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RESEARCH ARTICLE

Repowering of a wind energy production field - case study of SIDI-DAOUD field in northeastern Tunisia

Hassen Ayed Chraiga

Department of mechanical Engineering, High institute of technology study, General departure of technology study, Tozeur, Tunisia

Corresponding Author: hassen ayed chraiga: email: hassen.chraiga@isett.rnu.tn
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Abstract

Every energy production system, whether conventional or renewable, reaches its final limits after a period of operation predefined by the feasibility study for such a project. Then we'll have to think about renewal to maintain a certain level of reliability and availability as a factor of operational safety. This project seeks of studying the repowering of two 1st phases of wind farm in Sidi-Daoued in north Tunisia, which have reached the end of their life (20 years); it aims to identify three new configurations and to simulate different scenarios to determine which types of turbines are the most optimal for a repowering project. The three types of wind turbine selected were Vestas 4200kw, Nordex Acciona and Siemens-Gamesa, each with a power output of 4500kw. These are the best-known types of wind turbine in the world, and the heights of the hubs are very similar, at around 105m, so that a comparison can be made between the three models. Therefore, the average speeds are around 7.8 m/s2.The final number of turbines to be installed on site is around 13 turbines for the three scenarios, but the result favours the second scenario with Siemens-GAMESA wind turbines, where the annual production can exceed 210.1 GWH with a capacity factor equal to 41 percent.

Keywords: Wind energy; power; repowering; SAM

Introduction

Repowering a wind farm involves replacing old turbines with more powerful and efficient models to enhance energy production and efficiency (Cardinal, R et al.2023). This process is crucial as wind farms near the end of their operational life, typically after 20 years. Repowering can significantly increase electricity output, reduce the number of turbines needed, and improve integration into the electricity grid. It offers benefits such as increased energy production capacity, improved efficiency, reduced operating costs, progress towards decarbonization, better grid integration, preservation of employment, and improved community acceptance. Despite its advantages, slow permitting procedures and changing legislation have hindered widespread repowering efforts, with less than 10% of wind turbines reaching the end of their life currently being repowered (Abadie, L et al. 2021). Governments are urged to simplify permitting procedures and incentivize repowering to harness its potential in boosting wind power output efficiently and advancing renewable energy goals (Rekik, S., & Alimi, S. (2023).

Tunisia has implemented since the 1990s a strategy to develop wind energy. During the start-up phase, small-power wind turbines were installed to meet the energy needs of dispersed rural households. In 2000, a first 10-megawatt (MW) wind power plant with high-power wind turbines was installed. The positive results of this project prompted the Tunisian Electricity and Gas Company (STEG) to expand the wind farm. A first wind power plant has been installed in Sidi Daoud; Following this, a second plant was installed in the Bizerte region in the north of the country on two sites located in Métline and Kchabta. In addition, the total energy produced by wind power plants in Tunisia is about 750 GWh/year, allowing an annual saving of 153,000 tons of fuel (Bahar, et al. ,2022).Over the years, the wind turbines of the first plant began to show signs of wear and, like any other machine, they lost their performance. Thus, as wind installations age, owners are faced with decisions regarding the end of life of the wind farm. An alternative to extend the life of the project is repowering, which consists of replacing old turbines with new, modern and more powerful technologies (Bahar, et al 2022) a complete presentation on the powers, the number and the commissioning date of each unit of existing turbines in the Sidi Daoud field will be made in section 3, also the geographical representation of the turbines will be made in section 4, the calculation of wind power which will be presented with the Weibull curve and the wind rose will be treated in section 5, the choice of new turbines will be organized in the form of scenarios where each scenario presents a type of wind turbine. A simulation on the SAM software in section 6 carries out the study on the scenarios cited below

Establishment of a wind farm

A wind farm is made up of several wind turbines and a delivery station. The wind turbines are connected to each other or directly to the dedicated delivery station. This station is used to control, monitor production and send the electrical energy produced by the park to the electrical distribution network. This Delivery Station is thus connected to a source station; in order to distribute the electricity produced throughout the territory according to the national network. (Orcajo, G et al. 2022).

Total number of wind turbines to be placed in the site

Conditions to respect:

$(N1+1) * 10H < I$

$(N2 +1) *3D < L$

$N = N2 *N1$

with:

♦ I = Dimension of land perpendicular to the prevailing wind direction
♦ L = Dimension of the terrain parallel to the prevailing wind direction
♦ D = rotor diameter of Machine
♦ H = Pylon height
♦ N1= Number of wind turbines per row
♦ N2 = Number of rows of wind turbines
♦ N = Total number of wind turbines to be placed on the site

Sizing techniques

Wind power

The power of a wind turbine is calculating by the formula:

$$Pd=1/2.\ \rho.S.\ V^3 \quad (1)$$

With:
ρ: air density (kg/m3)
V: the average wind speed (m/s)
The electrical power supplied by the wind turbine at the output of the energy generation chain is the result of the mechanical power recovered on the shaft of the turbine after deduction of the mechanical and electrical losses inherent in the machine all of these electromechanical losses representing a few percent (from 2 to 5% depending on the wind speed) of the mechanical power (Montoya, L et al .2022)),

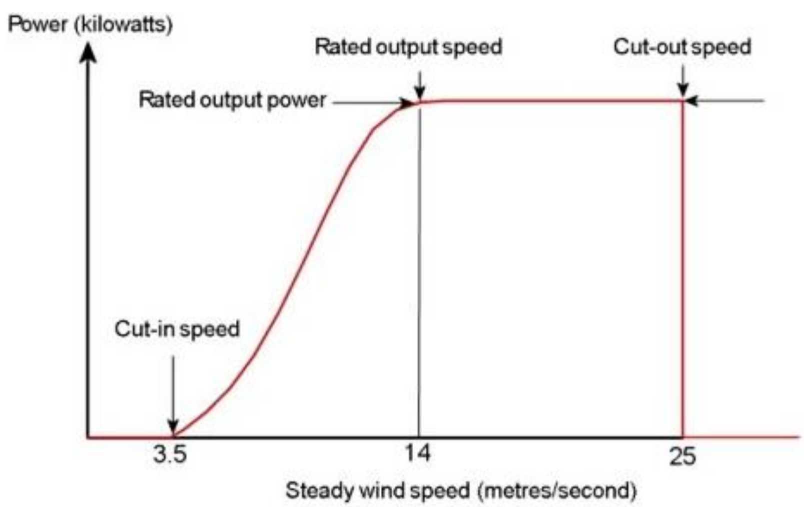

Figure 1. Operating ranges of a wind turbine (horizontal axis) as a function of wind speed

Energy production by a wind turbine

Below, we see the appearance of several variables depending on the wind speed:
-Power supplied by the wind turbine
- Wind speed distribution
- Energy production

Efficiency of a wind turbine

The efficiency of a wind turbine can never reach 100% (Veers, P et al 2023), This phenomenon is theoretical and can be understood intuitively. To recover the power of the wind, the wind turbine must slow it down (take speed). The more the wind turbine slows down the wind, the more power it draws. But at the same time, the more the wind turbine slows down the wind, the more it prevents it from passing and therefore the less flow there is. If the

wind turbine were a piece of wall (a giant concrete disc for example), it would slow the wind down to 100%. There is therefore an optimum fixed by the Betz limit. The speed behind the wind turbine must be equal to 1/3 of the speed before the wind turbine. So, the theoretical yield can reach 16/27.
The energy supplied by the wind turbine being converted from one form to another, this limit is therefore affected by all the yields specific to the various transformations (Li, J et al. 2022).

Table 1. The characteristics of the Sidi-Daoud wind farm

	Numbers of AG		Types	Total power (MW)	Unit power (KW)	Date of commissioning
Stage A	32		AE32	10.56	330	2000
Stage B	10	9	AE46	7.26	660	2003
		1	AE61		1320	
Stage C	26		AE61	34.32	1320	2009

Energy supplied by a wind turbine

The total energy production of the wind farm is calculated consider the average power of the wind turbines during the period analyzed and the total correction factor (kt). This parameter gathers several factors that act by reducing the final energy production.
The most important correction factors are: (Oliveira, H et al. ,2019).
(i) Aerodynamic Factor: Loss of aerodynamics through the blades due to dirt, rain, ice, snow, etc.;
(ii) Interference factor: interference from obstacles and other wind turbines. The spacing between wind turbines is ten times the diameter of the rotor in the direction of the wind and five times in the perpendicular direction.
(iii) unavailability factor: time while the wind turbine is not operational due to maintenance or repairs.
(iv) Interconnection factor: losses in the lines and equipment of the interconnection with the network.
(v) Utilization factor: time while the wind farm is disconnected from the grid due to low energy demand or high wind speeds.
Thus, taking into account all these factors, the energy production of the wind farm produced during a period T is:

$$EP = kt.\ Pave.\ T \quad (2)$$

With:
EP: the energy produced in (kWh)
T: the period time in hour (h)
P_{ave} : the average power in (kW).

The efficiencies of each element vary with the operating regime linked to the rotation speed of the propeller, which apart from the nominal regime further reduces the overall efficiency of the device, it seems difficult to exceed 70% of the Betz limit. (Coelho, P,2022)

$$\eta = \frac{P(v)}{P_d} \quad (3)$$

With:
$P(v)$: instantaneous power(kW)

P_d: available power

Table 2. Characteristics of existing turbines

	AE-32	AE-46	AE-61
Nominal power (Kw)	330	660	1320
Minimum Wind speed (m/s)	3	3	4
Rated Wind speed (m/s)	12.5	12.5	15
Maximum Wind speed(m/s)	20	25	25
Rotor diameter(m)	32	46	61
Scanned area(m²)	804	1662	2923
Number of blades	3		
Hub height(m)	30	43.5	58.5
Manufacturer	GAMESA		

Capacity Factor

Another important parameter for comparing wind turbine performance is the capacity factor (CF). It relates the real average power supplied by the turbine to the nominal one informed by the supplier (Xu, J et al.2023)).

$$\mathbf{CF}\ (\%)\ =\ (\frac{\mathbf{100} * \boldsymbol{Pmoy}}{\boldsymbol{Pmax}}\ )\ (4)$$

In practice it will be rather more than 25%.

Case study: Sidi-Daoud wind farm

This part will present the specific information of the wind farm studied, will describe the location of the wind turbines of the power plant and will present the equivalent characteristics. we will then define the term Repowering, before describing the different scenarios proposed. The essence of this concept is to leverage the infrastructure already built to deploy more efficient machines.

Current case

The case study chosen to be the object of the analysis of this work is the wind farm of SIDI DAOUED
The Sidi Daoud wind farm contains a power plant built on a fairly windy coast at the northern tip of Cap-Bon in Tunisia.
It was created and put into service by the Tunisian Electricity and Gas Company in 2000, about fifty kilometers from Tunis. Made up of around forty wind turbines, supplying 2% of the country's consumption, it is the only one of this type to be in service in 2009.

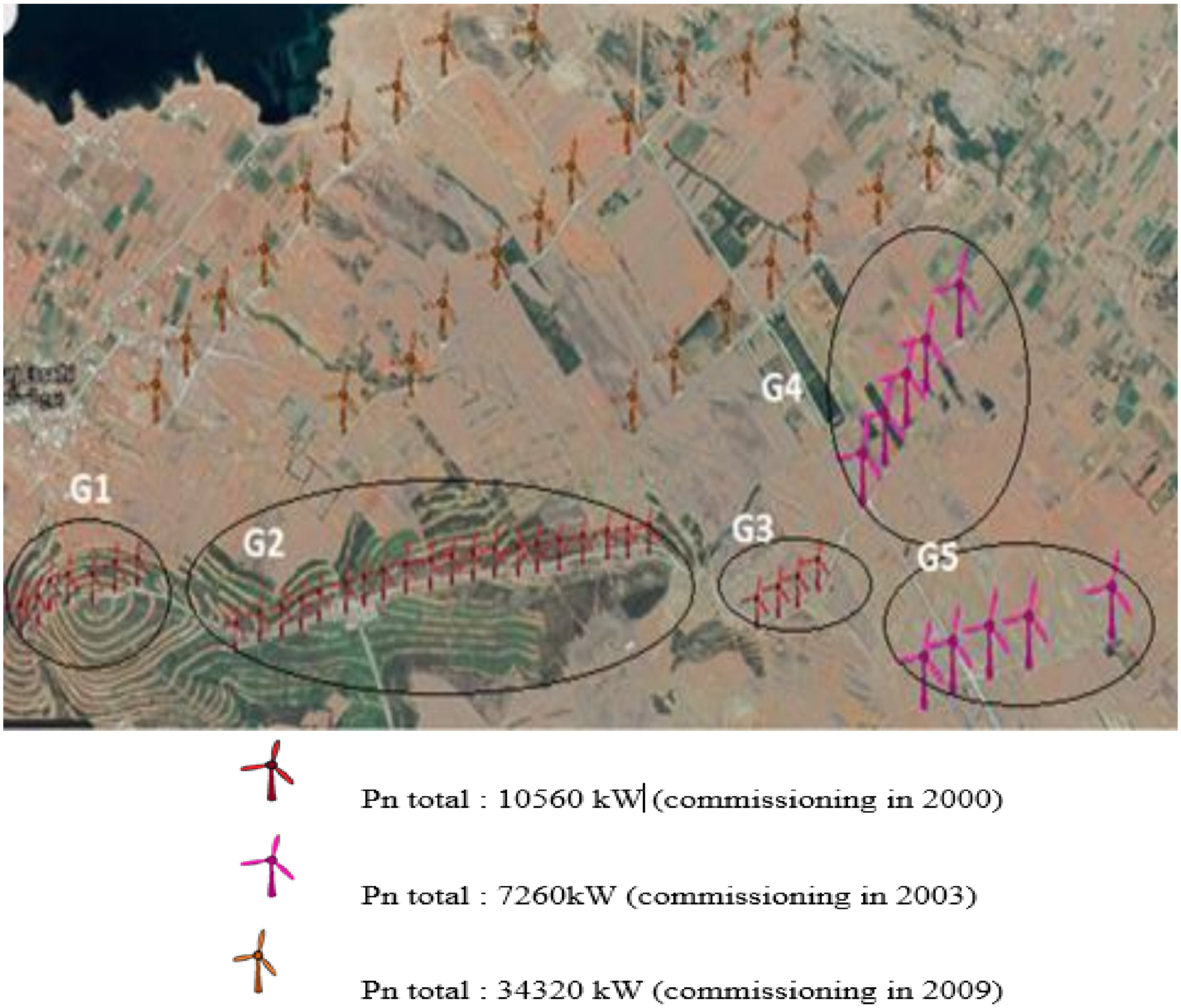

Figure 2. Geographical position of existing wind turbines

As shown in Table 2, the wind farm is equipped with 3 different Gamesa turbines. The same table shows the main characteristics of these turbine models. The (figure3) shows the power curve of the three-wind turbine proposed:

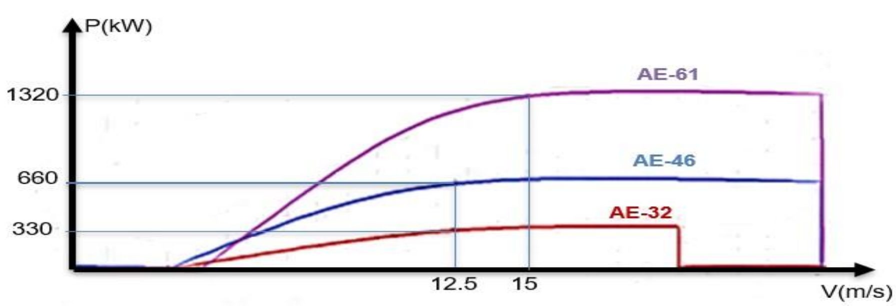

Figure 3. Power curve of the park's turbines

The current situation means that the generators of the first two phases have become obsolete, reaching their end of life of 20 years respectively in 2020 and 2023. It was therefore decided to proceed with the renewal of the two stages A and B by means of the Repowering

Repowering plan

This section aims to explain the Repowering options to be analyzed for the park; essentially, the models of the turbines considered, and the number of new wind turbines that can be deployed in order to replace the old turbines. The Repowering or "renewal" of a wind farm, which consists of replacing old machines with more efficient wind turbines, represents one of the solutions for optimizing the productivity and profitability of a site.
The advantages of Repowering are:
• The wind turbines currently on the market show considerable technological evolutions
• The replacement of old wind turbines with new ones makes it possible to produce more energy, with a lower overall impact on the environment, for a territory which already benefits from good local acceptability of the wind farm
• Thanks to technological progress, maintenance costs are falling
• Technical knowledge of the site facilitates the design of the renewal project: it is possible to rely on data already known and to take advantage of existing infrastructures (access, connection, for example) (Veers, P.and al. (2023).

Site wind characteristics

The local climate was analyzed at the nacelle height of each wind turbine in the project. The Weibull distribution of wind speeds (figure4) and the wind rose (figure5) were used to characterize this climate.
The graphs indicate that the prevailing winds come from the **N**orth**w**est sectors and that the most frequent winds have a speed close to 6 m/s.

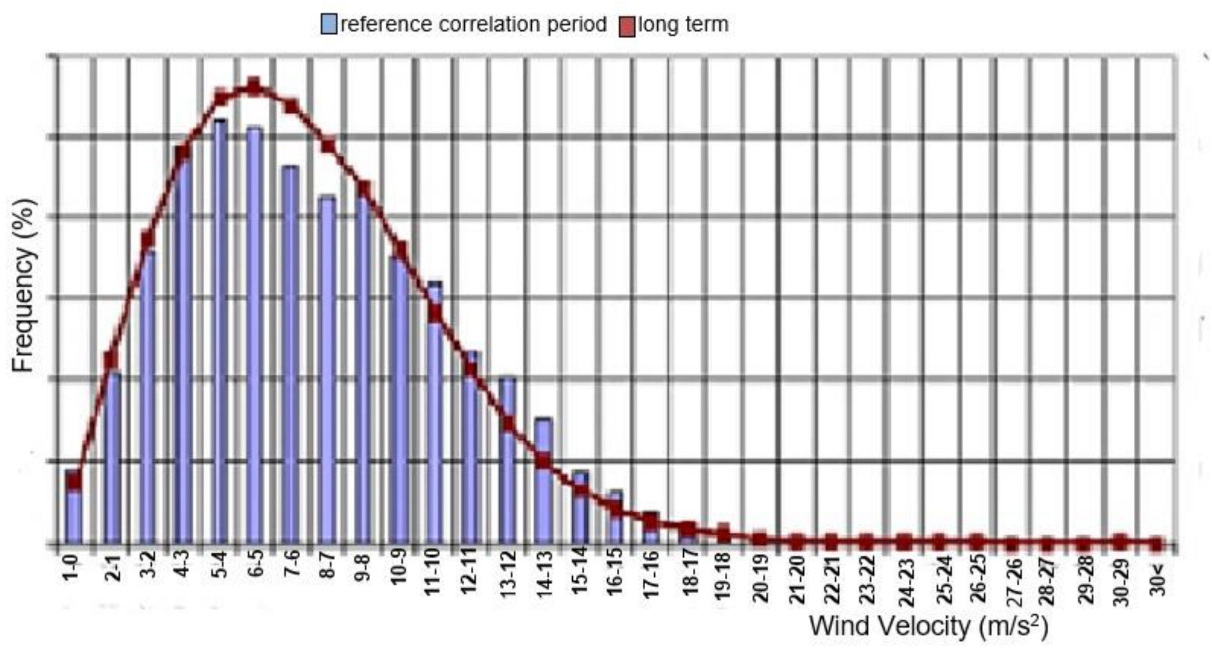

Figure 4. Reference period and long-term wind speed distribution (Source: STEG)

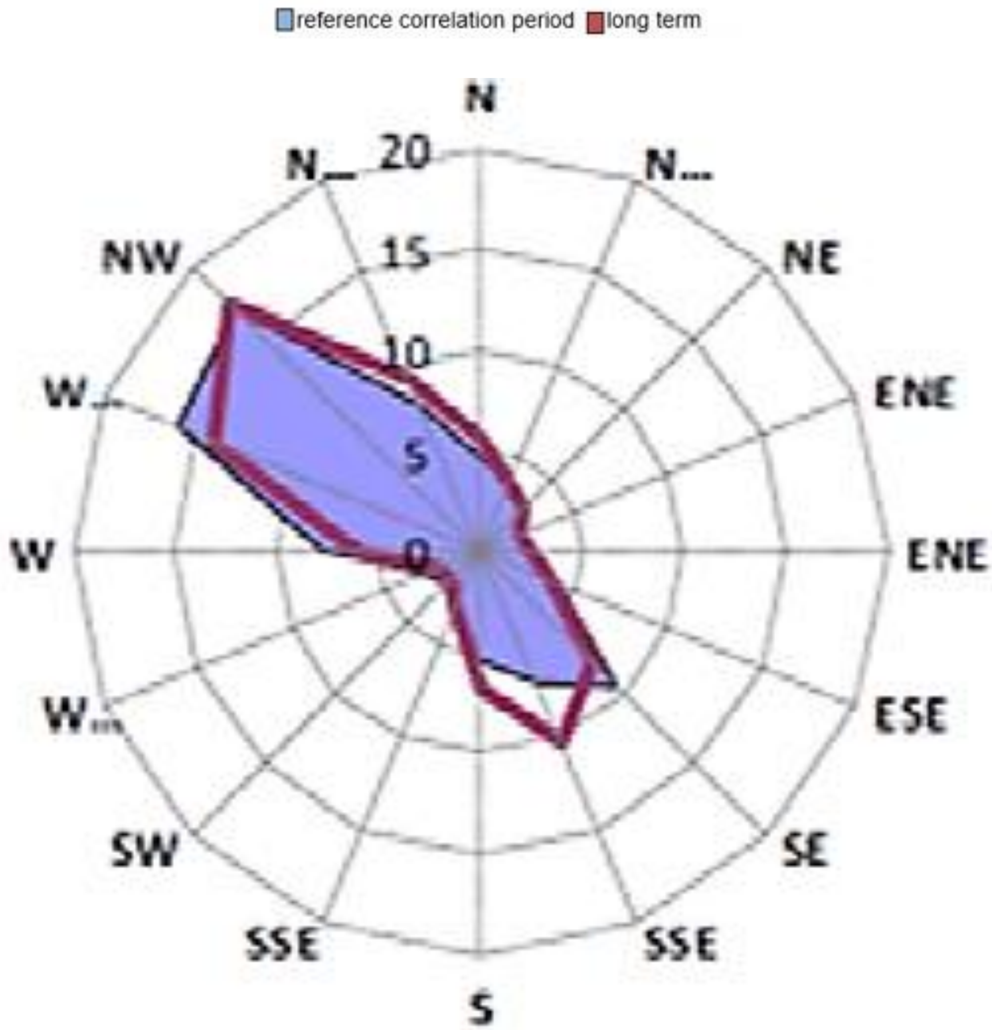

Figure 5. Reference period and long-term wind rose (Source: STEG)

Turbine choice

The type of wind turbine is an essential factor in calculating the final energy production of the park. There are a large number of turbine manufacturers and models on the market, and there is no set process that allows us to define the best one.

The following (table3) shows the world's largest manufacturers of wind turbines; vestas, Nordex Acciona and siemens-Gamesa. They together represent more than three quarters of the world market.

For the Repowering project of the SIDI DAOUED wind farm, 3 turbine configurations were proposed in order to choose the optimal one. The simulations will therefore have to be carried out for the 3 cases in order to be able to compare them; Each of these has a variety of possible blade sizes (indicated by rotor diameter) and tower heights. The following table presents the main characteristics of these models.

Table 3. the characteristics of the turbines to choose from

	Nordex-Acciona	Siemens-Gamesa	Vestas
Configuration	I	II	III
Wind Turbine Manufacturer/Model	N149-4.5MW	SG145-4.5MW	V136/4.2MW
Nominal power	4500KW	4500KW	4200KW
Rotor diameter (m)	149	145	136
Rotor swept area	17437m²	16513m²	14527m²
Hub height	105m	107.5m	105m

In this study, each scenario will have a different type of turbines available. To limit the number of scenarios considered, the diameter of the rotor will be considered as the largest possible for each model (the size already indicated in the table).

To calculate the energy produced by the wind farm, another piece of information is essential: it is the power curve of the turbine. The number of turbines that can be deployed in each case is defined as **13** turbines. Information is also needed on the recommended spacing between adjacent wind turbines. This parameter must be equal to the equivalent distance of five times the diameter of the rotor. Considering the above, the average distance between existing turbines is 100 m.

Definition of scenarios

there will be three configurations to study. We will therefore examine each scenario with the three different models of wind turbines available from Nordex 4500KW (scenario 1), Siemens-Gamesa 4500 kW (scenario 2) and Vestas 4200 kW (scenario 3). In each case, the turbine with the largest diameter was chosen for the rotor.

In addition to the type of turbine considered, it is necessary to define the number of turbines that will replace the old ones. This number is calculated based on the recommended lateral spacing between the impellers, which is about five times the rotor diameter.

From the aerial view of the wind farm - as shown in (figure 6), the turbines have been grouped into 5 groups and it has been considered that these groups do not interfere on each other.

By applying all these assumptions as well as those defined in the previous paragraph, we find how many turbines of these models can be installed to replace the 42 existing ones.

Table 4. Number of turbines to be replaced

Groups	Curent	Scénarios 1/2/3
G1	8	2
G2	20	5
G3	4	1
G4	5	3
G5	5	2
Total	42	13

The approach considered for the three scenarios is the same due to the similarity of the turbines in terms of power and rotor diameter, so we obtain the following wind turbine configuration:

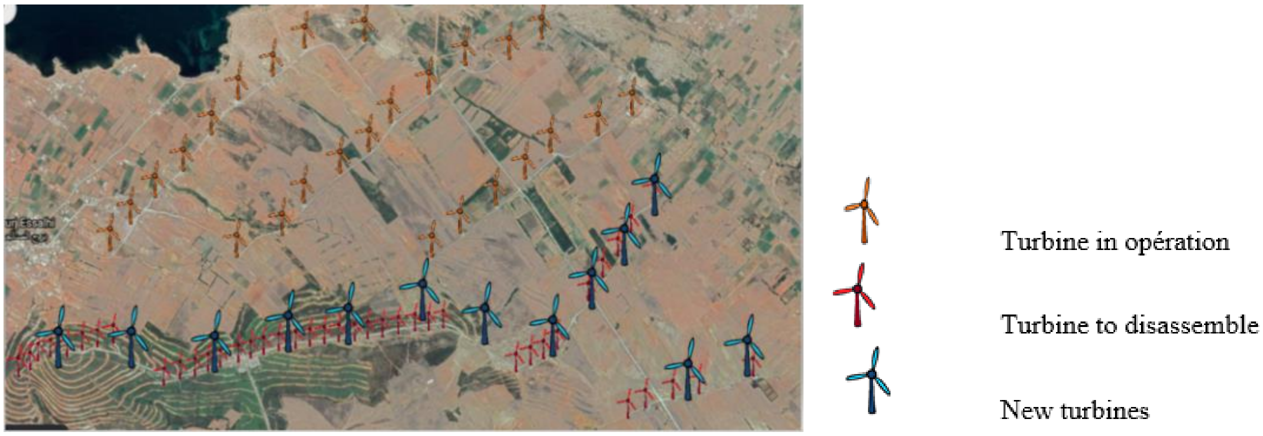

Figure 6. The position of the new turbines

Simulation by SAM software

Introduction

System Advisor Model, is a software that was developed by the National Renewable Energies Laboratory in collaboration with Sandia National Laboratories in 2005 (Gilman, P., et al,2011). SAM enables the modeling of economic and technical performance, it has been designed to facilitate decision-making for those involved in the renewable energy industry, ranging from project managers and engineers, to program designers. initiation, technology developers, and researchers.

Simulation techniques

In our case, we are interested in the technical model of wind turbines.

Wind source

In order to simulate a wind farm, the SAM software needs certain geographic data such as local roughness and weather conditions. Ideally, these data should be meticulously measured at the farm site , However, in feasibility studies, such data, measured on site, are difficult to obtain. To circumvent this problem, SAM allows the user to define the wind resource using the parameter of the wind distribution in Weibull.

Shear coefficient

The shear coefficient: is a measure of the variation in wind speed with height above the ground at the installation site of the turbine. The default value of 0.14 is a common assumption for the value of onshore wind resource studies, and the value 0.11 may be appropriate above water for offshore wind farms (Stival, et al. 2021).

Table 5. Data to be entered into SAM (source: STEG)

	Average wind speed V (m/s)	Shape parameter of Weibull (K)
N149-4.5 MW hight= 105 m	7,86	1,71
SG145-4.5 MW hight= 107.5 m	7,9	1,71
V136-4.2 MW hight 105 m	7,86	1,71

Turbulence intensity

The turbulence intensity is the standard deviation of the wind speed at a short time step divided by the average wind speed (Tai, S et al.2023). For smooth terrain like a flat plain with little vegetation and a low turbulence coefficient, a typical value might be 0.1 (or less over water for offshore wind farms). For a forest or an area with air mixing caused by thermal effects with a high turbulence coefficient, a typical value might be 0.5.

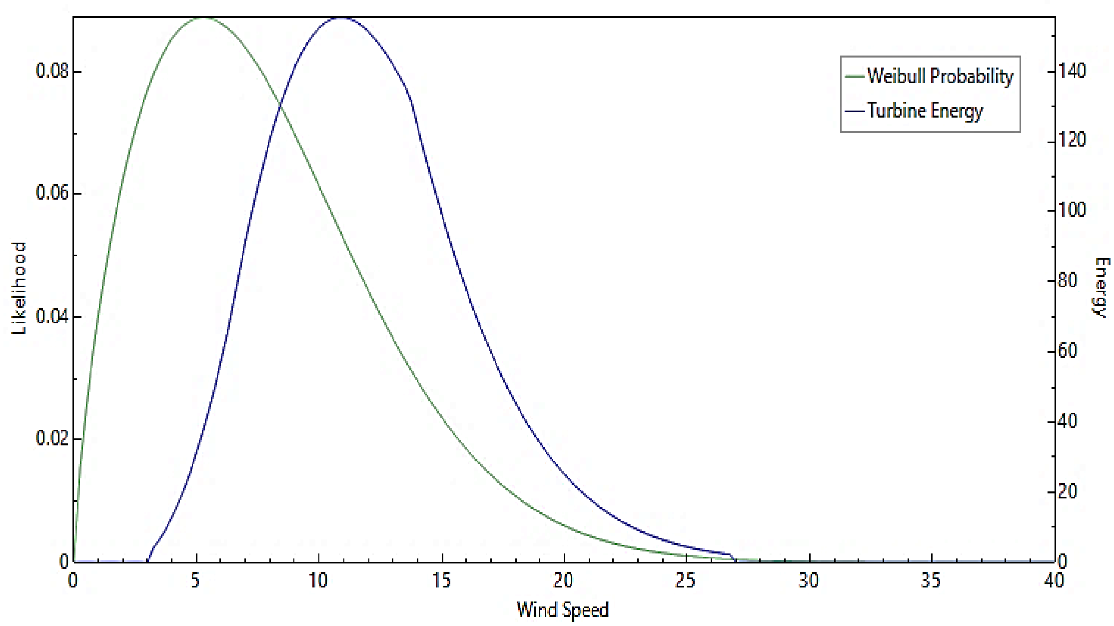

Figure 7. The Weibull distribution in SAM

Wind farm

SAM's Wind Power model can model a single wind turbine or a wind farm with more than one turbine.
In order to correctly position the wind turbines, SAM admits an algorithm which analyzes the map of the wind resources of the land and optimizes the positioning of the turbines from the data collected.

Table 6. The coordinates of the turbines (source: STEG)

Wind turbine	X(m)	Y(m)
B01	670327	4100047
B02	670755	4100080
B03	671226	4100047
B04	671678	4100187
B05	672074	4100242
B06	672461	4100339
B07	672882	4100214
B08	673278	4100186
B09	673493	4100456
B10	673695	4100731
B11	673845	4101016
B12	674483	4100101
B13	674076	4099946

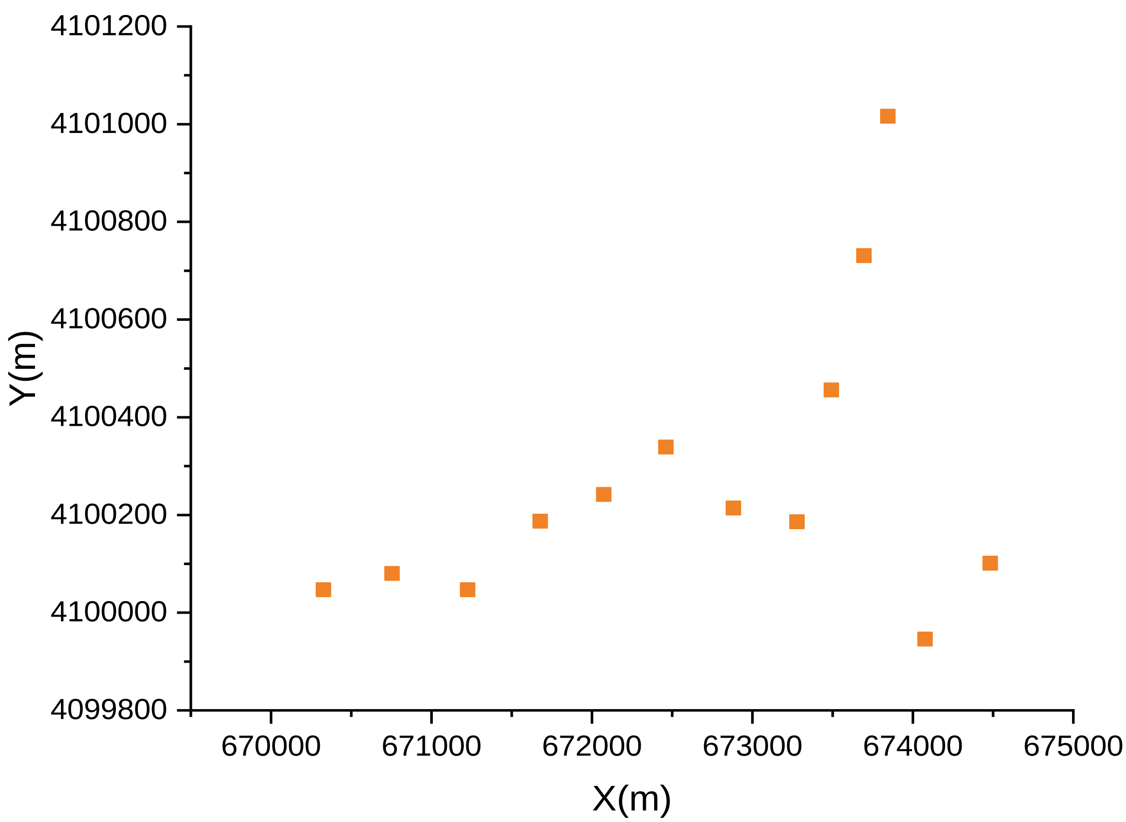

Figure 8. The position of the turbines on SAM

Production losses

The net electricity production is obtained by deducting the systematic production losses from the gross production (Musaev, et al. 2023)).

These losses are either calculated or estimated based on certain assumptions:

- Wake effect between wind turbines: Energy losses related to the decrease in the kinetic energy of the wind downstream of the wind turbine, i.e. 1.1%.
- Electrical losses: Losses related to the wind turbine transformer and transmission losses to the customer's head cabin. These losses have been estimated: transformer losses (~1%) + cable losses (~1%).
- Losses related to the formation of ice: Losses of production due to a decrease in performance and shutdowns of the wind turbine due to the accumulation of ice on the blades of the wind turbine. No losses were taken into account in our study.
- Hysteresis in strong winds: Losses of production during shutdown and restart cycles of the wind turbine caused by wind speeds close to the shutdown speed of the wind turbine. According to the calculated velocity distribution, these losses can be neglected.
- The other losses are taken by default.

The sum of the losses is 16.53% distributed as the graph in the following figure:

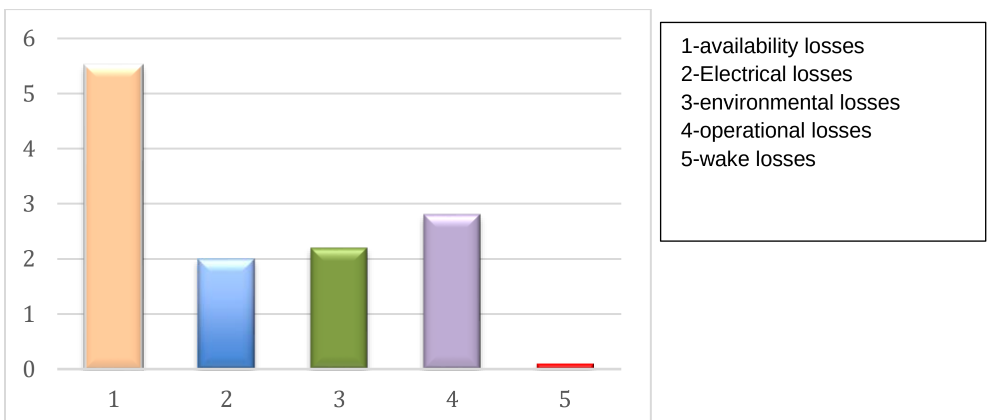

Figure 9. Losses graph (in %)

Simulation

The table presents the results of the annual energy production, the capacity factor and the P90.

The P90 value corresponds to the annual production level which should be exceeded with a probability of 90%

Table 7. The results of the technical simulation

	Annual Energy (GWh)	P90 (GWh)	Capacity Factor CF
Scénario 1	204,546	174,509	39,9%
Scénario 2	210,1	179,248	41%
Scénario 3	189,392	167,581	39,6%

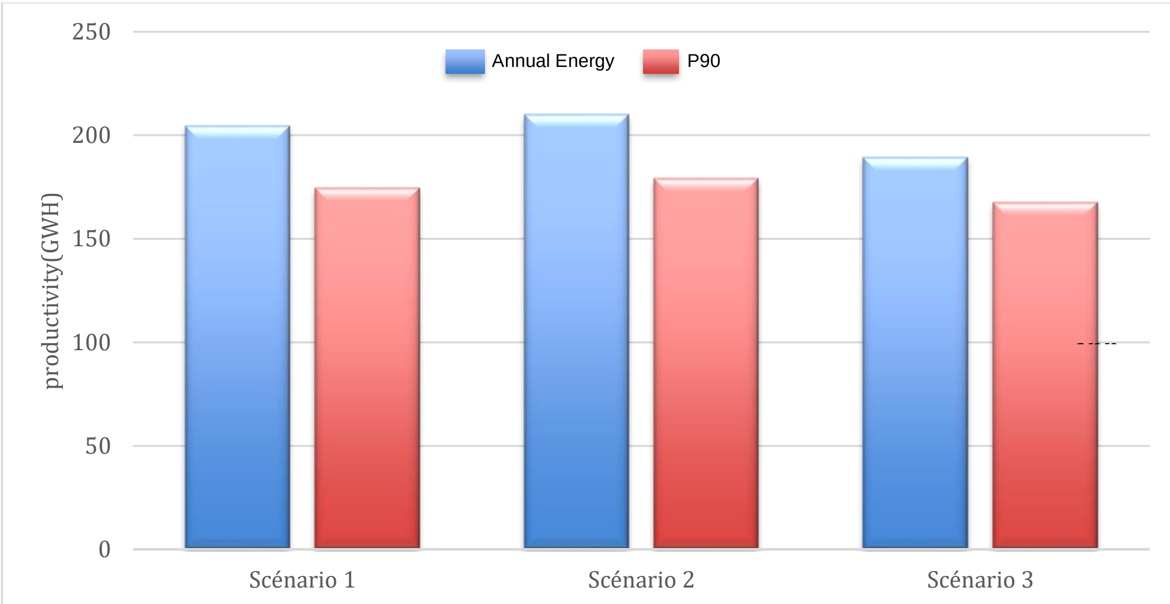

Figure 10. Difference in productivity between scenarios

The table also provides some key findings:

- The increase in the installed power of all the scenarios compared to the old one (45GWh).
- The higher the nominal power of the turbine, the higher the annual energy produced.
- The 4500 kW high-rise turbine has the highest capacity factor;
- Furthermore, it is important to note that all the capacity factors found are very high.

The next step in the methodology is to calculate the financial viability of these scenarios by taking as input the energy produced in each case.

Simulation results

The Repowering of the park with the 2nd scenario gives a better technical result. This performance is confirmed by the results of the installed power (4.5MW) which produces more energy, and which has a factor of higher capacity.

Table 8. Simulation results

	H (m)	P (MW)	AEP(GWh)	CF(%)
Scénario1	105	4.5	204.546	39.9
Scénario2	107	4.5	210.1	41
Scénario3	105	4.2	189.392	39.6

Conclusion

The increased hub height allows the rotor to catch winds at higher speeds. The diameter of the rotor is the parameter responsible for the area swept by the turbines, and therefore the larger the diameter, the greater the area swept, and the more power could be extracted from the wind. Knowing that the diameter of the wind turbines of the first scenario is 149m (corresponds to S=17437m²), 145m (S=16513m²) in the second, and 136m (S=14527

m²) for the third scenario. Wind speed is a factor that is high (7.9m/s) for the second configuration and therefore it allows power generation to occur at higher heights, which has a significant influence on AEP.
According to the results of the numerical simulation of the park, it can be noticed that there is an increase in the AEP for the wind turbine of scenarios 1 and 2.

Declaration

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Consent for publication: N/A

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Authors contribution: Sole author

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