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**BY**

**Badiaa BACHIRI**

# A guideline for utility-scale onshore wind farms distribution in Tunisia

Defended on 20/11/2021 before the following committite:

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# CERTIFICATION

This is to certify that the master's thesis entitled **" *A guideline for utility-scale onshore wind farms distribution in Tunisia*"** is a record of the original bona fide work done by *Badiaa BACHIRI* in partial fulfillment of the requirement for the award of Master Degree in Energy Engineering track at Pan African University Institute of Water and Energy Sciences (Including climate science)- PAUWES during the Academic Year 2020-2021.

Signed : Date:

Dr. Faten Attig Bahar $05^{th}$ , $November$, $2021$

# DECLARATION

I, Badiaa BACHIR , hereby declare that this thesis represents my individual work, realized to the best of my knowledge. I moreover announce that all data, fabric and comes about from other works displayed here, have been completely cited and referenced in agreement with the scholarly rules and ethics.

Signed : Date :

Badiaa BACHIRI $05^{th}$ , $November$, 2021

# Content

# Figure List

# Table List

# Nomenclature

WFDT: Daterflow detector Tap

ZVI : Zone of Visual Influence

STEG : Tunisian Company of Electricity and Gas

WSC : Wind Shear Coefficient)

PDF: Probability Density Function

PSSE: Power System Simulator for Engineering

STATCOM: Static Synchronous Compensator

MOGA: Multi-Objective Genetic Algorithm

NREA: New and Renewable Energy Authority

CO2: Carbon Dioxide

SDSS: Spatial Decision Support Systems

MCA: Multi-Criteria Analysis

ArcGIS: Arc Geographic Information Systems

RES: Renewable Energy Siting

MV: Medium-Voltage

LV: Low-Voltage

WTG:Wind Turbine Generator

# ABSTRACT

Wind energy, as a component of the green transition has been given a lot of attention in theTunisia since 2000. Moreover, the good wind energy potential is one of the motivations to develop the wind energy sector in the country,with a surface of 163,610 km² ,has an important air density and wind speed are important in the North and East seaside region .

The proposed project aimed to advice on the effective distribution of wind farms while considering the following aspect: the land availability, the terrain topology, the weather surveys and the national electrical grid balanceAccording to the criteria we set up, we could identify seven  suitable area for wind farms activities  namely :distributed in the north and the costal areas The results of the simulation using WindPro show that the most favorable and suitable site for wind farm implementation is in Kelibia with a capacity factor of 20% and annual energy 58,6 GWh/y.

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# INTRODUCTION OF THE PROJECT HOST INSTITUTIONS

This work setting up a framework adapted to the distribution and integration of renewable energies program in Tunisia.

**The Pan African University, the institute of water and energy sciences**

The Pan African University (PAU) is the result of the African Union Commission's continental attempts to rejuvenate higher education and research in Africa, as part of the Second Decade of Education for Africa and the consolidated Plan of Action for Science and Technology in Africa. It will set the standard for quality, increase the appeal and worldwide competitiveness of African higher education and research, and place the African University at the heart of the continent's growth.

The African Union Commission established the Pan African University Institute of Water and Energy Science (PAUWES) in 2014 as part of the Pan African University (PAU). It is hosted by the Abou Bakr Belkad University of Tlemcen and is looking for a new generation of highly educated, well-trained students who are committed to working as changemakers in the field of sustainable water and energy.

**The research laboratory Applied Mechanics and Systems Research (LASMAP)**

The research laboratory Applied Mechanics and Systems Research (LASMAP) is a research and technological development laboratory authorised by the Ministry of Higher Education and Scientific Research.It is aninterdisciplinary research laboratory attached to the University of Cartage, TunisiaPolytechnic School.

This research laboratory focuses on Structures, Renewable energy systems and technology , Biomechanics, Smart materials and dynamic systems.

LASMAP is the result of a merger between two research units at ENIT and EPT, and is used for the modelling and simulation of the mechanical behaviour of materials and structures, the development of numerical calculation codes for the simulation of the behaviour of solids, structures, flows and systems, and the design and modelling of structures and multiphysical systems, as well as the study of linear and non-linear dynamic experiments on structural systems. It contributes to the state of the art on scientific and technological issues. It is at the forefront of the development of methodologies, new product models and the improvement of existing methods in the fields of mechanics, construction, new materials, systems and closely related disciplines.

# General Introduction

Climate change is one of our society's most pressing issues, owing to its negative effects on the earth's ecosystem and global economy. Improving energy system efficiencies and huge renewable energy expansion have become critical for climate protection

The move to renewable energy will have numerous advantages, including the potential to develop human resources and skills. In this context, public institutions may choose to expand their current human capacity by holding additional training sessions on the technical, economic, administrative, and legal elements of renewable energy project development.

Tunisia's diverse economic sectors rely heavily on the energy sector. However, throughout the last two decades, the country has seen an increasing energy balance deficit, owing to its reliance on fossil fuels – oil and natural gas – to meet its rising energy demand. The decline of its own hydrocarbon resources has resulted in increased reliance on fossil fuel imports, which reached new highs in 2019 when the primary energy balance deficit reached 5 672 thousand tonnes of oil equivalent (ktoe), indicating that imported energy accounts for 49 % of total energy consumption. Tunisia's energy security may face serious challenges in the next years as domestic natural gas production declines.

Tunisia has chosen to begin on an energy transition as part of a larger sustainable economic and social development strategy in response to energy security problems and vulnerability to variable international energy prices. In 2013, a national energy discussion was begun to establish the new policy's strategic objectives through broad consultations with key energy players from a variety of institutions, public and private organizations, civil society, specialists, financial organizations, and academia, among others. The debate concluded that Tunisia must fully participate in the energy transformation. This should be based on a revision of the modes of production, processing, and energy consumption in order to increase the country's energy security, as well as to protect the economy's competitiveness and the environment.

Therefore, Tunisia worked to diversify its energy sources mix by utilizing its diverse array of renewable energy sources mainly the solar and Wind resources.

In fact, Tunisia is one of the Mediterranean countries with enough windy areas. During the past years, Tunisia has embarked upon wind energy programs. The first wind farm in Tunisia was brought into service in January 2000 in the region of Sidi Daoud: it is the first section of the farm that consists of 32 aerogenerators (Made AE-32) of 10.56MW capacity. The research work carried out in this thesis focuses firstly on the identification of the relevant location suitable for the wind farm implementation in the Tunisian territory.

This master thesis chapters are the following:

The first chapter introduced wind energy technology and the components of wind Turbine. In addition, it presented the literature survey on the onshore wind farms implementation experiences in north Africa and Tunisia.

The second chapter represented the methodology used in research and presented different criteria used to identify of the availability of land, grid network and topology land data. In this chapter the suitable sites of implementations wind farms are defined by analysing different maps through wind Atlas resource.

This last chapter is devoted to the presentation of all the results obtained from the WindPro software. These results are; Energy production, the frequency wind rose, capacity factor and wake losses.

# Chapter I: ONSHORE WIND FARMS AND WIND FARMS IMPLEMENTATION EXPERIENCES IN NORTH AFRICA : STATE OF THE ART

## 1. Introduction

The world's major concern revolves around environment protection, clean and healthy production, climate change and wellbeing of the next generation. Energy and all the mentioned concerns are intrinsically linked and the way we consume energy determines society's environmental impact. Thus, with the advances in renewable energy technologies, science has certainly come a long way in terms of progressing technologically and economically, and still needs to be implemented to save the environment of the planet Earth and promote human wellbeing in terms of human health and natural resources sustainability [1].Since a few decades, the interest in developing the wind turbine technology has grown and many researchers have attempted to develop and to perform reliable wind energy conversion systems.

This chapter provides an overview of wind energy potential assessment and wind farms implementations. It draws experiences from north Africa countries Onshore wind farms and wind farms implementation experiences in north Africa.

# 2. Wind Energy technology and Onshore wind farms

## 2.1. Wind Resource Estimation

Wind power has long been regarded as one of the most promising and economically viable renewable energy sources. An assessment of the wind resource available at any potential location is critical for ensuring maximum power output utilizing a certain type of wind electric generator. Oftenly, assessing wind potential in a location is more simple because of publicly available high-resolution wind resource data. Public wind data sources are now freely accessible thanks to recent improvements in computer modeling and the internet.

- **Maps of the Wind :** The best way to start looking for information on wind resources is to look for underlying data estimates that may have been utilized to produce state wind resource maps. Topographic maps can also be used to locate the tops of ridges and highest points in an area, allowing you to connect the overall data on a wind resource map to the places in the area with the most potential. A "Wind Power Class" is included in the wind resource maps to help describe the potential of a certain wind resource.[3]
- **Weather Models :** such as creating large-scale computer weather models to extrapolate wind conditions at a specific location based on past data. These

computer simulations of a site's wind resource are often less expensive than obtaining a year's worth of meteorological observations.[4]

Lenders are becoming more accepting of this method of resource assessment as scientists and lending institutions gain a better understanding of weather modeling and the wind industry. However, for validation of conditions at the site, lenders may require a combination of site specific meteorological measurements combined with computer models based on long-term weather data.Data from the site should be was compared to long-term weather data spanning ten years or more . Table 1**.** Summarizes the relevant tools used in the wind potential assessement.

| Task | Tools | Advanced Approach |
|---|---|---|
| Site Prospecting | Political and physical maps. European Wind Atlas. Met office statistics of nearby stations | Regional wind atlas produced with a mesoscale model. Integration of other feasibility parameters in GIS database |
| Measurement Campaign | 40-80 m tall masts, equipped with cups and vanes | Velocity profile and Turbulence characterization using dedicated instruments |
| Long-term Extrapolation | Measure-Correlate-Predict (MCP) methods | Onsite virtual met mast with historical and homogeneous wind time series |
| Microscale horizontal extrapolation | Wind Atlas Methodology (WAsP) | Non-linear model, different stabilities, built-in forest model |
| Microscale vertical extrapolation | Linear model, near-neutral and/or Experience | Profile calibration based on remote sensing and CFD modelling |
| Wind Farm Design | Wind farm design tools based on WAsP | Built-in wake effects CFD model |
| IEC Classification (Vref) | Extreme Value Analysis Methods IEC 61400-1 | Onsite virtual met mast with historical homogeneous wind speed time series |

**Table 1 :** Summarizes the relevant tools used to assess.[2]

## 2.2. Wind turbine Anatomy

The wind turbine converts wind kinetic energy into mechanical energy and the latter into electrical energy by means of an electrical generator. A typical wind turbine design is made up of five major and many auxiliary parts. The major parts are the **tower, rotor, nacelle, generator,** and **foundation** or **base.**

- **The base or foundation:** usually composed of reinforced concrete or steel, holds the upper structure of the turbine in place vertically.

- **The tower:** the transition piece, which is normally fixed to remedy any misalignment between two components, connects the tower to the foundation in some cases. Steel platerolled into a cylinder is the most popular tower style; most of them are cut, **rolled, and** welded together into conical subsections. Other turbines, however, are composed of lattice towers. The tower **a**lso stores the electrical conduits and offers access to the nacelle for maintenance via an inside ladder.
- **The nacelle:** is stabilized and physically placed on top of the tower, holds the major electro-mechanical components such as the gen**erator and g**earbox.

- **The rotor blades :** are generally composed of fiberglass or carbon fiber composites, catch **the wind's** energy. They are connected to the generator via a set of gears and rotate the generator slowly. A power wire connects each turbine and transmits the generated electric current [5]. Blades are the most fundamental composite-based component of a wind turbine, as well as the most expensive. A wind turbine blade is made up of two faces (on the suction and pressure sides), which are linked and reinforced by one or more integrated (shear) webs that connect the top and lower halves of the blade shell, or by a box beam (box spar with shell fairings) [6] .

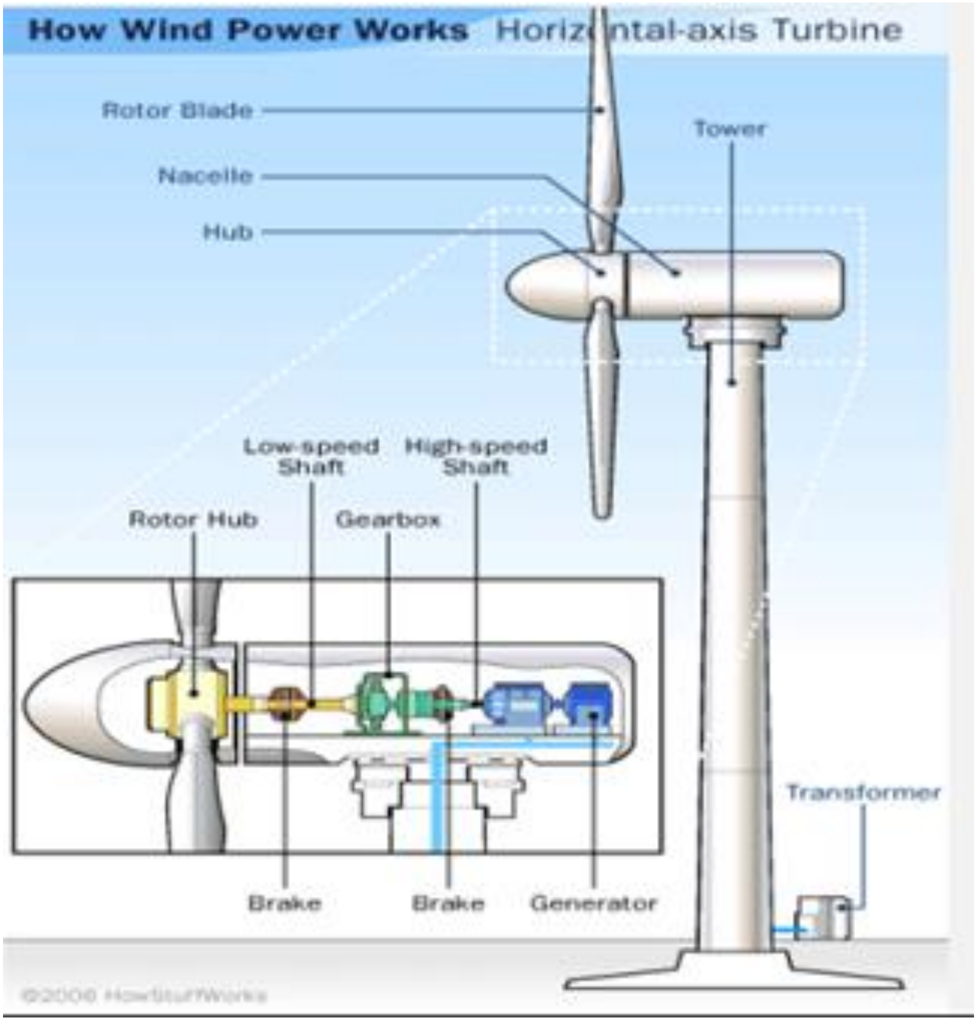



***Figure 1****: wind turbine anatomy[7]*

## 2.3. Wind farm design

Wind farms are built in areas known to be especially windy on a regular basis. The goal of wind farms is to maximize energy output while lowering capital and operating costs [8]. The factors that are most likely to influence the wind farm design are as follows:

- **Optimization of energy production**

The layout of the wind farm can be optimized once the wind farm limitations have been defined when wind farm ‘micro-siting' is another term for this procedure. The goal of such a procedure is to maximize the wind farm's energy production while lowering its infrastructure and operation costs. It can be difficult to manually calculate the best productive configuration for large wind farms. A computer optimization employing a WFDT for such sites could result in significant increases in expected energy production.

- **Visual influence**

The view of wind turbines from the surrounding region is referred to as ‘visual influence.' In many nations, the visual influence of a wind farm on the environment is a major concern, particularly in densely populated areas. The zone of visual influence (ZVI), or visibility footprint, can be computed using computational design methods to determine where the wind farm will be visible from. Larger turbines revolve at a slower rate than smaller ones, therefore a wind farm with a few larger turbines is usually preferable to one with a lot of smaller ones. A uniform area or straight line may be preferred to an uneven arrangement in some circumstances.

- **Noise**

Noise can sometimes be a limiting factor for the amount of producing capacity that may be installed on any one site in densely populated countries. Turbine makers have significantly reduced the noise produced by working turbines in recent years, although it remains a restriction.

The permitting authorities may compel the project to adhere to noise regulations, with fines if the project fails to do so. As a result, the turbine manufacturer may be able to offer a warranty on the noise generated by the turbines. If noise tests on one or more turbines are required, the guarantee may be backed up by agreed-upon testing methodologies.

- **Turbine loads**

The minimum turbine separation employed is an important part of the layout design. The minimum acceptable turbine spacing should be obtained from the turbine provider and adhered to in order to ensure that the turbines are not used outside of their design parameters. The optimal spacing for turbines is highly dependent on the terrain and wind rose for a given location. In the prevailing wind direction, larger distances between turbines and tighter spacing perpendicular to the prevailing wind direction will show to be more productive. Turbines with close spacing are more impacted by turbulence caused by up stream turbines wakes which reduce the performance of the wind production.

# 3. Energy and renewable situation in Tunisia

Recently, there has been a serious interest in wind energy development and this energy has become the fastest growing renewable energy source .In fact, 2020 was the best year in history for the global wind industry showing year-over-year growth of 53%. Installing more than 93 GW wind power in a challenging year with disruption to both the global supply chain and project construction has demonstrated the incredible resilience of the wind industry [9].Wind power's rapid growth is due to the substantial economic benefits it provides. Many rising and developing countries are becoming interested in wind energy to address their energy needs in this setting.

❖ **Energy Situation in Tunisia**

In Tunisia, the electrical energy production reached20,234 Gwh in 2019against 15,263GWh in 2010 or an average annual growth of 3%. STEG (the Tunisian company of electricity and gas) produced in 2019, 17,007 Gwh or 84% of the demand, of which only 2.8% are produced from renewable energy (500 GWH wind and 150 MWH solar).

With regard to the renewable energy activities in the country, Tunisia has opted primarily for solar energy and wind energy as both have significant potential throughout the territory. Moreover, the wind conditions are favorable to the development of wind energy (speed higher than 7m/sec at 60 meters height) in several regions: Nabeul, Bizerte, the central area of Kasserine, Tataouine, Medenine, Gabes. The wind potential is estimated at 8000 MW[10]. Figure 2 present the map of renewable projects in Tunisia from STEG.

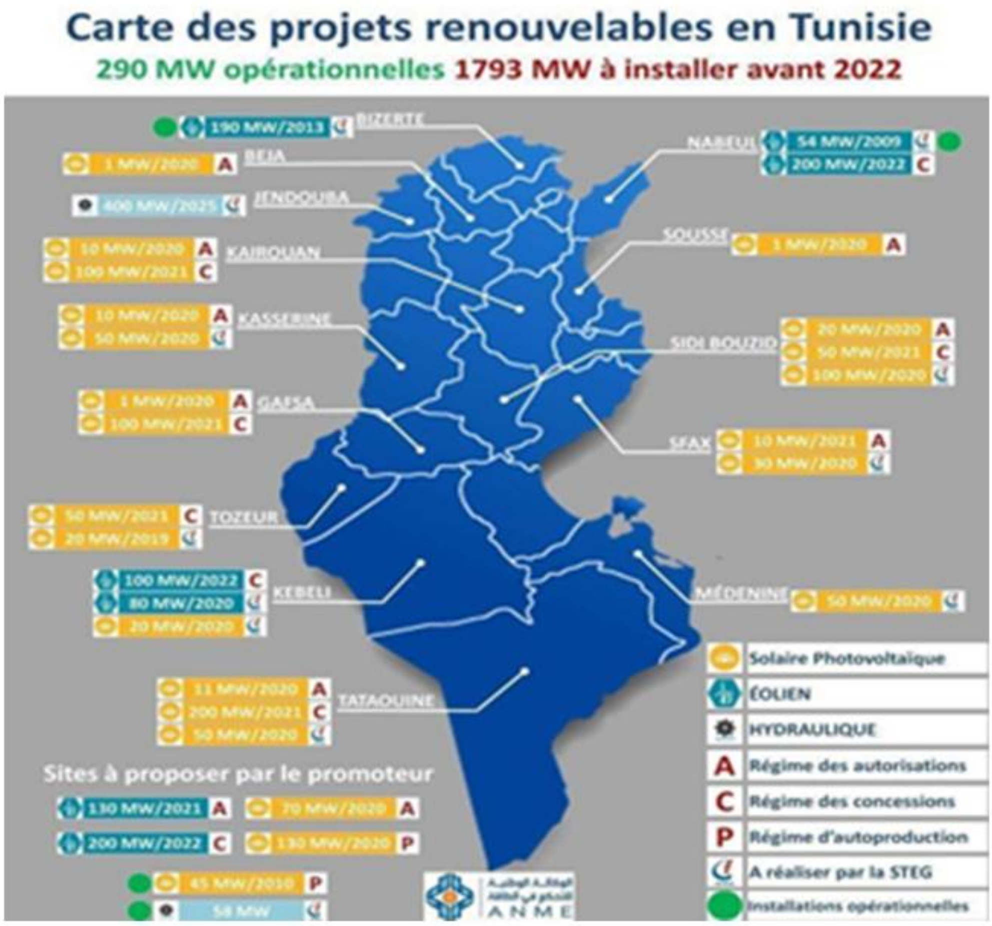



***Figure 2:*** *map of renewable projects in Tunisia ( STEG)*

### ❖ Wind energy situation in Tunisia

The national exploitation of wind power plants for the production of electrical energy began in 2000 with the commissioning of the first wind farm of Sidi Daoud (STEG) [11] [12] [13] [14]. The first park was built in 3 stages with respective powers of 11 MW in 2000, 9 MW in 2003 and 34 MW in 2009. An additional capacity of 119 MW was installed in the regions of Metline and Kchabta in the governorate of Bizerte. The functional capacity of these 2 new parks was increased by 67 MW over the period 2013-2015 to reach 186 MW in 2015.

The Tunisian wind farm currently totals a production capacity of 240 MW. The electrical energy produced in 2019 is 500GWh and the cumulative production from these wind farms during the period 2000-2019 has reached 4,047 GWh [10] .Figure 2. shows the location of STEG's wind farms in Sidi Daoud and in the region of Bizerte.the plans for 2030 aims to implement 1 755 MW of wind energy .


***Figure 3***: *Location of STEG's wind farms in Sidi Daoud and in the region of Bizerte*

# 4. Literature review on wind farms implementation and onshore wind production experiences in North Africa

- **Renewable and Wind energy implementation in Tunisa**

Many researchers worked to on the wind energy assessment in Tunisia, for example Dahmouni and al [11] did An assessment of wind energy potential and optimal electricity generation from wind in the site of Borj-Cedria located in Tunisia toestimate

The wind speed distribution, wind power density and mean wind speed. they analysed the wind speed data, collected at 10, 20, and 30 m height during 2008 and 2009 and the feasibility of a wind park project of a capacity of 1.5MW. Ben Amar and al [12] analysed the energy potential of the wind park implemented in Sidi Daoud and identified the impact of the different meteorological parameters on the electrical production such as the characteristic speeds of the wind and the frequency as well as the evaluation of its wind potential using aerogeneratorMade AE-32.Elamouri and Ben Amara [14] have analysed 17 synoptic sites indicated on the Tunisian territory geographical chart using two statistical methods (meteorological and Weibull) to evaluate the wind speed characteristics and the wind power potential at a height of 10m above ground level and in an open area. Mohamed Abbes and Jamel Belhadj [15] studied the operation of a commercial wind farm in the El- Kef region and investigated the local values of WSC (Wind Shear Coefficient) and air density when the wind speed frequency distribution was described by the Weibull PDF (probability density function). Elamouri and Ben Amar [14] investigated the wind vertical profile to the site Sidi Daoud in two measurement places (masts 3 and 4)at heights of 45, 50 and 60 m above ground level. Dahmouni and Ben Salah [16] evaluated wind energy potential in the central coasts of the Gulf of Tunis. measurements of wind speed and wind direction were conducted during 2008, using a 10-min time step. The treatment of 52 704 observations, allowed the authors to evaluate the mean wind speed, the standard deviation of wind speed, the turbulence intensity and the mean wind power density. In addition to this, other researchers worked on improving the performance of wind farms operation. Karoui and al [17]. investigated the impact of new wind turbines on the power grid, and performed simulations for two faults: a short circuit at the wind farm connection bus and a loss of a conventional power plant of the Tunisian grid.

These simulations are performed using commercial PSSE software containing different generic models of wind turbines. Simulations are carried out with real data from the Tunisian power grid that was provided to us by the Tunisian Electricity and Gas Company (STEG).

Ridha Karoui and al[18] have studied the impact of a STATCOM on the energy production in the wind farm based in Bizerte, the paper described also the technical requirements for connection of a wind energy system to the grid and outfit at the voltage dips (low-voltage ride through) according to STEG (Tunisian Company of Electricity and Gas). It also presents the structure of a static synchronous compensator.

- **Renewable and Wind energy implementation in North Africa**

In Egypt, Mohamed L. Shaltout and al [19] have studied the wind speed distribution is essential for wind energy resources assessment by design of wind farms and to get selection of suitable wind turbines. The two-parameter Weibull distribution function is widely used for wind energy resources assessment using seven statistical methods adopted to estimate its parameters and their estimation accuracy is compared based on some common estimation errors. Consequently, a multi-objective genetic algorithm (MOGA) is adopted to investigate the tradeoffs among the competing estimation errors and to enhance the assessment of wind energy resources. The measurements was taken in one-year at Gabal Al-Zayt wind farm in Egypt .They have used real wind data obtained from the New and Renewable Energy Authority (NREA) in Egypt for the period starting on May 1, 2018, and ending on April 30, 2019.Yassin Yehia Rady and al [20] have presented a quantitative assessment of future development scenarios for the power generation sector in Egypt. The evaluation has been taken at time period between 2018 and 2040 to identify power generation mix compared with the energy plans declared by the Egyptian government .

For Morocco, TouriaHaidi and al [21] have focused on the evolution of installed wind power capacity and its share in the global energy mix as well as its future prospects by year 2030 in Morocco . they presented a synthesis work based on an updated assessment of the carried-out wind projects and aiming to assess the realization of Morocco’s national energy strategy. H. BOUDOUNIT and D. SAIFAOUI [22] carried out a parametric study in order to investigate the potential of Dakhla wind farm in Morocco and the energy production of each configuration also the corresponding wake effect according to the different parameters. They have used three masts heights of 20m, 40m and 60m, in two weathervanes located at heights of 38m and 58m, at a height of 55m .

Algeria created the first wind farm in the southwest located in Adrar city [23] . Salah Mariha and al [24] studied the wind potential evaluation and design technique for a 10 MW wind farm in the Arzew , northwest Algeria, with the goal of improving the power grid's quality of service and increasing Algeria's participation in the use of renewable energy. The dominant wind directions, probability distribution, Weibull parameters, mean wind speed, and power potential of hourly wind data from 2005 to 2015 that corresponded to the wind potential of the site were analyzed and discussed.

MiloudBenmedjahed and al [25] evaluated the wind potential of four locations in southern Algeria, namely Adrar, In Salah, Illizi and Tamanrasset, using the Weibull distribution. The data were collected every 3 hours over 5 years. The data was collected every three hours for five years and used to calculate the annual energy produced in order to determine the quantity of three forms of fossil energy (natural gas, gasoil, and gasoline) preserved and the CO2 emissions averted.

A. Abderrahim and al [26] have calculated the wind potential in two Algerian regions Ilizi and Oran, located in the southeast and northwest of Algeria, respectively, based on months, seasons, and complete years. Using hourly data collected over a thirty-year period, an attempt is made to contribute to the updating of the wind map in this country. The wind data analysis is done using the Weibull function [27].

from the literature prospect, it is possible to conclude that in order to maximize the energy production of a wind farm, it is important to choose a model adequate to the region's wind resources and quality. As a result, if a wind turbine is designed specifically for the installation region, it can achieve optimum efficiency. However, designing a wind turbine for a single location is costly. As a result, a simulation must be run to choose the best machine among those already in use.

# 5. Conclusion

Wind energy is a very important source for clean and green electricity gernation and the use of this source of energy worldwide is getting more and more significant.

The literature prospect showed that many countries in North Africa are interested in the exploitation of wind. Also t in order to maximize the energy production of a wind farm, it is important to first investigate very well the studies site and collected the needed information on the wind speed quality and distribution.

# **Chapter II** : METHODOLOGY AND MODELS

## 1. **Introduction**

Selection criteria is the first stage in any wind farm project study where the organization of data collection in a readable format from the different sources on wind potential and grid situation is the main advice to explain in a methodology process . Moreover, the analysis of wind potential across the country and define the potential areas for relevant wind activity determine the possibility of wind energy production.

This chapter covers the methodology and model used to advise on the effective distribution of wind farms while considering the following aspect: the land availability, the terrain topology, the weather surveys and the national electrical grid balance.by analysing and design map using ArcGIS and WindPro software for estimating a wind turbine's energy output and assessing a wind farm's total energy potential.

## 2. **Methodology**

This thesis presents a GIS-based application for evaluating the potential suitability of an onshore wind energy farm to provide ready visual access to this information to investors, politicians, developers, researchers, students, and the public. This application will be useful for a preliminary site selection of a utility-scale and largely distributed wind energy, the site suitability analysis based on a set ofphysical, economic, and environmental criteria. The criteria including:

topography, wind power capacity,  power grid access into a Spatial Decision support systems (SDSS) as part of a multi-criteria analysis (MCA) approach to generate an onshore wind energy siting model, thus making it a valuable planning tool.

The first phase of the thesis is combining a the different information from the different maps:grid map, topology map and wind potential map using  ArcGIS  software.

the software ArcGIS is an effective approach to “solving” complex spatial problems like wind energy siting, which must balance numerous geographic, technical, environmental, economic variables[28].

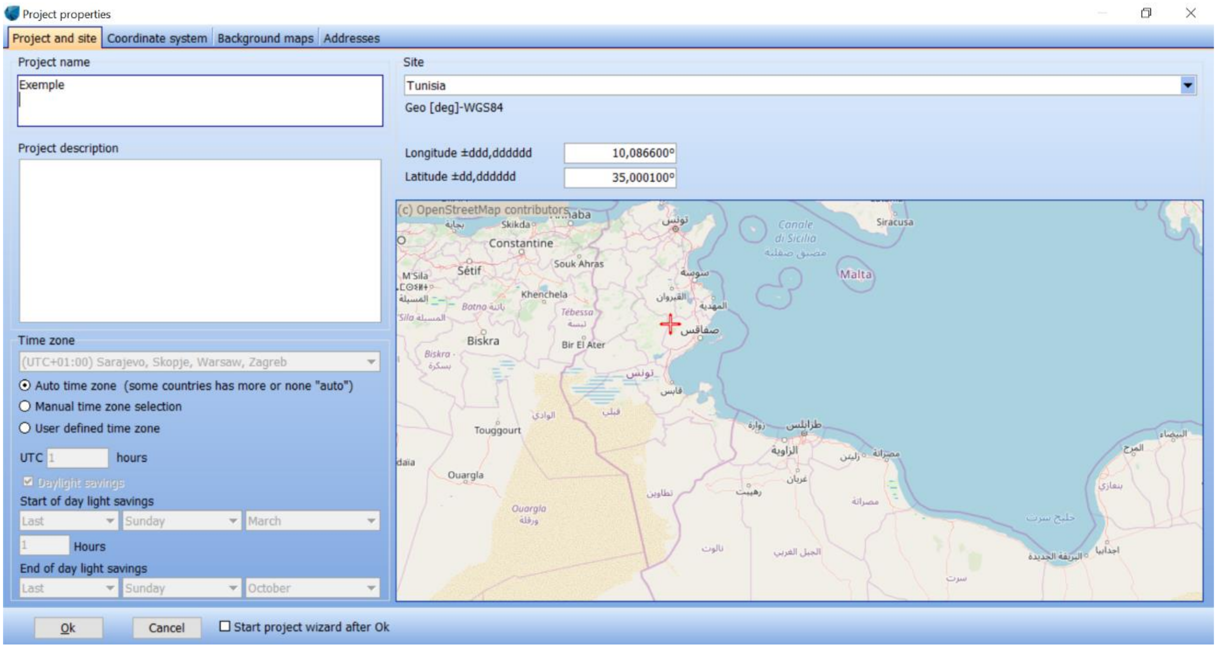



***Figure 4:*** *WindPro Interface software*

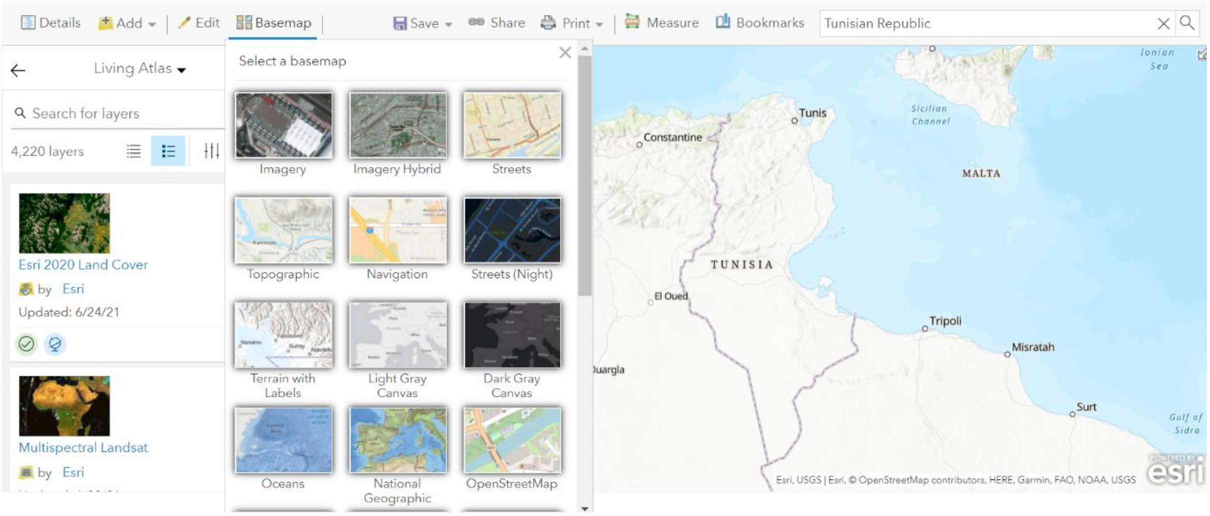



***Figure 5:*** *ArcGIS Interface software*

# 3. Wind farm siting using a geospatial analytic process

One of the most challenging phases of developing a wind farm is to find the most appropriate location to build it; this step can easily take years of feasibility studies.The principal objective of the siting process is to locate a wind turbine (or turbines) such that net revenue is maximised while minimising issues such as noise, environmental and visual impacts and overall cost of energy[29]With the aim of developing a successful wind project, the measurement of wind speed should be produced as accurately as possible; there are a variety of models to estimate wind speed such as mesoscale and microscale models.

Renewable energy siting (RES) Geographic information systems have been widely used to assist in searching for suitable sites for wind farms, by combining different layers, ArcMap, its dynamic tool, provides the functionalities of integrating a large spectrum of geospatial information into the decision making of wind energy development. The methodological framework of the wind siting assessment applied in this thesis to find suitability sites to (or "intending to") the schematic methodological framework for developing a wind farm is explained in Table 2.

| | | |
|---|---|---|
| Definition of Criteria | | |
| Data collecting | | |
| Wind potential | Gid Map | Land topology and land use |
| Organizing data | | |
| Exclusion Area | | Rated Area |
| Suitable Area | | |

**Table 2:** Schematic methodological framework, author´s diagram.

### 3.1. Selection of criteria and data

A set of three criteria were chosen for generating a wind energy suitability model, the criteria are presented in Table 3 below:

| criteria | Date Source | Reason for selection | Original data source |
|---|---|---|---|
| Wind energy potential | WindPro Software based on online data. Data holdings are based on an extract from www.dataforwind.com web site . This dataset is further processed and ready to be used in WindPRO | It covers everything from wind data analysis, calculation of energy yields, quantification of uncertainties, assessment of site suitability, to calculation and visualization of environmental impact. | Overview of the windPRO modules, windPRO 3.4[30] |
| distance from power grid | Provided by the national company of electricity and gas | analyse the situation of the distribution network and grid code | Paper and document provided by STEG |
| Land topology | Land Degradation Assessment in Drylands (LADA) | Define the situation of land topology in the country | National farm stratification and the subsequent targeting of sub-national territories for detailed WAW assessment. |
| Land use | A GIS-based approach | Define the available areas for implement wind farm | Wind Energy Assessment in Africa A GIS-based approach |

**Table 3**: criteria for generating a wind energy suitability model

### 3.2. Description of criteria

The different criteria evaluated in this thesis are wind energy potential, land topology, and national grid situation

- **Wind speed potential**

Wind resource is almost always a key consideration, the better the resource, the greater the potential power production and project revenues [31], the average wind speed criterion is widely used in all studies found in the literature and considers the most important criteria. Wind energy potential at 80 m map was obtained from the Wind Atlas from windPro

In which are explained the different characteristics of the wind potential in Tunisia in it are included wind speed, density, roughness, wind direction, among other resources.

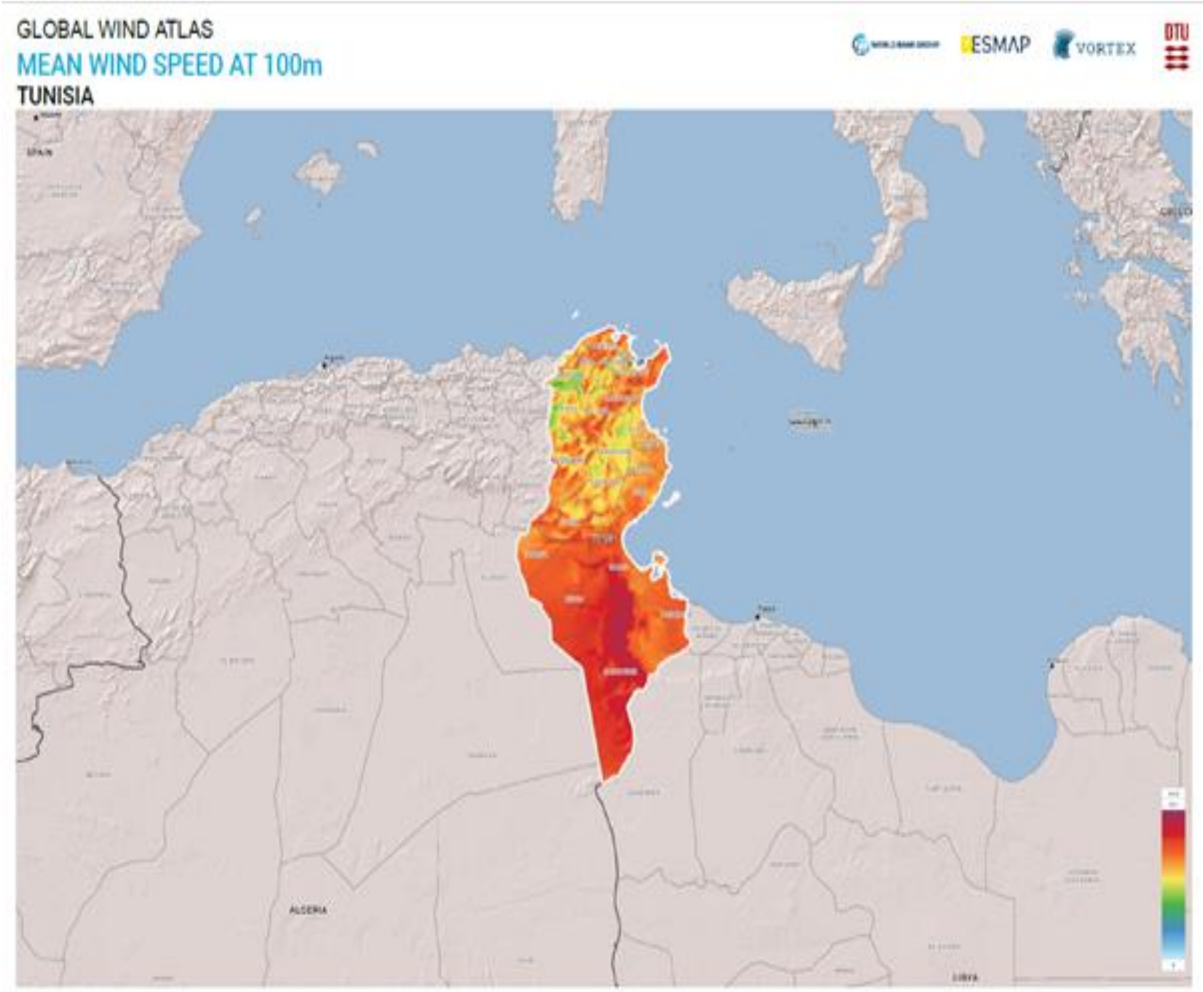



***Figure 6:*** *mean wind speed of Tunisia 2021(Global Wind Atlas)*

### 3 .3. Impact of the land topology and land use

Tunisia is a flat country as a whole, except for the northwest and west which are mountainous regions. The maximum altitude is 1544 m at the Chaambi mountain, near Kasserine. The mountain gradually gives way to low steppes and then to the eastern coasts which develop from Cap Bon to the Libyan border. In the south, it is the stony Hamadas desert that slopes, from the Ksour mounts, towards the dunes of the Great Eastern Erg. The coasts are cut by deep gulfs (Bizerte, Tunis, Hammamet, Gabes) and numerous islands (Kerkenna, Djerba...)[32].

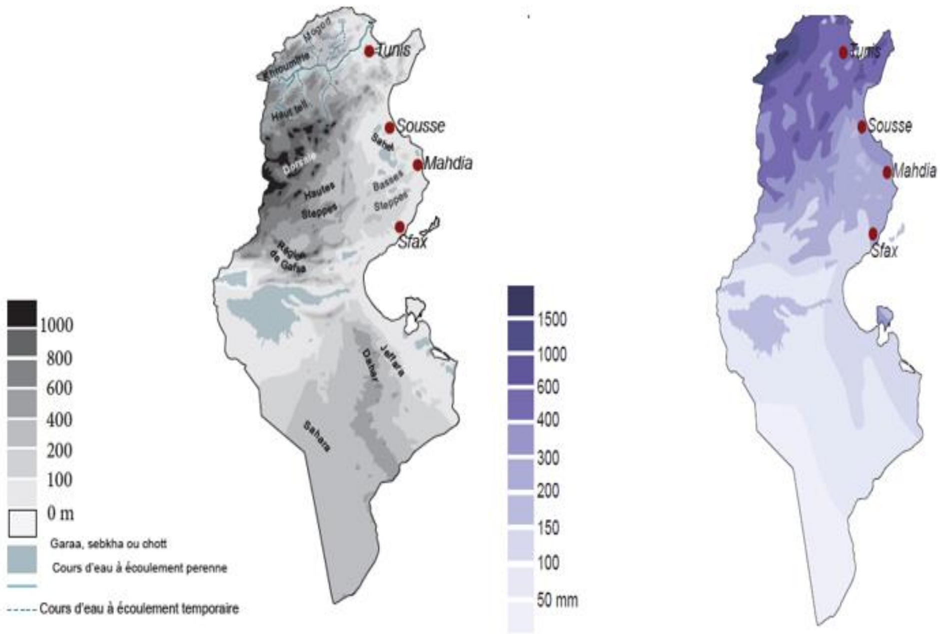



***Figure 7 :*** *The topography land and dominant climate map in Tunisia.[33]*

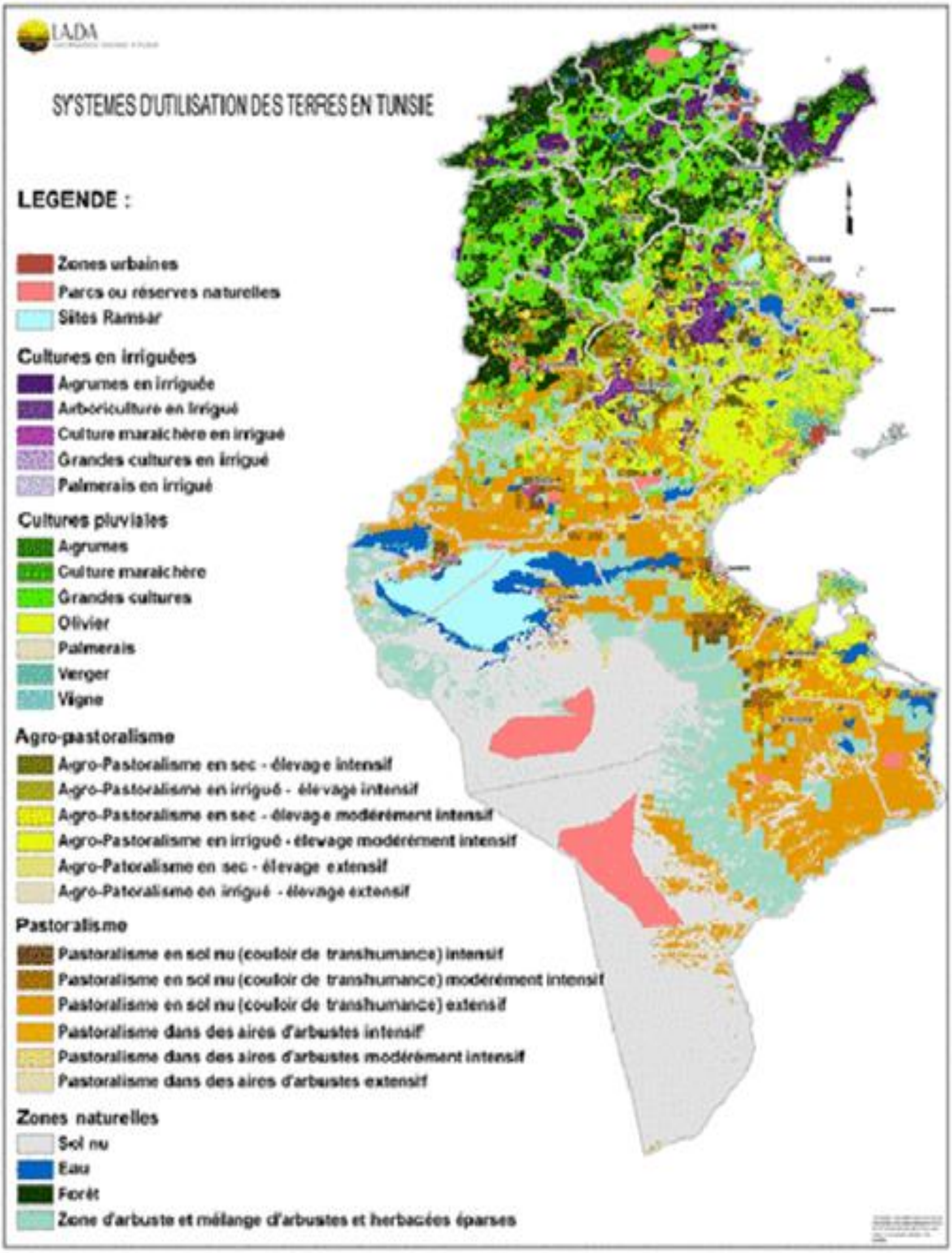



***Figure 8:*** *Land use map in Tunisia*

### 3.4. Impact of the grid

Wind turbines are connected to three types of electrical networks: transmissions, distribution, and direct to the delivery point. The three are distinguished by line voltage, and the current-carrying capacity is determined by the size of the conductor[34].

in Tunisia, Renewable energy power plants must participate in the voltage control of the transmission system in a continuous, dynamic and fast way. They must be equipped with an automatic voltage control system and be able to supply or and be able to supply or absorb, in steady state, the reactive power necessary to maintain the voltage within the limits of the eligible for operation of the transport network of the STEG [35].

The structure of the power system in Tunisia consists of a national transmission grid lignes with a voltage level between 90 and 400 kV, this high voltage transmission network is used to transport large amounts of power over long distances. This lignes of electricity has its central power production from different sources such as thermal, gas turbine ,gas turbine in project ,hydraulic ,combined cycle ,combine cycle in project , and wind turbine .

Two network hierarchies can be distinguished:

**-** the large-scale transmission and interconnection network, which transports large quantities of energy over long distances at 400 kV or 225 kV with a low level of loss .

**-** the regional distribution networks which distribute energy at the level of the regions which supply the public distribution networks as well as the large industrial customers[35].

The transmission grid is currently interconnected via one 400 kV line, two 225 kV lines, one 150 kV line and two 90 kV lines. Tunisia also has two 225 kV interconnections.

By the end of 2018, Tunisia's electrical distribution network had grown to 175 389 kilometers, with 59 691 kilometers of medium-voltage (MV) lines and 115 698 kilometers of low-voltage (LV) lines. In 2018, there were 75 065 MV/LV transformer substations, still improving in 2021.

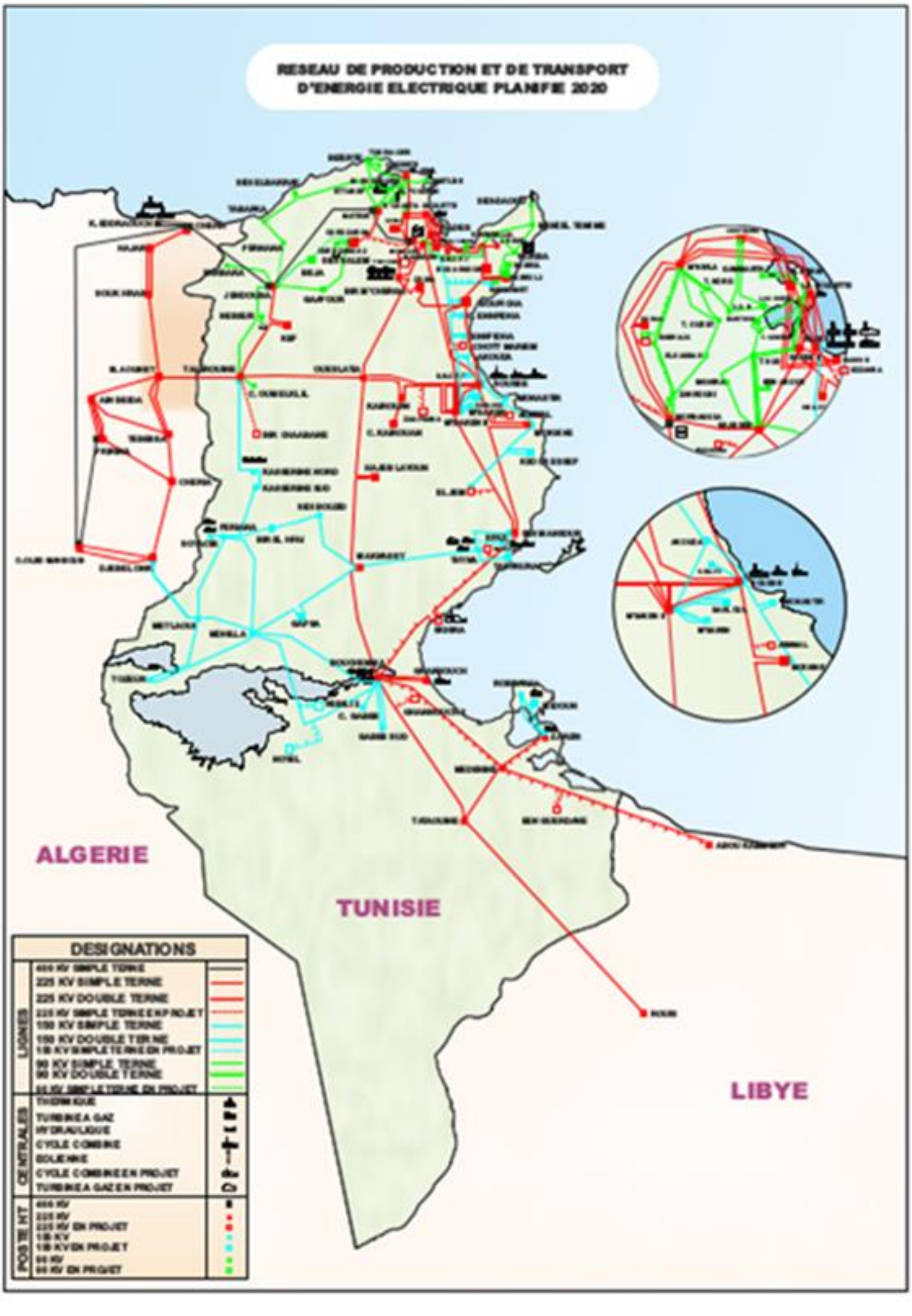



***Figure 9:*** *Electric power grid lignes for production and transmission network in Tunisia planned for 2020*

### 3.5 Exclusion areas

Following the methodological framework proposed in the beginning of this chapter .

The next step is to determine the restricted areas, also called exclusion areas; these areas are determined according to the legal regulation, wind assessment standards and literature review.

| Criteria | Exclusion parameter |
|---|---|
| Wind Speed | inf a 6 m/s at80 hight |
| Land Use | Forest Regional natural park Natural, Civil Reserve Bird reserve, montaigne Agroforestry Reserve Forest |
| Approximately to electrical grid | 1km |

**Table 4:**The different exclusion parameters corresponding to each selected criterion

Table 4. exposes the different exclusion parameters corresponding to each selected criterion. In the case of wind energy potential all the values below to 6 m/s are excluded, for natural environment parameters (forest, regional natural park, civil reserve and bird reserve) all are excluded: In the case of the slope criteria, as well as land used (agroforestry, reserve and forest). In particular cases such as urban centre and rivers are created Buffer zones i.e. minimum distance around each parameter.

## 4. **Conclusion**

Determination of the parameters and different criteriaare very important to precise the methodology and model used.In fact to investigate of the very windy and suitable location for wind energy activity ,it is necessary to analyse land used ; situation of grid connection and wind speed assessment in the hall of the country.the result of this investigation summarizing in a map that show the Areas where wind farms could be implemented in Tunisia.

This study enables analysis of the effective distribution of wind farms onshore and very relevant to energy transition in Tunisia.

# Chapter III : RESULTS AND DISCUSSION

## 1. Introduction

The final chapter is devoted to presenting all of the results achieved using the WindPro software. As a result, nearly Calculated Annual Energy for Wind Farm and its power curve can be simulated. A Weibull probability density representation and an annual wind rise for seven different locales are included in this chapter. These will aid in determining the characteristics of annual average speeds in relation to a dominant direction. This makes it possible to specify many wind turbine installations to make up a wind farm.

## 2. Wind farm project

The process of developing a wind farm project is complex, with several steps to be coordinated simultaneously, many of the tasks which are concurrent rather than sequential. Therefore developer must perform different tasks on the same project (Busby, 2012). The following is a wind farm development project review that describes the steps that a developer may apply to develop an onshore wind farm. Five typical phases of developing an onshore wind farm are considered: Selecting the optimal site, wind assessment, turbine selection, turbine output and turbine siting issues.

- **The Weibull probability density function**

A frequency or probability distribution, which Atlas model is based on, can also be used to characterize the basic properties of long-term fluctuations in wind speed. The Weibull probability density function, which is described in terms of two parameters, the shape parameter k and the scale parameter c, is a useful mathematical distribution function that has been proven to fit well with data [36].

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \qquad (\mathbf{1})$$

- **Energy Yield (E )**

The following equation is used to compute the wind energy output  or as known Energy yield from a WTG at a certain time[36]:

$$\boldsymbol{E = \frac{1}{2}\,\rho V^{3} A C_{e}} \qquad (\mathbf{2})$$

where:

**ρ** is the Air Density (kg/m³)

**V** is the Wind Speed (m/s)

**A** is the Area Swept by the Rotor (m²)

$\mathbf{C_e}$is the total efficiency of the WTG at the given wind speed

- **Capacity factor**

A greater capacity factor number indicates that the wind potential for the specific site is being better exploited. The yearly capacity factor is based on a time span of one year (8760 hours)[37].

$$Annual\ capacity\ factor = \frac{E_{WTyear}}{P_R\ 8760\ h} \quad (3)$$

Where :

$P_R$ **:** rated power (W)

$E_{WTyear}$ :is the annual energy output (Wh)

### 2.1. Selecting the sites for investigations

Figure 10 - as shown , allows to visualize the best locations where to implement wind farms that take into account: the wind potential, the terrain topology and the situation of the current electrical grid.

This figure is obtained from the maps and data analysis using ArcGIS software

This map shows that more potential for wind implementation is in the north and in the east flowed by less potential and south seasite area.

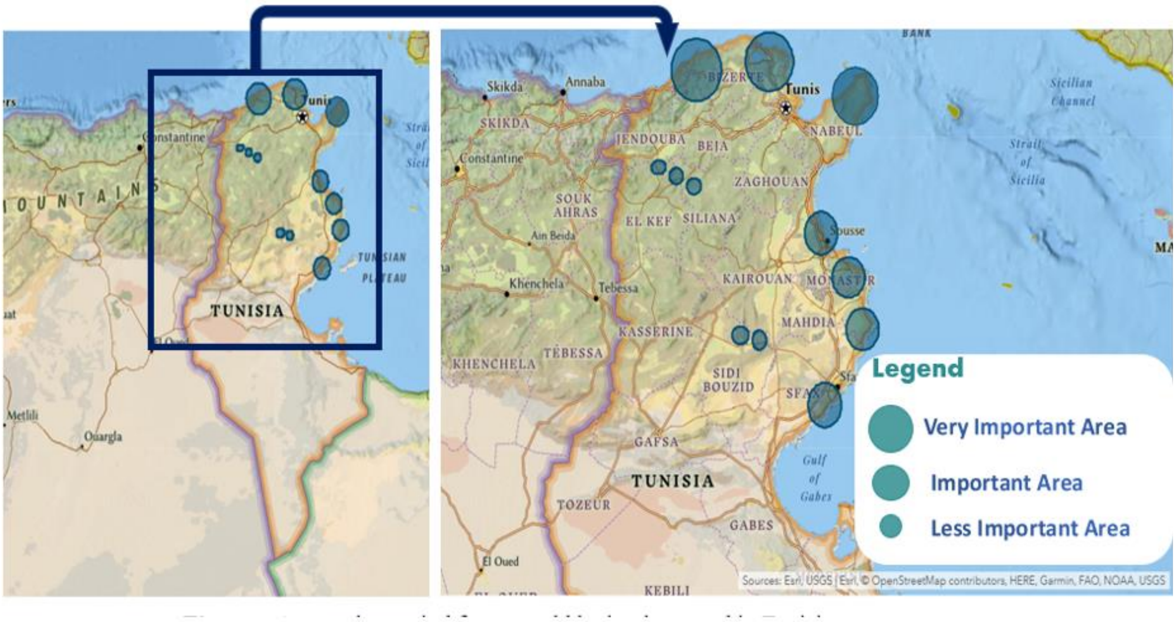



***Figure 10.*** *Areas where wind farms could be implemented in Tunisia*

### 2.2. Turbine selection

Many type of wind turbine generators can be implemented in the north of Tunisia which characterise by Class II such as Spain 's technology Gamesa [38], Neg Micon[39],Enercon [40].In fact , there is other technology from Germany as Vestas[41] ,Nordex[42] ;Sinovel[43]from China and Filand technology Winwind[44] .

The most operational farms of Sidi Daoud and Bizert are based on the Gamesa technology, when the strategy market of Tunisia is based on.

In the present study, several wind turbine manufacturers were analysed in order to adapt the most suitable turbine to the general characteristics of the study area and its strategy. Indeed, the region has mostly a frequency of wind speeds of 100 m exceeding 7 m/s. Consequently, the choice is an Spanish three-blade generator called: GAMESA

G128-5000 . Its rate power is 5000 kW. The rotor diameter is 128m. The maximum hub height is estimated to be 120 m. The grid connection frequency is 50/60 Hz.The wind class of this wind turbine is Class IEC IIA .Indeed,the wind data measured from WindPro tutorial, using the wind speed data recorded between 2010 and 2021.

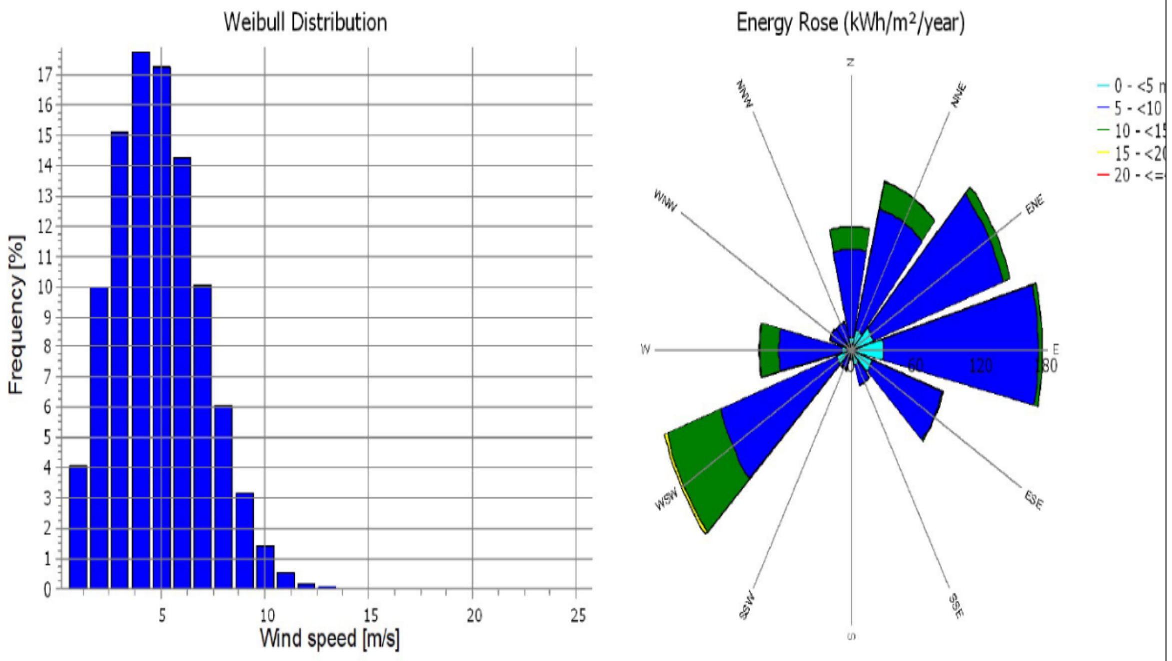
## 3. WindPro Simulations and Wind assessment

In this study we analyse using the WindPro software  seven distributed as follow: In the North and in the East seaside, namely: Gabes, kelibia , Medinine , Monastir , Sfax , Tabarka ,Tunis. Table5 presents the Longitude and Latitude of each site analysed in this section.

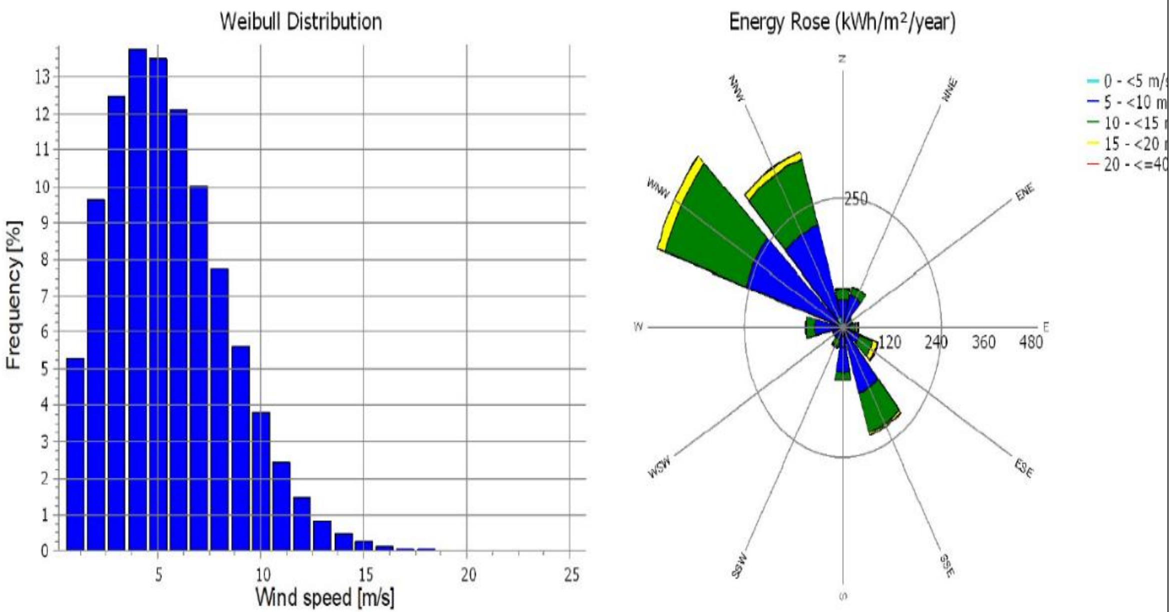
| Site | Longitude | Latitude |
|---|---|---|
| Gabes | 10,071808° | 33,908577° |
| Kelibia | 11,102753° | 36,858580 |
| Medinine | 10,545000° | 33,333000° |
| Monastir | 10,804016° | 35,770912° |
| Sfax | 10,767426° | 34,734306° |
| Tabarka | 10,767426° | 36,944485° |
| Tunis | 9,534546° | 33,884872° |

***Table 5:*** *geographic coordinates of the seven sites sites*

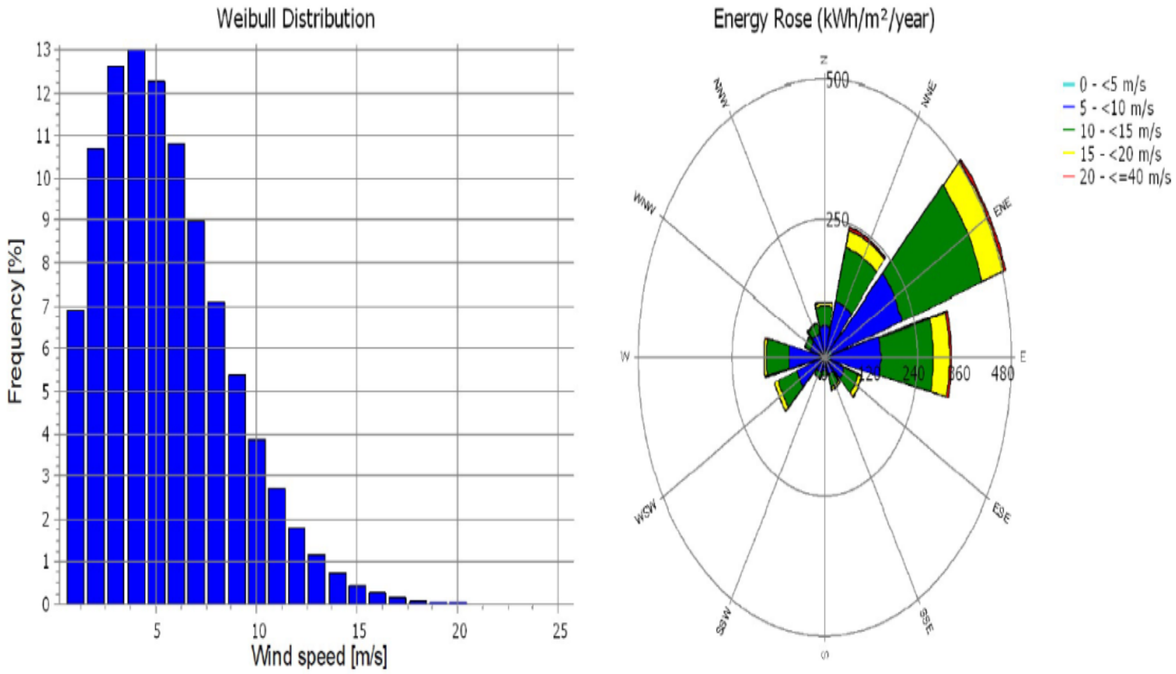
The weibull distribution and wind rose fi  shown in  figure 11, below of each site :



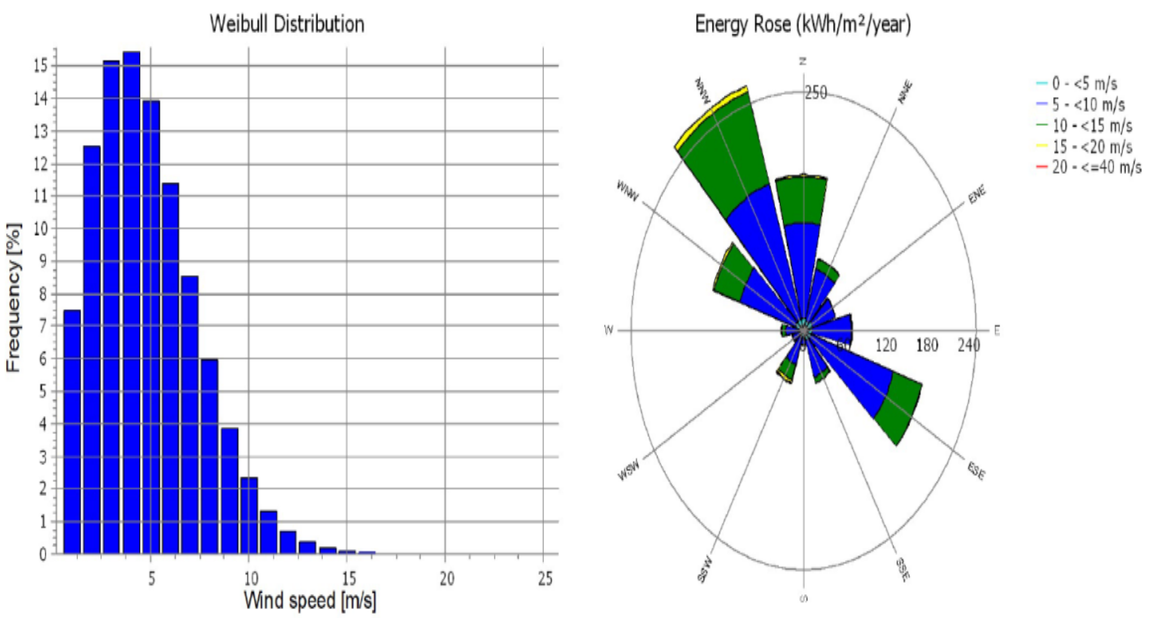

**Gabes**



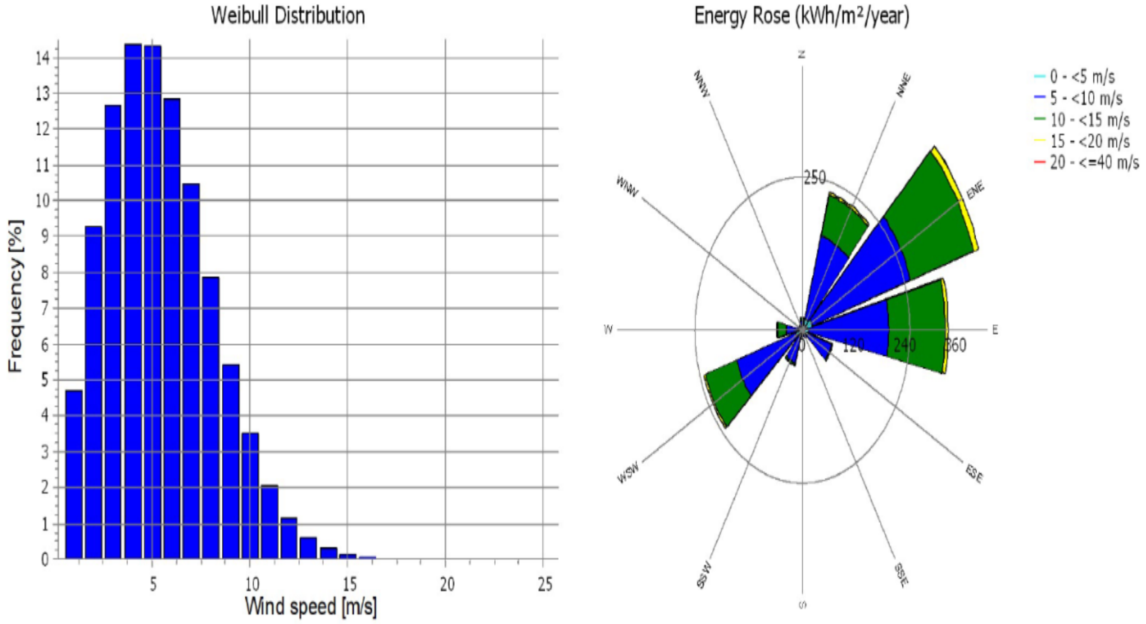

**Kelibia**



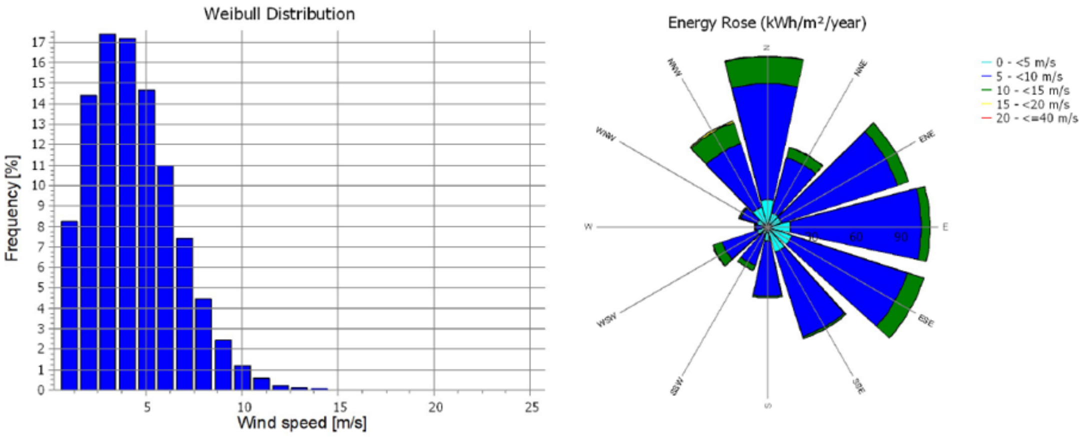

**Medenine**



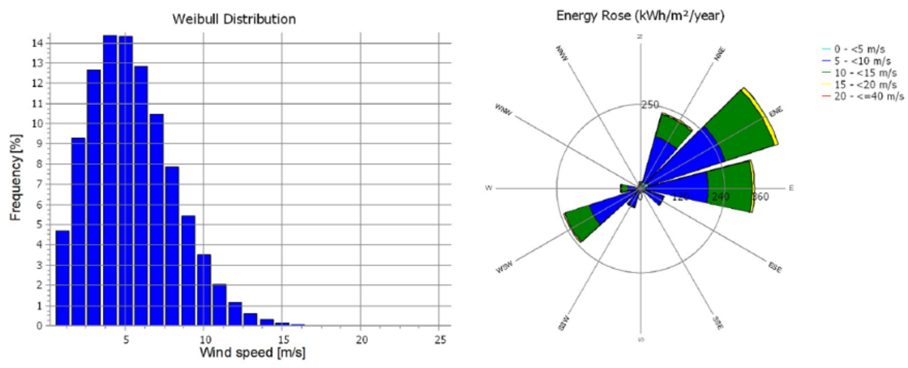

**Monastir**




**Tabarka**




**Sfax**




**Tunis**

*__Figure 11__: Weibull distribution and wind rose of each site*

We note that the most significant wind speed location is in Kelibia where the average wind speed value is 6.2m/s,correspondent at a frequency of 15.7%

On the other hand, Sfax which has mean wind speed of 5 m/s ,correspondent at a frequency of 3.6% .Morover,Gabes ,Medinine,Monastir ,Tabarka and Tunis have wind speed values ,respectively 5.4m/s , 5.8m/s ,5.5 m/s , 5 m/s ,5.2m/s , 6m/s, correspondent respectivelyat a frequency 10.5 % ,8.7%,8.2%, 8% ,3.7% .

### 3.1. Energy yield (E)

Figure 12 represent the variation of Energy yield in different sites in Tunisia obtained by simulations done with the wind ProSoftware.

. It shows that the highest values of energy yeild are observed in Klebia with 58586 Mwh/year as the wind speed average is the highest in that area.It is important to note, also, that Medinine and Tunis have an energy yeild nearest to klebia are respectively equal to 52116,1 Mwh/year and 50571,2 Mwh/year ,where the energy yeild of Gabes ,Tabarka ,Monastire are respectively equal to 34988 Mwh/year,36412,7 Mwh/year, 42075,8 Mwh/year .

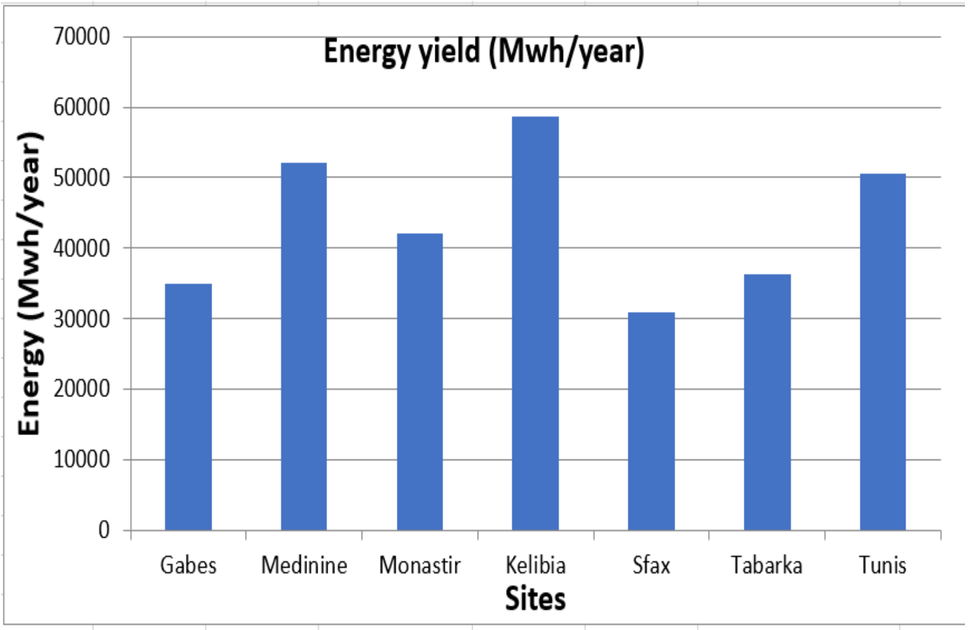



***Figure** 12: Energy yield (E)*

### 3.2. Energy losses/capacity factor

Figure 13 represent a variation of wake losses and capacity factors of the seven sites . As shown, the tow curves have a quasi symmetricalshape, when the capacity factor curve goes up and the wake losses curve goes down . Higher values of capacity factor are observed to Kelibia equal to 20.1% where it has the lowest wake losses equal to 3.4% .

However , the other sites have a relatively values varie between 10.5% and 17.8% for capacity factor and 5.3% and 10.6% for wake losses .

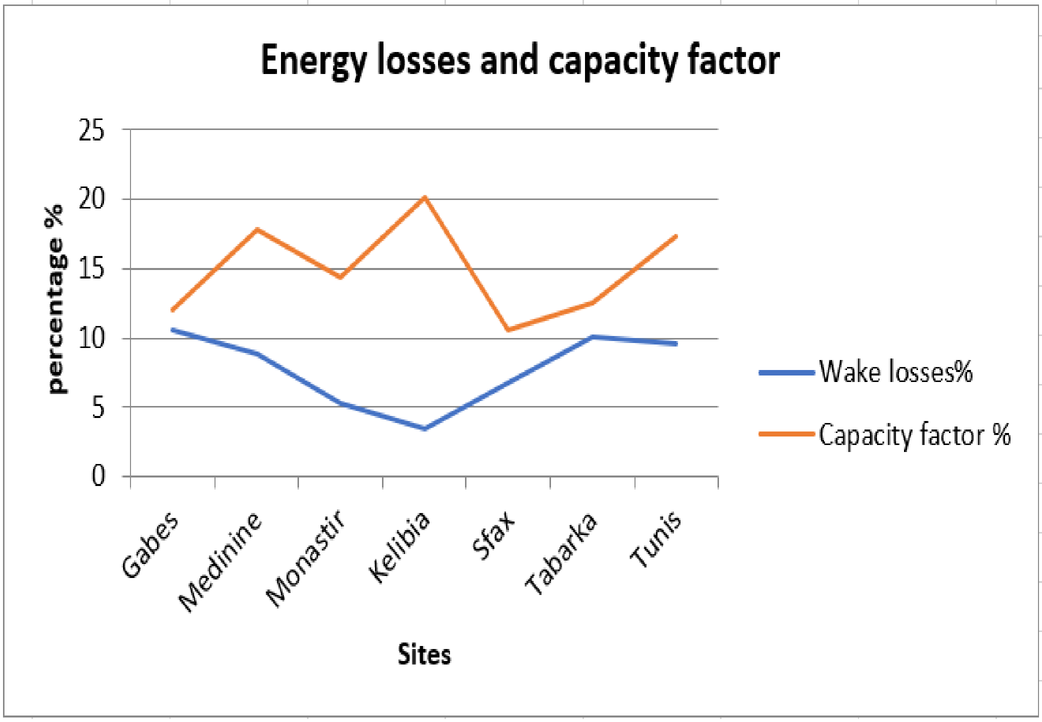



***Figure13 :*** *Energy losses/capacity factor*

## 4. Analysis of Wind farms in Tunisia Kelibia

kelibia is the most suitable site that provide the high energy output ,when Its the wind assessment ,grid connexion and land topology selected this area to be the most productive zones between the seven locations.

All WTGs, Air density varies with WTG Position 1.206 kg/m$^3$ -1.208kg/m$^3$

### 4.1. Kelibia Power curve

Figure 14 presents the variation of Power curve with mean wind spead where each wind turbines given by an air density varies to 1.206 kg/m³ -1.208kg/m³ .As shown, the power output of wind turbines quickly increases and takes its maximum value at the nominal wind speed of approximately 15 m/s corespondent of 5000 Kw . However, the power curve take its minimum value at mean wind speed does exceed 25 m/s.

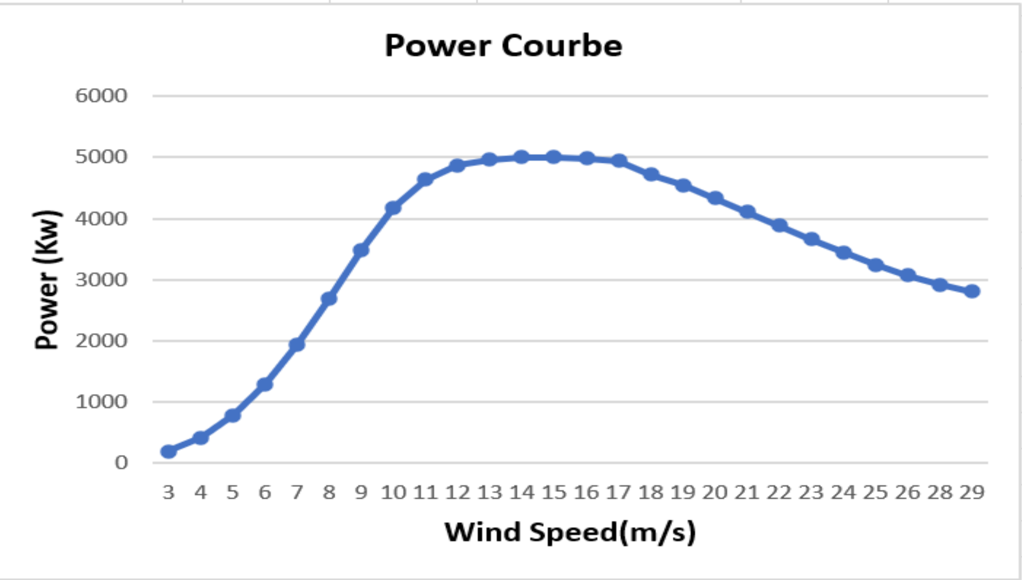



***Figure 14***. *Power curve*

- The farm contains six wind turbine generators of GAMESA G128-5000 with hub high of 36m et rotor diameter of 128m, when its power ratedis 5000 Kw.The full loadhoursis **1758hour/year .**
- Table 6 show the variation of the annual energy and wake losses of Kelibia for each wind turbine. We note that the wind turbine number 6 produce more energy comparing to the other where its annual energy value is 9978.8 Mwh/y with 1.4 % of wake losses.

| WTGs | AnnualEnergy(Mwh/y) | Wake losses(%) |
|---|---|---|
| 1 | 9790.8 | 3.1 |
| 2 | 9696.3 | 4.0 |
| 3 | 9681.5 | 4.2 |
| 4 | 9693.7 | 4.1 |
| 5 | 9744.9 | 3.6 |
| 6 | 9978.8 | 1.4 |

**Table 6.** variation of Anual energy and wake losses of Kelibia

## **5.** Conclusion

Tunisia has a good wind potential that makes it a favorablelocation to implement wind farms. The main results show as following :

- The turbine selection is an Spanish three-blade generator called: GAMESA G128-5000. Its rate power is 5000 kW. The rotor diameter is 128m. The maximum hub height is estimated to be 120 m. The grid connection frequency is 50/60 Hz. The wind class of this wind turbine is Class IEC IIA.
- In this study we selected seven locations in the suitable area for implementing wind farms which is :Gabes,Medenine, Kelibia,Monastir,Sfax,Tabarka,Tunisbase on the evalution of Weibull distributions and its wind rose .

- Energy yield of the seven location show that Kelibia is the best location according to the measure of its capacity factor and wake losses which are respectively 20% and 3.4% with an annual energy of 58586Mwh/y.

# GENERAL CONCLUSION

Wind energy, as a component of the green transition, has been given a lot of attention in Tunisia since 2009.Moreover, the good wind energy potential is one of the motivations to develop the wind energy sector in the country.It has made significant progress in the last decade to encourage private sector participation and accelerate the achievement of national goals. However, the assessment finds that there is a need to improve the mapping of renewable energy resources and create an energy planning framework with higher renewable energy shares to support Tunisia's renewable energy targets.

The thesis' findings include a research of possibilities for the most suitable site for constructing a wind farm that meets all of Tunisia's safety, environmental, and energy production regulations. This work is carried out using an approach, methodology, and model that includes a simulation with WindPro, data gathering, and analysis, and ultimately, a single selection among all the investigated options.

Therefore, this thesis addresses the integration studies of a wind farm in the Tunisian territory. First, the study focused on the selection of the most favourable site for the installation of the wind farm, using the Wind Atlas assessment map; topology and grid connections map. In fact, this investigation is based on the detection of the most favourable sites where the analysis of these maps concludes that the most favourable areas for wind farms are located north and east of the coastline .

the simulation based on selected of seven locations distributed in North and in the east seaside which are Gabes , kelibia , Medinine , Monastir , Sfax , Tabarka,Tunisi, where the results show that Kelibia is the most suitable site for implemented wind farm in this country with a capacity factor of 20% and annual energy  58586 Mwh/y where wake losses is 3.4%.In fact the wind turbine generator output is 8787.9 Mwh/y with the full load hour 1758 hour/year .This results could be improved in way to make them optimal .

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