Wind Energy in Tunisia: Opportunities for integration of storage technologies

Yasmine AYED

Dissertation presented to the Polytechnic Institute of Bragança to obtain the master's degree in Renewable energy and energetic efficiency Engineering within the Double Diploma with Université Libre de Tunis

Supervised by

Professor Luís Manuel Frölén Ribeiro

Professor Nizar SOMRANI

Bragança

2019

Abstract

This thesis has been conducted to couple hourly wind data of six different measurement station in Tunisia provided from Tunisian meteorological stations to the electricity consumption in a timeline fashion. The idea is to evaluate the wind potential for a few locations around Tunisia using Weibull distribution and Meteorological methods. The latent of wind power was statistically investigated including the average wind velocity and wind direction frequency data for 25 years (1990-2015) in 25 places in Tunisia. Using the two methodologies, 6 stations have been selected and considered as the most potent locations in term of wind energy, where the hourly average velocity is more than 4m/s and wind direction frequency exceeds 15%. The data was analyzed using MATLAB software in order to find out the generation of wind power. Weibull distribution was followed to calculate speed distribution in all the six areas chosen. A 3.2 MW wind turbine as been selected according to the findings of the hourly wind power potential. Results shows that Thala is the best area in Tunisia in term of wind energy. During September the energy production using 3.2 MW wind turbine exceeds 12 GWh in Thala. The last part of this project, is to compare hourly energy production and hourly energy consumption during January, March, July and September. The purpose of this comparison is to study the overproduction of power produced by the selected wind turbine and see if complementary storage energy devices are needed.

RESUME

Ce projet, consiste à coupler les informations horaires du vent fourmis des stations de météorologie de Tunis avec l'électricité consommé pendant la même durée du temps. L'idée de cette étude est de caractériser le champ de vent dans une zone et voir si des dispositifs d'énergie de stockage complémentaires sont nécessaires. Ce projet a conduit à examiner six sites différents en Tunisie en termes de potentiel éolien, en utilisant des informations issues de l'Institut National de Météorologie de Tunisie et à l'aide du logiciel MATLAB. Les critères utilisés afin de sélectionner les six sites à étudier est la valeur moyenne de la vitesse de vent et la fréquence de distribution de vent. Après l'analyse des données c'était avérer que Thala, Nabeul, Tozeur, Kibili, Gafsa et Bizert sont les sites les plus puissants en termes d'énergie disponible dans le vent, où la vitesse moyenne dépasse 4 m/s et la fréquence de distribution de vent est plus que 15%. Pour chacun de ces sites, une distribution de Weibull a été tracée et une comparaison de la vitesse du vent a été effectuée. Dans une deuxième étape, une simulation avec une éolienne de 3.2 MW de puissance. A partir des courbes de puissance, tracés en utilisant MATLAB, le résultat au niveau de Thala était le plus intéressant, une production de plus que 12 GWh au mois de septembre. Afin d'intégrer une technologie de stockage d'électricité, une comparaison entre la consommation et la production d'électricité doit être effectuer. Le choix de technologie de stockage doit être basé la capacité de stockage et le temps de décharge.

Acknowledgement

Firstly, I would like to thank Polytechnic Institute of Bragança and the Private Polytechnic Institute of Tunisia for giving me the opportunity to gain a lot of experience. My special sincere gratitude goes to my supervisors, Luís Manuel Frölén Ribeiro and Nizar Somrani for dedicating their precious time, giving advice and helping me from the beginning to end of this thesis. This work would not succeed without their great supports. I am also grateful to Abdelrazek Arif from the National Institute of Meteorology of Tunisia who provide me with the wind data. A special thanks to my parents and family members for encouraging me with love and care

Dedication

There are a number of people without whom this thesis might not have been written, and to whom I am greatly indebted.

To my mother and father who continue to learn, grow and develop and who have been a source of encouragement and inspiration to me throughout my life. May almighty God keep you and give your health.

To my sister, brother, grand-mother and friends who knowingly and unknowingly led me to an understanding of some of the more subtle challenges to our ability to thrive.

Most of all I am very much indebted to **Allah** who I powerfully have faith in providing me with strength, energy and bravery to work on this project.

Table of Contents

List of figures

List of Tables

List of equations

I. Introduction:

The fast-growing energy demand is particularly visible in Africa [1]. The African continent saw its consumption to 8% versus 0.6% in 2014. While, energy demand rose only by 0.5% in non-OECD countries (Organization for Economic Co-operation and Development). While it decreased by 0.3% in OECD [2]. Tunisia, an emerging country in North Africa, is historically presenting an energy mix mainly based of gas (part of it is locally produced or imported from Algeria, a cross-border country). The Tunisian energy mix is composed of fossil resources – mainly gas with 53% of the total primary energy consumed in 2014 [3]. The electricity production, distribution and transport activities are mostly held by STEG (Gaz and electricity national company), with 85% of the electricity produced in 2012 [4]. Today Tunisia is facing a huge energy deficit which has reached 4 Mtep in 2015, because of the energy consumption that has nearly doubled within 20 years between 1992 and 2012 due to the economic growth and the increase of the electrification rate (100 % in 2012). Overall production decrease in primary energy (especially crude oil), the last period due the slow new fields' exploration activity (lack). Since 2000, Tunisia has become a net energy importer [5]. The generation of electricity from green energy sources, for instance, wind, solar, hydro, geotherm, biomass energy, have widen possibilities to reduce the dispense measure of non-renewable energy source and pollution level. Wind energy is one of the cheapest sustainable energy for new development [3]. Wind energy have been exploited for hundreds of years [4] [5] where windmills have been used for pumping water or grinding grain. Today, the windmills, modern wind turbine can use the wind energy to generate electricity. Indeed, the wind energy is well developed, controlled and accessible. However, in order to rise wind farm's electrical generation performance, in a given location, a deep analysis of wind characteristics is required [6] [7]. In any installation of a wind system, the wind and the site must be considered as a the most important elements. In fact, the selection of the site influence on the wind turbine performances. Furthermore, the knowledge of the wind characteristics is fundamental to appraise the annual wind power of the selected location. Nevertheless, an exhaustive meteorological data on site must be taken and analyzed, fully during a year [8], to justify the reliability of the wind as a source of energy. Newly, researchers have shown an interest in wind energy potential in several regions of the world using different probability density functions (PDF).

This study is essentially related to the analysis of 25 synoptic sites indicated on the Tunisian territory geographical chart (figure 2). This work has two objectives: the analysis of wind data composed of measurement of wind speed, direction and frequency during a period of 25 years (1990-2015) measured at 10 m AGL (above the ground level). This data was provided by the National Institute of Meteorological of Tunisia. 142542 values per month for each parameter: wind direction and wind speed, where taken on regular hourly temporal bases and to study storage technologies and classify the given locations according to their need for electricity storage produced by wind power instead of integrating into the electric grid of Tunisia. These measurements were analyzed for pattern and occurrence, in order to select the most potent site in term of power generation to establish a wind farm.

1. Thesis organization:

This project consists on analyzing 25 years data of 25 stations of measurement in the Tunisian territory. Chapter 1 in the introduction of this thesis an provides a summary of the background of this thesis. Chapter 2 presents the background information and the algorithmic we use and mathematic aspect of my project. Chapter 3 provides a description of wind data used, as first step in thesis methodology and selecting the most potent locations according to average velocity and wind frequency direction. Then plotting curves of wind velocity according to time and power available in wind using MATLAB and 25 years data provided by the National Institute of Meteorology of Tunisia. Part 3 of the 3rd chapter is to simulate a 3.2 MW wind turbine. Part 4 of the 3rd chapter is analyzing power consumption of Tunisia during 4 different months of the year, January, March, July and September. Chapter 4 highlights opportunities storage technologies integration. According to comparison between production and consumption. Chapter 5 gives a summary of this dissertation as well as discusses on directions of future work.

II. Literature Review

1. Probability density of Weibull and cumulative function:

Weibull distribution is generally used in weather forecasting and wind power industry in order to describe wind speed distribution and estimate the wind power of a specific site [9]. This statistical tool models the probability that a wind blows at such speed on a site. Knowing this facilitates the choice of the wind turbine with optimal cut-in speed and the cut-out speed.

Wind speed variation can be typified by two parameters: the density of probability and cumulative distribution of Weibull. In fact, the first function point out the percentage of time for which the wind flows with a specific wind speed, it is mathematically represented in equation below [10]:

$$f(\vartheta) = \frac{df(\vartheta)}{d\vartheta} = \frac{K}{c} * \left(\frac{\vartheta}{c}\right)^{K-1} * e^{(-\frac{\vartheta}{c})^K} \quad \textbf{(1)}$$

Where υ, K>0 and c>0 are respectively the wind speed (m/s) and the shape factor (dimensionless).

The shape factor, *c*, characterizes the shape of the Weibull distribution. Standards performance figure afforded by wind turbine manufactures characteristically use a shape value of 2 which turn this distribution in Rayleigh Distribution [11].

The second function, cumulative distribution, gives the percent of time that the wind speed is less than or equal the wind speed V_0, where V_0 is the wind speed at reference height of measurement z_0, in the case of this study, z_0= 10m. It is expressed by the integral of the probability density function developed in equation 1 is written in equation 2:

$$f(\vartheta \leq \vartheta_0) = 1 - e^{-(\frac{\vartheta}{c})^k} \quad \textbf{(2)}$$

2. Characterized speeds of a specific site

The two Weibull parameters, *K* and *c* and the speeds of the studied location are related by the following relations:

$$v_m = c * \Gamma(1 + \frac{1}{k})$$

$$v_E = c * (1 + \frac{2}{k})^{\frac{1}{K}} \quad \textbf{(3)}$$

$$v_F = c * (1 - \frac{1}{k})^{\frac{1}{K}}$$

Where $v_m$is the mean speed, v_E is the most energetic speed and v_F is the frequent speed. And Γ is the defined gamma function, for any reality x positive not null, by:

$$\Gamma(\mathrm{x}) = \int_0^{+\infty} t^{x-1} e^{-t} dt \qquad \textbf{(4)}$$

3. Wind power:

Hardness wind energy can be used to generate electricity that can power millions of homes and businesses. Wind energy is the fastest growing source of electricity generation in term of annual installed capacity, in the past decade wind capacity has grown at an average rate of 30% per year [12]. Power is defined as the rate at which energy is utilized or converted, it can be expressed as energy per unit of time, as Joules per second (J/s) or it can be voices by watt (W) which is equal to 1 W= 1 J/s. Wind power depends on three different parameters; the amount of the air (density) following through the area of interest (flux); the energy stemmed on the wind is its kinetic energy.

The kinetic energy of any peculiar bulk of moving air, is equal to half the mass, m, of the wind times the square of its velocity V.

$$Kinetic\ energy = \frac{1}{2} * \dot{m} * v^2 \qquad \textbf{(5)}$$

The density of air at sea level is ρ =1.2256 Kg/m^3 at 15°C [13].

Mass (m) of air per second= air density*volume of air passing each second.

Power in the wind in Kinetic energy per unit of time (Watts):

$$P_w = \frac{1}{2} \rho A v^3 \qquad \textbf{(6)}$$

The equation (6) illustrates how the energy available in wind differs with the third power of the wind speeds. For example, in case of increasing twofold the wind speed, the generated energy that would be estimated will reach around eight times as much energy as the previous wind speed [14]. Whereof, the available annual energy E (kWh/m^2/year), per unit area is:

$$E = \frac{T}{1000} * P \qquad \textbf{(7)}$$

And T is the average length of a year, which is 8766 h [15].

4. Mean wind power density and energy density:

The power available in the wind is aa function of air density ρ, the area waylaying the wind A, and the instantaneous wind velocity v or speed. Using the Weibull methodology, the density of power available in wind (W/m^2) can be calculated using the forthcoming equations:

$$WDP = P(\vartheta) = \frac{P(\vartheta)}{A} = \frac{1}{2}\rho\vartheta^3\Gamma(1+\frac{3}{k}) \quad \textbf{(8)}$$

Where WDP is an abbreviation of Wind Density Power, and ρ is often written in a simple form [16], ρ=$\rho_0 - 1.1994 * 10^{-4} * H_m$. Where H_m is site elevation in meters.

There is just no escaping the fact that the amount of wind you have at your site determines how much power you can expect from a wind turbine of a given size. Albeit some people would ever consider placing a photovoltaic panel in the shade and expecting it to work. It is the same when people try the equivalent with their wind turbine.

5. Swept area:

As it is shown in equation 6, that the power available in wind is exponentially related to wind speed. Power is also linearly related to the area swept by wind turbine rotor. Doubling this area and you double the power available. Taking an example of wind turbine where the rotor spins about a horizontal axis. The area sweeps a disc the area of a circle:

$$A = \pi * R^2 \quad \textbf{(9)}$$

The area A (m^2) is the Windstream swept or intercepted by the rotor.

6. Electricity generated by wind turbine:

The power generated by a wind turbine can be calculated at different wind velocity as long as the area swept by wind turbine is known and the overall efficiency of the turbine generator (do not exceed the Betz limit, developed in section 6.2. Then, the number of hours at each wind speed is multiplied by the power generated at that wind speed in order to get the number of watt hours of power generated.

6.1 Power coefficient of wind turbine:

It is impossible to extract all the kinetic energy in the wind by wind turbines. Following the Betz law, the performance of the turbine is the maximum amount of energy that can be reaped by the wind turbine at its wind power available. The power coefficient, c_p, the power coefficient c_p (dimensionless) is an indicator of total wind turbine system efficiency. As shown in the expression below, c_p generally defined as the ratio of the electrical power generated by wind turbine, represented in power curve, P_T, divided by the wind power into the turbine P_W.

$$c_p = \frac{P_T}{P_w} = \frac{Produced\ energy\ by\ wind\ turbine}{energy\ available\ in\ wind} \quad \textbf{(10)}$$

Multiplying this value by power available in the wind in the same site and same period of time, to get the real power produced by the wind turbine.

$$P_T = \frac{1}{2} * \rho * A * V^3 * c_p \quad \textbf{(11)}$$

In order to find the area needed to establish the wind farm, an equality between the total value of energy consumption during the month of January, data provided by the Tunisian Company of Electricity and Gas, and the total value of energy production, gave, as a result, the area needed to plot the farm.

$$A = \frac{total\ consumption}{total\ production} \quad \textbf{(12)}$$

Another method used to calculate the power coefficient, consists on a combination of the efficiencies of all the subsystem components

$$Cp = \eta b \times \eta m \times \eta e \quad \textbf{(13)}$$

Where

ηb = blade aerodynamic efficiency, ηm=mechanical efficiency, ηe = electrical efficiency

6.2 Betz limit:

It is evident that a Cp of 1 (or 100%) is impossible. As the German physics has concluded is 1919, that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning the rotor. It is known, to this day, as Betz limit or Betz'law.

Using the Weibull distribution, the theorical maximum power, P (W/m^2), that can be extracted from an optimum wind turbine is limited by the Betz equation:

$$P = \frac{116}{227}\rho(1 + 3I^2)A^3\Gamma\left(1 + \frac{3}{K}\right) \quad \textbf{(14)}$$

Where, I is the turbulence intensity (I= 0.2 at 10m in open areas).

7. Rayleigh function:

As it is indicated above that the Rayleigh probability is a special case of Weibull distribution with a shape parameter equal to k=2, the Rayleigh distribution is defined by equation 14:

$$f_r(\vartheta) = \frac{\pi\vartheta}{2\vartheta_m^2} e^{-(\frac{\pi}{4}(\frac{\vartheta}{\vartheta_m}))^2} \quad \textbf{(15)}$$

Where υ_m is the mean wind speed. The Rayleigh cumulative function is developed in equation 16:

$$f(\vartheta \leq \vartheta_0) = 1 - e^{-\frac{\pi}{4}(\frac{\vartheta}{\vartheta m})^2} \quad \textbf{(16)}$$

8. Wind speed extrapolation:

The exact assessment of wind potential for a certain location needs the cognizance of the speed of the wind to various heights. The standard height of measurement is mostly z_0=10m, but to establish a wind project it is necessary to extrapolate wind speed at the hub height of the chosen wind turbine. Different laws are used to extrapolate wind speed values such as the log-linear law which is grounded on Monin-Obukhov similarity theory.

8.1 Roughness length:

The variation of height is not the same for all locations, it relies on the ground nature and terrain roughness [17]. The roughness of the ground can be expressed by its length (m) which generally varies between 0.0002 and 1.6 m [18]. These roughness values correspond to energy indexes which represent the amount of energy of the wind after passing through this roughness. In table 1, below it is regrouped the roughness length for some types of terrain [19]:

Table 1 - roughness length for some types of terrain

Type of terrain	Z_0 (m)
Flat: beach, ice, snow landscape, ocean	0.005
Open: law grass, airports, empty crop land	0.03
High grass, low crops	0.10
Rough: tall row crops, low woods	0.25
Very rough: forests, orchards	0.50
Closed: villages, suburbs	1
Towns: town centers, open spaces in forests	>2

The roughness length characterizes the nature of the roughness of the terrain, which influences the vertical wind speed profile. The rougher the terrain is, the bulker will be the influenced layer of air and velocity increases progressively with height.

8.2 The log-linear law:

The log-linear law is a physical model proclaiming that the wind speed at a height h_2, h_1 different to zero can be calculated by equation 17 [20]:

$$\vartheta_2 = \vartheta_1 * [\frac{\ln\left(\frac{h_2}{z_0}\right) - \psi_m\left(\frac{h_2}{L}\right)}{\ln\left(\frac{h_1}{z_0}\right) - \psi_m\left(\frac{h_1}{L}\right)}] \quad \textbf{(17)}$$

ϑ_2 is the speed of the wind to be calculated at the height h_2.

$\vartheta_1$is the speed of the wind measured at anemometer height h_1.

$\psi_m$is the Monine Obukhov stability function, characterize the atmospheric stability, depends essentially on the vertical distribution of temperature, resulted from radiation warming and cooling of the ground, and air convection blending of the contagious air to the surface.

L is the Monine Obukhov length (m).

z_0 is the roughness length (m).

In engineering studies, the log linear law is difficult to use for estimating wind profile at wind turbine hub height, generally log law is used [21].

8.3 Logarithmic law:

It is a special case of the log-linear law, provided that a neutral stability ($\psi_m = 0$), the equation 15 can be simplified to equation 18, which depends only on roughness length (z_0), h_2 and h_1:

$$v_2 = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \tag{18}$$

9. Storage technologies:

Energy storage is broadly known as a key allowing technology for renewable energy and particularly for wind and photovoltaics [22]. Conventional electricity networks are supplied by large centralized and predictable generating stations. An important characteristically assorting supply with demand needs a backup source of power on network, such as storage system. As it is known, wind energy is an intermittent, variable and non-dispatchable source of energy [23], as a result, supply cannot be switched on demand. Consequently, a storage system is needed.

Table 2 - Classification of energy storage technologies [24]

Mechanical storage	Electro-chemical storage	Thermal storage	Electrical storage	Chemical storage
Adiabatic CAES	Flow batteries		Supercapacitor	Hydrogen
Compressed air energy storage (CAES)	Lithium-ion batteries	Molten salt	Superconducting magnetic energy storage (SMES)	Synthetic natural gas
Flywheel (low speed)	Sodium-sulfur batteries (NaS)			

battery storage has limitations in terms of storage capacity and so is not suitable for every application as shown in Figure 1.

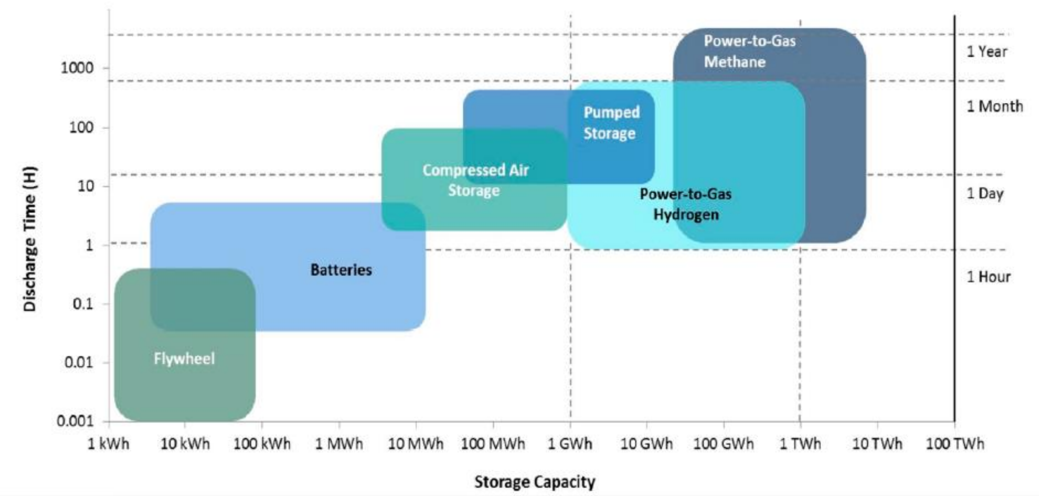


Figure 1 - Discharge time and energy capacity of the different storage energy technologies [24]

The parameters used to describe an energy storage device are: Power capacity which is the maximum instantaneous output that an energy storage device can provide measured in (kW) and (MW). Energy storage capacity is the amount of electricity the device can store measured in kWh and MWh. Efficiency indicates the quantity of electricity that can be recovered as a percentage of the electricity used to charge the device. Response time, is the length of time it takes the storage device to discharge. In addition to the above parameters, following parameters are used to describe rechargeable batteries: Charge to discharge ratio is the period of time it takes to charge the device relative to the time to discharge the device. Figure 1 regroups different electricity storage technologies, arranged by storage capacity and discharging time. Energy Storage devices by their nature are typically suitable for particular application, this is due to storage consumptions that can be provided from the various devices. In order to provide a fair comparison between the various energy storage devices. They have been regrouped into different groups based on storage capacity and discharging time. Three categories have been created. Devices large storage capacity (> 1GWh) and long discharging time which can reach 1 year. Power to gas hydrogen and power to gas methane belong to this group. Compressed air storage and pumped storage are characterized by an average storage capacity, varies between 10 MWh and 10 GWh and a discharging time varies from 1 hour to 1000 hours. Flywheel and batteries are generally smaller energy storage systems because of the low storage capacity (1kWh to 10 MWh) and short discharging period, less than 5 hours.

III. Materials and Methods

Tunisia is the smallest Maghreb country with surface 164x150 km^2, it opens largely on the Mediterranean Sea with 1298 km of coasts delimited in the west by Algeria and in the south by Libya [25]. In the south of Tunisia is the desert, composed from the elevated plateaus of rock and stone known as Hamadas, starting from the mounts of Ksour, in the direction of dunes of large eastern Erg, known also as sand seas. Figure 25 below summarize the Tunisian desert.

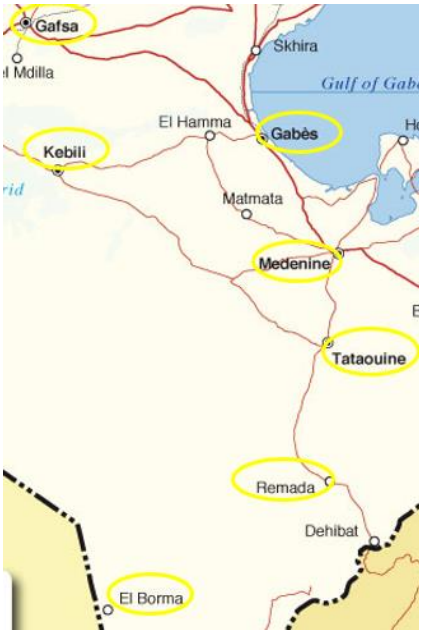
1. Metrological data:

The data used in this work are hourly data for 25 years and correspond to the period 1990 to 2015. The measurement of this data is obtained from a meteorological measuring station (MST), composed of cup generator anemometer from DEGREANE HORIZON, situated in 10m above the ground to measure wind speed in 25 different locations of Tunisia, weather-vane to collect wind directions and a data logger connected to a computer to store data. This data was provided by the National Institute of Meteorology of Tunisia (NIM) to characterize the wind field in some areas and see if complementary storage energy devices are needed or not. Figure 2 shows localization of measurement stations:

Figure - 2 Distribution of meteorological stations over Tunisian territory. *Figure from the Nations Online Project.*

Measurement stations can be distributed into 3 different groups according to the type of the area as it is shown table 3:

Table 3 - Measurement stations classification according to type of area

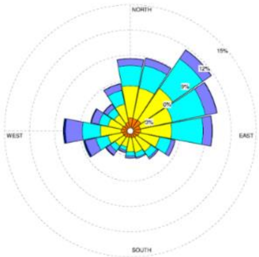
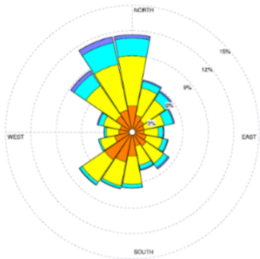
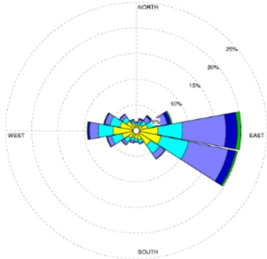
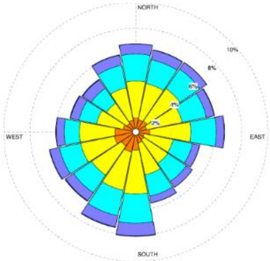
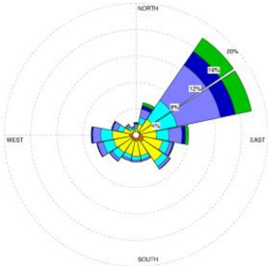
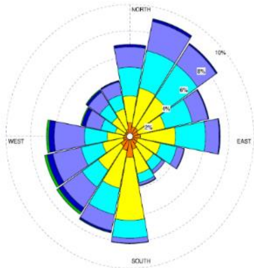
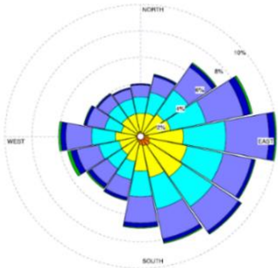
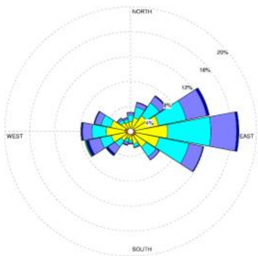
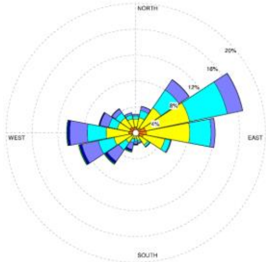
Area Type	Measurement station	Satellite view
Saharan area	Mednine, Kairouan, Tozeur, Sidi-bouzid, kebili, Tataouine, Borma, Gabes.	
Montainous area	Thala, Kasserine, Jandouba, Siliana, Kef, Beja	

Area Type	Measurement stations	Location in Tunisan Map
Costal area	Djerba, Monastir, Sfax, Nabeul, Bizert, Klibia, Mahdia	

1.1 Wind rose:

Wind rose diagram summarizes a very important information in practice for a given location which is the wind direction and average velocity using the legend represented below. The relative frequencies of wind coming from each of 25 sectors are shown in a wind rose (circle graph) for each site by the radial extent of the circle segments spanning the sectors. The contribution from each sector to the total mean speed is given by different colors, represented in wind rose's legend. Wind roses vary from one location to another and form the meteorological fingerprint. They only tell you the relative distribution of wind direction, not the actual level of the mean wind speed [26]. Wind speed is not the only inconstant parameter, wind direction can also vary. The objective of this part of study is to assess the contribution of each direction, in order to find the windiest direction over all months of the 25 years. Wind roses regrouped in table 4,5 and 6 using type of area as criteria, gives a very information-laden view diagrams of how wind velocity and directions are characteristically distributed at particle locations.

Table 4 - Wind roses of stations belonging to Saharan area of Tunisia according to 25 years data provided by national Institute of Meteorology of Tunisia

Area type	Wind rose		
Saharan area	 wind rose of Mednine	 Wind rose of Kairouen	 Wind rose of Tozeur
	 wind rose of Sidi Bouzid	 wind rose of Kebili	 wind rose of Tataouine
	 wind rose of El Borma	 wind rose of Gabes	 wind rose of Remada

From the 25 measurement stations, 9 stations selected appertain to desert part of Tunisia. In summer, aridity appears, in Saharan area, as result of dryness and heat allied to the Saharan air flow, with the presence of Chehili (hot wind) which blows from the desert in spring.

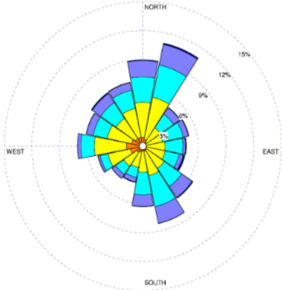
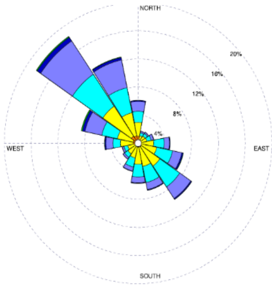
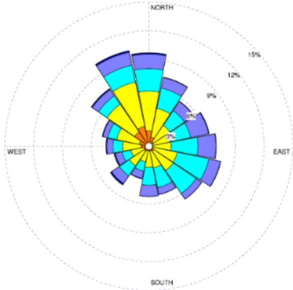
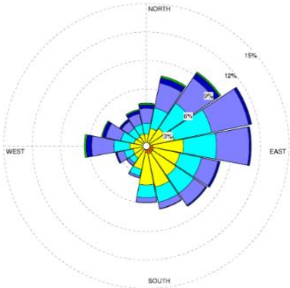
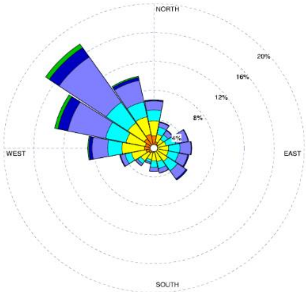
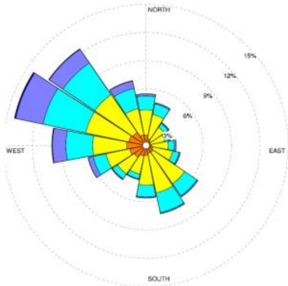
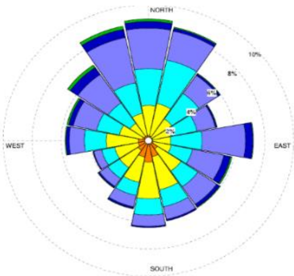
Wind roes of Gabes, Kebili and Tozeur in table 4, indicates a specific wind direction with a strong wind, these 3 areas present the energy zone and most promising for the exploitation of the wind. As it is shown in figure 10, that the frequent wind direction in Gabes is the east. In fact, the 3 spokes around the east direction (ENE, E, ESE) comprise 41% of all hourly wind directions with an average velocity equal to 4,03 $m.s^{-1}$. This also shows that the wind rarely blows from the north and north-northwest.

In the case of Mednine, the most frequent direction is the north-east, ENE and the east represented by the longest spokes, the wind in these directions is considered as a light breeze since the average velocity do not exceed 3.27 m/s.

In the the middle of Tunisia is located Kairouen which is considered as one of the lowest cities in term of altitude, 63 m, compared to Djbal-Chaanbi the highest point of tunisia, 1.553m. Its climate is therefore warmer and dry with regard to the coastline. Kairouan’s wind is considered as mild, it blows with an average velocity equal to 2.07 m/s, its wind rose is represented in table 4 shows the predominance of the north and NNW directions, which constitute 22% of all hourly wind directions.

Wind rose of Tataouine, El Borma and Sidi Bouzid shows a chaotic wind direction distribution. Wind is really almighty natural element which never stop blowing and will never stop, that is why obstacles, bad position of measuring station surrounded by buildings, change of the contour of the local terrain during the 25 years of measurement and uncertainty of wind vane, must be taken into account when processing the data analysis.

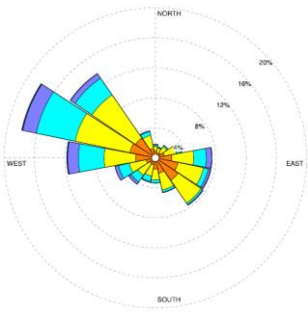
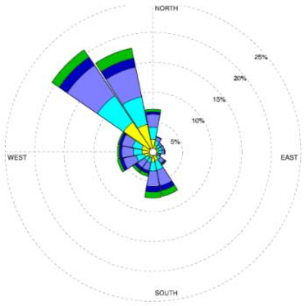
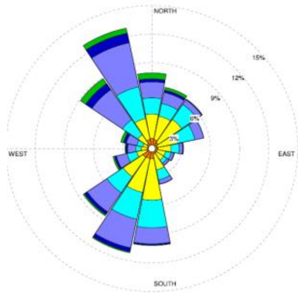
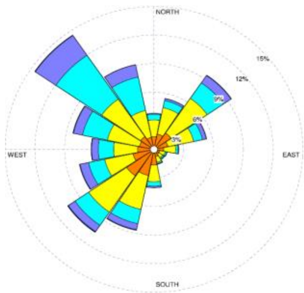
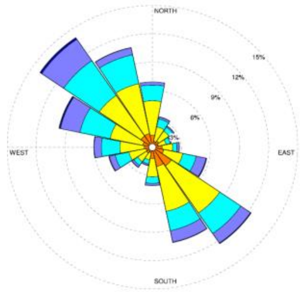
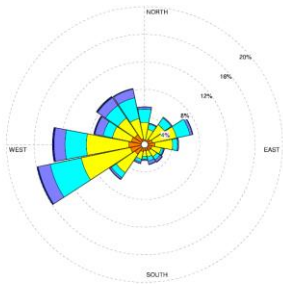
Table 5 - classification of wind roses of stations belonging to coastal provided by National Institute of Meteorology of Tunisia

Area type	Wind rose		
Coastal area	 wind rose of Mahdia	 wind rose of Nabeul	 wind rose of Sfax
	 wind rose of Djerba	 wind rose of Bizert	 wind rose of Klibia
	 Wind rose of Monastir	 	

Tunisia opens largely on the Mediterranean Sea with 1298 Km of coasts. These coasts are cut out by deep gulfs (Bizert, Tunis, Nabeul, Gabes) and islands (Kerknna, Djerba). The very favorable Atlantic trade wind and the Mediterranean influence from the North, enable to get a productive wind. Bizert and Nabeul, are two coastal area characterized by a potent wind and precise direction from where wind blows more. On the one hand, the longest spoke of the rose of Nabeul, represented in table 5, is affected to the North-west direction, with an average velocity 4,04 $m.s^{-1}$. On the other hand, Bizert which is situated in the extreme north of Tunisia, typify a north-west and west-northwest wind with 4,35 $m.s^{-1}$ as an average velocity.

Djerba is at 514 square kilometers, the largest island of North Africa, located in the Gulf of Gabes [27]. Examining winds from the ENE and E, the longest spokes of Djerba's wind rose represented in table 4, can determine that approximately 4% of the time the wind blows from the east and east-northeast at speed between 2.1 and 3.6 m/s and 9% of the time the wind is considered as moderate breeze since the average velocity meanwhile 5.7 to 8.8 m/s. Islands throughout the world are certainly prospective customers for wind turbines as the have plenty of coast but lack the connection to mainland power sources [28]. Most of the meteorological stations are situated in built up localities with wind monitoring masts placed on the roof of buildings. Due to such localities, buildings and trees act as obstacles which may be very close to the meteorological stations and therefore speed measured at the meteorological mast is low [29]. This phenomenon can be observed in table 4, Monastir's wind rose. Monastir sits in the northeast of Tunisia, on its central coast. It is milder than inland areas of Tunisia, which gave it advantage to be one of the windiest cities of Tunisia. But its anarchical wind direction distribution can be explained by the unstudied emplacement of measurement station.

Table 6 - classification of wind roses of stations belonging to mountainous area according to 25 years-data provided by the national Institute of meteorology of Tunisia

Area type	Wind rose		
Mountainous area	 wind rose of Beja	 wind rose of Thala	 wind rose of Kasserine
	 wind rose of Jandouba	 wind rose of Siliana	 wind rose of Kef

Wind speed increases with higher altitude, this what Geoffrey Hill, a researcher in the earth sciences center GÖTEBORG UNIVERSITY, affirms in his thesis about “wind prospecting of the Canary Islands”, this conclusion explains the well-organized wind roses of cities appertaining to mountainous area of Tunisia. In all wind roses of the table 3 above, an identification can be affirming that the available energy is provided, usually, by the west-northwest and north-west directions. Beja and Jandouba are characterized by a soft wind, as the average velocity do not outstrip 2.80 m/s during the 25 years of the pursuit. A smoothly wind coming essentially from the west and west north west directions, typify Tabarka, Kef and Kasserine, where the mean value of wind velocity always remains inferior than 5 m/s.

Rose's Thala shows that the wind during the 25 years of measurement blows, primarily from the northwest much of time. The northwest and north-northwest directions comprise 38% of all hourly wind direction. This wind rose represented in table 5 also provides details on speed from different directions. Examining winds from the northwest and north-northwest, the longest spokes, the average velocity from these directions is, approximately, 5,70 m.s^{-1}.

The first step in a wind power project is to assess the wind potential of the site. To start this task, a classification, represented in table 7, based on wind directions frequencies and wind velocity must be adopted to select the most potent sites from the 25 locations of Tunisia.

Table 7 - Station classification using average velocity and wind direction frequency, provided by National Institute of Meteorology of Tunisia

	Average Velocity (m/s)	**I Frequency < 12%**	**II Frequency 12% < f < 15%**	**III Frequency > 15%**
C	**V < 3**	Kairouen Tunis-carthage	Jendouba Kelibia	Beja
B	**3 < V < 4**	Mahdia, Mednine Sidi Bouzid, Sfax Tataouine	Siliana	Gabes Kef, Remada
A	**V > 4**	El Borma, Djerba Monastir	Kasserine, Tabarka	Bizerte, Gafsa, Kebili, Nabeul, Thala, Tozeur

The wind regime in those 25 stations was organized in 9 categories, depending on average velocity and wind direction frequency. Class [A, III] is the most potent group, since the hourly mean wind speed and the frequency, are respectively, exceeds 4 m/s and 15%. Frequency has been chosen as criteria because it notices wind turbulence in that area, more the frequency is high more the turbulence is low, as its shown in table 7, that frequency in Thala, Gafsa, Kebili, Nabeul, Thala and Tozeur exceeds 15% as a result, the land is flat and no wind turbulence influences measurements. El Borma, Djerba, Monastir, Kassrine and Tabarka are classified as potent area in term of wind velocity, its abundantly clear that the average velocity in these areas exceeds 4 m/s, but wind direction frequency is less than 15%, wind fluctuate, and this is maybe explained by the obstacles which surround measurement stations.

1.2 Measuring stations:

Geographical data change very slowly in time as compared to meteorological data [30]. For meteorological modelling, measurement results and analysis, geographical data are considered as a vital input information. Stations belonging to class (A, III) from table 1 above has been considered as the axe of data analysis because of their important wind resources and their productivity. In table 3 below, geographical characterizes of six stations selected has been regrouped:

Table 8 - Geographical properties of measuring station belonging to class (A,III)

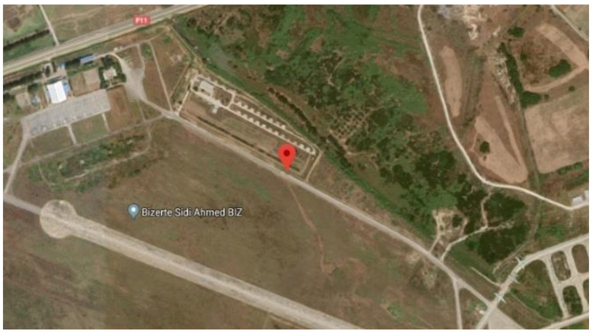
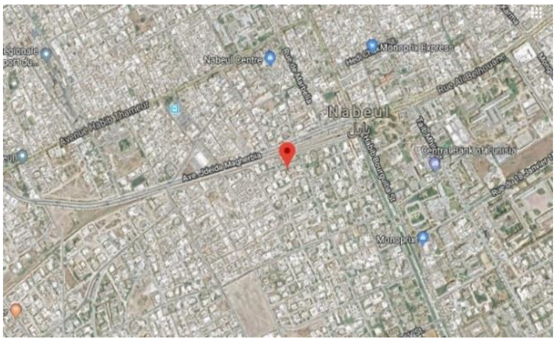
Stations	Region	Latitude, longitude	Altitude (m)	Satellite view
Thala	mountain ous	35°33', 08°41'	1,017	
Bizert	coastal	37°15', 09°48'	5	

Table 9 - Geographical properties of measuring station belonging to class (A,III) continuous

Tozeur	Saharan	33°55', 08°06'	23	
Kebili	Saharan	33°42', 08°58'	43	
Nabeul	coastal	36°27', 10°44'	14	
Gafsa	saharan	34°25', 08°49'	295	

The selected sites presented in tables 8 and 9 belong to different geographical location of Tunisia, Sahara where Tozeur, Kebili and Gafsa are situated, Bizert and Nabeul are a coastal area and Thala is a mountainous site. It is clear from satellite views of Tozeur, Bizert and Gafsa, that the measurement stations are situated in an airport, Thala’s measurement station is in Forest, the case of Kebili and Nabeul values are obtained from measurements stations situated in the center of city, the geographical situation can influence the measurement. This classification will facilitate the choice of the land roughness for each site in the following calculation.

IV. Results and Discussion

2. 1. Wind velocity:

1.1 Meteorological method:

In this project, wind speed data in the selected cities from three region of Tunisia, over a twenty five-year period from 1990 to 2015 were analyzed. Based on these data, wind speeds analyzed were processed using MATLAB computer software.

Table 10 - minimum, maximum and average values of the selected stations

Station	Minimum velocity ($m.s^{-1}$)	Maximum velocity ($m.s^{-1}$)	Mean velocity ($m.s^{-1}$)
Thala	5.03	6.32	5.90
Bizert	2.64	6.14	4.55
Gafsa	2.91	6.14	4.54
Kebili	0.17	4.94	4.99
tozeur	4.38	4.77	4.74
Nabeul	2.54	4.79	4.21

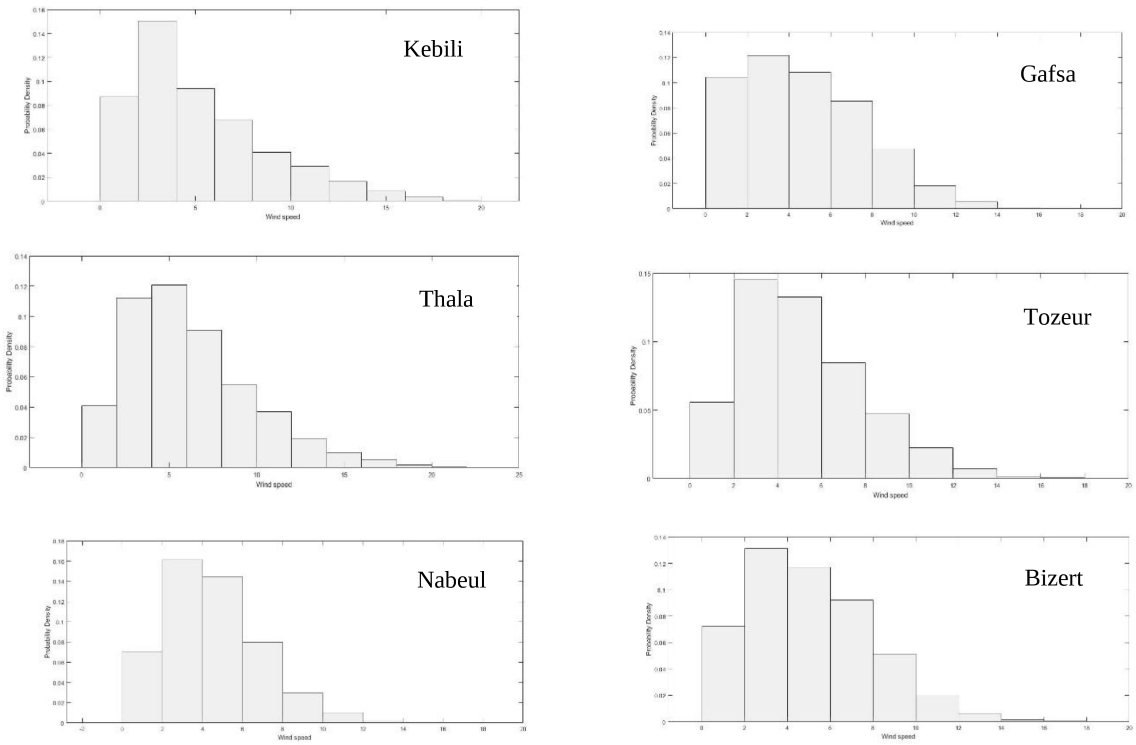


Figure 3 - Wind speed probability of different locations during the 25 years of measurement

The idea behind plotting a histogram, is to divide the data set into groups of equal length, which allows us to see clearly the patterns in the data instead of the detailed information we would get from what is basically a list of numbers. The most frequent velocities of Thala ranges between 4 and 5.5 m/s, it presents 14% from all Thala's velocity values. The recurrent velocity of Kebili, Nabeul, Tozeur, Gafsa and Bizert is more than 2m/s and do not exceeds 4m/s with and the probability density is respectively, 0.17, 0.16, 0.14, 0.12, 0.13.

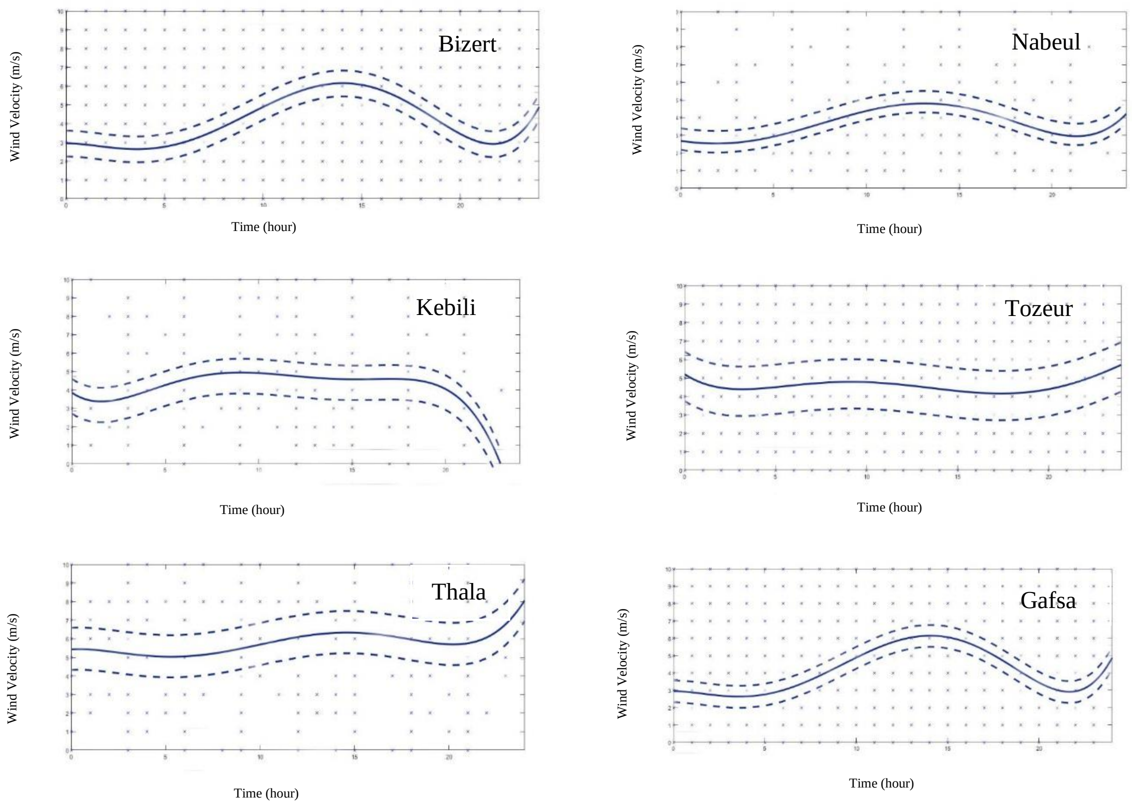


Figure 4 - Wind velocity variation according to time

upper and lower curves from the median with 25% Median curve of average velocity

In figure 4 average wind velocity during the 25 years of measurement is represented by a continuous line limited by discontinuous line which represent the upper and lower quartile. The fluctuance between the average speed curve and the quartiles gives an idea about the turbulence in the selected site. More the fluctuance is important, for example the case of Kebili, Tozeur and Gafsa, more the wind is turbulent. The wind is a variable and indeterminate green source, so for a detailed analyzes, plotting the variation of wind according to time it is an important step. The shape of curve helps on understanding the wind characteristics and identifying the most wind site. The main results obtained from the present study are summarized in table 9 and figure 4. The monthly mean wind speed curves illustrated in figure 4, shows the extreme values for the period of 1990 and 2015 in the selected stations in Tunisia. Wind mean speed in Tunisia is modest [25], the monthly mean wind speed values are mostly between 4 m/s and 5.7 m/s. The maximum value of the monthly mean wind speed is 6.32 m/s always measured between 14h and 15h in Thala. While the minimum value is 0.1732 m/s during the night from 23h to 00h in Kebili In Bizert, Nabeul, Gafsa and Kebili the monthly mean wind speed is mainly on 4 m/s, where the wind energy potential is adequate for wind energy applications. In Thala and Tozeur located, respectively, in the north-west and the south of Tunisia, it is determinate that produce electricity from wind is appropriate.

3. 1.2 Weibull distribution method:

The Weibull law, given by equation 1 above, based on two parameters, *k* which represents the mean wind speed (m/s) of the selected location, and *c* is called the shape of Weibull distribution (dimensionless), it varies, usually, from 1 to 3, it is prorated with the median wind speed, the higher the value of the higher the median wind speed. The wind potential of sites with a shape < 2 is considered as low, or even very strong. locations with fairly consistent wind speeds around the median would have a shape value of 3. Table 10 below, regroups the Weibull parameters of the selected locations:

Table 11 - Weibull parameters of the selected locations

Site	**c (m/s)**	**k**
Thala	6.65	1.75
Gafsa	5.19	1.62
Nabeul	4.22	1.47
Tozeur	5.35	1.85
Kebili	5.55	1.47
Bizert	5.10	1.69

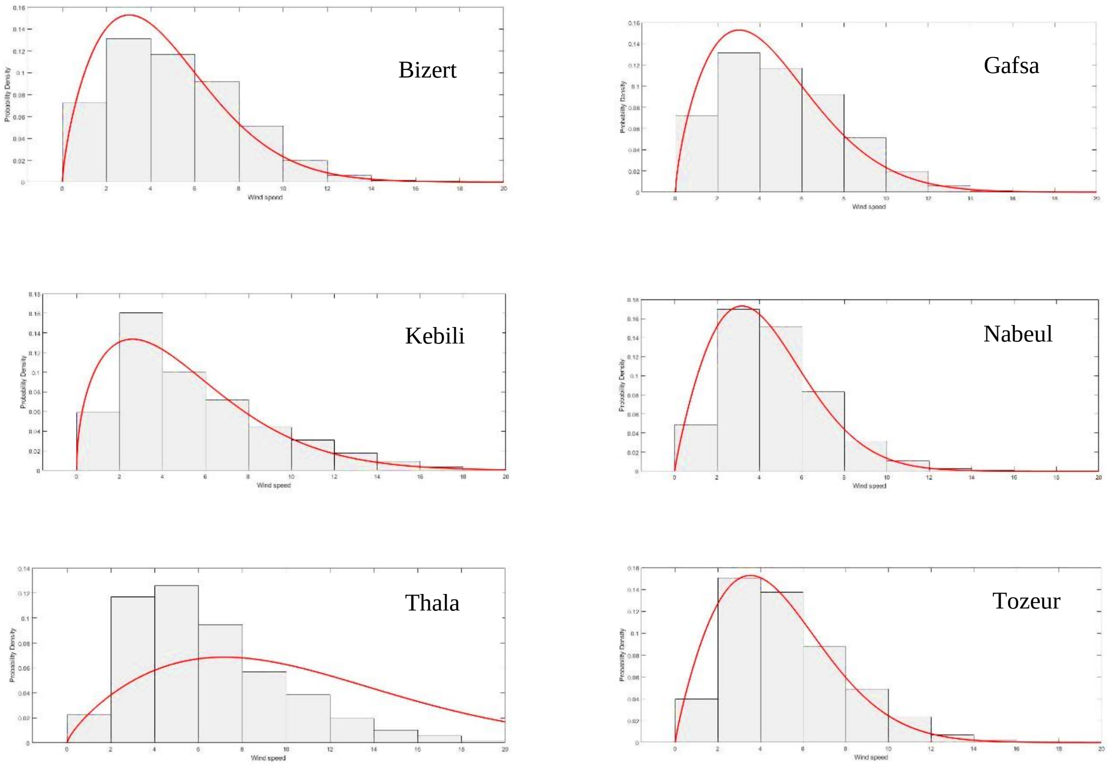


Figure 5 - Weibull distribution of wind data of the selected sites

If the wind speed tends to be close for a certain value, the Weibull distribution will have a high c value, and a peaked curve. This is a good point when choosing which wind turbine modal to place in the selected location. Tozeur 1.85, Thala 1.75 and Bizert 1.69 have the best three c values of the six studied sites.

2. Power available in wind

As there is not a specific wind turbine area A, all power curves below will be represented by wind power density (W/m^2). The wind potency and energy are evaluated respectively by equations (6) and (7) on top. Table 11, below, exhibits the acquired results for the 6 overall sites to 10m in open area.

Table 12 - Maximum hourly, annual Wind power and annual energy available in wind for different sites

Station	Maximum power density (W/m^2)	Annual energy ($KWh/m^2/year$)
Bizert	215.9	1892.5
Gafsa	216.0	1893.4
Kebili	257.2	2254.6
Nabeul	155.7	1364.8
Tozeur	176.2	1544.5
Thala	373.4	3273.2

Scrutinization of this table has led to the classification of these sites in different groups:

- A first group of good wind potential, noted (A), in which annual energy varies from 2000 to 3300 $KWh/m^2/year$. It is constituted of Thala, 3273.224 $KWh/m^2/year$, and Kebili, 2254.615 $KWh/m^2/year$. It covers 45.2% of the recoverable total energy of the 6 locations. Thala and Kebili are situated respectively in the west and the south of the country. This cluster presents the energy zone and most promising for the exploitation of the wind power.
- A second group of medium wind potential, noted (B) whose energy varies between 1600 and 1900 $KWh/m^2/year$. It comprises Gafsa and Bizert, which accounts for 30.9% of total energy.
- A third group of low wind potential noted (C) concerns Nabeul and Tozeur and covers 23.8% of total energy. Its wind energy varies between 1300 and 1500 $KWh/m^2/year$.

  Figure 28, highlights these three groups and particularly shows the importance of the first two sites of group A: Thala and Kebili. Thala occupies the first position in Tunisia where the annual wind energy evaluated and calculated according to 25 years data provided by the Institute National of Meteorology of Tunisia, at 10 m high in open area, is about 3300 $KWh/m^2/year$.

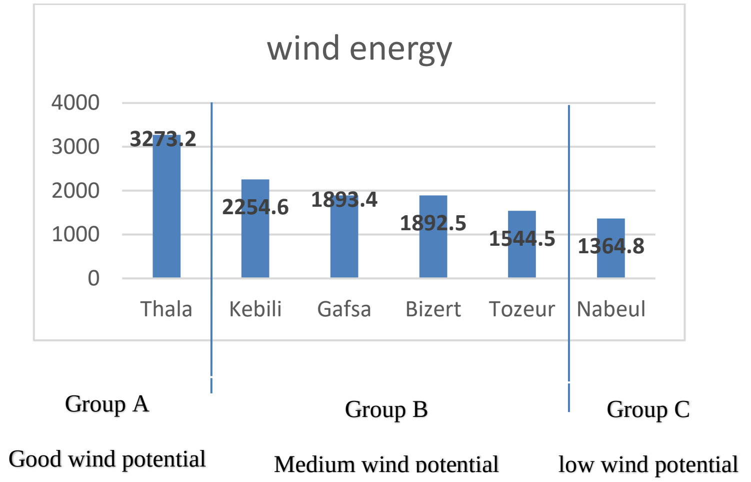


Figure 6 - sites classification according to wind potential, using 25 years data provided by INM

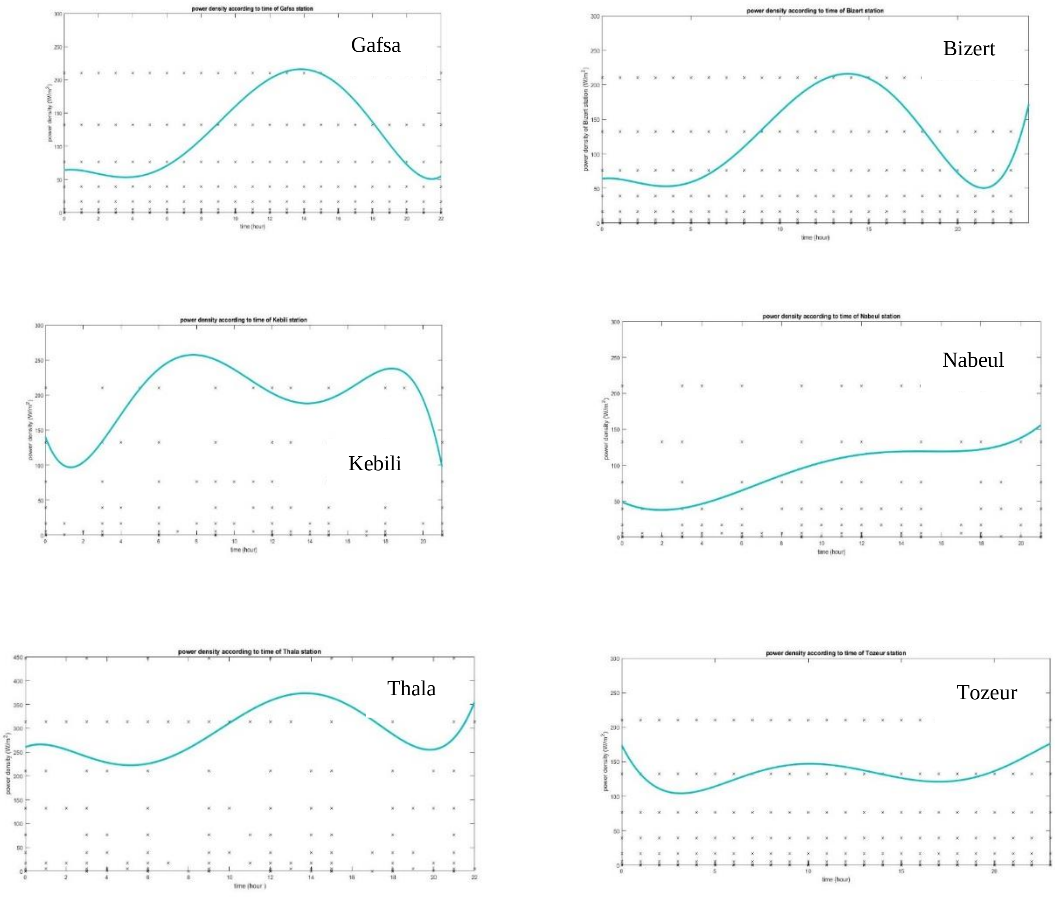


Figure 7 - Wind power density according to time

In this part, power curves were used to simulate the possible electrical power generated after predicting wind speed data through the hourly wind velocity analysis. Figure 7, presents the hourly mean density power available in wind during the 25 years of study for each location among the 6 stations chosen. It is abundantly clear that the biggest value of the hourly men power density occurred as 373.4 W/m^2, in Thala between 12h and14h. While the lowest value of it occurred as 155.7 W/m^2 in Nabeul.

3. Simulation for a 3.2 MW wind turbine:

In this part, a SW-3.2-113 wind turbine is a production of Siemens wind power A/S, a manufacture from Denmark was selected as an example. The wind turbine datasheet and power curve are summarized, respectively, in the table 12 and figure 8 below:

Table 13 - 3.2 MW wind turbine characteristics

Power			Rotor		Tower
Rated speed	Cut-in wind speed	Cut-out wind speed	Rotor diameter	Swept area	Hub Hight
12 m/s	3 m/s	25 m/s	113 m	1 ha	92.5 m

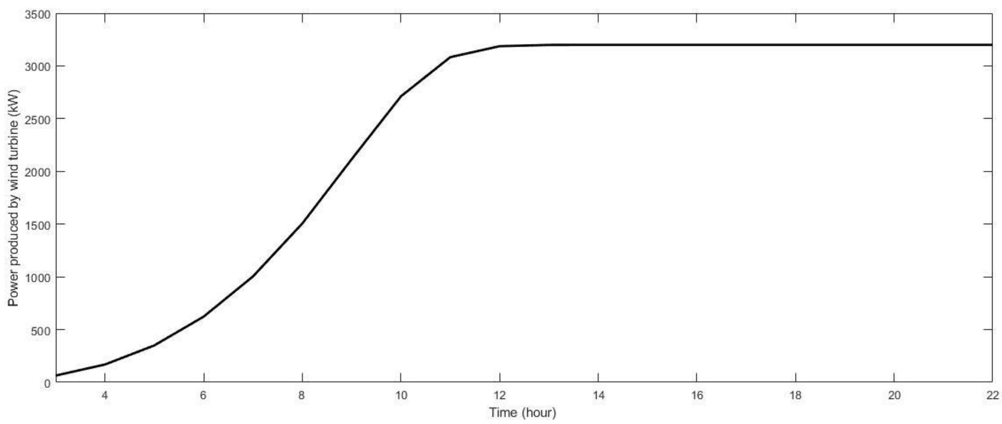


Figure 8 - 3.2 MW siemens wind turbine power curve [36]

The power curve of a wind turbine acquaints us about various essential properties such as the cut-in, rated and cut-out speed. The cut-in speed is the nethermost wind speed that permit the wind turbine to generate power. The rated speed represents the lowest speed that gets the wind turbine to generate at rated output. The wind speed goes from the cut-in speed until the rated speed, which allows the output power that is created by the machine to increase regularly to the rated output. The turbines stop above the cut-out speed for safety reasons, therefor, there is no production of power at extremely high wind speeds.

3.1 Wind speed extrapolation

The SWT-3.2-113 wind turbine power curve (figure 8) was used as reference to simulate the possible electrical power output according to the 25-year- wind speed data provided by INM and analyzed by MATLAB. In addition to its variation with time, wind speed is not the same at different heights, Wind speed at hub height is usually significantly higher than wind speed measured at anemometer height due to wind shear. The more we go away from the ground, it gets higher, but this relationship is not linear [31]. Since this data is measured at 10 m height and the hub height of the selected wind turbine is 92.5 m, the wind velocity of the studied locations was extrapolated to 92.5 m. The extrapolation laws were found to give the finest presentation of the wind speed at a specific height, being necessary step for the establishment of tall towers or more expensive devices. In the present study, the logarithmic law is used to extrapolate wind speed to different heights. Using roughness length according to type of terrain and the geographical characteristics regrouped in table 3 above, locations has been distributed in 3 groups as shows table 13.

Table 14 - Sites classification using geographical characteristics and roughness length

Type of area	Sites	Logarithmic law coefficient
Airport	Bizert, Tozeur, Gafsa	1,38
Center of the city	Nabeul, Kbili	1,92
Forest	Thala	1,74

According to logarithmic law coefficient, wind velocities has been extrapolated to the wind turbine hub height, 92.5 m. Weibull distributions of the extrapolated speeds are represented in figure 9:

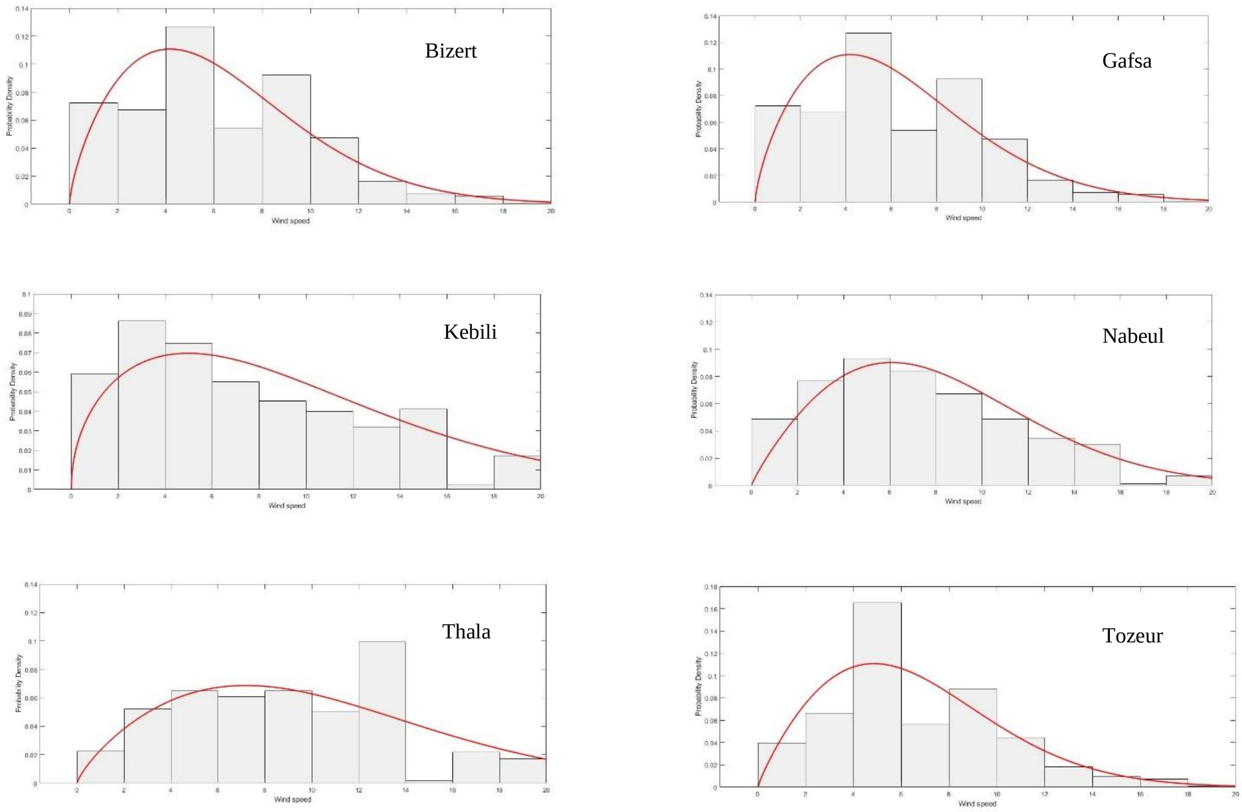


Figure 9 - Weibull distribution of extrapolated wind data of the selected locations

Table 15 - Weibull distribution parameters of the extrapolated wind speeds of the selected sites

Site	k (m/s)	c
Thala	11.75	1.75
Gafsa	7.05	1.62
Nabeul	9.13	1.47
Tozeur	7.38	1.85
Kebili	10.66	1.47
Bizert	7.05	1.69

3.2 Energy consumption

The wind data that is collected for the selected site should be rightly and profoundly analyzed and interrupted in order to estimate the potential of wind energy. With the help of the Tunisian

Company of Electricity and gas, the hourly energy consumption of Tunisia was provided in four different months of the year, January, March, July and September, belonging respectively to the four season, winter, spring, summer and autumn which represent the peak of consumption during the year. Unfortunately, the detailed consumption of the selected sites is not available in STEG’s database.

The power curves of the hourly consumption of Tunisia has been represented using MATLAB software:

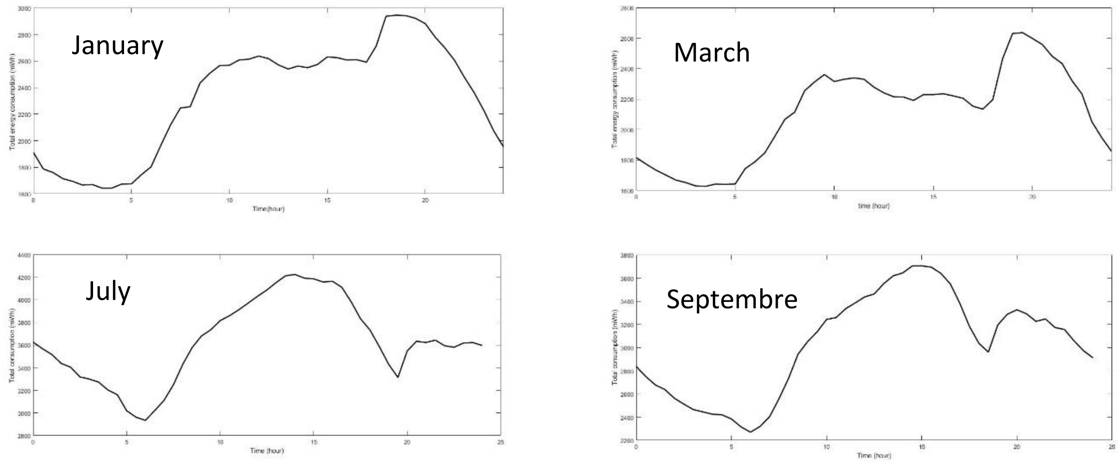


Figure 10 - Hourly energy consumption during January, March, July and September according to data provided by STEG

The lowest consumptions occur at 4h30 for both January and March with an average value respectively, 1650 MWh and 1600 MWh, the highest consumption occurs at 19h, with an average value of 2950 MWh during January and 2600 MWh in March. The average consumption increases during July and September with 70%. The highest and lowest values for July are respectively 4200 MWh at 14h and 3000 MWh at 6h. In September the average consumption is between 3750 MWh at 16h, and 2100 MWh at 7h. Different consumption habits influences on the average profile. It is clear that, in summer energy consumption increases especially in the middle of the day (12h to 15h) due to the temperature increasement, it can reach 45°C in July. In Winter and Autumn, the highest points of energy consumption are during the night between 18h and 24h, this period represents the after work in Tunisia, the reunion of family can increase the energy consumption. In fact, while some households have someone permanently in house (family member or housecleaner), others have people only in the morning and evening time. Further, this profile does not distinguish weekdays from weekends.

3.3 Energy production using 3.2 MW wind turbine:

Using energy consumption data, and power produced in wind turbine, other parameters can be determinate in order to stablish the comparison between hourly power production and consumption of the selected sites. In table 15 first column regroups the frequency of the wind velocity during the 25 years data provided by INM, calculated using the equation below:

$$Frequency\ (\%) = 24 * 31 * N$$

Where N is the percentage of number of time that a given wind speed repeats overall the totally of 25 years values.

Table 16 - Power available in wind for the 6 selected locations and the energy produced by the chosen wind turbine during January, March, July and September (according to 25 years data provided by INM)

Thala:

January:

Frequency (%)	Energy available in wind (mWh)	Energy produced by wind turbine (MWh)
8,4	572,8	229,3
11,3	1219,3	574,2
10,6	2360,7	963,9
11,8	3424,6	1379,2
9,7	5015,4	1365,2
8,7	10624,5	1993,6
11,8	728,4	96,0
0,5	8826,7	848,0
4,9	9753,3	704,0
3,8	10705,5	595,2
2,2	9293,6	406,4
2,1	7586,0	265,6
Total	**70111,5**	**9420,808**

March:

Frequency (%)	Power available in wind (mWh)	Energy produced by wind turbine (MWh)
8,3	580,9	232,56
11,2	1289,7	607,42
10,5	2802,0	1144,1
11,7	3985,8	1605,215
9,6	5655,2	1539,45
8,6	11460,2	2150,4
11,6	728,4	96,0
0,5	9359,6	899,2
4,9	9531,6	688,0
3,7	7367,2	409,6
2,2	8708,2	380,8
2,1	9322,6	326,4
Total	**70792,0**	**10079,1**

July:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (mWh)
11,0	791,3	316,8
15,3	1720,3	810,2
14,1	3359,9	1371,9
14,1	4403,0	1773,2
10,7	5403,9	1471,0
8,3	8902,1	1670,4
9,1	364,2	48,0
0,3	5262,7	505,6
2,8	4743,7	342,4
1,9	3338,3	185,6
1,0	2122,2	92,8
0,5	2467,7	86,4
Total	**42879,7**	**8674,4**

September:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (mWh)
11,0	909,2	363,9
13,7	2148,8	1012,0
13,1	4242,6	1732,3
14,3	5913,9	2381,7
10,9	7563,2	2058,8
8,6	13950,1	2617,6
8,9	412,8	54,4
0,3	9159,8	880
2,8	10418,3	752
2,2	9094,0	505,6
1,5	9001,0	393,6
1,0	6854,9	240
Total	**79668,7**	**12992,0**

Bizert:

January:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,5	616,4	239,4
11,1	1299,2	609,5
9,9	2005,3	991,9
7,8	3329,2	1594,3
7,5	4058,4	1831,5
5,7	7974,5	2968,5
7,6	968,8	261,7
0,6	5429,7	1072
2,6	5630,3	835,2
2,1	3893,0	444,8
1,1	4593,4	412,8
1,0	2223,7	160
Total	**46704,5**	**11652,3**

March:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,4	685,5	266,2
12,1	1496,2	702,0
11,1	2702,2	1336,6
10,3	4466,9	2139,2
9,8	5420,5	2446,2
7,5	9874,8	3675,9
9,1	1287,8	347,9
0,8	5608,0	1107,2
2,7	4853,7	720
1,7	3360,8	384
0,9	3489,6	313,6
0,8	2312,6	166,4
Total	**48979,0**	**13778,2**

July:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
11,0	599,8	232,9
10,4	1602,0	751,6
11,8	2868,3	1418,8
10,8	5296,6	2536,5
11,5	7216,2	3256,6
9,9	12173,4	4531,5
11,2	1925,8	520,3
1,2	5818,7	1148,8
2,7	3365,2	499,2
1,2	1148,3	131,2
0,3	819,0	73,6
0,2	400,2	28,8
Total	**43797,9**	**15152,56**

September:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
13,3	725,7	281,8
12,9	1634,1	766,7
12,3	2835,9	1402,8
10,9	4729,5	2264,9
10,5	5409,4	2441,2
7,6	7543,0	2807,9
7,1	720,7	194,7
0,5	3111,9	614,4
1,5	2329,8	345,6
0,8	1148,2	131,2
0,3	676,5	60,8
0,1	725,7	16
Total	**66585,5**	**12534,6**

Gafsa:

January

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,5	616,4	239,4
11,1	1299,2	609,5
9,9	2003,3	990,9
7,8	3329,2	1594,3
7,5	4058,4	1831,5
5,7	7974,5	2968,5
7,6	968,8	261,7
0,6	5429,7	1072
2,6	5630,3	835,2
2,1	3893,0	444,8
1,1	4593,4	412,8
1,0	2223,7	160
0,4	1914,5	112
0,3	1194,9	57,6
0,1	1194,4	48
0,1	378,0	12,8
Total	**46702,5**	**11651,3**

March :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,4	685,5	266,2
12,1	1496,2	702,0
11,1	2702,2	1336,6
10,3	4466,9	2139,2
9,8	5420,5	2446,2
7,5	9874,8	3675,9
9,1	1287,8	347,9
0,8	5608,0	1107,2
2,7	4853,7	720,0
1,7	3893,0	384,0
0,9	3360,8	313,6
0,8	3489,6	166,4
0,4	2312,6	89,6
0,2	1531,6	51,2
0,1	1062,1	25,6
0,1	637,08	6,4
Total	48979,0	13778,2

July :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
11,0	599,8	232,9
10,4	1602,0	751,6
11,8	2868,3	1418,8
10,8	5296,6	2536,5
11,5	7216,2	3256,6
9,9	12173,4	4531,5
11,2	1925,8	520,29
1,2	5818,7	1148,8
2,7	3365,2	499,2
1,2	1148,3	131,2
0,3	819,0	73,6
0,2	400,2	28,8
0,1	54,7	3,2
0,0	66,3	3,2
0,0	159,2	6,4
0,0	283,5	9,6
Total	**43797,9**	**15152,5**

September :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
13,3	725,7	281,8
12,9	1634,1	766,7
12,3	2835,9	1402,8
10,9	4729,5	22649,5
10,5	5409,4	2441,2
7,6	7543,0	2807,9
7,1	720,7	194,7
0,5	3111,9	614,4
1,5	2329,8	345,6
0,8	1148,2	131,2
0,3	676,5	60,8
0,1	222,3	16,0
0,0	109,4	6,4
0,0	66,3	3,2
0,0	159,2	6,4
0,0	35162,9	1190,4
Total	**66585,5**	**125346,1**

Tozeur:

January :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
17,8	1512,3	587,3
20,9	3120,0	1463,8
18,2	3382,8	1673,3
10,1	3647,8	1746,9
6,3	3563,7	1608,2
3,9	5651,1	2103,6
4,1	768,0	207,4
0,4	2949,9	582,4
1,1	2308,2	342,4
0,6	1232,3	140,8
0,3	1744,8	156,8
0,3	622,6	44,8
0,1	437,6	25,6
0,0	199,2	9,6
17,8	79,6	3,2
20,9	94,5	3,2
Total	**31314,5**	**10699,6**

March :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,0	1219,4	473,6
16,5	2905,4	1363,2
16,6	3970,3	1963,9
11,6	5608,2	2685,8
9,5	6476,8	2923,0
6,9	11127,8	4142,3
7,9	1937,7	523,5
1,0	7877,2	1555,2
2,9	8413,2	1248,0
2,3	5517,4	630,4
1,2	4949,6	444,8
0,8	2935,3	211,2
0,4	1641,1	96,0
0,2	1062,2	51,2
0,1	1513,0	60,8
0,1	189,0	6,4
Total	**67343,6**	**18379,2**

July :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
9,4	824,6	320,2
11,7	2030,2	952,6
12,3	3555,0	1758,5
10,8	7106,6	3403,3
12,6	10162,8	4586,5
11,5	19691,6	7330,2
14,5	2622,9	708,6
1,7	11118,9	2195,2
4,2	9685,9	1436,8
2,7	4061,0	464,0
0,9	3952,5	355,2
0,7	1022,9	73,6
0,1	382,9	22,4
0,0	132,8	6,4
0,0	159,3	6,4
0,0	94,5	3,2
Total	**76604,5**	**23623,1**

September :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
11,8	1056,3	410,2
14,8	2692,8	1263,4
15,9	4067,5	2012,0
12,3	6430,9	3079,7
11,3	7638,8	3447,4
8,4	11949,4	4448,2
8,8	1784,1	482,0
0,9	6758,8	1334,4
2,6	5824,5	864,0
1,7	2744,7	313,6
0,6	1246,3	112,0
0,2	578,2	41,6
0,1	218,8	12,8
0,0	132,8	6,4
0,0	79,6	3,2
0,0	94,5	3,2
Total	**53298,0**	**17834,1**

Kebili:

January :

Frequency (%)	**Power available in wind (MW)**	**Energy produced by wind turbine (MWh)**
22,5	28,5	111,1
17,4	175,7	286,3
10,9	373,3	404,2
7,1	577,1	482,6
4,5	711,1	375,3
3,5	958,9	306,2
4,3	1856,0	374,4
0,1	47,4	6,4
1,4	1314,9	124,8
1,1	1341,2	92,8
0,6	984,9	51,2
Total	**8368,8**	**2615,3**

March :

Frequency (%)	**Power available in wind (MW)**	**Energy produced by wind turbine (MWh)**
16,1	20,5	79,9
12,0	121,4	197,9
10,8	369,6	400,2
8,3	674,7	564,3
8,5	1347,0	710,9
6,7	1838,0	586,8
8,3	3632,7	732,8
0,2	142,1	19,2
3,8	3540,0	336,0
3,2	4023,5	278,4
2,2	3693,4	192,0
Total	**19402,7**	**4098,4**

July :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,0	15,8	61,7
11,2	118,5	193,0
10,0	355,8	385,3
9,0	763,5	638,4
8,9	1462,6	771,9
8,4	2397,3	765,4
10,4	4711,4	950,4
1,1	757,7	102,4
4,8	4652,6	441,6
3,0	4023,5	278,4
2,9	5047,6	262,4
Total	**24306,3**	**4851,1**

September :

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
15,0	19,6	76,3
12,6	130,6	212,9
10,2	358,3	388,0
9,5	790,1	660,8
8,4	1364,3	720,0
6,7	1887,9	602,8
9,9	4441,7	896,0
0,5	355,2	48,0
3,2	3034,3	288,0
2,5	3283,5	227,2
2,2	3878,0	201,6
Total	**19543,6**	**4321,7**

Nabeul:

January:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
17,3	32,6	127,1
18,1	293,7	478,8
14,6	968,8	1049,2
10,6	1580,2	1321,5
7,5	2167,9	1144,1
5,5	2956,7	944,1
5,5	4505,2	908,8
0,2	663,0	89,6
1,7	2191,4	208,0
0,7	1803,6	124,8
0,6	1292,7	67,2
Total	**18455,9**	**6463,2**

March:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
13,8	19,4	75,6
17,5	196,0	319,4
14,9	564,3	611,1
13,1	1180,7	987,4
9,4	1647,6	869,5
6,8	2067,7	660,2
7,5	3601,0	726,4
0,4	260,5	35,2
1,7	1786,8	169,6
0,9	1294,9	89,6
0,5	923,3	48,0
Total	**13542,3**	**4592,1**

July:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
12,5	19,0	74,0
17,2	222,2	362,1
18,2	860,2	931,5
11,9	1171,9	980,0
9,8	1988,7	1049,5
7,6	2557,2	816,5
7,0	3505,8	707,2
0,2	615,7	83,2
1,9	2056,6	195,2
0,6	1109,9	76,8
0,3	492,4	25,6
Total	**14599,4**	**5301,7**

September:

Frequency (%)	Power available in wind (MW)	Energy produced by wind turbine (MWh)
13,0	20,0	77,9
18,4	241,0	392,8
18,8	907,6	982,9
14,3	1429,3	1195,3
10,3	2115,9	1116,7
6,3	2437,3	778,2
4,6	2474,7	499,2
0,3	734,1	99,2
0,8	1078,9	102,4
0,5	924,9	64,0
0,1	123,1	6,4
Total	**12486,7**	**5315,0**

The determination of power available in wind and power produced by the 3.2 mW turbine, is an important step to calculate the area needed to establish the wind farm, number of machines and the power coefficient c_p of the wind turbine according to measurements. Results of the selected locations are regrouped in table 16 below:

Table 17 - Total energy consumption, Total power density production, area needed, power coefficient of the six selected locations

Thala:

January				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
113905	0,90	12,53	12	0.20
Mars				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
103233	988320,7	10,44	10	0.14
July				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
177971	855199,7	20,81	21	0.20
September				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
148486	1271140,2	11,68	12	0.16

Tozeur:

January				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
113904	1,06	10,72	11	0.34
Mars				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
103233	1.80	5,69	6	0.27
July				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
177971	2,29	7,76	8	0.30
September				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
148486	1.75	8,46	8	0.33

Nabeul:

January				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
113905	1,84	6,18	6	0.35
Mars				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
103233	0,45	23,16	23	0.33
July				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
177971	0,52	33,96	34	0.36
September				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
148486	0,52	28,39	28	0.42

Gafsa:

January				
Totalenergy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
113905	1,16	9,78	10	0.25
Mars				
Totalenergy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
103233	1,47	7,05	7	0.30
July				
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
177971	1,48	12,00	12	0.34
September				
Total energy consumption [MW]	**Total power density production [M/m²]**	**Area needed [m²]**	**Wind turbine number**	**Power coefficient**
148486	1,33	11,18	11	0.20

Kebili:

		January		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
113905	0,26	44,03	44	0.31
		Mars		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
103233	0,41	25,41	25	0.21
		July		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
177971	0,48	36,71	37	0.19
		September		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
148486	0,43	34,63	35	0.22

Bizert:

		January		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
113905	1,16	9,78	10	0.25
		Mars		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
103233	1,37	7,55	8	0.28
		July		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
177971	1,48	11,98	12	0.34
		September		
Total energy consumption [MW]	**Total power density production [MW/m²]**	**Area needed [ha]**	**Wind turbine number**	**Power coefficient**
148486	1,33	11,18	11	0.20

3.4 Comparison between Energy consumption and production

The rationalization of the use of energy requires a comparative analysis between consumption and production. Therefore, using curves provided by STEG (Tunisian Company of Electricity and Gas) and production curves obtained from analyzing, by MATLAB, 25 years data provided by INM (National Institute of Meteorology) an hourly comparison has been made, in the following part. for a precise study, four months in 4 different seasons have been chosen (January, Mars, July and September). Curves below has been plotted using MATLAB software. The right axe represents the total consumption (MWh) during one of the selected months for a given site (data provided by STEG). The left axe is the average production of the total number of the 3.2 MW wind turbine, calculated above. Since we have a lot of data one case will be picked in order to analyze results.

<u>January:</u>

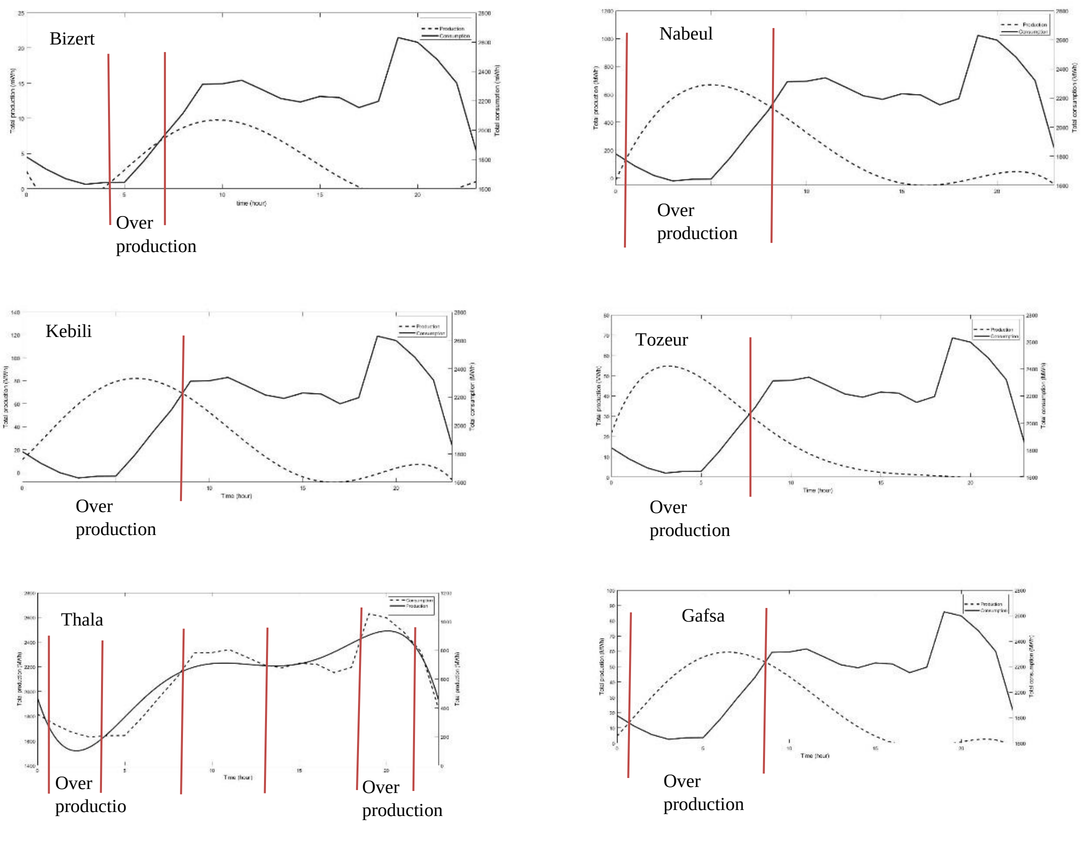


Figure 11 - Hourly comparison between energy consumption and energy production by 3.2 MW wind turbine

: Energy consumption : Energy production

March:

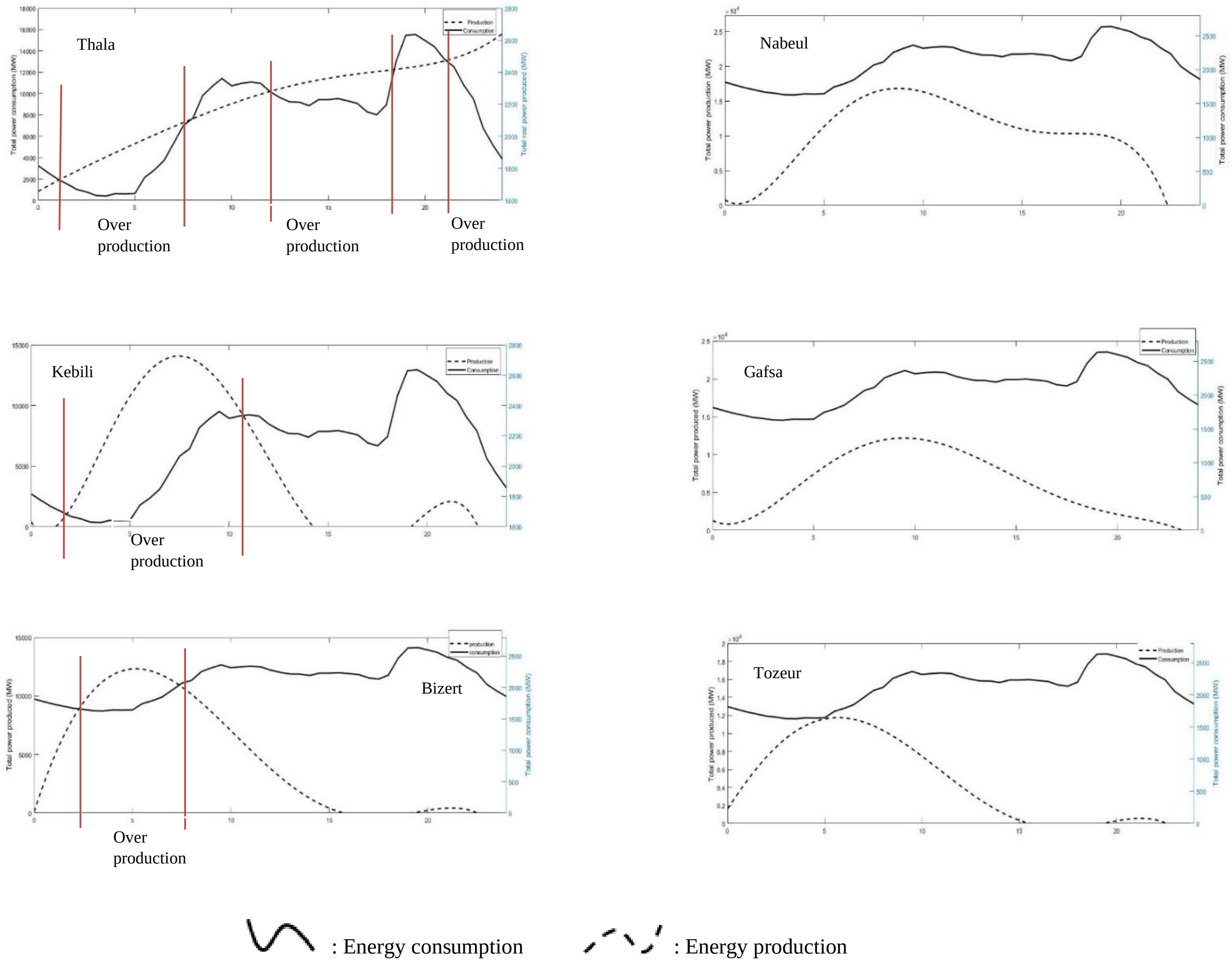


Figure 12 - Hourly comparison between energy consumption and energy production by 3.2 MW wind turbine

July:

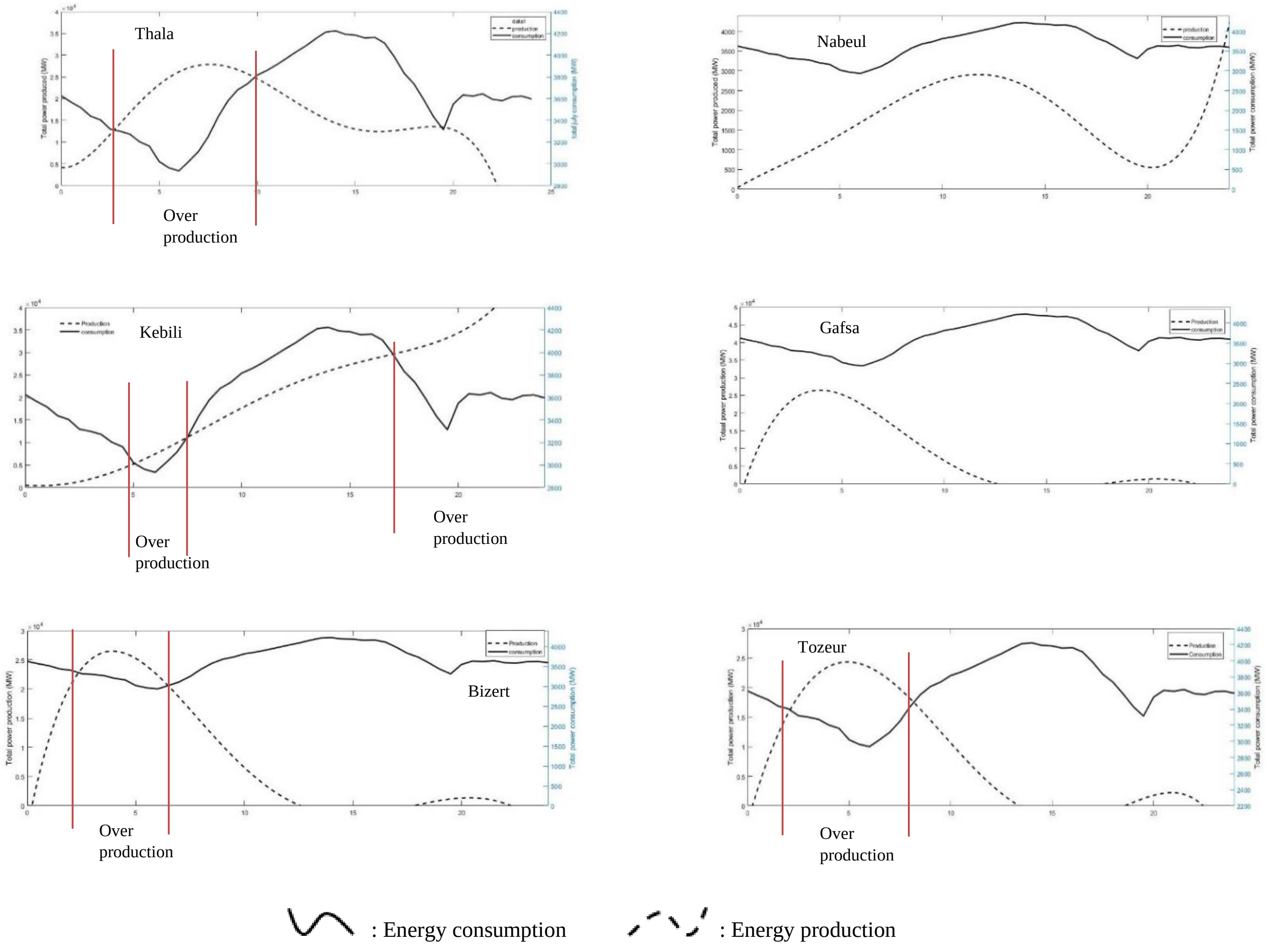


Figure 13 - Hourly comparison between energy consumption and energy production by 3.2 MW wind turbine

September:

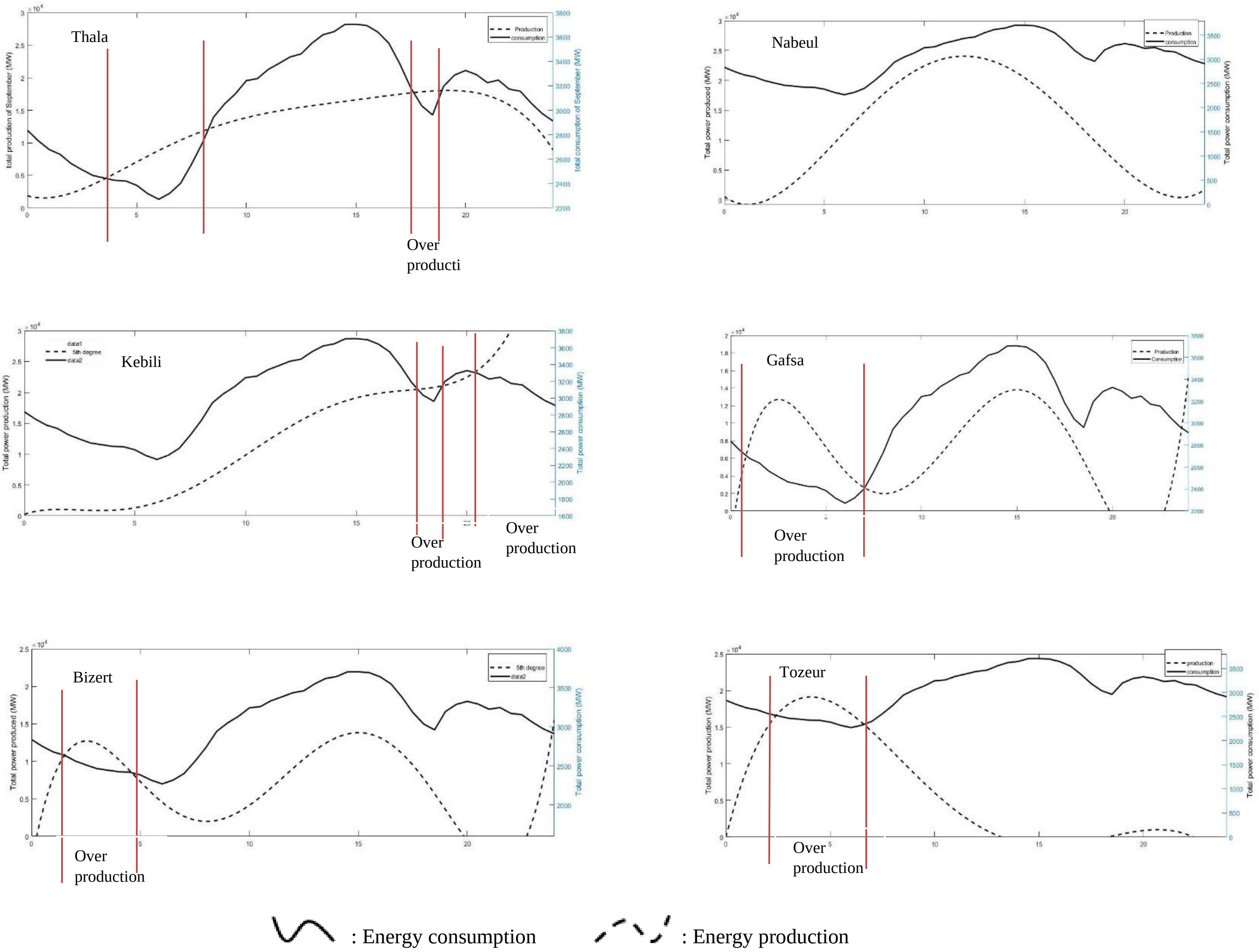


Figure 14 - Hourly comparison between energy consumption and energy production by 3.2 MW wind turbine

Nabeul represents an important energy production during the night from 01:30 to 08:00 in January, and reaches a maximum value equal to 650 MWh at 05:00, which represents 25% of the maximum value of energy consumption during January. If the wind potential increases in the same period of the day, an overproduction can be detected and energy storage will be possible. Based on this hypothesis, the qualitative analysis of energy consumption and power production during the 25 years of measurement, from 1990 to 2015, shows a phase shift of the both curves, an overproduction and an underconsumption, during the day in different location.

4. Energy storage

The methodology used in order to develop the quantitative analysis is, polynomial interpolation, it is one of the numerical analysis methods, consists on the interpolation of a given data set by the polynomial of lowest possible degree that passes through the points of the data set [32]. The demonstration of equation 19 below was detailed in part II.

$$p(x) = \sum_{i=0}^{n} (\prod_{\substack{0 \le j \le n \\ j \ne i}} \frac{x - x_j}{x_i - x_j}) * y_i \quad \textbf{(19)}$$

It is clear from curves above, that the excess of power production is represented by an area limited consumption and production curves. The aim of this part is to estimate the value of this excess. Yet, an integration of the polynomial interpolation is needed.

$$\int_{x_1}^{x_2} P(x) dx \quad \textbf{(20)}$$

Where x_1, x_2 the limits of the two curves, in this case of study, x_1, x_2 are the hours when the an overproduction is observed. The estimated values of overproduction in different sites are regrouped in table below:

January:

Table 18 - estimation of the overproduced power in different sites during January

Site	Curves limits		Production excess (MWh)
Thala	x_1= 01:09 x_2= 04:14	$P_1(x) = -0.18x^5 + 9.38x^4 - 186x^3 + 1740x^2 - 3150x - 700$	37.4
	x_1= 09:28 x_2= 13:08		277.3
	x_1=19:03 x_2= 21:06		173.6
Nabeul	x_1= 01:30 x_2= 08:00	$P_2(x) = -0.077x^5 + 4.78x^4 - 106x^3 + 860x^2 - 1550x - 1830$	11.3
Gafsa	x_1= 00:50 x_2= 09:20	$P_3(x) = -0.004x^5 + 1.08x^4 - 41x^3 + 1030x^2 - 270x - 500$	47.8
Tozeur	x_1=00:00 x_2= 07:00	$P_4(x) = 0.063x^5 - 4.7x^4 + 134x^3 - 1640x^2 + 6850x + 3800$	177.7
Bizert	x_1=00:00 x_2= 09:50	$P_4(x) = -0.073x^5 + 3.88x^4 - 58x^3 + 40x^2 + 2950x - 1030$	53.4

The total power consumption from 1990 to 2015 during January, is equal to 2847.5 GWh, according to data provided by the Tunisian Company of Electricity and Gas. It is abundant clear that the power production excess, in the same duration of measurement, represents a faint percentage from the totally energy consumption. For example, in Thala which is the most potent site, the overproduction represents 0.17% from the Total consumption value.

March:

Table 19 - estimation of the overproduced power in different sites during March

Site	Curves limits	Polynomial interpolation	Production excess (MWh)
Thala	x_1= 01:00 x_2= 08:00	$P_1(x) = 0.106x^5 - 1.12x^4 + 20.8x^3 - 144.6x^2 - 560x - 1150$	86.4
	x_1= 12:00 x_2= 18:00		271
	x_1=21:00 x_2= 00:00		586.5
Kebili	x_1= 04:00 x_2= 09:00	$P_2(x) = -0.248x^5 + 14.3x^4 - 275x^3 + 1860x^2 - 1960x - 1600$	48
Bizert	x_1=07:50 x_2= 02:50	$P_4(x) = -0.017x^5 + 0.17x^4 + 28x^3 - 510x^2 + 5740x + 2100$	53.4

July:

Table 20 - estimation of the overproduced power in different sites during July

Site	Curves limits	Polynomial interpolation	Production excess (MWh)
Thala	x_1= 03:00 x_2= 10:00	$P_1(x) = -0.36x^5 + 19.3x^4 - 352.7x^3 + 2075x^2 - 150x + 400$	115
Tozeur	x_1= 03:50 x_2= 07:00	$P_2(x) = -0.159x^5 + 3.1x^4 + 25.3x^3 + 1575x^2 + 11710x - 6600$	51.1
Kebili	x_1= 02:00 x_2= 07:50	$P_3(x) = 0.04x^5 - 1.3x^4 + 2.8x^3 + 245x^2 - 80x - 3270$	11.1
	x_1= 17:00 x_2= 00:00		104.5
Bizert	x_1=02:00 x_2= 06:50	$P_4(x) = 0.08x^5 - 7.9x^4 + 267.3x^3 - 3725x^2 + 19290x - 7600$	103.8

September:

Table 21 - estimation of the overproduced power in different sites during September

Site	Curves limits		Production excess (MWh)
Thala	x_1= 03:30 x_2= 08:00 x_1= 18:00 x_2= 19:00	$P_1(x) = -0.07x^5 + 4.1x^4 - 82.6x^3 + 665x^2 - 580x - 1100$	25 18.2
Tozeur	x_1= 02:50 x_2= 06:30	$P_2(x) = 0.02x^5 - 3.2x^4 + 132.4x^3 - 2165x^2 + 11380x - 3021$	56.4
Kebili	x_1= 18:00 x_2= 19:00 x_1= 20:30 x_2= 00:00	$P_3(x) = 0.14x^5 - 7.4x^4 + 122.4x^3 - 715x^2 + 13380x - 2780$	12 27.3
Bizert	x_1=01:50 x_2= 04:50	$P_4(x) = 0.47x^5 - 28x^4 + 582.4x^3 - 5065x^2 + 16380x - 6400$	33.1
Gafsa	x_1=00:50 x_2= 07:50	$P_5(x) = 0.48x^5 - 28x^4 + 580x^3 - 5000x^2 + 16000x - 3400$	65.2

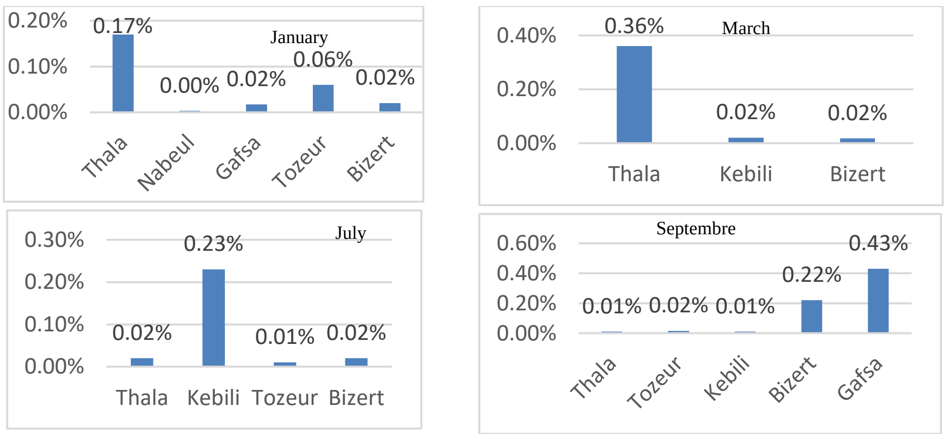


Figure 15 - Over-production percentage comparing to total value of power consumption

It is abundantly clear that curve of figure 14, shows an over consumption during the day as well. Using the same methodology developed above in order to calculate the over produced power, the estimation of over consumption values is regrouped in table below:

Table 22 - Estimation of overconsumption during January, March, July and September of Tunisia

January:

Site	Curves limits		Consumption excess [MWh]
Thala	x_1= 01:00 x_2= 03:07 x_1= 17:58 x_2= 20:06	$P_1(x) = -0.01x^5 + 0.62x^4 - 14x^3 + 140x^2 - 450x + 2000$	4.98 17
Tozeur	x_1= 08:50 x_2= 00:00		1185
Kebili	x_1= 05:00 x_2= 21:00		50.4
Bizert	x_1=00:00 x_2= 02:50 x_1=08:05 x_2= 00:00		5.6 50.4
Gafsa	x_1=00:00 x_2= 01:50 x_1=08:05 x_2= 00:00		2.1 1185
Nabeul	x_1=00:00 x_2= 03:00 x_1=11:00 x_2= 00:00		4.98 59.0

March:

Site	Curves limits		Consumption excess
Thala	x_1= 00:00 x_2= 01:07 x_1= 08:58 x_2= 12:06 x_1= 18:00 x_2= 21:06	$P_1(x) = -0.012x^5 + 0.7x^4 - 15x^3 + 140x^2 - 440x + 2000$	1.82 9.36 8.3
Tozeur	x_1= 00:00 x_2= 00:00		54
Kebili	x_1= 00:00 x_2= 01:50 x_1= 10:50 x_2= 00:00		2.64 35
Bizert	x_1=00:00 x_2= 02:00 x_1= 07:50 x_2= 00:00		5.6 44
Gafsa	x_1=00:00 x_2= 00:00		54
Nabeul	x_1=00:00 x_2= 00:00		54

July:

Site	Curves limits		Consumption excess [MWh]
Thala	x_1= 00:00 x_2= 02:50	$P_1(x) = -0.012x^5 + 0.7x^4 - 15x^3 + 140x^2 - 440x + 2000$	8.74
	x_1= 10:00 x_2= 00:00		60.2
Tozeur	x_1= 00:00 x_2= 02:00		54
	x_1= 08:50 x_2= 00:00		360
Kebili	x_1= 00:00 x_2= 05:00		16.6
	x_1= 07:50 x_2= 17:00		37.8
Bizert	x_1=00:00 x_2= 02:50		8.74
	x_1= 06:50 x_2= 00:00		437.2
Gafsa	x_1=00:00 x_2= 00:00		87.7
Nabeul	x_1=00:00 x_2= 23:50		85.3

September:

Site	Curves limits		Consumption excess [MWh]
Thala	x_1= 00:00 x_2= 03:50	$P_1(x) = 0.0022x^5 - 0.039x^4 - 2.4x^3 + 65x^2 - 380x + 3000$	9.01
	x_1= 08:00 x_2= 12:00		12.5
	x_1= 18:00 x_2= 21:00		9.9
Tozeur	x_1= 00:00 x_2= 02:50		8.3
	x_1= 06:50 x_2= 00:00		55.5
Kebili	x_1= 00:00 x_2= 17:50		51.9
	x_1= 19:00 x_2= 20:50		4.64
Bizert	x_1=00:00 x_2= 01:50		4
	x_1= 04:50 x_2= 00:00		60.5
Gafsa	x_1= 07:50 x_2= 00:00		47.6
Nabeul	x_1= 00:00 x_2= 00:00		60.4

The nature of wind is indeterminate, unpredictable and intermittent. The energy available in wind is considered as variable and weakly predictable. This variability is specified by the high frequency of output power changes and variability according to different time scales [33]. It is difficult to foresee exactly the electric power generated by the wind turbine [34]. Integrating wind power into power grid will have favorable impacts by reducing costs of operations of power system, as though less fuel will be consumed in conventional power plants. However, a full spectrum of problems for the operation on the electricity grid, due to the limited predictability and high inter-temporal variations of wind power. In the one hand, if the ratio of intermittent production is feeble and if wind power production is greatly dispersed over a large area and correlates with the charge then wind power is easier to integrate into the system [35], the problem is when the portion of production is higher than the power grid capacity. In the other hand, the no-implication of power generated by wind turbines in the system services make them behave as a passive generator from electrical aspects [36]. Not only the limited capacity of grid represents an issue, but also the limited distribution of electrical lines, some windy sites are often far from the consumption area, to construct new lines may take 10 years of work [37]. For the Tunisian case the distribution of power grid is represented on figure below:

Figure 16 - Tunisian electric grid, *Figure from STEG (the Tunisian Company of Electricity and Gas)*

It is definitely lucid, from figure on top, that the electric grid near to some windy sites is weak, 150 kV simple line for Thala's case, its low capacity makes the integration of over produced power impossible. The comparison between power consumption and production, evinces that some places requirement an electrical storage. In the upcoming part the selected sites will be classified according to storage need, using the following methodology:

Sites will be distributed in three different classes according to B sign, where B is:

$$B = hourly\ consumption - hourly\ production$$

B < 0: production is more than consumption, storage needed.

B = 0: The balance sheet of this site is zero and has reached its state of self-satisfaction.

B > 0: consumption is more than production, no need for storage.

Table 23 - sites classification according to B

sign (+) no storage needed, sign (-) storage needed, (0) self-satisfaction

	January	March	July	September
Thala	-	-	0	-
Nabeul	+	+	+	+
Gafsa	+	+	+	-
Tozeur	+	+	+	+
Kebili	+	-	-	
Bizert	0	-	+	+

According to power consumption and production values regrouped in tables above, it is conspicuous that the storage cannot be done in all he studied sites. Thala is characterized by an over production, which reach up 220%, 193%, and 137% respectively during January, March and September, in July, approximately, Thala attain its auto-satisfaction in term of power production. In Kebili, storage make sense in both months, March and July, when over production represents, respectively, 127% and 189% from the totally hourly consumption. Bizert reaches its self-satisfaction during January, and an over production of 7% more that the totally consumption value.

Table 24 Over-produced power (MWh)

	Over-produced power (MWh)			
	January	March	July	September
Thala	466.32	924.4	46.1	12.2
Bizert	-	3.8	-	-
Kebili	-	10.4	61.1	-
Gafsa	-	-	-	17.6

In order to choose the most storage system for a certain application, it is necessary to specify the requirements needed for the devices to have an appropriate performance. In the case of this study, the staple idea is to store energy when production exceeds consumption, being available thereafter when needed. A profit can be made by storing energy during off-peak hours, when electricity is cheap and then discharging during peak-hour, obtaining then an economic surplus in the process. The most important for energy usages, that the technology used must be characterized by a large storage capacity, low self-discharging rates and long lifetime. In order to select the most appropriate device, it is necessary to compare the performance of storage. Storage capacity, available power, discharging time, lifespan time and self-discharging values are regrouped in table below:

Table 25 - Storage technologies characteristic [38]

	Power rating	Discharge duration	Response time	Efficiency	Lifetime
Pumped hydro	100-4000 MWh	4-12h	Sec-min	0.7-0.85	30 years
CAES (compressed air energy storage)	100-300 MWh	6-20h	Sec-min	0.64	30 years
flywheel	< 1650 kW	3-120s	<1 cycle	0.9	20 years
Super-capacitor	< 100 kW	< 1m	<1/4 cycle	0.95	10,000 cycles
SMES (superconducting magnetic energy storage)	10 kW-10MW	1s-1m	<1/4 cycle	0.95	30 years
Lead-acid battery	< 50 MW	1m-8h	<1/4 cycle	0.85	5- 10 years
ZnBr flow battery	< 1 MW	<4h	<1/4 cycle	0.75	2000 cycles
V redox flow battery	< 3 MW	< 10h	unknown	70-85	10 years
Polysulphide Br flow battery	< 15 MW	< 20h	unknown	60-75	2000 cycles
Hydrogen (engine)	< 2 MW	As needed	secondes	0.29-0.33	10 -20 years

The 6 studied locations can be classified according the storage technologies to integrate. Thala represents the maximum overproduction value 943.9 MWh must be stored during 14 hours, integrating PHES (pumped hydraulic energy storage) device is the optimal solution for Thala's case. PHES is s the most mature and largest capacity storage technique available, consists of two large reservoirs situated at different elevation and a number of pump turbine units. During the off-peak electrical demand, water is pumped from the higher reservoir where is stored until it will be needed. When the overproduction period starts, the water stored in the upper reservoir is released trough the turbines, connected to generator that produce electricity. During March and September, Bizert, Gafsa and Kebili, are characterized by a low amount of electricity to be stored for a short period of time (less than 7 hours), integrating Batteries is the greatest solution for these areas. Battery is the most common storage device used nowadays, due to it maturity, relatively, low coast, long lifespan, fast response, and low self-discharge rate, used essentially for short term applications. During July, Kebili is characterized by an average amount of power overproduced, 61.1 MWh as it shows table 24. Integrating CAES (compressed air energy storage) is the optimal solution for this area.

V. Conclusion

The purpose of this thesis is to analyze wind potential in Tunisia and study the opportunities to integrate storage devices. Data used in this work was provided by the National Institute of Meteorology of Tunisia, has a resolution of 1 m/s in an hourly basis. Using cup generator anemometer situated in 10 m a.g.l, weather- vane and data logger, the data as measured during 25 years (from 1990 to 2015) in 25 different locations in Tunisia. Fist step of the methodology used was classifying measurement stations according wind direction frequency and average wind speed. Thala, Bizert, Tozeur, Gafsa, Nabeul and Kebili were the 6 selected stations as the most potent sites in term of wind energy. Where the wind is characterized as strong (more than 4 m/s) and a specific wind direction. All the selected stations revealed that West and North-West were the prevailing wind direction while the frequency exceeds 15%. Meteorological method consists on plotting wind velocity histograms using MATLAB software. Results shows that the frequent wind speed in the 6 locations is between 4 and 6 m/s at 10 m h.a.g.l. And between 6 and 11 m/s at 92.5 m h.a.g.l. Using Weibull distribution which is based on two parameters k and c, the mean wind speed and the shape of Weibull distribution respectively. Weibull curves were plotted using MATLAB, shows that Thala, Kebili and Tozeur have the best three k values of the test site. Thala had the greatest average wind speed compared to the other five sites 6.65 m/s. Next step in this project is to evaluate the power available I wind. As the energy available in wind differs with the third power of the wind speeds, the greatest power available in wind was observed in Thala, 373,4 W/m^2, then Kebili (257.2 W/m^2), and Gafsa (216.0 W/m^2). 3.2 MW wind turbine was selected to evaluate real results. Using logarithmic-law data was extrapolated to the hub height of the studied wind turbine 92.5 m. Always using Weibull distribution, Thala was the greatest area on hourly energy production 9 GWh, 10 GWh, 8 GWh and 79 GWh respectively in January, March, July and September. Power storage technologies integration in Tunisia is possible in some area where the electric grid is weak. different quantities and for different period of the day. The maximum quantity to be stored is in Thala, 1GWh for 10 hours per day, the best technologies to be integrated are CAES (compressed air energy storage), its capacities varies from 0.1 to 0.3 GWh and discharge storage can reach 20 hours and pumped hydraulic energy storage, it is characterized by a large energy storage capacity, 4 GWh, and a discharging duration varies between 4 and 12 hours. Wind potential in Tunisia can be classified as strong, but this power is not well exploited, The reasons why no wind farms are not I all over Tunisia, are probably because the access roads are unusable for the long heavy transport vehicles modern wind turbines require and that the high voltage grid system does not extend to these areas. Results can be more detailed and consistent if the data provided was with 10 minutes average and a greater resolution than 1m/s.

VI. References

[1] **I. e. A. A. e. B. A. D. HIchem Bidioui, «Wind Speed Data Analysis Using Weibull and Rayleigh**

Distribution Functions, Case Study: Five Cities Northern Morocco,» *ScienceDirect,* 2019.

[2] **«World Energy Balances 2017: Overview, International Energy Agency, (2017)».**

[3] **«the whole optimization algorithm-based controller for PMSG wind energy generation system**

4 February 2019».

[4] **«Burton, Tony, et al. Wind energy handbook. John Wiley & Sons, 2011».**

[5] **«Manwell, James F., Jon G. McGowan, and Anthony L. Rogers. Wind energy explained:**

theory, design, and application. John Wiley & Sons, 2010».

[6] **«D. Mazzeo, G. Oliveti, E. Labonia, Estimation of wind speed probability density function**

using a mixture of two truncated normal distributions. Renew. Energy, 115 (2018) 1260-1280.».

[7] **«V. Katinas, M. Marčiukaitis, G. Gecevičius, A. Markevičius, Statistical analysis of wind characteristics based on Weibull methods for estimation of power generation in Lithuania. Renew. Energy, 113 (2017) 190-201.».**

[8] **«M. Elamouri, F. Ben Amar / Renewable Energy 33 (2008) 758–768 ,wind energy potential in Tunisia, wind energy potential April 2018».**

[9] **«wind speed distribution Weibull-Reuk.co.uk».**

[10] **«T. Aukitino, M. G. M. Khan, M. R. Ahmed, Wind energy resource assessment**

for Kiribati with a comparison of different methods of determining Weibull parameters.

Energy Convers. Manag., 151 (2017) 641-660».

[11] Weatheronline.co.uk,"3 mai 2018. [Online]. Available: https://www.weatheronline.co.uk.

[12] Gloria Ayee, Marcy Lowe and Gary Gereffi, 2019, wind power: generating electricity and employment wind power, Summary, page 4.

[13] «Boyle G. 1996; renewable energy, power for a sustainable future, the open university oxford, England p275».

[14] «Wizelius, T., 2007. Developing Wind Power Projects: Theory and Practice. Earthscan.».

[15] «IEC/TC 62600-100 (2012».

[16] «K.M. Nor, M. Shaaban, H.A. Rahman, Feasibility assessment of wind energy resources in Malaysia based on NWP models, Renew. Energy 62 (2014) 147e154».

[17] «A. Hemami, "Wind turbine technology", Cengage Learning series in Renewable Energies, USA, 2012».

[18] «J. Wieringa. "Updating the Davenport roughness classification». Journal of Wind Engineering and Industrial Aerodynamics. 1992.41:44, 357-368».

[19] «E. H. Lysen, "Introduction to wind energy second Edition, the countries, developing services wind energy Consultancy Netherlands, 1983».

[20] «G. Gualtieri, S. Secci, "Comparing methods to calculate atmospheric stability-dependent wind speed profiles: a case study on coastal location", Renewable Energy, 36, pp 2189-2204, 2011».

[21] G. Gualtieri, "Surface turbulence intensity as a predictor of extrapolated wind resource to the turbine hub height", Renewable Energy, 78, pp 68- 81, 2015..

[22] Leahy, Martin J Connolly, David Buckley, Denis N, 2010, Wind energy storage technologies chapter 1.

[23] Wei Tong Kollmorgen Corp., USA, 2010, Wind power generation and wind turbine design 662.

[24] «Power to Gas: The Case for Hydrogen White Paper; California Hydrogen Business Council: Los Angeles, CA,».

[25] «M. Elamouri, F. Ben Amar / Renewable Energy 33 (2008) 758–768».

[26] «Krohn 2000 Danish Wind Turbine Manufacturers Association.Windpower.org».

[27] «Chisholm, Hugh, ed. (1911). “Jerba». Encyclopedia Britannica. 15 (11th ed.). Cambridge University Press. p. 322».

[28] «wind prospecting of the canary island Geoffrey hill goteborg 2003».

[29] «THE EFFECT OF OBSTACLES CLOSE TO THE ANEMOMETER MAST LOCATED ON A BUILDING ON WIND FLOW IN THE WASP MODEL».

[30] «Site assessments for wind turbine Capstone Project Final Report, hassan Krech 2016».

[31] «Wind Speed Extrapolation and Wind Power Assessment at Different Heights, 2017».

[32] «Tiemann, Jerome J. (May–June 1981). "Polynomial Interpolation". I/O News. 1 (5): 16. ISSN 0274-9998. Retrieved 3 November 2017».

[33] «AIE, "Renewables for Power Generation Status & Prospects", 2003.».

[34] «DENA, "Energy Management Planning for the Integration of Wind Energy into the Grid in Germany, Onshore and Offshore by 2020", Final Report, Consortium DEWI / E.ON Grid / EWI / RWE Transport Grid, Electricity / VE Transmission –02/2005».

[35] «Pavlos S. Georgilakis, Technical challenges associated with the integration of wind power into power systems, Renewable and Sustainable Energy Reviews 12 (2008) 852–863.».

[36] «N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, "Embedded generation", The Institution of Electrical Engineers (IEE), London, 2000».

[37] «Integration of Wind Energy into Electricity Systems: Technical Challenges and Actual Solutions».

[38] Leahy, Martin J Connolly, David Buckley, Denis N, 2010, Wind energy storage technologies chapter 1, page 146