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Estimation of hydrogen production using wind energy in Algeria

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Abstract

In response to problems involved in the current crisis of petrol in Algeria, with the decrease in the price of the oil barrel, the rate of growth in domestic electricity demand and with an associated acceleration of global warming, as a result of significantly increased greenhouse gas (GHG) emissions, renewable energy seems today as a clean and strategic substitution for the next decades. However, the greatest obstacles which face electric energy comes from renewable energy systems are often referred to the intermittency of these sources as well as storage and transport problems, the need for their conversion into a versatile energy carrier in its use, storable, transportable and environmentally acceptable are required. Among all the candidates answering these criteria, hydrogen presents the best answer. In the present work, particular attention is paid to the production of hydrogen from wind energy. The new wind map of Algeria shows that the highest potential wind power was found in Adrar, Hassi-R'Mel and Tindouf regions. The data obtained from these locations have been analyzed using Weibull probability distribution function. The wind energy produced in these locations is exploited for hydrogen production through water electrolysis. The objective of this paper is to realize a technological platform allowing the evaluation of emergent technologies of hydrogen production from wind energy using four wind energy conversion systems of 600, 1250, 1500 and 2000 kW rated capacity. The feasibility study shows that using wind energy in the selected sites is a promising solution. It is shown that the turbine " De Wind D7" is sufficient to supply the electricity and hydrogen with a least cost and a height capacity factor. The minimum cost of hydrogen production of 1.214 \$/kgH2 is obtained in Adrar.

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Keywords: Wind energy, Weibull parameters, Capacity factor, Alkaline electrolysis, Hydrogen production, Algeria;

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1. Introduction

Globally, the share of renewable energies in power generation is 13.2% of the power generated in the world in 2010. The majority still comes from fossil fuels such as oil (32.4%), coal (27.3%), natural gas (21.4%) and nuclear energy (5.7%) [1]. In Algeria, Oil occupies an important place in the country's economic development. The increase in oil revenues following the increase in volumes produced jointly and energy prices has allowed an average growth in GDP of 4% per year between 2001 and 2007. With assumptions of economic growth rate of 3% and a growth rate of 1.6% per year for the period 2007-2030, the rate of growth in energy demand would be between 2.8% and 4.3% per year, for the projection period it will absorb 61.5 (Mtoe) of primary energy in 2020 and 91.54 Mtoe in 2030 against 52 Mtoe in 2020 to 66.45 Mtoe in 2030, in the low scenario [2].

Within the framework of the national program of renewable energy development and energy efficiency in Algeria, an electricity company Sonelgaz carried out many projects of electricity production based on wind and solar energy to power the isolated villages and remote houses of south Algeria. These projects include the project of a wind power plant of 10 MW in Adrar, the project of solar gas hybrid power plant of 150 MW in Hassi R'mel. At present, Sonelgaz is leading the way towards the development and utilization of renewable sources of energy in the country in general and it is expected that about 22 000 MW of power generating capacity of electricity will be from renewable energy sources in 2030, of which 12 000 MW will be intended to meet the domestic electricity demand and 10 000 MW destined for export [3].

In the recent years, wind power becomes an important source of environmental-friendly energy and one of the most promising energy sources. There are several advantages to use wind energy such as the wind is a free, clean and inexhaustible energy source. Wind energy can provide suitable solutions to the global climate change and energy crisis. The utilization of wind power essentially eliminates emissions of CO_2, SO_2, NO_x and other harmful wastes as in traditional coal-fuel power plants or radioactive wastes in nuclear power plants. Wind energy dramatically reduces the dependence on fossil fuels which strengthen global energy security. According to World Wind Energy Association [4], the world wind power capacity reached 196,630 MW in 2011. The top two countries on the chart are China (44,733 MW in 2011) and the U.S (40,180 MW in 2010) [5].

There are particularity reasons to use wind energy in Algeria for electrifying remote sites which cannot be connected to the power network (mountain, deserts and isolated villages). Moreover, the use of windmills for pumping water from underground [6] in order to satisfy water needs of isolated villages. In addition, it helps to develop national industries. However, the greatest obstacles which face electric energy comes from wind energy systems are often referred to the intermittency of wind, storage and transport problems; the need for their conversion into a versatile energy carrier in its use, storable, transportable and environmentally acceptable is required. Of all the candidates answering these criteria, hydrogen presents the best answer; it is the most abundant element in the universe; it is not pollutant [7]. Hydrogen produced from renewable energy sources offers the promise of a clean and sustainable energy carrier. Hydrogen's potential production from renewable energy resources such as solar [8-10], geothermal energy [11-14], Hydrogen production from oil palms biomass as a potential source [15].

Currently hydrogen production by water electrolysis process using wind energy is regarded to have the lowest life cycle GHG emissions of all hydrogen pathways, wind energy has a low cost of electricity ($/kWh) after hydraulic power among all renewable options [16], as an example energy generation costs for solar PV systems are typically 6–18 times higher than for equivalent wind turbine systems [17].Various studies have been reported in the literature on wind energy based on hydrogen production in different countries [18-20]. In contrast, few studies are found about hydrogen production in Algeria [21].

In this work, the data were collected from different sites of Algeria are used to determine the wind hydrogen production. The various resources necessary for a viable exploitation of wind hydrogen are examined. Water electrolysis system is considered. Estimations of the production cost are carried out for different sites and different wind turbine systems. The results are discussed taking into consideration the sustainable development of the region. An approximate costs analysis, which included a total investment estimate, was performed. The cost of electricity production was also calculated for comparison purposes. Finally, the results are discussed.

2. Simulation of the electricity production by wind turbine

2.1. Wind data and site description

The South of Algeria is marked by higher wind velocities than the North; this is particularly true in the South-West where velocities are more than 4m/s and exceed 6m/s in the Adrar region. Regarding the North, it appears that the average velocity is not very high. However, we notice microclimates in the coastal areas of Oran, Béjaïa and Annaba, as well as in the region bounded by Béjaïa in the North and Biskra in the South. [22]. In this paper we chose Adrar, Hassi-R'Mel and Tindouf regions.

The table. 1. Shows the annual Weibull shape factor k and the scalar factor c(m/s) of Adrar, Hassi-R'Mel and Tindouf regions at a height of 10m.

Table 1. Geographical coordinates and Weibull parameters used in the study at a height of 10 m[22].

Site	Longitude (deg)	Latitude (deg)	Altitude (m)	k	C(m/s)
Adrar	-0.28	27.88	263	2.15	7.2
Hassi-R'Mel	3.28	32.93	764	1.82	6.88
Tindouf	-8.13	27.70	413	2.15	6.41

2.2. Weibull distribution

In the present study we use the Weibull probability density function. The cumulative distribution function F(v) and the Weibull distribution f(V) are given by [23-24]:

$$f(V)=\left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1}\exp\left(-\left(\frac{V}{c}\right)^{k}\right) \quad ; \quad F(V)=1-\exp\left(-\left(\frac{V}{c}\right)^{k}\right) \tag{1}$$

Where, k is the shape factor, c (m/s) is the scalar factor, and V is the wind speed. There are several methods used to determine these two parameters [24-25].

2.3. Extrapolation of wind speed

The wind speed data used in this paper were measured at a height of 10 m. the speed at any height can be calculating using [25-26]

$$V_2=V_1\left(\frac{Z_2}{Z_1}\right)^{\alpha} \tag{2}$$

Where, V_1 (m/s) is the actual wind speed at a height of Z_1 (m); V_2 (m/s) is the wind speed at the required height Z_2 (m) and α is the wind speed power law coefficient defined by [25, 27]:

$$\alpha=\frac{0.37-0.088\ln(V_1)}{1-0.088\ln(Z_1/10)} \tag{3}$$

In this paper k and c varies according to the height [25, 27]:

$$\frac{k_2}{k_1}=\frac{1-0.088\ln(Z_1/10)}{1-0.088\ln(Z_2/10)} \quad ; \quad \frac{c_2}{c_1}=\left(\frac{Z_2}{Z_1}\right)^{m} \quad ; \quad m=\frac{0.37-0.0881\ln(c_1)}{1-0.0881\ln(Z_1/10)} \tag{4}$$

2.4. Estimation of capacity factor

The operation of the wind turbine is limited by the cut-in speed V_{cin} and the cut-off speed V_{cout}. Therefore, the average electrical output power P of the generator can be calculated by the following integral [28]:

$$P = \int_{V_{cin}}^{V_r} \left(a + bV^k\right) f(V)\,dV + P_r \int_{V_r}^{V_{cout}} f(V)\,dV \quad \text{(W)} \tag{5}$$

Where, P_r (W) is the rated electrical output power of the generator; a and b are given by:

$$a = \frac{P_r V_{cin}}{V_{cin}^k - V_r^k} \quad ; \quad b = \frac{P_r}{V_r^k - V_{cin}^k} \tag{6}$$

The capacity factor is defined as the ratio of the average power output to the rated output power of the generator [17, 28] and is given by:

$$CF = \frac{\exp\left[-\left(V_{cin}/c\right)^k\right] - \exp\left[-\left(V_r/c\right)^k\right]}{\left(V_r/c\right)^k - \left(V_{cin}/c\right)^k} - \exp\left[-\left(\frac{V_{cout}}{c}\right)^k\right] \tag{7}$$

Therefore, the yearly energy production of such turbine is given by:

$$W = CF.P_r.(8760) \quad \text{(Wh/yr)} \tag{8}$$

The technical data and the price of the four commercialized wind machines used in this study are summarized in table 2.

Table 2. Commercial wind turbine characteristics [29]

Characteristics	De Wind 48	De Wind D6	De Wind D7	De Wind D8
Hub height z(m)	40	65	70	80
Rated power (kW)	600	1250	1500	2000
Swept area (m^2)	1808	3019	3846	5027
Cut-in speed V_{cin} (m/s)	2.5	2.8	3	3
Rated speed V_r (m/s)	11.5	12.5	12	13.5
Cut-out speed V_{cout} (m/s)	25	25	25	25
Price ($)	530,000	1,065,000	1,338,000	1,800,000

3. Hydrogen production at the local wind power plant

3.1. System description

The system which we have investigated in this study is an installation of massive hydrogen production from wind power. It consists of a wind turbine, an AC/DC converter and an alkaline electrolyser Fig.1. In this system, the AC output of the wind turbine is converted to a DC voltage suitable for electrolyser operation through an AC/DC converter.

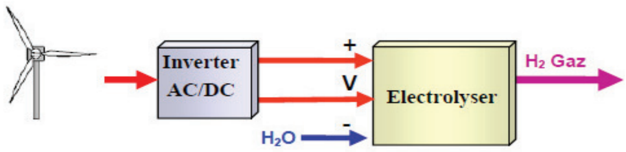


Fig. 1. Wind hydrogen system production

In this process, the wind energy is first converted to mechanical energy through wind turbine to produce electricity which then could be used for water electrolysis system for hydrogen production via alkaline electrolysis by passing electricity through two electrodes.

3.2. Electrolysis system

The generated electric by wind energy system will be sent to the electrolyzer to drive electrolysis process, as presented in Fig. 2. Actually there is different kind of electrolyzers [21], the electrolyzers that usually tested for wind electrolyses are the alkalines ones [5, 8, 16] because it is one of the easiest methods for hydrogen production [11]. The PEM ones are in the state of development [21]. In this paper the capacity of electrolyzer chosen is 52.5 KWh/kg which is equivalent to about 75% in efficiency [11].The amount of hydrogen mass produced from wind energy is given as follow:

$$M_{H2} = \frac{\eta_{el}.W}{LHV_{H_2}} \qquad (KgH_2/yr) \qquad (9)$$

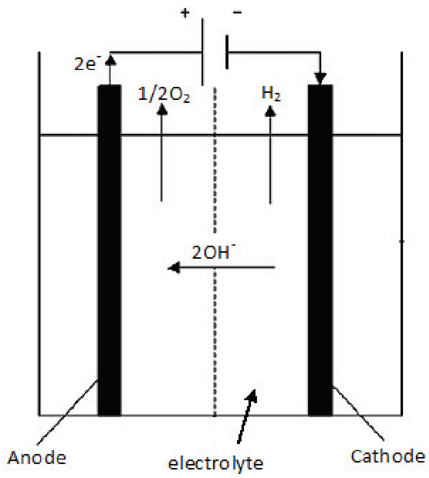


Fig. 2. Alkaline water electrolysis process

4. Economics Analysis

The cost of the hydrogen production C_{H2} was the key economic parameter chosen for size optimization of the hydrogen production devices and it is expressed as:

$$C_{H_2} = \frac{C_{ele} + C_w}{M_{H_2}.T} \qquad (\$/Kg) \qquad (10)$$

Where, C_{ele}($) is the capital, operating and maintenance cost of electrolyzer; C_w: energy cost ($); M_{H2}(Kg/yr) is the annual hydrogen production; T represent the project lifetime and set as 20 year.

4.1. Investment cost of wind power plant

The economic viability of the wind energy projects depends on its ability to generate electricity at a low operating cost per unit energy [30]. The economics of wind power is based on different parameters such as investment costs, operation and maintenance costs, site selected, electricity production and wind turbine characteristics. Among all the parameters listed, the right choose of turbine site is the most important parameters to achieve economic viability. Different methods are generally used to estimate the operating cost of a unit energy produced by the wind energy conversion system [31-33]. In this study, the estimation of the cost per unit (CPU) is done by estimating the specific cost per kilowatt hour, which is expressed as the ratio of accumulated net present value of all the costs (PVC) to the total energy (E_{tot}) produced by the system during the wind turbine lifetime [29,34].

$$CPU = \frac{C_w}{E_{tot}} \qquad (\$/kW) \qquad (11)$$

The present value of costs (PVC) of electricity produced per year can be calculated by the following formula:

$$PVC = C_i + C_{omr}\left[\frac{(1+i)}{(r-i)}\right]\left[1-\left(\frac{1+i}{1+r}\right)^t\right] - S\left(\frac{1+i}{1+r}\right)^t \qquad (\$) \qquad (12)$$

where C_i is the initial investment cost includes the turbine price plus its 20% for the cost of civil work, installation, connection cables to the grid; C_{omr} is operation, maintenance and repair cost. C_{omr} is taken as 25% of the annual cost of the turbine (machine price/life time); S is the scrap value taken as 10% of the original investment; t is the lifetime of turbine in years (20 years); i and r are the inflation rate and interest rate which were taken to be 15% and 12% respectively [34].

4.2. Electrolysis cost

The economic modeling of the electrolyser is presented in many previous works, in which the investment includes three main costs namely; capital, replacement and O&M costs. The total investment of electrolyser depends on the size of the hydrogen production facility. The electrolyser capital cost is determined by the required maximum hydrogen production rate, the effective electrolyser efficiency and the estimated specific capital cost per kW_e at nominal production [35].

$$C_{ele} = C_{elec,u}\frac{M_{H_2}K_{el,th}}{8760.f.\eta_u} \qquad (\$/kW) \qquad (13)$$

Where, $C_{elec,u}$ ($/$kW_e$) is the unit cost of electrolyser, $K_{el,th}$ (kWh/kg) is the theoretical specific energy required by the electrolyser and f is the capacity factor.

The reference case considers an electrolyser unit cost of 368 $/kWe, which corresponds to target values established by [36]. We assume that the replacement costs and annual operating costs equal to 25% and 2% of the first cells investment. Operation life of the electrolyser used takes 7 years.

5. Results and discussion

The present study helps designers and users to choose the most suitable wind turbine for the Algerian sites because the right chooses of turbine-site is the most important parameters to achieve economic viability. In this paper, four wind turbines were chosen (De Wind 48, De Wind D6, De Wind D7, De Wind D8), the energy output from theme at all the regions was calculated. The annual energy output for Adrar varies between 2540.30 MWh/yr using De Wind 48 and 7979.60 MWh/yr using De Wind D8, the energy output for Hassi-R'Mel was found to be 2470.74 MWh/yr and 7856.90 MWh/yr, however the energy output for Tindouf varies between 2142.10 MWh/yr and 6662.07 MWh/yr.

As shown in Tab. 3 and according to the annual energy output for each location, the high capacity factor at all selected sites is obtained by De Wind D7 machine, 53% is obtained for the site of Adrar, the second best capacity factor of 51% was found in Hassi-R'Mel and 45% for the site of Tindouf.

Table 3, shows that the minimum cost of 0.0132 $/kWh is obtained in Adrar and Hassi-R'Mel using De Wind D6 model and De Wind D7 respectively, while at Tindouf region the minimum cost of electricity generated was found to be 0.0149 $/kWh using De Wind D7 model.

The minimum cost of unit energy per kWh of energy does not exceed 0.0132 $/kWh at all sites which is very competitive price compared to the price of electricity paid by the consumer of domestic sector in Algeria (0.054 $/kWh). This cost will decrease further with the development of wind energy technology.

Table 3. Cost analysis for selected wind turbines

Site	Turbine	Capacity factor	Yearly energy (MWh/yr)	Cost per unit ($ /kWh)
Adrar	De Wind 48	0.48	2540.30	0.0137
	De Wind D6	0.49	5328.55	0.0132
	De Wind D7	0.53	6910.30	0.0144
	De Wind D8	0.46	7979.60	0.0148
Hassi-R'Mel	De Wind 48	0.47	2470.74	0.0141
	De Wind D6	0.47	5198.36	0.0135
	De Wind D7	0.51	6658.70	0.0132
	De Wind D8	0.45	7856.90	0.0151
Tindouf	De Wind 48	0.41	2142.10	0.0163
	De Wind D6	0.41	4497.93	0.0156
	De Wind D7	0.45	5913.71	0.0149
	De Wind D8	0.38	6662.07	0.0178

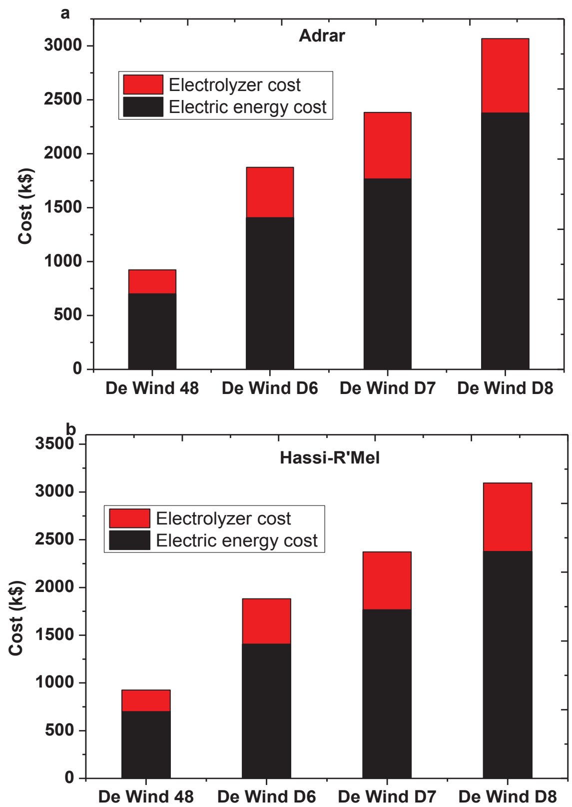
It appears clearly that the hydrogen production depends on the site and the size of the wind turbine. Tab. 4, shows that the highest production value at all sites are obtained by De Wind D8. The maximum production of 113.99 tH_2/yr is observed in Adrar, the second best value of 112.24 tH_2/yr is obtained from the site of Hassi-R'Mel, then the site of Tindouf with 95.17 tH_2/yr, but the cost of electricity and hydrogen production from this WT is considered the highest cost according to Tab. 3 and Tab. 4. The minimum cost of H_2 produced by the WTs which have the minimum cost of unit energy per kWh in different sites are: 76.12 tH2/yr in Adrar using De Wind D6; 95.12 tH2/yr in Hassi-R'Mel and 84.48 tH2/yr in Tindouf using De Wind D7.

These results indicate that for the same site we obtain different values of hydrogen rate when we increase the WT size. Obviously, this means that the Weibull wind speed distribution can make the difference. On another hand, we noticed that the increase rate of hydrogen production for the four sizes of WT is approximately equal to the increase of the rated power of WTs.

Table 4. Cost analysis of hydrogen production

Site	Turbine	H_2 production (tH_2/yr)	Cost per unit ($ /kWh)
Adrar	De Wind 48	36.290	1.284
	De Wind D6	76.122	1.243
	De Wind D7	98.719	1.214
	De Wind D8	113.994	1.362
Hassi-R'Mel	De Wind 48	35.296	1.311
	De Wind D6	74.262	1.266
	De Wind D7	95.124	1.248
	De Wind D8	112.241	1.378
Tindouf	De Wind 48	30.601	1.463
	De Wind D6	64.256	1.414
	De Wind D7	84.482	1.365
	De Wind D8	95.172	1.568

The hydrogen production cost breakdown shows that the electricity energy cost accounts for 75% of the total project investment of the wind energy based hydrogen station, while the capital cost of electrolyser represent around 25% of the total cost, Fig. 3. From this result, the strong impact of the electricity production costs is confirmed, followed by the impact of electrolyser expenses and investment.



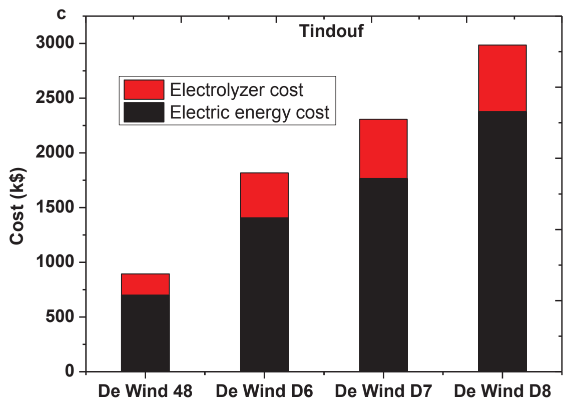


Fig. 3. Hydrogen production cost breakdown at three selected site: (a) Adrar; (b) Hassi-R'Mel; (c) Tindouf

6. Conclusion

The present study gives a simplified methodology to evaluate the hydrogen production from the wind energy available at each site using different wind turbine. The wind energy potential and economic analysis in three selected locations were examined. In term of capacity factor and energy produced, the high capacity factor at all selected sites is obtained by De Wind D7 machine, the later can produce 6910.30 MWh/yr in Adrar, 6658.70 MWh/yr in Hassi-R'Mel and 5913.71 MWh/yr in Tindouf. according to the cost analysis, the minimum cost of 0.0132 $/kWh is obtained in Adrar using De Wind D6 model, while at Tindouf and Hassi-R'Mel regions the minimum cost of electricity generated was found to be 0.0149 $/kWh using De Wind D7 model.

Moreover, the results indicate that the hydrogen production strongly depends on the site and the wind turbine was selected. The maximum value of hydrogen produced by the WTs which have the minimum cost of unit energy per kWh in different sites are: 76.12 tH_2/yr in Adrar using De Wind D6; 95.12 tH_2/yr in Hassi-R'Mel using De Wind D7; 84.48 tH2/yr in Tindouf using De Wind D7. The hydrogen production cost shows that the electricity energy cost has a strong impact, followed by the impact of electrolyser expenses and investment.

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