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WIND FARM DESIGN APPROACH: FEASIBILITY AND OPTIMIZATION STUDY - CASE OF THE DAKHLA SITE IN MOROCCO

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ABSTRACT

Centuries ago wind energy was used for the work of mills, in the 12th century it underwent a transformation into a wheel straightened in the vertical plane, which boosted its power, years later, in the 19th century, wind energy was used to produce electrical energy in areas not connected to the electrical grid. This study, aims to evaluate the potential and the production of Dakhla wind farm in Morocco, in this paper, we present in detail the wind potential of the site (wind speeds, dominant direction ...) and the energy production of each configuration and the corresponding wake effect according to the different parameters, This paper proposes a parametric study for dimensioning wind farms, and propose an effective process to choose the adequate wind turbine technology for the wind farm, by comparing deferent wind turbines technologies with deferent unit power, according to deferent scenarios “cases”. A technical study has been conducted as well as an economic study, in order to define the suitable wind turbine technology for the Dakhla wind farm.

1. Introduction

The rise in fuel prices and their scarcity following the oil shock as well as the depletion of fossil resources; due to the demand pressure created by rapid industrial growth; and their environmental damage, which accelerates the degradation of the ecosystem, have pushed states to resort to renewable energies, and for the purpose of diversifying energy resources to wind energy [1]. Radical use of national energy resources; the case of wind energy that is available in several regions; has helped to meet a portion of electricity consumption while reducing imports [2]. The interest in this energy has come as a result of the introduction of tax incentives and state incentives, and adequate regulation for the development of this sector has been put in place[3], which has encouraged and attract foreign investors who are interested in developing wind farms projects [4]. Many researchers treated the Wind turbine blades (WTB) from a point of view

structure, these WTB are designed the way to recuperate the kinetic energy from wind [5]. Other researcher treated the subject of loads in which the WTB are subjected to the aerodynamic, centrifugal and gravity loads[5] as well as from a point of view fatigue stresses, durability and stiffness and the main role of composite materials in the development of the WTB [6]. Other researcher treated composites materials within the framework of their mechanical properties. Furthermore, studied the response of wind turbine under impact, and the effect of spars structure[6]. Moreover, others tested the stiffness of the wind turbine blade under extreme climatic conditions, and had identify the sensitive zones on the blade. Other researchers treated the subject of wind turbine from a point of view vibration by carrying bounding tests [7]. Another studies, show the relationship between damage on polymer material and the generated heat [9].

The main objective of this study is to develop an effective process for the dimensioning wind farms and optimizing the production of wind turbine, as well as reducing wake effect, therefore, rise the efficiency of the wind farm. This paper proposes a parametric study for dimensioning wind farms, and propose an effective process to choose the adequate wind turbine technology for the wind farm, by comparing deferent wind turbines technologies with deferent unit power, according to deferent scenarios “cases”. A technical study has been conducted as well as an economic study, in order to define the suitable wind turbine technology for the Dakhla wind farm.

2. Background of Wind turbine Energy

2.1. Global Wind resources

According to a study carried out by the World Meteorological Organization (WMO), it has been estimated that 27% of the Earth's surface is exposed to wind speeds above 5.1m/s at a height of 10m [10]. In order to take advantage of this potential, the International Renewable Energy Agency (IRENA) has been launched in 2013 the first World Atlas for solar energy and wind energy [11][12][13]. This new Atlas, carried out through the collection of data from research institutes, aims to evaluate the resources of renewable energies around the world [14]. Recently, researchers have been able to create an interactive map of the wind currents of the planet using digital data from several meteorological organizations. Updated every three hours, and accessible to all, "Earth Wind Map" shows the position and movement of winds in the world with accuracy. The configuration of the wind power distribution on different continents shows that the windiest currents are found in northern Europe, northeastern North America, southern South America, southeastern Asia, to the South Pole, and MENA [15].

2.2. World statistics of Wind energy

The availability of the wind energy and the research carried out for its evaluation in different continents of the globe, in addition to regulations to promote wind energy, have allowed several developers to invest in wind farm projects. Globally, one can then present the evolution of the installation of wind turbines in the globe in a graph: Worldwide installed capacity has evolved successively to reach 486 GW in 2016, which is 20 times that installed in 2001, covering a significant amount of energy needs, which has the consequence of decreasing the use of fossil fuels and therefore less resignation of greenhouse gas, favorable for the climate, for the human being as for the investors [16]. The wind energy sector in Europe is ranked first with a large production capacity enabling it to supply 10.4% of the electricity production of the European Union, while the sector of wind energy in Africa is ranked last, except that in relation to developing countries, the integration of renewable energies generally and wind energy specifically contributes to increasing the share of electricity produced from domestic renewable sources, and allows thus improving energy security, access to electricity, the soundness of national fiscal prospects and the transition to a more sustainable energy sector [17].

3. Description of the problem

Morocco's energy bill is a heavy burden on the balance of trade, since the exploitable conventional energy resources are limited, and depend by 95% of its energy supply on energy importation (external). this situation pushed the public authorities to implement an energy strategy based on securing supply through the diversification of energy sources, particularly for the production of electricity [18][19][20]. As part of this energy strategy, Morocco is engaged in a vast wind program, to support the development of renewable energies and energy efficiency which aims to ensure a rational use of energy in the interest of reducing the energy bill, in addition to energy supply with the adoption of an approach based mainly on sustainable development. The integrated Moroccan wind energy project, spread over a period of 10 years, will allow the country to bring the installed electrical power, from wind, from 282 MW in 2010 to 2258 MW, commissioning of these parks is planned by 2020.

3.1. Farm location

Figure 1 show the site of Dakhla for which this study is made, has a flat, desert, low roughness terrain “0.16”, unoccupied and easily accessible, which will expand the Moroccan electricity grid. The mast installed in the wind farm, records the average wind speeds every 10 minutes, on three heights of 20m, 40m and 60m, in addition to two weathervanes located at heights of 38m and 58m, at a height of 55m. a thermometer and lower at a height of 10m a barometer and a hygrometer.

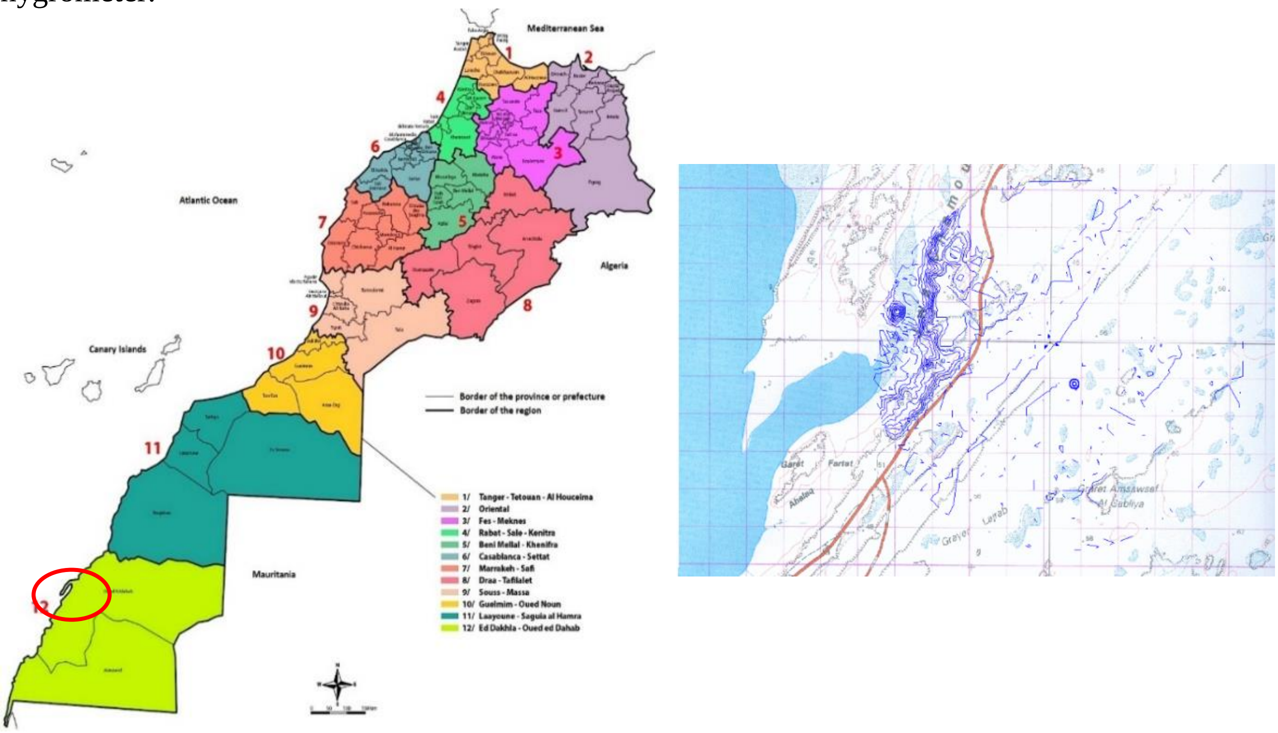


Figure 1. Morocco map and satellite picture of the area planned for the wind farm

3.2. Farm characteristics

3.2.1 Average speeds, monthly and annually

The wind speed data collected by the mast is the basis for calculating average daily, monthly and annually speeds at the three levels of 20m, 40m and 60m and the average speed at the hub of a wind turbine considered 78m. These speeds are represented in Table 1. The data in Table 1 are given by The National Office of Electricity and Potable Water (ONEE) Morocco [21].

Date \ Height	**20m**	**40m**	**60m**	**78m**
January	6,86	7,76	8,44	8.80
February	5,88	6,58	7,04	7.35
March	6,42	6,96	7,43	7.74
April	9,11	9,58	10,23	10.67
May	9,19	9,64	10,26	10.70
June	8,06	8,58	9,02	9.40
July	8,56	9,32	9,92	10.35
August	9,61	10,27	10,87	11.34
September	8,03	8,79	9,31	9.71
October	6,61	7,39	7,78	8.11
November	6,48	7,47	8,16	8.51
December	6,66	7,50	8,16	8.44
Annual speed	7.63	8.33	8.89	9.28

Table 1: Spatio-temporal variation of monthly and annually average speeds 21

3.2.2. Wind direction

Represented by the Wind Rose; a polar diagram which allows to know the relative times expressed in percentage during which the wind has blown in a determined direction. From the measurement data of the direction and wind speed of the chosen site, one obtains the following WR, Figure 2. Thereby, it turns out that the dominant direction is NNE-NE, it is quite obvious to orient the wind turbines perpendicularly to this direction.

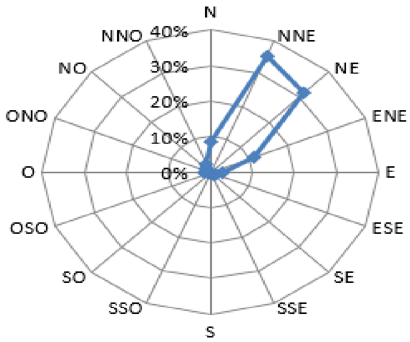


Figure 2. Wind rose for the wind farm.

3.2.3. Weibull Distribution

Figure 3, represents the percentage of time when the speed is recorded in the year, which allows to know the most frequent speed classes.

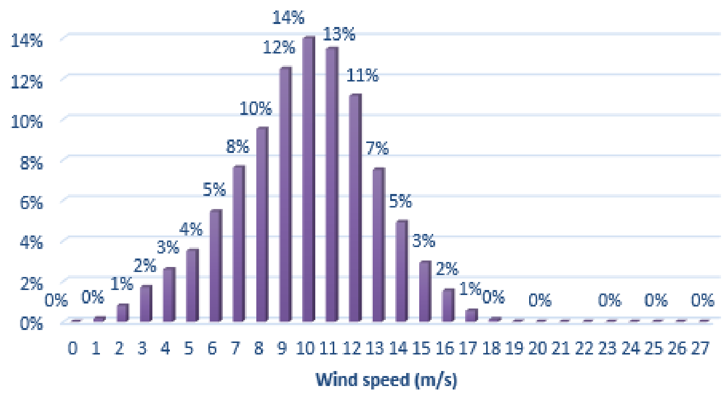


Figure 3. Frequency distribution of the wind at 78m

For this site the average speed that appears most over a whole year are in three classes between 9m/s and 11m/s with an appearance percentage of 39%, of which the highest percentage of 14% is

for 10m/s. The probability density for a wind speed shown in Figure 3, and can be calculated using the following expression.

$$\mathbf{P(v)} = \left(\frac{\mathbf{K}}{\mathbf{A}}\right).\left(\frac{\mathbf{V}}{\mathbf{A}}\right)^{\mathbf{K-1}}.\mathbf{e}^{\left(\frac{v}{A}\right)^{\mathbf{k}}} \text{ Where: } \mathbf{K \geq 1 \quad ; \quad V \geq 1, \text{ and } A \geq 1} \qquad (1)$$

3.3. Configuration used

For this study, one chose three models of wind turbines with three delivered powers completely different to show that a wind turbine with a large power is not always the right choice for all wind farms. Figure 4 shows the three configurations that will be the subject of this study:

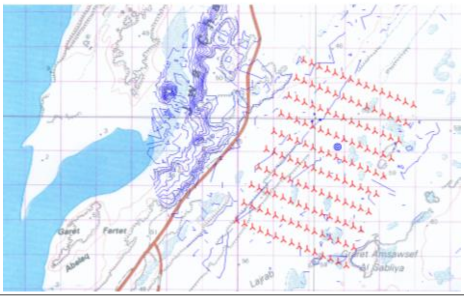
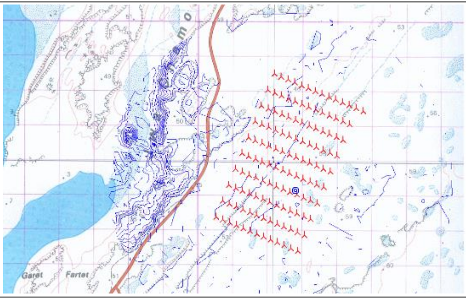
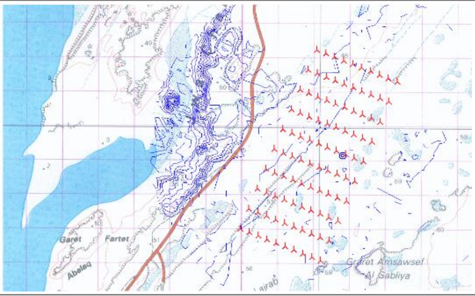
G80-2MW 15*10		For this configuration we opt for Gamesa wind turbine, G80-2MW, with a Hub diameter of 80m and a nominal power of 2 MW.
E71-2,3 MW (13*10) +1		For this configuration we opt for ENERCON wind turbine, E71-2.3MW. The Hub diameter is 71m, and the nominal power 2.3MW.
V90-3MW 10*10		For this configuration we opt for VESTAS wind turbine, V90-3MW with a nominal power of 3 MW, and a Hub diameter of 90m.

Figure 4. Wind turbines distribution for a 300 MW plant

3.4. Cases of the Technical Study

The study is done for each of the three wind turbines cited above, in the same wind farm, so the same conditions, the spacing of installed wind turbines is seven times the diameter of the rotor in the direction of the prevailing winds, and three times the diameter perpendicular to the direction of prevailing winds. The studied cases are the following:

a. One fix the maximum power of 300 MW then calculate the corresponding needed area for each according to the rule 3D*7D configuration as well as the resultant energy.
b. One uses the largest surface found in the first case and fix a maximum power installed of 300 MW, and distribute the wind turbine of each configuration in the area and keeping the same distance between two wind turbine in the same row, as well as the same distance for every two successive rows. Then find the resultant energy of each configuration.
c. One uses the largest surface found in the first study by the rule 3D*7D and conclude the maximum number of wind turbines for each configuration, with the respect of 3D*7D rules. Then, calculate the resultant energy.

3.5. Economic study

The overall cost of the wind kWh provided to the grid by a fleet of wind turbines takes into account the initial capital expenditure and the annual updated operating and maintenance-maintenance expenses.

The discounting of expenditure refers to the fact that all project costs are taken into account over the fixed observation period, by discounting the expenditures and the value of the energy produced by the project in the future. As well as the initial investment is included.

The economic study will be based on the following assumptions:

- In the first place one will consider that the construction of the park will be done over a period of 2 years for which one will calculate the investment price, then consider that the lifespan of the park is 20 years so one will calculate the production during all this time as well as maintenance and operating costs, knowing that the price of KWh is computable by the following formula:

$$Cost\ of KWh = \frac{the\ total\ discounted\ investment}{net\ productible}$$

- Maintenance and operating expenses represent 3% of the investment amount and the inflation rate is 2%.
- And finally we consider that the cost of an aero-generator is 1300 US$ and the cost of m2 is worth 2US$.

4. Results and discussion

4.1. Technical study

The energy output of the fleet varies according to the power and the height of the hub of the wind turbine. For the same type of wind turbine, the higher the hub is, the more one gains in production, and the wake effect decreases.

Let us recall the aim of this study, which is to choose the set of wind turbines that will produce a maximum of energy with the minimum of wake effect in the conditions of the chosen wind farm. The comparison made for this purpose relates this study around the G80-2MW wind turbine at 100m, for its high production and a low wake effect, Table 2.

	G80-2MW		**E71-2,3 MW**		**V90-3MW**	
Diameter (m)	80		71		90	
3D/7D (m)(m)	240/560		231/497		270/630	
Installed power (MW)	300		301.3		300	
Area (ha)	1761.28		1290.5		1451.52	
Hub height (m)	78	100	99	113.5	80	105
Capacity factor	39.7%	43.7%	36.7%	38.8%	36.3%	40.6%
Efficiency	81.8%	83.6%	80.3%	81.1%	81.2%	83.3%
Energy according to the roughness (MWh)	1419399	1527435	1342138	1403976	1305773	1425631
Reduction due to wakes	18.2%	16.4%	19.7%	18.9%	18.8%	16.7%
Resulting energy (MWh)	1045201	1149818	970374	1024344	953676	106824

Table 2: Results of different configurations for the same installed power

However. One cannot decide at this stage, which one is the optimal choice. It is necessary to make a second study consisting of fixing the largest area corresponding to G80-2MW wind turbines, and to allocate the two other types of wind turbines on this surface in order to know if their productions will be better. Then one gets the following comparative table:

The distribution of wind turbines in the wind farm for a total installed power of 300 MW in the same area “largest area” generates the results summarized in Table 3. According to a comparison,

one finds that the G80-2MW wind turbine remains the best, its energy production and its capacity factor are the highest, one also note that an increase in area, generates an increase in production and a slight decrease in the wake effect rate, which is very visible in the case of the wind turbine E71-2.3MW.

	G80-2MW	E71-2.3MW	V90-3MW
Diameter "D" (m)	80	71	90
Area (ha)		1761,28	
Distance between rows (m)	560	561	559
Distance between wind turbines in the same row (m)	240	259	372
Installed power (MW)	300	301.3	300
Capacity factor	43.7%	40.7%	41%
Efficiency	83.6%	85%	84%
Energy according to the roughness (MWh)	1527 435	1403976.1	1425630.8
Reduction due to wakes	16.4%	15%	16%
Resulting energy (MWh)	1149817.9	1073936.5	1077320.9

Table 3: Results of configurations for the same area and the same installed power

The following study consists keeping the same area "the largest" for a distribution as already defined (7D*3D), and one will seek the power to install for each of the two wind turbines E71 and V90. Following this distribution, one obtains the results shown in Table 4.
For the same area, the E71-2.3MW wind turbine installed capacity is higher than that of V90-3MW, for this purpose the production increases with the increase in the number of wind turbines, if one wants to install a greater power of about 400 MW it would be favorable to opt for a wind turbine type E71-2.3MW.

	G80-2MW	E71-2.3MW-	V90-3MW
Diameter "D" (m)	80	71	90
Area (ha)		1761.28	
3D/7D (m)(m)	240/560	231/497	270/630
Number of wind turbines units	15*10	16*11	13*9
Installed power (MW)	300	404.8	351
Capacity factor	43.7%	38.40%	40.60%
Efficiency	83%	80.30%	83.30%
Energy according to the roughness (MWh)	1527435	886252.40	1425630.80
Reduction due to wakes	16.4%	19.7%	16.7%
Resulting energy (MWh)	1149817.9	1362840.84	1246443.84

Table 4: Results of configurations for the same area and different installed powers

The evaluation of the wind potential and the data analysis of the wind farm using the WindPro calculation and modeling software allowed to choose the best wind turbines (in terms of height, rotor diameter, power, etc.) as well as their location in the field to maximize the wind potential of the park and to estimate its future production, to complete this study it is necessary to make an economic analysis of the project to estimate the amount of investment and the cost KWh for each case.

4.2. Economic study

The calculation of the cost of the KWh, investment cost, net producible and the cost of maintenance is carried out by an Excel spreadsheet and provides the following results:

1st case: For an installed power of 300 MW, as already deduced above for this power wind turbine G80-2MW-100m, seems the most efficient in the conditions of the site, its production rate is high compared to the other two, therefore the cost of KWh product is the lowest. Table 5.

	G80-2MW	E71-2.3MW	V90-3MW
Installed power (MW)	300	301.3	300
Net production (GWh)	9463.42	8439	8792
Amount of investment (M US$)	496.05	497.12	495.38
Average cost discounted (US$/KWh)	0.05241	0.05851	0.05635

Table 5: The result of the economic study for an installed power 300 MW

2nd case: For a power of 300 MW we distribute V90 and E71 wind turbines in the same area "the largest", then run the simulation to have the production results. In addition, simulation results are used to generate the content of Table 6.

The increase in area as already explained affects the producible, because it also increases, this increase makes the price of KWh decreases, although the cost of KWh for E71 and V90 has decreased but it remains high compared to that of GAMESA, as for the first case it is recommended to install wind turbines G80-2MW for a power of 300 MW.

	G80-2MW	E71-2.3MW	V90-3MW
Installed power (MW)	300	301.3	300
Net production (GWh)	9463.42	8852	8879
Amount of investment (M US$)	495.99	498.16	495.96
Average cost discounted (US$/KWh)	0.05241	0.05627	0.05586

Table 6: Result of the economic study for the same area size and an installed power 300 MW

3rd case: At this level, as already explained, one increases the installed power for each type of wind turbine according to the unit power and the fixed area, then one launch the simulations in WindPro to get the results, these results are exploited for the calculation of the cost of KWh and get the Table 7. The increase in the installed capacity implies an increase of the producible and the amount of investment, consequently the price of the KWh increases also, it is to note that the cost of the KWh the cheapest is that of G80, except that the price of the E71 KWh is acceptable and provided its high output it is optimal for a total power of 404 MW.

	G80-2MW	E71-2.3MW	V90-3MW
Installed power (MW)	300	404.8	351
Net production (GWh)	9463.42	11 221	10 261
Amount of investment (M US$)	496.024	668.023	579.74
Average cost discounted (US$/KWh)	0.05241	0.05953	0.05649

Table 7: The result of the economic study for the same area size and different installed powers

4.3. Technical and economic study

To sum up, all the results obtained, one can say that for a power of 300 MW, one can opt for the wind turbine type G80-2MW, it is technically and economically efficient, while if one wants to install a higher power of 400 MW, one can consider installing wind turbines type E71-2.3MW. Table 8.

	G80-2MW	E71-2.3MW
Net production (GWh)	946342	11221
Installed power (MW)	300	404.8
Area (ha)	1761.28	1761.28
7D/3D (m)/(m)	240/560	231/497
Average cost discounted (US$/KWh)	0.05241	0.05953
Investmentpayback (Years)	2	3

Table 8: The result of the technical and economic study

To complete this study and in order to improve the overall efficiency of the wind farm, it is necessary to reduce the wake effect in these two cases and for this purpose, we are interested in the optimization of the location of the wind turbines.

4.4. Modeling and optimization of wind farm production

The aim is to increase the distances between the wind turbines as much as possible according to the diameter of the rotor so that the turbulence caused by each of the wind turbines are minimized to the maximum, the parameters and simulation results are giving in "Table 9"

After optimization, which necessitated an increase in the area of the land used by doubling it, one notices that there is an increase in the production, the capacity factor and the efficiency in addition to a decrease in the wake effect.

The optimization is done on several levels, firstly one chose the higher hub, provided that their production is better, and the wake effect is less, then in order to maximize the production of Energy Park one has sufficiently spaced the wind turbines in the field. It remains to know that it is not at all true in the case of a wind farm; that the increase of the power of the wind turbines is accompanied by an increase of the production.

The power of the wind turbine is not sufficient as it is explained above to choose, the choice depends on the conditions of the zone of implantation, and any wind turbine has its own properties and performs well under certain conditions.

	G80-2MW		**E71-2.3MW**	
Diameter (m)	80		71	
Optimization	Before	After	Before	After
3D (m)	240	320	231	299
7D (m)	560	800	497	710
Installed Power (MW)	300		404.8	
Area (ha)	1761.28	3319.68	1761.28	3319.68
Capacity factor	43.7%	47.2%	38.8%	42.4%
Efficiency	83.6%	90.3%	81.1%	88.6%
Energy according to the roughness (MWh)	1527435	1527 435	1403976.1	1886252.4
Reduction due to wakes	16.4%	9.7%	18.9%	11.4%
Resulting energy (MWh)	1149817.8	1379573	1024343.3	1671785

Table 9: The result of the technical study after the optimization

4.5. Economic study after optimization

Table 10shows an increase in the net production. Which is obvious because of the increase in the area, and also an increase in the amount of the investment, on the other hand, the price per kilowatt-hour decreases, which is a plus. For the investor.

	G80-2MW		**E71-2.3MW**	
Installed power (WM)	300		404.8	
Optimization	Before	After	Before	After
Net production (GWh)	9463.42	10 221	11 221	12 389
Amount of investment (M US$)	498.402	500.00	671.218	672.898
Average cost discounted (US$/KWh)	0.05266	0.04892	0.05982	0.05431

Table 10: The result of the economic study after the optimization

For any project, it is necessary to check two important factors: the feasibility and the profitability of the project. According to this study, the chosen site is windy; its average wind speed reaches 8.9m/s at a height of 60m. A deserted site with interesting properties making it a future wind farm. Figure 5 show the approach followed to design and optimize the Dakhla wind farm.

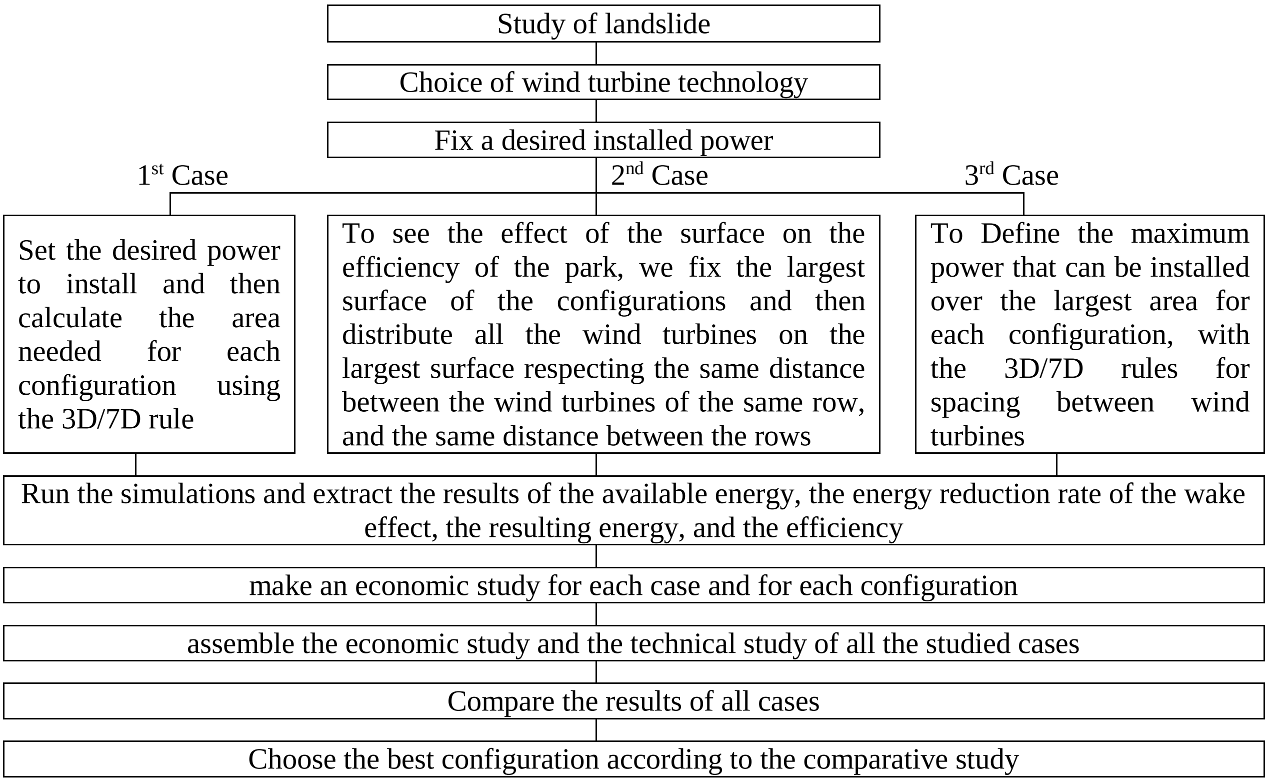


Figure 5. Methodology of designing wind farms charts flow

Conclusion

Morocco has invaluable wind power and other energy wealth, the good exploitation of these resources will guide it to the right path, it will limit the exports of oil and coal and will increase the efficient use of natural gas and wind energy. Although investment in this area is a heavy burden, its impact is more relevant in the short and long-term to ensure sustainable development. At both global and national levels, wind energy has grown, and global installed capacity is increasing every year as long as most electricity needs can be met by wind generation. This study shows the energy production of three types of wind turbines within the Dakhla site, the wake effect produced, and an estimate of the amount of investment in which the cost of the wind turbines was used, the cost of the installation. And the cost of maintenance, however, the amount should also include the price of the transport and injection to the network (which includes transformers and the construction of an electrical network in this region), so that the choice of the type of wind turbine returns to the farm owner.

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