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Wind Turbine-Fuel Cell Power System for Supplying Isolated Sites

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Abstract

The present work aims to develop a dynamic Wind Turbine-Fuel Cell (WT-FC) hybrid power system under Simulink to meet the energy needs of dwellings in the south of Algeria. The Enercon E40 wind turbine model with a rated power of 500 kW was selected. Simulations were performed for four sites, namely Tinfouye, Belkbir, Tabelbala and Tindouf using daily wind data ranging between 2004 and 2018. The results indicated that Tindouf has a high mean speed of 5.57 m/s at 10 m, resulting in a power density of 194 W/m^2. However, a low average speed of 4.81 m/s is recorded at the site of Tabelbala. The maximum energy production is recorded at Belkbir reaching 4183.96 MWh/year with 0.9141 C$/kWh. Therefore, a high-power density of 239 W/m^2 was noted in Tabelbala. In the environmental analysis, Belkbir was found to have the highest avoided carbon dioxide (CO_2) emission rate of 1829.64 tons CO_2/kWh.

Keywords: Wind energy, hydrogen, electrolyzer, Fuel cell, isolated.

1. Introduction

Many researchers have assessed wind resources and conducted statistical analyses of wind potential in southern Algeria [1]-[2]-[3]. In 2019, Abderrahim updated the Algerian wind map based on hourly wind data collected over a period of more than 30 years [4]. Bouchiba also contributed to a study on the feasibility of implementing a 60 megawatt (MW) wind power plant in the Laghouat region [5]. A study was conducted on the potential of a 10 MW wind farm in Adrar in the southern region of Algeria, considering different types of wind turbines [6]. The windiest regions of Algeria are located in the southern part of the country, with average annual winds ranging from 5 to 6 m/s at a height of 10 meters [7]. This significant wind potential is sufficient to power isolated areas where extending the national grid would be excessively costly. However, due to the intermittent nature of wind energy and the mismatch between supply and demand, it is necessary to store it. The use of hydrogen as a means of storage has been widely considered. In this case, wind energy provides the necessary power and excess energy is used to produce hydrogen. The produced hydrogen can then be converted back into electricity using a fuel cell if wind energy is insufficient to meet energy needs. Hybrid systems thus provide a solution to combat increasing CO_2 emissions and insufficient electricity supply in isolated areas [8]-[9].

Further research has been conducted to verify if these systems are reliable enough to meet energy needs [10]. Additionally, a microgrid powered by a hybrid solar PV-battery-hydrogen system has been identified as promising [11]-[12].

Several studies using Simulink models have been conducted. In 2013, a hydrogen-based energy system model was presented, created using Simulink [13]. A Simulink model of an energy system consisting of a photovoltaic system, a PEM electrolyzer, and a hydrogen storage system was presented [14]-[15]. Additionally, another model of a hybrid energy system using Matlab/Simulink was presented, which utilizes solar energy, lithium-ion or lead-acid batteries, and hydrogen storage [16]-[17]. In 2020, Firtina-Ertis conducted a study examining the feasibility and optimal sizing design of an autonomous wind/hydrogen hybrid power system for a house in Catalca, Turkey [18].

In recent work, Gonçalo Calado and Rui Castro identified key characteristics of integrating hydrogen solutions into offshore wind power [19]. Cheng Cheng and Llewelyn Hughes studied the role of offshore wind power in producing renewable hydrogen in Australia [20]. In 2023, Komorowska developed a Monte Carlo-based framework to assess the competitiveness of hydrogen production from offshore wind power [21]. Additionally, Carta evaluates wind energy sources in the coastal and offshore regions of the Persian Gulf and the Oman Sea using numerical simulation and satellite data, highlighting maximum and minimum wind speeds as well as areas with maximum extractable wind energy [22].

The objective of this study is to provide a techno-economic and environmental analysis of hydrogen production using low and high-temperature electrolyzers powered by renewable and waste heat energy sources. It also aims to evaluate the profitability of these solutions as well as their CO_2 emissions.

2. Study areas and wind data

A hot and arid desert climate is a characteristic of the selected isolated regions, which are located in the south of the country. As shown in Figure 1, we have identified the geographical locations of the isolated study sites.

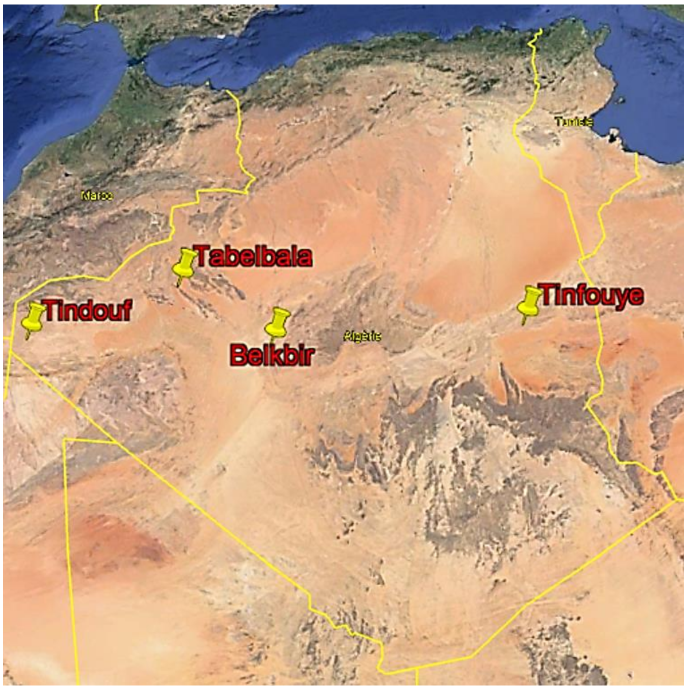


Fig 1. Geographical sites

The geographical coordinates of the selected sites are shown in Table 1.

Table 1. Geographical coordinates of the sites

Site	Latitude (°)	Longitude (°)	Altitude (m)	Vmean at 10 m (m/s)
Tinfouye	28.43	7.55	475	4.92
Belkbir	27.84	-0.19	278	5.51
Tabelbala	29.42	-3.25	564	4.81
Tindouf	27.67	-8.13	431	5.57

Daily wind data ranging from 2004 to 2018, provided by the National Office of Meteorology (ONM) are used.

3. Methodology

3.1 Study objective

This study develops a dynamic model of a hybrid system consisting of a wind turbine, electrolyzer, and fuel cell under a Simulink environment in order to provide energy to four isolated sites in the south of Algeria, Tinfouye, Belkbir, Tabelbala, and Tindouf. As a result of the energy excess, hydrogen is produced and can be reused as needed. In figure 2, we can see a descriptive diagram.

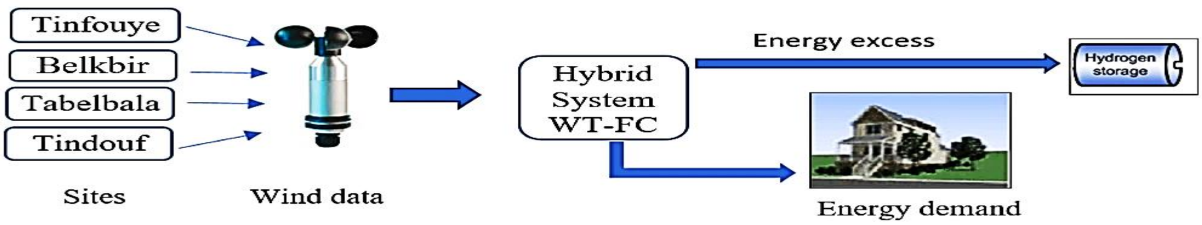


Fig 2. Descriptive diagram

3.2 Energy demand

Consumption is high during the winter season reaching a maximum of 214.67 kW in January. However, the energy demand is very low during the other seasons, reaching a minimum of 27.23 kW in May (Fig. 3).

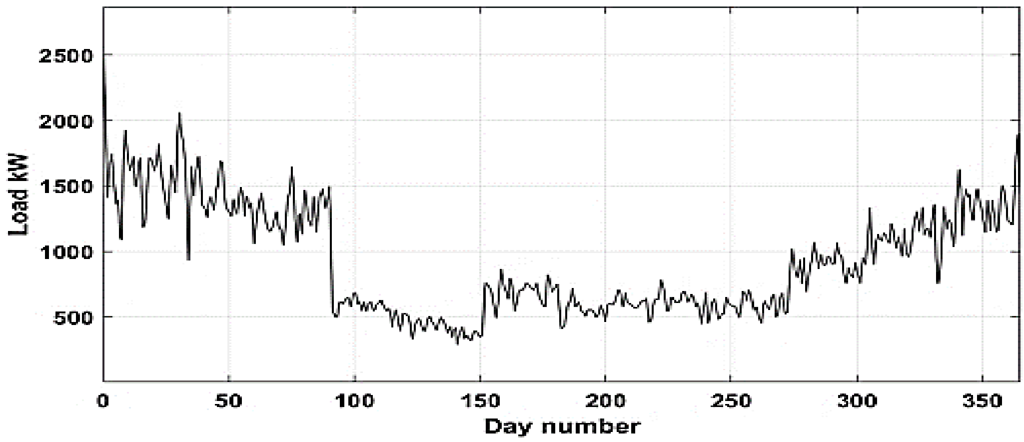


Fig 3. The charge of the 10 houses of the different sites

3.3 Wind turbine characteristics

The power curve of the selected wind turbine is shown in Figure 4.

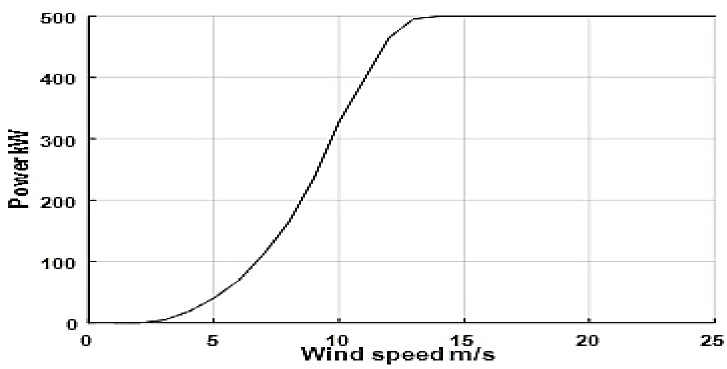


Fig 4. Power curve of the Enercon E40 wind turbine

3.4 System description

As shown in Figure 5, the developed system includes a number of different blocks.

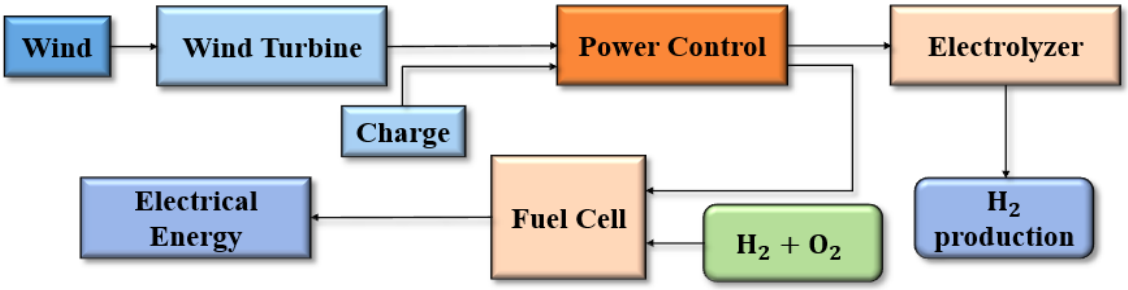


Fig 5. System components

The wind generator provides the energy needed and the excess energy is used to generate hydrogen. The generated hydrogen is then stored to be converted into electricity using a fuel cell in the case where wind energy is not sufficient to provide the required energy needs.

3.5 Modeling

The Weibull distribution is often an adequate approximation for the wind speed distribution and provides a satisfactory fitting of wind speed [22]. The measured data can be sorted into wind speed classes of 1 m/s each. It is used to evaluate the effectiveness of wind potential. The probability density function f(V) is given as follows [23]:

$$f(V) = \left(\frac{k}{V}\right)\left(\frac{V}{C}\right)^{k-1} \exp\left[-\left(\frac{V}{C}\right)^{k}\right] \quad (1)$$

The power density as a function of the Weibull parameters is estimated using the following [24]:

$$DP = \frac{1}{2} \times \rho \times C^3 \times \Gamma\left(1 + \frac{3}{k}\right) \quad (2)$$

We can also estimate the average energy density in a given site over a period defined as follows [25]-[26]:

$$DE = DP \times T \quad (3)$$

The rate of hydrogen production in an electrolyzer is given by the following [27]:

$$n_{H_2} = \frac{\eta_F \times n_C \times i_e}{2 \times F} \quad (4)$$

Where: i_e is the electrolyzer current. n_C is the number of electrolyzer cells in series. η_F is the Faraday efficiency which is the ratio between the real and theoretical quantity of hydrogen produced in the electrolyzer, it can be given by following:

$$\eta_F = 95.5 \times \exp\left(\frac{0.09}{i_e} - \frac{75.5}{{i_e}^2}\right) \tag{5}$$

The quantity of hydrogen and oxygen consumed in the fuel cell depends on the input and output flow rates, the current extracted from the fuel cell and also on the volume of the electrodes.
The different partial pressures are given as follows [28]:

$$P_{H_2} = \frac{{}^{1}/_{K_{H_2}}}{\tau_{H_2} \times S + 1} \times \left(q_{H_2}^{in} - 2 \times K_r \times I\right) \tag{6}$$

$$P_{O_2} = \frac{{}^{1}/_{K_{O_2}}}{\tau_{O_2} \times S + 1} \times \left(q_{O_2}^{in} - K_r \times I\right) \tag{7}$$

$$P_{H_2O} = \frac{{}^{1}/_{K_{H_2O}}}{\tau_{H_2O} \times S + 1} \times (2 \times K_r \times I) \tag{8}$$

Where τ_{H_2} is hydrogen time constant (s):

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2} \times R \times T} \tag{9}$$

Similarly, oxygen time constant and water time constant can be obtained.
The thermodynamic potential E is [7]:

$$E = \left[E_0 + \frac{R \times T}{2 \times F} \times \log\left(\frac{P_{H_2} \times P_{O_2}^{1/2}}{P_{H_2O}}\right)\right] \tag{10}$$

The ohmic voltage losses of fuel cell is [27]:

$$\eta_{ohmic} = -I \times R_{int} \tag{11}$$

The overvoltage due to the activation resistance is [28]:

$$\eta_{act} = -B \times \ln(C \times I) \tag{12}$$

The fuel cell output voltage can be determined from the combined effect of thermodynamics, mass transport, kinetics and ohmic resistance, it is defined as follows [28]:

$$V = E + \eta_{act} + \eta_{ohmic} \tag{13}$$

The power of the fuel cell is a function of current and voltage, it is defined by the following [7]:

$$P = V_{stack} \times I \tag{14}$$

3.6 Energy cost

The estimated cost per kWh of energy produced using wind energy is done as follows [6]:

$$CE = \frac{PVC}{E_P \times t} \tag{15}$$

Where PVC is the present value cost.

3.7 Carbone dioxide emissions

Power generation from wind energy has the benefit of not contributing to global warming. It produces around 12.7 gCO_2/kWh of electricity generated, compared with about 450 gCO_2/kWh for gas-fired power stations. [29]- [30].

4. Results and discussions

4.1 Statistical analysis at 10 m

4.1.1 Annual Weibull distribution at 10 m

As can be seen from Figure 6, Tindouf has the largest range of wind speeds (30 m/s), with a mean speed of 5.57 m/s. However, Tabelbala has 239 W/m² mean annual power density and a mean annual energy density of 2093.64 kWh/m².

According to the high value of the scale parameter and the value of the shape parameter, we deduce that these sites have steady and regular wind speeds.

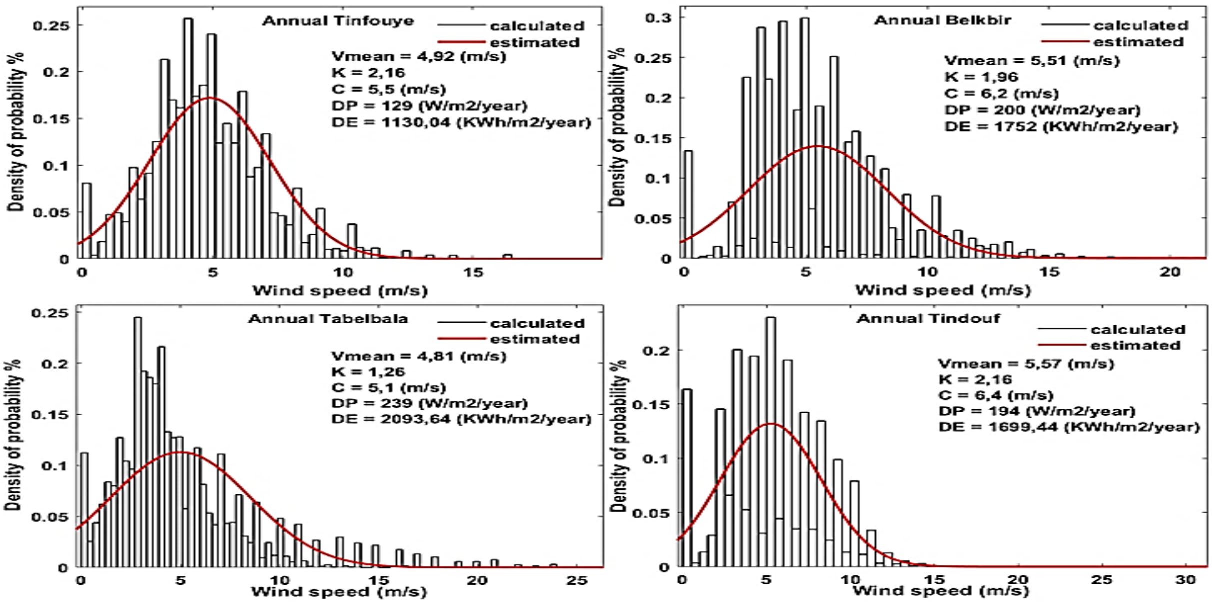


Fig 6. Weibull distribution at 10 m

4.1.2 Annual wind roses at 10 m

In Figure 7, we see that there are very high frequencies for the region of Tindouf, with approximately 23 % for the dominant direction West North West (WNW), and with 21.2 % for the predominant direction West (W).

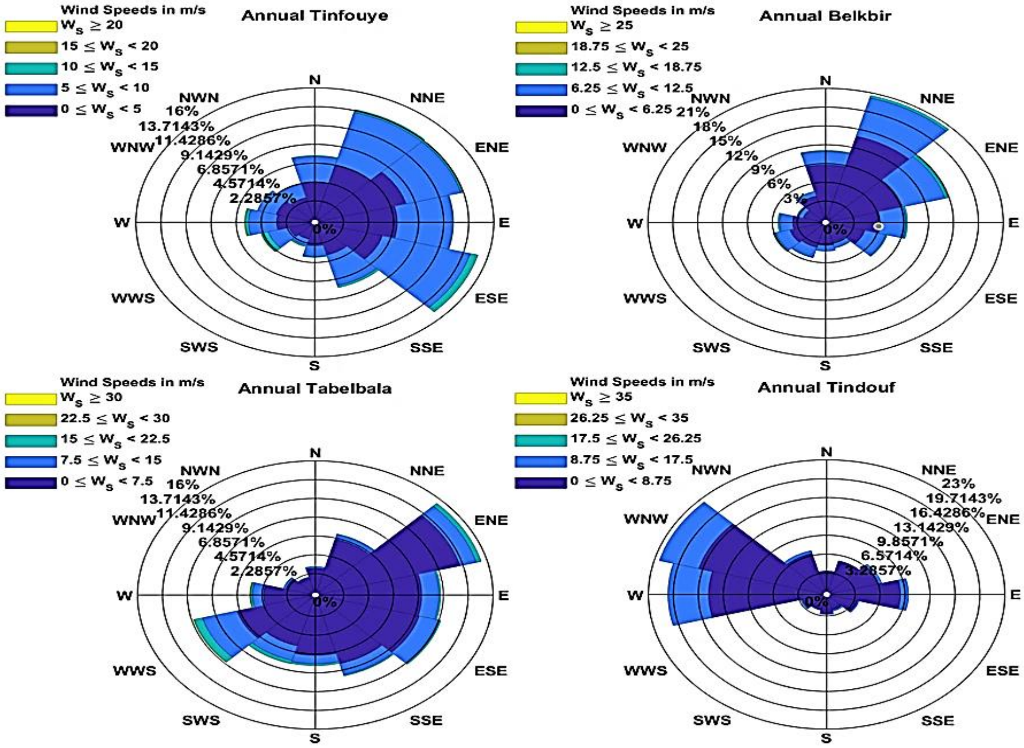


Fig 7. Wind roses at 10 m

4.1.3 Monthly speed variation at 10 m

The mean monthly wind speed ranges from 3.46 m/s in December to 8.34 m/s in June at the Tabelbala site (Fig. 8).

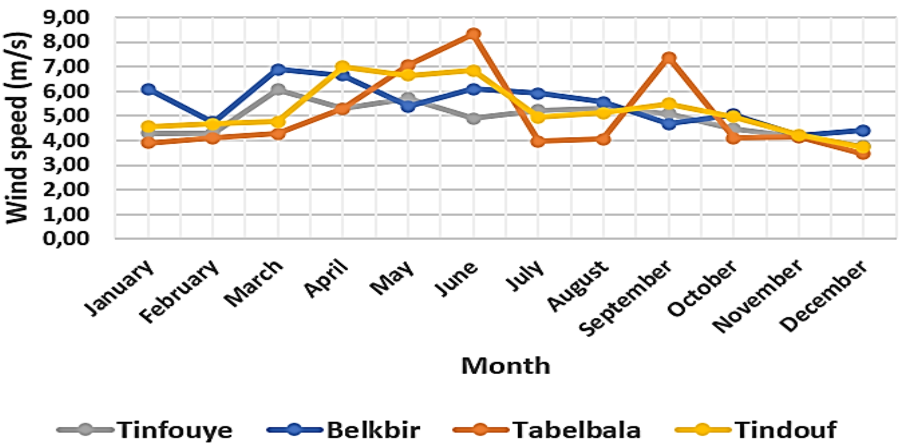


Fig 8. Monthly variation of the average wind speed at 10 m from the ground

4.2 Analysis at hub height

4.2.1 Wind speed data at 70 m

The mean wind speeds are 11.27 m/s for Tinfouye, 12.37 m/s for Belkbir, 11.39 m/s for Tabelbala, and 11.87 m/s for Tindouf. The evolution of wind speed at 70 m is shown in Figure 9.

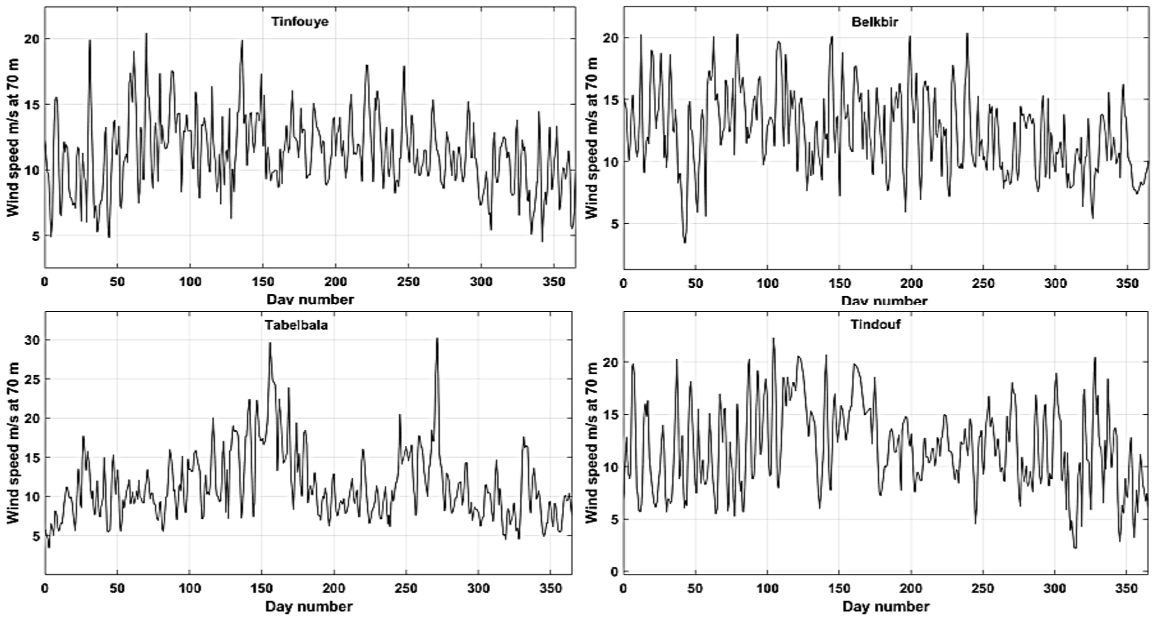


Fig 9. Wind speed at 70 m

4.2.2 Energy produced at 70 m

At a height of 70 meters above the ground, the energy production varies continuously throughout the year. Belkbir has the highest average wind power at 389.13 kW.

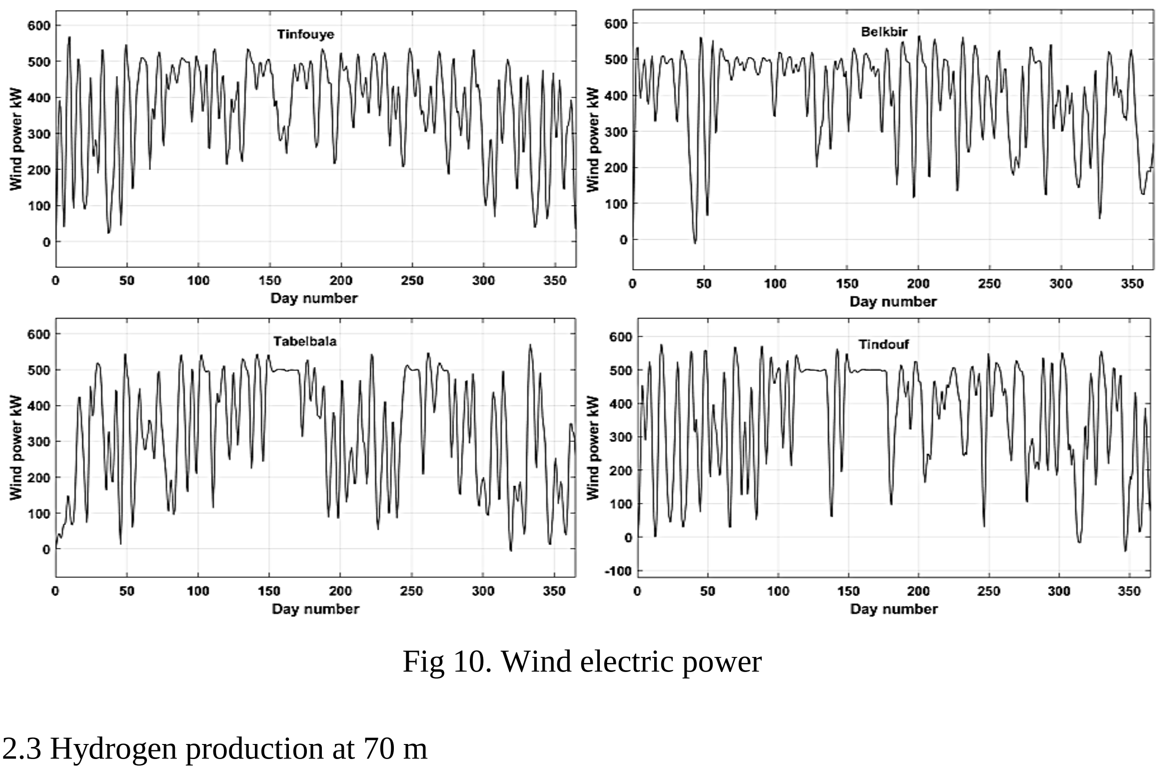


Fig 10. Wind electric power

4.2.3 Hydrogen production at 70 m

The excess wind energy is used to generate hydrogen. Tinfouye produces the highest average quantity of hydrogen (0.00127 kmol/s).

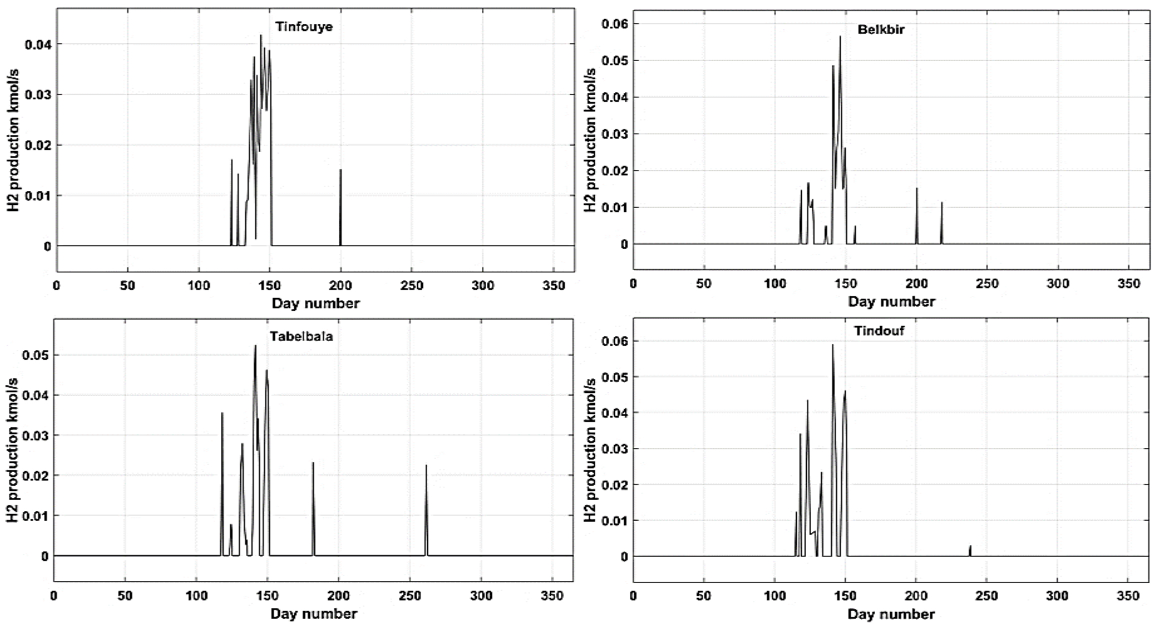
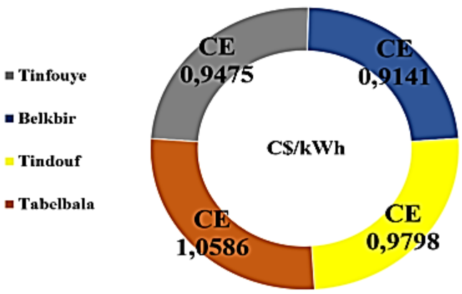


Fig 11. Hydrogen production

4.3 Economic and environmental analysis

Belkbir has the lowest cost of energy production about 0.9141 C$/kWh. An important amount of carbon dioxide (CO_2) is avoided by the E40 (1829.64 tons CO_2/kWh).



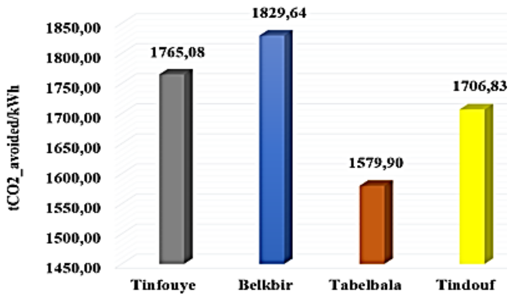


Fig 12. Energy production costs

Fig 13. CO_2 quantities avoided

5. Conclusions

Renewable energies are becoming increasingly prevalent in the production of electricity. Therefore, new technologies have been developed, such as hybrid autonomous systems, which combine renewable energies with other sources of energy.

According to the wind data provided by the National Office of Meteorology (O.N.M) for a period of 15 years (2004-2018), these four isolated regions of Algeria (Tinfouye, Belkbir, Tabelbala, Tindouf) seem to have an interesting wind potential with a mean annual speed of 4.92 m/s, 5.51 m/s, 4.81 m/s, and 5.57 m/s respectively at 10 m above the ground. We deduce that wind farms with standalone hybrid systems of the Wind-Electrolyzer-Fuel Cell (WG-FC) type are expected to be installed on these four sites. To analyze the dynamic behavior of this system, a simulation program using Matlab/Simulink was developed. An example simulation was applied to the four reported sites with available meteorological data. The results obtained showed that the Enercon E40 wind turbine allows energy production for the four sites (Tinfouye, Belkbir, Tabelbala, and Tindouf) of 4036.32 MWh/year, 4183.96 MWh/year, 3612.85 MWh/year and 3903.12 MWh/year and a production cost of 0.9475 C$/kWh, 0.9141 C$/kWh, 1.0586 C$/kWh and 0.9798 C$/kWh respectively at the height of 70 m.

The use of wind energy as a source of energy reduces the quantity of CO_2 that is emitted into the atmosphere by 97.18 percent. It is for this reason that this installation is very advantageous, as it provides isolated sites, as well as preserving the environment.

6. References

[1] BENMEDJAHED, Miloud, MAOUEDJ, Rachid, et MOUHADJER, Samir, Wind energy resource assessment of desert sites in Algeria: energy and reduction of CO_2 emissions, International Journal of Applied Power Engineering (IJAPE) 2020; vol. 9, no 1, p. 22.

[2] Benmedjahed, M., Maouedj, R., Mouhadjer, S., Menni, Y., Ameur, H., Dahbi, A., Saba, D., Touahri, T. "Analysis of the wind resources in Saharan Atlas of Algeria: Adrar region as a case study." Iranian (Iranica) Journal of Energy & Environment 2021; 12.2: 155-160.

[3] Fares Meziane, Farouk Chellali, Kamal Mohammedi, Ilyes Nouicer & Nourdine Kabouche. Wind flow simulation and characteristics prediction using WAsP software for energy planning over the region of Hassi R'mel. International Journal of Green Energy 2021; 18 : 6, 634-644.doi : 10.1080/15435075.2021.1875470.

[4] Abderrahim A., Ghellai N., Bouzid Z., Menni Y. Wind energy resource assessment in south western of Algeria. Mathematical Modelling of Engineering Problems, 2019; Vol. 6, No. 2, pp. 157-162.

[5] Oumelkhier BOUCHIBA, Tahar MERIZGUI, Bachir GAOUI, Saliha CHETTIH, Ali CHEKNANE. 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. Romanian Journal of Information Technology and Automatic Control 2022; Vol. 32, No. 4, 45-58.

[6] Said Diaf, Gilles Notton, Djamila Diaf. Technical and economic assessment of wind farm power generation at Adrar in Southern Algeria, Energy Procedia 2013; 42, 53 – 62.

[7] Meziane, F.; Khellaf, A.; Chellali, F. Study and dimensioning of a Wind-Electrolyzer-Fuel cell system for the power supply of an isolated site. Renewable Energy Review SIENR'12 Ghardaïa 2012 ; 381 – 391.
[8] M. Belatel, F. Benchikh, Z. Simohamed, F. Ferhat et F.Z. Aissous. Technologie du couplage d'un système hybride Technologie du couplage d'un système hybride à combustible pour la production de l'électricité verte. Constantine, Revue des Energies Renouvelables Vol. 14 N°1 (2011) 145 – 162, Mars 2011.
[9] Gabour, A. ; Metatla, A. Optimal design and comparison between renewable energy, hybrid energy and non-renewable energy systems : case of Skikda, Algeria. Constantine, Third International Conference on Energy, Materials, Applied Energetics and Pollution, October 30-31, 2016.
[10] N'guessan S. Attemene, Krehi S. Agbli, Siaka Fofana, Daniel Hissel. Optimal sizing of a wind, fuel cell, electrolyzer battery and supercapacitor system for off-grid applications. 25 May 2019.
[11] Dawood, F.; Shafiullah, G.M.; Anda, M. Stand-Alone Microgrid with 100% Renewable Energy: A Case Study with Hybrid Solar PV-Battery-Hydrogen. Sustainability 2020; 12, 2047.
[12] Mohseni, S.; Brent, A.C.; Burmester, D. A comparison of metaheuristics for the optimal capacity planning of an isolated, battery-less, hydrogen-based micro-grid. Applied Energy 2019; 259, 114224.
[13] Trifkovic, M.; Sheikhzadeh, M.; Nigim, K. Modeling and control of a renewable hybrid energy system with hydrogen storage. IEEE Trans. Control Syst. Technology 2013 ; 22, 169–179.
[14] Albarghot, M.; Sasi, M.; Rolland, L. MATLAB/Simulink modelling and experimental results of a PEM electrolyzer powered by a solar panel. In Proceedings of the IEEE Electrical Power and Energy Conference (EPEC), Ottawa, ON, Canada, 12–14 October 2016; pp. 1–6.
[15] Muhammad Maaruf1, Muhammad Khalid. Hybrid Solar/ PEM Fuel Cell/ and Water Electrolyzer Energy System for All-Electric Ship 2022; IEEE Kansas Power and Energy Conference (KPEC).
[16] Bati Ernest Boya Bi, Prosper Gbaha, Magloire Paul Ekoun Koffi, Kamenan Blaise Koua. Modélisation Des Composants D'un Système Hybride Panneaux Photovoltaïque – Stockage D'énergie Via L'hydrogène – Batteries, European Scientific Journal January 2018 ; edition Vol.14, No.3 ISSN : 1857 – 7881 (Print) e - ISSN 1857- 7431.
[17] Möller, M.C. ; Krauter, S. Hybrid Energy System Model in Matlab/Simulink Based on Solar Energy, Lithium-Ion Battery and Hydrogen. Energy 2022; 15, 2201.

[18] Firtina-Ertis, Irem; Acar, Canan; Erturk, Ercan. Optimal sizing design of an isolated stand-alone hybrid wind-hydrogen system for a zero-energy house. Applied Energy 2020; 274: 115244.

[19] Calado, Gonçalo, and Rui Castro. Hydrogen production from offshore wind parks: Current situation and future perspectives. Applied Sciences 2021;11.12:5561 doi.org/10.3390/app11125561.

[20] Cheng, C., & Hughes, L. The role for offshore wind power in renewable hydrogen production. Journal of Cleaner Production 2023; 136223.

[21] Komorowska, A., Benalcazar, P., & Kamiński, J. Evaluating the competitiveness and uncertainty of offshore wind-to-hydrogen production: A case study of Poland. International Journal of Hydrogen Energy 2023.

[22] Ghafarian, P., & Mohammadpour Penchah, M. Wind resource assessment over the Persian Gulf and Oman Sea using a numerical model simulation and satellite data. Journal of Ocean Engineering and Marine Energy 2023 ; 1-10.

[22] Carta, J.A.; Ramirez, P.; Velazquez, S. A review of wind speed probability distributions used in wind energy analysis. Cases studies in the Canary Islands. Renewable and Sustainable Energy Reviews, Volume 13, Issue 5, June 2009; Pages 933-955.

[23] Hulio, Z.H.; Jiang, W.; Rehman, S. Technical and economic assessment of wind power potential of Nooriabad, Pakistan. Energy, Sustainability and Society 2017; vol. 7, no. 1, p. 35.

[24] Patel, M.R. Wind and solar power systems. Florida, America : CRC Press 1999.

[25] Keyhani, A.; Ghasemi-Varnamkhasti, M.; Khanali, M.; Abbaszadeh, R. An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran. Energy 2010;35(1):188-201.

[26] Islam, M.R.; Saidur, R.; Rahim, N.A. Assessment of wind energy potentiality at Kudat and Labuan, Malaysia using Weibull distribution function. Energy 2011; 36;985-992.

[27] Khan, M.J.; Iqbal, M.T. Dynamic Modeling and Simulation of a Small Wind-Fuel Cell Hybrid Energy System, Renewable Energy 2005; Vol. 30, N°3, pp. 421 – 439.

[28] Uzunoglu, M.; Alam, M.S. Dynamic Modeling, Design, and Simulation of a Combined PEM Fuel Cell and Ultracapacitor System for Stand-Alone Residential Applications. IEEE Transactions on Energy Conversion 2006; 21(3), 767–775.

[29] Ardente, F.; Beccali, M. ; Cellura, M. ; Lo Brano, V. Energy performances and life cycle assessment of an Italian wind farm. Renewable and Sustainable Energy Reviews 2008; 12: 200–217.

[30] Haddouche, S.K.; Boudia, S.M. Wind Resource Assessment at Illizi Site in the Algerian Sahara with Environmental Analysis. 7th International Renewable and Sustainable Energy Conference (IRSEC) 2019; Agadir, Morocco 1-6.