Hungarian University of Agriculture and Life Sciences

Institute of Technology

# THESIS

**Amjad Mohamed**

**Mechanical Engineering**

Gödöllő

**2023**

# Hungarian University of Agriculture and Life Science

## Szent István Campus

### Mechanical engineering

# Performance analysis of KHALLADI wind farm

**Primary Supervisor:** Dr. Schrempf Norbert Attila
Associate Professor,
Head of department MATE

**Author:** **Amjad Mohamed**
TOJ3X0

**Institute/Department:**

**Mechanical Engineering**

**Gödöllo, 2023**

**INSTITUTE OF TECHNOLOGY**

HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

**INSTITUTE OF TECHNOLOGY MECHANICAL ENGINEERING (MSC)**

# THESIS

Worksheet for

***Amjad Mohamed (TOJ3X0)***

(MSc) student **Entitled:**

## Performance analysis of the KHALLADI wind farm in Morocco

**Task description**:

This subject is based on the analysis of power curves and operational data (production, availability to identify any abnormalities relating to the profitability of the project. The analysis is done according to the criteria of the IEC 61400-12-2 standard with the introduction of a confidence coefficient to weigh the performance of each machine. This allowed me to detect the underperforming machines that need to be studied to identify the main causes. The impact of this underperformance was quantified in terms of losses in order to loss rates in extreme cases. Measures to improve and mitigate the problems raised were proposed.

**Department: Department of Civil Engineering and Energy**

**Consultant:** *Dr. Schrempf Norbert Attila, Associate Professor,* MATE, head of department MATE

**Supervisor:** *Dr. Schrempf Norbert Attila, Associate Professor,* head of department MATE,

**Submission deadline:** 31 March 2023
31 March 2023.

**Approved** **Received**

(Head of department) (Host course leader) (Student)

As an independent consultant of the author of this thesis I hereby declare that the student took part in the planned consultations.

Gödöllő, 31 March 2023.

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(Consultant)

# TABLE OF FIGURES

Figure 1: Solar and wind energy resources in Morocco ........ 10
Figure 2: Renewable energy projects in Morocco ........ 11
Figure 3: Windmill ........ 12
Figure 4: Wind turbine by Charles Bruch 1888 ........ 12
Figure 5: Gesder's first three-bladed wind turbine ........ 13
Figure 6: Main components of a wind turbine ........ 14
Figure 7: Wind turbine with horizontal axis ........ 15
Figure 8: Savonius wind turbine ........ 15
Figure 9: Darrieus wind turbine ........ 15
Figure 10: Rotary wing wind turbine ........ 16
Figure 11: Offshore wind turbines ........ 16
Figure 12: Wind formation ( the georoom, August 2020) ........ 18
Figure 13: The wind rose and the different wind directions ........ 19
Figure 14: Anemometer: cup, ultrasonic and laser ........ 20
Figure 15: Mast and its components (Yutthana Tirawanichakul, 2021) ........ 21
Figure 16: Weibull distribution ........ 22
Figure 17: Drag and lift forces illustrated on a cross section of an aircraft wing ........ 25
Figure 18: Normal flow and stalled flow ........ 26
Figure 19: Pitch mechanism ........ 27
Figure 20: Google maps of Khalladi Park (July 2020) ........ 29
Figure 21: Layout of the park on the SCADA system ........ 29
Figure 22: Components of the Vestas V90-3MW wind turbine ........ 33
Figure 23: SCADA interface showing the different measured data ........ 35
Figure 24: General power curve of a wind turbine ........ 36
Figure 25: Contractual power curve of the V90-3MW machine ........ 37
Figure 26: Windographer home interface ........ 39
Figure 27: Types of wind farms by operating time ........ 42
Figure 28: Contract and operational curve representing Group 1, SCADA ........ 45

Figure 29: Contract and operational curve representing Group 2, SCADA ... 46
Figure 30: Group 3 contract and operational curves ... 46
Figure 31: Operating curve of machine 09 before filtration ... 47
Figure 32: Curve of machine 09 after filtration ... 48
Figure 33: Power curve of the WTG02 machine ... 48
Figure 34: Power curve of the WTG08 machine ... 49
Figure 35: Power curve of the WTG01 machine ... 49
Figure 36: Power curve of the WTG13 machine ... 50
Figure 37: Power curve of the WTG04 machine ... 50
Figure 38: Power curve of machine 09 ... 51
Figure 39: Power curve of the WTG33 machine ... 51
Figure 40: Power curve of the machine 30 ... 52
Figure 41: Exporting data to Windographer ... 53
Figure 42: Machine model selection ... 53
Figure 43: determination of standard losses ... 54
Figure 44: Calculation of the theoretical net ... 54
Figure 45: Histogram of comparison between loss rates and availability ... 56
Figure 46: Sectoral analysis of 12 wind sectors ... 58
Figure 47: Lidar ... 59
Figure 48: How Lidar works ... 59

# TABLE OF TABLES

Table 1: Speed and power data of the contractual power curve of the V90-3MW machine ... 36
Table 2: Classification of the 40 turbines in the park according to the normalization ... 44
Table 3: Classification of turbines into three groups ... 45
Table 4: Group 3 turbines ... 45
Table 5: Energy loss rates ... 55
Table 6: Availability of the eight machines studied ... 55
Table 7: Classification of causes and impacts of underperformance for the eight wind turbines studied and possible solutions ... 57

# TABLE OF CONTENTS


TABLE OF FIGURES 1
TABLE OF TABLES 3
TABLE OF CONTENTS 4
ABSTRACT 6
INTRODUCTION 7
I. LITERATURE REVIEW 9
1. General issues 9
2. Renewable energy in Morocco 9
2.1 Renewable energy resources in Morocco: 9
2.2 Renewable energy projects in Morocco: 11
3. Wind Energy: 11
3.1Wind and energy production: 11
3.1.1 Background: 11
3.1.2 Components of a wind turbine: 13
3.1.3 Types of wind turbines: 15
3.2 Wind power: 17
3.1.1 Wind resources: 17
3.1.2 Wind directions and the wind rose: 19
3.1.3 Wind measurement: 19
3.1.4 Weibull distribution: Variations in wind speeds: 22
3.1.5 Energy production: 23
3.3 Functional principle 25
3.3.1 How does a wind turbine harness the energy of the wind? 25
3.3.2 Influence of aerodynamic phenomena: trailing lift and stall, on the wind turbine rotor: 26
3.3.3 Wake effect: 28
3.3.4 Turbulence: 28
4. Presentation of the KHALLADI wind farm 28
4.1 Park design: 28
4.2 Specifications of Vestas V90-3MW Turbine: 30
4.2.1 Description of the pod : 30
4.2.2 Rotor description: 31
4.2.3 Regulation and control systems: 32

4.2.4 Sensors : 32
5. Issues: 33
5.1 Definitions: 34
5.1.1 SCADA : 34
5.1.2 Power curve: 35
5.1.3 Availability: 37
5.1.4 Windographer: 38
II. WORKING METHODOLOGY 40
1. Methodology: 40
2. Justification of the choice of turbine: 41
3. SCADA data filtering: 41
4. Power curve analysis: 41
5. Quantification of losses: 46
6. Cause analysis: 46
6.1 Construction phase: 47
6.2 Environmental site conditions: 47
6.3 Incorrect execution of the maintenance program: 47
III. PERFORMANCE ANALYSIS: APPLICATION TO KHALLADI PARK 48
1. Choice of turbines to be studied 48
2. Data filtering: 51
3. Performance Analysis: 52
4. Quantification of losses: 52
4.1 Calculation of the contractual energy: 53
IV. RESUL TS OF THE PERFORMANCE ANALYSIS 56
1. Results of the Khalladi wind farm performance analysis 56
2. Sector analysis: 57
3. Root Cause Analysis: 58
4. Installation of a lidar to correct the orientation of the basket: 58
5. Technical and economic study of the use of Lidar: 60
CONCLUSION AND SUMMARY 61
BIBLIOGRAPHY 64
ANNEXES 66
ACKNOWLEDGMENT 76

# ABSTRACT

Wind farms are now seen as a potential new source of energy in full development in Morocco; in this regard, Morocco is proposing 2000 MWh. Because practically all wind turbine installations have a lifespan of less than ten years, it is worthwhile to investigate the performance of these devices in accordance with international standards.

The purpose of this paper is to examine the performance of the KHALLADI wind farm, which was built in 2018. This topic is centered on the examination of power and operating data curves (production, availability) to discover any abnormalities that may affect the project's profitability. The study is carried out in accordance with the IEC 61400-12-2 standard, with the introduction of a confidence coefficient to weight the performance of each machine. This allowed me to identify underperforming machines that needed to be studied in order to determine the root reasons.

The impact of this underperformance has been evaluated in terms of losses in order to determine the loss rates in the most extreme circumstances. Measures have been offered to enhance and alleviate the difficulties mentioned.

# INTRODUCTION

The history of human beings and the conquest of energy have always been inseparable. In the beginning, man's needs were modest: heating, food and lighting, so energy was essentially linked to the mastery of fire. Since the advent of civilization, industrial development and the appearance of the machine, other sources of energy have been discovered such as coal, oil and gas.

In the 20th century, mankind experienced the appearance of hydroelectricity and nuclear energy, but despite this, the consumption of energy did not cease to grow, the need for energy is still in continuous growth.

So the challenge was great: How to meet the growing, even exponential, energy needs while fossil resources are becoming scarce and the environmental alarm bells have been ringing for a long time?

The solution was to look for new resources that would be sustainable and above all clean from an environmental point of view, so we talk about renewable energy. The renewable energy sector includes all forms of energy that are almost inexhaustible, some like water and wind have been used for thousands of years, others are recently discovered, such as solar energy, and some of them must be used rationally, if we do not want them to run out.

Endowed with a strong potential in solar and wind energy, Morocco is committed to a sustainable development plan in order to become the first supplier of renewable energy in North Africa. In this context, several solar and wind projects have been completed and others are under development.

Wind energy being a new and promising source of energy in Morocco, the country with 895MW already installed, aims to reach the 2GW of wind origin by 2030. This dissertation is the result of continuous work in the NOMAC Company in charge of the operation and maintenance of the KHALLADI wind farm.

Production monitoring is the major mission of the operation and maintenance team. The challenge is to reach the production described in the business plan, which, due to the intermittency of the wind resource, and other factors that affect the performance of the park, is still not reached.

For this reason, performance analysis is a daily obligation in the park. So, the objective of this work is to study and analyze the performance of the wind turbines of the park based on different techniques, in order to define the aspects and causes of the under performance of the park and to determine thereafter, the corrections necessary to the good performance.

To this end, the subject will be covered in chapters:

- Presenting in the first chapter, a literature review, in which I go over the situation I'm discussing, explaining the problematic, general issue, and the general information regarding the technologies used in this work. I will present in a general way, renewable energies, more specifically in Morocco, even more precisely, I will focus on wind energy in Morocco, which is our main interest in this topic. Moreover, I am going to present the KHALLADI farm, its design and specifying the turbine used plus other aspects related, before concluding by the problematic or the main issue.

- In chapters II, III and IV, I will present the work done in this final study project, starting with the problem of performance analysis in the wind farm, then presenting the methodology to be followed to analyze the performance and after that, I will put in the application of this methodology to the KHALLADI wind farm, and lastly, the results of the analysis will be presented, as well as the proposed solutions for performance improvement.

# I. LITERATURE REVIEW

## 1. General issues

In Morocco, wind farms are currently considered a promising new source of energy in full development, in this sense Morocco is considering 2000 MWh.

Since almost all wind turbine installations do not exceed 10 years, it is interesting to study the performance of these machines according to international standards *(Analysis of Wind Data an Wind Energy Potential of the East of Mohammedia, Morocco, December 2018).*

This final year project is interested in analyzing the performance of the KHALLADI wind farm built in 2018 based on different scientific techniques.

This subject is based on the analysis of power curves and operational data (production, availability) in order to identify any abnormalities relating to the profitability of the project. The analysis is done according to the criteria of the IEC 61400-12-2 standard with the introduction of a confidence coefficient to weight the performance of each machine. This allowed me to detect the under-performing machines that need to be studied in order to identify the main causes.

The impact of this underperformance was quantified in terms of losses in order to have the loss rates in extreme cases. Measures to improve and mitigate the problems raised were proposed.

## 2. Renewable energy in Morocco

### 2.1. *Renewable energy resources in Morocco:*

In order to reduce its dependence on energy (95% of the country's consumption is exported from foreign suppliers Algeria and Spain), as well as its greenhouse gas emissions (144 tons/year $CO_2$), Morocco has set a national strategy for sustainable development, which is based on the different sectors of renewable energy: wind, solar and hydroelectric, this strategy aims to increase the share of renewable energy in national production from 42% in 2020 to 52% in 2030 *(Ministry of Energy of Morocco official website*).

Indeed, Morocco benefits from a considerable potential in renewable energies, with an annual irradiation which exceeds 2200KWh/m² in particular in the southern and south-eastern regions, average wind speeds higher than 10m/s in the northern zone (Tangier - Tetouan) and the coastal strip from Tarfaya to Lagouira. Without forgetting the share of hydraulic resources as well as geothermal, biomass and maritime micro power plants.

Lately, the strategy is starting to bear fruit and aims to exploit the very favorable conditions Morocco enjoys in order to reach a production of 2GW in wind, 2GW in solar and 2GW in hydroelectricity by 2020.

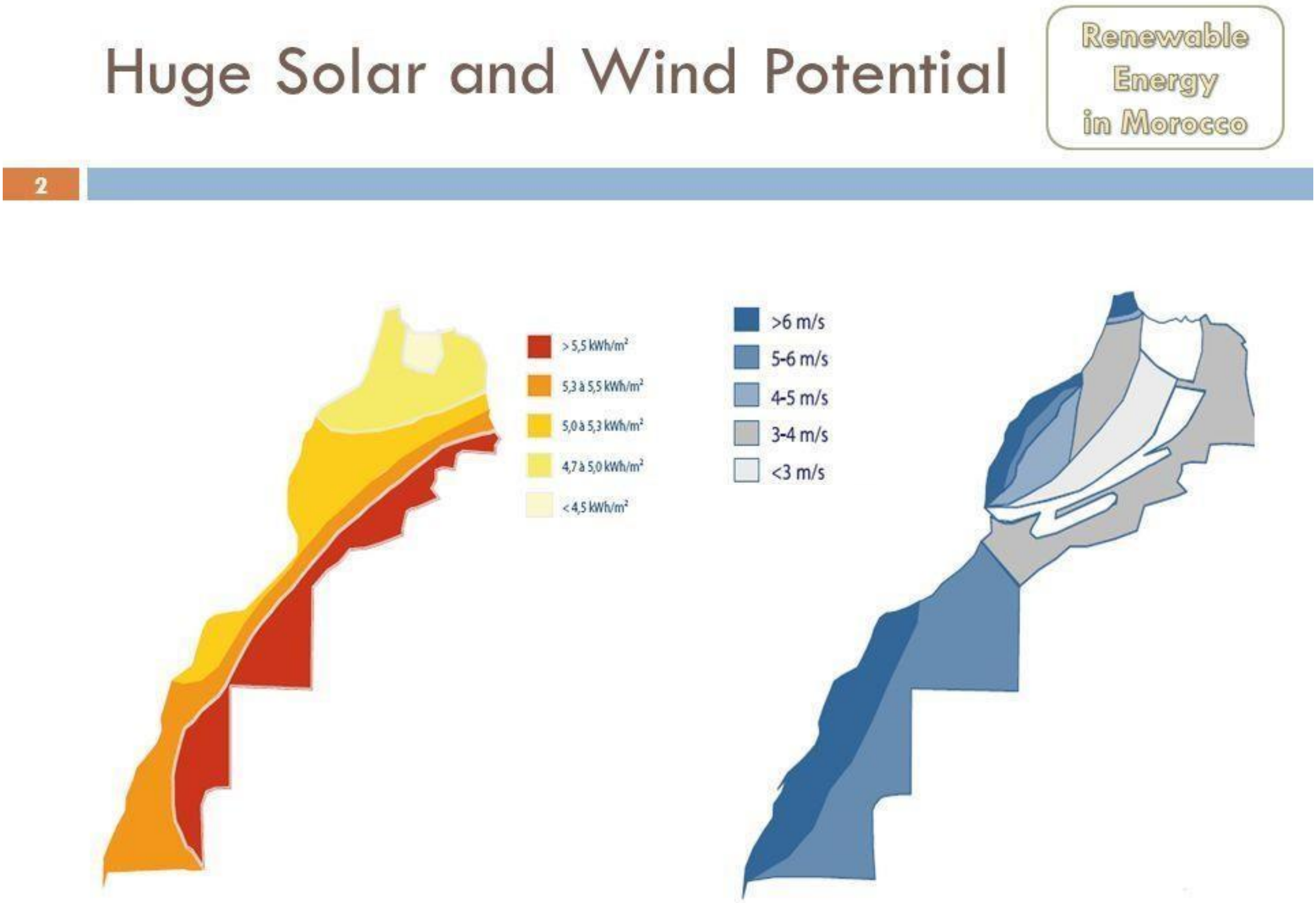



*Figure 1: Solar and wind energy resources in Morocco (slideplayer (2011))*

2.2. *Renewable energy projects in Morocco:*

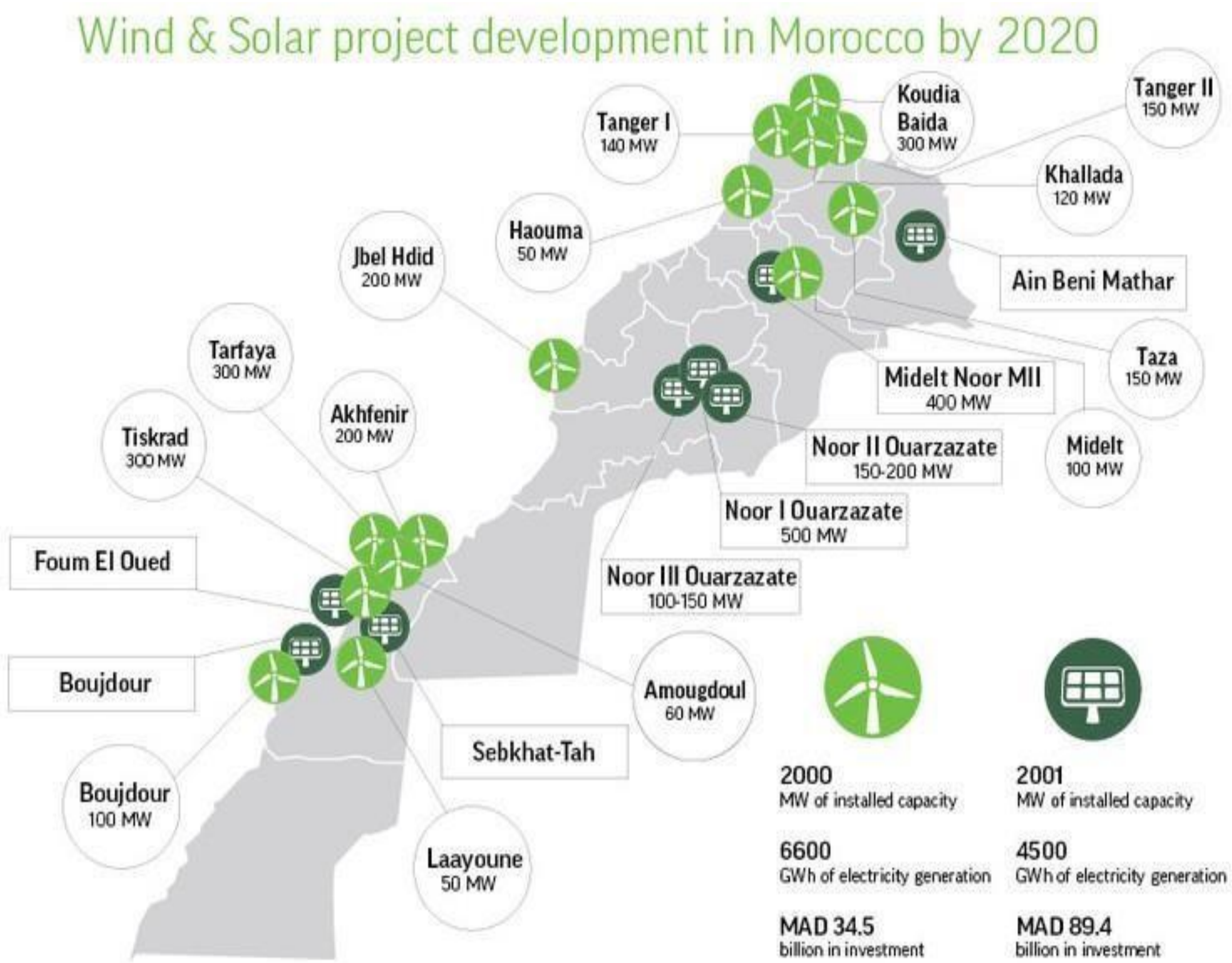



*Figure 2: Renewable energy projects in Morocco (renewablesnow (2017))*

# 3. Wind Energy:

## 3.1. *Wind and energy production*:

### 3.1.1. Background:

- Windmills are the oldest form of wind power that man has invented, they appeared in the East in the year 600 and then in Europe around the 12th century *(EDF online magazine (n.d.)).*

*Figure 3: Windmill (Wikipedia)*

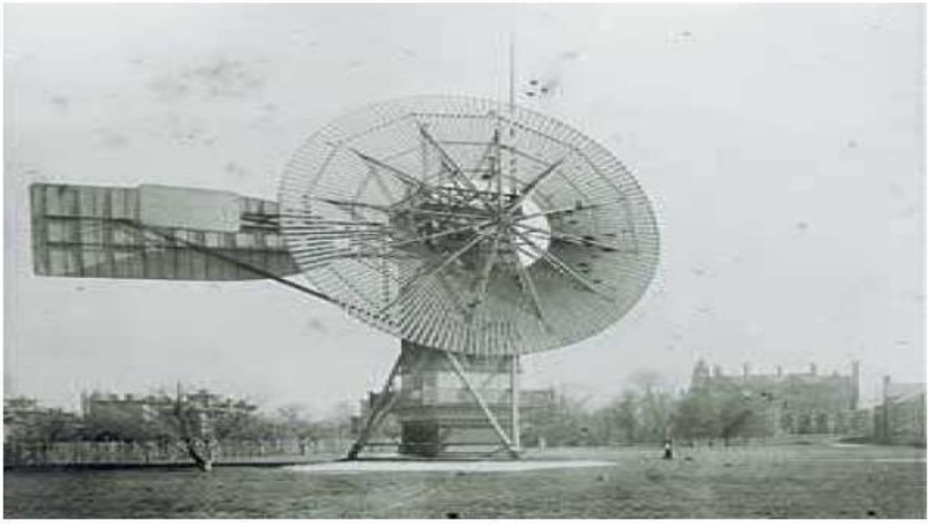


*Figure 4: Wind turbine by Charles Bruch 1888 (Wikipedia)*

- In 1891, Poul La Cour discovered that the shape and number of wind turbine blades had an influence on efficiency.

- During the Second World War the Danish FL Smidth created the first three-bladed wind turbine.

*Figure 5: Gesder's first three-bladed wind turbine (Wikipedia)*

- In 1957, the Gedser turbine was set up by the Danish Johannes Juul, three-bladed and equipped with an electromagnetic steering system, an asynchronous generator and aerodynamic brakes, this model was the first to produce alternating current *(Ackermann, T., & Söder, L. 2002).*

- In 1990, the two Danish companies Vestas and Alstom were the first to build the model of offshore wind turbines, a promising technology especially in countries with a high population density.

- Over time and with the progress of mechanics and aerodynamics, the productivity of wind turbines continues to improve and between 2000 and 2002 the production of electricity from wind power has been multiplied by 28 to reach 1039 TWh of world production.

### 3.1.2. Components of a wind turbine:

A wind turbine is a device that harnesses the kinetic energy of the wind and transforms it into mechanical energy, which in turn is transformed into electrical energy. This is the definition that answers the question: what is a wind turbine?

A definition that can be considered simple, but the process behind these conversions is actually a little more complicated than that. The main components of a wind turbine are:

| | | |
|---|---|---|
| 1♦The tower | 5♦ The slow tree | 9♦ The generator |
| 2♦The blades | 6♦ The multiplier | 10♦ The orientation system |
| 3♦The hub | 7♦The fast tree | 11♦ The control and command system |
| 4 ♦The pod | 8♦The braking system | 12 ♦The hydraulic system |

13♦The cooling and air conditioning

14♦The anemometers and wind vane

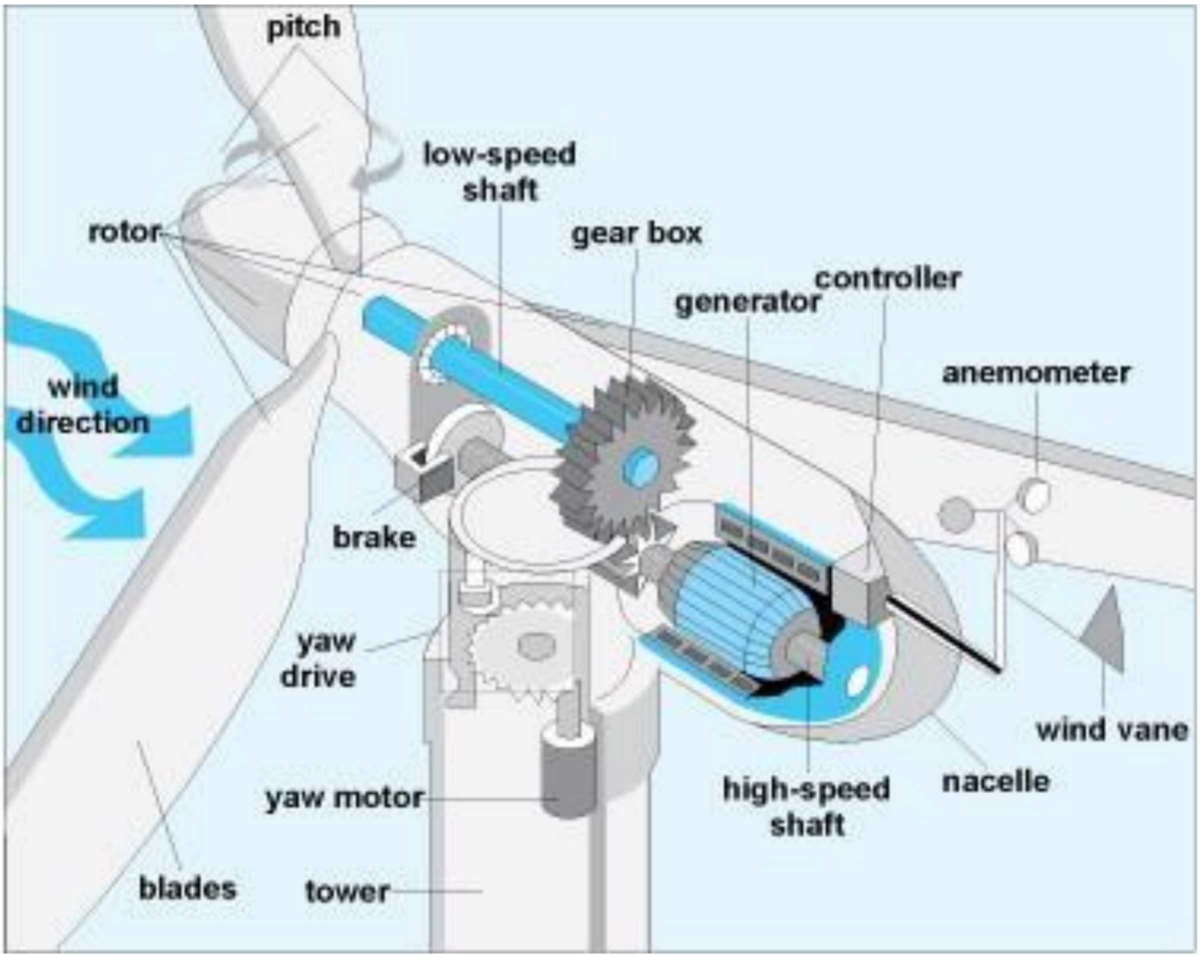



*Figure 6: Main components of a wind turbine (Accessscience -Department of Energy)*

### 3.1.3. Types of wind turbines:

Wind turbines are classified according to the position of the rotor in relation to the axis:

**Horizontal axis wind turbines**: this is the classic and most widespread model in the world.


*Figure 7: Wind turbine with horizontal axis (Wikipedia)*

**Vertical axis wind turbines:**

**Savonius type:** composed of two half cylinders linked to a vertical axis **Darrieus type:** characterized by vertical parabolic or helical blades.

*Figure 8: Savonius wind turbine (Wikipedia)*

*Figure 9: Darrieus wind turbine (Wikipedia)*

**Rotary wing type:** This type resembles the shape of a sailing ship


*Figure 10: Rotary wing wind turbine (Wikipedia)*

**Offshore wind turbines:** The exploitation of the offshore wind resource seems to be extremely promising, especially in densely populated countries with difficulties in finding suitable sites on land. Construction costs are higher at sea than on land; however, the electricity production of offshore wind turbines is also higher.

*Figure 11: Offshore wind turbines (governing (2019))*

## 3.2 *Wind power :*

### 3.2.1 Wind resources:

Like the energy found in fossil fuels, renewable energy (except tidal and geothermal) is derived from solar energy. In fact, the sun emits some 174,423,000,000,000-kilowatt hours of energy to our planet every hour. About 1% to 2% of the energy emitted by the sun is converted into wind energy *(Connaissance Energies (n.d.)).*

**How do you do it?**

The sun warms the areas around the equator at altitude 0 much more than other areas of the globe, so, having a lower density than cold air, the warm air rises to an altitude of about 10 km and then spreads north and south, then falls back down and returns to the equator following cooling.

If the earth did not rotate, the air currents would go to the north and south poles, but because of the rotation of the earth, any movement in the northern hemisphere undergoes a deviation to the right and any movement in the southern hemisphere undergoes a deviation to the left, these deviations are due to the Coriolis force.

In both hemispheres and at approximately 30° latitude, the Coriolis force prevents the warm air currents from moving further and the air begins to sink at that latitude, creating an area of high pressure.

At the equator, air currents rise, producing an area of low pressure over the land that attracts air masses from the north and south.

These movements of air masses from high pressure areas to low pressure areas form the so called wind.

The troposphere is defined as the part of the atmosphere surrounding the earth and 10 km thick, and it is on this very thin part that meteorological phenomena and the greenhouse effect occur. A distinction is also made between geostrophic winds and surface winds:

**Geostrophic winds:** Products of temperature and pressure differences and are not influenced by the ground surface. They are found at heights greater than 1 km above the ground.

**Surface winds:** They are found up to 100 m in height and are influenced by the ground surface (roughness and obstacles).

In the field of wind energy, surface winds and their energy capacity are of the greatest interest.

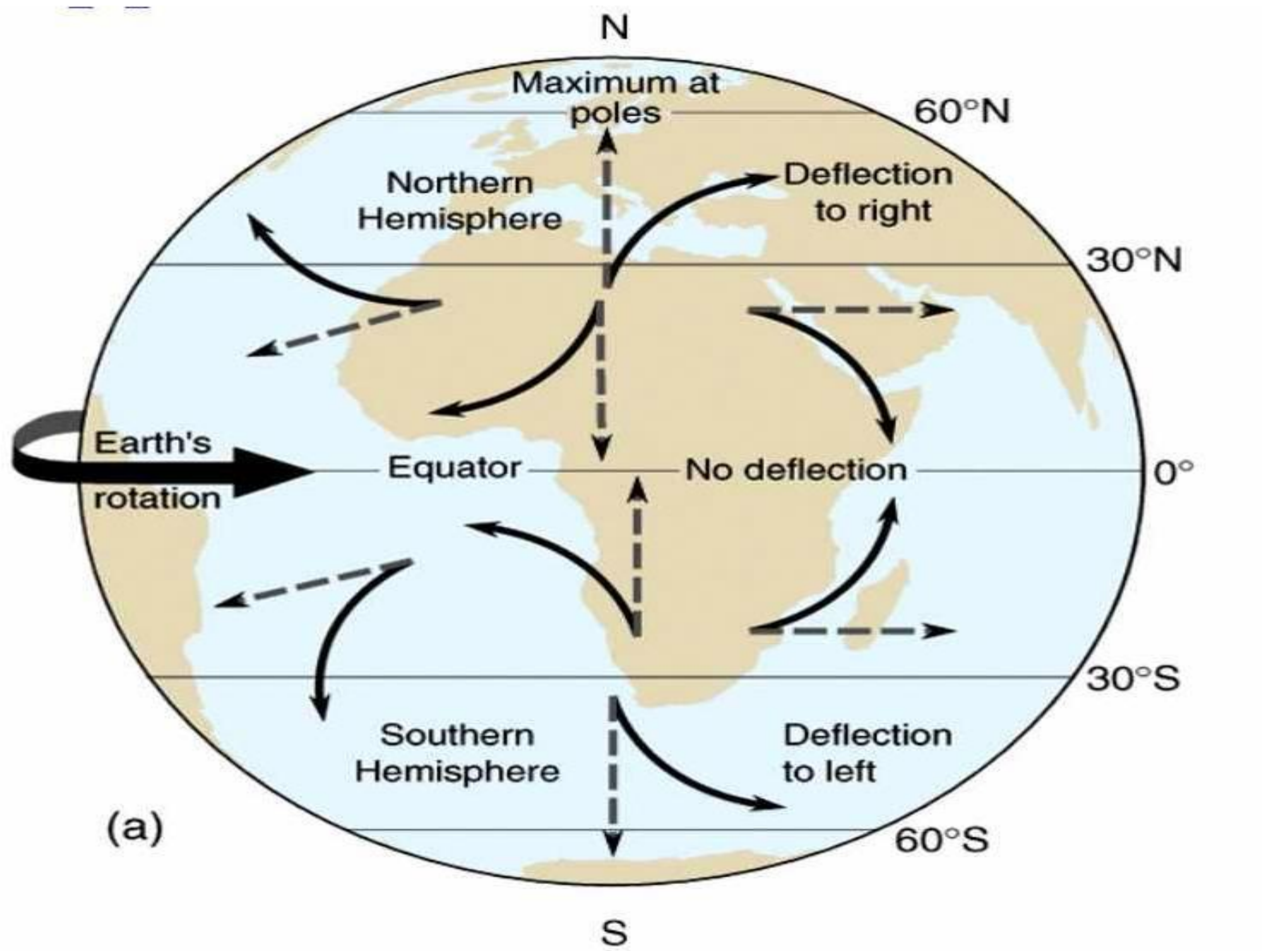



*Figure 12: Wind formation (the georoom, August 2020)*

### 3.2.2 Wind directions and the wind rose:

The wind rose plays a very important role in locating suitable sites for the installation of a wind farm. It allows us to know which dominant directions in a site there are.

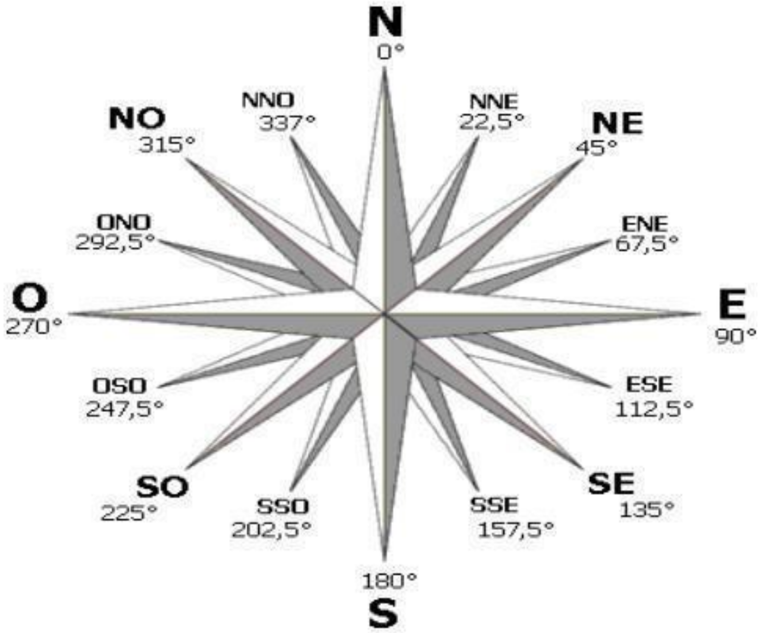



*Figure 13: The wind rose and the different wind directions (Wikipedia)*

The wind rose can be considered as a kind of climatological fingerprint; it differs from one region to another.

### 3.2.3 Wind measurement:

The wind is described by its speed and direction: Wind speed is usually measured by an anemometer, while direction is measured by the wind vane.

**The anemometer:** it is an instrument for measuring wind speed and pressure, associated with a wind vane, it also allows to specify the wind directions.

The oldest model of anemometers is the one that consists of three cups installed on a horizontal axis and must be placed at a height of ten meters to avoid obstacles on the surface that can affect the accuracy of measurements.

Currently there are a variety of anemometers that give accurate measurements, namely ultrasonic anemometers and Laser (Lidar) anemometers; their operation is based on the recording of phase changes of sound or light reflected by air molecules.

*Figure 14: Anemometer: cup, ultrasonic and laser (Wikipedia)*

**Measuring mat:** The wind speed varies proportionally to the height and its variation is strongly influenced by the roughness of the ground, indeed, a strong roughness slows down considerably the wind speed.

$$v_2 = \frac{v_1 \ln\left[\frac{h_2}{z_0}\right]}{\ln\left[\frac{h_1}{z_0}\right]}$$

- **v** : speed
- **h** :altitude
- **z0** : the length of the roughness

For this reason, it is important to carry out the wind measurements with a measuring mast, the height of which corresponds to the height for which the wind measurements are desired, in order to avoid the effect produced by the mast itself or by the roughness.

The mast is usually equipped with tools that provide atmospheric pressure and humidity data. The data of the whole is recorded in a recorder.

Data Logger, measurements are taken every twenty minutes and the data is communicated to the control station via a communication system.

The study of the wind in a wind farm requires great precision, because the speed decreases with each obstacle, since it captures part of the wind energy, and then the intensity of turbulence increases.

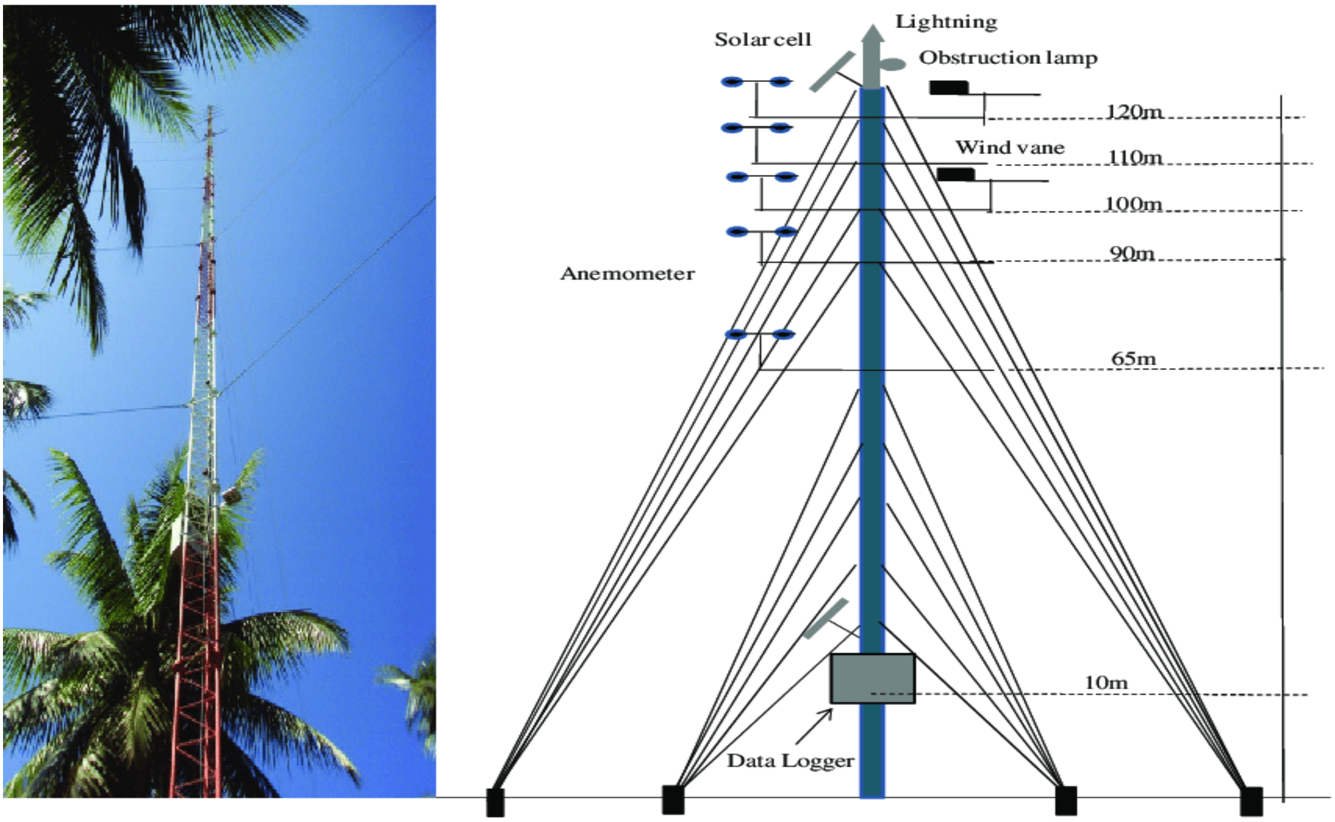



*Figure 15: Mast and its components (Yutthana Tirawanichakul, 2021)*

### 3.2.4 Weibull distribution: Variations in wind speeds:

Before installing a wind farm, it is necessary to describe the variations in wind speeds at the given site, manufacturers use this information to improve the performance of the wind turbines, while investors use it to estimate the revenues from electricity production *(Weibull and Rayleigh Statistics).*

The Weibull distribution often provides a good approximation of the wind speed distribution, Its characteristic function is:

$$F(v) = \frac{k}{A}[(\frac{v}{A})^\wedge(k-1)]e^{-(\frac{v}{A})^\wedge k}$$

With:

**F (v):** the frequency of occurrence

**k:** shape parameter and is 1, 2 or 3

**c**: scaling parameter and close to the average speed, [m/s]

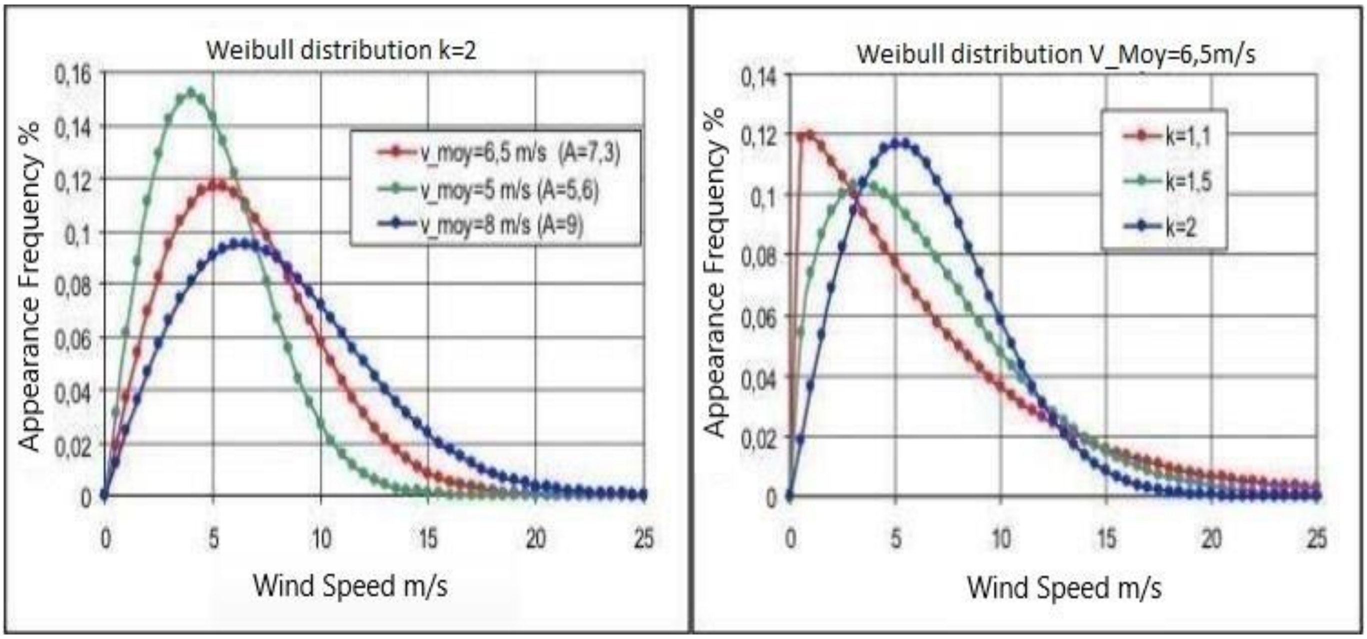



*Figure 16: Weibull distribution*

The figure shows several Weibull distribution curves as a function of the different parameters.

I noticed that the variations of the average speeds as well as their probabilities of occurrence, depend on the two parameters k and A.

In the field of wind energy, we are generally interested in the speed interval between 4m/s and 25ms, so I'm taking k=2 and A=8.

### 3.2.5 Energy production:

As mentioned earlier, a wind turbine captures the kinetic energy of the wind and transforms it into mechanical energy and then into electrical energy. So, from the kinetic energy of the wind I can deduce the energy or power recovered by the wind turbine.

The kinetic energy of a moving particle is defined by:

$$Ec = \frac{1}{2}mv^2$$

With:

**Ec:** the kinetic energy of the particle in Joule [J]

**m**: the mass of the air particle in [Kg]

**v:** velocity of the motion of the particle in [m/s]

Since air is composed of many particles, each having a kinetic energy, it is impossible to calculate the energy of each air particle, so it is more convenient to use the mass flow rate, which is by definition: the mass that crosses an area S per unit of time, for a uniform flow.

$$\frac{dm}{dt} = \rho S v$$

On the other hand, I have the power is the quantity of energy per unit of time supplied by a system to another:

$$P = \frac{dE}{dt}$$

So the power supplied by the wind to the turbine is:

$$P = \frac{dEc}{dt}$$

$$\Leftrightarrow$$

$$P = \frac{1}{2}\frac{d[mv^2]}{dt}$$

$$\Leftrightarrow$$

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

**P**: the power in Watt [W].

**ρ**: the density of air in [Kg m/s] and is 1.225kg.m/s under standard temperature and pressure conditions: T=25°C and P=1 atm

**S**: Swept area [$m^2$]

**v**: Wind speed [m/s]

The power delivered to the wind turbine depends on the air density, the speed and the area swept by the rotor, so an increase in one or all of these parameters will increase the power at the rotor input, however, losses resulting from the nature of the site and the roughness, losses resulting from mechanical and electrical components must be considered.

Betz's law determines that a wind turbine can only ever recover 16/27 contained in the wind, and thus the power recovered by a wind turbine is given by:

$$= \frac{1}{2}\rho S v^3 Cp$$

*recovered P*

With: Cp the power coefficient and there is

$$0 < Cp < \frac{16}{27}$$

## 3.3 *Functional principle*

### 3.3.1 How does a wind turbine harness the energy of the wind?

In order to understand how a wind turbine works, it is important to introduce some notions of aerodynamics: lift and drag.

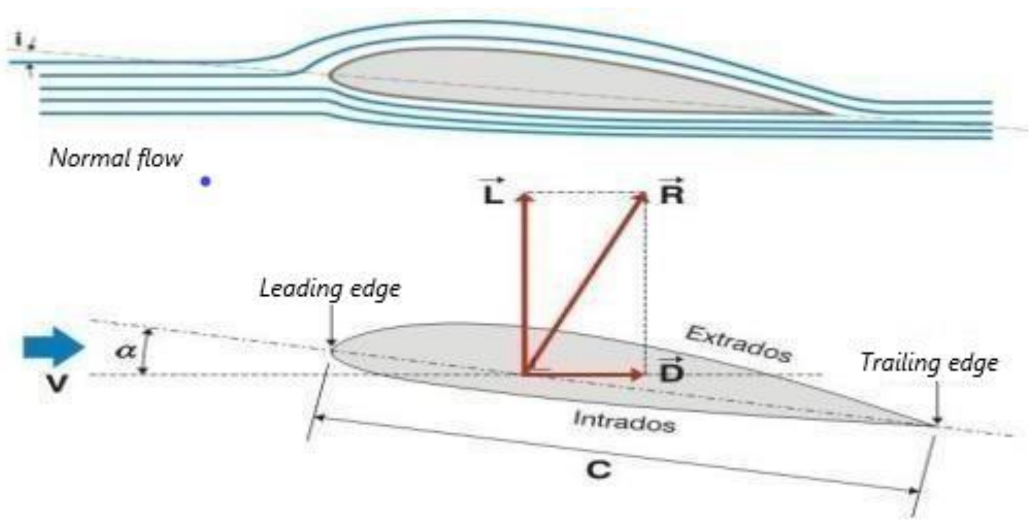



*Figure 17: Drag and lift forces illustrated on a cross section of an aircraft wing (mpoweruk (2005))*

The figure above shows a cross section of an aircraft wing.

The straight line that connects the two ends, the leading edge and the trailing edge.

The air velocity upstream of the wing forms an angle α with the chord, α is therefore called the angle of attack.

The larger the angle, the greater the airflow to the upper surface, so that on the upper surface the garlic accelerates the airflow, on the lower surface the garlic slows the airflow. This creates a depression on the upper surface and an increase in pressure on the opposite side.

Thanks to these pressure differences in the two sides of the garlic, a force is created that is globally oriented upwards. And it is thanks to this force that birds and planes can fly. 37

This force can like any other force can be broken down into several components, in our case, in the figure above, the component in the direction of flow is called drag force (D, drag) while the component whose direction is perpendicular to the direction of flow is called lift force (L, Lift).

The lift force increases with the angle of attack until a certain angle, where the lift force drops sharply, because beyond this angle the airflow does not change its initial trajectory after contact with the wing, so the flow does not accelerate, and therefore the pressure on the upper surface increases and the lift force also decreases.

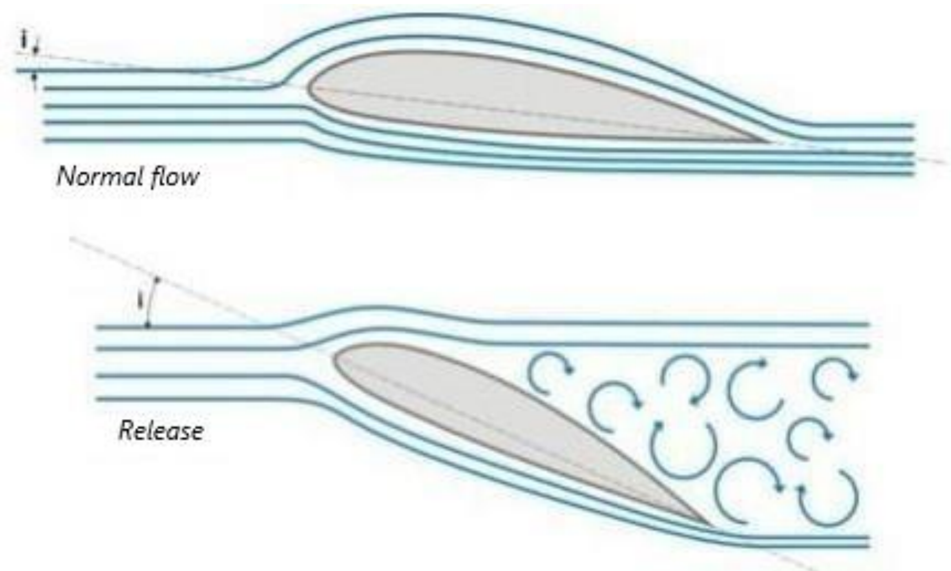



*Figure 18: Normal flow and stalled flow (pilotfriend ( 2013))*

### 3.3.2 Influence of aerodynamic phenomena: trailing lift and stall, on the wind turbine rotor:

These concepts are applicable to wind turbines, except that the problem becomes a little more complex because of the rotation of the blades, which generally have a higher speed than the wind.

Considering the blades rotating at a nominal speed n [rpm or Hz], the tangential speed of rotation of the blades is given by:

$$U = 2 * \pi * r * n$$

With:

**U**: tangential speed of rotation of the blade in [m/s]

**r**: the height of the blade [m]

**n**: nominal rotor speed [Hz].

So the maximum speed will be obtained at the tip of the blade.

Adding this speed I always have the wind speed which decreases under the effect of the blade, which is in the ideal case the wind speed incident on the turbine, the combination of these two speeds allows us to define the relative speed Vr. The relative velocity Vr and the angle of attack are used to estimate the force that will be applied on the blade profile.

Another important parameter is also introduced: the pitch angle.

The pitch angle is the angle between the chord and the plane of orientation of the blade, and it is a parameter that can be adapted and does not depend on the flow.

On the other hand, the angle of attack depends on the relative speed and the stall angle, as shown in the figure below:

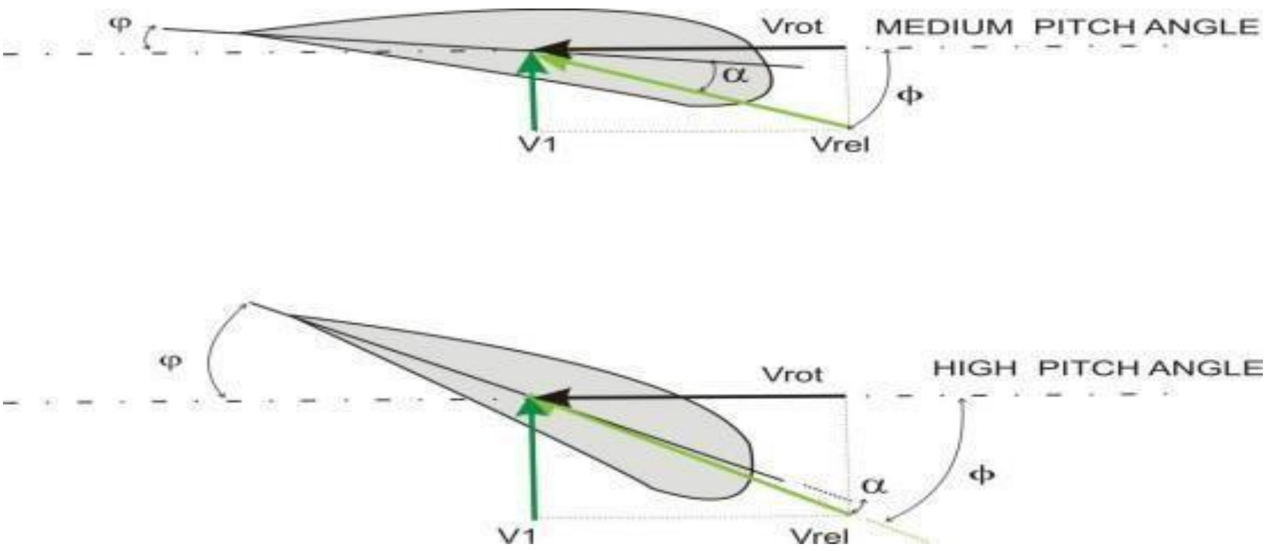



*Figure 19: Pitch mechanism (researchgate (2021))*

The pitch angle can be increased to minimize the maximum forces on the blades and thus reduce the power, in the case of strong winds, the blades can be feathered in relation to the wind direction to break it completely. As I can decrease the stall angle to increase the power. *3.3.3 Wake effect:*

Facing the wind, a wind turbine captures a large part of the wind and transforms it into mechanical and electrical energy, therefore the wind downstream of the turbine is always turbulent and slowed down compared to the wind upstream of the rotor. This is called the wake effect.

### 3.3.3 Turbulence:

Turbulence is a random disturbance of wind speeds and directions. This phenomenon is often noticed in terrains with high roughness and obstacles.

Turbulence makes it difficult for a wind turbine to recover kinetic energy from the wind, and turbulence increases the fatigue of the mechanical components of the turbine.

The greater the height of the tower, the more turbulence is avoided from the ground.

# 4 Presentation of the Khalladi wind farm

## 4.1 *Park design:*

The 120 MW wind farm consists of 40 wind turbines with a power of 3 MW each, placed along the ridge of Jbel Sendouq, belonging to the province of Fahs Anjra, 30 km from Tangier, has a production capacity of up to 380GWh per year.

The project covers an area of 180 ha, around the Jbel Sendouq ridge, an area that includes roads, housing for security guards, wind turbines, and the operation and maintenance station. In 2014, ACWA Power acquired the stake in the Khalladi wind farm and in September 2015, construction work began and was to be completed in two years.

During the same period, a 225Kv HV power line, 24 Km long, was built by Cegelec to connect the park to the ONEE substation located west of the city of Tetouan. Once the construction work has been completed, Nomac is committed to ensuring the operation and maintenance of the park.

On June 29, 2018, the park began its first injections into the National Grid. The Khalladi park is equipped with Vestas V90-3MW turbines, with three 45m long blades and an 80m high tower.

Below, two captures, the first one of a part of the park on google maps and the second one showing the distribution of the wind turbines in the park:


*Figure 20: Google maps of Khalladi Park  (July 2020)*


*Figure 21: Layout of the park on the SCADA system*

## 4.2 *Specifications of Vestas V90-3MW Turbine:*

### 4.2.1 Description of the pod :

Located at the top of the mast, the nacelle contains all the equipment allowing the operation of the wind turbine, its cover is generally made of composite materials; fiberglass for the V90-3MW model.

- Gearbox :

Also known as a gearbox, it is a mechanism for changing the speed of rotation between the input and the output, and is used to transform the low-speed, high-torque power produced by the rotor into high-speed, low-torque power that is transmitted to the generator.

Indeed most electric generators require a certain range of speeds to turn, generally from 1000 to 2000 rpm, while the frequency of rotation of the rotor is related to the diameter of the rotor, it is all the slower the larger the diameter of the rotor. Hence the importance of multiplying the speed obtained by the wind generator before driving the generator (Vestas Official Website).

- Yaw system :

The yaw system rotates the entire nacelle, ensuring that the blades are always facing into the wind

- Brake system :

During very strong winds, the braking system ensures the survival of the wind generator by reducing the mechanical stress on the machine in case of over speed on the rotor. The turbine brakes by feathering the rotor blades. The individual pitch cylinders ensure a triple braking safety.

In addition, a hydraulic system supplies pressure to a disc brake located on the main gear high speed shaft. The disc brake is considered the parking brake.

- Generator:

It is an asynchronous generator with 4 poles and a wound rotor, it converts the mechanical energy of the rotor into electrical energy.

- Transformer:

The step-up transformer is located in a separate compartment at the rear of the nacelle. The transformer is a three-phase dry-type cast resin transformer specifically designed for wind turbine applications.

The windings are connected in delta on the medium voltage side, unless otherwise specified. The windings are connected in star on the low voltage side (1000 V and 400 V). The 1000 V and 400 V nacelle systems are a TN system, where the star point is connected to earth. The arresters are mounted on the medium voltage (primary) side of the transformer.

Available output voltages are in 0.5 kV steps from 10 to 34.5 kV, with 36 kV (um) being the highest peak voltage of the equipment. The processing room is equipped with arc detection sensors.

- Cooling and air conditioning system:

If the temperature of the air inside the basket exceeds a certain level, the poppet valves will open to the outside. A fan motor will draw in outside air to cool the nacelle air.

The gear lubricating oil, the cooling water of the unit and the variable speed unit are cooled by a separate air inlet, using separate water/air cooling systems. The water coolers are thermally insulated from other parts of the nacelle. A separate fan cools the transformer.

The heat exchanger system is mounted in a separate compartment in the upper rear part of the pod.

### 4.2.2 Rotor description:

It is the rotating part of the wind generator; it includes the hub and the blades and allows the kinetic energy of the wind to be transformed into mechanical energy.

- Hub:

It is mounted directly on the slow speed shaft of the gearbox, it supports the blades and it is equipped with a regulation system which allows it to modify the pitch of the blades.

- Pitch control system:

Placed in the hub, the pitch mechanism ensures that the blades are positioned at the optimum pitch angle. Changes in blade pitch angle are made by hydraulic cylinders capable of rotating the blade by 95°. Each blade has its own hydraulic cylinder.

- Blades:

Made of glass and carbon fiber, the blades are designed for optimized output and minimal reflection of noise and light. The V90 blade design minimizes the mechanical loads applied to the turbine.

### 4.2.3 Regulation and control systems:

The machine and production control data are obtained from several sensors:

- Weather conditions: wind direction and speed, temperature
- Machine conditions: temperature, oil level and pressure, cooling water level, vibrations.
- The connection to the network: active power, reactive power, cos φ, voltage, current, frequency.

### 4.2.4 Sensors:

- The machine is equipped with two ultrasonic wind sensors located on top of the gondola.
- The tower and platform are equipped with optical smoke detectors.
- Each blade is equipped with a lightning detector
- The accelerometers record the movements of the top of the tower to eliminate adverse movements and vibrations.
- The turbine is also equipped with GPS which is mainly used to synchronize the turbine's clock, allowing the logs of one turbine to be compared with those of other turbines in the same area.
- The transformer and the low voltage switchboards are protected by an arc protection system.


*Figure 22: Components of the Vestas V90-3MW wind turbine (Wikipedia)*

# 5 Issues:

The technical operation of a wind farm is a tedious task which, beyond the classic production supervision, requires a fine and regular analysis of the production data in order to detect any anomaly.

The analysis of the data of a wind farm in operation is crucial and must be done regularly. By creating specific performance indicators from the raw production data, the asset manager is able to detect possible anomalies and start looking for a solution with the maintenance providers.

In this context, the International Electro technical Commission has presented the IEC 6140012 standard, which aims to provide a uniform methodology for measuring, analyzing and reporting the energy performance characteristics of horizontal axis wind turbines producing electricity.

The power performance of wind turbines is characterized by the measured power curve and the estimated annual energy production.

The calculation of the power curve uses the wind speeds measured at the nacelle. These speeds are influenced by the turbine rotor and therefore they must be corrected for this effect of distortion of the flow. The procedures for determining this correction are described in the methodology.

This work therefore proposes an analysis methodology based on IEC 61400-12, to evaluate the performance of the KHALLADI wind turbines, using operational production data extracted from the SCADA control and data acquisition system (wind speed, power and energy produced, wind direction and nacelle), and then several optimization measures are suggested to improve performance.

The topic will cover the following questions:

- What is the impact of underperformance on returns?
- What are the sub-performance machines?
- What are the main reasons for underperformance?
- What measures can be taken to minimize and eliminate this impact?

## 5.1 *Definitions:*

### 5.1.1 SCADA :

A Supervisory Control and Data Acquisition (SCADA) system is software for process control and real-time data collection from remote sites.

SCADA technology can be used in any industrial process, including power plants, oil and gas, telecommunications, transportation, and water and waste management.

SCADA systems consist of hardware and software components. The hardware components collect data and gather it on a computer running SCADA software. The computer then processes this data and presents it in a timely manner. In addition, the SCADA system records and logs all events in a file stored on a hard disk or sends them to a printer.

The SCADA system also issues alarms when conditions become hazardous.

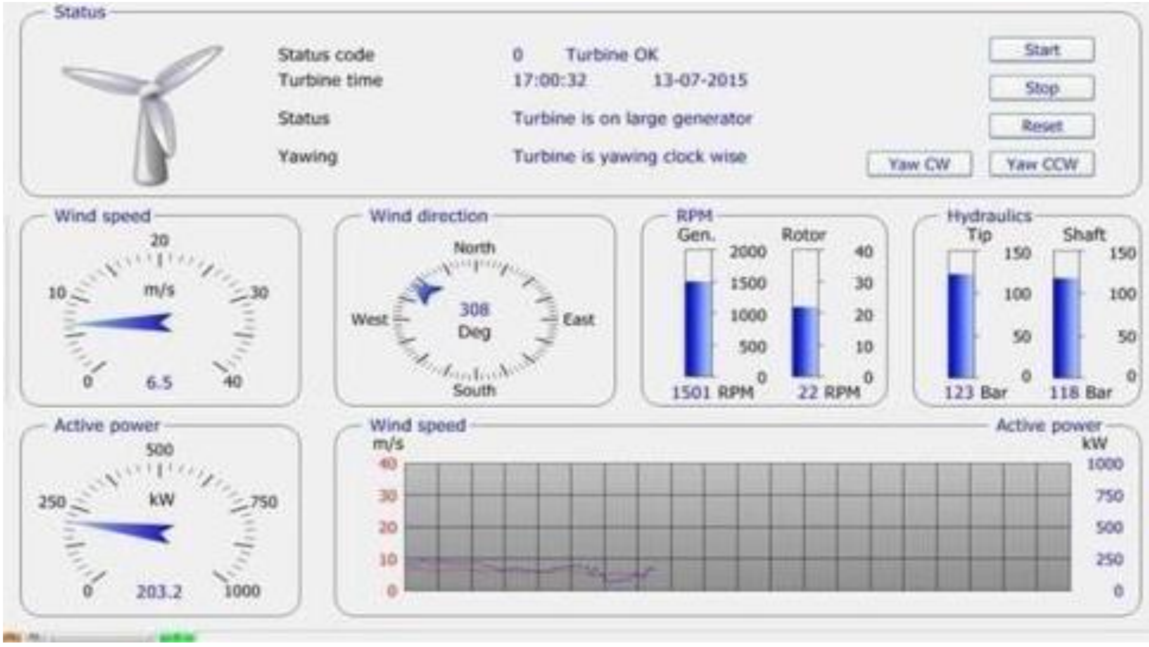


*Figure 23: SCADA interface showing the different measured data*

### 5.1.2 Power curve:

The power curve is a graph showing the electrical power produced by the wind turbine as a function of different wind speeds.

Usually these curves are given by the wind turbine manufacturers and are certified by a laboratory and defined under standard test conditions. Thus the contractual power curve represents a kind of assurance for the operators regarding the actual performance of the wind turbine.

The power curve is characterized by three parameters:

- **The minimum start-up speed (cut-in wind speed):** this is the wind speed at which the wind turbine starts to deliver useful power
- **The maximum or cut-off wind speed:** this is the maximum acceptable speed for the wind turbine. Beyond this speed, the wind turbine is automatically stopped to preserve its integrity.
- **Rated power:** this is the maximum electrical power that can be extracted from the wind turbine.

Generally, the power curves take the following shape:

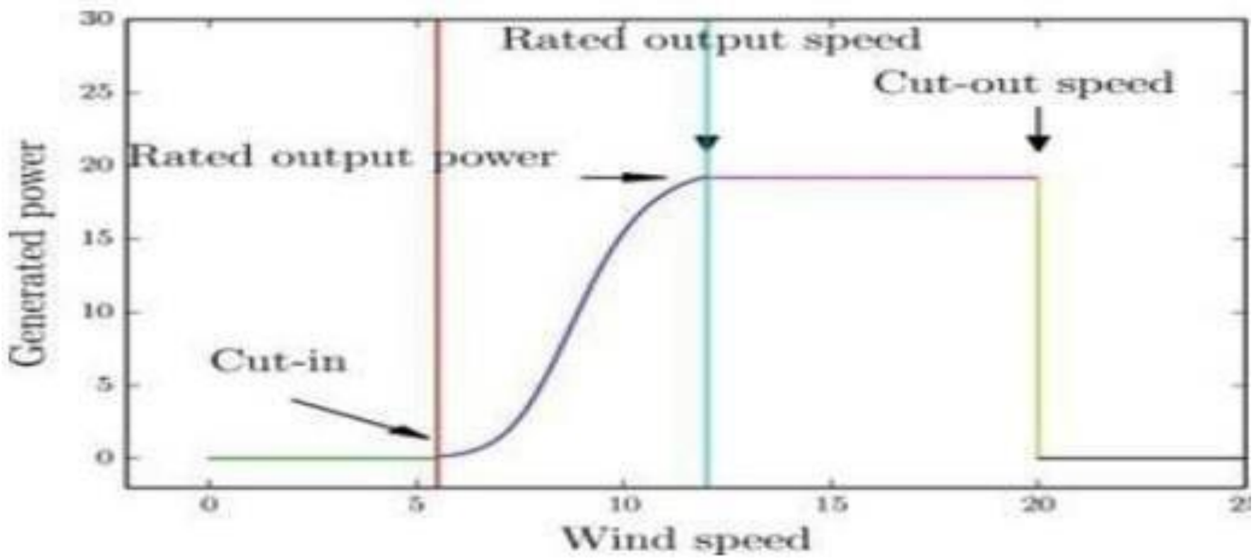



*Figure 24: General power curve of a wind turbine (theroundup (2012))*

Vestas V90-3MW turbine data and contractual power curve:

| Wind speed (m/s) | Power (W) |
|---|---|
| 4 | 77 |
| 5 | 190 |
| 6 | 353 |
| 7 | 581 |
| 8 | 886 |
| 9 | 1273 |
| 10 | 1710 |
| 11 | 2145 |
| 12 | 2544 |
| 13 | 2837 |
| 14 | 2965 |
| 15 | 2995 |
| 16 | 3000 |
| 17 | 3000 |
| 18 | 3000 |
| 19 | 3000 |
| 20 | 3000 |
| 21 | 3000 |
| 22 | 3000 |
| 23 | 3000 |
| 24 | 3000 |
| 25 | 3000 |

*Table 1: Speed and power data of the contractual power curve of the V90-3MW machine*

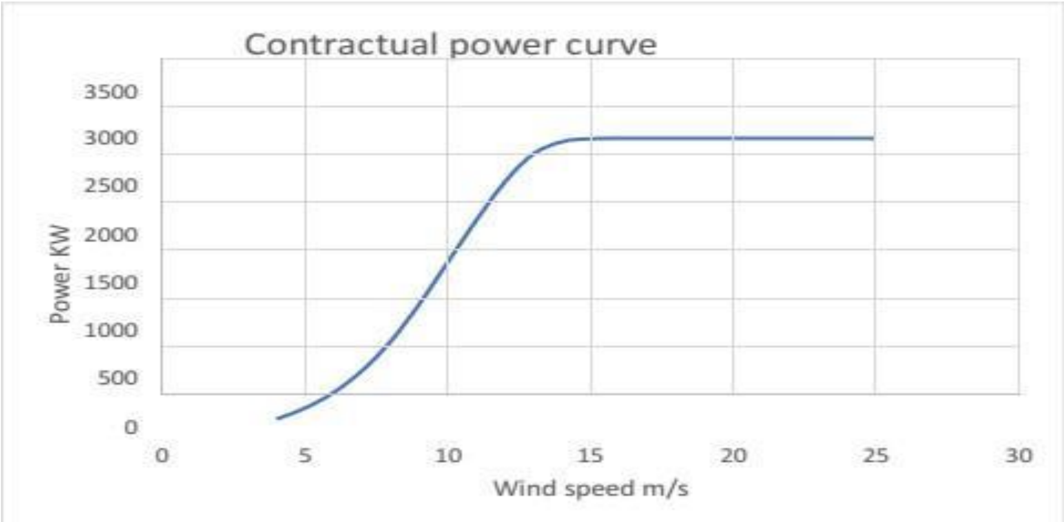



*Figure 25: Contractual power curve of the V90-3MW machine*

### 5.1.3 Availability:

The term "availability" used in the wind turbine industry is a measure of the potential of a wind turbine or wind farm to generate electrical energy.

- Technical and contractual availability:

➢ **Contractual availability: this is** a measure given by the turbine supplier and negotiated in an agreement with the operation and maintenance department for a given project. Contractual availability values can often not be used directly as a factor for energy loss and must necessarily be based on technical availability.

➢ **Technical availability:** or effective turbine availability seeks to describe the performance of the turbine. Indeed, turbines are supposed to generate electricity when the site conditions are within the specified operating ranges, which is always not the case, in case of maintenance or shutdown, the production decreases as well as the efficiency of the turbine, hence the importance of availability

▪ Methods for calculating availability from SCADA data: Availability can be calculated as a ratio of two time values or as a ratio of energy values:

$$\text{Availability in terms of time} = \frac{\text{length of time the turbine was available}}{\text{Total time considered}}$$

$$\text{Availability in terms of energy} = \frac{\text{energy produced by the turbine potentially}}{\text{Expected energy}}$$

The time-based availability calculation is easier to calculate but does not take into account variations in wind speeds. It is common for turbines to have lower availability during periods of high wind than during periods of low wind, high winds cause increases in generation and loads, which can increase the number of outages and downtime.

So, if a project is able to limit the maintenance and service time of a wind turbine to low wind hours, that turbine will produce more energy than another with the same total downtime, but which will suffer from failures, especially during windy periods.

### 5.1.4 Windographer:

Windographer is the industry's leading software for the analysis of wind resource data measured by a measuring mast, such as: wind speed, standard deviation, direction, temperature, pressure and relative humidity.

The program quickly imports data from almost any format and automatically determines the data structure and facilitates the analysis of this data.

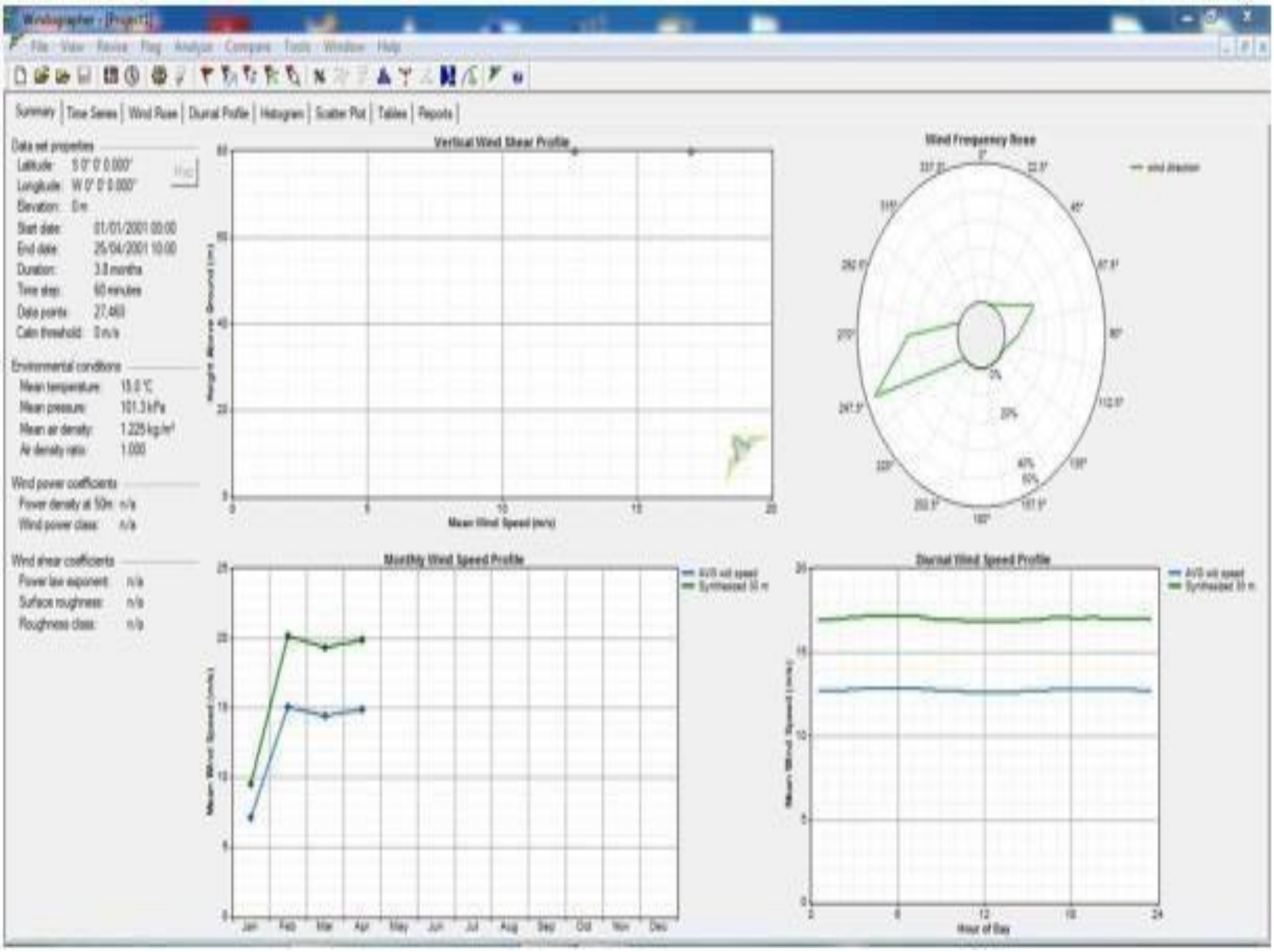



*Figure 26: Windographer home interface*

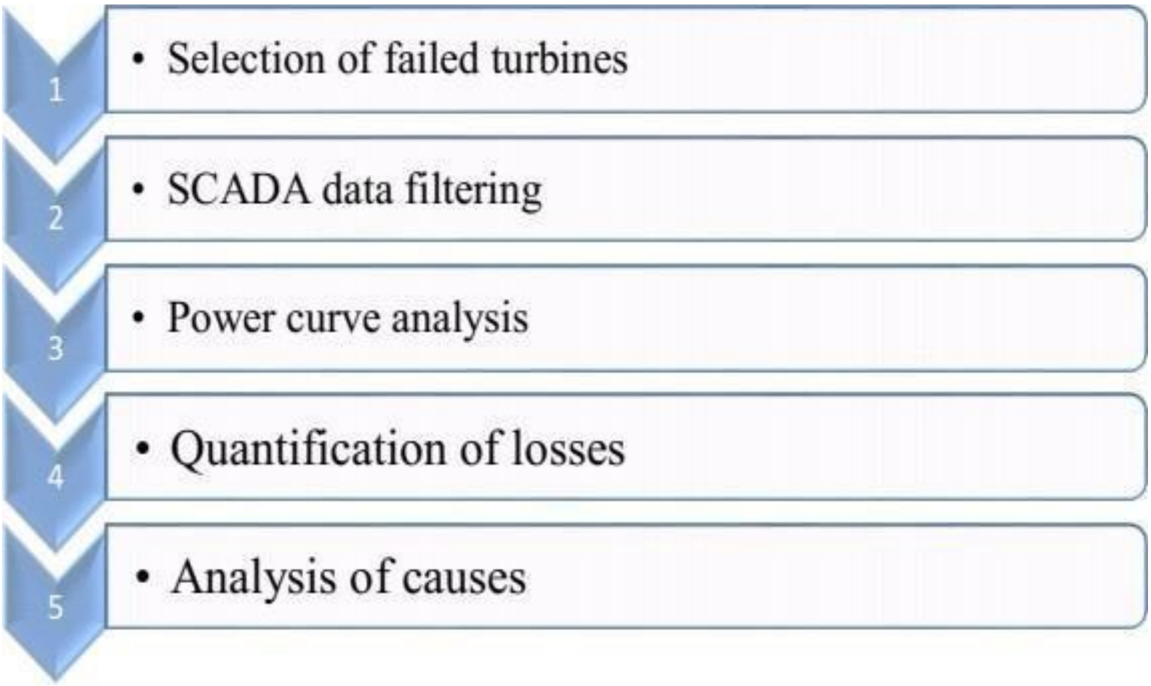
# II. Working Methodology

## 1. Methodology:

As already mentioned before, the performance analysis of the turbines is mainly based on the analysis of the power curve, which has to be calculated from the SCADA data.

The objective is to define the turbines representing a case of underperformance, to plot their power curves and to analyze them in order to detect the causes of the underperformance and to correct them afterwards. The turbines representing the underperformance are the:

- ➢ With a high availability rate >97% and low production
- ➢ With low availability and low production to do this, I will follow the following methodology:



## 2. Justification of the choice of turbine:

The normalization coefficient for each turbine is calculated by the following formula:

$$\mathbf{F}\boldsymbol{i} = \frac{\textbf{Active Production WTG } \boldsymbol{i}}{\textbf{average of all productions}}$$

I am interested in turbines with a coefficient Fi<94%, the 6% being considered as a tolerated uncertainty rate, 3% related to losses due to wind conditions and 3% related to the availability of the machine. So any loss above 6% is strongly linked to underperformance.

## 3. SCADA data filtering:

The SCADA system provides as mentioned above measurements of wind speed, power, energy and direction for every 10 min. The data for the selected turbines will be filtered by Excel, and the filtration consists of:

- ➢ Eliminate wind speeds below the starting speed of 4m/s
- ➢ Eliminate speeds above the 25m/s stopping speed
- ➢ Eliminate powers below 0
- ➢ Eliminate all points representing a false reading

## 4. Power curve analysis:

Draw the curve P=f (v) using the powers and speeds after filtration and superimpose it with the contractual curve.

The analysis consists in studying the gap between the operational power curve and the contractual curve at each speed point. Indeed, a large deviation reflects a real problem of underperformance, the cause of which varies from one turbine to another.

## 5. Quantification of losses:

Calculation of the active energy losses corresponding to each speed point, calculating the difference between the contractual energy that the turbine must generate, and the operational energy produced that the SCADA system provides.

The contractual energy is not given by the supplier or by the SCADA system, it is calculated using the following relationship:

$$E_i\ contr = V_i * frequency * P_i * duration\ (h)$$

## 6. Cause analysis:

The causes and consequences of underperformance are many and varied, and change depending on the length of time the fleet has been in operation. A fleet that has been in operation for 10 years or more will be more difficult to analyze than a fleet that has been in operation for one year.

The following table represents the different types of wind farms according to the duration of operation:

| Type of site | 1-5 years | 5-10 years | 10-20 years |
|---|---|---|---|
| A | X | | |
| B | | X | |
| C | | | X |

*Figure 27: Types of wind farms by operating time*

The Khalladi wind farm belongs to the first category with an operational life that does not exceed 1 year. For this category, the causes of underperformance are generally related to:

### 6.1. *Construction phase:*

During installation, components such as blades, gearboxes, generators, etc. can become deformed and fail. In addition, misalignment problems can occur due to poor nacelle calibration.

6.2. *Environmental site conditions:*

When choosing a site for a wind farm, it is necessary for the investors to define the meteorological conditions of the site, in particular: the average annual speed, the degree of turbulence, the extreme gusts which can occur in a future period of 50 years...

This data will allow the developers to define an optimal location for each wind turbine so that they can operate perfectly whatever the weather conditions they will face during operation. *6.3 Incorrect execution of the maintenance program:*

A poor maintenance and quality program during the first years of operation can lead to serious underperformance of the wind farm.

# III. Performance Analysis: Application to Khalladi Park

## 1. Choice of turbines to be studied

| Turbines | Active energy produced kWh | Normalization coefficient : F(%) | Availability (%) |
|---|---|---|---|
| WTG18 | 3420380,3 | 114,069687 | 99,77 |
| WTG14 | 3404841,3 | 113,551461 | 99,38 |
| WTG16 | 3351753,3 | 111,780976 | 98,99 |
| WTG17 | 3333821,3 | 111,182944 | 98,54 |
| WTG38 | 3329790,3 | 111,04851 | 99,03 |
| WTG25 | 3329457,3 | 111,037405 | 99,92 |
| WTG20 | 3321023,3 | 110,756131 | 98,7 |
| WTG23 | 3320100,3 | 110,725349 | 99,64 |
| WTG24 | 3262895 | 108,817552 | 97,86 |
| WTG28 | 3259397,3 | 108,700904 | 99,9 |
| WTG39 | 3259202 | 108,69439 | 99,85 |
| WTG40 | 3256778 | 108,61355 | 99,22 |
| WTG21 | 3248388,3 | 108,333753 | 99,34 |
| WTG22 | 3199692,3 | 106,709742 | 91,45 |
| WTG31 | 3199030,3 | 106,687664 | 99,51 |
| WTG15 | 3158954,3 | 105,351129 | 98,94 |
| WTG37 | 3152114 | 105,123005 | 99,71 |
| WTG32 | 3145266 | 104,894625 | 99,5 |
| WTG36 | 3144158,3 | 104,857683 | 99,87 |
| WTG19 | 3094920,3 | 103,215595 | 97,89 |
| WTG10 | 3088252,3 | 102,993218 | 99,14 |
| WTG26 | 3061216,3 | 102,091567 | 99,43 |
| WTG12 | 2977854,2 | 99,3114409 | 98,24 |
| WTG27 | 2954187,2 | 98,5221464 | 99,9 |
| WTG11 | 2950374 | 98,3949762 | 98,87 |
| WTG06 | 2945623,2 | 98,236537 | 99,63 |
| WTG29 | 2915162,2 | 97,2206626 | 99,36 |
| WTG35 | 2884021,2 | 96,1821102 | 99,01 |
| WTG03 | 2862695,2 | 95,4708881 | 99,7 |
| WTG34 | 2848675,2 | 95,0033211 | 99,74 |
| WTG07 | 2844855,2 | 94,8759241 | 99,63 |
| WTG05 | 2834578,2 | 94,5331861 | 99,22 |
| WTG04 | 2815873,2 | 93,9093743 | 99,38 |
| WTG01 | 2760837,2 | 92,0739237 | 98,01 |
| WTG08 | 2758737,2 | 92,0038887 | 99,13 |
| WTG02 | 2658259,2 | 88,6529473 | 99,64 |
| WTG09 | 2633242,2 | 87,8186303 | 89,5 |
| WTG33 | 2520008,2 | 84,0422763 | 98,98 |
| WTG13 | 2492718,2 | 83,1321547 | 98,65 |
| WTG30 | 940888,9 | 31,3786459 | 92,12 |

*Table 2: Classification of the 40 turbines in the park according to the normalization*

Based on the normalization coefficient, turbines are classified into three categories:

| | |
|---|---|
| Group 1 | F>97% |
| Group 2 | 94%<F<97% |
| Group 3 | F<94% |

*Table 3: Classification of turbines into three groups*

Following the criteria for the choice of turbines to be analyzed, I have the turbines of the first and second group, which do not represent cases of underperformance, so I will be interested only in the turbines of the third group, whose normalization factor is below 94%.

| Group 3: F<94%. | | | | | | | |
|---|---|---|---|---|---|---|---|
| WTG01 | WTG02 | WTG04 | WTG08 | WTG09 | WTG13 | WTG30 | WTG33 |

*Table 4: Group 3 turbines*

**Verification:**

The figures below represent for each group, the operational power curves superimposed on the contractual power curve.

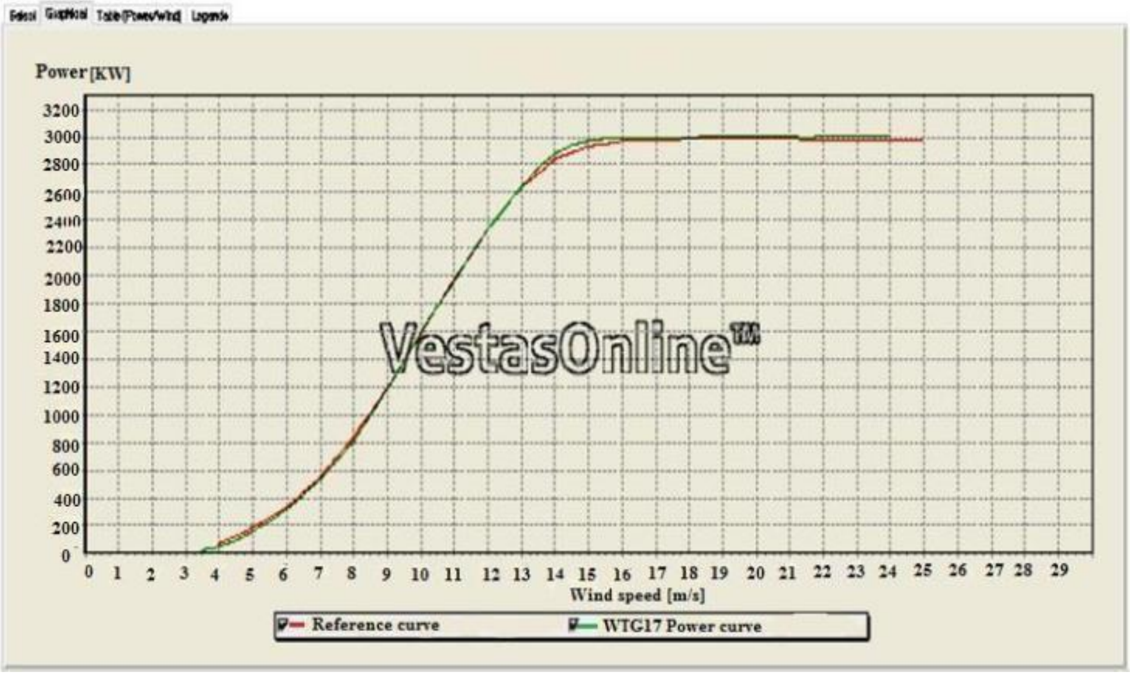



*Figure 28: Contract and operational curve representing Group 1, SCADA (VestasOnline)*

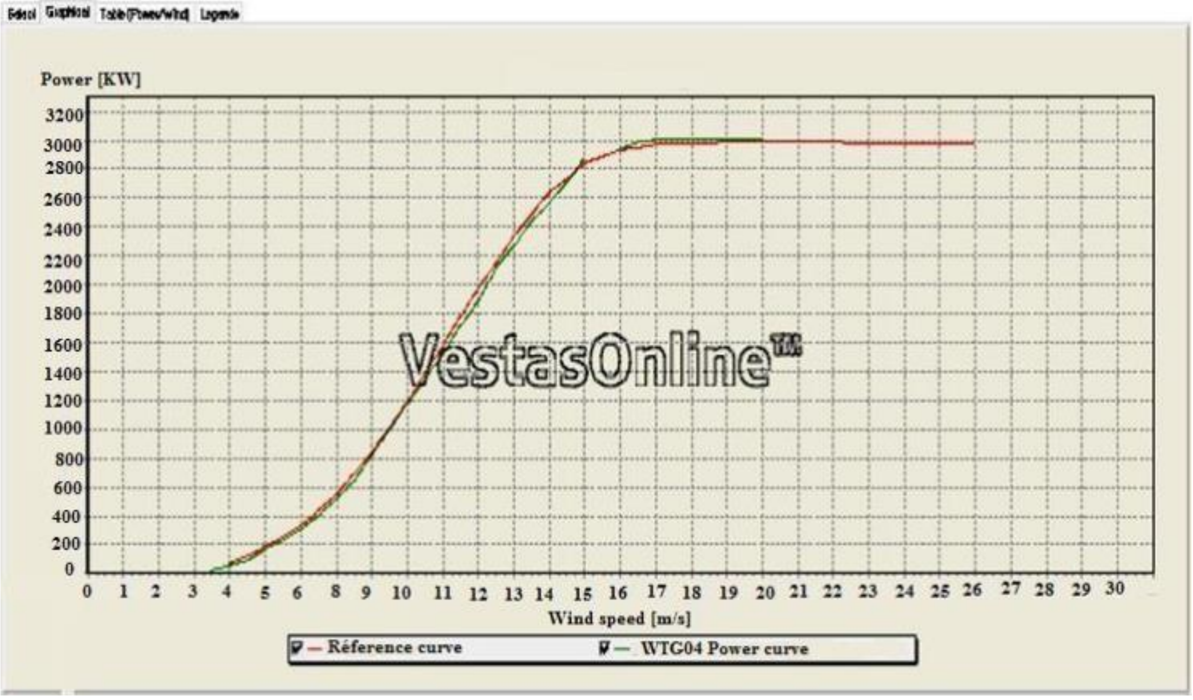



*Figure 29: Contract and operational curve representing Group 2, SCADA (VestasOnline)*

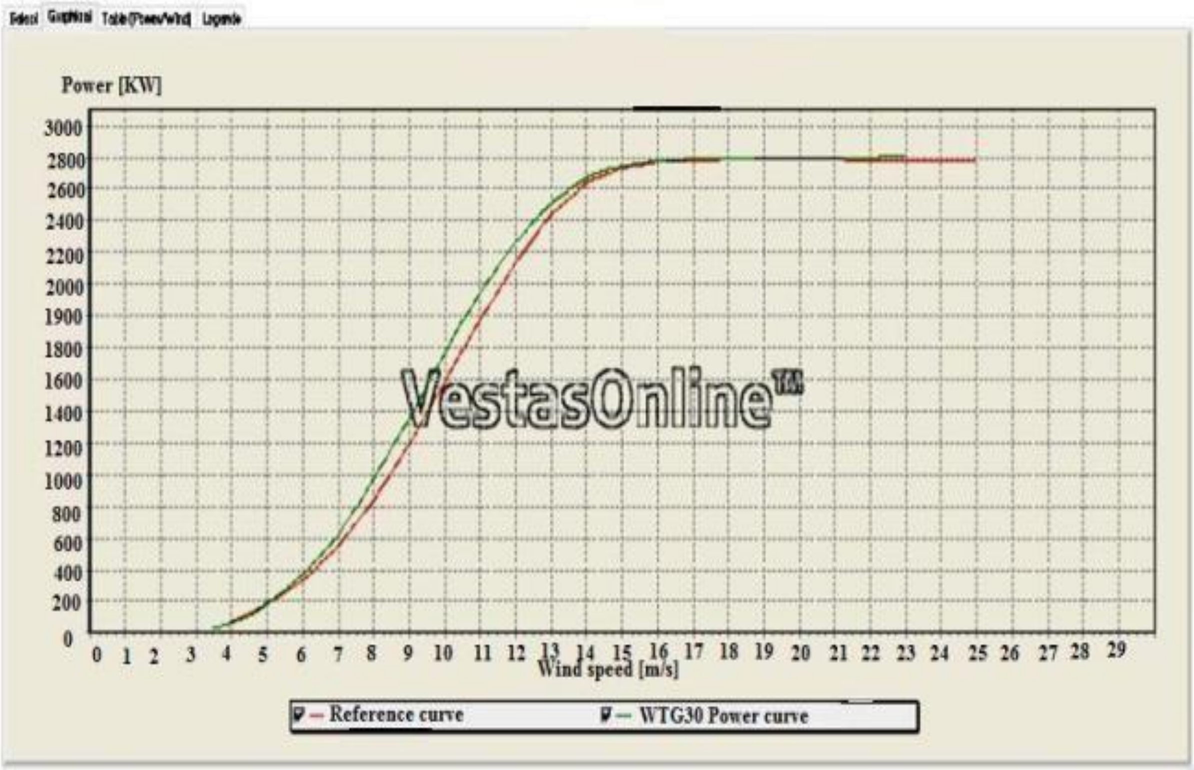



*Figure 30: Group 3 contract and operational curves (VestasOnline)*

By comparing the curves of the three groups, I notice that, contrary to the first and second groups, the operational curve (in red) of the third group represents a remarkable deviation from the contractual curve (in green), this deviation means that the turbine does not manage to reach the contractual curve therefore this is the case of an under performance.

## 2. Data filtering:

The case of turbine 9 belonging to the third group will be dealt with as an example. In the first instance:

- ➢ Wind speeds **<4m/s** and **>25m/s** are filtered
- ➢ I filter the values of powers <0
- ➢ Then I eliminate all the points reflecting a false reading.

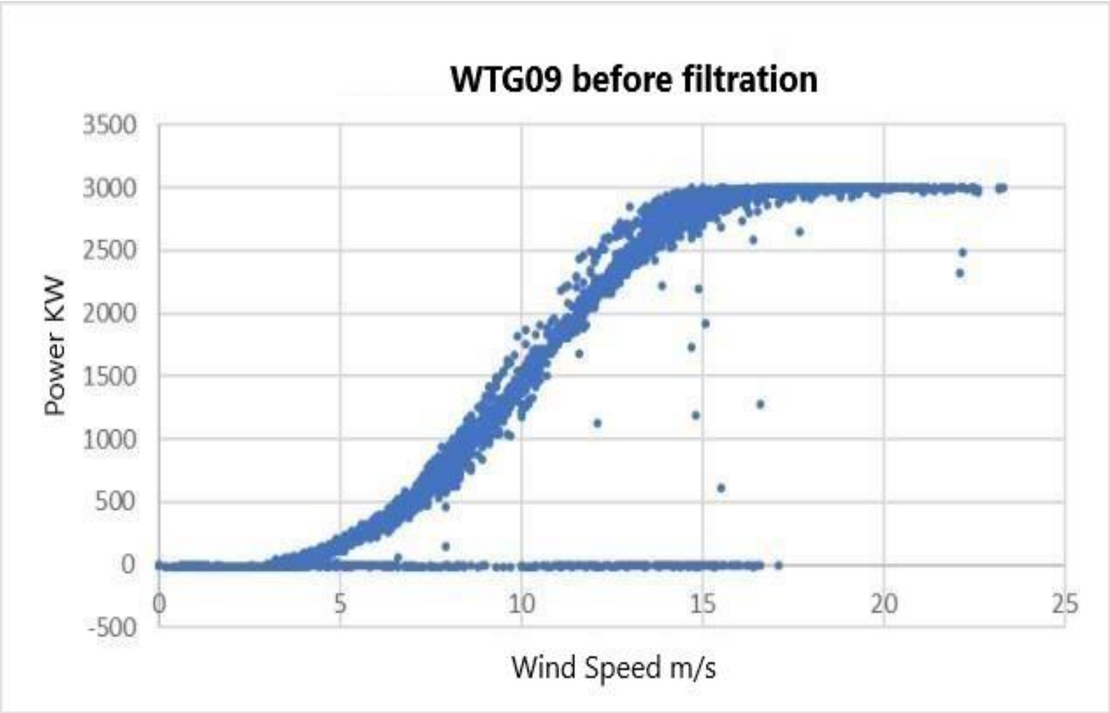



*Figure 31: Operating curve of machine 09 before filtration (VestasOnline)*

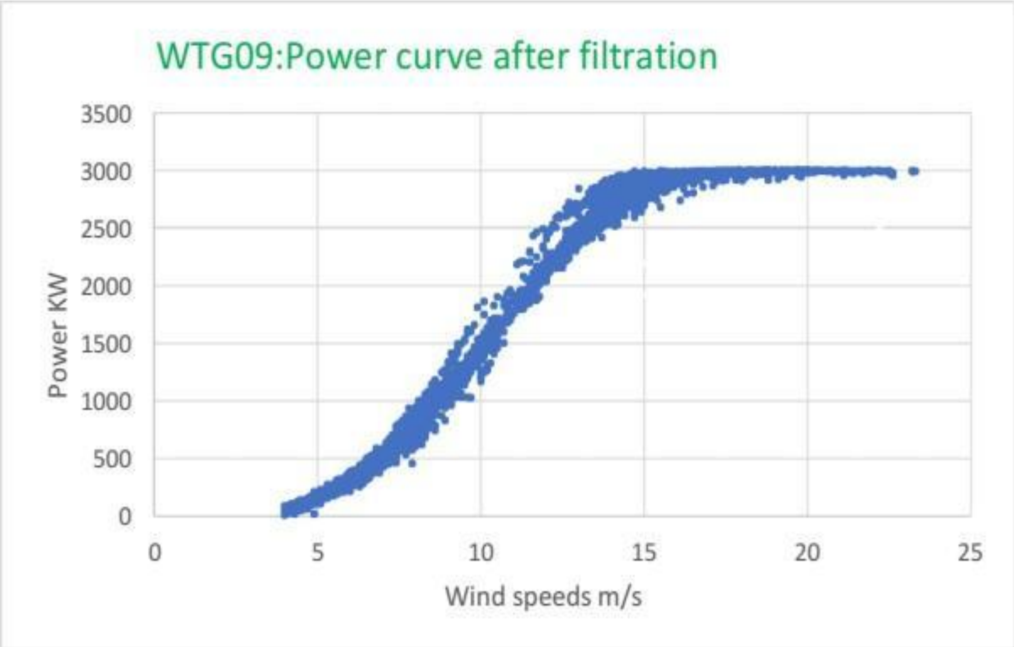



*Figure 32: Curve of machine 09 after filtration*

## 3. Performance Analysis:

After filtering the data, the power curves of the eight turbines were created and superimposed on the contractual curve of the V90-3MW turbine:


*Figure 33: Power curve of the WTG02 machine*


*Figure 34: Power curve of the WTG08 machine*

On this figure I notice that: between 4m/s (starting speed) and 10 m/s, the points of the operational curve and the contractual curve are superimposed, but from 15 m/s onwards all the points are below the curve, which means that the turbine is in a state of underperformance, mainly due to the problem of turbulence which appears at high speeds.


*Figure 35: Power curve of the WTG01 machine*

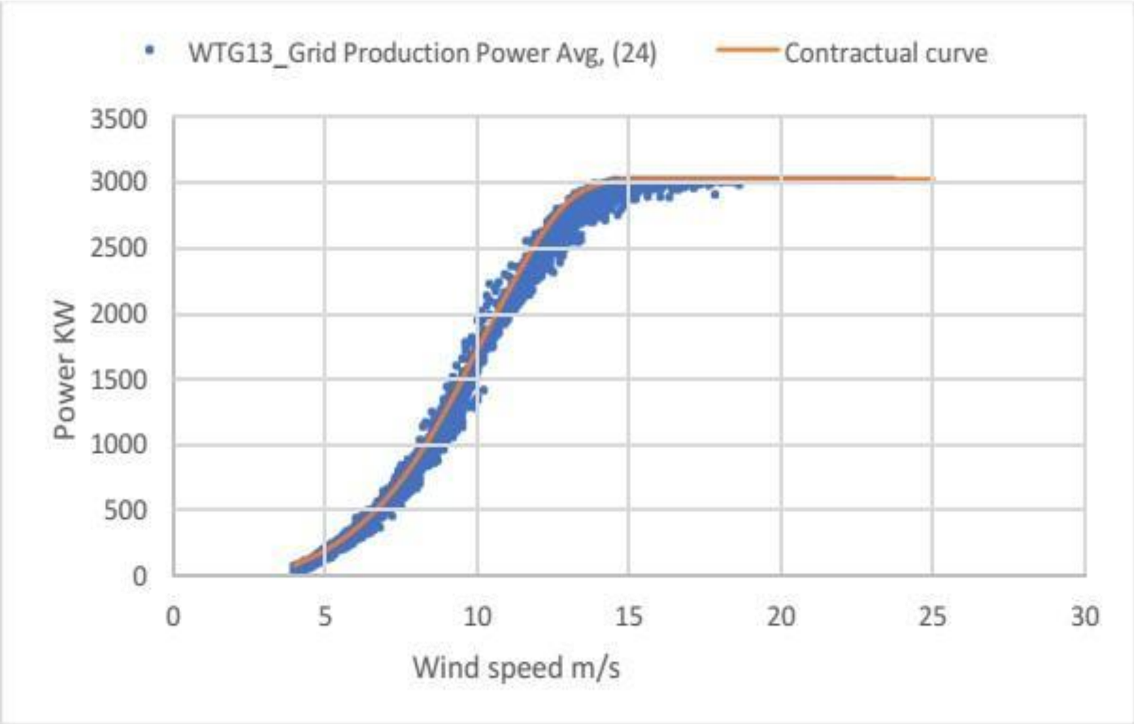



*Figure 36: Power curve of the WTG13 machine*

Similarly, above, I notice that the production is optimal up to the interval [12m/s, 15m/s], where the underperformance appears due to turbulence


*Figure 37: Power curve of the WTG04 machine*


*Figure 38: Power curve of machine 09*

In the case of these two turbines, all the points, from the start of the turbine to its stop, are under the contractual curve. Therefore, turbulence is not the only problem, but it is possible that a component is failing, and then a study must be carried out to detect the origin of the problem.


*Figure 39: Power curve of the WTG33 machine*

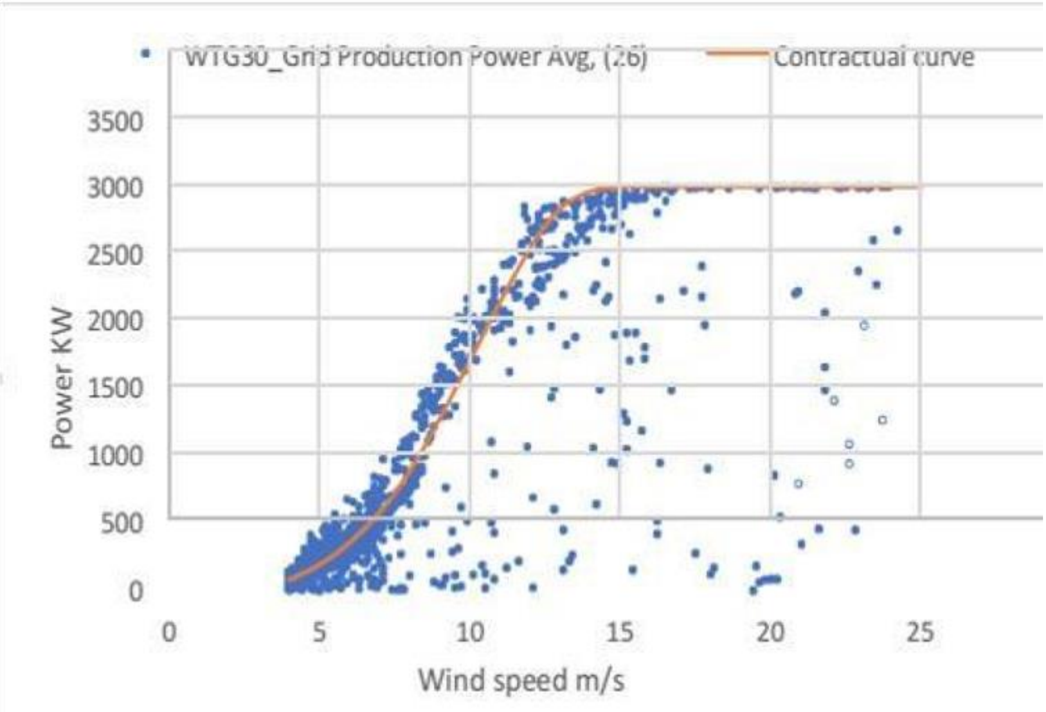



*Figure 40: Power curve of the machine 30*

This figure represents a double power curve, the gap between the two curves is very large, and the points of the curve are scattered so the underperformance is serious in this case.

In the case of turbine 30, the turbine represents a real problem for the park managers, because the machine is in good condition and its availability is always high. The cause of the under performance of the machine 30 is known, it is a bad orientation of the nacelle. Indeed, when the wind turbine was installed, it was not well calibrated with respect to the north, so the nacelle is always badly oriented because of its position and cannot follow the variations of the wind direction.

## 4. Quantification of losses:

As already mentioned in the methodology, the quantification of losses is the calculation of the difference between the contracted energy of the machine and the energy actually produced by the same machine.

The operational energy is given by the SCADA system, while the contractual energy must be calculated. In fact, the Windographer software allows us to facilitate this task and gives us the contractual energy values from the wind speed values and the machine availability value.

4.1. *Calculation of the contractual energy:*

➢ Export of machine data from SCADA: Wind speed, power, energy....

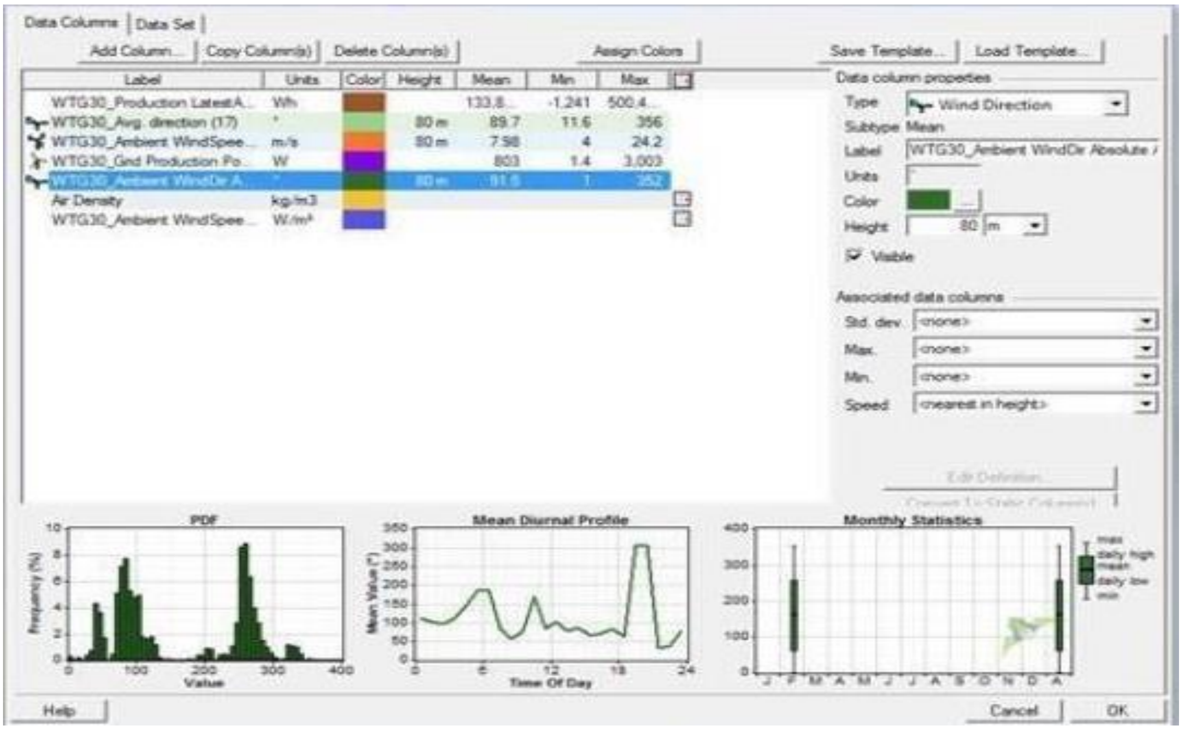


*Figure 41: Exporting data to Windographer*

➢ The model of the machine chosen to be studied: Vestas V90-3MW :

*Figure 42: Machine model selection*

➢ The defined availability value that corresponds to the actual operation of the site:

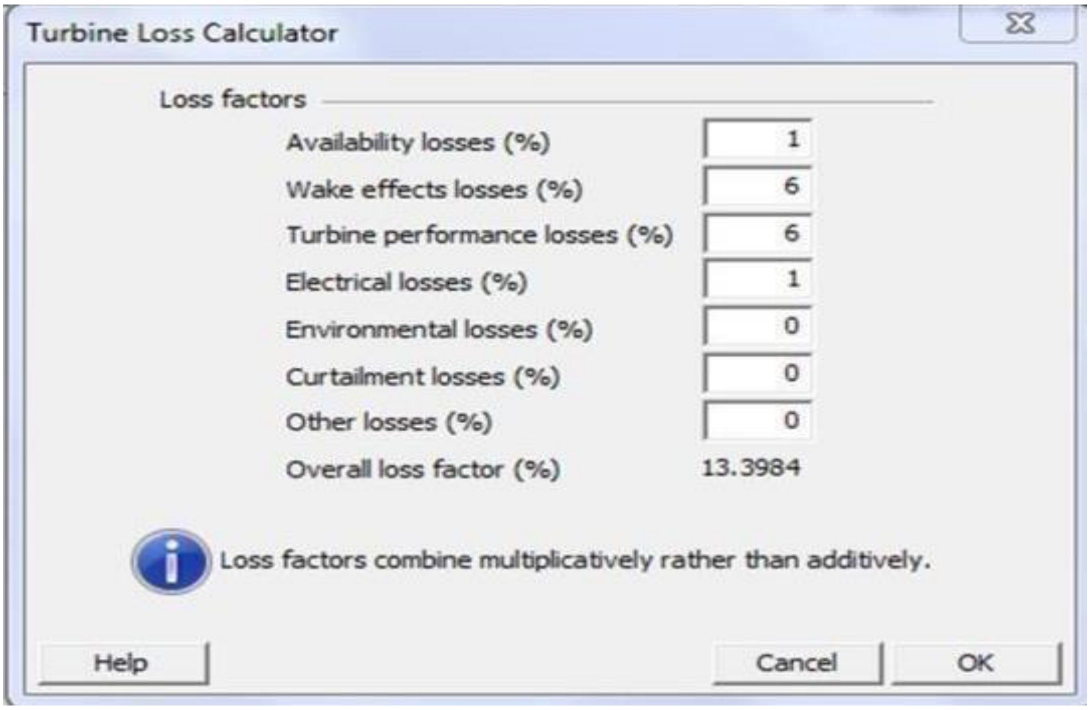



*Figure 43: determination of standard losses*

4.2. *Results of the calculations*:

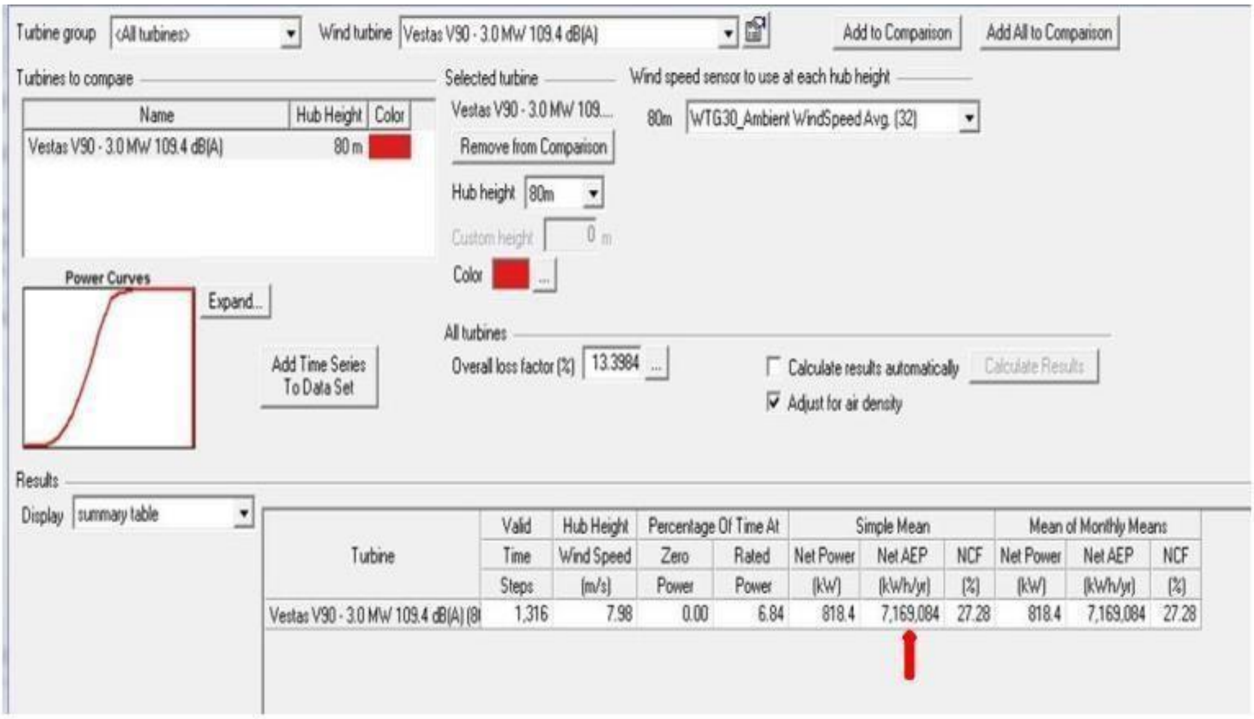



*Figure 44: Calculation of the theoretical net*

The same calculation process is applied for the other machines.

The table below shows the values of contracted and operational energy and the difference between the two in MWh and percentage %.

| WTG | Contractual energy (MWh) | Measured energy (MWh) | rt esen Energy (MWh) | Energy losses %. |
|---|---|---|---|---|
| WTG30 | 597,42 | 176,13 | 421,29 | 70,52 |
| WTG13 | 1896,58 | 994,03 | 902,54 | 47,59 |
| WTG09 | 1896,58 | 914,33 | 982,25 | 51,79 |
| WTG08 | 1148,60 | 952,58 | 196,02 | 17,07 |
| WTG04 | 1255,51 | 975,83 | 279,68 | 22,28 |
| WTG33 | 1231,63 | 816,58 | 415,05 | 33,70 |
| WTG02 | 1254,67 | 893,36 | 361,31 | 28,80 |
| WTG01 | 1301,05 | 944,24 | 356,80 | 27,42 |

*Table 5: Energy loss rates*

The following table contains the availability values for each machine:

| WTG | Availability |
|---|---|
| WTG30 | 92,12 |
| WTG13 | 98,65 |
| WTG09 | 89,5 |
| WTG08 | 99,13 |
| WTG04 | 99,38 |
| WTG33 | 98,98 |
| WTG02 | 99,64 |
| WTG01 | 98,01 |

*Table 6: Availability of the eight machines studied*

Using these two tables, the following graph was created:

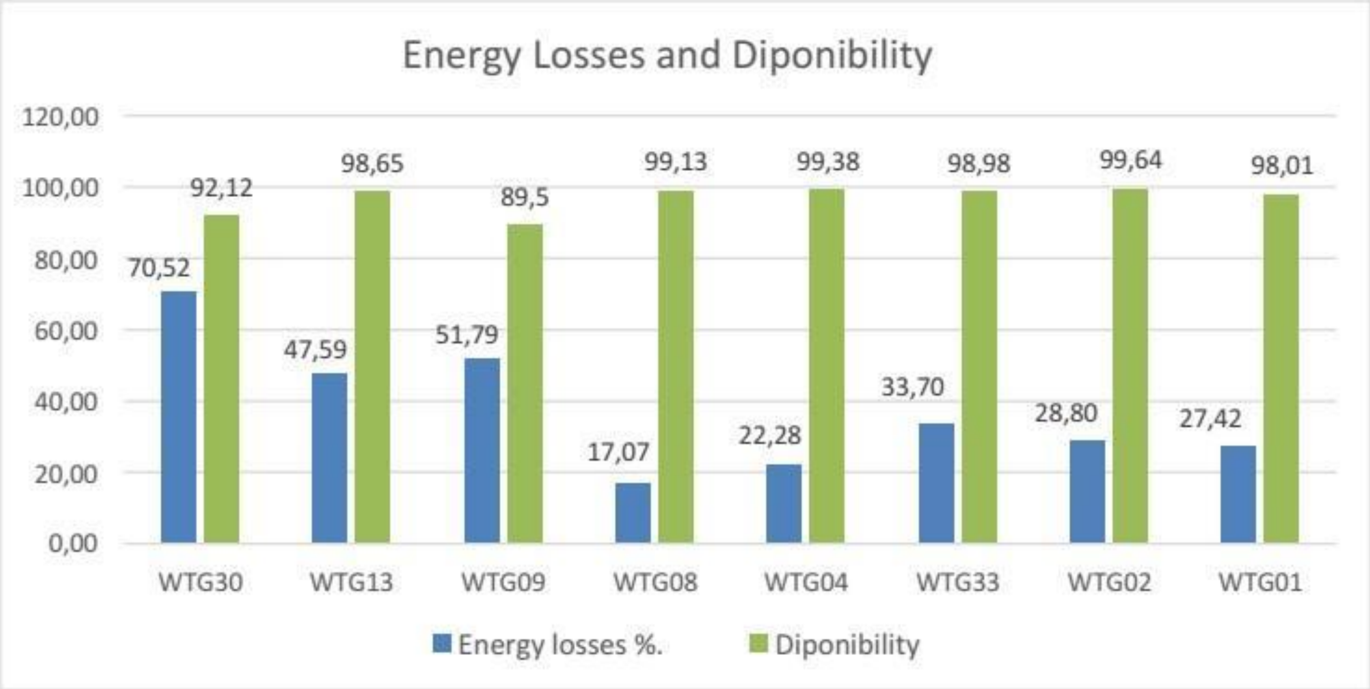



*Figure 45: Histogram of comparison between loss rates and availability*

The histogram gives us for each wind turbine studied the energy losses compared to the theoretical energy and the availability during the whole study period. It can be seen that wind turbines 30, 13, 09 and 33 represent significant losses and require an in-depth study, while the other wind turbines represent moderate losses with simple solutions

# IV. Results of the performance analysis

## 1. Results of the KHALLADI wind farm performance analysis

The following table represents the summary of the study, the normalization factor of each turbine, the causes of underperformance, the consequences and the probable impact of these causes on the machine or on the revenue.

| WTG | Normalization coefficient | Causes | Solution potential | Term on the long impact |
|---|---|---|---|---|
| 4 | 0.94 | Turbulence | Sector analysis | - Fatigue, damage to the main components.<br>- Higher operating and maintenance costs for the repair |
| 1 | 0.92 | Turbulence | Sector analysis | |
| 8 | 0.92 | Turbulence | Sector analysis | |
| 2 | 0.89 | Turbulence | Sector analysis | |
| 13 | 0.83 | Underperformance | Analysis of causes Roots | Losses in the income |
| 9 | 0.88 | Underperformance | Analysis of causes Roots | |
| 33 | 0.84 | Underperformance | Analysis of causes Roots | |
| 30 | 0.31 | Misdirection | Correction of the orientation with a Lidar for a complete alignment with the north direction | |

*Table 7: Classification of causes and impacts of underperformance for the eight wind turbines studied and possible solutions*

## 2. Sector analysis:

This is an advanced analysis that aims to establish a power curve for each wind sector, in other words, if the wind rose has 12 sectors, then 12 power curves must be made so that each power curve represents a wind sector. The purpose of this solution is to indicate the wind sectors responsible for the underperformance.

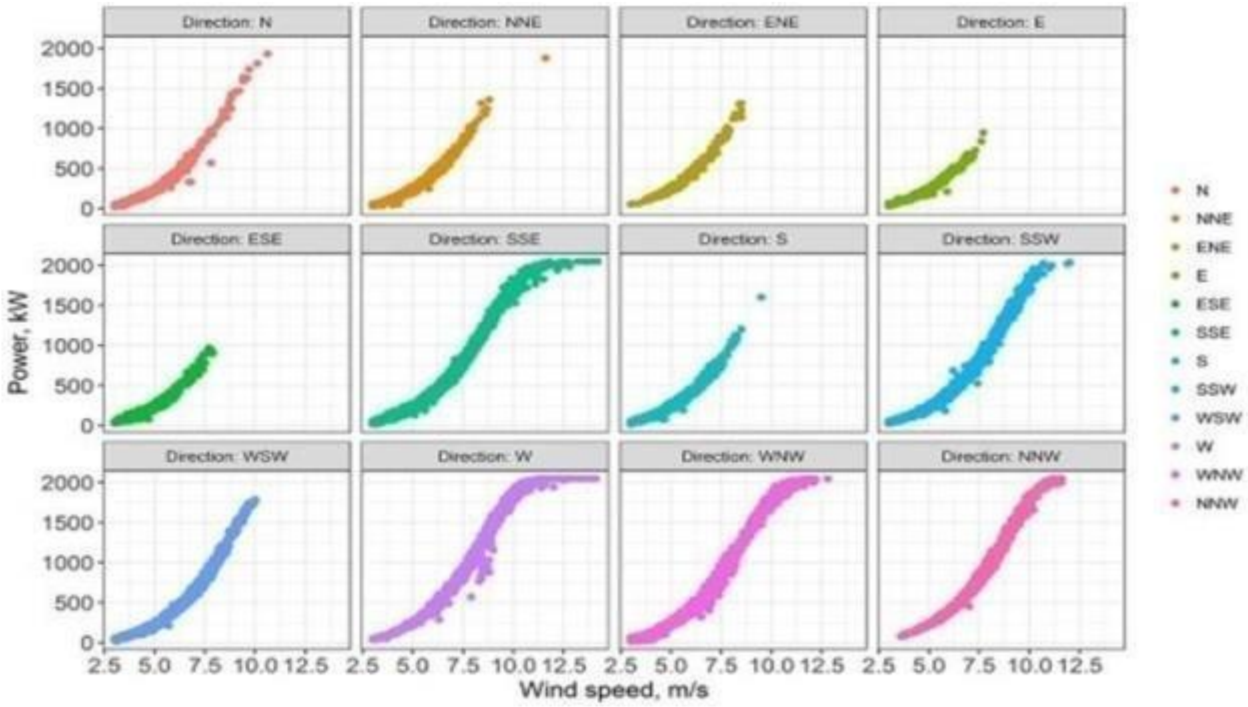



*Figure 46: Sectoral analysis of 12 wind sectors*

The figure below shows a sectoral analysis for a wind rose of 12 wind sectors, for each sector a power curve has been made in order to detect the wind sector responsible for the underperformance.

## 3. Root Cause Analysis:

When identifying a machine component (Yaw-motor, steering system, generator...) a root cause study is essential to understand the impact of this equipment on the underperformance. This study shows us the real cause of the problem, whether it is during the manufacturing of the equipment or its calibration...

## 4. Installation of a lidar to correct the orientation of the basket:

During the installation of the wind turbine, the calibration of the equipment is a very sensitive factor that can lead to very important losses if we are not careful. As in the case of machine 30, the poor calibration of the nacelle in relation to the north is the major cause of the under performance of the machine. In order to correct this problem, it is essential to use Lidar. LIDAR technology is a laser based optical remote sensing method for measuring wind speed and direction from a distance.

Then the erroneous readings of the nacelle anemometers will be corrected, and the machine can operate normally.


*Figure 47: Lidar (Wikipedia)*

The figure above explains how a Lidar works:

The device emits a laser beam into the air, which is reflected when it comes into contact with air particles.

The reflection of these light waves allows the Lidar to detect the speed and direction of the wind.

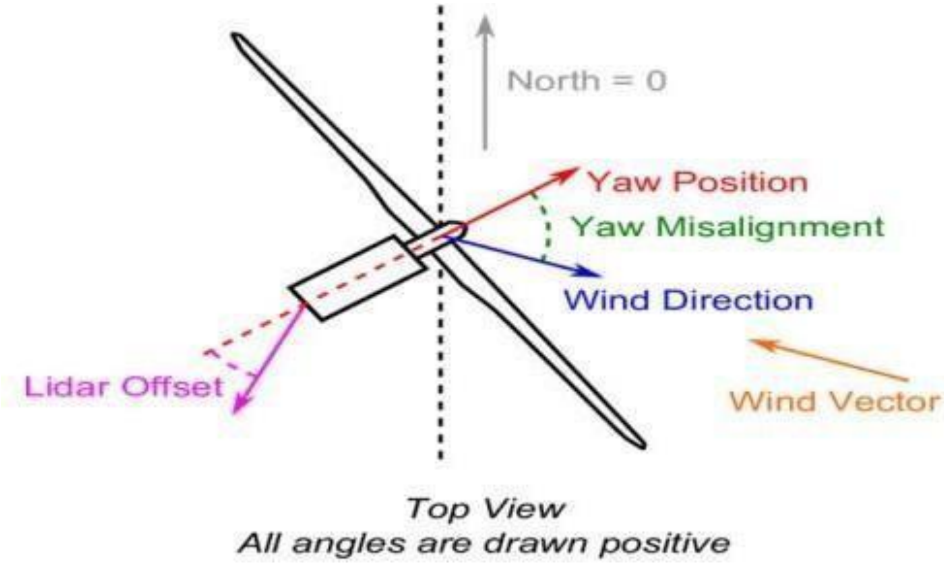



*Figure 48: How Lidar works (Slideshare (2017))*

## 5. Technical and economic study of the use of Lidar:

- Calculation of the value of the losses during one year for the WTG30 wind turbine:

The duration of the analysis was 4 months, it is estimated that misdirection represents losses of 10%, and that this loss rate is standard and does not vary during a year, therefore:

- Energy lost in a year:

$$\textbf{Losses (12 months)} = 421.29 * 0.1 * \frac{12}{4}$$

$$\textbf{Losses (12 months)} = 126.387\ \text{MWh}$$

The calculated price of these lost MWh for one year knowing that the average price of 1MWh is 60$.

$$\textbf{Losses (\$)} = 7583.22\$$$

**Cost-effectiveness of the solution:**

The price of the Lidar in the market with its implementation is estimated at $100,000 During the entire operating period of 20 years, the cost of losses in wind turbine 30 caused by the orientation is

$$\textbf{Losses (20years)} = 7583.22 * 20$$

$$\textbf{Losses (20years)} = 151664.4\ \$$$

Therefore, during the entire period of operation, the Lidar solution will allow us to have a gain of:

$$\textbf{Gain} = \text{price of losses (20years)} - \text{LIDAR price} = 51664.4\$$$

It is therefore deduced that this solution is profitable, and moreover, the solution will allow to protect the machine against bad weather conditions that weaken its components, whose maintenance or spare cost is really more important than the income from losses.

# CONCLUSION AND SUMMARY

The performance analysis of wind turbines is an indispensable asset for wind farm operators in order to keep an eye on production requirements.

The method used is simple to implement and is based on concrete indicators for monitoring the machines, these indicators are the normalization coefficients used in the justification of the choice of wind turbines (94%). However, underperformance requires both significant and costly means, namely the use of Lidar, orientation studies, and root cause analysis of machine equipment.

Moreover, if I visualize the coefficients calculated during the choice of turbines for the wind turbines of group 1 I notice that this coefficient exceeds 100% which means that the rate of wind resources was high at the level of these wind turbines and this positively influences the curves of measured powers and thus the performance of these machines makes it possible to compensate for the losses of the other machines in under performance. Therefore, the KHALLADI wind farm is performing well and still meets the business plan.

Having worked on this rather interesting and complicated subject, this opportunity allowed me to apply my academic background and expand my knowledge in the field of renewable energies and more precisely in the operation of wind farms. Moreover, I had the opportunity to work with a leading software for the analysis of wind resource data and to understand the important phenomena and concepts that influence the performance of wind farms.

The conclusion that I will have to make after this experience, is that in order to avoid the maximum problems of underperformance in a wind farm, it is of great importance to study, analyze and dimension everything well before the installation, considering the sensitivity of the production to the wind conditions and to the location of the turbines, therefore it is necessary for the future operators to learn from the experiences of the already existing parks.

The obstacles and difficulties considered in this study are related to the lack of resources in the company's archives and the lack of time and means. The lack of resources in the company's archives is mainly due to the fact that the design studies of the park are carried out by UPC Renewables, the first developer of the project before the sale of the contract to ACWA Power, while the lack of time and means, I was facing with the analysis and identification of the root causes of the underperformance of the machines and the discovery of the different aspects of maintenance that these machines of very large size and technology undergo.

For this reason, I hope that this modest work will be the subject of future studies and research in the field of wind energy generally and performance analysis is more specifically.

## STUDENT DECLARATION

Signed below, **Amjad Mohamed** student of the Szent István Campus of the Hungarian University of Agriculture and Life Science, at the MSc Course of Mechanical Engineering declare that the present Thesis is my own work and I have used the cited and quoted literature in accordance with the relevant legal and ethical rules. I understand that the one-page-summary of my thesis will be uploaded on the website of the Campus/Institute/Course and my Thesis will be available at the Host Department/Institute and in the repository of the University in accordance with the relevant legal and ethical rules. Confidential data are presented in the thesis: no

Date: 2023, March 31.

Student

## SUPERVISOR'S DECLARATION

As primary supervisor of the author of this thesis, I hereby declare that review of the thesis was done thoroughly; student was informed and guided on the method of citing literature sources in the dissertation, attention was drawn on the importance of using literature data in accordance with the relevant legal and ethical rules.

Confidential data are presented in the thesis: yes no *

Approval of thesis for oral defense on Final Examination: approved not approved *

Date: 2023 March 31.

____________________ Signature

***Please, underline the correct choice!**

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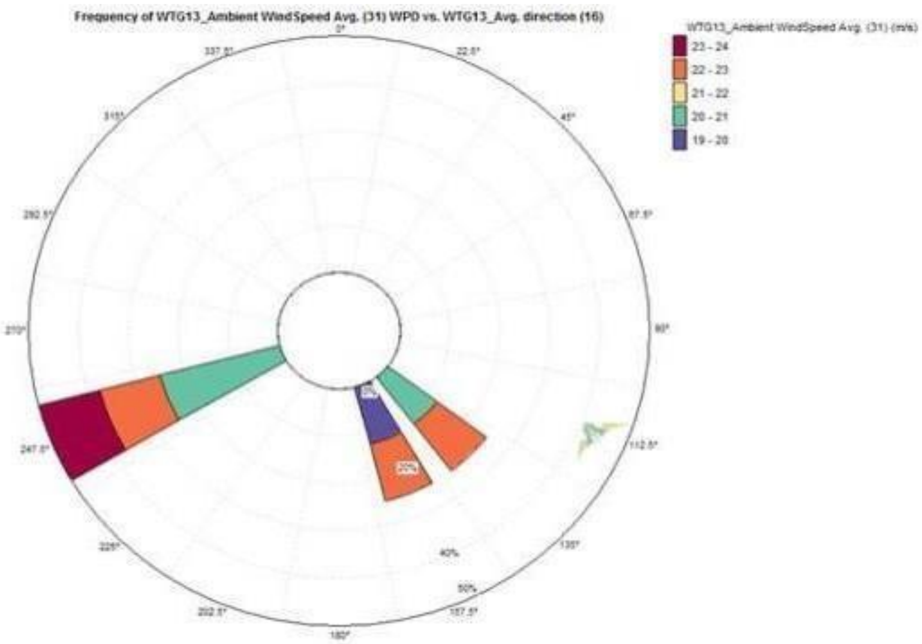
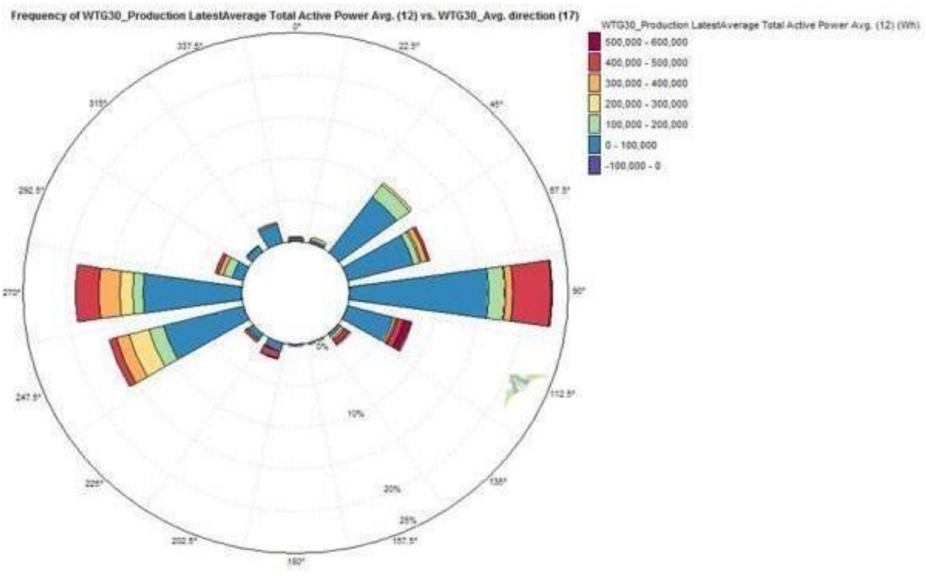
# ANNEXES

**The wind directions given by the Windographer:**

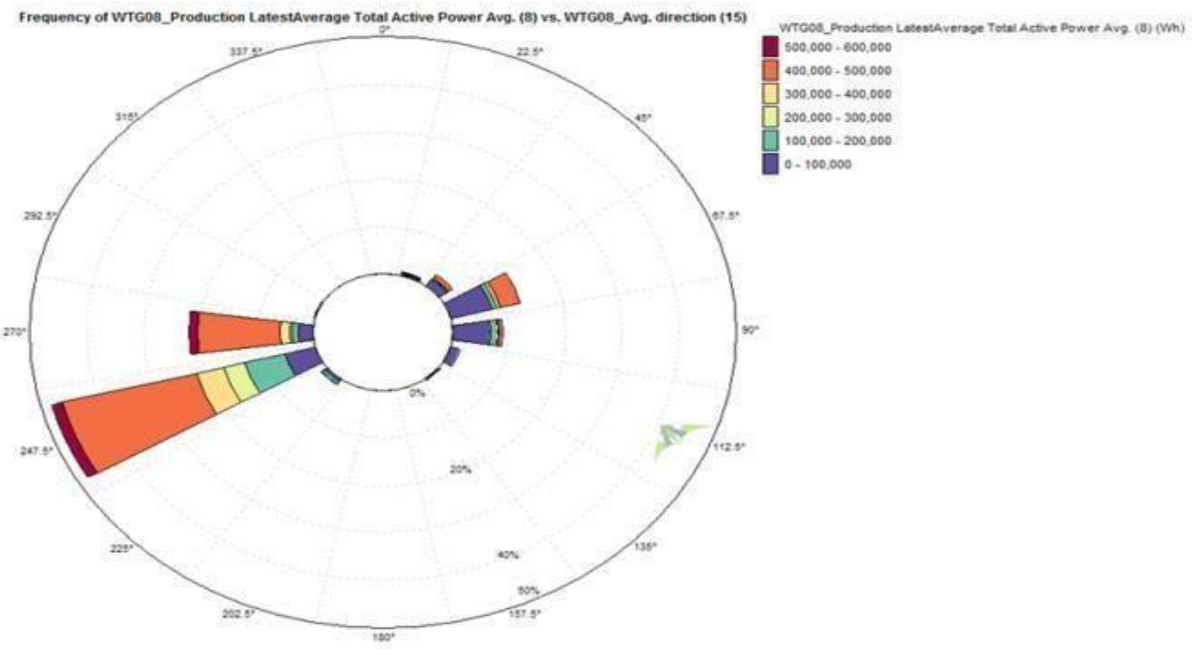
**WTG13**



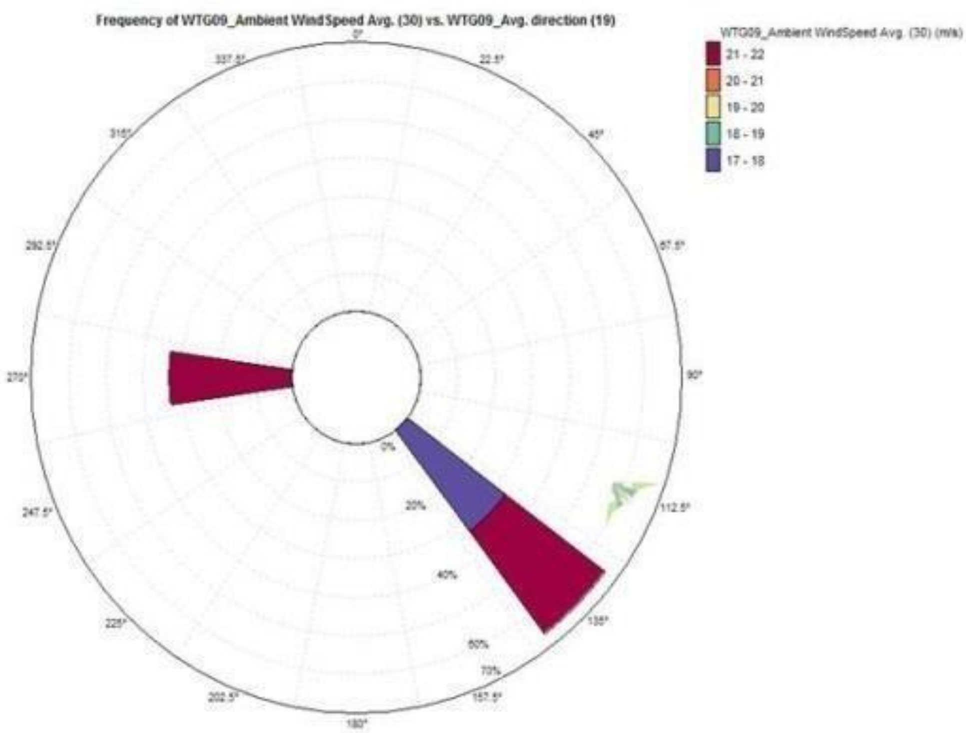

**WTG30**



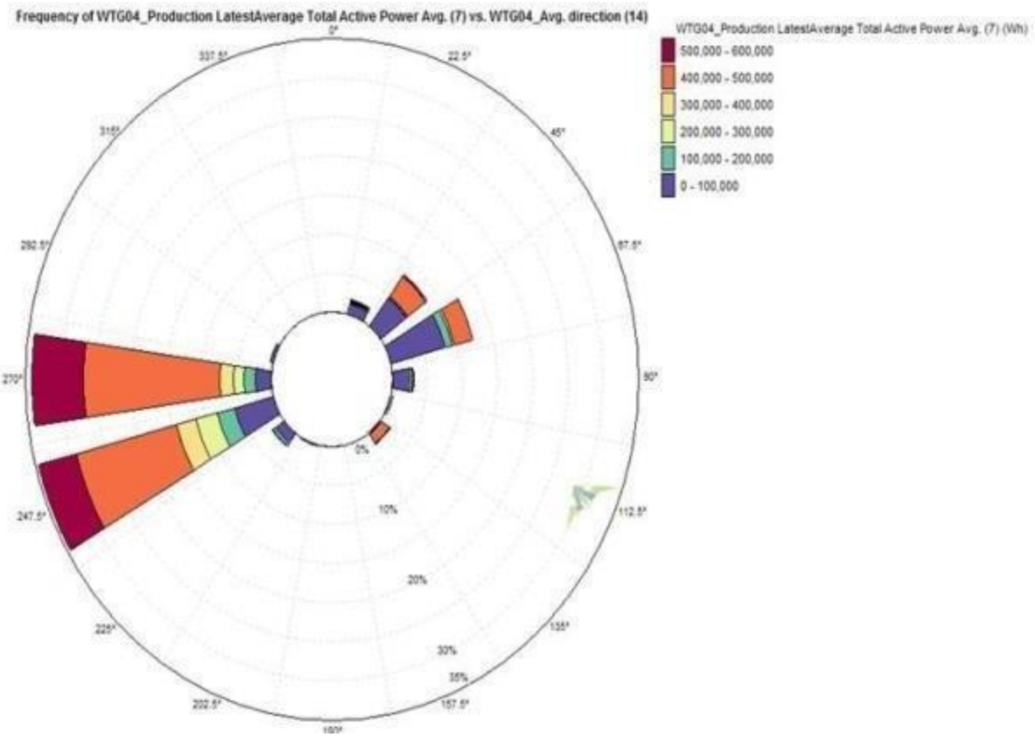
**WTG8**


Frequency of WTG08_Production LatestAverage Total Active Power Avg. (8) vs. WTG08_Avg. direction (15)
WTG08_Production LatestAverage Total Active Power Avg. (8) (Wh)
500,000 - 600,000
400,000 - 500,000
300,000 - 400,000
200,000 - 300,000
100,000 - 200,000
0 - 100,000
0°
22.5°
45°
67.5°
90°
112.5°
135°
157.5°
180°
202.5°
225°
247.5°
270°
292.5°
315°
337.5°
0%
20%
40%
60%

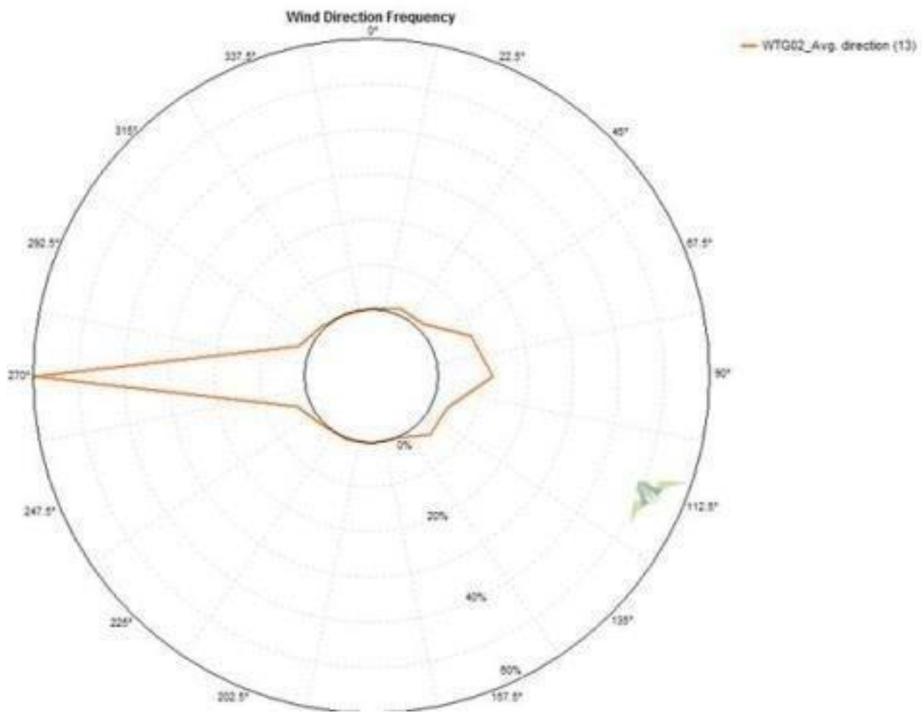
**WTG09**


Frequency of WTG09_Ambient WindSpeed Avg. (30) vs. WTG09_Avg. direction (19)
WTG09_Ambient WindSpeed Avg. (30) (m/s)
21 - 22
20 - 21
19 - 20
18 - 19
17 - 18
0°
22.5°
45°
67.5°
90°
112.5°
135°
157.5°
180°
202.5°
225°
247.5°
270°
292.5°
315°
337.5°
0%
20%
40%
60%
70%

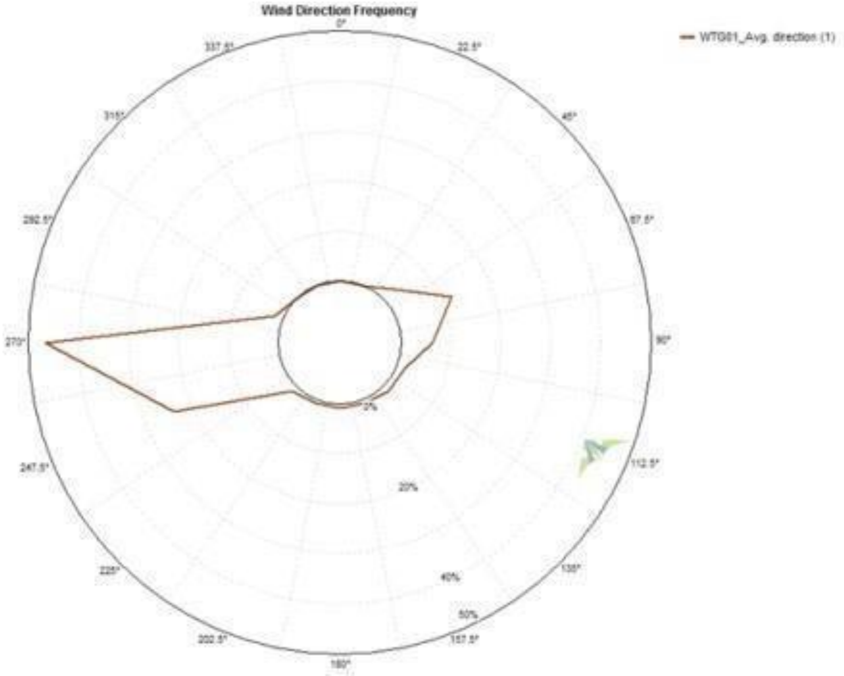
WTG04


Frequency of WTG04_Production LatestAverage Total Active Power Avg. (7) vs. WTG04_Avg. direction (14)
WTG04_Production LatestAverage Total Active Power Avg. (7) (Wh)
500,000 - 600,000
400,000 - 500,000
300,000 - 400,000
200,000 - 300,000
100,000 - 200,000
0 - 100,000
0°
22.5°
45°
67.5°
90°
112.5°
135°
157.5°
202.5°
225°
247.5°
270°
292.5°
315°
337.5°
0%
10%
20%
30%
35%

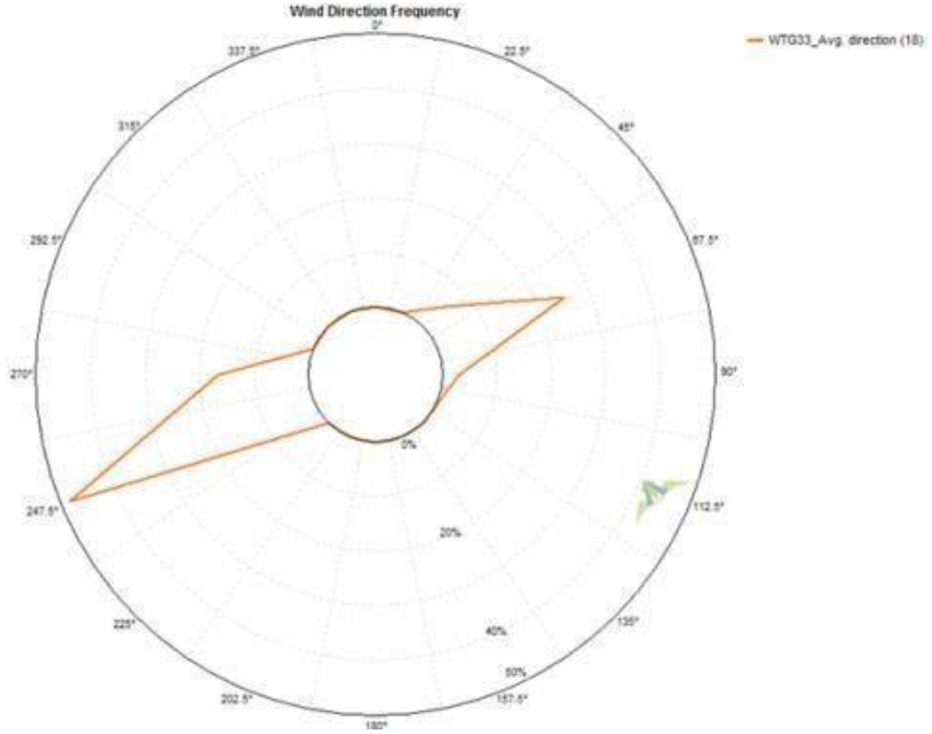
**WTG02**


Wind Direction Frequency
WTG02_Avg. direction (13)
0°
22.5°
45°
67.5°
90°
112.5°
135°
157.5°
202.5°
225°
247.5°
270°
292.5°
315°
337.5°
0%
20%
40%
60%

**WTG01**

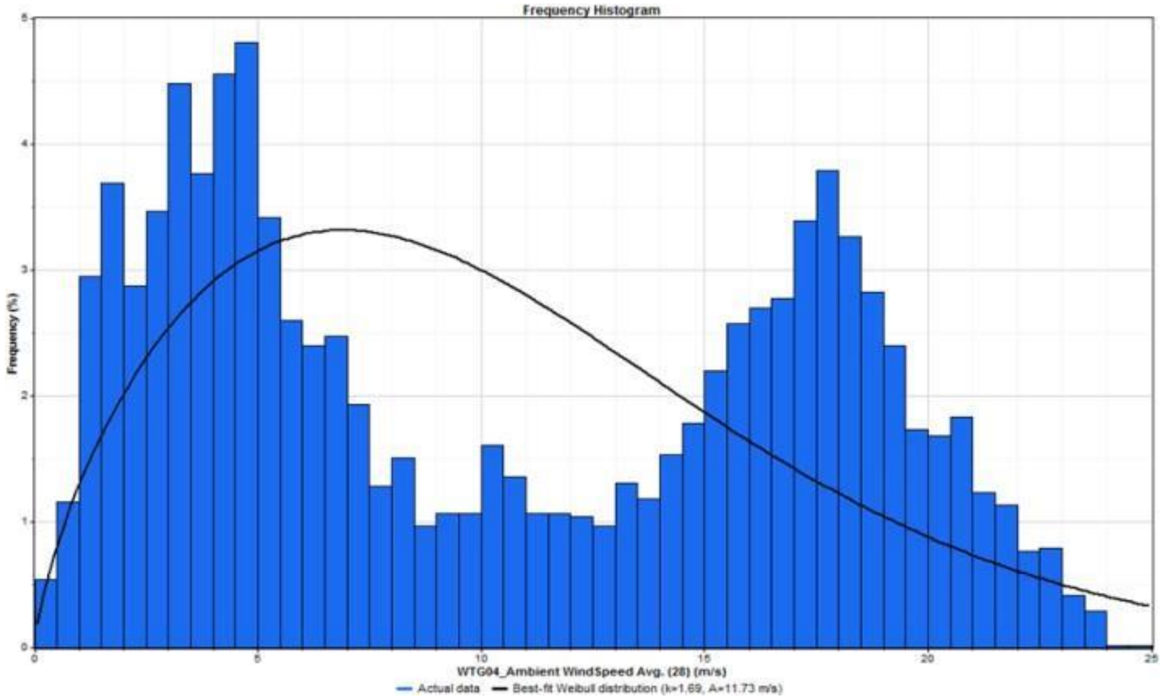

Wind Direction Frequency
0°
22.5°
45°
67.5°
90°
112.5°
135°
157.5°
180°
202.5°
225°
247.5°
270°
292.5°
315°
337.5°
0%
20%
40%
50%
WTG01_Avg. direction (1)

**WTG30**

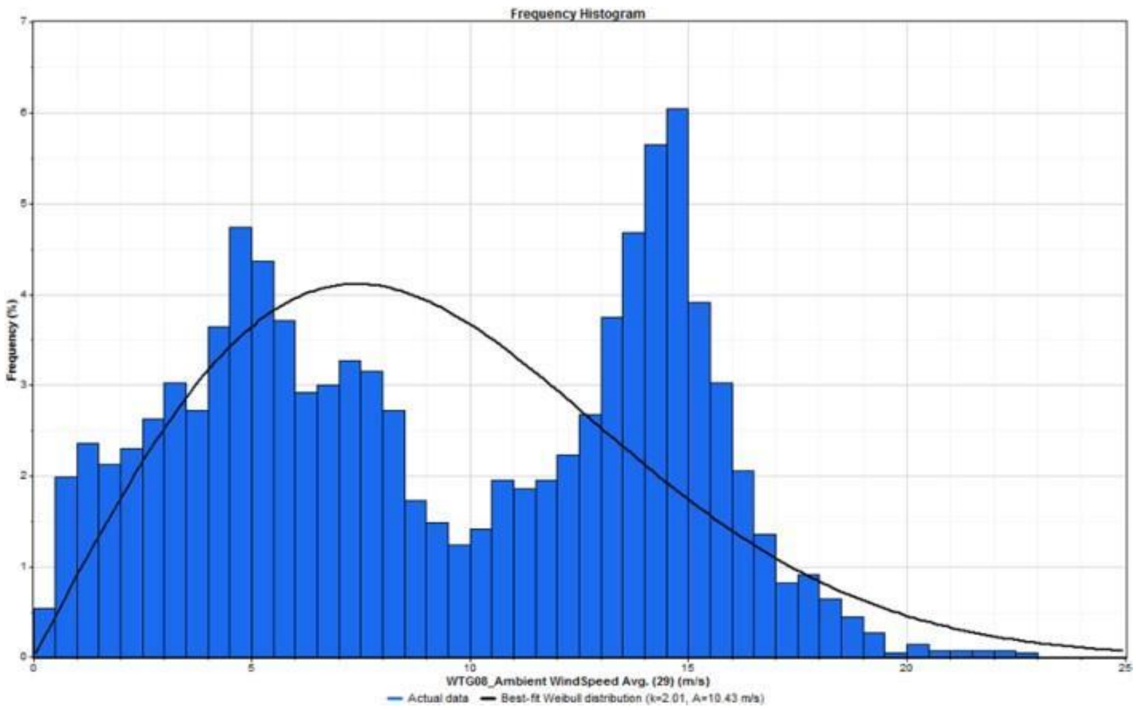

Wind Direction Frequency
0°
22.5°
45°
67.5°
90°
112.5°
135°
157.5°
180°
202.5°
225°
247.5°
270°
292.5°
315°
337.5°
0%
20%
40%
50%
WTG33_Avg. direction (18)

**Weibull distributions done by the Windographer:**

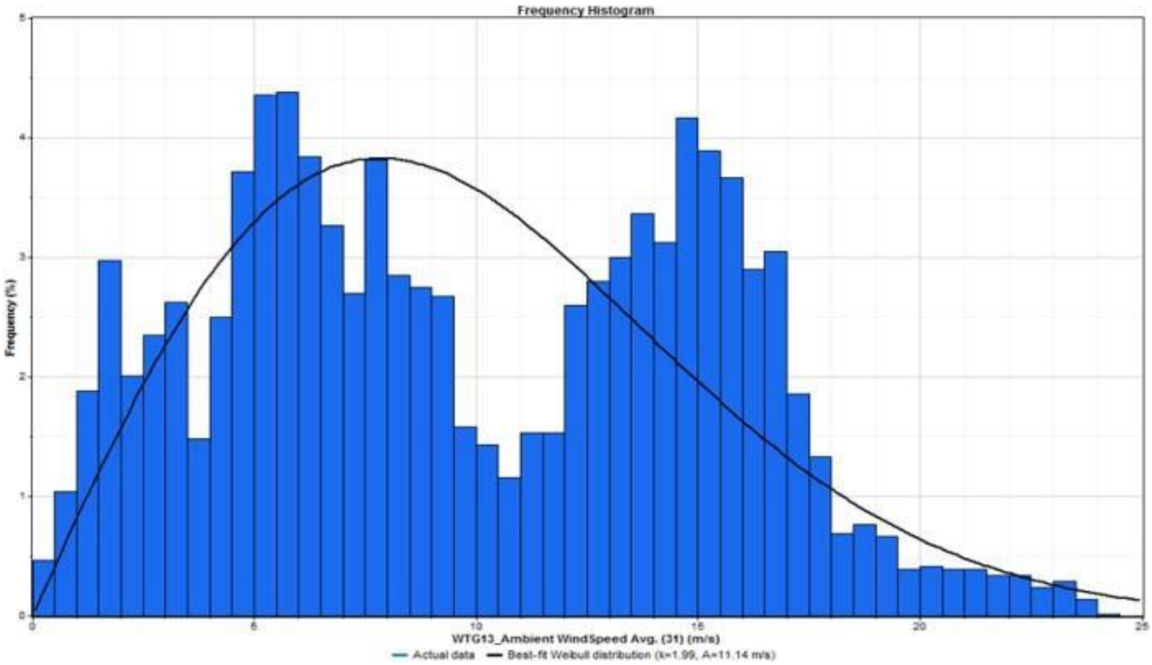
**WTG02**



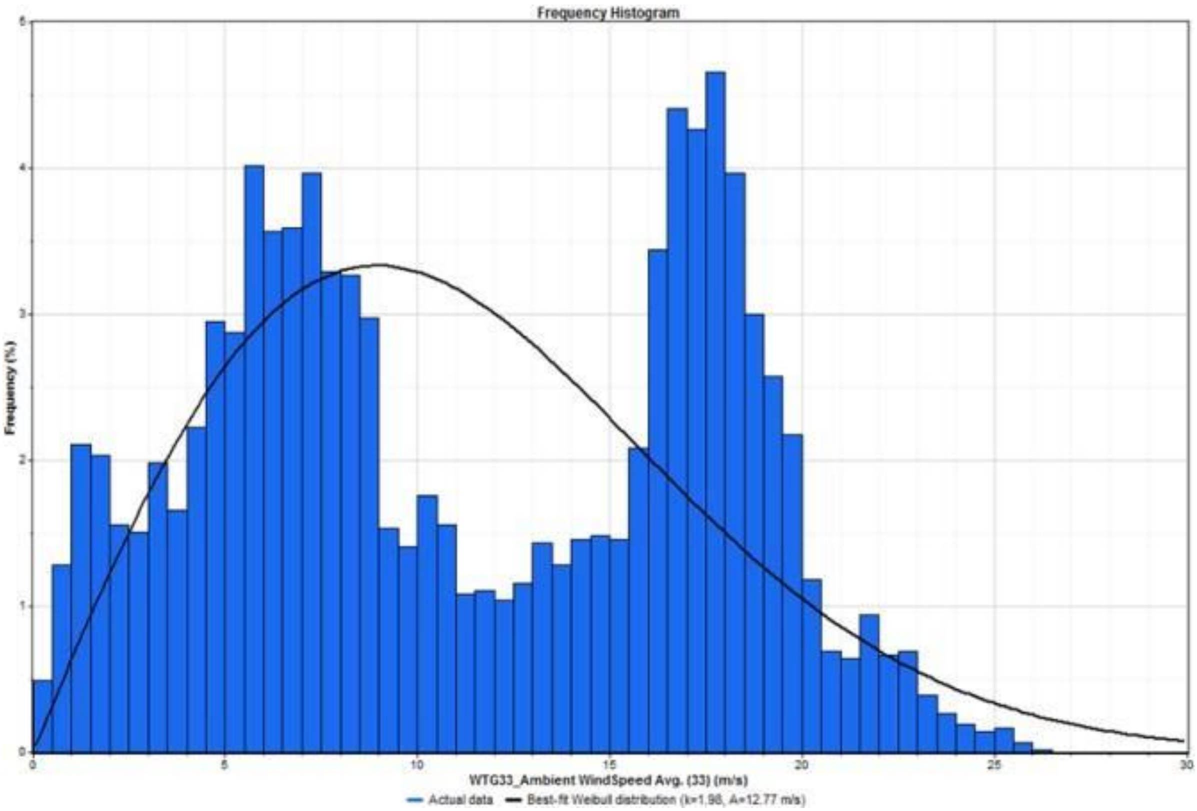

**WTG08**



**WTG13**

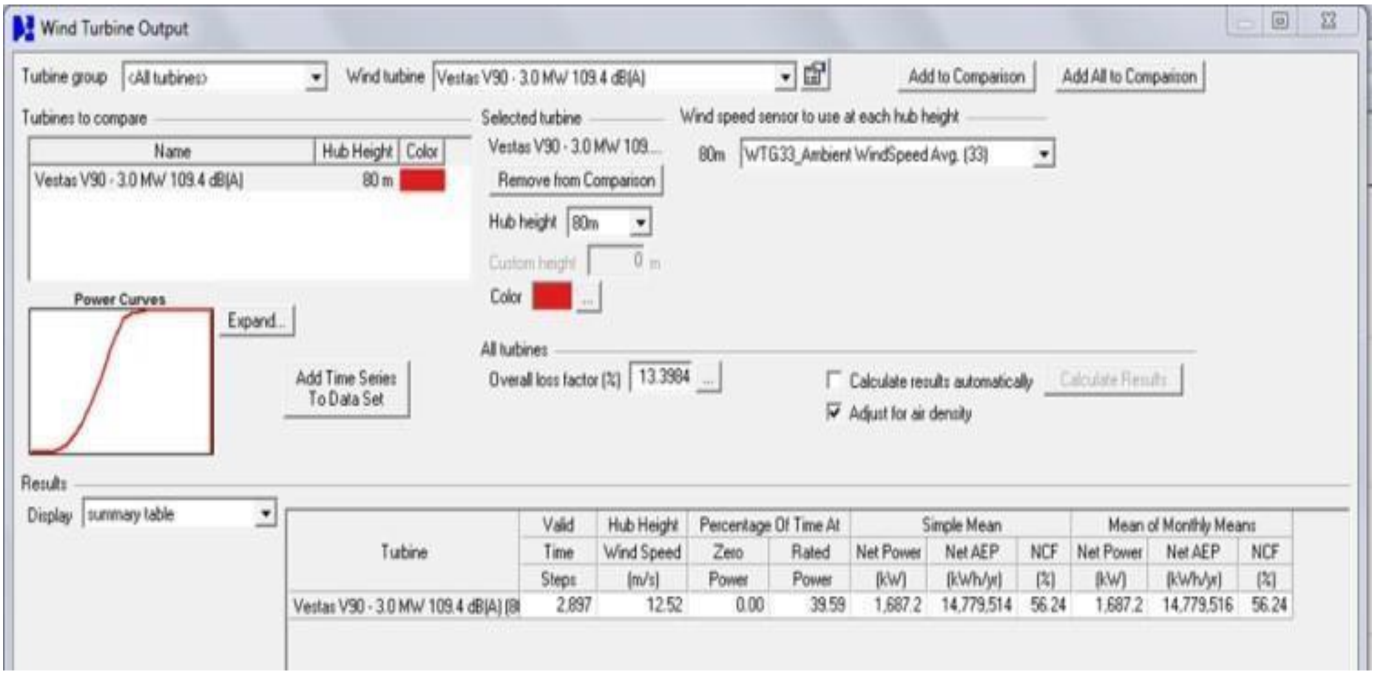

Frequency Histogram
Frequency (%)
WTG13_Ambient WindSpeed Avg. (31) (m/s)
Actual data
Best-fit Weibull distribution (k=1.99, A=11.14 m/s)

**WTG33**

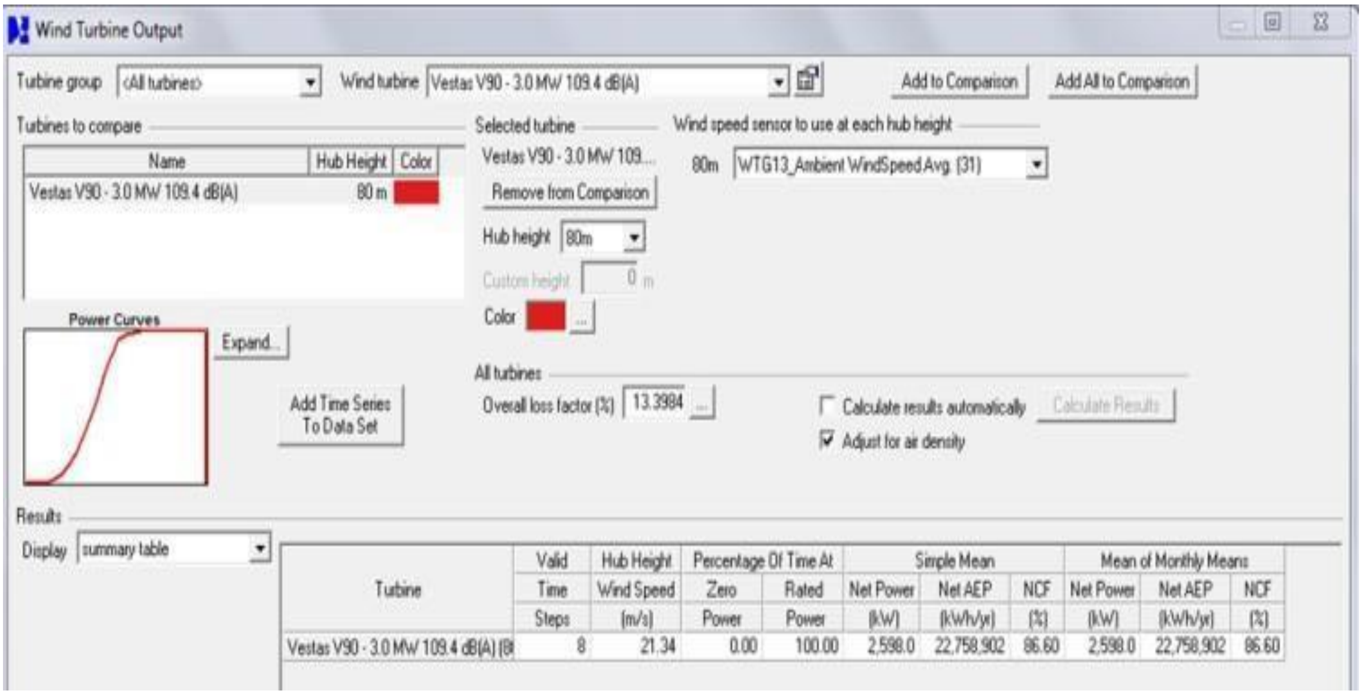

Frequency Histogram
Frequency (%)
WTG33_Ambient WindSpeed Avg. (33) (m/s)
Actual data
Best-fit Weibull distribution (k=1.98, A=12.77 m/s)

**The theoretical energies calculated by the Windographer:**

**WTG30**




**WTG01**



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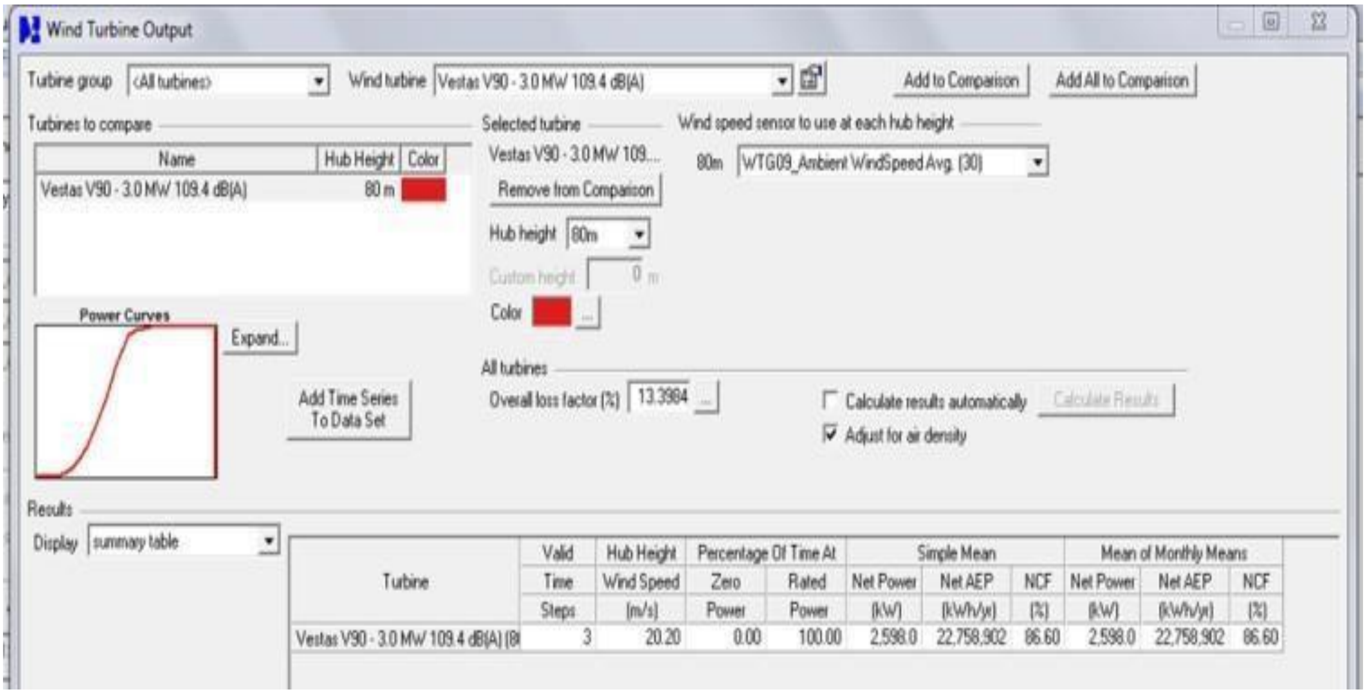
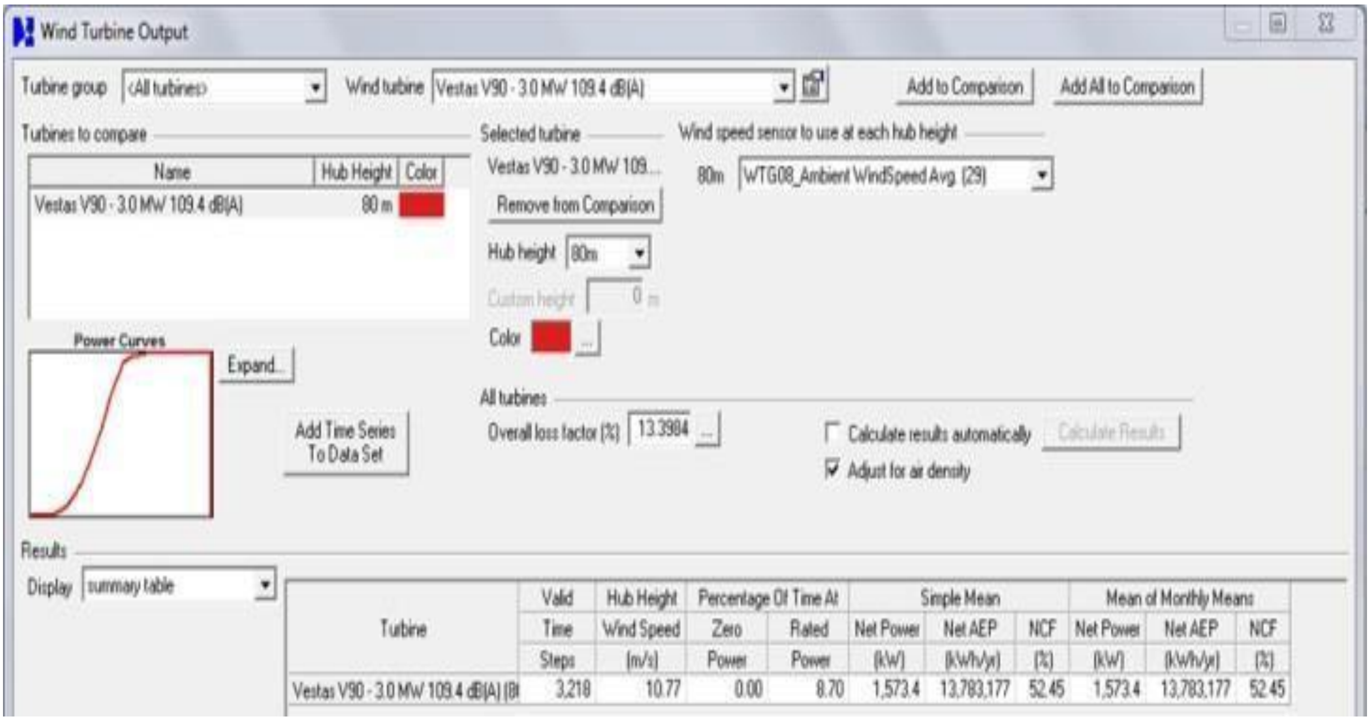
**WTG02**




**WTG04**



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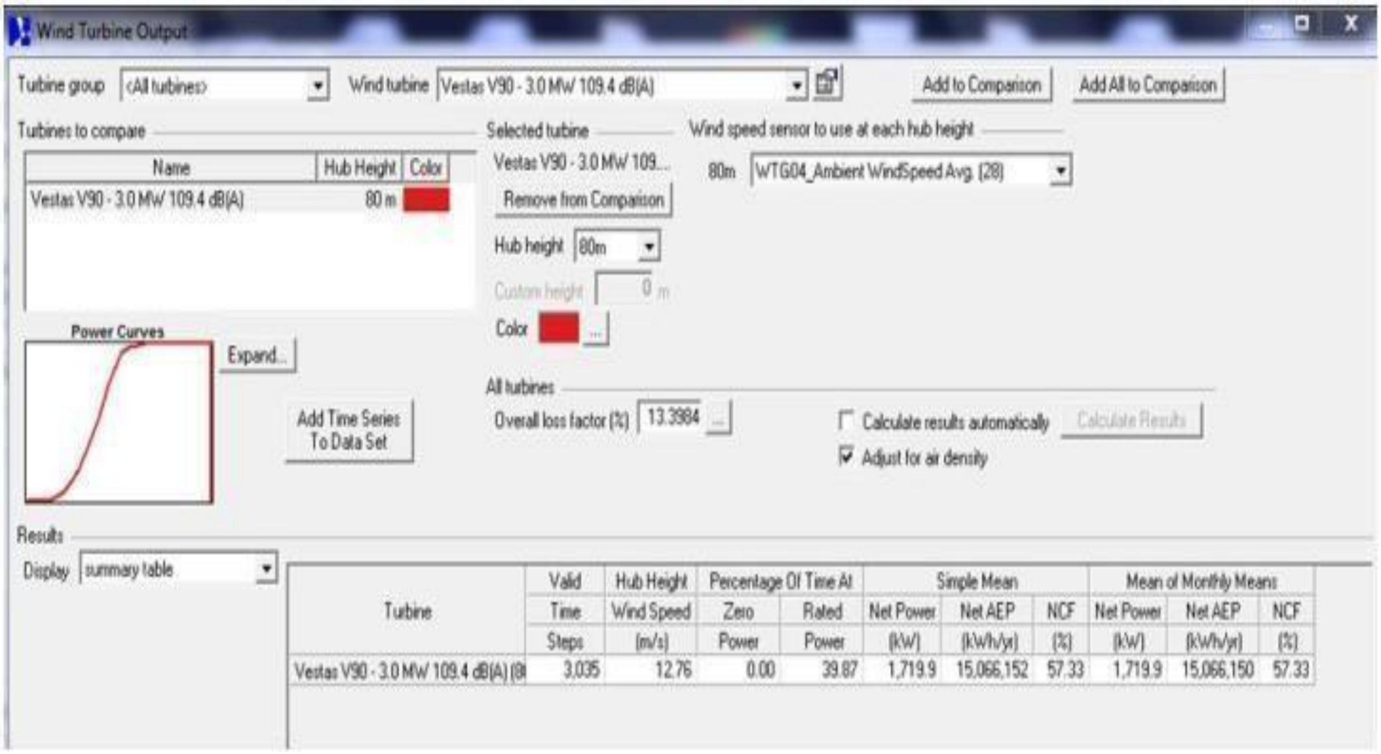
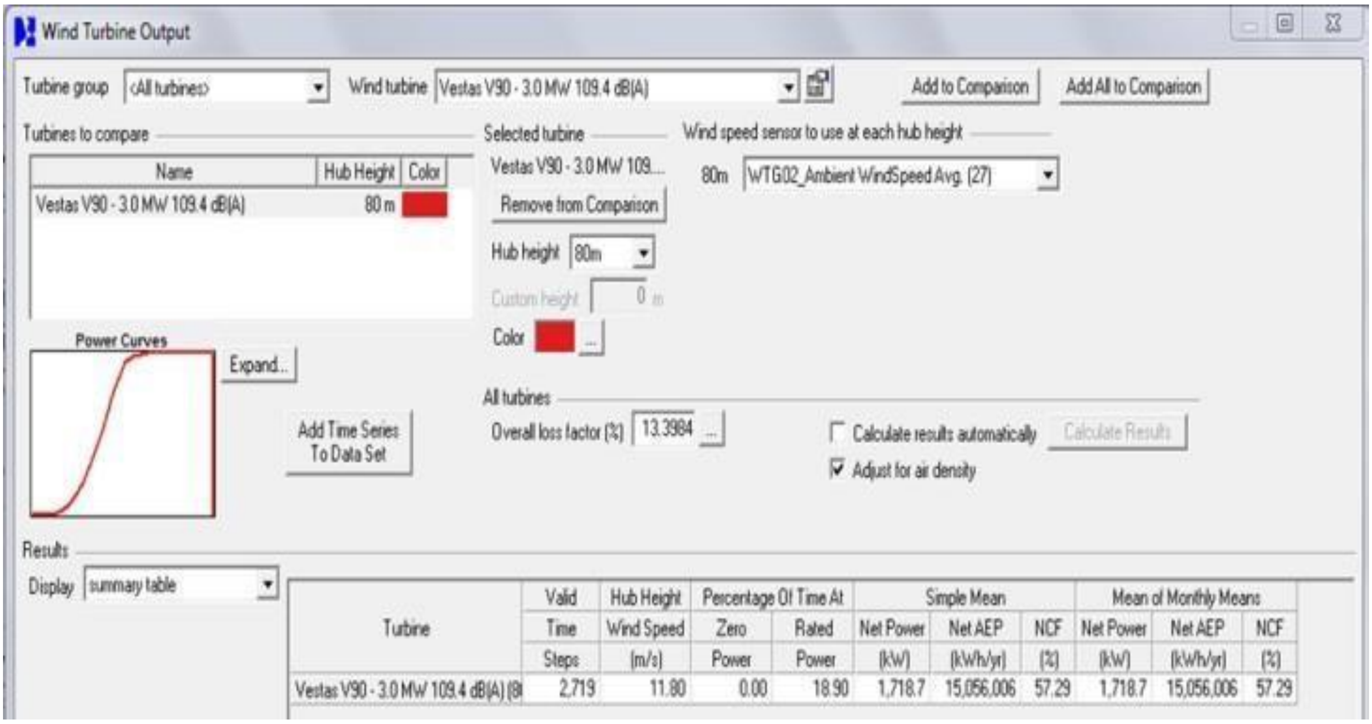
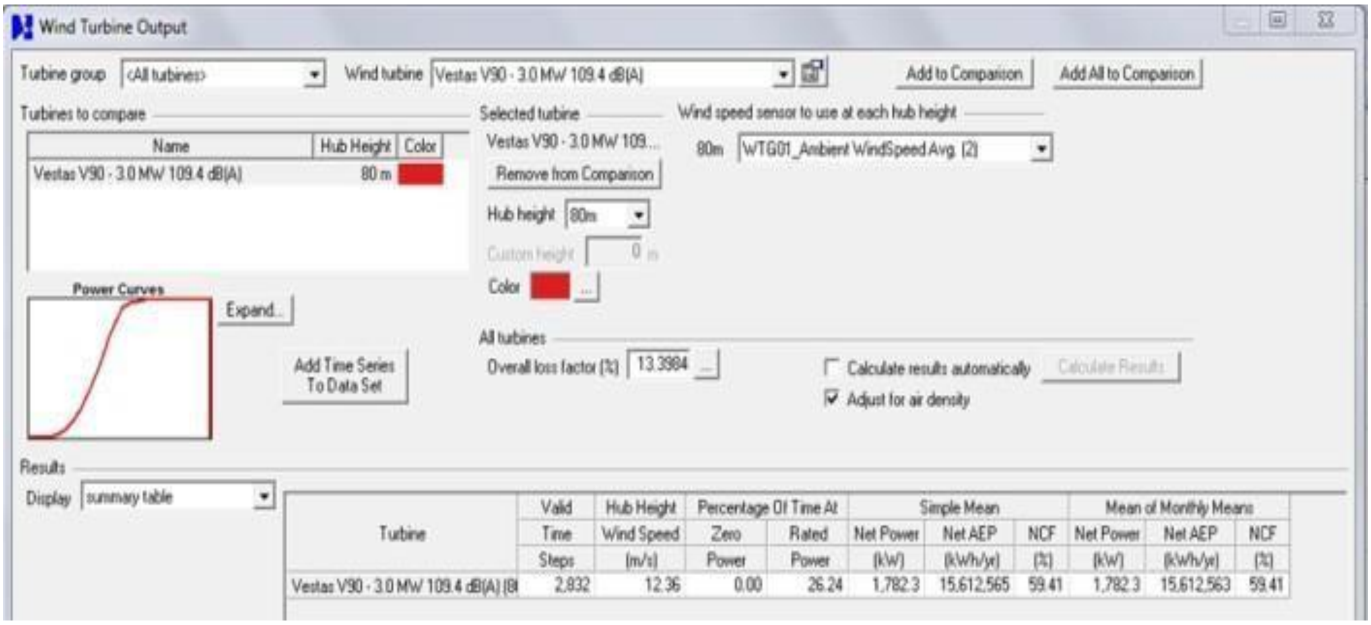
**WTG08**



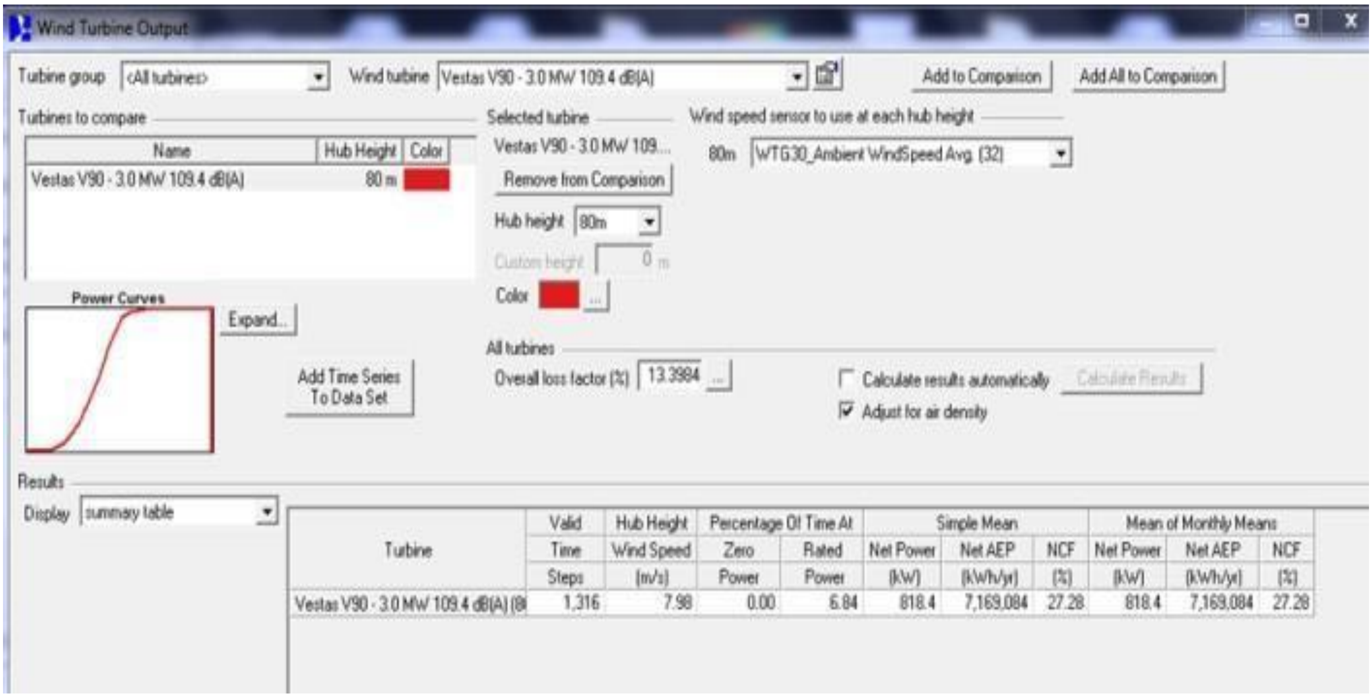

**WTG09**



**WTG13**


Wind Turbine Output
Turbine group <All turbines>
Wind turbine Vestas V90 - 3.0 MW 109.4 dB(A)
Add to Comparison
Add All to Comparison
Turbines to compare
Name Hub Height Color
Vestas V90 - 3.0 MW 109.4 dB(A) 80 m
Selected turbine
Vestas V90 - 3.0 MW 109...
Remove from Comparison
Hub height 80m
Custom height 0 m
Color
Wind speed sensor to use at each hub height
80m WTG01_Ambient WindSpeed Avg. (2)
Power Curves
Expand...
Add Time Series To Data Set
All turbines
Overall loss factor (%) 13.3984
Calculate results automatically
Calculate Results
Adjust for air density
Results
Display summary table
Turbine | Valid Time Steps | Hub Height Wind Speed (m/s) | Percentage Of Time At Zero Power | Rated Power | Simple Mean Net Power (kW) | Net AEP (kWh/yr) | NCF (%) | Mean of Monthly Means Net Power (kW) | Net AEP (kWh/yr) | NCF (%)
Vestas V90 - 3.0 MW 109.4 dB(A) (8 | 2,832 | 12.36 | 0.00 | 26.24 | 1,782.3 | 15,612,565 | 59.41 | 1,782.3 | 15,612,563 | 59.41

**WTG33**


Wind Turbine Output
Turbine group <All turbines>
Wind turbine Vestas V90 - 3.0 MW 109.4 dB(A)
Add to Comparison
Add All to Comparison
Turbines to compare
Name Hub Height Color
Vestas V90 - 3.0 MW 109.4 dB(A) 80 m
Selected turbine
Vestas V90 - 3.0 MW 109...
Remove from Comparison
Hub height 80m
Custom height 0 m
Color
Wind speed sensor to use at each hub height
80m WTG30_Ambient WindSpeed Avg. (32)
Power Curves
Expand...
Add Time Series To Data Set
All turbines
Overall loss factor (%) 13.3984
Calculate results automatically
Calculate Results
Adjust for air density
Results
Display summary table
Turbine | Valid Time Steps | Hub Height Wind Speed (m/s) | Percentage Of Time At Zero Power | Rated Power | Simple Mean Net Power (kW) | Net AEP (kWh/yr) | NCF (%) | Mean of Monthly Means Net Power (kW) | Net AEP (kWh/yr) | NCF (%)
Vestas V90 - 3.0 MW 109.4 dB(A) (8 | 1,316 | 7.98 | 0.00 | 6.84 | 818.4 | 7,169,084 | 27.28 | 818.4 | 7,169,084 | 27.28

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# Acknowledgment

No work is truly individual, insofar as it is the sum of an experience or an attempt at reflection, the external aids or influences cannot be ignored, even less, denied.

I would first like to express my sincere gratitude to thesis supervisor Dr. Schrempf Norbert Attila of the Department of Civil Engineering and Energy at MATE University. Whenever I faced a problem or had a question about my thesis topic selection. He consistently advises me, keeping me in the right direction.

I would also like to acknowledge Mrs. Ghizlane Marghadi Engineer and friend, as my second supervisor/ Consultant. Despite the difficulties and geographical obstacles, she still gives me her time and valuable comments. I am so grateful for all her encouragement and motivation

My sincere gratitude also to all university and dormitory staff at MATE University that I could not write one by one in this text. They were the major contributors in my daily life in Hungary, helping me with almost everything even before I arrived in Hungary.

It goes without saying. I thank you, Tempus Public Foundation for allowing me to study and receive scholarships in Hungary through Stipendium Hungaricum. Because of them, I finally could pursue my master's degree in Europe. I could say all experiences, friends, and opportunities in Europe are thanks to them.

At the end of this modest work, I would like to address my deep gratitude and sincere thanks above all, to GOD, for everything that I'm deeply grateful for, to my friends for all the support and all the fun we have had in the last two years. Every moment with you is like a refreshment from my study. Finally, I must express my very eternal gratitude to my family for providing me with constant support and encouragement throughout my years of study and through the process of writing this thesis.

This accomplishment would not have been possible without them. Thank you.

Author,

Amjad Mohamed

**STATEMENT ON CONSULTATION PRACTICES**

As a supervisor of _____AMJAD MOHAMED_______________ (Student's name) ___TOJ3X0_____(Student's NEPTUN ID), I here declare that the final essay/thesis/master's thesis/portfolio[1] has been reviewed by me, the student was informed about the requirements of literary sources management and its legal and ethical rules.

I recommend/don't recommend[2] the final essay/thesis/master's thesis/portfolio to be defended in a final exam.

The document contains state secrets or professional secrets: yes no*[3]

Place and date: ________________ year _______________ month_______ day

_____________________

Internal supervisor

---

[1] Please select applicable and delete non-applicable.
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