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Temitope Raphael Ayodele , [Thapelo Mosetlhe](#) * , [Adedayo Ademola Yusuff](#) ,
Ayodeji Samson Olatunji Ogunjuyigbe

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Article

Energy, Economic and Environmental (3E) Assessment of Wind Powered Electricity Generation with Hydrogen Storage in Vesleskarvet, Antarctica

Ayodele T.R ¹, Mosetlthe T.C ^{2*}, Yusuff A.A ² and Ogunjuyigbe A.S.O ¹

¹ Power Energy Machine and Drive Research Group (PEMD), Department of Electrical and Electronic Engineering, Faculty of Technology, University of Ibadan, Ibadan, Nigeria

² Department of Electrical Engineering, College of Science, Engineering and Technology, University of South Africa, Florida Campus. South Africa

* Correspondence: mosettc@unisa.ac.za; Tel.: +27711854301

Abstract

Clean and sustainable electricity could be generated from hydrogen produced from renewable energy resources. This paper performs assessment of Energy, Economic and Environmental (3E) potentials of hydrogen/fuel cells for electricity generation in Vesleskarvet. This site is a remote area located in Antarctica and is being used as the base for South African National Antarctic Programme (SANAE IV). The hydrogen which was used as feedstock to the fuel cell was generated from the wind energy resource of Vesleskarvet using water electrolysis technique. Four large wind turbines: DE Wind D7, ServionSE MM100, Alstom E110 and Gamesa G128 designated as WT₁, WT₂, WT₃ and WT₄, respectively were selected to determine which of them best matches the wind characteristics of the site for hydrogen production. Key results reveal that the capacity factor of the wind turbines is 62.78%, 58.37%, 63.80% and 57.94%, respectively. WT₄ has the best annual hydrogen production potential of about 307 tons per annum with the cost of electricity of 2.47 \$/kWh and payback period of 5.4 years.

Keywords: electricity generation; hydrogen production; fuel cell; economic assessment; environmental benefits; South Africa

1. Introduction

Vesleskarvet is a South Africa base located in Antarctica and is basically used for research purpose throughout the year in the area of physical sciences such as biology, marine, geology, oceanography etc. [1]. Electricity and heat needs for the researchers as well as their research activities are met basically using diesel generators. In recent times, efforts are geared towards using renewable energy resources to cut down on carbon footprint as well as reduce the high cost associated with diesel fuel which accounts for the bulk of running expenses at the location [2]. Of the various renewable energy sources in Antarctica, wind was identified as a resource which could help support the required electricity and heat demands [3]. In fact, Antarctica is known to have the best wind resources in the world [4], hence the need to determine how best this resource could be harnessed for energy support.

One of the reasons wind generators are often disregarded by the utility operators is the intermittent nature of wind speeds which could change at any given time thereby creating mismatch between the demands and supply. The incessant changeability nature of wind speeds could undermine the integrity of the grids and could also lead to increase cost of ancillary services [5]. Storage technology has been identified as one of the strategies of mitigating intermittent nature of wind power and one of the identified storage technology is the use of hydrogen storage [6]. Hydrogen could be combined with fuel cells to act as a good electricity storage. While hydrogen stores electricity

in form of chemical, the fuel cells converts back into electricity and deliver to the grid when required [7]. Hydrogen therefore has the capability to mitigate the intermittency in electricity generation by providing the required balance between surplus and shortage [8]. Hydrogen can totally replace conventional fossil fuel since it has properties (both physical and chemical) that is comparable to fossil fuel. Also, environmental pollution as well as transportation cost could be highly reduced because hydrogen could be produced locally where it is needed [9]. There are various ways to produce hydrogen, however one of the sustainable ways to produce hydrogen from wind resources is through water electrolysis techniques [10,11].

Different authors have worked on the potential of hydrogen production from wind resources in different part of the world. For example, [Apostolou and Enevoldsen](#) [12] presented the potential of hydrogen as a multifunctional storage application for wind power. It was pointed out that wind-hydrogen coupled systems could support autonomous electrical networks as well as mitigate CO₂ emissions significantly. [Alavi et al](#) [13] investigated the capability of wind energy for hydrogen production in the South Eastern province of Sistan & Baluchestan in Iran. The authors utilised both the actual average wind turbine power curve and Weibull model to analyse four different wind turbines with a capacity of 300-900 kW for hydrogen production. It was found that EWT Directwind 500/54 wind turbine provided the best capacity factor among different wind turbines examined with the highest value of 50.77% at the site (Lutak). It was also reported that the turbine produced 39.82 ton of hydrogen per annum. In another separate investigation conducted by the same authors, [Alavi et al](#) [14] performed feasibility study on the use of wind energy system for hydrogen production in Chabahar. It was concluded that Vestas V164 wind turbine presented the highest hydrogen production with the yearly value of 194.36 ton per annum. [Kodicherla et al](#) [15] have analysed the hydrogen production from wind resources in three selected stations of Fiji Islands. The authors selected six different wind turbines: Polaris P15-50, Vestas V47, Polaris P50-500, Polaris P62-1000, WWD 1-60 and Vestas V110-2.0 with different rated powers and characteristics for the investigation. The authors revealed that Vestas V110-2.0 provided an highest capacity factors of 77.06% among the wind turbines for the station at Labasa in Fiji. Feasibility study on hydrogen production from wind energy resource of Ghardaia was investigated by [Aiche-Hamane](#) [16]. The study was based on the estimation of the hydrogen rate produced by a 5 kW electrolyser fed by the electricity provided by a 10 kW wind turbine. The variation in monthly hydrogen production was also studied. The authors showed that hydrogen production rate from wind-hydrogen system was greatly influenced by the height of wind turbines. It was also revealed that the maximum hydrogen production from wind resource of Ghardaia was in the month of May with the value of about 395 Nm³ while the minimum production was in the month of October with the value of 187 Nm³. In the work of [Douak and Settou](#) [17], the wind energy potential and economic analysis in three selected locations of Algeria were examined for hydrogen production. Various wind turbines were also investigated in terms of capacity factor, energy production and hydrogen generation potential. It was concluded that the cost of electricity has a strong impact on the cost of hydrogen production, followed by electrolyser expenses and investment. Generally, hydrogen production strongly depends on the site and the wind turbine selected for its production. Researches have shown that, larger wind turbines favour hydrogen production at a lower cost compared to smaller wind turbines [6], hence larger wind turbines should come to mind when hydrogen production is in focus.

Hybrid renewable energies (i.e. consisting of two or more renewable energy sources) have also been utilised for the production of hydrogen. For example, the possibility of using excess energy from hybrids between hydropower and wind power for hydrogen production in Brazil has been conducted by [Nadaleti et al](#) [18]. The authors concluded that 3 hours of hydrogen production per day using surplus energy from the hybrid renewable energy farm would generate 2×10^{10} Nm³ It was also revealed that total of 42.78 MWh per annum excess power corresponding to 4.88 kW was utilized in electrolyser per annum with the cost of energy of about 0.303 \$ /kWh. Similarly, [Sorgulu, and Dincer](#) [19] have utilised the hybrid of concentrated solar power and wind energy systems in combination with electrolyser, fuel cell and absorption cooling subsystems to supply power and

hydrogen to a residential building. The results of the study showed that the hybrid system was feasible, viable, efficient, environmentally friendly and sustainable. It was also revealed that total of 42.78 MWh per annum excess energy, corresponding to a continuous power of 4.88 kW, was utilized in electrolyser to produce hydrogen at the rate of 0.035 g/s by an electrolyser with a cell area of 50 cm².

Some researchers have also conducted researches on the economic viability of hydrogen production from wind energy generators: Ayodele and Munda [6] investigated the economic viability of hydrogen production from the wind resources of 15 locations in the coastal region of South Africa using 11 different wind turbines. It was concluded that site Napier present the best yield of hydrogen production with 226.82 metric tons of hydrogen at 1.4 \$/kg using wind turbine (Gamesa G128) having rated power of 4.5 MW, cut in wind speed of 4 m/s, rated wind speed of 13 m/s and cut-out wind speed of 18 m/s. Techno-economic analysis of hydrogen refuelling station powered by hybrid of wind and photovoltaics (PV) system was performed for Izmir-Cesme, Turkey using hybrid optimisation model for electric renewable (HOMER) software [20]. The authors revealed that the levelised cost of hydrogen production was between \$7.526-7.866/kg indicating that hydrogen refuelling station powered by renewable energy is economically feasible for Izmir-Cesme, Turkey. Iqbal *et al* [21] investigated the economic feasibility using wind energy potential of eight sites in Sindh province of Pakistan. The results showed that the wind generated renewable hydrogen is economically viable at the levelised cost of 4.02–4.310 \$/kg-H₂ depending upon the amount of wind available for power production. It was also revealed that the total wind generated electricity potential for Pakistan is 119,410 MW, which could theoretically produce an average of ~ 5200 kg/day of hydrogen annually.

While hydrogen generation potential as well as its economic viability have been evaluated for many potential sites around the world, little has been done on the electricity generation potential derivable from such green hydrogen when used as a feedstock to fuel cell in a standalone system with the objective of generating electricity. Moreover, there is paucity of literature on the environmental benefits of utilizing hydrogen-fuel electricity generator over diesel generator for remote locations. Since hydrogen can be produced at the point of use, stored and use for electricity generation when required, then hydrogen based fuel cell can be used as a substitute for diesel generators that is currently being used at SANAE IV station. Also, the variability issue associated with wind turbines can totally be eliminated. This paper therefore contributes in this direction by first evaluating the amount of hydrogen that could be produced from Vesleskarvet, and then determine the electricity generation potential from such generated hydrogen for electricity generation via fuel cells. The economic and environmental benefits of such arrangement over diesel generator were also performed.

2. Site Description and Data Collection

Vesleskarvet Nunataks is located in Antarctica and it serves as South African base for National Antarctic Expedition usually refer to SANAE IV [1]. The site is located at on latitude 71°40'22"S and longitude 2°50'26"W [22]. The site has abundance wind resources which could be a great potential for hydrogen production [23]. However, the site has a challenge of low temperature which could go as low as -40 °C during winters [24] and this could be detrimental to the operating design of wind turbines since they are designed to operate between the temperature of -10°C to +40°C [25]. In recent times, wind turbine are now equipped with heating devices that could allow wind turbine to operate in extreme weather condition and this could be deployed in a site like Veslaskarvet [26]. The data used in this study to evaluate the potential of hydrogen production obtainable from Vesleskarvet consisted of daily average wind speed obtained at the anemometer height of 10m over a period of eleven years. The data was gotten from South African Weather Service (SAWS).

3. Methodology

This section presents the models used to evaluate the wind power potential of Vesleskarvet for the purpose of hydrogen production. The electricity generation potential of hydrogen-fuel cell, the economic analysis as well as the environmental assessment models are also presented.

3.1. Wind Characteristics Model

It has generally been proved that two parameter Weibull probability distribution function could model wind speeds of many sites around the world accurately[27]. Therefore. This distribution function was adopted to model the wind speeds of Vesleskarvet as follows [28]:

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \times \exp\left(-\frac{v}{c}\right)^k \quad (1)$$

where k is the shape parameter (it has no unit) and c is the scale parameter in (m/s) and it gave the information on how good the wind resources of a site is, v is the wind speed in (m/s). Both k and c can be determined using [29]:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} ; 1 \leq k \leq 10 \quad (2)$$

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (3)$$

where v_m is the average wind speed and σ is the standard deviation of the observed wind speed, respectively. $\Gamma(\cdot)$ is a gamma function and has characteristics as follows:

$$\int_0^{\infty} \xi^{x-1} \exp(-\xi) d\xi \quad \text{and} \quad \Gamma(1+x) = x\Gamma(x) \quad (4)$$

Equations (5) and (6) can be used to determine the average wind speed (v_m) and the standard deviation (σ), respectively.

$$v_m = \frac{1}{n} \left[\sum_{i=1}^n v_i \right] \quad (5)$$

$$\sigma = \sqrt{\frac{1}{n-1} \left[\sum_{i=1}^n (v_i - v_m)^2 \right]} \quad (6)$$

where n is the number of wind speed data observed at the anemometer height and v_i is the i th observed wind speed.

Another important parameter that is used to describe the wind characteristic of a given site is the turbulence intensity (TI). It is defined as the ratio of the wind speed standard deviation to its average [30]. TI is a measure of the intensity of the wind velocity fluctuation, in a given time period, and depends on terrain, atmospheric stability and wakes from neighbouring turbines. A high level of turbulence causes the wind turbine efficiency and durability to decrease while lower turbulence results in less maintenance and better performance of wind turbine [31]. Turbulence intensity is site specific and differs from one site to another.

$$TI(\%) = \left(\frac{\sqrt{\frac{1}{n-1} \left[\sum_{i=1}^n (v_i - v_m)^2 \right]}}{\frac{1}{n} \left[\sum_{i=1}^n v_i \right]} \right) \times 100 \quad (7)$$

3.1.1. Re-Defining Wind Speed to Turbine Hub Height

Wind speeds are different at different heights, and most wind speeds are usually observed at a height different from the wind turbine hub heights. It is therefore necessary to re-define the wind speed from the observed height to the hub height of the wind turbines [32,33] using the expression as follows:

$$v_h = v \left(\frac{H_h}{H} \right)^m \quad (8)$$

where v_h is the wind speed at the hub height H_h and v is the wind speed at the observed height H . The exponential m is the factor that depends on surface roughness and atmospheric stability. It is usually in the range of 0.05-0.5, the most frequently adopted value applicable to well exposed site is 0.14 [31]. In view of the fact that the selected site for this investigation is well exposed, a value of 0.14 is therefore adopted in this study. However, shear exponent of this site could be subjected to further investigation.

3.1.2. Estimation of Capacity Factor and Electricity Generation Potentials of Wind Turbines

Capacity factor (C_f) is defined the ratio of actual energy generated by a given wind turbine over a given period of time to the energy produced from continuous operation at full rated power of the wind turbine over that period [5]. It is a function of wind regime in which the wind turbine operates as determined by the shape and scale parameter of the wind resource at the site as well as the design parameter of the wind turbine as determined by the cut in wind speed, rated wind speed and cut out wind speed of the wind turbine. The capacity factor of a wind turbine at any given site can be written as follows [34]:

$$C_f = \int_{v_{ci}}^{v_r} \frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} f(v) dv + \int_{v_r}^{v_{co}} f(v) dv \quad (9)$$

where $f(v)$ is the Weibull distribution function as given in (1), v_{ci} is the cut-in wind speed of the wind turbine, v_r is the rated wind speed of the wind turbine, v_{co} is the cut-out wind speed of the wind turbine. Equation (9) can be re-arranged to yield the following relations [35]:

$$C_f = \left(\frac{2c^2}{v_r^2 - v_{ci}^2} \right) \frac{\Gamma\left(\frac{2}{k}\right)}{k} \times \left(\gamma\left(\left(\frac{v_r}{c}\right)^k, \frac{2}{k}\right) - \gamma\left(\left(\frac{v_{ci}}{c}\right)^k, \frac{2}{k}\right) \right) - e^{-\left(\frac{v_{co}}{c}\right)^k} \quad (10)$$

where γ is the lower incomplete gamma function and has a property of (11)

$$\gamma(u, a) = \left(\frac{1}{\Gamma(a)} \right) \int_0^u x^{a-1} e^{-x} dx \quad (11)$$

Therefore, the amount of electrical energy that can be generated by any wind turbine at any given period of time in kWh can be determined using:

$$P_{Elect} = \eta_m \times \eta_g \times P_r \times C_f \times t \quad (12)$$

where C_f is the capacity factor of the wind turbine, P_r is the wind turbine rated power in kW as provided by the manufacturer, t is the time in hours within the period under consideration, η_m is the mechanical transmission efficiency due to gear box and η_g is the generator efficiency and they are both taken as 0.85 and 0.85, respectively [36]. Four large wind turbines with the technical data furnished in Table 1 are adopted in this paper for hydrogen production at the site (Vesleskarvet

Nunataks). This is because the earlier study revealed that large wind turbines are best suited for hydrogen production compared to small or medium wind turbines [6].

Table 1. Large Wind Turbine Technical Data [6].

Turbine Model	Designate	Rated Power Output(kW)	Hub Height (m)	V_{ci} (m/s)	V_r (m/s)	V_{co} (m/s)	Area (m^2)	Lifetime (Year)
DE wind D7	WT ₁	1500	70	3	12	25	3846	20
ServionSE MM100	WT ₂	2000	100	3	11	22	7854	20
Alstom E110	WT ₃	3000	100	3	11.5	25	9469	20
Gamesa G128	WT ₄	4500	140	4	13	18	12873	20

3.2. Hydrogen Production Using the Wind Regime of Vesleskarvet Nunataks

In this paper the wind resources of Vesleskarvet is utilised mainly for hydrogen production and thereafter used for electricity generation using PEM fuel cell as depicted in Figure 1.

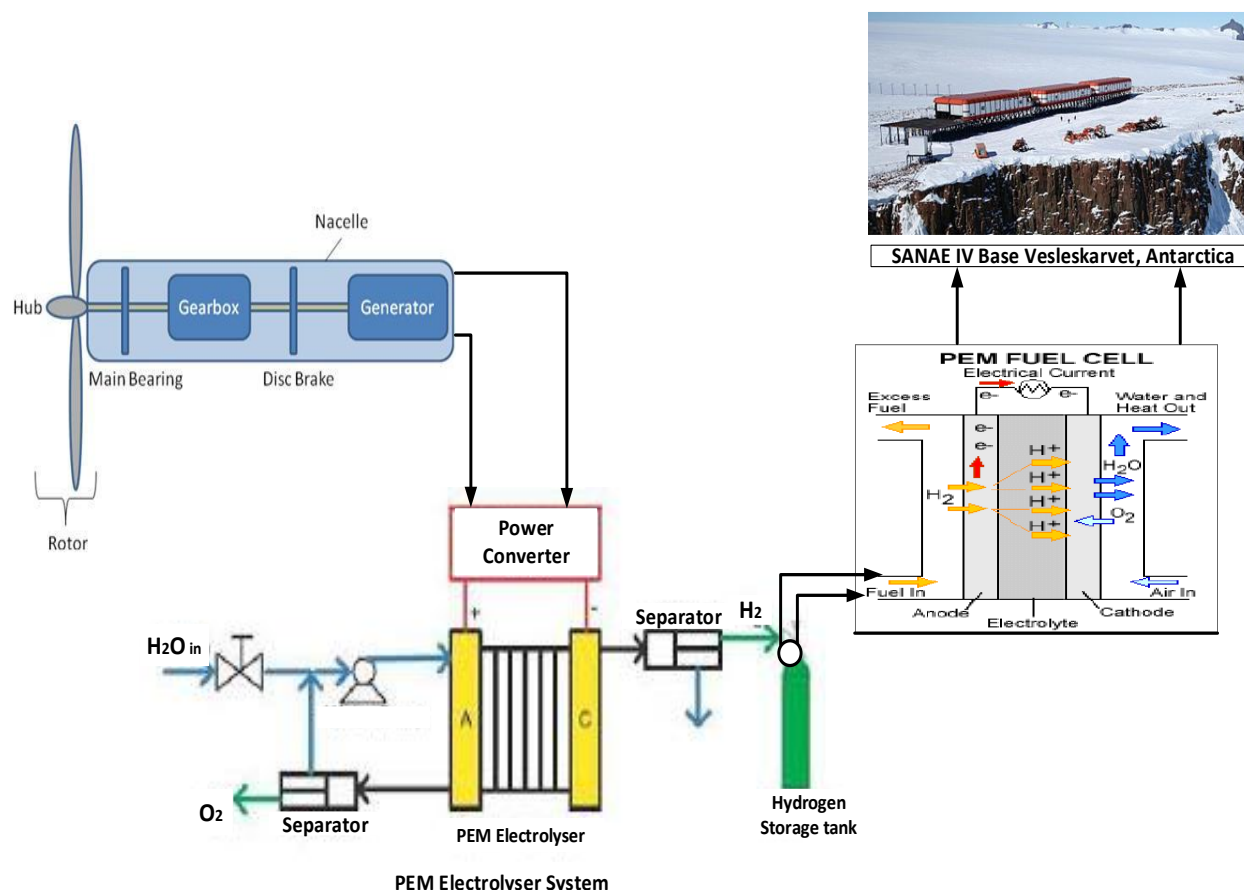


Figure 1. Schematic diagram of hydrogen production for electricity generation at SANAE IV base (Vesleskarvet, Antarctica).

With the advent of advanced power electronics and local capacitor bank, the synchronous wind turbine can be made to supply required frequency and voltage. There are two common electrolyser for hydrogen production which are the alkaline and the Proton Exchange Membrane (PEM)

electrolysers. In this paper, PEM electrolyser is adopted for hydrogen production. The PEM electrolysers first came into commercial usage in 1960s by General Electric, it uses water as an electrolyte solution and a polymer electrolyte membrane. This helps to avoid the incessant recovery and recycling of the potassium hydroxide electrolyte solution which is seeing as a disadvantage in alkaline electrolysers [37]. Moreover, PEM electrolyser has higher efficiency compared to alkaline electrolyser, it has compact units which makes it appropriate for dynamic operations, and it responds faster to load changes. However, its disadvantage is that the electrode catalysts (platinum and iridium) and membrane materials are expensive, and their lifetime is not as long as that of alkaline electrolysers.

A 900 kW capacity PEM electrolyser which requires a DC electrical energy demand of 54 kWh [38] with water requirement of about 10.6 litres [39] for every 1 kg of hydrogen production was adopted in this paper. Therefore, the amount of hydrogen (kg) from the process of water electrolysis can be estimated using:

$$M_H = \frac{P_{Elect} \times \eta_{rec}}{E_l} \quad (13)$$

where P_{Elect} is the electrical output of the wind turbine in kWh as determined in (11), η_{rec} is the rectifier efficiency and is taken as 0.9 [39], E_l is the electrolyser energy demand which is taken as 54 kWh/kg for a typical PEM electrolyser [38]. The quantity of hydrogen generated in tons-H₂ can be estimated by dividing the amount of hydrogen in kg (M_H) by 1000.

The volume of water requirement for hydrogen production in cubic meter can be written as follows:

$$W = \frac{10.6 \times M_{H_2}}{\rho_W \times 1000} \quad (14)$$

where ρ_W is the density of water (i.e. 1 kg/m³)

3.4. Storage of Generated Hydrogen

Hydrogen generated from the Vesleskarvet wind resource via water electrolysis can be stored either in liquid state in cryogenic tanks or as gas in high pressure compressed gas cylinders. In this paper, the hydrogen produced is assumed to be stored in gas state in a compressed gas cylinders.

Therefore, the volume of compressed hydrogen gas (V_{H_2comp}) in m³ can be evaluated as follows [9]:

$$V_{H_2comp} = \frac{M_H \times \eta_{comp}}{\rho_{VH_2}} \quad (15)$$

where, M_H is the amount of hydrogen produced (kg) as determined in (13), η_{comp} is the compression efficiency given as 95% [40], ρ_{VH_2} is the density of the compressed hydrogen gas given as 36 kg/m³ [41]

3.5. Electricity Generation Potential of Fuel Cell

Hydrogen based fuel cells are well known for their high efficiencies [19]. Hydrogen on its own is not an energy source but a carbon free energy carrier with high density [42]. Generated and stored hydrogen either goes directly to a fuel cell to produce electricity or through a compressor to run the fuel cell at high pressure. The amount of electricity derivable (kWh) from a fuel cell can be modelled as follows:

$$FC_{elect} = V_{H_2comp} \times LHV_{H_2} \times \eta_{fc} \times \rho_{VH_2} \quad (16)$$

where LHV_{H_2} is the lower heating value of hydrogen gas taken as 33.3 kWh/kg [43], η_{fc} is the efficiency of the fuel cell taken as 0.6 [9], ρ_{VH_2} is the density of compressed hydrogen gas in kg/m³.

3.6. Economic Model of Wind Turbine, Electrolyser and Fuel Cell

In this section, the unit cost of energy from the wind turbine, the unit cost of hydrogen production from PEM electrolyser as well as the cost of electricity generation from fuel cell generator are estimated. First, the capital costs of the wind turbine ($C_{cap(WT)}$), electrolyser ($C_{cap(El)}$), hydrogen tank (HT) and the fuel cell ($C_{cap(FC)}$) were determined from their specific costs, respectively as follows:

$$C_{cap(WT)} = S_{WT} \times Pr \quad (17)$$

$$C_{cap(El)} = S_{El} \times P_{El} \quad (18)$$

$$C_{cap(FC)} = S_{FC} \times P_{FC} \quad (19)$$

$$C_{cap(HT)} = S_{HT} \times P_{HT} \quad (20)$$

where S_{WT} , S_{El} , S_{FC} and S_{HT} are the specific cost of wind turbine, electrolyser, fuel cell and Hydrogen tank, respectively, and are taken as 115 \$/kW [44], 900 \$/kW [38], 5700 \$/kW [45], 665\$/kg, respectively. Similarly, Pr , P_{El} , P_{FC} and P_{HT} are the rated capacity of the wind turbine, electrolyser, fuel cells and Hydrogen tank which are 2000 kW, 185 kW, 250 kW and 300kg, respectively.

The unit cost of electricity from the wind turbine ($C_{Elect(WT)}$) per kWh is often calculated by discounting and levelising investment as well as operation and maintenance (O&M) costs over the lifetime of the turbine (i.e the life cycle cost (LCC)), and then dividing them by the annual electricity production as given in (21).

$$C_{Elect(WT)} = \frac{(LCC_WECS)}{P_{Elect}} \quad (21)$$

where LCC_WECS is the life cycle cost (LCC) of the wind energy conversion system and can be evaluated as follows:

$$LCC_WECS = C_{Cap(WT)} + C_{O\&M(WT)} + \sum_{a=1}^A (f_a \times C_{Cap(WT)}) \quad (22)$$

where $C_{O\&M(WT)}$ is the operation and maintenance cost associated with wind energy conversion system, A is the number of cost components taken into consideration during the calculation of LCC and in this case $A=5$ (i.e. installation, converter, civil work, battery bank and miscellaneous). The counting index f_a is the fractional percentage of cost of other components with respect to the capital cost of wind turbine. For example, f_a is taken as: f_1 = installation (10%), f_2 = converter (3%), f_3 = civil work (9%), f_4 = battery bank (9%) and f_5 = miscellaneous (7%) [29].

Similarly, the cost of hydrogen production (C_{H_2}) per m³ can be estimated as follows:

$$C_{H_2} = \left(\frac{LCC_El, HT}{V_{H_2comp}} \right) + C_{Elect(WT)} \quad (23)$$

where LCC_El, HT is the life cycle cost of the electrolyser system as well as hydrogen storage and can be evaluated as follows:

$$LCC_{El,HT} = C_{Cap(El)} + C_{O\&M(El)} + \sum_{b=1}^B (h_b \times C_{Cap(El)}) + C_{cap(HT)} + C_{O\&M(HT)} + L_c \times C_{cap(HT)} \quad (24)$$

where $C_{O\&M(El)}$ is the operational and maintenance cost associated with the electrolyser, B is the number of cost components taken into consideration in determining the LCC of the electrolyser and in this case $B=2$. h_b is taken as installation cost (12%) and stack replacement (40%) [45]. L_c is taken as the installation cost of the hydrogen tank (10%)

Also, the cost of electricity generation using fuel cell ($C_{Elect(FC)}$) per kWh can be estimated using:

$$C_{Elect(FC)} = \left(\frac{LCC_{FC}}{FC_{Elect}} \right) + C_{H_2} \quad (25)$$

where LCC_{FC} is the life cycle cost of fuel cell and can be calculated as follows:

$$LCC_{FC} = C_{Cap(FC)} + C_{O\&M(FC)} + L_d \times C_{Cap(FC)} \quad (26)$$

where $C_{O\&M(FC)}$ is the operation and maintenance cost of associating with fuel cell, L_d is taken as installation cost of fuel cell (20%).

The operation and maintenance ($C_{O\&M(.)}$) cost is the cost associated with operating and maintenance of any of the wind turbine, electrolyser, the fuel cell and the tank over their lifetime and can be determined using [34]:

$$C_{O\&M(.)} = C_{O\&M_{init}(.)} \times \left(\frac{1+inf}{1+int} \right) \times \left[\frac{1 - \left(\frac{1+inf}{1+int} \right)^T}{1 - \left(\frac{1+inf}{1+int} \right)} \right] \quad (27)$$

where $C_{O\&M_{init}(.)}$ is the initial operation and maintenance cost for any of the wind turbine, electrolyser and fuel cell for the first year and are taken as 5% of the capital cost in each case [46]. It should be noted that the symbol “(.)” indicates either of wind turbine, electrolyser or fuel cell as the case may be. The inf , int are the current inflation and interest rates in South Africa, which are taken as 4.5% and 6.5%, respectively [47] while T is the life time period of the project and is taken as 20 years.

3.7. Estimation of Environmental Benefits of Hydrogen based Fuel Cell Electricity generation

The environmental benefits of hydrogen was made based on the comparison with diesel fuel as diesel generators are the most common generating set used in electrification of remote communities. The amount of diesel fuel that could be displaced by hydrogen gas as well as the amount of emissions that could be avoided as a result of partial or complete combustion of diesel fuel are presented in this section.

3.7.1. Diesel Fuel Displacement by Hydrogen gas.

The amount of diesel fuel that would be displaced in litres ($D_{fl(displ)}$) if diesel fuel is replaced by equal amount of hydrogen gas for electricity generation in fuel cell was determined using (28) [9,48]. The displacement is based on the lower heating values (LHV) of diesel fuel with respect to that of hydrogen gas.

$$D_{fl(dis)} = \frac{V_{H_2comp} \times LHV_{H_2} \times \eta_{fc} \times \rho_{VH_2}}{\left(\frac{LHV_{Dfl}}{3.6} \right) \times \eta_{Dfl} \times \rho_{Dfl}} \quad (28)$$

where, η_{Dfl} is the efficiency of the diesel fuel generator which is taken as 33% [49–51], LHV_{Dfl} is the lower heating value of diesel fuel whose value is taken as 42.5 MJ per kg [52,53], ρ_{Dfl} is the density of diesel fuel and its value is taken as 0.837 kg per litre [54], 3.6 is used as the conversion factor from MJ to kWh.

3.7.2. Emission Mitigation by the use of Hydrogen Gas in Fuel Cell

The two main emissions resulting from combustion of fossil fuels are the carbon dioxide (CO₂) and carbon monoxides (CO). CO₂ is a greenhouse gas which traps heat in the Earth's atmosphere resulting in global warming. CO is a pollutant that is of global concern because it is dangerously poisonous. It can cause suffocation if sufficient amounts are present in the surrounding air [55]. It does not give warning of its presence because it is colourless and tasteless and hence must be reduced in the atmosphere as much as possible. The amount of carbon dioxide emission (E_{CO_2}) and carbon monoxide (E_{CO}) emission (both in kg) that could be prevented in going into the surrounding air by using hydrogen- fuel cell electricity generator rather than diesel generator can be estimated using:

$$E_{CO_2} = S_{E(CO_2)} \times D_{fl(dis)} \quad (29)$$

$$E_{CO} = S_{E(CO)} \times D_{fl(dis)} \quad (30)$$

where $S_{E(CO_2)}$ is the specific emission of carbon dioxide per litre of diesel fuel taken as 2.7 kg/litre [56] while $S_{E(CO)}$ is the specific emission of carbon monoxide per litre of diesel fuel taken as 0.00766 kg/litre [56].

3.7.3. Hydrogen Fuel Cell Electricity Generation Avoidance Cost

Investments in wind turbine powered hydrogen-fuel cell electricity capacity will continue to avoid diesel fuel cost and carbon cost throughout the entire lifetime of the project. The cost of diesel fuel (\$) saved per time if diesel fuel is substituted with hydrogen gas can be calculated as:

$$C_{Dflsav} = D_{fl(dis)} \times C_d \quad (31)$$

where C_d is the current price of diesel fuel in South Africa and is given as 0.870 \$/L [57].

The carbon dioxide avoidance cost of hydrogen based electricity generator can be determined using:

$$C_{A_CO_2} = \frac{E_{CO_2}}{1000} \times k_{CO_2} \quad (32)$$

where E_{CO_2} is the CO₂ emission avoided (kg) by substituting hydrogen gas for diesel fuel as determined in (29), k_{CO_2} is the average price of carbon dioxide allowance and is given as \$29.5/tCO₂ [58], the 1000 is used to convert kgCO₂ to tCO₂.

3.8. Payback Period

The interest of every investor is to know the probable period needed to recoup an investment, hence, the need to determine the payback period of the hydrogen-fuel cell based electricity generation

system. Payback period is concerned with the number of periods (years) needed to pay back an initial investment with positive net income. Therefore, the payback period in years is determined as:

$$PBP = \frac{LCC_{WT} + LCC_{El} + LCC_{FC}}{C_{Dflsav} + C_{A_{CO_2}}} \quad (33)$$

4. Results and Discussion

The results depicting the wind characteristics of Vesleskarvet, capacity factor and energy (electricity) generation potential of four selected wind turbines based on the wind energy resources of the Vesleskarvet are presented. Also, the hydrogen production potential of the wind turbines and the electricity generation potential of fuel cell are presented in this section. The economic viability of the project and environmental benefits accrue from the project are presented.

4.1. Characteristics of Wind Regime of Vesleskarvet

The monthly and annual wind characteristic of Vesleskarvet were examined by calculating the mean wind speed (v_m), the standard deviation (σ), turbulence intensity (TI), the shape (k) and the scale parameters (c). The results are presented in Table 2. The results revealed that the mean wind speed at 10 m anemometer height varies from January to December. The minimum wind speed 8.27 m/s occurs in January and the maximum wind speed 12.88 m/s occurs in August, while the annual average wind speed is 10.87 m/s. The standard deviation of the wind speed ranges between 4.67 m/s in January to 7.21 m/s in May. This indicates that the wind speeds deviate by large amount from the mean wind speed resulting into high value of turbulence intensity. Although, the turbulence intensity calculated using the mean wind speed and standard deviation would be influenced by synoptic and seasonal variations. The TI varies from 48.94% in March to 65.27% in May indicating that the wind speeds in the month of March is more steady compared to other months. The highest value calculated for the month of May reveals that the month of May is more turbulent compared to other months. The implication of this is that the energy extractable in the month of May could be lower compared to other months due to high level of turbulence [31]. The scale parameter which indicates how peak the wind speeds are at the site ranges from 1.62 in the month of November to 2.17 in the months of February and March. The scale parameter which determines how windy the site is varies between 9.31 m/s in the month of January and 14.51 in the month of August. This indicate that August is the windiest month in the year while the January the least.

Table 2. Wind Characteristics of Vesleskarvet Nunataks at 10 meter anemometer height [31].

Months	v_m (m/s)	σ (m/s)	TI (%)	k	c (m/s)
Jan	8.27	4.67	56.47	1.86	9.31
Feb	9.80	4.81	49.06	2.17	11.07
Mar	10.87	5.32	48.94	2.17	12.27
Apr	11.58	6.18	53.40	1.98	13.06
May	11.05	7.21	65.27	1.59	12.31
Jun	12.14	6.76	55.67	1.89	13.68
Jul	11.61	6.91	59.47	1.76	13.04
Aug	12.88	7.07	54.89	1.92	14.51
Sep	11.35	6.02	53.02	1.99	12.81
Oct	11.96	6.49	54.27	1.94	13.49

Nov	10.16	6.52	64.21	1.62	11.34
Dec	8.79	5.22	59.40	1.76	9.87
Annual	10.87	6.30	57.94	1.81	12.23

4.2. Capacity Factor and Electrical Power Generation Capacity of Wind Turbines

Capacity factor (C_f) gives the ratio of total actual energy produced by a wind energy conversion system over a period of time to the amount of energy it would have produced at full capacity at that period. C_f is a function of the design of the wind turbine and it determines how a wind turbine matches well with the wind characteristics of the site. Therefore, the windiest site may not necessary give the best capacity factor if the parameters of the wind turbine does not match well with the wind characteristics of the site. The electricity generation potential of wind turbine depends largely on the rated power of the wind turbine as well as the capacity factor. The monthly C_f and the electricity generation potential (P_{Elect}) of the four selected large wind turbines based on the wind resource of Vesleskarvet are presented in Table 3.

Table 3. Monthly wind turbine capacity factors and electricity generation estimation of wind turbines using wind regime of Vesleskarvet for hydrogen production.

Months	Parameters	Wind Turbines			
		WT_1	WT_2	WT_3	WT_4
Jan	C_f (%)	59.00	61.30	62.76	56.95
	P_{Elect} (MWh)	533.73	735.90	1131.20	1539.70
Feb	C_f (%)	67.97	66.80	70.58	64.75
	P_{Elect} (MWh)	553.26	724.44	1148.90	1581.20
Mar	C_f (%)	69.20	64.62	70.51	64.56
	P_{Elect} (MWh)	623.57	776.40	1270.70	1745.40
Apr	C_f (%)	65.41	59.40	65.91	59.98
	P_{Elect} (MWh)	570.41	690.15	1149.60	1569.30
May	C_f (%)	58.13	53.90	58.96	53.25
	P_{Elect} (MWh)	523.88	647.126	1062.60	1439.5
Jun	C_f (%)	63.00	56.27	63.10	57.25
	P_{Elect} (MWh)	549.47	654.37	1100.60	1497.80

Jul	Cf (%)	61.21	55.69	61.69	55.90
	P_{Elect} (MWh)	551.57	669.17	1111.90	1511.10
Aug	Cf (%)	62.15	54.34	61.76	55.95
	P_{Elect} (MWh)	560.04	652.88	1113.10	1512.70
Sep	Cf (%)	65.90	60.26	66.60	60.66
	P_{Elect} (MWh)	574.75	700.67	1161.60	1587.10
Oct	Cf (%)	64.23	57.60	64.43	58.54
	P_{Elect} (MWh)	578.81	692.10	1161.2	1582.50
Nov	Cf (%)	58.93	55.90	60.32	54.54
	P_{Elect} (MWh)	513.90	650.27	1052.20	1426.90
Dec	Cf (%)	59.71	59.84	62.47	56.64
	P_{Elect} (MWh)	538.08	719.07	1125.90	1531.4

From the table (Table 3), the months of February and March present the best values of capacity factors across all the wind turbines denoting that wind generators produced more power during these months compared to other months. One of the interesting result here is that, these months (February and March) are not the windiest month at the site yet present the best Cf and energy generation potential. This is because these months present lower turbulence intensity compared to other months. The months of May presents the least value of capacity factor as well as least electricity generation potentials. This could also be attributed to high value of turbulence intensity recorded in the month. Figure 2 shows the annual capacity factor as well as the annual electricity generation potential of the selected wind turbines. The figure reveals that wind turbine WT_3 presents the best overall capacity factor with overall annual capacity factor of 63.8 % while WT_4 has the least capacity factor (57.94 %). However, the electricity generation capacity largely depends on the rated capacity of the wind turbine, hence the largest wind turbine (WT_4) generates the highest electricity with annual generating capacity of 1.84×10^4 MWh. The least electricity generating turbine is WT_1 with the annual generating capacity of 0.66×10^4 MWh.

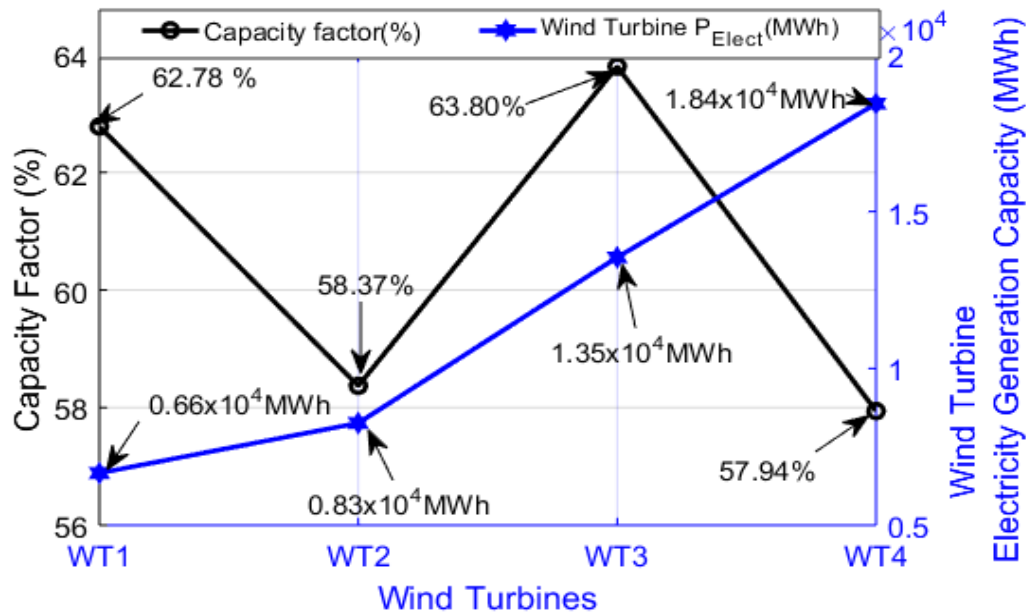


Figure 2. Annual capacity factor and electricity generation capacity of the wind turbines.

4.3. Hydrogen Production Potential Using the Wind Regime of Vesleskarvet

The quantity of hydrogen produced by the electrolyzers powered by the wind turbines (M_H) using the wind resource of Vesleskarvet, the compressed storable hydrogen gas as feedstock to fuel cell (V_{H_2comp}) as well as the volume of water requirement for hydrogen production during the electrolysis of water (W) are furnished in Table 4. The table reveals that the highest hydrogen production occurs in the month of March across all the wind turbines. This is expected since the C_f of the wind turbines are highest at this month. The lowest hydrogen production across the wind turbines is experience in the month of May. This may be attributed to the effect of high turbulence during this month which reduces the performance of wind turbines for electricity generation. Generally, wind turbine WT₄ present highest hydrogen production. This is in agreement with the earlier studies that hydrogen production are more favoured by larger wind turbines compared to the smaller ones [6]. The volume of water requirement for hydrogen production is also more in the month of March. This is because more water is required to meet the requirement of hydrogen production during this month.

Table 4. Monthly hydrogen generation potential, compressed hydrogen gas storable and water requirement for the hydrogen production.

Months	Parameters	Wind Turbines			
		WT ₁	WT ₂	WT ₃	WT ₄
Jan	M_H (tons)	8.89	12.27	18.85	25.66
	V_{H_2comp} (m ³)	234.74	323.66	497.50	677.20
	W (m ³)	94.29	130.00	199.83	272.02
Feb	M_H (tons)	9.22	12.07	19.15	26.35
	V_{H_2comp} (m ³)	243.33	318.62	505.31	695.44
	W (m ³)	97.74	127.98	202.98	279.35

Mar	M_H (tons)	10.39	12.94	21.18	29.09
	V_{H_2comp} (m ³)	274.26	341.47	558.89	767.66
Apr	W (m ³)	110.17	137.16	224.50	308.36
	M_H (tons)	9.51	11.5	19.16	26.15
	V_{H_2comp} (m ³)	250.88	303.53	505.59	690.19
May	W (m ³)	100.77	121.95	203.09	277.24
	M_H (tons)	8.73	10.79	17.71	23.99
	V_{H_2comp} (m ³)	230.41	284.61	467.36	633.13
Jun	W (m ³)	92.55	114.33	187.73	254.32
	M_H (tons)	9.16	10.01	18.34	24.96
	V_{H_2comp} (m ³)	241.66	287.80	484.04	658.76
Jul	W (m ³)	97.07	115.60	194.43	264.61
	M_H (tons)	9.19	11.15	18.53	25.19
	V_{H_2comp} (m ³)	242.59	294.31	489.02	644.62
Aug	W (m ³)	97.44	118.22	196.43	266.97
	M_H (tons)	9.33	10.88	18.55	25.21
	V_{H_2comp} (m ³)	246.32	287.15	489.57	655.32
Sep	W (m ³)	98.94	115.34	196.66	267.25
	M_H (tons)	9.58	11.68	19.36	26.45
	V_{H_2comp} (m ³)	252.78	308.17	510.88	698.04
Oct	W (m ³)	101.54	123.79	205.21	280.39
	M_H (tons)	9.65	11.53	19.35	26.38
	V_{H_2comp} (m ³)	254.57	304.38	510.73	696.01
Nov	W (m ³)	102.26	122.26	205.15	279.58
	M_H (tons)	8.57	10.84	17.54	23.78
	V_{H_2comp} (m ³)	226.02	285.99	462.75	627.58
Dec	W (m ³)	90.79	114.88	185.88	252.09
	M_H (tons)	8.97	11.99	18.77	25.52
	V_{H_2comp} (m ³)	236.66	316.26	495.18	673.51
	W (m ³)	95.06	127.04	198.91	270.54

The annual hydrogen production, annual compressed hydrogen gas for storage and the annual water requirement are depicted in Figure 3.

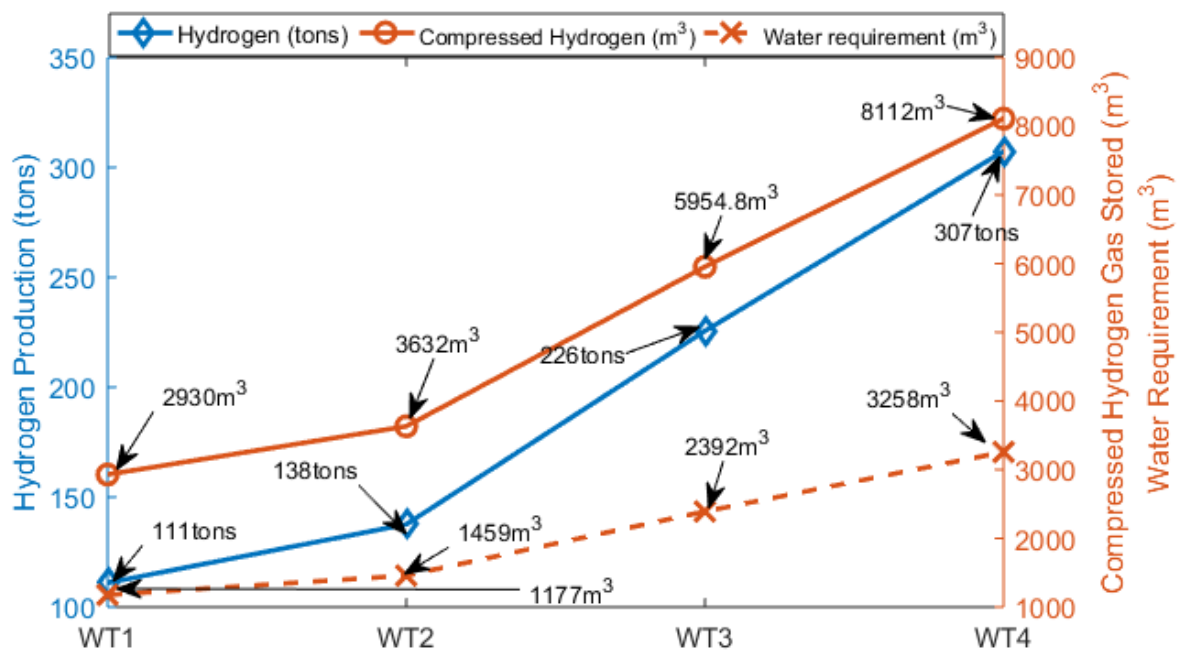


Figure 3. Annual hydrogen production of the wind turbine based on the wind characteristics of the site, compressed hydrogen gas and water requirement for hydrogen production.

Figure 3 shows that the wind turbine WT₁, WT₂, WT₃ and WT₄ could produce about 111, 138, 226, and 307 tons of hydrogen annually, respectively. This translates into about 2930, 3632, 5954.8 and 8112 cubic meter (m³) of compressed hydrogen gas that could be stored annually, respectively. This shows a huge potential for hydrogen production from this site. The annual water requirements to achieve these levels of hydrogen production were calculated to be about 1177, 1459, 2392, and 3258 cubic meter (m³), respectively.

4.4. Electricity Generation Potential of Fuel Cell using Hydrogen Generated

The compressed hydrogen gas could be used as feedstock to the PEM fuel cell for the purpose of electricity generation. The electricity generation potential of the fuel cell was determined using (16) and the results are depicted in Figure 4. The results reveal that the months of March and May experience the best and the least electricity generation potential across the wind turbines, respectively. The monthly electricity generation potential of the fuel cell using hydrogen produced from wind turbines WT₁, WT₂, WT₃ and WT₄ in the month of March are 198, 246, 402 and 552 MWh, respectively while that of May are 166, 205, 336 and 455 MWh, respectively. The annual electricity generation potential of fuel cell using hydrogen feedstock generated by the wind turbines as depicted in Figure 5 are 2, 2.6, 4.3 and 5.8 GWh, respectively.

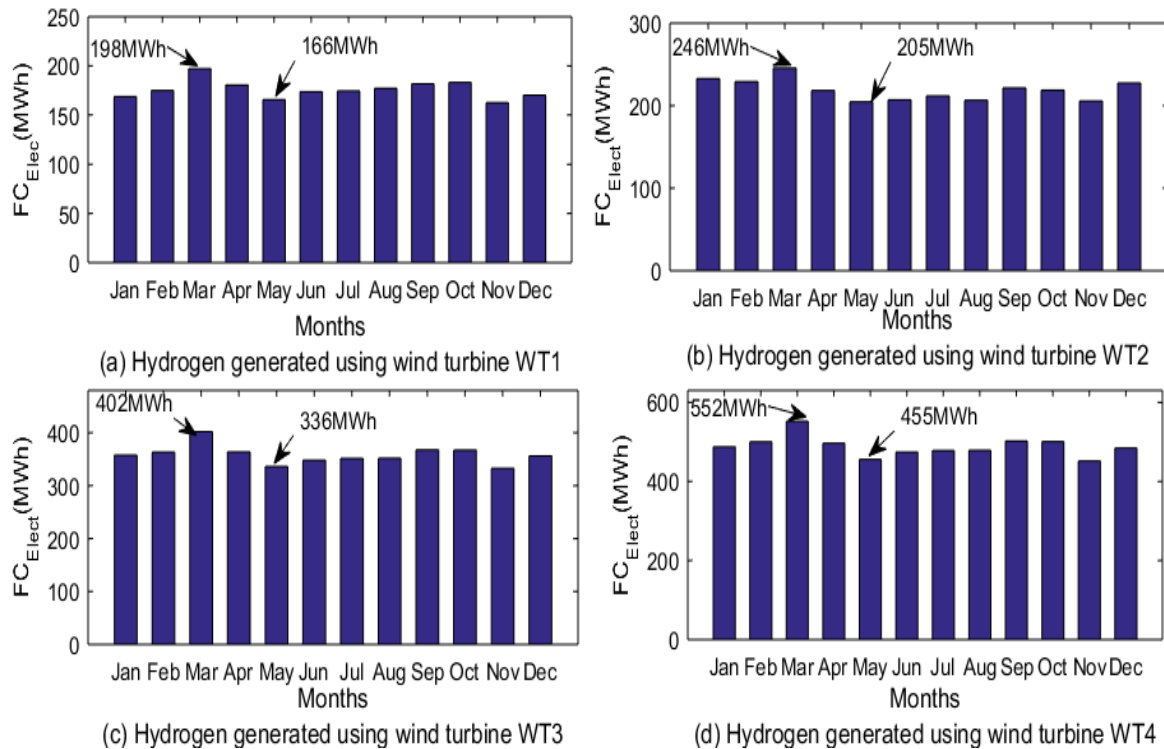


Figure 4. Monthly electricity generation potential of fuel cell from the hydrogen produced using the wind resource of Vesleskarvet.

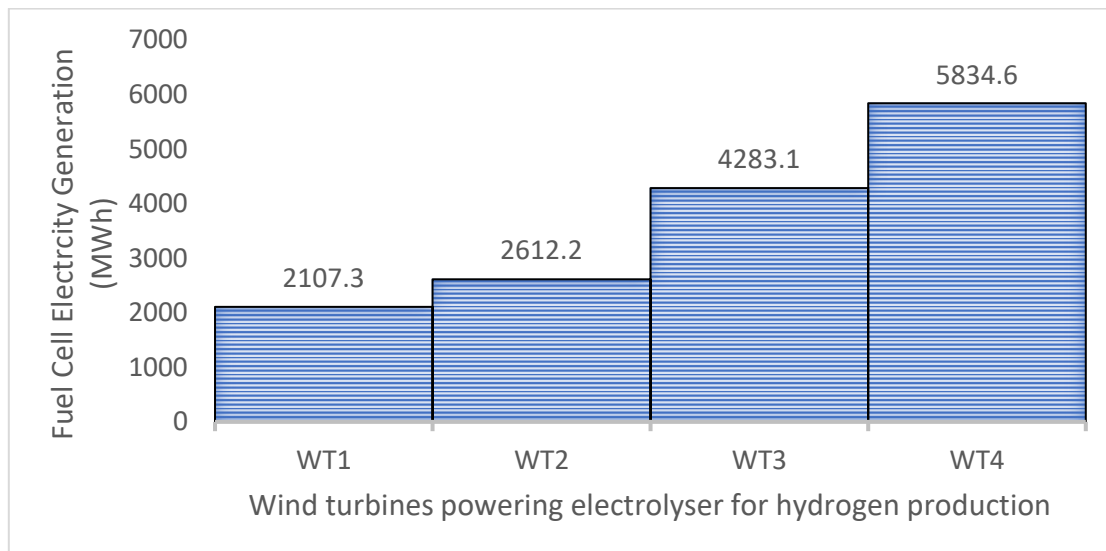


Figure 5. Annual electricity generation potential from fuel cell using hydrogen generated from wind resource of Vesleskarvet.

4.5. Economic Analysis of Hydrogen-Fuel Cell based Electricity using Wind Resource of Vesleskarvet

The economic viability of any project is important for sustainability of such project. Therefore, the unit cost of electricity in kWh generated by the wind turbines, the cost of hydrogen production by the electrolyser as well as the cost of electricity generation by the fuel cell were calculated and the results are presented in Figures 6, 7 and 8, respectively.

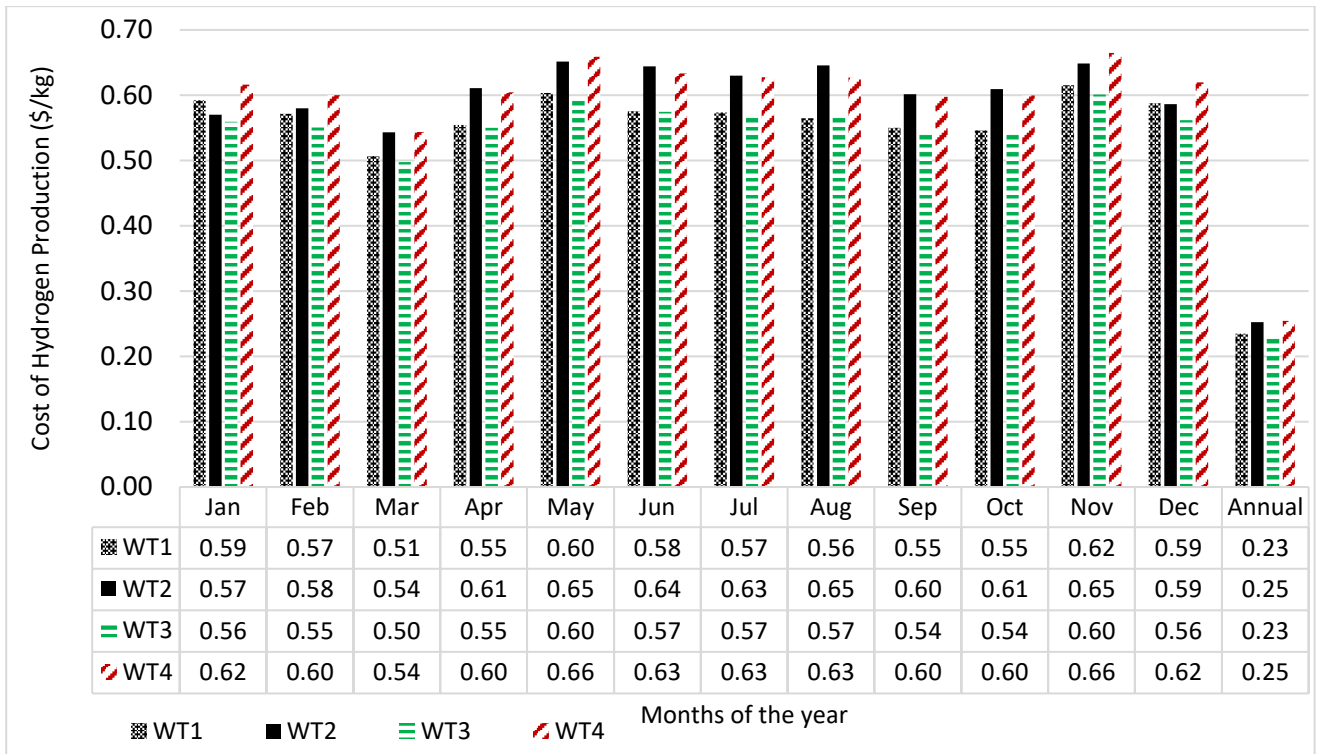


Figure 6. Monthly variation in the cost of energy from wind turbine using wind energy resource of Vesleskarvet.

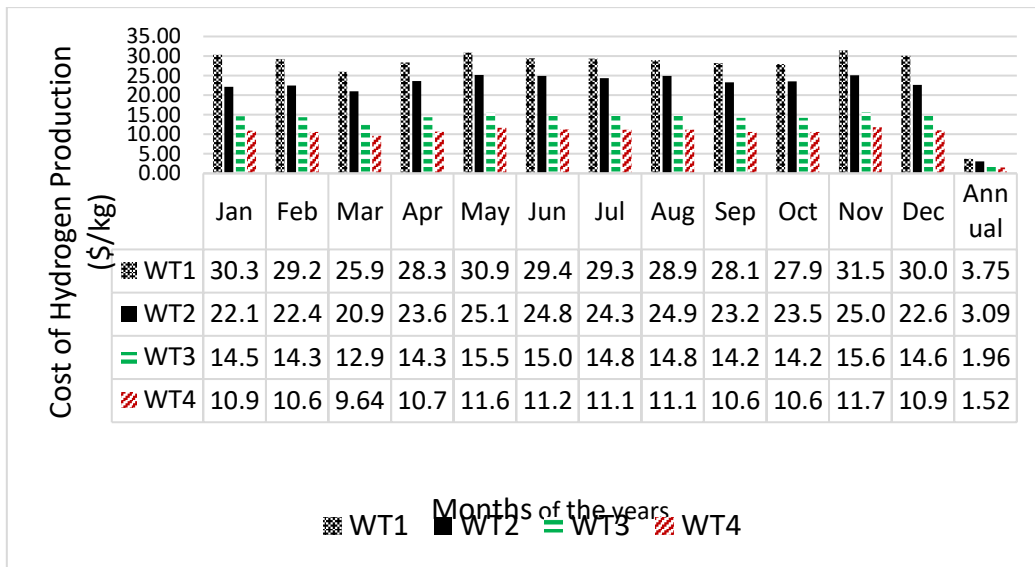


Figure 7. Monthly variation in the cost of hydrogen production from electrolyser using wind energy resource of Vesleskarvet.

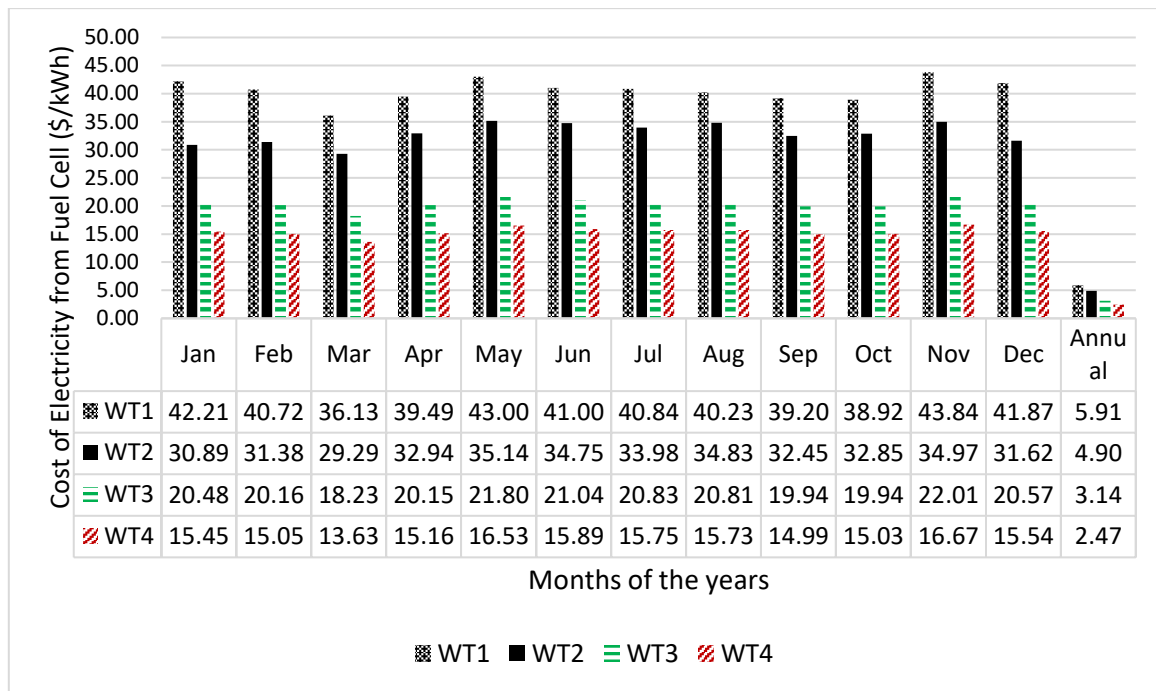


Figure 8. Monthly variation in the cost of electricity generation from fuel cell using wind energy resource of Vesleskarvet.

Figure 6 reveals that wind turbine WT₃ has the best unit cost of energy across all months while the most unfavourable cost of energy comes from WT₄. The reason for WT₃ presenting the best cost is due to high capacity factor of the wind turbine compared to the other turbines indicating that the wind turbine operating parameters match well with the wind characteristics of the site. Generally, November presents highest cost of energy across all the wind turbines. It should be noted that the cost of energy is higher when the wind turbines do not operate continually throughout the years. For example, the cost of energy when the wind turbines operate in the month of January only are 0.59, 0.57, 0.56 and 0.62 \$/kWh, respectively. However, if the wind turbines were to be operated continually throughout the year, the cost of energy for the wind turbine would be 0.235, 0.253, 0.231 and 0.254 \$/kWh, respectively. Similarly, the annual cost of hydrogen as depicted in Figure 7 are 3.75, 3.09, 1.96 and 1.52 \$/kg. Wind turbine WT₄ presents the best cost of hydrogen production. This is expected due to the large size of the wind turbine compared to the other turbines [6]. Figure 8 depicts the annual cost of electricity at location where fuel cell is deployed. The figure shows that the cost of electricity using fuel cell in which its hydrogen was generated by wind turbines WT₁, WT₂, WT₃ and WT₄ are 5.91, 4.90, 3.14, and 2.47 \$/kWh, respectively. Wind turbine WT₄ (Gamesa G128) with cut in wind speed of 4 m/s, rated wind speed of 13 m/s and cut out wind speed of 18 m/s present the best cost of energy. When this cost is compared with the unit cost of electricity from the conventional generators in South Africa (0.132 \$/kWh [57]), then it is clear that the unit cost of electricity using fuel cell is far higher compared to the conventional generation. However, the environmental benefits of fuel cell electricity generators far outweighs the conventional electricity generators. If the environmental benefits were to be incorporated into the cost of energy, then the unit cost of electricity from fuel cell generator may be more competitive with the conventional generation.

4.5. Environmental Benefits of Fuel Cell Electricity Generation

The environmental benefits of generating electricity from fuel cell were quantified by comparing it with the diesel generators which are generally used for standalone electrification in isolated locations. The amount of diesel fuel in litres ($D_{fl}^{(dis)}$) that would be displaced annually if diesel generators were to be replaced by fuel cell generators were calculated. Also the amount of CO₂ (

E_{CO_2}) and CO (E_{CO}) emissions that would be saved from the environment annually were determined. The annual cost of diesel fuel (C_{Dflsav}) that would be avoided as well as the carbon dioxide avoidance cost ($C_{A_CO_2}$) due to the use of hydrogen rather than diesel that would be gained were estimated. All the results are presented in Table 5. The results in the table revealed that huge amounts of savings can be made in terms of diesel fuel and emissions indicating that the environmental benefits of fuel cell are huge compared to the diesel generator. The payback period (PBP) of the hydrogen production systems powered by wind turbines WT₁, WT₂, WT₃ and WT₄ were calculated to be 9.8, 8.6, 6 and 5.4 years, respectively. This is considered a good project since all the years are far less than the system life time of 20 years.

Table 5. Benefits of hydrogen based fuel cell electricity generation.

Parameters	Wind Turbines for hydrogen production			
	WT ₁	WT ₂	WT ₃	WT ₄
$D_{fl(dis)}$ (litres)	6.46×10^5	8.01×10^5	1.31×10^6	1.79×10^6
E_{CO_2} (kg)	1.75×10^6	2.16×10^6	3.55×10^6	4.83×10^6
E_{CO} (kg)	4.95×10^3	6.14×10^3	1.01×10^4	1.37×10^4
C_{Dflsav} (\$)	5.62×10^5	6.97×10^5	1.14×10^6	1.56×10^6
$C_{A_CO_2}$ (\$)	5.15×10^4	6.38×10^4	1.05×10^5	1.43×10^5
PBP (years)	9.8	8.6	6	5.4

5. Conclusion

The economic potential and environmental assessment of hydrogen fuel cell for electricity generation using wind energy resource of Vesleskarvet have been performed. The followings are concluded from the study:

- i. The daily mean wind speed of Vesleskarvet varies from 8.27 m/s in January to 12.88 m/s in August with annual daily average value of 10.87 m/s at 10 m anemometer height.
- ii. The turbulence intensity varies from 48.94% in March to 65.27% in May with annual average value of 57.94%
- iii. The shape parameter varies from 1.76 in June to 2.17 in February and March with annual average value of 1.81.
- iv. The scale parameter lies between 9.31 m/s in January to 14.51 m/s in August with average annual value of 12.23 m/s.
- v. The annual capacity factor and electricity generation potential for wind turbines (WT₁, WT₂, WT₃, WT₄) are (62.78%, 58.37%, 63.80% and 57.94%, respectively) and (6600 MW, 8300 MW, 13500 MW and 18400 MW, respectively).
- vi. The annual hydrogen production potential by the electrolyser powered by WT₁, WT₂, WT₃ and WT₄ are 111 tons, 138 tons, 226 tons, 307 tons, respectively.
- vii. The annual electricity generation potentials of the fuel cell powered by the wind turbines are 2107.3, 2612.2, 4283.1, and 5834.6 kWh, respectively.

viii. The annual costs of electricity generation of the wind turbines, electrolyser and fuel cell are (0.235, 0.253, 0.231, 0.254 \$/kWh), (3.75, 3.09, 1.96, 1.52 \$/kg) and (5.91, 4.90, 3.14, 2.47 \$/kWh), respectively.

ix. The estimated payback periods for the project are 9.8, 8.6, 6 and 5.4 years

Competing Interests: The authors declare that there is no any competing interest regarding the publication of this manuscript. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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