS

Annul avg Wind Speed: 11m/s
Weibull shape parameter: k 2.2
Wweibull scale parameter 12.4 m/s
Turbulence intensity: IEC B
Max inflow angle: (vertical): 0o
Structural design lifetime : 25 years

**Rotor**
Diameter: 164.0 m
Swept area: 21,124.0 m²
Number of blades: 3
Rotor speed, max: 12.1 U/min
Tipspeed: 104 m/s
Type: 80
Power density 1: 378.7 W/m²
Power density 2: 2.6 m²/kW

**Electrical**
Frequency: 50 Hz
Converter Type: Full Scale Converter
Generator type: Permanent magne
Voltage: 33-35 and 66,000.0 V

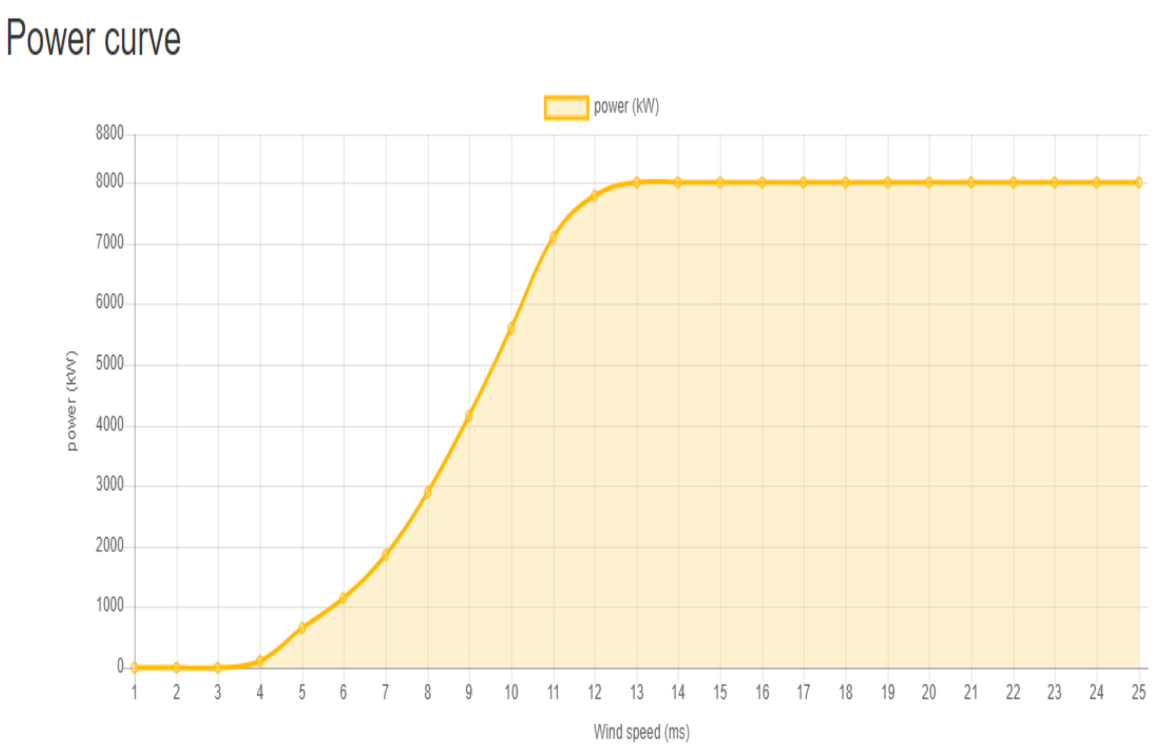


Figure 9. Vestas V164- 8,00 - Turbine Power Curve

## 4. Enercon E-126 - 7.580

TECHNICAL SPECIFICATIONS

Rated Power: 7580 kW

Cut in Speed: 3 m/s

Rated wind Speed: 16.5 m/s

Cut out wind Speed: 34 m/s

Diameter: 127 m

Swept Area: 12668 m2

Number of Blades: 3

Rotor Max Speed: 12 U/min = 0,0088 m/s ( 1 meter/second is equal to 1349,8)

Power Density 1: 598,4 W/$m^2$

Power Density 2: 1.7 $m^2$/kW

Tower height: 135 m

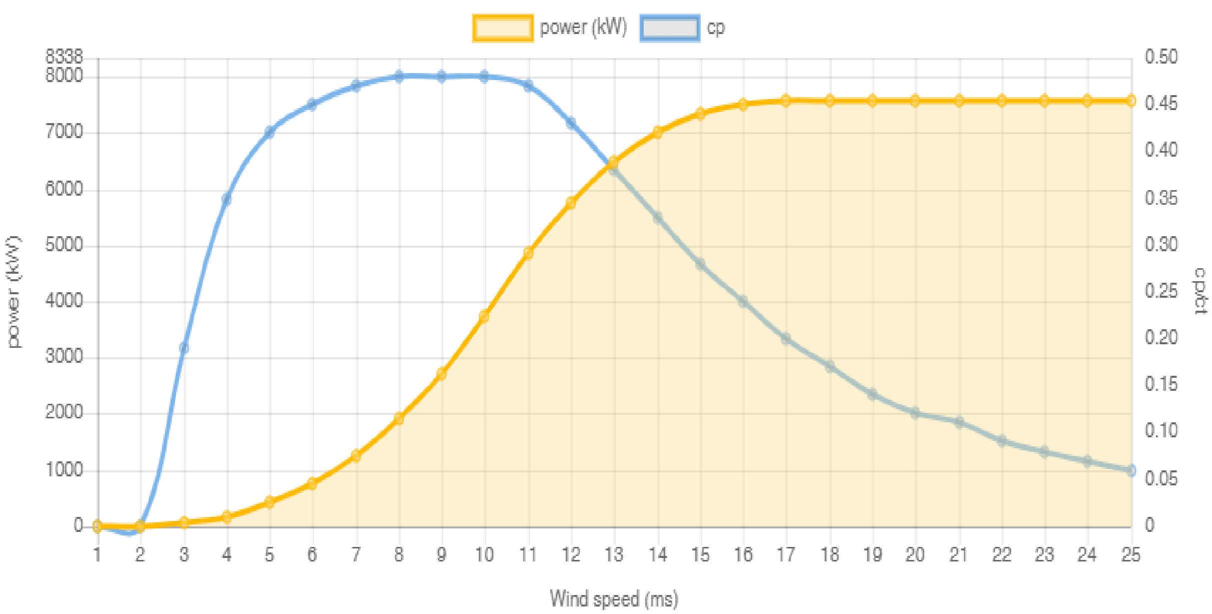


Figure 10 . Enercon- E7.58

## 5.2 Power Specifications of each Turbine

The exploitation of the proportion of wind power was carried out at predetermined points in the Greek marine area, which meet certain strict criteria and for which the development of wind parks has been approved by the Energy Regulatory Authority. The selection of the locations for the offshore wind park installation is based on the wind potential of each area and will be determined from the annual mean wind power density**.** They were used 4 different models of wind turbines with a variety of Power form 7 MW- 9.5 MW accompanied with their Power curve, from which below data were extracted, more specifically in below Table we can see the Power production in combination with the wind speed as given from the manufacturer.

| | **Vestas V164 - 7.0** | **Vestas V164-9.5** | **Vestas V164- 8,00** | **Enercon E-126 7.58** |
|---|---|---|---|---|
| **V(m/s) (wind speed)** | P[KW] | P[KW] | P[KW] | P[KW] |
| **1** | 0 | 0 | 0 | 0 |
| **2** | 0 | 0 | 0 | 0 |
| **3** | 0 | 0 | 0 | 72 |
| **4** | 100 | 109 | 129 | 180 |
| **5** | 755 | 825 | 695 | 420 |
| **6** | 2150 | 1220 | 1320 | 629 |
| **7** | 3190 | 2210 | 1830 | 1205 |
| **8** | 4395 | 2915 | 2890 | 1810 |
| **9** | 5480 | 3850 | 4120 | 2675 |
| **10** | 6430 | 4790 | 5590 | 3665 |
| **11** | 6880 | 5922 | 7080 | 4798 |
| **12** | 7000 | 6891 | 7860 | 5785 |
| **13** | 7000 | 8151 | 8000 | 6405 |
| **14** | 7000 | 9500 | 8000 | 7120 |
| **15** | 7000 | 9500 | 8000 | 7215 |
| **16** | 7000 | 9500 | 8000 | 7495 |
| **17** | 7000 | 9500 | 8000 | 7580 |
| **18** | 7000 | 9500 | 8000 | 7580 |
| **19** | 7000 | 9500 | 8000 | 7580 |
| **20** | 7000 | 9500 | 8000 | 7580 |
| **21** | 7000 | 9500 | 8000 | 7580 |
| **22** | 7000 | 9500 | 8000 | 7580 |
| **23** | 7000 | 9500 | 8000 | 7580 |
| **24** | 7000 | 9500 | 8000 | 7580 |
| **25** | 7000 | 9500 | 8000 | 7580 |

**Table 1**. Power Curve Data for each Turbine

## 5.3 Investigation of wind power density in several areas, based on a 20 years data aggregation.

The data provided include wind speed values (m/s) based on numerical models of spatial analysis for 0,2 deg in a height of 100 meters, measured with a periodicity of an hour for the period of time mentioned above. Initially, was calculated the wind power density for every hour in each area point, then for every year of each area point was calculated the mean value of it. Finally for every area point was calculated one mean value of wind density for the whole 20 years. The purpose of this procedure aimed to extract the 50 points of the areas which approach the higher mean wind density in these 20 years were taken into consideration. The power density is determined using below formula.

$$P = \frac{1}{2}\rho V^3$$

$\rho V^3$ (19)

P: wind power density

Due to the massive volume of available data, the calculations of mean wind density & mean wind speed were achieved using a proprietary multi-paradigm programming language – Matlab 2019a. Evaluating the power density results, is then matched each set of coordinates with the proper area. Taking into consideration the limitations mentioned in the section 3.5 and 4.2 and the highest density values, then the suitable sites are finally selected in chapter

## 5. 4 Determination of Areas of 5 Offshore Wind Parks

After evaluation accomplished in chapter 5.3 the final areas, wind density and sea depth are indicated in below Table:

1. North Mykonos
2. North Corfu-Othonoi
3. North Kassos
4. Agios Efstratios
5. Kimi

| AREA | ANNUAL MEAN WIND POWER DENSITY | MEAN WIND SPEED (m/s) | DEPTH (m) |
|---|---|---|---|
| North Mykonos | 531.66 | 8.92 | 211 |
| North Corfu-Othonoi | 382.16 | 5.57 | 202 |
| North Kassos | 505.54 | 8.96 | 488 |
| Agios Efstratios | 603.69 | 7.93 | 153 |
| Kimi | 531.66 | 6.45 | 51 |

**Table 2.** Annual Mean Wind Power Density

Below areas were selected as the most appropriate as they are in line with the regulations & restrictions that have been already mentioned

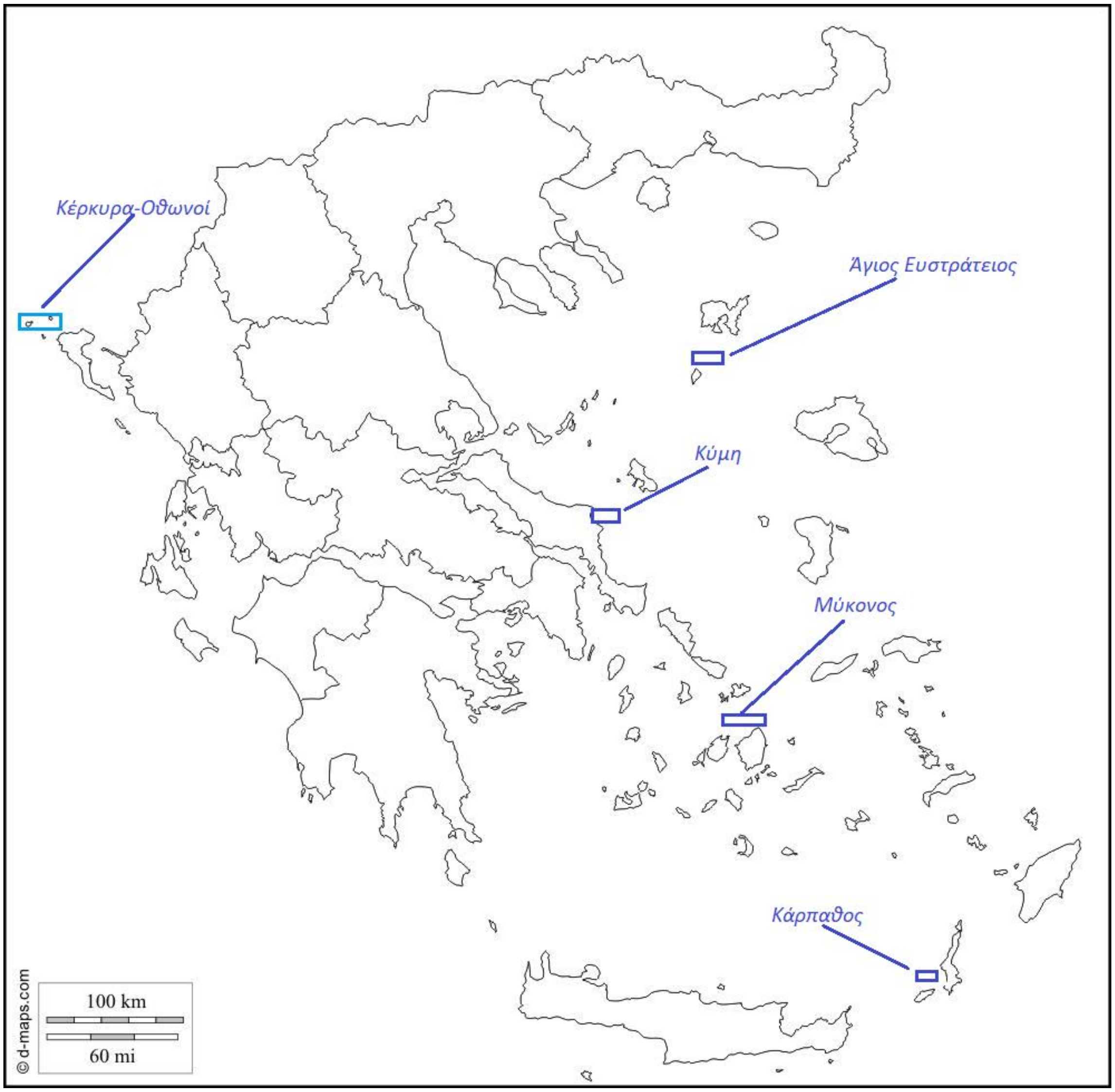


**Figure 11.** Areas of Potential Wind Parks

## 5.5 Determination of operation for Turbines in each area

Supposing that each turbine operates in each area, the Turbine Power is calculated in combination with the power curves given from the manufacturer and the wind speed of each area from the 20 years' available data.

Taking into consideration the restriction of cut in & cut out speed, the total running hours of each turbine is being approached in order to calculate the generated power of each turbine in every area.

*Weibull Method:*

The accuracy in prediction of wind energy can be achieved by modelling the wind speed and power simultaneously. The wind speed at a site varies randomly and its variation in a certain region over a period of time can be represented by different probability distribution functions. A commonly used and accepted distribution is the two-parameter Weibull distribution

An important factor that should be calculated is the shape parameter:

$$\boldsymbol{k} = \left(\frac{\mathbf{0.9874}}{\frac{\sigma}{U}}\right)^{\mathbf{1.0983}} \tag{20}$$

**σ**,is the standard deviation of wind speed for the whole 20 years

**U**, is the mean value of wind speed for the whole 20 years

K, shape factor,

$$a = \frac{P_r * V_c^k}{V_r^k - V_c^k} \tag{21}$$

$$b = \frac{P_r}{V_r^k - V_c^k} \tag{22}$$

$$P = a + b * V^k \tag{23}$$

V: wind speed from data set measurements for the whole 20 years

When the value of k exceeds 2, it means that the quality and wind potential existence are high.

The mean annual value of Power of every turbine, in case each one of them operates in every of the 5 areas can be calculated based on the below formula

$$\text{Pmean}_{\text{annual}} = \frac{\sum_{i=1}^{20} \textbf{Pmean}_{\textbf{P}_{\textbf{per}_{\textbf{year(i)}}}}}{\textbf{20}} \quad (24)$$

| **AREA** | **TURBINE** | **Pmean_annual (kw) For 1 turbine &20 years** | **Energy (MWh) For 1 turbine &20 years** |
|---|---|---|---|
| North Mykonos | **Vestas V164 - 7.0** | 4784.7 | 4.78 |
| North Corfu-Othonoi | | 3517.8 | 3.51 |
| North Kassos | | 4145.6 | 4.14 |
| Agios Efstratios | | 5116.6 | 5.11 |
| Kimi | | 3597.9 | 3.59 |
| | **Vestas V164-9.5** | | |
| North Mykonos | | 4915.4 | 4.91 |
| North Corfu-Othonoi | | 3381.2 | 3.38 |
| North Kassos | | 4289.9 | 4.28 |
| Agios Efstratios | | 5286.1 | 5.28 |
| Kimi | | 3620 | 3.62 |
| | **Vestas V164- 8,00** | | |
| North Mykonos | | 5367.5 | 5.36 |
| North Corfu-Othonoi | | 4039.8 | 4.03 |
| North Kassos | | 4730.2 | 4.73 |
| Agios Efstratios | | 5849.1 | 5.84 |
| Kimi | | 4112.4 | 4.11 |
| | **Enercon E-126 7.58** | | |
| North Mykonos | | 2667.1 | 2.66 |
| North Corfu-Othonoi | | 2061.1 | 2.061 |
| North Kassos | | 2275.8 | 2.27 |
| Agios Efstratios | | 3072.6 | 3.07 |
| Kimi | | 2075.1 | 2.07 |

**Table 3**. Results of Wind Power Production In Each Area For Every Turbine

As it is indicated in the above Table the areas with the higher Power production are:

1. North Ag Efstratios in combination with the Vestas V164- 8.00 – P=**5849.1 kW**
2. North Mykonos in combination with the Vestas V164 - 8.00 – P=**5367.5 kW**
3. North Ag Efstratios in combination with Vestas V164-9.5 -- P= **5286.1 kW**
4. North Ag Efstratios in combination with Vestas V164 – 7.0 -- P= **5116.6 kW**
5. North Mykonos in combination with Vestas V164-9.5 -- P= **4915.4 kW**

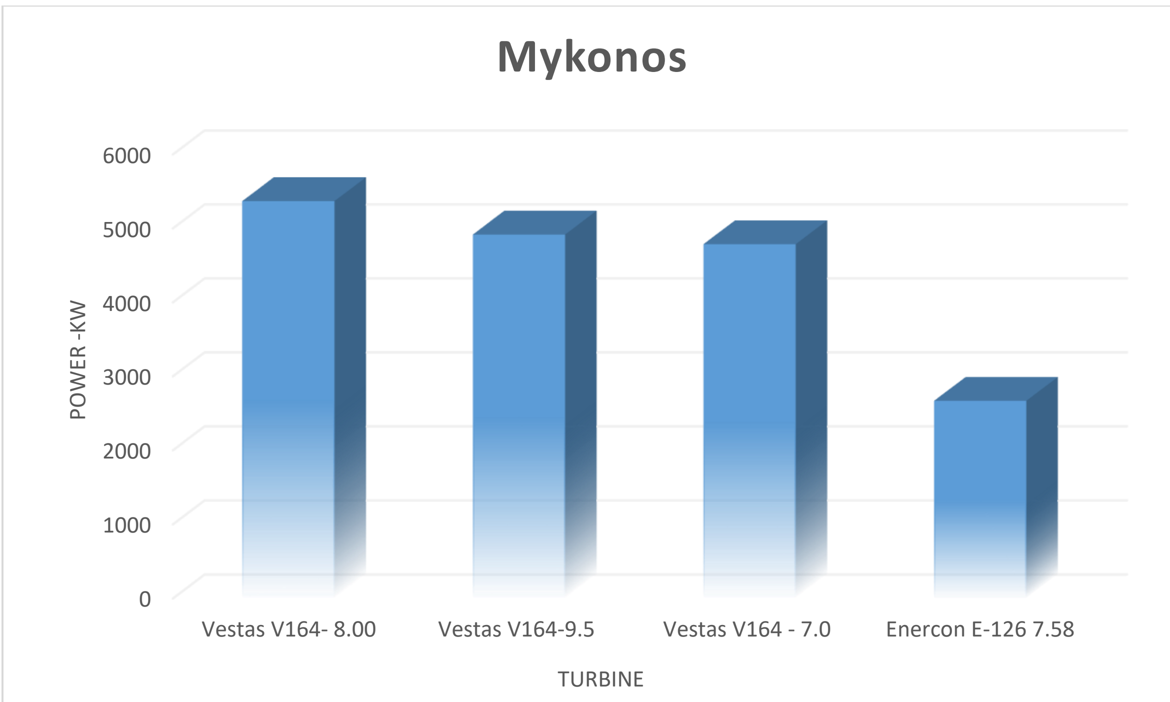


Figure 12. Power Production of 4 Turbines in Mykonos

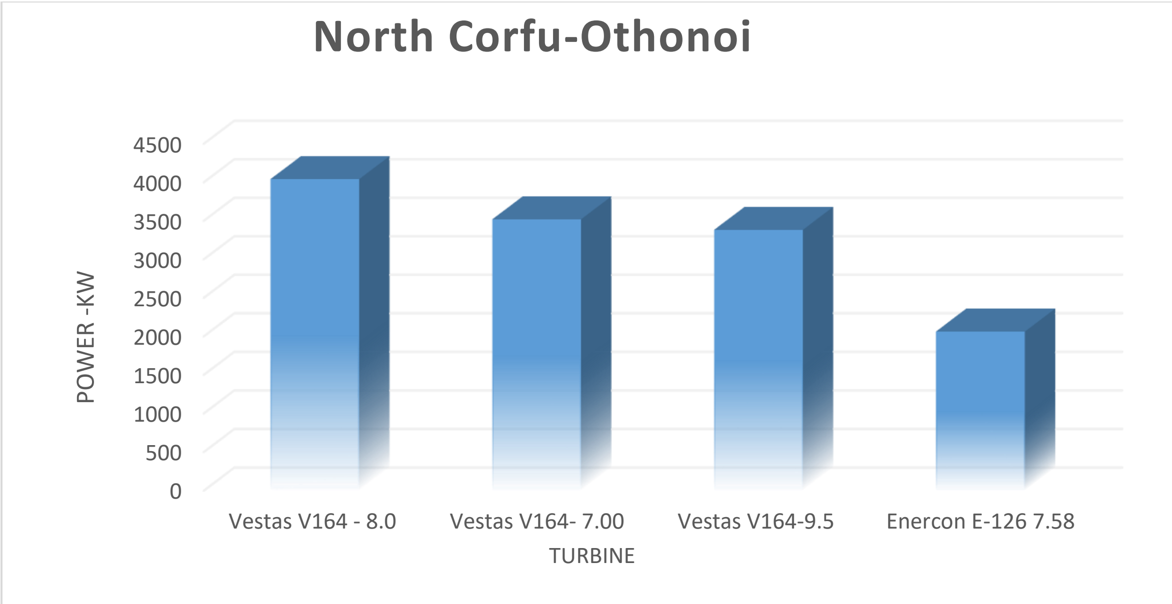


Figure 13. Power Production of 4 Turbines in North Corfu-Othonoi

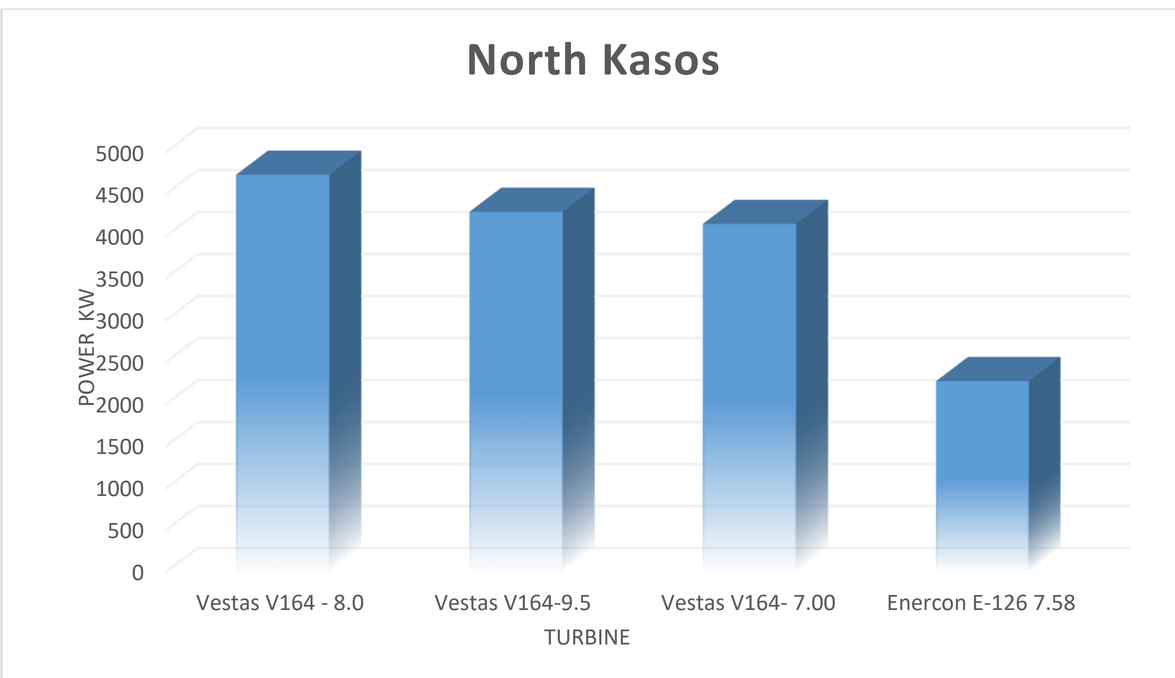


Figure 14. Power Production of 4 Turbines in north Kassos

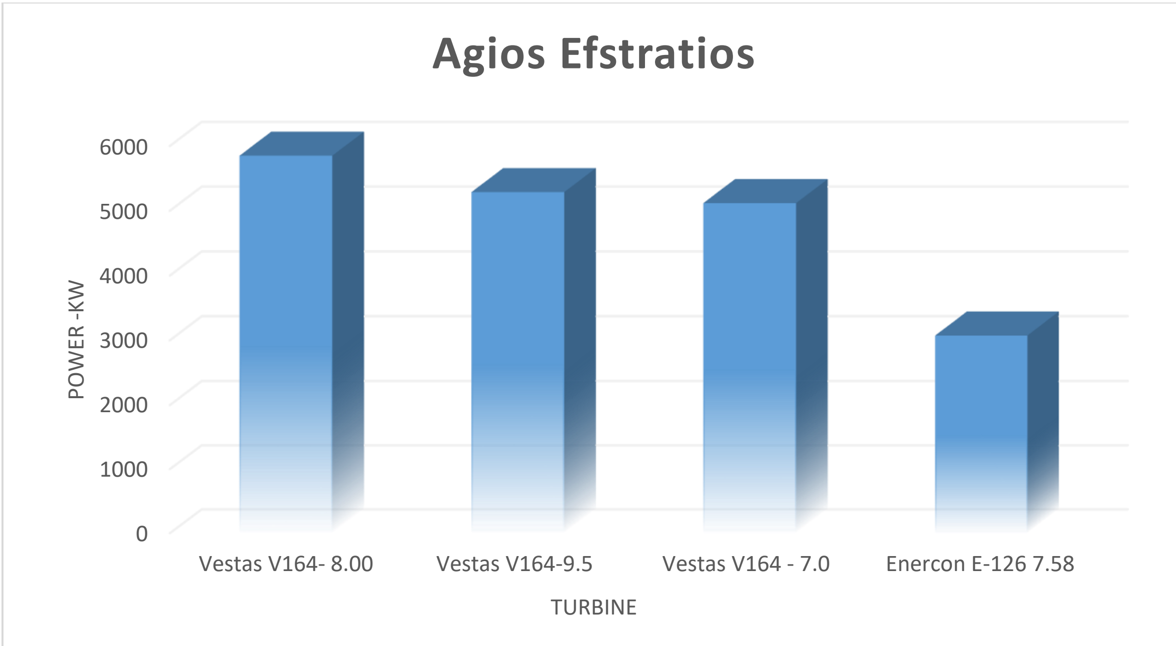


Figure 15. Power Production of 4 Turbines in Agios Efstratios

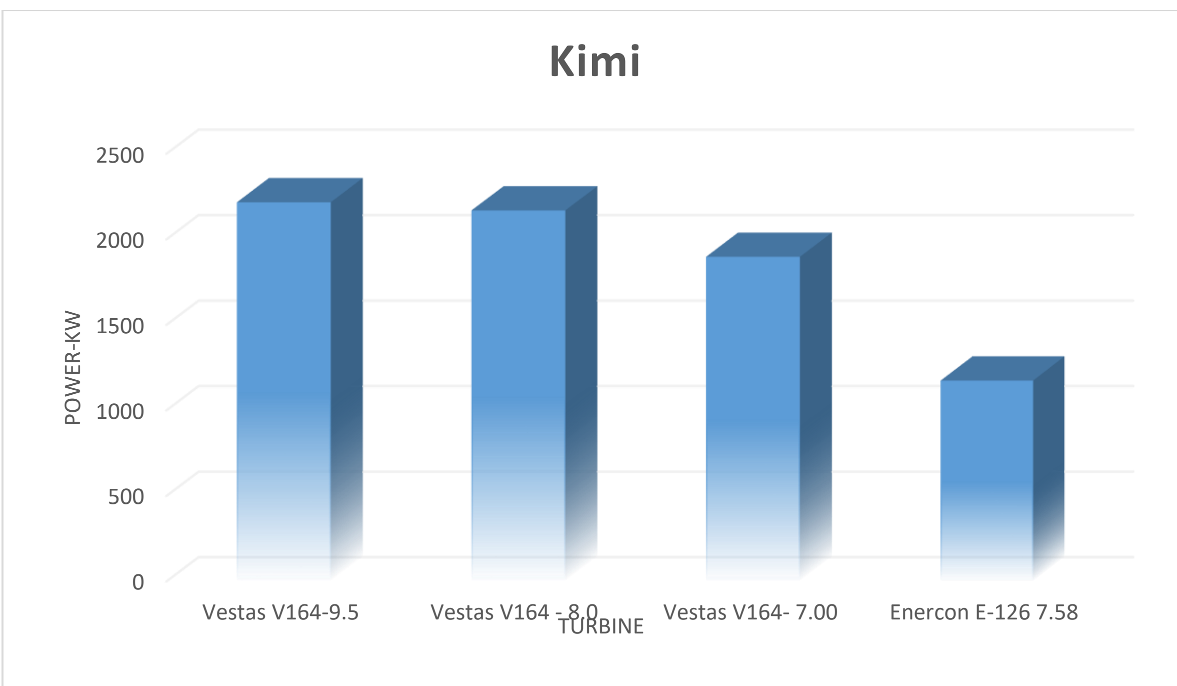


Figure 16. Power Production of 4 Turbines in Kimi

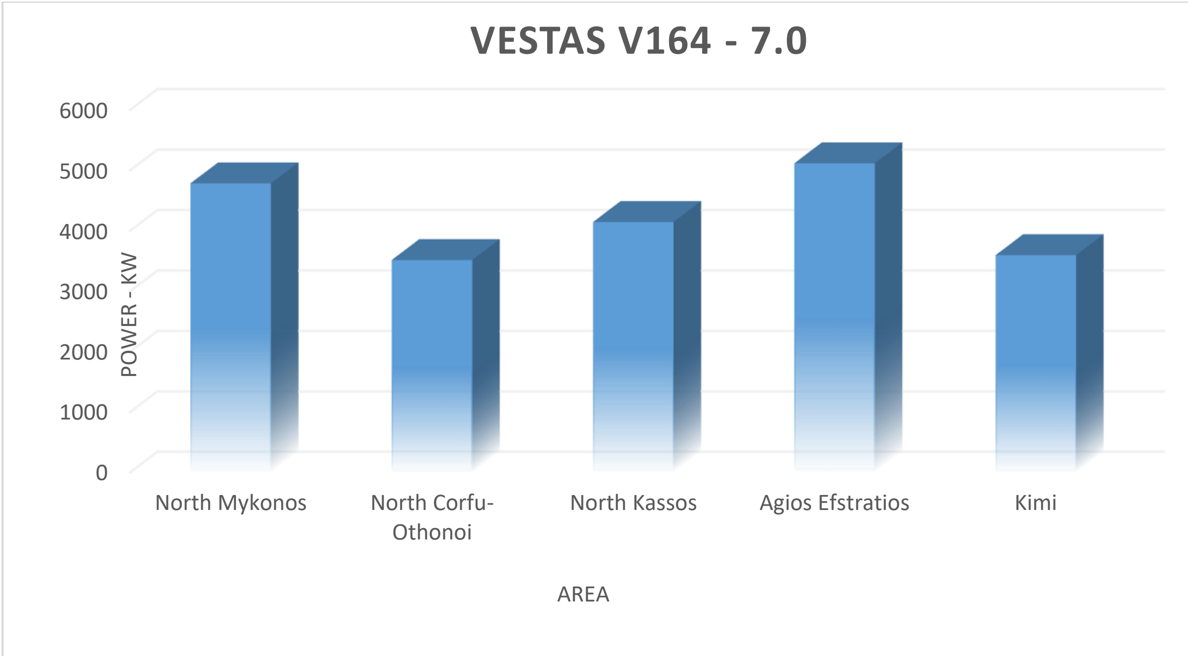


Figure 17. Power Production of Vestas-V164-7 in each area

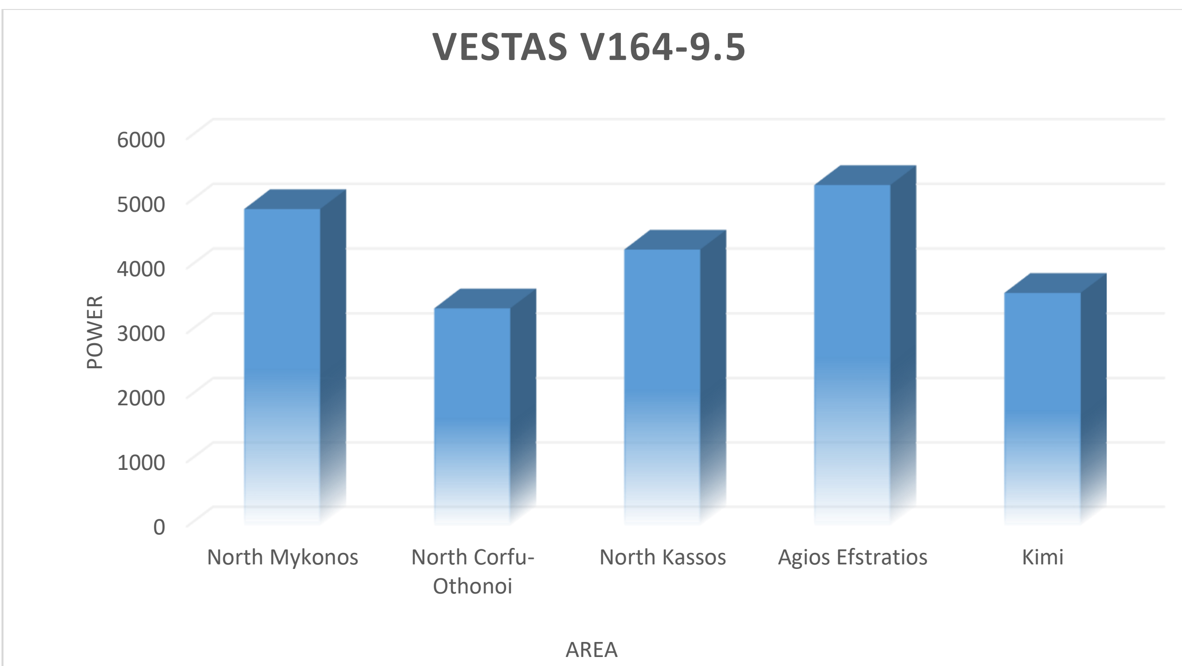


Figure 18. Power Production of Vestas V164-9 in each area

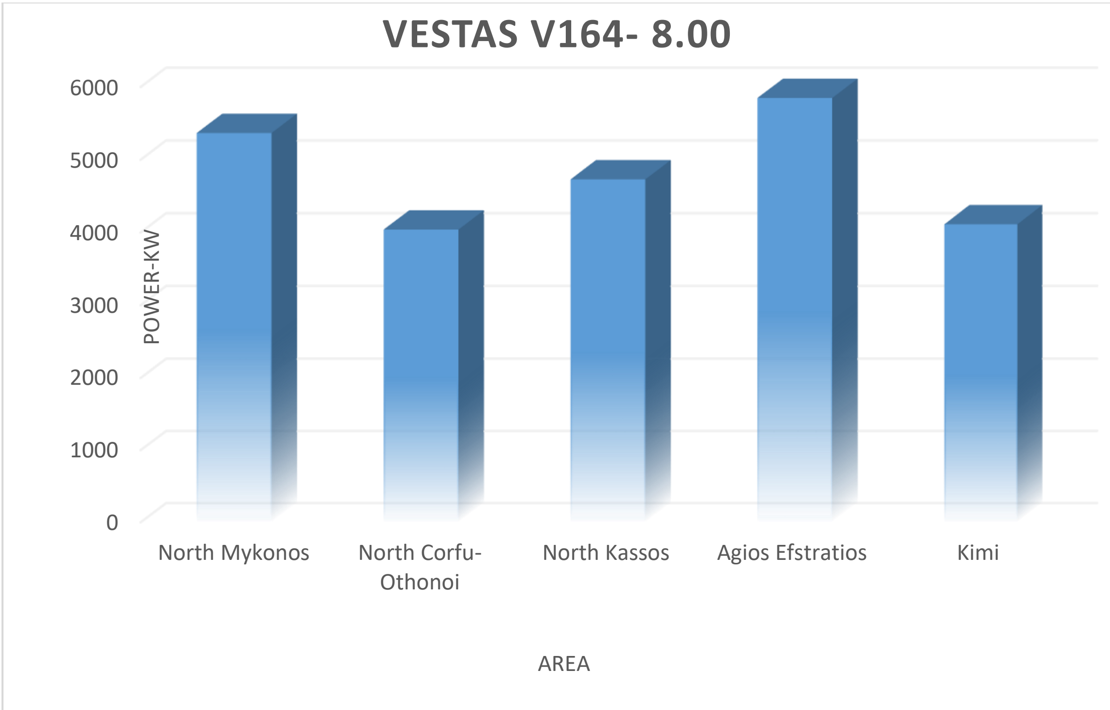


Figure 19. Power Production of Vestas V164-8 in each area

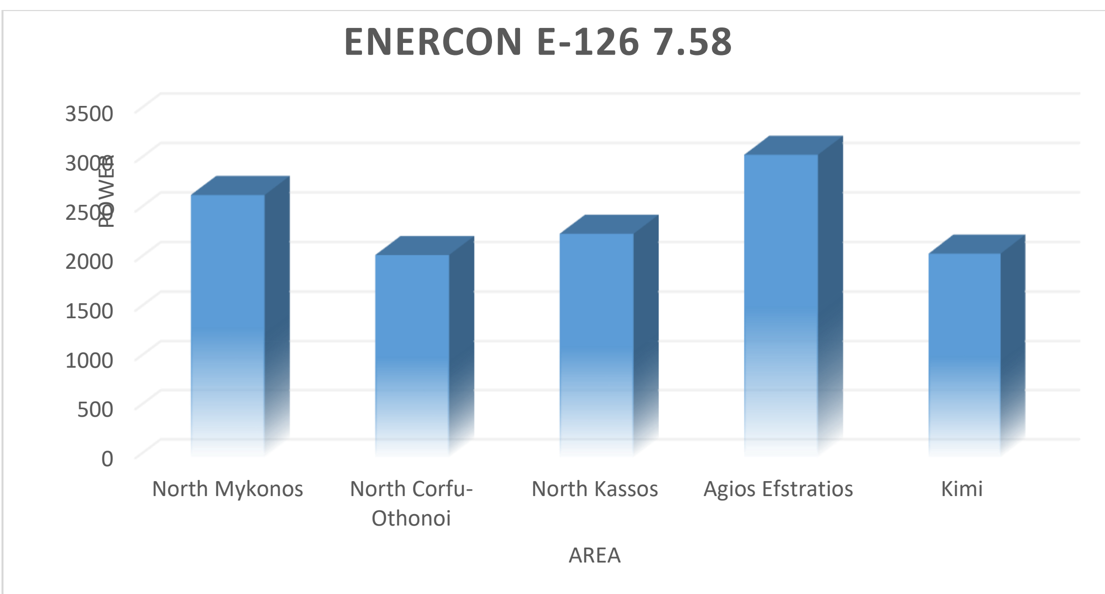


Figure 20. Power Production of Enercon –126 - 7.58 in each area

## 5.6 Mean Annual Variability (MAV) & Intern Annual Variability (IAV)

A significant uncertainty in the estimate of energy from a wind plant is the interannual and interseasonal variation in energy output. These estimates are typically based on wind data that have been collected on-site for one or more years. The mean annual **MAV** variability refers to the **effect of seasonality** on power supply, within a year. This indicator is particularly useful because the variability of wind speed from season to season is quite large

$$\mathbf{MAV} = \left(\frac{1}{J}\right) \sum_{j=1}^{J} \frac{s_u(j)}{m_u(j)} \qquad (25)$$

Where:

$S_u$: the standard deviation of wind speed per year,

$m_u$: the mean value of wind speed per year

J: the total years (in our case J = 20)

The IAV variability over time indicates a measure of the **variability of wind speed** in the region, **between years**. This indicator is particularly useful because the time series of speed values used contains 20 years of data.

$$\mathbf{IAV} = \frac{s_{m_u(j)}}{\widetilde{m}_u} \qquad (26)$$

Where:

$s_{m_u}$: the standard deviation of the annual average values of wind speed .

$\widetilde{m}_u$: the total mean value of the wind speed, for the 15 years of the time series of the data.

| Area | MAV | MAV (%) | IAV | IAV (%) |
|---|---|---|---|---|
| **North Mykonos** | 0.4634 | 46 % | 0.046 | 4.6% |
| **North Corfu-Othonoi** | 0.617 | 62% | 0.056 | 5.6% |
| **North Kassos** | 0.4337 | 43% | 0.038 | 3.9% |
| **Agios Efstratios** | 0.5680 | 57% | 0.047 | 4.7% |
| **Kimi** | 0.5408 | 54% | 0.053 | 5.3% |

**Table 4**. MAV & IAV Values

From Table 4, it is visible that the volatility of the 2 rating indicators is low, so it means that the variation between the seasons of the year (MAV index), and from year to year (IAV index) is low.

This is exactly what is required, because a possible area is generally evaluated for its entirety. In order to proceed with the installation of an Offshore Wind Far, it is required that the wind speed values are high and stable, with the least possible fluctuations throughout the year, but also over time throughout the life of the project.

As shown in Table 2, the areas with the least effect of seasonality (MAV (%)) & interannual (IAV), which are considered as most suitable for the installation of a offshore park, are North Mykonos and North Kassos, while the area with the greatest effect of seasonality on the power supply is Othonoi-Corfu, so it is considered the most inappropriate choice of a wind park

## 5.7 Percentage of hours working for each turbine in each area

Based on the cut in & cut out speed of each turbine, it is feasible to extract the operational hours, as long as the wind speed of each area it is known.

| **Area** | **Turbine** | **Percentage of Operation For 20 Years (%)** |
|---|---|---|
| | | |
| **North Mykonos** | Turbine 1-Vestas V164-7MW | 85.9 % |
| | Turbine 1-Vestas V164-9.5MW | 91.7 % |
| | Turbine 1-Vestas V164-8 MW | 85.9 % |
| | Turbine 4-ENRC | 90.6 % |
| **North Corfu-Othonoi** | Turbine 1-Vestas V164-7MW | 61.2 % |
| | Turbine 1-Vestas V164-9.5MW | 73.8 % |
| | Turbine 1-Vestas V164-8 MW | 61.2 % |
| | Turbine 4-ENRC | 73.4 % |
| **North Kassos** | Turbine 1-Vestas V164-7MW | 87.9 % |
| | Turbine 1-Vestas V164-9.5MW | 93 % |

| | | |
|---|---|---|
| | Turbine 1-Vestas V164-8 MW | 87.9 % |
| | Turbine 4-ENRC | 91.2 % |
| **Agios Efstratios** | Turbine 1-Vestas V164-7MW | 77.9 % |
| | Turbine 1-Vestas V164-9.5MW | 86.1 % |
| | Turbine 1-Vestas V164-8 MW | 77.9 % |
| | Turbine 4-ENRC | 85.8 % |
| **Kimi** | Turbine 1-Vestas V164-7MW | 72.9 % |
| | Turbine 1-Vestas V164-9.5MW | 83.6 % |
| | Turbine 1-Vestas V164-8 MW | 72.9 % |
| | Turbine 4-ENRC | 82.6 % |

**Table 5.** Mean Operational hours' percentage of each turbine

**As it is shown in the above table, the most effective turbine with the combination of the areas are:**

1. North Kassos in combination with the Turbine Turbine 1-Vestas V164-9.5MW in a percentage of 93 %

Above is being justified as Kassos retains the higher annual mean wind speed & also Vestas 9.5 operates in a greater range of speeds in contrast with the Vestas 7 & Vestas 8

2. North Mykonos with Turbine 1-Vestas V164-9.5MW in a percentage of 91.7 %

After Kassos, Mykonos has the second higher annual mean wind speed and in combination with Vestas 9.5 which operates in a greater range of speeds it justified this high percentage of the operation for the whole 20 years

For the below 3 combinations, similar factors has contributed to this high percentages

3. North Kassos with Turbine 4-ENRC 91.2%

4. North Mykonos Turbine 4-ENRC 90.6 %

5. North Kassos with Turbine 1-Vestas V164-7MW 87.9 %

# 6 Selected Ways of Foundation

## 6.1 Foundation of Wind Turbines OWPs in 5 areas of Greece

In order to assure the functionality & sustainability of each OWP's positioning, the relevant restrictions and bathymetry were taken into consideration in order to determine the way of foundation. So In combination and investigating these methods in section 3.5, 4.2 and 5.4 for this project, the most appropriate way of foundation is shown below

**Kimi**

- Monopile = 50 m. which has a depth of 51 m where this kind of foundation is the most appropriate

**Rest Areas**

- Semi Subm. >100 m depth

Or

- Spar Boy >120 m depth
-

# 7. Economic Elements and Annual Power Production

## 7.1 Economical Elements

In order to compare the wind turbines with each other and determine which one is the most suitable for installation in the respective area, there is a necessity for their homogenization. These are wind turbines of different companies, different power with different impeller height (hub height) and different surface area of the impeller (swept area). So the only way to homogenize them was to convert into financial data.

The most appropriate indicator for this conversion was the Levelized Cost of Energy (LCOE). This indicator represents the sum of all the expenses during the life of a wind farm, which are related to the current economic situation (adjustment to inflation), and are finally formed on the basis of annual energy production. The LCOE index is specific to the measurements of the cost of electricity generated by a wind turbine and it is defined as follows:

$$\mathrm{LCOE} = \frac{\text{Annualised CAPEX+Annualised OPEX}}{\text{Average Annual Energy Production}} \qquad (27)$$

**Capital expenditures (Capex)** are funds used by a company to acquire assets such as property, plants, technology, or equipment. It is often used to undertake new projects or investments by a company.

Making capital expenditures on fixed assets can include repairing a machinery or purchasing an equipment. This type of financial outlay is made by companies to increase the scope of their operations or add some economic benefit to the operation.

Especially for the installation of a wind farm the main Capex expenditures are purchase and installation of wind turbines, construction, cabling and project supervision costs etc).

**OPEX (Operational Expenditures)** represents the cost of the operation and maintenance of the project (transport, repairs, spare parts), salaries, insurance during the operation of the project), throughout its life and maintenance.

Relevant calculations were made based for a scenario where 100 turbines were installed in each area.

Basic parameter that was used, is the power of the turbine, so consequently was calculated the annual gross power output of the entire wind farm (in MWh).

## 7.2 Annual Power Production

### 7.2.3 Weibull Distribution

The wind variation for a typical site is usually described using the so-called Weibull distribution

In order to determine the available wind potential of an area, it is not sufficient to be aware of the mean annual wind value, but it is also required the probability distribution of wind speed. The probability distribution function of wind speed is one of the significant wind characteristics for the estimation of the performance of wind energy conversion systems and wind energy potential, as well as the environmental and structural design and analysis. It is essential for wind industry to be able to characterize the difference of wind speeds. Such information is required to optimize the design of wind turbines, to reduce energy generating costs. And in this case, the Weibull probability distribution function has been estimated for each is based on average wind speed for 20 years. This assessment is achieved by analyzing wind data using Weibull probability function to find out the characteristics of wind energy conversion

Effect shape factor on the probability distribution curve as a following:

$k \leq 1$ the probability distribution function curve shape exponential.

$1<k<2$ the probability distribution is considered Weibull -shape distribution or Gaussian.

The shape factor k is calculated base in the below formula

$$\boldsymbol{k} = \left(\frac{0.9874}{\frac{\sigma}{U}}\right)^{1.0983} \tag{28}$$

| Areas | Shape factor K |
|---|---|
| North Mykonos | 2.28 |
| North Corfu-Othonoi | 1.66 |
| North Kassos | 2.05 |
| Agios Efstratios | 1.82 |
| Kimi | 1.92 |

**Table 6.** Weibull shape factor k

Consequently the function gamma is calculated for the value ( 1+1/k), in order to be used in probability density distribution of wind speed. Given the function Gamma(x) and the annual mean value of the velocity (already calculated,( Table 2 ), the Weibull Scale factor is obtained, with the contribution of an exponential relation.

$$\text{Weibull Scale} = \frac{\mathbf{U_{yearly\ average}}}{\mathbf{e}^{\ln\Gamma\left(1+\frac{1}{k}\right)}} \tag{29}$$

The Weibull cumulative distribution function (probability of each value of wind was then used, which is defined as follows

$$\mathbf{F(x;\alpha,\beta) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}}} \tag{30}$$

**α:** k (Shape Factor)

β: Γ (Weibull Scale)

x: wind speed (1 - 25m/s)

Consequently are calculated the number of hours each turbine operates in each speed.

Also the power production was calculated based on the power curve which is described from the below formula

$$\mathbf{Power\ Curve} = \frac{\mathbf{U^3}}{\mathbf{12}} * \mathbf{P_{rated}} \tag{31}$$

**U: wind speed** (1 - 25m/s)

$P_{rated}$: P given for each turbine as per tech data of manufacturer

It is worth mentioning that these percentages refer to the power produced by the turbine based on the wind and do not yet include the losses until the production of net power in the form of electricity. Next is the power output of the turbine in MWh, multiplying the operating hours by the power curve of the turbine (in MW), as follows:

$$\textbf{Power Production (MWh)} = \sum_1^{25}.(\textbf{ number of hours per year} * \textbf{Power Curve}) \quad (32)$$

$$\textbf{Gross Power Production per farm} = \textbf{20 x Power Production (MWh)} \quad (33)$$

In below table is indicated the above described procedure in case that V164-7,0MW operates in Agios Efstartios, same procedure was implemented for all combinations of 4 turbines with the 5 areas

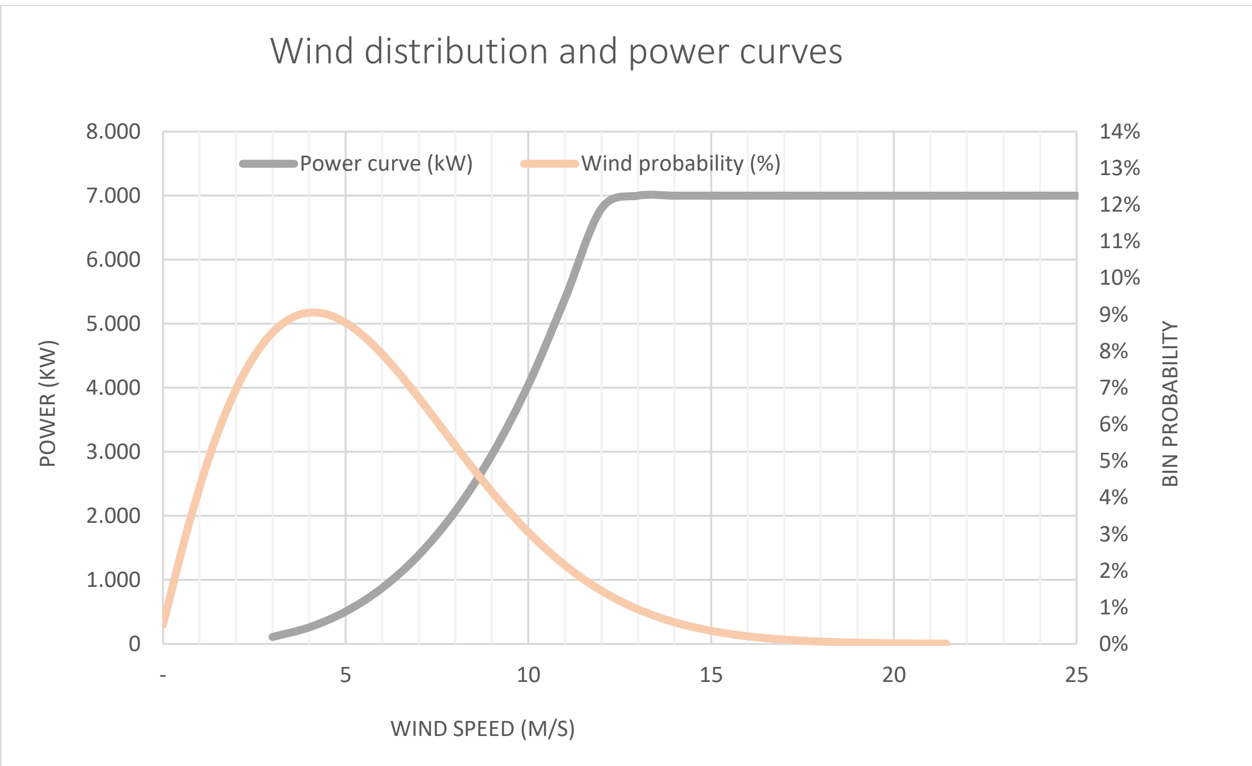


Figure 21. Wind Distribution & Power Curve for Vestas 164-7.00 MW in Agios Efstartios

| V164-7,0MW Vestas | Rated Power (MW) | Shape Factor k | Yearly average wind speed (m/s) | Weibull Scale (m/s) |
|---|---|---|---|---|
| Agios Efstratios | 7 | 1.82 | 7.93 | 8.9 |
| Wind speed (m/s) | Probability (%) | Number of hours per year | Power Curve (Kw) | Power Production (MWh) |
| 0 | 0,5% | 46 | 0 | 0 |
| 1 | 3,3% | 289 | 0 | 0 |
| 2 | 5,6% | 489 | 0 | 0 |
| 3 | 7,2% | 635 | 109 | 69 |
| 4 | 8,4% | 732 | 259 | 190 |
| 5 | 8,9% | 783 | 506 | 396 |
| 6 | 9,0% | 793 | 875 | 694 |
| 7 | 8,8% | 769 | 1.389 | 1.068 |
| 8 | 8,2% | 719 | 2.074 | 1.491 |
| 9 | 7,4% | 651 | 2.953 | 1.923 |
| 10 | 6,5% | 573 | 4.051 | 2.321 |
| 11 | 5,6% | 491 | 5.392 | 2.647 |
| 12 | 4,7% | 410 | 6.800 | 2.790 |
| 13 | 3,8% | 335 | 7.000 | 2.345 |
| 14 | 3,1% | 267 | 7.000 | 1.872 |
| 15 | 2,4% | 209 | 7.000 | 1.462 |
| 16 | 1,8% | 160 | 7.000 | 1.119 |
| 17 | 1,4% | 120 | 7.000 | 840 |
| 18 | 1,0% | 88 | 7.000 | 618 |
| 19 | 0,7% | 64 | 7.000 | 446 |
| 20 | 0,5% | 45 | 7.000 | 316 |
| 21 | 0,4% | 31 | 7.000 | 220 |
| 22 | 0,2% | 21 | 7.000 | 150 |
| 23 | 0,2% | 14 | 7.000 | 101 |
| 24 | 0,1% | 9 | 7.000 | 66 |
| 25 | 0,1% | 6 | 7.000 | 43 |
| **Summary** | | | | 23187 |

**Table 7**. Power Production of V164-7,0MW in Ag. Efstratios

In order to calculate the Gross Power Production of each model in every area, the above summary is multiplied with 20 (total wind turbines in each farm). The gross Production describes the total Power for each wind park generated from 20 turbines

| **Vestas V164- 7.00** | **Gross Power Production** [MWh] per farm for 20 years [MWh] |
|---|---|
| Areas | |
| North Mykonos | 570.427 |
| North Corfu-Othonoi | 241.053 |
| North Kassos | 564.919 |
| Agios Efstratios | 463.716 |
| Kimi | 315.483 |

Table 8. Gross Power Production of Vestas V164- 7.00

| **Vestas V164- 9.5** | **Gross Power Production** - per farm for 20 years [MWh] |
|---|---|
| Areas | |
| North Mykonos | 769.364 |
| North Corfu-Othonoi | 325.552 |
| North Kassos | 762.274 |
| Agios Efstratios | 625.812 |
| Kimi | 425.852 |

Table 9. Gross Power Production of Vestas V164- 9.5

| **Vestas V164- 8.00** | **Gross Power Production** - per farm for 20 years [MWh] |
|---|---|
| Areas | |
| North Mykonos | 652.236 |
| North Corfu-Othonoi | 275.596 |
| North Kassos | 645.915 |
| Agios Efstratios | 530.195 |
| Kimi | 360.706 |

Table 10. Gross Power

| **Enercon E-126 7.58** | **Gross Power Production** - per farm for 20 years [MWh] |
|---|---|
| Areas | |
| North Mykonos | 613.632 |
| North Corfu-Othonoi | 259.677 |
| North Kassos | 607.993 |
| Agios Efstratios | 499.156 |
| Kimi | 339.669 |

Table 11. Gross Power Production of Enercon E-126 7.58

## 7.3 Losses

It is necessary to include the energy losses during the conversion of the generated power based on wind, into net power in the form of electricity. One of the most important forms of loss is the turbulence. Turbulence and power loses are increased due to wind turbine wake interactions in large offshore wind farms. An average percentage of Power losses due to wakes are approximately 10 %. Turbulence often occurs from a front turbine affecting the turbines that follow behind it, always in the direction of the wind. The wind behind a turbine follows a turbulent flow, which automatically leads to a reduction in the energy produced in its passage. For this reason, the arrangement of the turbines is very important when locating an offshore wind farm, as well as the minimum distance between them should be kept.

There are also internal power losses that can be defined as these related to the components within the wind farm. This includes the transmission losses within the cables, the transformer power losses, and other power losses such as the ones at the point of common coupling (PCC) within the switching station

Another important factor was the expected average Availability of the wind farm turbines, for the entire life of the project. This factor essentially represents a percentage, which must be applied to the gross energy produced (Annual gross power production per farm), in order to produce the net energy produced, which is related to the time in which the turbines are under operation

Below table shows the loss values applied to each turbine model separately.

| | Turbine 1-Vestas V164-7MW | Turbine 2-V164-9.5 MW | Turbine 3 - V164-8 MW | Turbine 4-ENRC 7.58 MW |
|---|---|---|---|---|
| Wake Loses | 6% | 4.75% | 5.5% | 5.71% |
| Electrical Loses | 5% | 5% | 5% | 5% |
| Availability | 94% | 94% | 94% | 94% |

Table 12. Losses

So taking into consideration the losses, the net power production is calculated below:

$$\textbf{Net Power Production} = \textbf{Annual Gross Power Production} * (\textbf{1} - \textbf{Wake losses} - \textbf{Electrical losses}) * \textbf{Availability}$$
(34)

| **Vestas V164- 7.00** | **Net Power Production** [MWh] per farm for 20 years |
|---|---|
| **Areas** | |
| North Mykonos | 477.219 |
| North Corfu-Othonoi | 201.665 |
| North Kassos | 472.611 |
| Agios Efstratios | 387.944 |
| Kimi | 263.933 |

Table 13. Net Power Production of Vestas V164- 7.00

| **Vestas V164- 9.5** | **Net Power Production** [MWh] per farm for 20 years |
|---|---|
| **Areas** | |
| North Mykonos | 652.690 |
| North Corfu-Othonoi | 276.182 |
| North Kassos | 646.675 |
| Agios Efstratios | 530.907 |
| Kimi | 361.271 |

Table 14. Net Power Production of Vestas V164- 9.50

| **Vestas V164- 8.00** | **Net Power Production** [MWh] per farm for 20 years |
|---|---|
| **Areas** | |
| North Mykonos | 548.726 |
| North Corfu-Othonoi | 231.859 |
| North Kassos | 543.408 |
| Agios Efstratios | 446.053 |
| Kimi | 303.461 |

Table 15. Net Power Production of Vestas V164- 8.00

| Enercon E-126 7.58 | **Net Power Production** [MWh] per farm for 20 years |
|---|---|
| **Areas** | |
| North Mykonos | 505.095 |
| North Corfu-Othonoi | 215.076 |
| North Kassos | 502.865 |
| Agios Efstratios | 412.954 |
| Kimi | 281.180 |

Table 16. Net Power Production of Enercon E-126 7.58

## 7.4 Calculation of weights for individual components of each wind turbine

To calculate CAPEX, it was first necessary to calculate their weights individual components of a wind turbine. This process was achieved with them similarity laws concerning the comparison of two machines of different power between theirs. The comparison was performed using a standard power wind turbine 6 MW, for which all weight values were known as data from the beginning.
Part of the wind turbine, for which the weight was calculated, was the submerged - **Submerged tower weight**. The weight of this section was calculated with the following formula: (Source: PK Haviaropoulos/Revekka Kouli)

$$\frac{m_{submerged}}{m_{s\_6MW}} = \frac{P_{MW}}{6_{MW}} \tag{35}$$

Another section for which calculations were made was its main section pillar (Pylon weight), up to the height of the impeller. This is essentially his part pillar located outside the sea. The weight of this section was calculated with the following formula:

$$\frac{m_{pylon}}{m_{p\_6MW}} = \left(\frac{P_{MW}}{6_{MW}}\right)^{\frac{2.6}{2}} \tag{36}$$

The calculations continued, with the part of the wind turbine consisting of fuselage **(Nacelle) as well as the blades of the wind turbine** (Wind turbine weight), which is essentially that part of the wind turbine in which the conversion of wind energy into electricity takes place. The weight of this section
was calculated with the following formula

$$\frac{m_{\text{wind turbine}}}{m_{t\_6MW}} = \left(\frac{P_{MW}}{6_{MW}}\right)^{\frac{3}{2}} \tag{37}$$

Finally, the weight of all installation and foundation materials was calculated wind turbine (Foundation weight). Essentially, this burden concerns him all support equipment of each wind turbine. The weight of these elements calculated as follows.

$$m_{\text{foundation}} = m_{\text{submerged}} * P_{MW} \tag{38}$$

Table 22. Presents the values of weights for all individual parts of the wind turbine- **Monopile in Kymi** as described in the above formulas. The values for the standard 6MW wind turbine will help in order for the weights of the other turbines to be calculated. The weight are important parameters which will enable us to calculate the cost of each compartment

| Weights-Kymi | 6 MW | 7 MW | 9.5 MW | 8 MW | 7.58 MW |
|---|---|---|---|---|---|
| Submerged tower | 200 | 233 | 316 | 266 | 252 |
| Pylon | 200 | 244 | 363 | 290 | 271 |
| Wind turbine (nacelle & blades) | 380 | 480 | 757 | 585 | 539 |
| Foundation | | 1631 | 3008 | 2133 | 1915 |
| Total | | 2588 | 4444 | 3274 | 2977 |

Table 17. Weight for 1 turbine Monopile

## 7.5 CAPEX

As mentioned above, CAPEX refers to the total cost of investment capital required to create such a project. More specifically, calculations include the cost of purchasing and installing the wind turbines, the cost of cabling and connecting the park to the existing cabling network, the insurance during the construction of the project, the guarantees during the uninstallation-decommissioning of the project, the costs for selection of the most suitable location, as well as the costs for the overall management of the project.

Regarding the cost for the purchase of wind turbines, they result from the respective weights calculated above, accompanied by a cost table of the individual materials and parts of the turbine, which was given as an initial data. The cost table contained standard cost values (€ / kg) in case of installation of an offshore wind farm, which included 100 turbines, as was the initial hypothetical scenario.

| **Typical Cost for units amount** | **€/kg** |
|---|---|
| Submerged tower | 4,5 |
| Pylon | 4,0 |
| Foundation | 4,5 |
| | €/MW |
| Turbine | 1.3 million |

Table 18. Presentation of the costing table of the individual parts of a turbine.

For example, in case of calculating the cost for the main part of a 7MW turbine pillar, the procedure based on Tables 14 and Table 15 is performed as follows

$$\text{Cost of Pylon} = \frac{244*4}{1000} = 0.976 \quad (\text{M€/unit}) \tag{39}$$

The calculation of installation cost was is based on a Monopile wind turbine of 7Mw

| Costs-Kymi | 7 MW | 9.5 MW | 8 MW | 7.58 MW | |
|---|---|---|---|---|---|
| Submerged tower | 1.048.500 | 1.422.000 | 1.197.000 | 1.197.000 | [RK] |
| Pylon | 976.000 | 1.252.000 | 1.060.000 | 1.004.000 | [RK] |
| Wind turbine (nacelle+blades) | 7.100.000 | 9.350.000 | 8.400.000 | 7.854.000 | [31] |
| Foundation Installation | 2.333.000 | 3.665.000 | 2.666.000 | 2.466.000 | [RK] |
| Pylon & Turbine Installation | 2.233.000 | 3.265.000 | 2.266.000 | 2.200.000 | [RK] |
| Array Cabling | 1.916.000 | 2.957.750 | 2.332.700 | 2.124350 | [RK] |
| **CAPEX for 1 Turbine** | 15.606.500 | 21.911.750 | 17.921.700 | 16.782.350 | |
| **CAPEX for 20 Turbine** | 312.130.000 | 438.235.000 | 358.434.000 | 335.647.000 | |

Table 19. Capex for Monopile in Kymi

| **Costs-rest areas-Float - Spar** | 5/6 MW | 7 MW | 9.5 MW | 8 MW | 7.58 MW | |
|---|---|---|---|---|---|---|
| Wind turbine (nacelle+blades) | - | 7.100.000 | 9.350.000 | 8.400.000 | 7.854.000 | [31] |
| Pylon | - | 976.000 | 1.452.000 | 1.160.000 | 1.084.000 | [RK] |

| | | | | | | |
|---|---|---|---|---|---|---|
| Materials/platform | 1.700.000 | 2.193.000 | 2.809.250 | 2.439.500 | 2.316.250 | [30] |
| Anchor | 342.000 | 441.180 | 565.155 | 490.770 | 465.975 | [30] |
| Mooring/ropes | 119.000 | 153.510 | 196.647 | 170.765 | 162.137 | [30] |
| Installation | - | 7.200.000 | 9.750.000 | 8.000.000 | 7.550.000 | [32] |
| Array Cabling | - | 2.816.000 | 3.157.750 | 2.916.000 | 2.890.000 | [RK] |
| **CAPEX for 1 Turbine** | | 18.879.690 | 24.340.802 | 21.577.035 | 22.242.362 | |
| **CAPEX for 20 Turbines** | | 377.593.800 | 486.816.000 | 431.540.700 | 444847240 | |

Table 20. Capex for Float-Spar in Rest Areas

$$\mathbf{CAPEX} = \sum(\text{Foundation} + \text{Submerged tower} + \text{Pylon} + \text{Wind turbine} + \text{Foundation \& submerged tower installation} + \text{Pylon \& turbine installation} + \text{Array cabling}) \quad (40)$$

In addition is calculated the Insurance during construction:

$$\mathbf{Insurance\ during\ construction} = 0.8\% * (\text{Pylon} + \text{Wind turbine}) + 1.65\% * (\text{Submerged tower} + \text{Pylon \& turbine installation} + \text{Array cabling} \quad (41)$$

| **Insurance Kymi** | 7 MW | 9.5 MW | 8 MW | 7.58 MW |
|---|---|---|---|---|
| **Insurance 20 turbines** | 3.007.335 | 4.219.087 | 3.028.201 | 2.823.855 |

Table 21. Insurance during construction in Kymi

| **Insurance Rest areas** | 7 MW | 9.5 MW | 8 MW | 7.58 MW |
|---|---|---|---|---|
| **Insurance 20 turbines** | 4267440 | 5381677.5 | 4818880 | 4532480 |

Table 22. Insurance during construction in Rest Areas

## 7.6 EPC

Finally below is described some additional costs which include the guarantees during the dismantling-decommissioning of the project the costs for the selection of the most suitable location. The cost of connecting the park with the existing cabling networks. As well as the costs for the overall management of the project during its construction.

A typical EPC's functions in the process of commissioning an energy project can be broadly categorized as: engineering, procurement and construction.

**Engineering:** The engineering phase which can be up to a multi-year process for very large projects begins with a site survey and feasibility analysis; it results in a full design of the wind project including the number and arrangement of turbines as well as buildings and roads that will be used for operations and maintenance activities. This design will be used to inform procurement needs and guide construction.

**Procurement:** Procurement entails the purchase of all physical equipment and materials and the hiring of all labor required to complete the wind project. Equipment and materials include construction vehicles and key generation infrastructure such as turbines. The timing of procurement activities impacts total installed project costs because early delivery may result in storage costs and late delivery may cause delays in construction. Transportation and delivery of wind project materials can be particularly complicated due to the large size of turbine components.

**Construction:** In the construction phase the turbines are installed and all supporting infrastructure is built. For wind projects the term "balance of plant" is used to refer to all components of a wind project apart from the turbines (e.g. cables. access roads. foundations). Generally multiple companies will be involved in construction with specific tasks (e.g.. electrical systems. roads. etc.) subcontracted from a general contractor to specialists.

| Decommissioning strategy | Projection parameters | Cost estimate parameters |
|---|---|---|
| Complete removal. partial removal or leave in-situ. reuse recycle disposal approach. piles cut off just above the level of the bedrock seabed. monitoring strategy for components that remain in-situ. HDD bored capped etc | Number. type weight of key components vessel types. distance of project site from port onshore storage. disposal facilities etc. | Day rates. permits. vessels. dredging and barge boat mobilization and demobilization costs. seasonality duration lifting gear labor dive operation costs.etc |

| EPC Costs for Monopile<br>(Engineering. Procurement and Construction cost) | [33][RK]<br>For 7 MW |
|---|---|
| Decommissioning guarantee (M€/unit/7MW) | 0.3 |
| Project management (M€) per farm | 1.8 |
| Site development (M€) per farm | 1.8 |
| Grid connection costs (M€) per farm | 16 |

Table 23. EPC Parameters for Monopile for a 7MW Turbine

| EPC Costs for Spar<br>(Engineering. Procurement and Construction cost) | [RK]<br>For 8 MW |
|---|---|
| Decommissioning guarantee (M€/unit/8 MW) | 0.4 |
| Project management (M€) per farm | 1.9 |
| Site development (M€) per farm | 1.9 |
| Grid connection costs (M€) per farm | 17 |

Table 24. EPC Parameters for Spar for a 8MW Turbine

$$\mathbf{EPC}_{\mathbf{monopile\_spar}} = \Big((\text{CAPEX} + \text{Insurance during construction} + \text{Decommissioning guarantee}) * 20 \text{ turbines} + \sum(\text{Project management} + \text{Site development} + \text{Grid connection costs})\Big) \quad (42)$$

| EPC/ farm | 7 MW | 9.5 MW | 8 MW | 7.58 MW |
|---|---|---|---|---|
| MONOPILE | 340.737.335 | 468.054.088 | 387.062.201 | 364.070.856 |
| SPAR | 407.461.240 | 526.197.718 | 465.159.580 | 421.729.720 |

Table 25. EPC costs for each turbine model

## 7.7 OPEX

This cost includes:

- Annual maintenance per turbine with technicians
- Condition based replacement of smaller components
- Minor and/ or Major repairs of components and cables
- Transportations through small vessels
- Personnel. accommodation and port facilities
- Replacement of larger parts and require for a larger crane vessel

| **OPEX Costs Monopile+Spar** | **M€/year/7MW [RK] [34]** |
|---|---|
| Total salaries | 0.76 |
| Transport vessel cost | 0.2 |
| Spares parts | 1.3 |
| Special vessels | 0.5 |

Table 26**.** OPEX indicative costs

In addition the total annual insurance cost is calculated below:

$$\mathbf{Farm\ insurance\ costs} = \mathbf{0.7\%} * \mathbf{EPC} \quad (43)$$

Based on the above costs the requested OPEX –Total Annual OPEX per Farm is calculated below:

$$\mathbf{OPEX\ \_monopile} = \sum(\text{Total salaries} + \text{Transport vessel cost} + \text{Spares parts} + \text{Special vessels} + \text{Farm insurance costs}) \quad (44)$$

$$\mathbf{OPEX\ \_spar} = \sum(\text{Total salaries} + \text{Transport vessel cost} + \text{Spares parts} + \text{Special vessels} + \text{Farm insurance costs}) \quad (45)$$

The economic element that varies between Opex monopile and Opex spar, is the Farm insurance cost which includes the EPC that is different for the above mentioned ways of foundation [M€ /farm & M€ /year]

| **OPEX Per Park** | **7 MW** | **9.5 MW** | **8MW** | **7.58 MW** |
|---|---|---|---|---|
| Monopile-Kymi | 5.145.161 | 6.736.379 | 5.891.435 | 5.598.496 |
| Spar-Rest Areas | 5.612.229 | 6.867.712 | 6.438.117 | 6.002.108 |

Table 27. Total OPEX costs

## 7.8 Weighted Average Cost of Capital - WACC

WACC is the weighted average cost of finance where the weighting is based on the share of funds provided from different sources. Especially for offshore wind park is the discount rate over the lifetime of the project. as determined by the capital structure (*Debt Share*) and (*Debt Interest Rate*) and financing costs (*Equity cost*) .In order to finance an offshore wind project developers may either choose (i) balance sheet finance or (ii) a combination of equity and non-recourse debt (project finance).

*Equity cost* is one of the most important parameter for LCOE reducing WACC has a significant impact on LCOE. as if it is reduced 1 unit then LCOE can be reduced 6%.

Gaining knowledge and experience in such a major constructions can lead to *systematic risk* reduction reflecting WACC reduction too.

Based on European projects WACC is considered to be 10% - 9%. For this specific project WACC is considered to be vary between the limits of 12%--13%. [Source: RK].

So finally WACC can be calculated based on the below formula:

$$\mathrm{WACC} = (\mathrm{Debt\ share} * \mathrm{Debt\ interest\ rate}) + \mathrm{Equity\ cost} * (1 - \mathrm{Debt\ share}) \qquad (46)$$

The below table contains the standard values in order to calculate WACC are considered to be constant without being influenced from each area and wind turbine model [Source: RK]

| **Discount Rate**<br><br>**MONOPILE & SPAR** | **%**<br>**[RK]** |
|---|---|
| Debt interest rate | 8% |
| Equity cost | 17% |
| Debt share | 50% |
| WACC | 12.5% |

Table 28**.** WACC for Spar & Monopile

## 7.9 LCOE-Levelized Cost of Energy

The purpose of using LCOE is to compare and evaluate the cost of electricity production.

It is sufficient in comparing the cost of a unit of energy (€ per megawatt hour of electricity (€/MWh)

The project is referred to an offshore wind park which contains 20 turbines with a life duration of 20 years (+2 years of installation). In order to estimate LCOE which is the requested value and of the utmost importance for the proper evaluation of the farm. OPEX. CAPEX & WACC were previously calculated.

In addition it was also calculated Annual net power production for each area in combination with each turbine.`

For the first 2 years when the construction of the wind farm is still in progress. it is reported that the installed capacity is 33% and 67% of the total respectively for the 1st and 2nd year.

CAPEX (in M €) is related to the price of "EPC" which it has been already calculated divided by 2 and recorded as CAPEX price for the 1st and 2nd year respectively. In addition. CAPEX includes the decommissioning costs of the park which is obviously recorded only in the 22nd year of the project and is calculated as follows**:**

$$\text{Decommissioning costs} = 0.3\ (\text{M€/unit}) * 20(\text{turbines}) = 6\ (\text{M€}) \qquad (47)$$

OPEX it was also calculated and includes the maintenance costs and insurance of each farm. This cost is worth recording this cost from the 3$^{rd}$ until the 22$^{nd}$ year of each offshore wind farm

It is worth mentioning that the total Cost consist the sum of CAPEX and OPEX:

$$\text{Cost flows} = \text{CAPEX} + \text{Maintenance at sea} + \text{Insurance cost} \qquad (48)$$

Consequently it is calculated the discount ratio of WACC for each year separately

$$\text{Discount ratio} = \frac{1}{(1+\text{WACC})^{\text{year}}} \qquad (49)$$

With the help of the WACC cost reduction index the Net Expenditure Costs - Discounted Costs flows (in M €) were obtained which are adjusted to the economy of each country based on the interest rates borrowing costs and inflation of each. The calculation was performed based on the following formula

$$\text{Discounted Costs flows} = \sum_{y=1}^{y=22}(\text{Cost flows} * \text{Discount ratio}) \qquad (520)$$

In addition based on WACC cost reduction index was calculated the net generated power - Discounted production for the entire life of the project was obtained which was calculated as follows:

$$\text{Discounted production} = \sum_{y=1}^{y=22}(\text{Production} * \text{Discount ratio}) \qquad (51)$$

All the above calculations were performed in order to calculate the final cost LCOE - Levelized Cost of Energy (in € / MWh) which is a criterion for comparing the different models of wind turbines with each other in order to use the most suitable for each study area. The calculation was performed based on the following formula:

$$\text{LCOE} = \frac{\text{Discounted Costs flows}}{\text{Discounted production}} \qquad (52)$$

| *Areas* | *Wind Turbine* | *LCOE (€/MWh)* |
|---|---|---|
| ***North Mykonos*** | Vestas V164 - 7.0 | 297 |
| | Vestas V164-9.5 | 280 |
| | Vestas V164- 8.00 | 295 |
| | Enercon E-126 7.58 | 301 |
| ***North Corfu-Othonoi*** | Vestas V164 - 7.0 | 703 |
| | Vestas V164-9.5 | 661 |
| | Vestas V164- 8.00 | 699 |
| | Enercon E-126 7.58 | 707 |
| ***North Kassos*** | Vestas V164 - 7.0 | 300 |
| | Vestas V164-9.5 | 282 |
| | Vestas V164- 8.00 | 298 |

| | | |
|---|---|---|
| **Agios Efstratios** | Enercon E-126 7.58 | 302 |
| | Vestas V164 - 7.0 | 366 |
| | Vestas V164-9.5 | 344 |
| | Vestas V164- 8.00 | 363 |
| **Kimi** | Enercon E-126 7.58 | 368 |
| | Vestas V164 - 7.0 | 445 |
| | Vestas V164-9.5 | 456 |
| | Vestas V164- 8.00 | 444 |

Table 29. LCOE for each park

# 8. Συμπεράσματα

Σκοπος της μελέτης ήταν η διαπίστωση της βιωσιμότητας ενος Υπεράκτιου Αιολικού Πάρκου στην Ελλάδα. Με διαθέσιμα 4 διαφορετικά μοντέλα ανεμογενητριών όπου κάθε ένα απο αυτά μελετήθηκε στις ακόλουθες περιοχές, North Mykonos, North Corfu-Othonoi, North Kassos, Agios Efstratios, Kimi. Αξίζει να σημειωθεί οτι οι περιορισμοί που αφορύν τη χωροθέτησή τους πληρούνται και ώς κριτήριο αξιολόγησης ήταν η ενεργειακή καθώς και η οικονομική απόδοση τους στις επιμέρους περιοχές, ώστε τελικά να επικρατήσει ο βέλτισος συνδυασμός μοντέλου και location.

Τα διαθέσιμα δεδομένα ήταν η καμπύλη ισχύος καθε ανεμογενήτριας απο τον κατασκευαστή, απο όπου εξήχθη η ισχύς συναρτήση της ταχύτητας. Επιπλέον δεδομένα που δώθηκαν ήταν το ιστορικό ταχυτήτων ανέμου που είχαν καταγραφεί για 20 χρόνια ανα μία ώρα, με σκοπό να υπολογιστεί η πυκνότητα ισχύος ως προυπόθεση για τον υπολογισμό της ετήσιας ισχύος της κάθε τουρμπίνας, παράλληλα τα δεδομένα αυτά ήταν απαραίτητα για τον υπολογισμό της μέσης ταχύτητας ανέμου στη κάθε περιοχή. Επειδή ο όγκος των δεδομένων που έπρεπε να διαχειριστεί ήταν μεγάλος, γι αυτό και έγινε χρήση του Matlab 2019a. Μετά το πέρας των υπολογισμών διαπιστώθηκε ότι ηπεριοχή με το μεγαλύτερο αιολικό δυναμικό και επομένως τη μεγαλύτερη μέση ταχύτητα ανέμου ήταν η Kassos, με μέση ταχύτητα ανέμου 8,96 m/s ενώ τη μικρότερη τιμή έιχε North Corfu m 5.57 m/s.

Ένας ακόμη παράγοντας που εξετάστηκε ήταν το ποσοστό λειτουργίας της καθε ανεμογενήτριας σε κάθε μία απο τις 5 περιοχές, εάν υποθετικά λειτουργούσαν στις περιοχές αυτές. Μετά τη διαείρηση των δεδομένων προέκυψε ότι ηVestas –V-164 9.5 MW θα λειτουργούσε με ποσοστό 93% καθ όλη τη διάρκεια των 20 ετών, αυτό διακαιολογείται καθώς Kassos retains the higher annual mean wind speed & also Vestas 9.5 operates in a greater range of speeds in contrast with the Vestas 7 & Vestas 8.

Ένα ακόμη κριτήριο αξιολόγησης ήταν το οικονομικό. Υπολογήστικαν τα κόστη για την εγκατάστασή τους καθώς και για τη συντήρηση καθόλη τη διάρκεια λειτουργίας τους τα 20 χρόνια που είναι και ο πρσδόκιμος χρόνος ζωής τους.

Πιο συγκεκριμένα υπολογήστικε ο οικονομικός δείκτης, Levelized Cost of Energy (LCOE) ο οποίος περιλαμβάνει τη Weibull distribution which is often used to characterize wind regimes because it has been found to provide a good fit with measured wind data επίσης περιλαμβάνει το CAPEX, OPEX, Losses και φυσικά το annual power production.

Λαμβάνοντας υπόψιν όλα τα παραπάνω, τη μεγαλύτερη βαρύτητα είχε το LCOE που καθόρισε την επιλογή της πιο κατάλληλης ανεμογενήτριας σε συνδυασμό με τη περιοχή.

Ως η πιο κατάλληλη κρίθηκε η Vestas V-164-9.5 Mw εφόσον θα λειτουργούσε στη περιοχή της Μυκόνου με τιμή 280 Ε/MWh, έπειτα πάλι η Vestas V164-9.5 – σε περίπτωση που θα έιτουργούσε στη Kassos με τιμή 282 Ε/MWh. Ενώ ο πιο ακατάλληλος συνδυασμός θα ήταν η Enercon E-126 7.58 στη περιοχή North Corfu

# Conclusion

The purpose of the study was to determine the viability of an Offshore Wind Farm in Greece. With four different available models of wind turbines, where each one of them was studied in the following areas: North Mykonos, North Corfu-Othonoi, North Kassos, Agios Efstratios, Kimi. It is worth mentioning that the restrictions regarding their location are met and as an evaluation criterion was their energy production and economic efficiency in the individual regions, concluding finally in the prevailing combination of model and location based on their optimal performance.

The available data and specifically power curve of each wind turbine was provided from the manufacturer, from which was derived the power as a function of speed. Additional data that was provided, was the wind speed history records for 20 years with an interval of an hour, with main target to estimate the power density as a prerequisite for calculating the annual power production of each turbine, at the same time this data was necessary to calculate the average speed wind in each area. Based on the fact that excessive volume of data had to be managed, a multi-paradigm programming language was used, more specifically Matlab 2019a. After several complex calculations it was concluded that the area with the highest wind potential and therefore the highest average wind speed was Kassos, with an average wind speed of 8.96 m / s, while the lowest value was in North Corfu with a value of wind speed 5.57 m / s.

Another factor that was examined was the percentage of operation of each wind turbine in each of the 5 areas. The data analysis revealed that Vestas-V-164 9.5 MW would operate at 93% in Kassos for the entire 20 years, this is justified as Kassos retains the higher annual mean wind speed & also this turbine operates in a greater range of speeds in contrast with the rest models.

One more standard used in order to evaluate this project, was the financial. So major costs were calculated regarding their installation as well as their maintenance throughout their operational life time which is expected to be 20 years. More specifically, it was estimated the economic index, Levelized cost of energy (LCOE), which includes the Weibull distribution, as it is often used to characterize wind regimes based on the fact that it provides appropriate adaptation to wind measurement data. Some financial elements that were includes, was CAPEX, OPEX, Losses and of course Net Annual Energy Production.

Taking into account above parameters, of the utmost importance was the LCOE that determined the final selection of the most suitable wind turbine in combination with the area Vestas V-164-9.5 was considered the most optimal if it would operate in the region of Mykonos with a price of 280 E / MWh, then again Vestas V164-9.5 in case it would operate in Kassos with a price of 282 E / MWh. While the most inappropriate combination would be the Enercon E-126 7.58 in the North Corfu area

**List of Figures**

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# ANNEX 1

MATLAB CODE

```
WindSpeeds = era5windspeed100m2d(:, 6:1670);
Year = era5windspeed100m2d(:,1);

 WindSpeeds = table2array(WindSpeeds);
 Year = table2array(Year);

% A whole 175320 x 1660 array with wind densities at every point for 20 years
WindDensity =0.5*1.2*WindSpeeds.^3;

% empty array to be filled with mean density for every point for each year
WD_means_per_year = zeros(20,1665);

for i = 0: 19

   index = find(Year == 2000 + i);
   WD_means_per_year(i+1, :) = mean(WindDensity(index,:));

end

WD_means = mean(WD_means_per_year); % vector with the 20 total means

MaxWD_50 = maxk(WD_means,50) ;

for i = 1: size(MaxWD_50,2)
MaxWD_50_Locations(i) = find(WD_means == MaxWD_50(i));

end

% results

% an array 20x1665 (WD_means_per_year) with means for every point for each year
% an array 1x1665 (WD_means) with th total 20-year means for each point
% an array 1x50 (MaxWD_50) with the 50 larger means observed along the 20-year period
% an array (MaxWD_50_Locations) with the corresponding coloumn numbers of
% locations

windspeed1=era5windspeed100m2d(:,986);
Year = era5windspeed100m2d(:,1);
windspeed1= table2array(windspeed1);
 Year = table2array(Year);
 S11=std(windspeed1)
 for i = 0: 19
```

```
   index = find(Year == 2000 + i);
   windspeed1_means_per_year(i+1, :) = mean(windspeed1(index,:));

end

windspeed1_means = mean(windspeed1_means_per_year); % vector with the 20 total means
windspeed2=era5windspeed100m2d(:,88);
Year = era5windspeed100m2d(:,1);
 windspeed2= table2array(windspeed2);
 Year = table2array(Year);
  S22=std(windspeed2)
 for i = 0: 19

   index = find(Year == 2000 + i);
   windspeed2_means_per_year(i+1, :) = mean(windspeed2(index,:));

end

windspeed2_means = mean(windspeed2_means_per_year); % vector with the 20 total means
windspeed3=era5windspeed100m2d(:,1216);
 Year = era5windspeed100m2d(:,1);
 windspeed3= table2array(windspeed3);
 Year = table2array(Year);

%calculation of turbine 1 in area 1
Power12=-0.0023*Area1.^6+0.153*Area1.^5-
3.2929*Area1.^4+20.271*Area1.^3+99.963*Area1.^2-436.54*Area1;
for i = 0: 19
     index = find(Year == 2000 + i);
   Power11_means_per_year(i+1, :) = mean(Power11(index,:));
   PowerA11=mean(Power11_means_per_year(i+1, :));
End

Velocities = era5windspeed100m2d(:,[1, 986, 88, 1216, 903, 797] );
Velocities=table2array(Velocities)
results_4_25 = zeros(20,6);
results_3_25 = zeros(20,6);
results_3_34 = zeros(20,6);
area =  [986, 88, 1216, 903, 797];
results_4_25(:,1) = 2000:2019;
results_3_25(:,1) = 2000:2019;
results_3_34(:,1) = 2000:2019;

for i = 0:19

      for j = 1:5
```

```
      v= era5windspeed100m2d( Velocities(:,1)== 2000+i, area(j)); %velocities of area j for year
2000+i
      v=table2array(v)

      results_4_25(i+1, j+1) = size(v(v > 4  &  v <25 ),1); % size of vector of velocities that satisfy
demand 1
      results_3_25(i+1, j+1) = size(v(v > 3  &  v < 25 ),1); % size of vector of velocities that satisfy
demand 2
      results_3_34(i+1, j+1) = size(v(v > 3  &  v < 34 ),1); % size of vector of velocities that satisfy
demand 3
   end
end
```