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Technical and Economical Study of Hydrogen Production Using Darrieus Wind Turbine in Various Sites of Algeria

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Abstract

Due to the rising demand for gas and the accelerating impact of global warming caused by significant increases in greenhouse gas (GHG) emissions, hydrogen production from renewable energy has emerged as an optimal alternative to conventional gas. This study focuses on hydrogen production using a 10-kW wind turbine across 13 locations in Algeria, which are categorized into three distinct climatic regions: coastal, highland, and southern. Feasibility analysis reveals that the energy produced in the southern region accounts for over 50% of the total energy generated across all regions. Additionally, the study found that the minimum cost per kilogram of hydrogen is approximately \$1.98/kg in Adrar (southern region), \$3.26/kg in Algiers (coastal region), and \$2.72/kg in Djelfa (highland region). These findings suggest that hydrogen produced from wind energy presents a viable alternative to oil and gas in southern Algeria.

Keywords: *Wind energy; Hydrogen production; Hydrogen cost; PEM electrolyzer; Algeria.*

1. Introduction

Environment climate change due to fossil fuel consumption has increased pressure to generate new clean energy. The exploitation of fossil fuels creates pollution on local, regional, and global scales. Most countries around the world are now convinced that the increase of carbon dioxide and other greenhouse gases in the atmosphere lead to threatening consequences such as global climate change and sea level rise [1]. As reported at the international energy agency [2], the energy generation accounts for over 80% of the anthropogenic greenhouse gases with emissions resulting from the production, transformation, handling and consumption of all kinds of energy commodities. As a result, there is an increasing need for new and greater sources of energy for future global energy and transportation applications. To overcome these problems, green hydrogen produced from renewable energies may be an alternative fuel because it is environmentally acceptable, economically competitive, technically feasible, and readily available. Moreover, hydrogen is the most abundant element in the universe [3].

Hydrogen can be produced using various renewable energy sources, including solar [4,6], Wind [7], geothermal using CO_2 as working fluid [8], biomass [9-10], and hydropower [11-13]. Other studies use hybrid power systems to produce hydrogen such as solar-wind [14]. in Algeria, many studies have been conducted to estimate hydrogen production from solar energy such as [15-23], Wind [7,22,24-25], and geothermal [8]. These studies focus on evaluating the feasibility, cost-effectiveness, and environmental impact of using Algeria's abundant renewable resources for sustainable hydrogen production. Researchers have analyzed various regions, taking into account factors like solar irradiance in the Sahara, wind potential, and biomass availability in agricultural areas. Findings indicate that Algeria has significant potential for hydrogen production, especially in the southern regions where solar energy is most intense. Currently hydrogen production by water electrolysis process using wind energy is regarded to have the lowest life cycle GHG emissions of all hydrogen pathways [13,22].

Actually, there is two kinds of electrolyzer that almost used for hydrogen production [26], Alkaline and proton exchange membrane, the alkaline solution is a common electrolyte used for water electrolysis and it covers the majority of the market. However, PEM electrolyzer have various advantages over alkaline ones. One of the most important advantages is PEM electrolyzer can operate at high pressures up to 200 bars and this removes the compression stage of hydrogen which needs to be stored in tanks after the electrolysis [27]. Compressing hydrogen inside the electrolyzer is an isothermal process which is the most efficient way to compress hydrogen. PEM electrolyzer have less parasitic losses and higher efficiency than alkaline electrolyzer which also decreases the cost of hydrogen production [28]. In addition, highly pure hydrogen can be produced with a long-life time by PEM electrolyzer and good suitability with renewable energy systems where the amount of electricity varies randomly according to the wind and solar intermittencies [29]. Since there is no chemical electrolyte such as KOH used in alkaline electrolyzer, they are ecologically clean. Moreover, PEM electrolyzer have smaller sizes and mass because of the simple and compact design [30].

In this study, wind speed data were collected from 13 stations located in three different climatic regions of Algeria at a height of 10 m, and a 10-kW Darrieus-type vertical axis wind turbine was used to determine the power produced, annual energy output, and capacity factor at each location. Additionally, a PEM electrolyzer was employed to convert the generated electricity into hydrogen. Finally, an economic analysis was conducted to determine both the levelized cost of electricity generated by the Darrieus wind turbine and the levelized cost of hydrogen produced by the PEM electrolyzer. The paper is organized as follows: (1) wind data and site descriptions, (2) system description of the wind/hydrogen setup, (3) mathematical modeling of wind energy, hydrogen production, and economic analysis using the levelized cost method, (4) results and discussion, and (5) conclusions.

2. Wind data and site description

Figure 1. Distribution of the sites selected [31]

The wind data were obtained from the reference [31] of 13 stations located in different region of Algeria, these sites are characterized by different geographical and climatic zone. The Figure 1 shows the distribution of the sites selected. The Tab 1 shows the geographical coordinate for the selected stations. The Table 2 shows the annual Weibull shape factor k_1, the scalar factor c_1(m/s), and the power density of the selected sites at a heigh of 10m.

3. System description

The system of hydrogen production from wind power consists of a wind turbine, an DC/DC converter and a PEM electrolyzer as shown in Figure 2. In this system, 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 PEM electrolysis by passing electricity through two electrode. The wind turbine characteristics are given by the Table 3.

Figure 3 shows that the proton exchange membrane (PEM) water electrolysis process. it consists of a rigid barrier of solid oxide electrolyte (SOE) conductor (ceramic material) with two electronic conductors respectively, to ensure the anode and cathode functions. When water particles react at the anode, they produce oxygen and positively charged protons, which move through the SOE to the cathode and combine with electrons to form hydrogen (Figure 3), illustrating the PEMEL functioning idea [32].

PEM electrolyzer electrode reactions are:

Anode: $2H_2O = 4\ H+ + O_2 + 4\ e-$

Cathode: $4\ H+ + 4\ e- = 2H_2$

Overall: $2H_2O + energy = 2H_2 + O_2$

Table 1. Geographical coordinates of the selected stations [31].

Site	Coordinates		
	Latitude (deg)	Longitude (deg)	Altitude (m)
Coastal region			
Annaba	36^0 49′N	07^0 49′E	05
Skikda	36^0 53′N	06^0 54′E	01
Bejaia	36^0 43′N	05^0 4′E	01
Algiers	36^0 43′N	03^0 15′E	24
Oran	35^0 38′N	00^0 37′W	90
Highland region			
Tébessa	35^0 25′N	08^0 7′E	820
Sétif	36^0 11′N	05^0 15′E	1033
Djelfa	36^0 41′N	03^0 15′E	1144
South region			
Adrar	27^0 49′N	00^0 17′W	263
Béchar	31^0 37′N	02^0 14′W	811
Ghardaïa	32^0 24′N	03^0 48′E	468
In Amenas	28^0 03′N	09^0 38′E	561
Tamanrasset	22^0 47′N	05^0 31′E	1377

Table 2. Renewable sources at a heigh of 10m [31].

Site	K_1	C_1 (m/s)	V_1 (m/s)	P_{w1}(W/m²)
Coastal region				
Annaba	2,96	4,18	3.73	44.99
Skikda	1,76	4,1	3,3	65,44
Bejaia	2,99	3,54	3.17	27,22
Algiers	1,73	4,54	4.05	91.00
Oran	2,3	4,88	4.32	83.27
Highland region				
Tébessa	1,71	3,65	3,25	47,89
Sétif	2,8	4,29	3,82	49,97
Djelfa	1,81	5,24	4,64	130,41
South region				
Adrar	2,15	7,2	6,37	283,12
Béchar	1,67	4,25	3,81	78,71
Ghardaïa	1,72	4	3.57	62.75
In Amenas	2,2	5,2	4.6	104,33
Tamanrasset	1.47	5.45	4.93	205.98

Table 3. Wind turbine characteristics.

Type	Hub height z	Rated power	Cut-in speed V_c	Rated speed V_r	Cut-out speed V_c	Price
Darrieus	24m	10 kW	2m/s	10m/s	20m/s	$/kW

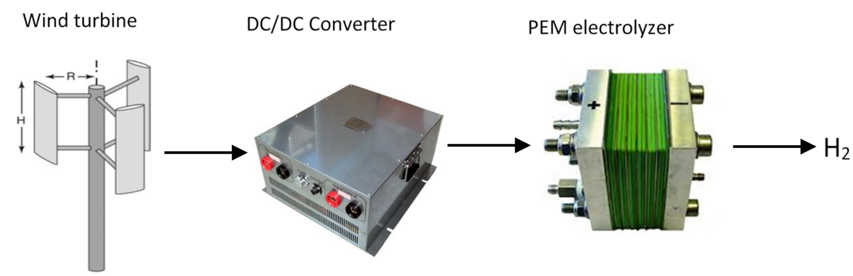

Figure 2. Wind hydrogen system production.

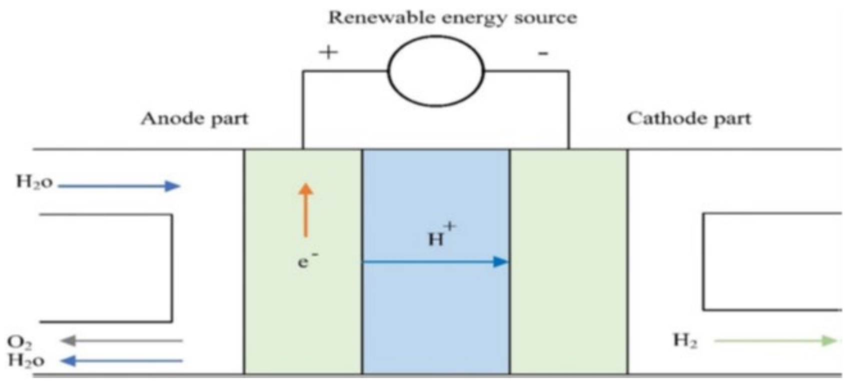

Figure 3. PEM water electrolysis process [32].

4. Mathematical model

4.1. Wind energy

4.1.1. Weibull distribution

The Weibull probability density function f(V), and the cumulative distribution function F(v) are given by [7,33]:

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

where k is the shape factor; c (m/s) is the scalar factor; and V is the wind speed.

4.1.2. 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 the following equations [34-35]:

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

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 [7,34]:

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

Similarly, the values of k and c varies also according to the height [7,34]:

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

4.1.3. Potential of wind energy

The density of average potential wind available on a site is given by:

$$P_w = \frac{1}{2}\rho {V_m}^{3}; \ \ \mathrm{W/m3)} \tag{5}$$

where ρ=1.225 kg/m^3 is the air density; the mean speed V_m and the cubic average speed of wind can be calculated by the following expression [34]:

$$V_m = C\Gamma\left(1+\frac{1}{k}\right) \;; \qquad V_m^3 = C^3.\Gamma\left(1+\frac{3}{k}\right) \tag{6}$$

where Γ is the gamma function, and is given by:

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt \tag{7}$$

4.1.4. Estimation of capacity factor

The capacity factor is defined as the ratio of the average power output to the rated output power of the generator [7,34] and is given by:

$$CF = \left(\frac{exp\left[-\left(\frac{V_{cin}}{c}\right)^k\right] - exp\left[-\left(\frac{V_r}{c}\right)^k\right]}{\left(\frac{V_r}{c}\right)^k - \left(\frac{V_{cin}}{c}\right)^k} - exp\left[-\left(\frac{V_{cout}}{c}\right)^k\right]\right) \tag{8}$$

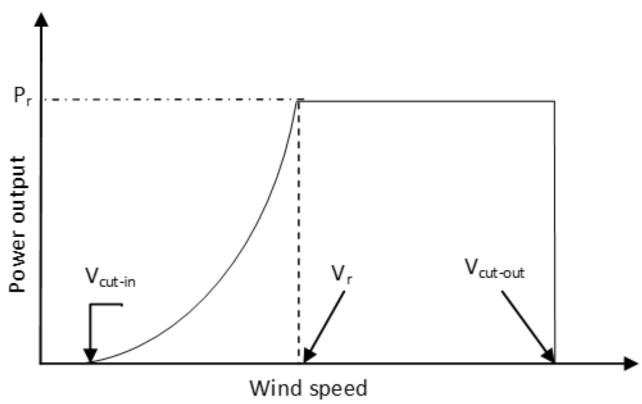

Figure 4. Power curve characteristics of wind turbine.

The operation of the wind turbine is limited by the cut-in speed V_{cin} and the cut-off speed V_{cout} as shown in Figure 4. Therefore, the average electrical output power P of the generator can be calculated by the following expression [28]:

$P_W = CF.P_r$; (kWh) (9)

where P_r is the rated power of the wind turbine.

4.1.5. Energy production by wind turbine

The yearly energy production of such turbine is given by [7,35]:

$$E_W = CF.P_r.(8760); \text{ (kWh/yr)} \tag{9}$$

4.2. Hydrogen potential model

The electricity generated by wind energy system will be sent to the electrolyzer to drive electrolysis process, as presented in Figure 1. In this paper, the capacity of electrolyzer chosen is 52.5 KWh/kg which is equivalent to about 75% in efficiency [7]. The amount of hydrogen mass produced from wind energy is given as follow [36]:

$$m_{H2} = \frac{\eta_1.\eta_2.\eta_{conv}.E_g}{LHV_{H2}}; \text{ (kgH}_2\text{/yr)} \tag{10}$$

$$V_{H2} = 11.2.m_{H2}; \text{ (Nm}^3\text{H}_2\text{/yr)} \tag{11}$$

where m_{H2} [kg] is the hydrogen gas mass produced; Eg [kWh] is the wind energy production during the lifetime of the project; $LHVH_2$ [kWh/kg] is the hydrogen lower heating value; η_{conv} is the efficiency coefficient of DC/DC converter; η_1 and η_2 are the efficiency of the electrolysis system and the additional efficiency coefficient that included to take into account the energy losses in the electrolyzer, respectively.

5. Economic analysis

The cost of the hydrogen production by wind energy are expressed as follow:

$$C_{H_2-w} = \frac{C_w+C_{elec}}{m_{H2}.T} \quad (\$/kg) \tag{12}$$

where T, C_w, C_{elec} are the project lifetime and set as 20 years, wind turbine cost, and electrolyzer cost, respectively.

5.1. Electricity cost

The economics of power produced is based on different parameters such as investment costs, operation and maintenance costs, site selected, electricity production. 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 [7,33].

$$CPU = \frac{PVC}{E_g}, \ (\$/kWh) \tag{13}$$

The present value of costs (PVC) of electricity produced can be calculated by the following formula [7,31,37]:

$$PVC = C_i + C_{omr}\left[\frac{(1+i)}{(r-i)}\right]\left[1-\left(\frac{1+i}{1+r}\right)^t\right] - S\left(\frac{1+i}{1+r}\right)^t; \ (\$) \tag{14}$$

where C_i is the initial investment cost includes the turbine price plus its 20% for the cost of civil work; installation, connection cables; C_{omr} is operation, maintenance and repair cost. C_{omr} is taken as 3% 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 6% and 5% respectively [31].

5.2. Hydrogen cost

The economic modeling of the electrolyzer is presented in many previous works, in which the investment includes three main costs namely; capital, replacement and O&M costs [38].

$$C_{elec} = C_{i,elec} + C_{m,elec} + C_{rep,elec} \tag{15}$$

The electrolyzer capital cost is determined by the size of the hydrogen production facility, the electrolyzer efficiency, and the estimated specific capital cost per kWe at nominal production as shown in equations (16) and (17) [7,38].

$$C_{elec} = C_{elec,u}; (\$/kW) \tag{16}$$

$$K_{el,th} = 3.5418 Q_{H2max}; (kW) \tag{17}$$

where C_{elec} ($) is the capital cost of electrolyzer, $C_{(elec,u)}$($/kWe) is the unit cost of electrolyzer, $K_{el,th}$ (kWh/kg) is the theoretical specific energy required by the electrolyzer and f is the capacity factor. The reference case considers an electrolyzer unit cost of 368 $/kWe, which corresponds to target values established by [7]. The replacement and operating costs equal to 25% and 2% of the first investment respectively.

6. Results and discussion

In this study, a FORTRAN program is developed based on the flowchart, as shown in Figure 5.

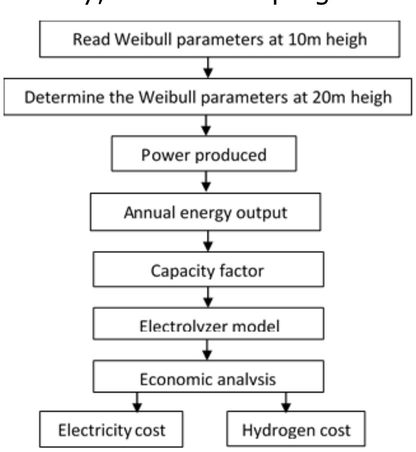

Figure 4. Power curve characteristics of wind turbine.

The program reads first the annual Weibull shape factor k, the scalar factor c(m/s) and the power density of the selected sites at a heigh of 10m as shown in the Table 2. Secondly, determine the Weibull parameters at a heigh of 24m. Then, calculate power produced, annual energy output, and capacity factor at each location. After that, the amount of hydrogen that can be produced from the generated electricity. Finally, the program determines both the levelized cost of electricity generated by the Darrieus wind turbine and the levelized cost of hydrogen produced by the PEM electrolyzer.

The Table 5 provides detailed information on various sites categorized by region, focusing on renewable energy metrics. The regional Analysis shows that fore the coastal region: Annaba has a low-capacity factor(0.12) and energy production (10.16 MWh/yr); Skikda has a higher capacity factor (0.23) and energy output (20.7 MWh/yr) compared to Annaba; Bejaia characterized by the lowest energy production (5.882 MWh/yr) and capacity factor (0.067); Algiers has the highest hydrogen production in this region (359.22 kg/yr), with a good capacity factor (0.29); Oran: Solid energy output (22.44 MWh/yr) and significant hydrogen production (320.62 kg/yr).

For the Highland Region: Tébessa has Moderate capacity factor (0.19) and hydrogen production (244.13 kg/yr); Sétif has Lower capacity factor (0.19) and energy output (12.20 MWh/yr); Djelfa has Highest capacity factor (0.35) and energy production (30.76 MWh/yr) in this region, along with strong hydrogen output (439.49 kg/yr).

Table 4. Renewable sources at a heigh of 24 m.

Site	k	c (m/s)	v (m/s)	V_m^3	P_w(W/m²)
Coastal region					
Annaba	3.21	5.18	4.64	135.07	82.73
Skikda	1.91	5.08	4.51	184.12	112.78
Bejaia	3.24	4.44	3.98	84.96	52.04
Algiers	1.87	5.59	4.96	249.18	152.62
Oran	2.49	5.97	5.30	234.96	143.91
Highland region					
Tébessa	1.85	4.57	4.06	138.13	84.60
Sétif	3.03	5.30	4.74	148.26	90.81
Djelfa	1.96	6.38	5.65	351.85	215.51
South region					
Adrar	2.71	8.55	7.60	656.10	401.86
Béchar	1.81	5.26	4.67	216.89	132.84
Ghardaïa	1.86	4.97	4.41	176.72	108.24
In Amenas	2.52	5.61	4.98	193.11	118.28
Tamanrasset	1.59	6.61	5.93	520.38	318.73

For South Region: Adrar has the highest capacity factor (0.51), power output (5.1 kW), and yearly energy production (44.32 MWh/yr), with the most hydrogen produced in the table (633.16 kg/year); Béchar: Good capacity factor (0.26) and energy output (23.12 MWh/yr); Ghardaïa: Moderate production figures; In Amenas: Strong hydrogen production with good energy metrics; Tamanrasset: High-capacity factor and notable hydrogen output.

Table 5. Evaluation of electricity and hydrogen production of the selected cites.

Site	Capacity factor	Power (kW)	Yearly energy (MWh/yr)	H_2 production (kg/year)
Coastal region				
Annaba	0.12	1.16	10.16	145
Skikda	0.236	2.362	20.7	296
Bejaia	0.067	0.671	5.882	84
Algiers	0.29	2.870	25.145	359.22
Oran	0.256	2.562	22.44	320.62
Highland region				
Tébessa	0.19	1.951	17.089	244.13
Sétif	0.14	1.393	12.20	174.323
Djelfa	0.35	3.512	30.76	439.49
South region				
Adrar	0.51	5.1	44.32	633.16
Béchar	0.26	2.640	23.12	330.316
Ghardaïa	0.231	2.308	20.216	288.801
In Amenas	0.305	3.048	26.698	381.405
Tamanrasset	0.4	3.989	34.943	499.181

The Table 6 presents the cost analysis related to hydrogen production across various sites in different regions. The regional analysis shows that for the Coastal Region: Annaba: Relatively high cost per kg of hydrogen ($7.60); Skikda: Best cost per kg ($3.89) and low cost per kWh, indicating efficient production; Bejaia: High cost per kg ($12.89), suggesting less efficient production; Algiers: Very low cost per kg ($3.26) and the lowest cost per kWh ($0.042); Oran: Competitive hydrogen production costs ($3.62).

Table 6. Cost analysis of hydrogen production.

Site	PVC ($)	Cost per unit of electricity ($ /kWh)	Total Cost of H_2 ($)	Cost per unit of H_2 ($ /kg)
Coastal region				
Annaba	21134.25	0.104	22060	7.6
Skikda	21134.250	0.051	23019.805	3.894
Bejaia	21134.250	0.180	21670.268	12.89
Algiers	21134.250	0.042	23425.877	3.261
Oran	21134.250	0.047	23179.658	3.615
Highland region				
Tébessa	21134.250	0.062	22691.701	4.647
Sétif	21134.250	0.087	22246.342	6.381
Djelfa	21134.250	0.034	23937.969	2.723
South region				
Adrar	21134.250	0.024	25173.510	1.988
Béchar	21134.250	0.046	23241.502	3.518
Ghardaïa	21134.250	0.052	22976.654	3.978
In Amenas	21134.250	0.040	23567.422	3.090
Tamanrasset	21134.250	0.030	24318.777	2.436

Table 7. Cost breakdown for hydrogen production infrastructure.

Site	Turbine cost ($)	Turbine cost (%)	Electrolyzer cost ($)	Electrolyzer cost (%)
Coastal region				
Annaba	21134.25	96	925.77	4
Skikda	21134.25	92	1885.56	8
Bejaia	21134.25	89	2657.37	11
Algiers	21134.25	90	2291.63	10
Oran	21134.25	91	2045.41	9
Highland region				
Tébessa	21134.25	93	1557.45	7
Sétif	21134.25	95	1112.09	5
Djelfa	21134.25	88	2803.72	12
South region				
Adrar	21134.25	84	4039.26	16
Béchar	21134.25	91	2107.25	9
Ghardaïa	21134.25	92	1842.40	8
In Amenas	21134.25	90	2433.17	10
Tamanrasset	21134.25	87	3184.53	13

For the Highland Region: Tébessa: Moderate costs with $4.65 per kg of hydrogen; Sétif: Higher cost per kg ($6.38) despite a reasonable electricity cost; Djelfa: Lowest cost per kg of hydrogen in the region ($2.72), showcasing strong efficiency.

For the south region: Adrar: The lowest cost per kg of hydrogen overall ($1.99), highlighting very efficient production; Béchar: Reasonable costs at $3.52 per kg; Ghardaïa: Competitive cost of $3.98 per kg; In Amenas: Low cost per kg ($3.09) and good efficiency; Tamanrasset: Low cost per kg ($2.44), indicating effective production.

The Table 7 presents the cost breakdown for hydrogen production infrastructure across different regions in Algeria, with a focus on two main components: turbines and electrolyzer.

Coastal Region: Here, the turbine cost percentage is generally high (ranging from 89% to 96%), suggesting that most of the investment goes into electricity generation rather than the electrolyzer.

Highland Region: Sites in this region have moderately high turbine cost percentages (ranging from 88% to 95%). Djelfa has the highest electrolyzer cost percentage at 12%.

South Region: The turbine cost percentage is slightly lower in the South (ranging from 84% to 91%), indicating that electrolyzer have a more substantial share of the budget in this region. For example, Adrar has an electrolyzer cost percentage of 16%, the highest in the table, due to higher hydrogen production requirements.

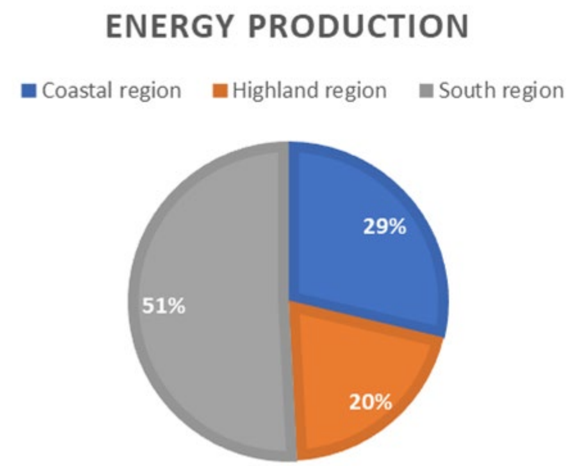

Figure 6. Energy production in different regions.

This pie chart presented in Figure 6 shows the distribution of energy production across three regions in Algeria: Coastal, Highland, and South. Coastal Region contributes 29% of the total energy production. Highland Region contributes 20% of the total energy production. However, South Region has the largest share, contributing 51% of the total energy production. As a result, the south region produces more than 50 % of the total energy produced for the same wind turbine.

7. Conclusion

The present study find that Adrar stands out as the most efficient site overall, demonstrating high production across all metrics. The Coastal region generally shows lower capacity factors and energy production compared to other regions. Djelfa, located in the Highland region, has notable energy production and capacity factors, significantly contributing to hydrogen production. There is a clear correlation between higher energy production and hydrogen output across most sites.

In terms of cost efficiency, Adrar is the most economically viable site for hydrogen production, offering the lowest costs for both electricity and hydrogen production. Additionally, sites like Algiers and Djelfa have particularly low electricity production costs, which enhances the overall economic feasibility of hydrogen production.

Regarding regional variability, the South region generally offers more favorable costs for hydrogen production, while the Coastal region shows greater cost variation. This study can be a valuable resource for evaluating the economic feasibility of hydrogen production at different sites, guiding investment decisions and operational strategies.

Furthermore, the findings suggest that in regions with higher hydrogen production potential, such as the South, a larger portion of the budget is allocated to electrolyzer. In contrast, the Coastal and Highland regions allocate more towards turbines, reflecting local renewable energy availability and hydrogen production demands. This aligns with previous data indicating that the South region has the highest potential for wind energy generation, making it a primary area for hydrogen production. The Coastal and Highland regions, with lower energy production, contribute less to the overall hydrogen production capacity compared to the South.

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