Techno-economical optimization of wind energy potential and implementation of an electrical energy system equivalent to a 60 MW production plant in the Laghouat region

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Abstract: This work is a contribution to the techno-economic study of the feasibility of setting up the wind power plant with a capacity of 60 MW for electricity production in the Laghouat region. The wind power plant is equipped with a hydrogen storage system to ensure continuity of service and the autonomy of consumption during the night of the existing photovoltaic power plant in the study area. This current study focuses on the site of EL kheneg corridor Elhouita, from daily data of wind speed-readings taken every 10 minutes and at an altitude of 10 meters, between 2012 and 2014, obtained by the auxiliary metrological station of Laghouat, located in the same studied corridor. It appears that the wind on this site is regular and is spreading in a South-West (SW) direction, with stable average seasonal speeds between 5.71 m/s in autumn, and 7.44 m/s in summer. Using statistical laws for the temporal characterization of wind parameters and extrapolation laws for the spatial characterization of wind speed to express the statistical estimate of the wind energy potential at different altitudes. Then, the wind direction is established for the orientation of the turbo-generators in the implementation phase. After, the prediction of the electrical energy produced is evaluated while taking into account the choice of wind turbines and their load factors. Finally, the economic study to estimate the unit cost of wind energy in ($/kW) and the cost of hydrogen production in ($/kg).

Keywords: Wind Turbine, Wind Energy Production, Weibull Distribution, Wind Energy Potential, Wind Speed Analysis, Electrical Energy System.

1. Introduction

Since 2011, Algeria has launched a program for the exploitation of renewable energies, where the wind energy constitutes the second axis of development within a production, which will reach 5 GW in 2030 (CREG, 2015). Given, the region of Laghouat is underestimated as a potential wind region in the Algerian wind mapping carried out in 2004, (Kasbadj & Merzouk, 2000) and the planning of the Algerian power grids did not plan the implementation of the wind power plants in the region until nowadays. Several studies (Chellali et al., 2011) gave a new truth about the wind mapping in this region, based on the study of the HASSI R'MEL site. This is a windy site, where the speed reaches an average of 6.1m/s, in comparison with other sites in the region, that are always underestimated, hence the region beeing characterized by a wind speed which varies from 4.1 m/s to 4.9 m/s. This work focuses on the finding of the windy corridors in the studied region, since ecological indicators show signs of the presence of an enormous wind potential in a few sites in the targeted region. Several studies of the wind field of a number of sites surrounding the city of Laghouat give an annual average wind speed, as follows: the southern region (Bouchiba, 2021) <V> = 6.12m/s, the western region <V> = 4.46m/s (Bouchiba et al., 2021), the southeast region (Bouchiba et al., 2021) <V> = 3.85m/s, and the southwest region <V> = 6.50m/s. The focus of this research is the southwest area of Laghouat, which is the zone of EL- KHNEG. To know better the velocity division density function in this place, it is essential to evaluate the wind density from the meteorological measurements, acquired with the help of the auxiliary metrological station of Laghouat (Bouchiba et al., 2020). The results obtained confirm the feasibility of this work, this region having an enormous wind potential of 691W/m², which is very high compared to that estimated at Adrar of 281W/m² (Diaf & Notton, 2013). The unit cost of production of one kg of hydrogen is 0.87$/kg. It should be noted that work has been underway in this region since 2016 to develop a photovoltaic power plant with a capacity of 60 MW.

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2. Presentation of the study area

The El KHNEG site is located in the 13 km southwest part of the city of Laghouat at an altitude of 750 m above the sea level (Figure 1). Table 1 shows the geographic coordinates of the site.

Table 1. Geographic coordinates of the El KHNEG site (Google Maps 2022)

Geographic data	
Latitude	33.75°
Longitude	2.82°
Altitude	750m

Figure 1. Site studies, the region of Elkheneg (Google Maps 2022)

3. Mathematical formulation

The frequency analysis of the wind speed highlights the predominant speed classes (Lima et al., 2010). Therefore, the task of choosing the wind turbines that provide the best performance and the economic analysis of the power plant is easier.

3.1. Spatio-temporal characterization of the wind speeds

The spatio-temporal characterization of the wind speed is necessary for the estimation of the energy production of a normalized wind turbine (Rosen et al., 1999).

3.1.1. Modified Weibull distribution

On sites, where the frequency of calm wind speeds is relatively high, the modified Weibull law is used (Boudia, 2013). Modified Weibull's law as written in Eq. (1). (Bivona et al., 2003).

$$f(V)\left\{\begin{matrix} ff_0 & if\ V=0 \\ (1-ff_0)\times\left(\frac{k}{C}\right)\left(\frac{V}{C}\right)^{k-1}\times\exp\left(-\left(\frac{V}{C}\right)^{k}\right) & if\ V\neq 0 \end{matrix}\right\} \quad (1)$$

where: $f(v)$ is the frequency of occurrence of the wind speed; k and C are the Weibull factors respectively a shape parameter and a scale parameter, $ff0$ is the percentage of zero wind speed (Azagnandji et al., 2021). The two Weibull factors are used to determine the characteristic velocities of the site (Junyi et al., 2020). Note that the speeds to be calculated are:

- **The average wind speed**

  If the calm ff_0 is less than or equal to 15%;

$$\langle V\rangle = C.\Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

If the calm ff_0 is better than 15%;

$$\langle V\rangle = \left(1-ff_0\right)C.\Gamma\left(1+\frac{1}{k}\right) \tag{3}$$

- **The wind speed carrying the maximum amount of energy**

$$\langle V\rangle = C.\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{4}$$

3.1.2. Vertical extrapolation of Weibull parameters

The evaluation of the Weibull factors k_2 and C_2 at the level of the wind turbine allows the appreciation of the wind potential at the level of the propeller (Diaf & Notton, 2013).

$$k_2 = \frac{k_1\left[1-0.0081\ln\left(\frac{Z_1}{10}\right)\right]}{1-0.0081\ln\left(\frac{Z_2}{10}\right)} \tag{5}$$

$$C_2 = C_1\left(\frac{Z_2}{Z_1}\right)^n \tag{6}$$

$$n = \left[\frac{0.37-0.08881\ln\left(C_1\right)}{1-0.0881\ln\left(\frac{Z_1}{10}\right)}\right] \tag{7}$$

where, Z_1 is the reference altitude in [m], Z_2 is a wind turbine height in [m].

3.2. Wind potential

3.2.1. Available power density

The available wind power density (WPD) is a helpful method to appreciate wind power in a site without considering a particular wind turbine (Amed et al., 2008). It is measured by watts over square meters, defined by Eq. (8) (Benmedjahed et al., 2014).

$$\frac{P_{dis}}{A} = \frac{1}{2}\rho.C^3.\Gamma\left(1+\frac{3}{k}\right) \tag{8}$$

where ρ is the density of the air.

3.2.2. Wind power plant

The wind power plant is a very important parameter (Boudia at al., 2019); it makes it possible to quantify the energy produced during a time T by the wind turbines or the wind farm. Eq. (9) (Azagnandji et al., 2021).

$$E_{out} = N_{wt}.P_{out}.T \tag{9}$$

$$P_{out} = P_R \left\{ A - \exp\left(-\left(\frac{V_f}{C_2} \right)^{k_2} \right) \right\} \tag{10}$$

$$A = \frac{\exp\left(-\left(\frac{V_C}{C_2} \right)^{k_2} \right) - \exp\left(-\left(\frac{V_R}{C_2} \right)^{k_2} \right)}{\left(\frac{V_R}{C_2} \right)^{k_2} - \left(\frac{V_C}{C_2} \right)^{k_2}} \tag{11}$$

where P_{out} is the wind turbine output energy, and P_R is the rated power, V_R is the rated wind speed, V_C is the cut-in wind speed, V_f is the cut-out wind speed of the wind turbine, and N_{wt} is *a* number of wind turbines.

3.2.3. Capacity factor C_F

The C_F is a mechanism that authorizes the assessment of the productivity of a WT or any other energy production facility (Al-Ghriybah et al., 2019). It can be calculated by Eq. (12) and is expressed in percentages.

$$C_F = \frac{E_{out}}{E_R} = \frac{P_{out}}{P_R} \tag{12}$$

$$E_h = 8760.C_F \tag{13}$$

3.2.4. Hydrogen production system

The objective of this step is to estimate the quantity and the unit cost of hydrogen that can be produced from the wind energy of the power plant.

- **hydrogen mass**

The amount of energy produced from wind power can be converted into mass of hydrogen using an electrolyzer, as follows (Douak & Settou, 2015):

$$M_{H_2} = \frac{\eta_{ele}.E_{out}}{LHV_{H_2}} \tag{14}$$

where: M_{H2} (kg/ year) is the amount of hydrogen mass, η_{ele} is the yield of the electrolyser, and LHV_{H2} is a low heat value of hydrogen (33.3 kWh/kg) (Douak & Settou, 2015).

3.3. Economic Analysis

3.3.1. Unit cost of energy

The economic viability of wind projects depends on their ability to generate electricity at a low cost per operating unit of energy, and it is necessary to make an accurate estimation of all costs involved in generating electricity over the lifetime of the system. Different methods are generally used to estimate operating cost of one unit of energy produced by the wind conversion system.

- **Cost of a wind turbine**

The turbine cost (*Cwt*) is given as follow (Gökçek & Genç, 2010):

$$C_{wt} = C_{spe} \times P_R \tag{15}$$

where: C_{spe} is a turbine's specific cost.

Table 2 gives C_{spe} for several size ranges related on *Pr*.

Table 2. Range of specific cost of wind turbines based on the rated power [9].

Wind turbine size P (kW)	Specific cost ($/kW)	Average value ($/kW)
< 20	2200 - 3000	2600
20 - 200	1250 - 2300	1775
200 >	700 - 1600	1150

- **Present value of costs**

The present value of costs (*PVC*) of electricity includes both initial costs (IC) and operation, maintenance and repair cost ($C_{om\ (p)}$), is given as follows (Himri et al., 2020) by Eq. (16) and (Junyi et al., 2020) Eq. (17):

$$PVC = I_c + C_{om(p)} \tag{16}$$

$$C_{om(P)} = C_{om(r)} \left[\frac{(1+i)}{(d-i)} \right] \times \left[1 - \frac{(1+i)^t}{(1+d)} \right] \quad d \neq i \tag{17}$$

The I_C ($) introduces the turbine cost ($), civil work ($) and installation price ($). The civil works are supposed to be 30% of the turbine cost. The annual maintenance cost (C_{omr}) was assumed to be 15% of the annual price of the turbine price (Said, 2013).

- **Wind energy unit cost**

The unit cost energy (*UCE*) in ($/kWh) is expressed by (Meziane et al., 2021):

$$UCE = \frac{PVC}{AEP} \tag{18}$$

where AEP is the energy E_{out} produced during a time T=8760 hours.

3.3.2. Unit cost of hydrogen

The unit cost of hydrogen production in ($/kg) UCH_2 is expressed by:

$$UCH_2 = \frac{C_{ele} + C_{wt}}{M_{H_2} . T} \tag{19}$$

$$C_{ele} = C_{ele-u} \times \frac{M_{H_2} \times K_{ele-th}}{8760 \times \eta_{ele}} \tag{20}$$

where C_{ele} is the capital cost of operating and maintaining the electrolyser; C_{wt} is the cost of energy *($);* M_{H2} (kg/yr) is the annual hydrogen production; *T* is the lifetime of the project and is set at 20 years, K_{el-th} is the theoretical specific energy required for the electrolyser and C_{ele-u} is the unit cost of the electrolyser. For this case, (K_{el_th}) and (C_{elec_u}) were considered to be 39.7 kWh/kg H2, respectively 368 $/kW (Meziane et al., 2021).

3.4. Wind farm sizing

3.4.1. The wind rose

The compass rose is built to get an idea of the distribution of wind speeds and directions; it is built from meteorological observations made in a region over one or more years. When locating a wind site, the compass rose gives an idea of the direction of the prevailing winds (Bouchiba, 2021).

3.4.2. Installation conditions

In order to optimize the operation of wind farms, certain measures must be taken into account (Merzouk et al., 2012). Indeed, a wrong choice of certain parameters could be detrimental to a wind turbine installation (Elamouri et al., 2008). In order to avoid the phenomenon of crowding, the distance between wind turbines for the installation of wind turbines on a site must take into account the dimensions of the terrain perpendicular and parallel to the prevailing wind direction (GhriybahAl et al., 2019). The conditions to be met are as follows (Faida et al., 2010).

$$(N_1+1)\times 10H < I.N_{wt} \tag{21}$$

$$(N_2+1)\times 3D < \mathrm{L} \tag{22}$$

$$N_{wt} = N_1 \times N_2 \tag{23}$$

where, I represent the dimension of the land perpendicular to the predominant direction of the wind, L is the dimension of the land parallel to the predominant direction of the wind, D is the rotor diameter of the machine; H is height of the pylon, N_1 is the number of wind turbines per row, N_2 is the number of rows of wind turbines, N_{wt} is the total number of wind turbines to be placed on the site.

4. Application

4.1. Wind parameters

Figure 2a shows the position of the global wind speed measuring instruments on each day, which consists of global wind speed information in this research study (Bouchiba et al., 2022). The automatic weather station system assembly is composed of four main parts, such as the sensor module, the communication module, the data acquisition module and the power module. The sensor module is mainly composed by various types of weather sensors, the different sensors can measure the data of different weather elements. After the sensor completes the weather item measurement, depending on the difference between the analog signal and the digital signal, the sensor signal is accessed to the acquisition device through the analog adapter and the digital adapter. The average wind speed is the simplest indicator of the quality of wind resources in a region and is illustrated by Figure 2b that shows the daily variation in the wind speed for a few selected days of the year in the studied site.

Figure 2a. Instrumentations position for the measuring overall wind speed in per day

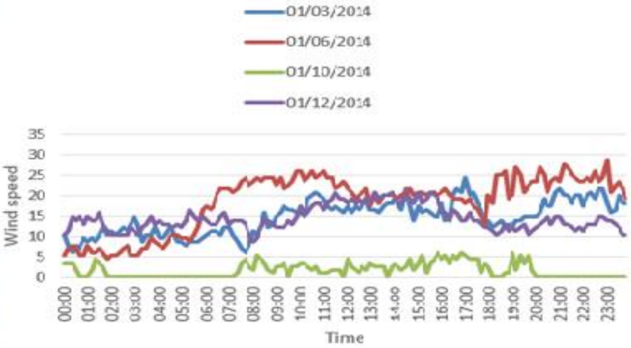

Figure 2b. Daily wind speed

The results of the annual and seasonal statistical study of the wind speed readings of each 10 min and at 10 m height, including the annual and seasonal Weibull distribution and the wind parameters are presented, respectively by Figure 3 and Table 3. These calculations clearly show that the annual calm ff_0 is 0.1926> 0.15, moreover the seasonal calm varies between 0.1423 for the season of spring and 0.259 for the season of autumn.

Figure 3 shows that almost all the distributions are extended which confirms the existence of a high number of high velocities in this region. Table 3 illustrates that the annual scale factor is higher than the optimal form factor 1.5 with high annual scale factor values of 8.92 m/s, which proves that our region has enormous wind energy potential (Bonfils et al., 2010).

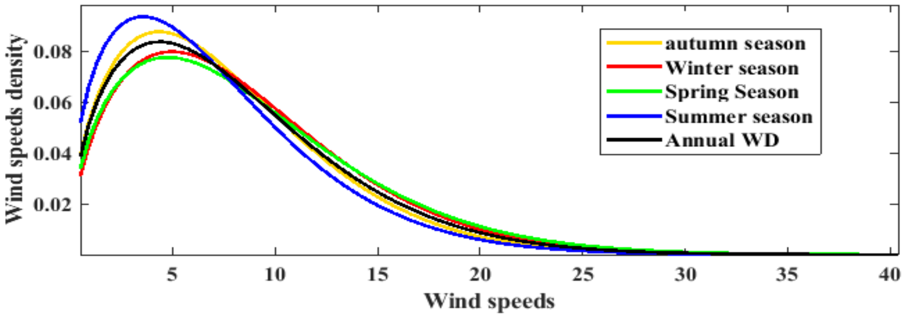

Figure 3. Yearly and seasonal Weibull distribution

Table 3. Parameters wind source, characteristic velocities, and available wind potential

Parameters	*k*	*c [m/s]*	ff_0	*V [m/s]*	V_{Em}*[m/s]*	*Pdis/A [W/m²]*
Yearly	**1,513**	**8,923**	0.192	**6,501**	12,04	**691,94**

Figure 4 illustrates the seasonal wind speeds and the density of the average seasonal wind potential available.

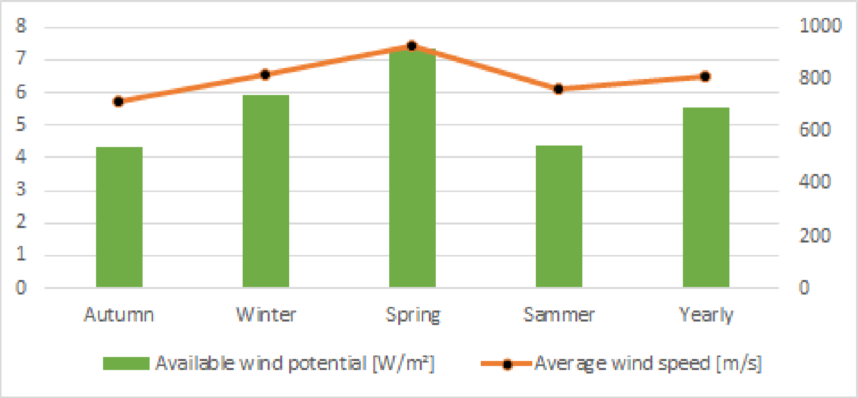

Figure 4. Annual and seasonal energy characteristics

The extrapolation of the Weibull parameters allows to estimate the wind potential for different heights; the Weibull distributions and the wind parameters of the studied site are presented in Figure 5 and Table 4.

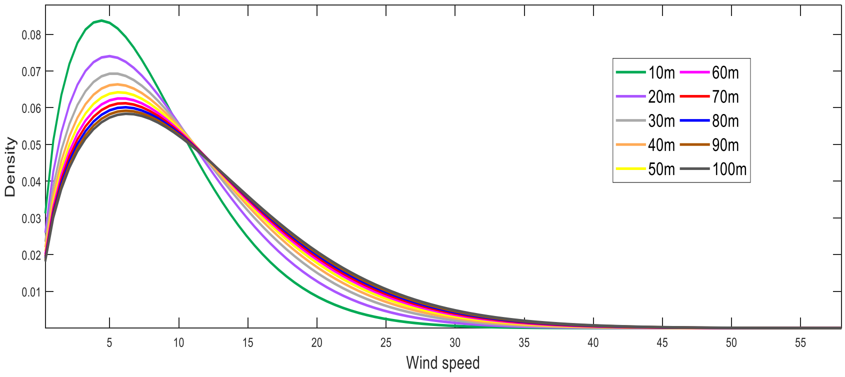

Figure 5. Weibull distribution at different height

Table 4. Annually wind parameters at different height

Wind parameters	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
k										
C [m/s]	8,922	10,089	10,772	11,257	11,632	11,939	12,199	12.424	12.622	12.80
<*v*> [m/s]	**6,50**	7,34	7,84	8,19	8,46	8,69	8,88	9,04	**9,19**	9,32
V_{EM} [m/s]	14,91	16,86	18,00	18,81	19,43	19,95	20,38	20,76	21,09	21,38
V_F [m/s]	4,37	4,94	5,27	5,51	5,70	5,85	5,97	6,08	6,18	6,27
Pdis/A [W/m²]	**691,14**	998,39	1215,1	1386,5	1530,1	1654,5	1765,8	1865,2	**1956,00**	2039,

A reading of the wind parameters for this site indicates that this region has a potential wind speed of <*V*> = 6.50m/ s, calculated by Eq. (3) and an average available power density of <*Pdis/A*> = 691 W/m², calculated by Eq. (8). As high as that at Adrar, which is the windiest site in Algeria (<*V*> = 6.3 m/s et *Pdis/A* = 283 W/m²) (Benmedjahed et al., 2014), (Diaf & Notton, 2013).

The statistical study of the speed-readings indicates the form factor k = 1.514 and the scale factor C = 8.923. For the same value of *k,* the increase in the value of *C* represents an increase in the average speed value, which means an increase in the number of high wind speed values and a decrease in the number of low speed values.

The wind speed distribution curve is then more flattened and with a maximum which shifts to the right,as illustrated in Figure 3. At 10 m height is observed that 85.88% of the speeds are in the range of 3 m/s at 25 m/s.

The analysis of the curves shown in Figure 5 depicts a variation in average seasonal wind speed and seasonal wind potential. The autumn, winter and spring seasons are the most interesting, while the summer season is the least windy. Note that the wind potential increases with height, at 90 m the values reaching almost three times the values calculated at 10 m in Table 3, but the shape of the curves remains identical to that at 10 m; Figure 5.

4.2. Adaptation and choice of wind turbines

The following analysis aims to help designers and users to choose the most suitable wind turbine for a 60 MW wind farm that can be installed in this region, as indicated in section I. In this context, five commercial wind turbines (WWWD-1D60, GE1.5sL,V90-2MW,G114-2.5MW and V90-3MW) with different power ratings, have been selected. The technical data of the chosen WT types are summarized in Table 5.

Table 5. Technical data of different commercial wind turbines used in the analysis

Wind Turbines	Cut-in speed [m/s]	Cut-off speed [m/s]	Rated speed [m/s]	Rated power [kW]	Power density [W/m²]	Hub height [m]	Diamètre du rotor [m]
WWD-1 D60	3.6	20	12.5	1000	353.7	50/70	60
GE 1.5sl	4	25	13	1500	322,1	64.7/80/85	77
V90 2MW	4	25	13	2000	314.4	80/95/105	90
G114-2.5MW	2	25	10	2500	244.9	64/80/93/120	114
V90-3MW	4	25	15	3000	471.5	80/105	90

For the installation of a 60 MW wind power plant, 60 wind turbines (WWD-1 D60) or 40 wind turbines (GE1.5sL) or 30 wind turbines (V90-2MW) or 24 wind turbines (G114-2.5MW) or 20 wind turbines (V90 of 3MW) are needed.

The annual energy and hydrogen production as well as the capacity factor are illustrate in Figure 6, and the Table 6 shows the energy production of the installed wind turbines and the operating rate of the wind power plant. The annual energy and hydrogen production of the 60 MW wind farm ranges from 259.7 GWh – 3500 tons of hydrogen for WWWD-1D to 371.85 GWh – 5020 tons of hydrogen for G114. The C_F varies slightly according to the wind turbines, between 50% (WWD-D60) and 70% (G114-2.5MW), and a maximum operating rate equal to 6197 hours/year for G114-2.5 MW.

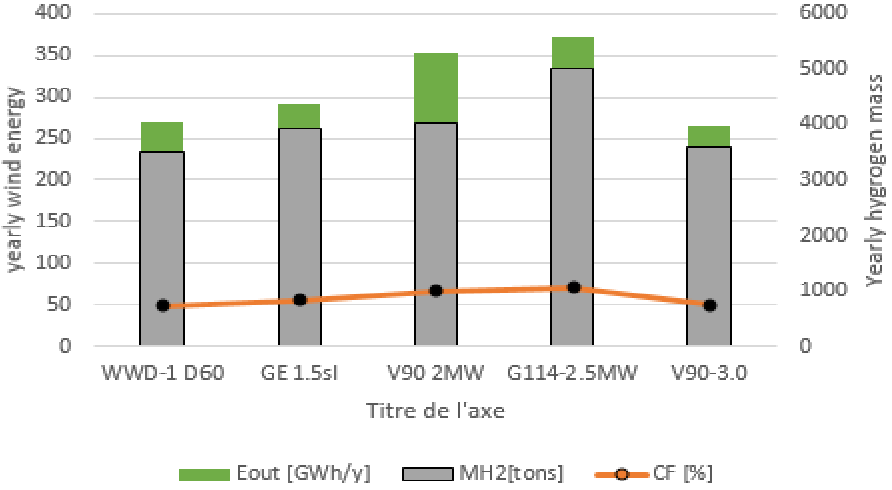

Figure 6. Yearly energy and capacity factor

Table 6. Annual operating rate of wind turbines

Wind turbines	WWD-1 D60	GE 1.5sl	V90 2MW	G114-2.5MW	V90-3.0
P_{out} [MWh]	494	832	1338	1768	1518
T_h [h/year]	4329,19	4858,29	5860,44	6195,07	4432,56
MH_2 [tons]	3500	3930	4040	5020	3590

4.3. Economic feasibility

The cost per KW of energy produced and the unit cost per kg of hydrogen depend on the type of wind turbine as well as the wind characteristics of the plant location. The results of the energy cost and unit cost of hydrogen analysis performed in this study for each wind turbine are shown in Figure 7.

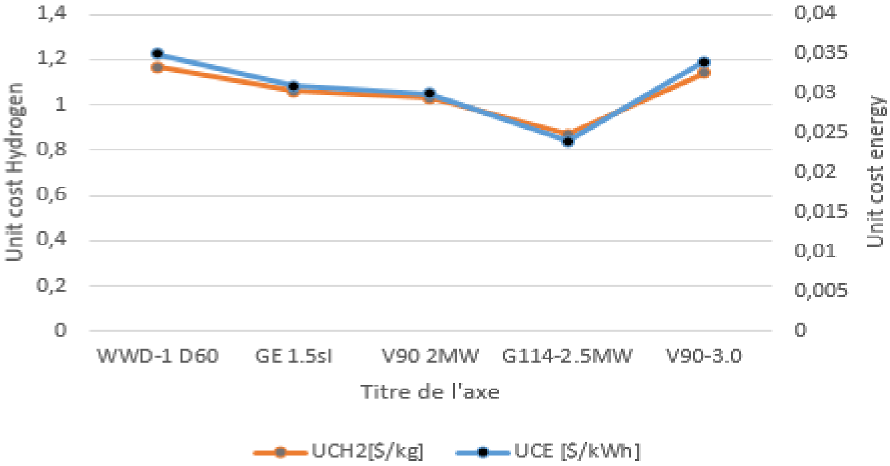

Figure 7. Unit cost energy and hydrogen of the wind power plant

The cost of electricity production per kW varies from 0.024$ to 0.035$, respectively from WWD-1D60 and G114-2.5MW and does not exceed the price of electricity in Algeria of 0.054 $/kWh (Benmedjahed et al., 2014). Regarding the unit cost of hydrogen production, interestingly, its value varies from 0.87$/kg to 1.168$/kg. The best wind turbine that should be installed based on the annual energy produced, the unit cost of energy and the unit cost of one kg of hydrogen in the proposed wind farm is the G114-2.5 MW type, not only because it has a large capacity factor of 70%, but also for its high annual green hydrogen production of 5020 tons per year.

4.4. Placement of wind turbines

The compass rose in Figure 8 shows more important variations. The southwest winds are the predominant element, reaching 22.52%; the frequency of winds is also high in the northwest and northeast sectors: 19.05%; 19.79. Finally, southerly winds are the least frequent: 2.72%. Analysis and control of wind statistics show that there is predominance of wind in the southwest (SW), northeast (NE) and Northwest (NO) directions.

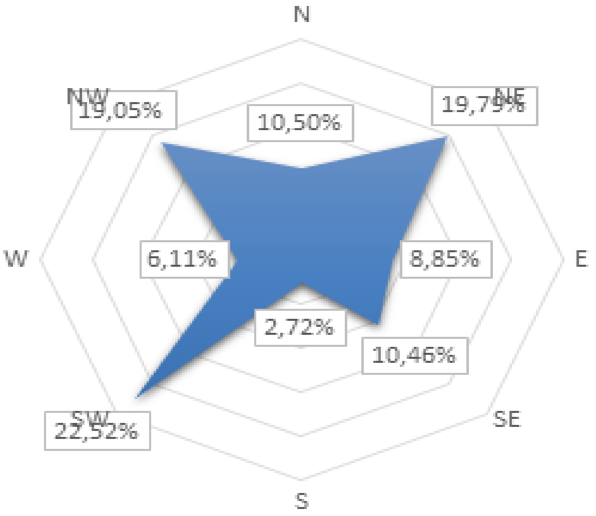

Figure 8. The Wind rose

Taking into account the dimensions of the selected wind turbines presented in Table 5 and the adapted layout of the wind turbines according to formulae 21, 22 and 23, the results of Table 7 are obtained. It simultaneously collects the number of WTs installed on the site (24 WTs), per line and per row, as well as the optimum dimensions of the wind farm installation site.

Table 7. The optimal dimensions of the implementation field

The optimal dimensions	G114-2.5MW		
N_1	24	12	**6**
N_2	1	2	**4**
I_{opt}	968.75	503.75	**271.25**
L_{opt}	684	1026	**1710**
S_{opt}	66.26	51.68	**46.38**

5. Conclusions

This work aims to study the potential of the wind farm, evaluate the energy production, the hydrogen production and the economic feasibility of the wind power plant of the El KHENEG site in the Laghouat region. It appears that the wind on this site is regular and spreads in a southwest (SW) direction, with stable average seasonal speeds between 5.11 m/s in autumn and 7.44 m/s in spring. Note that 6.5 m/s is the annual average speed with a potential of 691W/m² at an altitude of 10 m, obtaining the best average wind speeds favoring good electricity production, that is by extrapolation at the altitudes of 70 m, 80 m, 93 m, 95 m and 105 m, corresponding to the heights of the masts**.** This study forecasts the wind power of the studied park, based on a judicious choice of machine.

If the G114-2.5MW type wind turbine is chosen, the wind potential of this site at a height of 93m has an average speed of 9.12 m/s and an energy density of 1956W/m^2 for the distinguished trend. Running 24 machines provides a power of 60MW for an annual energy production of 371.85GWh, which can produce 502 tons of green hydrogen at a significant unit cost of energy estimated at 0.024 $/kWh, compared to the price of a kilowatt-hour price in Algeria of 0.054$/kWh (Benmedjahed et al., 2014) and a unit cost of hydrogen of 0.87$/kg.

Finally, the surveys and calculations support the ecological hypothesis of the windy corridor predicted on this site, in the Laghouat region, an unprofitable prejudice on the potential and energy side. Clearly, this study will allow to propose a new vision for planning renewable energy resources in the Algerian network of the region.

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