INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 44 (2019) 17669–17687

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Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa

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ARTICLE INFO

Article history:
Received 27 March 2019
Received in revised form
9 May 2019
Accepted 11 May 2019
Available online 4 June 2019

Keywords:
Hydrogen production
Wind energy
Water electrolysis
Economic analysis
South Africa

ABSTRACT

In recent times, more attention is given to renewable and clean energy sources that could ameliorate the current shortage of electricity plaguing South Africa. Due to the comparable use of hydrogen to fossil fuel in the transportation, industrial and electricity sector, hydrogen could be a potential solution to the current energy crises especially when produced from a clean and sustainable source. One of the most appropriate methods of green hydrogen production is the use of wind energy via water electrolysis. This paper therefore investigates the capability and viability of hydrogen production from the wind energy resources of South Africa using the actual wind speed obtained at 60 m anemometer height. Sensitivity analyses are also conducted to gain insight into the possible influences of wind turbine operating parameters on the cost of hydrogen production. Wind regime of fifteen (15) different sites across five (5) major provinces are analysed for possible wind-hydrogen production using eleven (11) different off-the-shelf wind turbines ranging from small to large categories. Some of the key results revealed that the mean wind speed (V_m) varies from 5.07 m/s in Eston (S12) to 8.10 m/s in Napier (S5). Wind turbine WT_9 (ServionSE MM100) with rated wind power of 2 MW, cut-in wind speed of 2 m/s, rated wind speed of 11 m/s, cut-out wind speed of 22 m/s and turbine hub-height of 100 m has the highest capacity factor (*Cf*) across all the sites with the values that range from 24.04% in Eston (S12) to 54.55% in Napier. Site S5 presents the best hydrogen production potential with annual hydrogen production that ranges between 6.51 metric-tons with turbine WT_1 and 226.82 metric-tons of hydrogen with turbine WT_{11}. Wind turbine WT_9 has the least cost of electricity generation ranging from 0.23$/kwh at site S5 to 0.42 $/kwh at site S13. Also, the cost of hydrogen is lowest at site S5 and ranges between 39.55 $/kg using wind turbine WT_1 and 1.4 $/kg using wind turbine $WT_{11.}$ The sensitivity analysis conducted revealed that rated wind speed has significant effect on the cost of hydrogen production compared to other wind turbine parameters.

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https://doi.org/10.1016/j.ijhydene.2019.05.077
0360-3199/

Introduction

Efforts are being made worldwide to reduce carbon emission with the aim of reducing global warming that is impacting negatively on the global climate. This carbon-constrained challenge has necessitated alternative energy sources to replace the current need of carbon sources for electricity generation and transportation [1]. Development of hydrogen economy with the use of hydrogen as a potential substitute to fossil fuel could be one of the promising solutions to replace the current carbon dependent economy. Hydrogen on its own is not a primary energy source, but an energy carrier which partially offers the benefits of fossil fuels (i.e. flexibilities) with a low carbon footprint. It also offers a means of integrating high shares of intermittent renewable electricity into the energy system. Hydrogen can be produced via varieties of sources and it can be stored in many ways given room for accessibility and easy distribution.

In recent times, South Africa is faced with various energy challenges such as unscheduled outages, shortage of electricity generation, blackouts and electrical energy poverty especially in rural communities [2]. This has led to several intervention programs by the South African government on energy and energy efficiency with a strong focus on the off-grid renewable energy solutions [3]. One of the underlined resolutions is the production of green hydrogen from clean and renewable energy sources for meeting the electricity and transportation gap in the country especially in the rural settings [4]. To achieve this, South African government has come up with national program on hydrogen production tagged HYSA (Hydrogen South Africa). The aim of HYSA is to provide a clear direction for effective deployment of hydrogen and fuel cell technology in South Africa. Hydrogen on its own can serve as a useful fuel for use in buildings and transportation, and when combined with fuel cell can be used to generate electricity [5]. Hydrogen can be stored in many ways, and this provides flexibility for electricity generation from intermittent renewable energy sources thereby mitigating the fluctuation in demand and supply of electricity [6]. The storability also enhances decentralised electricity generation (off-grid generation) making it attractive for remote communities where grid extension is difficult to achieve and uneconomical. One of the renewable energy of interest in South Africa is the wind energy [7]. Most of the good wind resources are found in the coastal region of South Africa [8]. As at 2010, the total installed wind capacity in South Africa was less than 10 MW. However, with the various intervention programs at increasing the recoverable energy from wind resource, the country has reached 2 GW of wind power installed capacity by the end of 2018, making South Africa one of the regional leaders in wind power installation and deployment in Africa [9]. One of the ways to further increase the share of wind energy in the overall generation mix of South Africa is the production of hydrogen from wind energy.

Many researches on hydrogen production have emerged in recent years because it is believed that the world is gradually coming to the reality of hydrogen economy and hydrogen is considered as the future energy carrier [10]. Hydrogen production via water electrolysis process using wind energy is currently adjudged one of the hydrogen pathways with lowest life cycle greenhouse gas emissions with competitive cost of hydrogen production [11]. Various studies have been conducted on techno-economic assessment of hydrogen production via water electrolysis from both the hybrid and the standalone wind energy conversions systems: a technical and economic analysis of large scale hydrogen production using wind energy of Western Canada has been carried out by Olateju et al. [12]. In their study, a 563 MW integrated wind-hydrogen model with energy storage was proposed. The model utilised real-time wind energy data to determine the optimal size of the electrolyser. The authors observed that for a particular electrolyser-battery configuration, the lowest hydrogen production cost is obtained when their respective capacity factors were approximately equivalent. Likewise, techno-economic assessment of hybrid photovoltaic-wind power plant for hydrogen production via water electrolysis was conducted by Qolipour [13] using Homer software for Hendijan area in the South West of Iran. It was revealed that the annually electrical energy production by the hybrid system was 3,153,762 kW h with hydrogen production of 31,680 kg using system configuration consisting of a GE 1.5sl wind turbine model, a 4-kW photovoltaic system and a 100 kg hydrogen tank. Also, Murat and kale [14] carried out a design of hydrogen refuelling station using HOMER software for Izmir-Cesme, Turkey. The hydrogen was produced from the hybrid of wind and solar energy available in the city. The results revealed that the cost of hydrogen production was between 7.5 and 7.9 $/kg indicating that refuelling station powered by renewable energy could be economically viable for the city. In another work, Al-Sharafi et al. [15] investigated the potentials of power generation and hydrogen production via solar and wind energy resources at different locations in the Kingdom of Saudi Arabia. Their results showed that the optimum cost of hydrogen was 43.1 $/kg. The potential for the hydrogen production via electrolysis process using wind and solar energy of Algeria has been conducted by Rahmouni et al. [16]. The authors later generated the renewable energy-hydrogen production map for Algeria. Their study revealed that In Adrar, Laghouat, Tamanrasset and Tindouf located at the southern and southwestern region of Algeria have the best potential for hydrogen production with the value exceeding the estimated 8×10^4 tons/km^2/year of renewable hydrogen. Mostafaeipour et al. [17] conducted research on the viability and economic potential of wind energy for electricity generation as well as hydrogen production from the industrial and agricultural sectors of four cities of Ardebil province of Iran. The authors indicated that the cities of Namin and Ardebil have the best wind energy resources with wind power densities of 261.68 and 258.99 W/m^2, respectively. It was also revealed that 5 kW and 100 kW wind turbine were the best choice for both the electricity generation and hydrogen production for the city of Ardebil with the payback period of 13 and 5 years.

Various authors have also investigated other aspects of hydrogen besides the techno-economic potentials. For example, a model of integrating curtailed wind energy with hydrogen energy storage has been developed based on real time data of a typical wind farm by Zhang and Wan [18]. The authors showed the importance of hydrogen energy storage technology on wind energy curtailment. Rezaei-Shourok et al. [19] have conducted a study on wind farm locations prioritizing for the purpose of hydrogen production in the Fars province of Iran using Data Envelopment Analysis (DEA) method. The authors validated their results using Analytical Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) methods. It was concluded that Izadkhast city was the most favourable location for construction of wind farm for hydrogen production. The location would yield average hydrogen production of 21.9 ton/year with a 900 kW wind turbine. The effectiveness of the recorded wind speed noises on the wind turbine power and the amount of hydrogen production was evaluated by Alavi et al. [20]. The authors revealed that the amount of hydrogen production changed slightly and its variation was negligible when the value of signal to noise ratio was more than 20 dB. Niculescu et al. [21] are concerned with the environmental implications of using hydrogen as an energy carrier. The authors were of the opinion that if hydrogen based economy is made to replace the present fossil fuel-based energy system and a leakage rate of 1% is allowed to occur, then it would result into climate impact of 0.6% of the current fossil fuel based system. Conversely, in a research conducted by Reiter and Lindorfer [22] on the life cycle assessment of power-to-gas systems of hydrogen and methane production from renewable energy sources (i.e wind and solar), the authors revealed that hydrogen produced from renewable energy sources showed better ecological performance compared to the fossil-based alternatives. Solomin et al. [23] developed an autonomous wind-hydrogen powered plant in which the wind turbine is responsible for power generation while the hydrogen module serves as the backup. The project was thought to be useful in any part of the world including Arctic and Antarctic. An intelligent control algorithms was also included for minimizing the starting and stopping phase thereby extending the lifetime of the plant. Also, an intelligent operating strategy that is capable of maximizing wind energy utilization and could also exploit times of low electricity prices for electrolysis has been proposed by Gruger et al. [24]. This strategy was based on imperfect forecasts and non-linear electrolyser behaviour. The authors revealed that the proposed technique was able to reduce hydrogen production costs by about 9.2% and increases wind energy utilization by about 19%, respectively.

It has also been reported in the literature that more intermittent renewable energy could be integrated into the grid using hydrogen as the storage system. In doing this, hydrogen are produced in the time of excess renewable energy resources which could be reconveted to serve as backup during limited resources. For example, Ishaq et al. [25] have conducted studies on integrated wind turbine energy system with a hydrogen fuel cell and proton exchange membrane electrolyser to provide electricity and heat to a community of households. In their work, the hydrogen system was used as a storage system by producing hydrogen during high wind speeds. The excess electricity generated was supplied to the electrolyser to produce hydrogen which was stored in a storage tank. The stored hydrogen was thereafter used in the fuel cell to provide electricity during periods of low wind speeds to overcome the shortage of electricity supply. The authors revealed that the overall energy and exergy efficiencies of this system at a wind speed 5 m/s were determined to be 20.2% and 21.2%, respectively. In the same way, Sorgulu and Dincer [26] combined both the concentrated solar power and wind energy systems with electrolyser, fuel cell and absorption cooling subsystems for power and hydrogen production for residential applications. The objective was to manage the excess power through water electrolysis to produce and store hydrogen. The authors revealed that the integrated system was efficient, environmentally friendly and sustainable. In another study, Colbertaldo et al. [27] conducted research on the energy balance of a large-scale regional electric system with a focus on the deployment of renewable energy sources using hydrogen-based Power-to-Power (P2P) storage. The authors revealed that the hydrogen-based P2P storage system was attractive compared to the battery energy storage systems-based system. Likewise, a spatially and temporally resolved optimization model was used by Welder et al. [28] to examine the economic pathways for using excess electricity to cover positive residual loads by means of different technologies to reconvert hydrogen into electricity. The investigations were conducted based on an energy scenario for 2050 in which surplus electricity from Northern Germany was available to cover the electricity grid load in the Federal state of North Rhine Westphalia (NRW). The authors were of the opinion that large-scale hydrogen storage and reconversion using hydrogen infrastructure built for that purpose could make a meaningful contribution to the expansion of the electricity grid. Papadopoulo et al. [29] were of the opinion that hydrogen production using PV and wind turbine via water electrolysis could add value to an already existing renewable energy installation as long as the electrolyser is not underutilized. The authors also observed that PV as the only energy source could lead to underutilisation of electrolyser due to unavailability of solar resources during the night-time. It was however believed that hybridizing wind turbine with PV could make higher contributions to hydrogen production.

From the various studies in the aforementioned literature, it is obvious that production of hydrogen from renewable energy resources is environmentally advantageous. However, there is a need to conduct techno-economic viability at every potential location where hydrogen production is of good interest. This is because, the potential and economic profitability of hydrogen production is site specific. To the best knowledge of the authors, this has not been conducted in South Africa. With the great interest in hydrogen economy in the country, there is need to determine the sites suitability and economic viability of renewable hydrogen production from various potential sites. This will aid decision making for optimal investment in green hydrogen production in the country. Also, the possible impacts of various operating parameters of wind turbines (i.e. the cut-in wind speed, cut-out wind speed, rated wind speeds and turbine hub-height) on the cost of hydrogen production has not been found in the literature to the best understanding of the authors. This paper therefore bridges this gap by determining the viability of green hydrogen production via water electrolysis using wind energy resources of South Africa. Also, the effect of wind turbine and site parameters on the cost of hydrogen production are also determined.

Wind data assessment

The study on the potential of hydrogen production in South Africa was conducted using the wind speed data of fifteen (15) locations spread across five (5) of the nine (9) provinces (Eastern Cape, Western Cape, Norther Cape, Free State, Kwazulu-Natal) of South Africa. The wind speed is a 10-min average data observed at 5 different levels of anemometer height (i.e 10, 20, 40, 60 and 62 m). The wind speeds were made available through the wind atlas for South Africa (WASA) website [30]. WASA is a project undertaken by a five-member team with distinct and important roles towards a single goal. The teams include: the South African National Energy Development Institute (SANEDI), The University of Cape Town Climate System Analysis (UCT-CSAG), Council of Scientific and Industrial Research (CSIR), South African Weather Services (SAWS), and DTU wind energy. The main goal is to use numerical wind atlas methods to develop great capacity that would enable planning of large-scale exploitation of wind power in South Africa. The project is financially supported by the Global Environmental Facility GEF) and the Royal Danish Embassy (RDE) through the South African Wind Energy Project (SAWEP) [31]. The location of masts, the towns in which the masts are located within South Africa as well as the altitude of the site above the sea level is shown in Table 1. The spread of the locations across South Africa regions is as depicted in Fig. 1. In this paper, the wind speed observed at the anemometer height of 60 m was used to determine the potential of hydrogen production in South Africa. The most recent and complete data observations over a period of one year were used for each of the sites.

Methodology on wind energy -hydrogen production pathway

For any wind power-related project such as hydrogen production from wind powered-water electrolysis, the knowledge of the characteristics of the wind regimes of the proposed site is important as it gives good idea on the economic viability of the locations for green hydrogen production.

Modelling of wind characteristics of the sites

The insight into the wind characteristics of any given wind regime can be well understood from the wind distribution of the site. This involves the determination of the appropriate wind distribution that fits the wind regime of the site, knowledge of the shape and scale parameter of the wind distribution as well as the mean and standard deviation of the wind speed. Many of the earlier studies of wind distribution across various locations in South Africa revealed that Weibull distribution is the most appropriate fit for wind speed in South Africa [7,8,32]. Therefore, Weibull distribution is used to determine the wind characteristics of the sites. The general form for Weibull distribution is given as [33,34]:

$$f(v_i) = \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} \exp\left[-\left(\frac{v_i}{c}\right)^{k}\right] \tag{1}$$

where k and c are the Weibull shape and scale parameters, respectively. The shape parameter is a dimensionless quantity and determines how peak the wind speeds of the sites are. The scale parameter has a unit of wind speed (m/s) and it determines how windy the site is. The k and c can be approximated as [35]:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \tag{2}$$

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

where v_m and σ are the mean and standard deviation of the wind speed respectively and they can be determined using the following:

$$v_m = \frac{1}{Nd}\sum_{i=1}^{Nd} v_i \tag{4}$$

Table 1 – The description of the 15 sites across 5 provinces of South Africa.

S/n	Site index	Town	Location	Altitude A.S.L (m)	Period of data observation
1	S1	Alexander Bay	28° 36′ 06.7″S, 16° 39′ 51″E	144	Jan–Dec 2018
2	S2	Calvinia	31° 31′ 29.7″ S, 19° 21′ 38.7″E	823	Jan–Dec 2018
3	S3	Vredendal	31° 43′ 49.4″S, 18° 25′ 10.11″E	240	Jan–Dec 2018
4	S4	Vredenburg	32° 50′ 41.2″S, 18^0 06′ 34.5″E	22	Jan–Dec 2012
5	S5	Napier	34° 36′ 41.6″S, 19° 41′ 30.3″E	280	Jan–Dec 2016
6	S6	Sutherland	32° 33′ 24.4″S, 20° 41′ 28.7″E	1583	Jan–Dec 2018
7	S7	Prince Albert	32°58′ 00.2″S, 22° 33′ 23.8″E	1047	Jan–Dec 2018
8	S8	Humansdorp	34^0 06′ 32″S, 24° 30′ 49″E	110	Jan–Dec 2018
9	S9	Noupoort	31°15′ 05.76″S, 25^0 01′ 50.19″E	1800	Jan–Dec 2018
10	S10	Butterworth	32^0 05′ 26.5″S, 28^0 08′ 09.0″E	926	Jan–Dec 2018
11	S11	Rhodes	30° 48′ 51.62″S, 28° 4′ 25.32″E	2578	Jan–Dec 2017
12	S12	Eston	29° 51′ 0.43″S, 30° 31′ 42.38″E	771	Jan–Dec 2018
13	S13	Jozini	27° 25′ 34.17″S, 32° 9′ 58.11″E	81	Jan–Dec 2018
14	S14	Memel	27° 52′ 54.08″S, 29° 32′ 36.6″E	2050	Jan–Dec 2018
15	S15	Winburg	28° 37′ 11.89″S, 27° 7′ 23.41″E	1507	Jan–Dec 2018

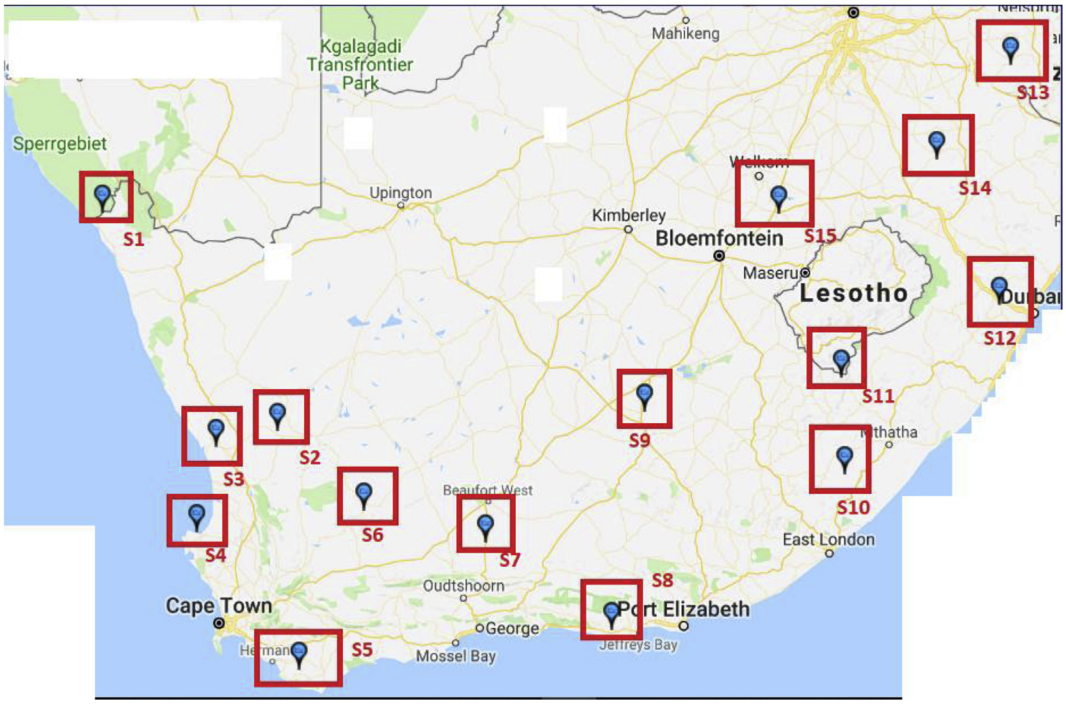

Fig. 1 – Location of wind mast spread across South Africa.

$$\rho = \frac{1}{Nd}\sum_{i=1}^{Nd}(v_i - v_m)^2 \tag{5}$$

where $Nd$is the number of data set.

Wind speed at hub height

Most wind speeds are observed at the height different from the turbine hub height, it is therefore necessary to re-define the wind speed from the anemometer height (H) (i.e wind speed at the observed height) to the turbine hub height H_h. This was determined using [36]:

$$v_{hi} = v_i\left(\frac{H_h}{H}\right)^{m_{(i)}} \tag{6}$$

where $v_{hi}$is the wind speed at the turbine hub height$H_h$and $v_i$is the wind speed at the anemometer height,H. In this paper, the wind speed was observed at 60 m anemometer height. The exponential shear, $m_{(i)}$is the factor that depends on surface roughness and atmospheric stability [36]. It is site specific and it is usually in the range of 0.05–0.5 [37]. The value of $m_{(i)}$ can be determined by taking the measurement of wind speed at two different anemometer heights. In this paper, $m_{(i)}$was determined using the wind speed observed at 40 m and 60 m anemometer height.

$$m_{(i)} = \frac{\log\left(\frac{v_i}{v_{40(i)}}\right)}{\log\left(\frac{H}{H_{40}}\right)} \tag{7}$$

where $v_i$is the wind speed at 60 m anemometer height H and $v_{40(i)}$is the wind speed observed at 40 m anemometer height H_{40}.

The exponential shear of a given site can therefore be determined using

$$m = \frac{1}{Nd}\sum_{i=1}^{Nd} m_i \tag{8}$$

Mechanical power from wind turbine

In this paper, actual hourly wind speed data directed to wind turbine hub height based on the given site exponential shear was used to determine the power output of the various selected wind turbines. To achieve this, a code was written in Matlab which converts the 10-min average wind speed to 1-h average. This was achieved by determining the mean of every six 10-min average wind speed data over the entire data collection. For a pitch controlled turbine, the hourly mechanical power at hour i, can be approximated using the power curve based on parabolic law as follows [38]:(9)

$$P_{M_i} = \begin{cases} P_r\dfrac{v_{hi}^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & (v_{ci} \leq v_{hi} \leq v_r) \\ P_r = \dfrac{1}{2}\rho A C_p V_r^3 & (v_r \leq v_{hi} \leq v_{co}) \\ 0 & (v_{hi} \leq v_{ci} \text{ and } v_{hi} \geq v_{co}) \end{cases} \tag{9}$$

where A is the turbine swept area (m^2), $\rho$is the air density (kg/m^3), v_{hi} is the hourly wind velocity at turbine hub height, $C_p$is the coefficient of performance of the turbine, it is a function of tip speed ratio and the pitch angle. Theoretically, it has a maximum value of 0.59 known as Betz limit. The variable wind speed turbine has the ability to track the maximum $C_p$by adjusting the turbine speed as the wind speed varies. There are different types of generator technologies around the world that are used for wind power applications (i.e. synchronous generator, doubly-fed induction generators, squirrel cage induction generators, synchronous reluctance generator, permanent magnet synchronous generator etc.). However, the most adopted WECS for wind power application is the variable-speed wind turbine with a Doubly Fed Induction Generator (DFIG) as a result of many advantages it offers over others [39] and it is assumed in this paper. Being an induction generator, it is more rugged and cheaper compared to synchronous generator. DFIG has the capability for active and reactive power control thereby eliminating the use of a capacitor bank which is popular with the squirrel cage induction generators. The variable speed capability of DFIG lowers the mechanical stress imposed on gearbox thereby extending the life span of gearbox. The controllability of the speed makes it possible to use an aerodynamic pitch control, which effectively limits the generated power during high wind speed [40]. One of the most desirable characteristic of DFIG in wind energy applications is that the amplitude and frequency of its output voltage are maintained at a constant value irrespective of the change in wind speed at the wind turbine rotor [41].

Analytical model of capacity factor

The capacity factor (*Cf*) of a wind turbine is one of the metrics used in selecting appropriate off-the-shelf wind turbine for a given site. It gives insight into the economic viability of a wind turbine in relation to a specific site. *Cf* can be defined as the ratio of the average output power of a wind turbine over a period of time to its potential output power if it had operated at rated capacity over the same period of time [42]. It can be mathematically modelled as follows:

$$Cf = \frac{E_{avg}}{E_{rat}} \tag{10}$$

where $E_{avg}$is the average mechanical power of the wind turbine over a period of time and $E_{rat}$is the rated mechanical power of the wind turbine over the same period of time. Both the $E_{avg}$and E_{rat}can be determined using the following relations:

$$E_{avg} = \sum_{i=1}^{Q} P_{M_i} \tag{11}$$

$$E_{rat} = P_r Q \tag{12}$$

where Qis the number of hours in the period of time under consideration.

Electrical energy from a wind energy conversion system

A wind energy conversion system (WECS) consists mainly of the wind turbine, a gearbox and the generator as depicted in Fig. 2. The speed of a wind turbine cannot match the high speed of electrical generator due to its inertia. A gearbox is generally used to increase rotational speed from a low-speed rotor to a higher speed electrical generator [40]. Therefore, the electrical energy output of a typical WECS can be modelled using:

$$E_{WECS} = E_{avg}\eta_m\eta_g \tag{13}$$

where, $\eta_m$is the mechanical transmission efficiency of the gear box and is taken as 0.85 and $\eta_g$is the generator efficiency taken as 0.95 [8].

In this paper, hydrogen production as well as the economic viability was determined for each of the locations using 11 different wind turbines. The wind turbine specifications ranging from 200 kW to 4.5 MW were obtained through manufacturer websites and published literature. The wind turbines were classified into 3 categories: the small scales, the medium scale and the large scale wind turbines [11,16,42]. In this paper, the small scale wind turbines are defined as the ones in which the rated power is less than 500 kW, the medium scale wind turbine is chosen to be the one greater than 500 kW but less that 1000 kW (i.e. 500 ≤ WT ≤ 1000 kW) while the large scale category falls into wind turbines whose rated power is 2 MW and above (i.e. ≥ 2 MW). The turbines as obtained from different sources are depicted in Table 2.

Hydrogen production via water electrolysis using wind turbines

Fig. 3 reveals a schematic diagram of a wind-powered hydrogen production installation system which consists of wind energy conversion system (WECS) (i.e. wind turbine, gearbox, electrical generator), rectifier which converts the AC voltage output of the WECS to DC output suitable for the

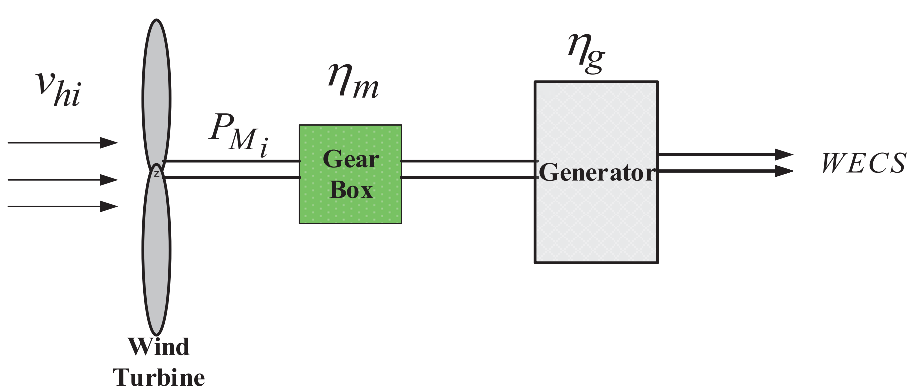

Fig. 2 – Block diagram of wind energy conversion system.

Table 2 – Wind Turbine specifications for different manufacturer.

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)
Small Turbines								
MICON	WT_1	200	30	4	14	25	2827	20
Nord tank	WT_2	300	31	4	13	25	2463	20
NEPC-MICON	WT_3	400	30.5	4	15	25	3019	20
Medium Turbines								
Norwin 47/500	WT_4	500	65	4	13	25	1735	20
DE Wind 48	WT_5	600	40	2.5	11.5	25	1808	20
Norwin 47/750	WT_6	750	65	4	15	25	1735	20
Gamesa G58	WT_7	850	65	3.5	12	21	2642	20
Large Turbines								
DE wind D7	WT_8	1500	70	3	12	25	3846	20
ServionSE MM100	WT_9	2000	100	3	11	22	7854	20
Alstom E110	WT_{10}	3000	100	3	11.5	25	9469	20
Gamesa G128	WT_{11}	4500	140	4	13	18	12873	20

operation of electrolyser and high pressure hydrogen tank for hydrogen storage.

The principle of water electrolysis is simply to pass a direct current between two electrodes immersed in an electrolyte to electrochemically split water [12]. To achieve this using wind energy based electricity, the energy in the mass of air is first extracted by the wind turbine and converted to mechanical energy. The wind turbine drives the electrical generator through the gear box to produce electricity. The function of the gearbox is to match the slow wind turbine speed to the fast speed of electrical generator. The electricity generated is rectified to a suitable DC output, then used for water electrolysis for hydrogen production via the electrolyser by passing electricity through two electrodes. Rectifier is an electronic device that is considered an harmonic source which feeds distorted currents into the supply system resulting into harmonic pollution [43]. The consequence of harmonics in the supply lines is to generally lower the quality of the electricity supply [44]. There are some standards that ensure the network distortion does not exceed permissible levels for proper operation of connected equipment such as the AS 2279–2 (Australia), IEC 555-2-4 (Europe), VDE 0839 Teil 2–4 (Germany), IEEE 519–1992 (USA) and IEC 61000-2-4-2002 (worldwide). These standards recommend limits for harmonic levels at various points within the system (i.e THDV $\leq$ 5% limit on each harmonic component). There are various rectifier architectures to ensure that these limits are met. The use of insulated-gate bipolar transistor (IGBT) active rectifier with the inclusion of DC link inductor in the filtering section reduces harmonic distortion to acceptable level that will ensure smooth running of the electrolyser [45].

Electrolyser

The common available commercial water electrolysers for hydrogen production are the alkaline and the proton exchange membrane (PEM) electrolysers. Most commercial electrolysers operate in an alkaline medium (30 wt % KOH solution) at temperatures of 60–80 °C [46]. The operating pressure varies from atmospheric to a 5 bar pressure for conventional electrolysers and to a 10–30 bar pressure for advanced electrolysers [46,47]. In this paper, the PEM electrolyser was selected because the issues of low current, hydrogen density, partial load, and low pressure operation that are the shortcomings of the alkaline electrolysers are overcome. PEM makes use of platinum as electrode which is found in abundance in South Africa. It offers fast dynamic response times, large operational ranges, high efficiencies, and very high gas purities (99.999%) [48] which could be directly used without further purification [49].

According to Hinkley et al., a typical 900 kW capacity of PEM electrolyser requires DC electrical energy demand of

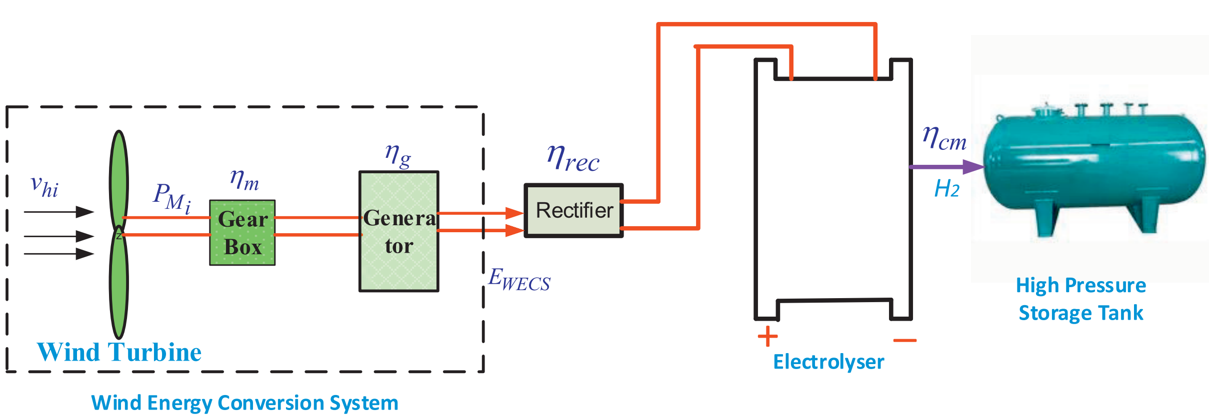

Fig. 3 – Schematic Diagram of hydrogen production chain from wind turbine to storage.

54 kW h [49] with water requirement of 10.6 kg [34] for every 1 kg of hydrogen production. Therefore, the amount of green hydrogen (kg) from the process of water electrolysis in kg can be estimated using:

$$M_{H_2} = \frac{E_{WECS}\eta_{rec}}{E_{ez}} \tag{14}$$

where E_{WECS} is the electrical energy output of WECS as determined using (13), η_{rec} is the rectifier efficiency and is taken as 0.9 [34], $E_{ez}$is the electrolyser energy demand which is taken as 54 kW h/kg for a typical PEM electrolyser [49]. The quantity of hydrogen produced can be converted to metric tons by dividing by 1000.

Hydrogen storage

The hydrogen produced is required to be stored for many stationary applications. However, hydrogen storage has a serious challenge due to it low volumetric density of 0.089886 kg/m^3 [50]. For instance, 1 kg of hydrogen at room temperature (20 °C) and atmospheric pressure (1 atm) occupies a volume of 11.13 Nm^3. For the purpose of storage, this huge volume needs to be reduced for ease of storage. To achieve this, work is either applied to compress hydrogen, or to reduce its temperature below the critical temperature. There are various methods of hydrogen storage as furnished in Table 3. However, the most common and matured storage technology is the high-pressure gas cylinders with a maximum pressure of 200 bar. In recent years, due to advancement in technology, new lightweight composite gas cylinders have been developed which are able to withstand pressures up to 800 bar thereby allowing hydrogen gas to reach a volumetric density of 36 kg/m.^{3}

In this paper, advanced 80Mpa high pressure compressed gas tank made of composite such of carbon fiber with a polymer liner (thermoplastic) was selected for hydrogen storage [51]. Therefore, the volume of compressed hydrogen gas (m^3) can be determined using the following relation:

$$Q_{H_2} = \frac{M_{H_2}\eta_{cm}}{\sigma_c} \tag{15}$$

where M_{H_2} is the amount of green hydrogen (kg) as obtained using (14), $\sigma_c$is the density of the compressed hydrogen at 800 bar, 25°C given as 36 kg/m^3 [50]. $\eta_{cm}$is the compression efficiency of a reciprocating compressor and is taken as 0.95 [52]. Low speed reciprocating compressors was selected because they are commonly used compressor for applications that require a very high compression ratio and it has higher efficiency compared to other compressors [53].

Economic analysis

In this section, the economic viability of energy production from the commercially available wind turbine as well as the cost of resulting hydrogen based on the wind regime of the selected locations of South Africa are presented.

Economic analysis of wind energy project

Economic viability of green hydrogen production is a function of the cost of electrical energy derivable from wind turbine installed at a local site. However, the cost depends on how much of energy that can be extracted from the wind turbine from the local wind regime which is a function of how well the wind turbine designed operating parameters (i.e cut-in, rated and cut-out wind speed) match the wind regime and the capital cost of the wind energy project. The capital cost of a wind energy project C_{WEP} comprises of the cost of wind energy conversion system (WECS) including tower and the controllerC_{wecs}, battery bankC_{bb}, inverterC_{invt}, civil workC_{cw} and the cost of miscellaneous equipment C_{misc}(interconnecting cable, control panels etc.) [54]. Therefore, the capital cost of wind power project can be expressed as:

$$C_{WEP} = C_{wecs} + C_{bb} + C_{invt} + C_{cw} + C_{misc} \tag{16}$$

In this paper, levelised energy cost (LEC) was used to estimate the probable cost of electricity from a given wind power project. LEC is the cost charged on electricity generated from a given source to break even [55]. It is an economic metric of determining the economic viability of generating energy from a given generating plant over its life period i.e. the initial investment, Operation and maintenance etc [56]. The levelised wind energy cost for a wind power project can therefore be determined as follows:

$$C_{lec} = \frac{C_{wecs}Q_{wec} + C_{invt}Q_{invt} + C_{cw}Q_{cw} + C_{bb}Q_{bb} + + C_{misc}Q_{misc} + C_{(om)esc}}{E_{WECS}} \quad (\$/\text{kWh}) \tag{17}$$

where Q_{wecs},Q_{bb},Q_{invt}, $Q_{cw}$and $Q_{misc}$are the capital recovery factor for wind energy conversion system, battery bank, inverter, civil work and miscellaneous components respectively. E_{WECS}

Table 3 – Hydrogen Storage Methods and their density [50].

Storage Method	Storage condition	Density (kg-H_2/m^3)
1 High Pressure gas Cylinder	Up to 800 bar	36
2 liquid hydrogen in cryogenic tanks	At temperature of 21 K	70.8
3 Adsorbed hydrogen on materials with a large specific surface	At temperature less than 100 K	20
4 absorbed on interstitial sites in a host metal	at ambient pressure and temperature (20 °C and 1atm	150
5 Chemically bonded in covalent and ionic compounds (Complex Compound)	at ambient pressure (1atm)	150
6 through oxidation of reactive metals, e.g. Li, Na, Mg, Al, Zn with water		>150

is the electrical energy output of a typical WECS, $C_{(om)esc}$is cost of operation and maintenance escalated. The capital recovery factor can be calculated using:

$$Q = \frac{r(1+r)^T}{(1+r)^T - 1} \quad (18)$$

where $r$is the given discount rate and $T$is the useful system life time (year). The values of $r$and Tdepend on the wind power project component and the values are provided in Table 5.

In this paper, the capital cost of any wind energy project (C_{WEP}) can be estimated from the specific cost of wind turbine used for the project [57,58] and can be written as:

$$C_{WEP} = S_{wecs} P_r \ (\$) \quad (19)$$

where $S_{wecs}$and P_r are the specific cost and rated power of the wind turbine engaged for such project. The range of specific cost based on size of wind turbine as reported in [33,59,60] are shown in Table 4. The average of the specific cost range as used in [33] was adopted as the specific cost (S_{wec}) of wind turbine in this paper.

The cost of other components ($) that comprise the wind power projects can be determined as follows:

$$C_{wecs} = f_1 C_{WEP} \quad (20)$$

$$C_{invt} = f_2 C_{WEP} \quad (21)$$

$$C_{cw} = f_3 C_{WEP} \quad (22)$$

$$C_{bb} = f_4 C_{WEP} \quad (23)$$

$$C_{misc} = f_5 C_{WEP} \quad (24)$$

where $f_1, f_2, f_3, f_4$and$f_5$are the fractional percentage of cost of wind energy project (C_{WEP}) and the values as obtained from [59,61,62] are depicted in Fig. 4.

The cost of operation and maintenance escalating $C_{(om)esc}$($/annum) can be calculated using:

$$C_{(om)esc} = \frac{m_o}{r - e_{om}}\left[1 - (1+e_{om})^n (1+r)^{-n}\right] \quad (25)$$

where $m_o$and $e_{om}$are cost of operation and maintenance for the first year and the ratio of escalation of the operation and maintenance respectively and the values are taken as 5% and 3.5% of the cost of wind energy project [32]. . n is the life time of project life time and is given as 20 years. Other economic parameters as used in this paper are shown in Table 5.

Economic analysis of hydrogen production from wind energy

Levelised cost of hydrogen method was used in the evaluation of hydrogen cost per kg [49,63]. Aside from the cost of electricity generation from WECS, other components cost that contribute to the total investment cost of electrolyser for hydrogen production include: the capital cost of electrolyser (C_{ct_ez}), the installation cost of the electrolyser (C_{ist_ez}), operation and maintenance cost (C_{om_ez}) and stack replacement cost (C_{stk}) [49]. Therefore, the total investment cost of electrolyser ($) can be written as follow:

$$C_{T\_ez} = C_{ct\_ez} + C_{ist\_ez} + C_{stk} + C_{om\_ez} \quad (26)$$

The capital (C_{ct_ez}) can be determined from the specific cost (S_{ez}) of the electrolyser ($/kW) using the follows:

$$C_{ct\_ez} = S_{ez} G \quad (27)$$

where G is the capacity of the electrolyser in kW. In this paper, 185 kW capacity of PEM electrolyser with specific cost of 900 $/kW as obtained from [49] was used. Other costs were determined as follows [49]:

$$C_{ist\_ez} = h_1 C_{ct\_ez} \quad (28)$$

$$C_{stk} = h_2 C_{ct\_ez} \quad (29)$$

where h_1 and h_2 are the percentage fractional cost of electrolyser capital cost and the values are given as 12% and 40%, respectively.

The operational and maintenance cost was evaluated over the entire life of the electrolyser using:

$$C_{om\_ez} = C_{intial} \times \left(\frac{1+a}{1+b}\right) \times \left[\frac{1 - \left(\frac{1+a}{1+b}\right)^T}{1 - \left(\frac{1+a}{1+b}\right)}\right] \quad (30)$$

where a and b are the inflation rate and interest rate respectively which are taken according to South African reserve bank report as 4.5% and 6.5% [64]. T is the life cycle of the electrolyser which is taken as 20 years.

The levelized cost of hydrogen ($/kg) can be estimated using the following:

$$LCO\_H_2 = \frac{C_{T\_ez}}{M_{H_2}} \quad (31)$$

Therefore, the total cost of hydrogen production ($/kg) at the local site can be determined as:

$$C_{H_2} = LCO\_H_2 + C_{lec} \quad (32)$$

Table 4 – Specific cost of wind Turbines [33].

Wind turbine size (kW)	Range of specific cost ($/kWh)	Average specific cost (S_{wec}) ($/kWh)
<20	2200–3000	2600
20–200	1250–2300	1775
>200	700–1600	1150

Table 5 – Other economic parameter for wind energy project [32].

S/N	Wind energy project component	Discount rate Values (%)	Useful life time (years)
1	Wind turbine	10	20
2	Inverter	5	10
3	Civil work	5	20
4	Battery bank	5	7
5	Misc components	3.5	20

Results and discussion

This section presents the results as well as the detailed discussion on hydrogen production from wind energy resources

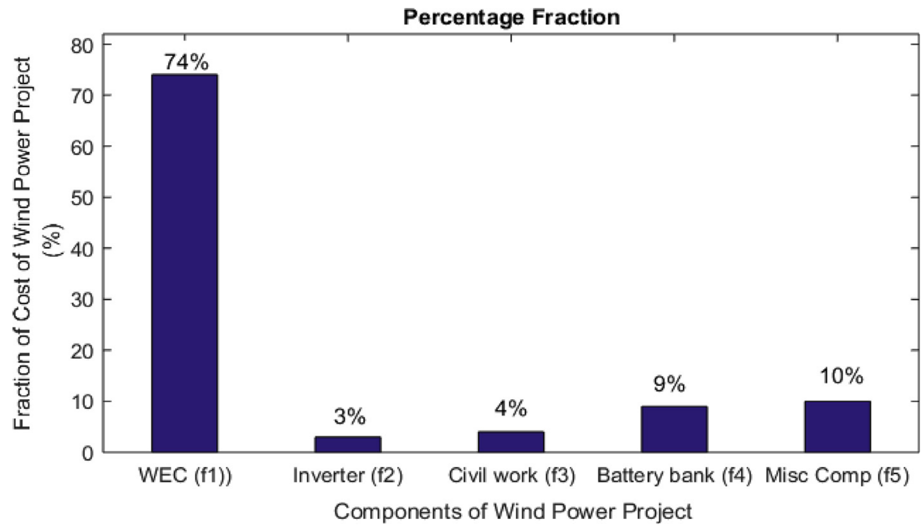

Fig. 4 – Fraction of cost of component.

of South Africa. The various wind characteristics of the sites are highlighted, the cost of energy as well as that of hydrogen are presented. The results of the sensitivity analyses on the impacts of wind turbine operating factors on the economic gains/burdens of wind-powered hydrogen production are also furnished in this section.

Characteristics of South African wind regime

The mean wind speed, standard deviation, shape and scale parameters as well as the exponential shear of each of the 15 sites cutting across five main provinces of South Africa at 60 m anemometer height are presented in Table 6. The table revealed that the mean wind speed (V_m) varies from 5.07 m/s in Eston (S13) to 8.10 m/s in Napier (S5) indicating that Napier is the windiest of all the sites. The standard deviation of the wind speed (ρ) ranges from 2.52 m/s in Eston to 4.3 m/s Rhodes (S11) indicating that intermittency in wind speed is highest in Rhodes and lowest in Eston.

Table 6 – Characteristics of wind speed of the selected site at 60 m anemometer height.

		V_m(m/s)	ρ(m/s)	k	c(m/s)	m
S1	Alexander Bay	6.25	3.91	1.66	7.00	0.088
S2	Calvinia	5.91	3.09	2.03	6.68	0.033
S3	Vredendal	6.97	3.43	2.16	7.87	0.082
S4	Vredenburg	6.67	3.31	2.14	7.53	0.210
S5	Napier	8.10	3.99	2.16	9.15	0.146
S6	Sutherland	7.42	3.54	2.23	8.38	0.136
S7	Prince Albert	6.84	3.03	2.42	7.71	0.091
S8	Humansdorp	6.98	3.62	2.04	7.90	0.214
S9	Noupoort	7.99	3.57	2.40	9.01	0.115
S10	Butterworth	6.49	3.37	2.04	7.32	0.046
S11	Rhodes	7.90	4.30	1.94	8.92	0.056
S12	Eston	5.07	2.52	2.13	5.73	0.155
S13	Jozini	5.14	2.84	1.90	5.79	0.251
S14	Memel	7.40	3.63	2.17	8.36	0.059
S15	Winburg	6.12	2.88	2.26	6.91	0.146

The shape parameters (k) varies from 1.66 in Alexander-Bay (S1) to 2.42 in Prince Albert (S7). This shows that the wind distribution is more peaked in Alexander-bay compared to other sites while the wind speeds are more spread in Prince Albert. The scale parameter (c) which is another metrics for determining how windy a site is ranges from 5.73 m/s in Eston to 9.15 m/s in Napier confirming the wide difference in wind energy potential of the two sites. The table also reveals that besides Napier, other sites with considerable wind energy potential are Sutherland (S6), Noupoort (S9), Rhodes (S11) and Memel (S14) with the scale parameters of 8.38, 9.01, 8.92 and 8.36 m/s, respectively. The exponential shear (m) which is a measure of wind variations with altitude varies from 0.033 in Calvinia (S2) to 0.251 in Jozini (S13). This shows that change in wind speed with height is highest in Jozini indicating that more wind energy can be captured at this site using wind turbines with considerable high hub heights.

Energy and hydrogen production potential from the South African sites using commercially available wind turbines

Efforts were also made to determine the annual capacity factors, probable energy production (GWh), mass of possible hydrogen production (metric-ton) as well as the volume of compressed hydrogen storable in high pressured tank (m^3) for each of the sites from the various available wind turbines. The results are presented in Table 7. The Table reveals that wind turbine 9 i.e. WT_9 (ServionSE MM100) with rated wind power of 2 MW, cut-in wind speed of 2 m/s, rated wind speed of 11 m/s, cut-out wind speed of 22 m/s and turbine hub-height of 100 m has the best capacity factor (*Cf*) across all the sites. The turbine has *Cf* that ranges from 24.04% in Eston (S12) to 54.55% in Napier. Generally, it was observed that large wind turbines have better *Cf* compared to other categories of wind turbine. Wind turbine 3 i.e. WT_3 (NEPC-MICON) with rated wind power of 400 W, cut-in wind speed of 4, rated wind speed of 15, cut out wind speed of 25 and nub-height of 30.5 returned the lowest capacity factors across all the sites. The turbine capacity factors vary between 6.07% in Jozini (S13) and 24.39% in

Table 7 – The annual capacity factor (%), annual wind turbine electrical energy potential (GWh), annual hydrogen production (metric-ton) and annual compressed hydrogen stored in high pressure tank (m^3).

Sites	Para meters	Wind Turbines Performance										
		Small Wind Turbines			Medium Wind Turbines				Large wind turbines			
		WT_1	WT_2	WT_3	WT_4	WT_5	WT_6	WT_7	WT_8	WT_9	WT_{10}	WT_{11}
S1	Cf(%)	18.87	21.71	16.6	24.77	30.97	19.36	30.15	30.48	35.91	33.92	28.05
	E_{WECS}(GWh)	266.98	460.7	469.6	876.1	1312	1027	1813	3234	5080	7198	8928
	M_{H_2}(ton)	4.45	7.68	7.83	14.6	21.86	17.12	30.2	53.89	84.67	119.97	148.80
	Q_{H_2}(m^3)	117.42	202.6	206.5	385.3	576.9	451.7	797.4	1422	2234	3166	3927
S2	Cf(%)	15.48	18.03	13.45	19.18	27.46	14.37	23.76	25.22	30.06	27.87	20.37
	E_{WECS}(GWh)	218.95	382.6	380.5	678.3	1166	762.5	1429	2677	4253	5914	6484
	M_{H_2}(ton)	3.65	6.38	6.34	11.31	19.43	12.71	23.81	44.61	70.88	98.57	108.1
	Q_{H_2}(m^3)	96.30	168.3	167.4	298.3	512.6	335.4	638.3	1177	1870	2601	2852
S3	Cf(%)	21.52	25.09	18.72	28.77	36.69	21.84	34.39	36.03	42.94	40.37	32.44
	E_{WECS}(GWh)	304.39	532.5	529.8	1018	1557	1159	2068	2823	6074	8566	10326
	M_{H_2}(ton)	5.07	8.88	8.83	16.96	25.96	19.31	34.46	63.71	101.2	142.77	172.1
	Q_{H_2}(m^3)	133.88	234.2	233	447.5	684.9	509.6	909.33	1681	2672	3768	4542
S4	Cf(%)	15.28	18.14	13.35	26.46	30.62	20.03	31.98	34.22	44.17	41.51	35.44
	E_{WECS}(GWh)	216.83	386.1	378.9	938.4	1303	1065	1928	3641	6266	8833	11311
	M_{H_2}(ton)	3.61	6.44	6,.1	15.64	21.72	17.76	32.14	60.69	104.4	147.21	188.5
	Q_{H_2}(m^3)	95.35	169.8	166.6	412.7	573.1	468.5	848.02	1601	2756	3885	4975
S5	Cf(%)	27.62	31.78	24.39	38.90	44.71	30.87	44.54	46.47	54.55	52.22	42.75
	E_{WECS}(GWh)	390.73	674.4	690.1	1376	1898	1638	2678	4930	7717	11082	13609
	M_{H_2}(ton)	6.51	11.24	11.50	22.93	31.63	27.30	44.63	82.17	128.6	184.7	226.82
	Q_{H_2}(m^3)	171.85	296.6	303.5	605.2	834.6	720.3	1178	2168	3394	4874	5986
S6	Cf(%)	21.90	25.43	19.24	31.61	38.09	24.53	37.30	39.40	47.81	45.21	36.70
	E_{WECS}(GWh)	309.86	539.6	544.4	1118	1617	1301	2243	4181	6764	9594	11682
	M_{H_2}(ton)	5.16	8.99	9.07	18.64	26.94	21.69	37.38	69.68	112.7	159.9	194.70
	Q_{H_2}(m^3)	136.28	237.3	239.5	491.7	710.9	572.3	986.5	1839	2975	4219	5138
S7	Cf(%)	18.87	22.16	16.40	26.20	34.28	19.63	32.07	33.90	41.85	38.89	30.56
	E_{WECS}(GWh)	266.9	470.2	464.1	926.6	1455	1041	1928.4	3597	5921	8253	9728
	M_{H_2}(ton)	4.45	7.84	7.74	15.44	24.25	17.35	32.14	59.95	98.68	137.56	162.13
	Q_{H_2}(m^3)	117.39	206.8	204.1	407.5	639.8	457.9	848.14	1582	2604	3630	4278
S8	Cf(%)	17.22	20.24	15.13	29.03	32.91	22.42	34.39	36.72	46.31	43.97	36.65
	E_{WECS}(GWh)	243.6	429.5	428.1	1027	1397	1189	2068	3897	6551	9330	11666
	M_{H_2}(ton)	4.06	7.16	7.14	17.11	23.28	19.82	34.46	64.94	109.2	155.5	194.4
	Q_{H_2}(m^3)	107.2	188.9	188.3	451.5	614.2	523.1	909.4	1714	2881	4104	5131
S9	Cf(%)	26.75	30.88	23.54	36.67	43.99	28.65	42.82	44.69	53.24	50.38	41.15
	E_{WECS}(GWh)	378.5	655.3	666	1297	1867	1520	2575	4742	7533	10692	13098
	M_{H_2}(ton)	6.31	10.92	11.10	21.62	31.11	25.33	42.91	79.03	125.6	178.2	218.29
	Q_{H_2}(m^3)	166.46	288.2	192.9	570.4	821.8	668.4	1132	2085	3313	4703	5761
S10	Cf(%)	19.13	22.16	16.69	23.98	32.53	18.20	29.08	30.61	36.37	33.92	25.71
	E_{WECS}(GWh)	270.6	470.2	472.2	848	1381	965.8	1748.4	3248	5146	7199	8183
	M_{H_2}(ton)	4.51	7.84	7.89	14.13	23.01	16.10	29.14	54.14	85.77	120	136.4
	Q_{H_2}(m^3)	119	206.8	207.7	373	607.2	424.8	768.97	1429	2263	3166	3599
S11	Cf(%)	28.26	31.66	25.37	33.95	41.94	27.49	38.60	40.46	45.78	43.78	32.68
	E_{WECS}(GWh)	399.9	671.9	717.70	1201	1781	1459	2321	4294	6477	9291	10401
	M_{H_2}(ton)	6.66	11.20	11.96	20.01	29.67	24.31	38.68	71.56	106.0	154.9	173.4
	Q_{H_2}(m^3)	175.9	295.5	315.68	528.1	782.9	641.5	1021	1888	2849	4086	4575
S12	Cf(%)	7.18	8.57	6.24	12.24	17.12	9.08	15.95	17.91	24.04	22.14	17.02
	E_{WECS}(GWh)	101.58	181.9	176.6	432.9	726.6	481.7	959.2	1900	3402	4698	5417
	M_{H_2}(ton)	1.69	3.03	2.94	7.22	12.11	8.03	15.99	31.67	56.70	78.29	90.29
	Q_{H_2}(m^3)	44.68	80.0	77.67	190.4	319.6	211.8	421.9	835.8	1496	2066	2383
S13	Cf(%)	6.95	8.38	6.07	14.59	17.33	10.83	18.56	20.71	29.32	27.19	23.38
	E_{WECS}(GWh)	98.25	177.8	171.68	516.2	735.5	574.5	1116	2197	4148	5770	7442
	M_{H_2}(ton)	1.64	2.96	2.86	8.60	12.26	9.58	18.60	36.62	69.12	96.16	124.04
	Q_{H_2}(m^3)	43.25	78.18	25.51	227.0	323.5	252.7	490.9	966.4	1824	2538	3273
S14	Cf(%)	24.47	28.02	21.59	30.68	39.50	23.88	36.36	37.98	44.25	41.82	32.06
	E_{WECS}(GWh)	346.15	594.5	610.8	1085	1677	1267	2186	4030	6260	8875	1021
	M_{H_2}(ton)	5.77	9.91	10.18	18.09	27.94	21.11	36.44	67.17	104.3	147.9	170.1
	Q_{H_2}(m^3)	152.24	261.5	268.7	477.3	737.4	557.2	961.6	1772.	2753	3903	4489
S15	Cf(%)	12.86	15.28	11.17	20.56	26.44	15.26	25.71	27.77	36.19	33.51	27.01
	E_{WECS}(GWh)	181.87	324.2	316.0	727.2	1122.	809.6	1546	2947	5120	7111	8598
	M_{H_2}(ton)	3.03	5.40	5.27	12.12	18.71	13.49	25.77	49.12	85.34	118.5	143.3
	Q_{H_2}(m^3)	79.99	142.6	139	319.8	493.6	356.1	680	1296	2252	3128	3781

Napier (S5). It was generally observed that Napier presents the best capacity factors for all categories of wind turbines ranging from 24.03% with turbine WT_3 to 54.55% with WT_9. This is expected as the site has the highest mean wind speed of 8.10 m and considerable high standard deviation of 3.99 m/s. Site S13 (Jozini) has the least capacity factors for small wind turbine category, while site S12 (Eston) has the least capacity factor for medium and large wind turbines categories.

One of the interesting results is that *Cf* may be lower in sites with higher mean wind speed compared to the sites with lower mean wind speed especially with larger wind turbines. This can be attributed to the difference in the exponential shear (m) which varies from site to site. Larger wind turbines have higher hub heights and therefore have higher *Cf* at sites with higher m compared to sites with lower m. For example, site S3 (Vredendal) has higher mean wind speed of 6.97 m/s compared to site S4 (Vredenburg) with mean wind speed of 6.67 m/s. However, site S3 has lower m of 0.082 compared to Site S4. Table 7 reveals that Site S4 with lower mean wind speed but higher m has better performance for medium and larger wind turbine compared to the site S3. This is because, these categories of wind turbines have higher hub height and since site S4 has higher variation of wind speed with altitude, then the wind turbines with higher hub heights are more favoured.

The amount of energy generated (GWh) is a function of the *Cf*, the higher the *Cf* of a wind turbine at a given site, the more the electricity generation potential of the turbine at that site. Site S5 has the highest electricity generation potential across all categories of wind turbines which ranges from 390.73 GW h per annum with turbine WT_1 to 13609 GW h per annum with turbine WT_{11}. Wind turbine WT_{11} presenting the highest electricity generation across all the sites. This is expected as this turbine has the highest rated power of all the wind turbines. Its annual electricity generation potential varies from 5417 GW h in site S12 to 13609 GW h in site S5. The least electricity generation potential sites across all categories of wind turbines was experienced in sites S12 and S13, indicating that these sites are potentially weak for hydrogen-production project compared to the other sites.

Table 7 also revealed that the quantity of hydrogen production (metric tons) and the compressed hydrogen storable (m^3) across all the sites are functions of the size of wind turbines and the *Cf* of the wind turbine at the sites. Site S5 presents the best hydrogen production potential with annual hydrogen production that ranges between 6.51 metric-tons with turbine WT_1 and 226.82 metric-tons of hydrogen with turbine WT_{11}. Also the annual storable compressed hydrogen for this site was evaluated to be between 171.85 m^3 to 5986 m^3 of hydrogen for the wind turbines, respectively. Sites S12 and S13 present the least hydrogen production with maximum annual production of 90.29 and 124.04 metric-tons of hydrogen, respectively from wind turbine WT_{11}. The maximum storable compressed hydrogen for these sites was estimated at 2383 m^3 and 3273 m^3 per annum, respectively. The minimum hydrogen production for sites S12 and S13 is from WT_1 with 1.69 and 1.64 metric-tons per annum. Generally, most of the sites have good potential for hydrogen production suggesting a good outlook for hydrogen economy in South Africa.

Economic analysis of South African site for green hydrogen production

Economic viability of electrical energy and hydrogen production obtainable from each of the wind turbines across the entire sites were also investigated and the results are presented in Table 8. The table revealed that wind turbines with the highest *Cf* presents the lowest cost of energy. Wind turbine WT_9 has the highest *Cf* across all the sites with the least cost of electricity generation ranging from 0.23$/kWh at site S5 to 0.42 $/kWh at site S13. On the other hand, wind turbine WT_1 presents the highest cost of electricity generation ranging from 0.67$/kWh in site S11 to 2.72$/kWh in site S13. It can be generally observed from the table that site S5 is the most viable site for generating electricity for hydrogen production with the cost of electricity ranging from 0.69$/kWh using wind turbine WT_1 to 0.23$/kWh when turbine WT_9 is used. Sites S12 and S13 are the most cost intensive for hydrogen production with the cost of electricity ranging from 0.51 to 2.64$/kWh and 0.42 to 2.72 $/kWh, respectively with WT_9 being the cheapest wind turbine and WT_1 the least.

The cost of hydrogen depends on how much of hydrogen can be produced per time from a given wind turbine, therefore larger wind turbines generally present lower cost of hydrogen production compared to the small and medium size category. The cost of hydrogen is lowest at site S5 and ranges between 39.55$/kg using wind turbine WT_1 and 1.4$/kg using wind turbine $WT_{11.}$ Using small wind turbines is generally not favourable with very high cost of hydrogen production up to 152.13 $/kg in site S12 and 157.2 $/kg in site S13 when the smallest wind turbine WT_1 is used. However, the cost could be as low as 3.52$/kg and 2.57$/kg at sites S12 and S13, respectively, when the WT_1 is replaced with the largest wind turbine WT11. This is partly due to the lower capital cost of large wind turbine in $/kW and higher electricity generation capacity. The cost of hydrogen generally varies between 1.44/kg in site S5 to 3.52$/g in site S12 when WT_{11} is utilised. The turbine has rated power generation 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. Therefore, the use of large wind turbines in South African sites can produce cheaper green hydrogen which could support transportation, distributed electricity generation as well as meeting the industrial needs.

Sensitivity analysis

Sensitivity analysis is necessary to be performed in order to gain insight into the dependency of a given system characteristic on some defined input variables. In this paper, the possible impact of operating parameters i.e. the cut-in wind speed (v_{ci}), rated wind speed (v_r), cut-out wind (v_{co}) and turbine hub height (H_h) on the possible hydrogen yield (Q_{H_2}), cost of hydrogen (C_{H_2}), capacity factor of wind turbines (*Cf*) as well as the cost of electricity from wind turbine (C_{lec}) were carried out. In the same way, the effect of exponential shear (m) on the possible yield of hydrogen as well as their effects on cost of production were also determined.

Table 8 – Cost of energy based on annual wind energy production ($/kWh) and the cost of hydrogen production based on annual hydrogen generation ($/kg).

Sites	Para meters	Wind Turbines Performance										
		Small Wind turbines			Medium wind turbines				Large wind turbines			
		WT_1	WT_2	WT_3	WT_4	WT_5	WT_6	WT_7	WT_8	WT_9	WT_{10}	WT_{11}
S1	C_{lec}($/kWh)	1.01	0.57	0.74	0.50	0.39	0.64	0.41	0.402	0.34	0.36	0.44
	C_{H_2}($/kg)	57.87	33.52	33.07	17.83	11.97	15.42	8.78	5.10	3.33	2.471	2.14
S2	C_{lec}($/kWh)	1.22	0.68	0.91	0.64	0.45	0.85	0.52	0.49	0.41	0.44	0.60
	C_{H_2}($/kg)	70.58	40.37	40.82	23.03	13.48	20.77	11.15	6.16	3.98	3.01	2.95
S3	C_{lec}($/kWh)	0.88	0.49	0.66	0.43	0.33	0.56	0.37	0.34	0.29	0.30	0.38
	C_{H_2}($/kg)	50.76	29.00	29.32	15.35	10.09	13.67	7.70	4.31	2.79	2.08	1.85
S4	C_{lec}($/kWh)	1.24	0.67	0.92	0.46	0.40	0.61	0.38	0.36	0.28	0.30	0.35
	C_{H_2}($/kg)	71.27	40.00	41.00	16.64	12.05	14.86	8.26	4.53	2.70	2.01	1.69
S5	C_{lec}($/kWh)	0.69	0.39	0.50	0.32	0.27	0.30	0.28	0.26	0.23	0.23	0.27
	C_{H_2}($/kg)	39.55	22.90	22.51	11.35	8.28	9.67	5.95	3.34	2.19	1.61	1.40
S6	C_{lec}($/kWh)	0.86	0.48	0.64	0.39	0.32	0.50	0.33	0.31	0.26	0.27	0.33
	C_{H_2}($/kg)	49.87	28.62	28.53	13.97	9.72	12.17	7.10	3.94	2.50	1.85	1.63
S7	C_{lec}($/kWh)	1.00	0.55	0.75	0.47	0.36	0.63	0.38	0.36	0.29	0.32	0.40
	C_{H_2}($/kg)	57.90	32.85	33.47	16.86	10.80	15.21	8.26	4.58	2.86	2.16	1.96
S8	C_{lec}($/kWh)	1.10	0.61	0.81	0.42	0.37	0.55	0.36	0.33	0.27	0.28	0.34
	C_{H_2}($/kg)	63.43	35.96	36.28	15.21	11.25	13.31	7.70	4.23	2.58	1.91	1.64
S9	C_{lec}($/kWh)	0.71	0.40	0.52	0.34	0.28	0.43	0.29	0.27	0.23	0.24	0.30
	C_{H_2}($/kg)	40.82	23.57	23.32	12.04	8.41	10.42	6.18	3.48	2.25	1.66	1.46
S10	C_{lec}($/kWh)	0.99	0.55	0.74	0.51	0.38	0.67	0.42	0.40	0.34	0.36	0.48
	C_{H_2}($/kg)	57.11	32.85	32.89	18.42	11.38	16.40	9,11	5.08	3.29	2.47	2.33
S11	C_{lec}($/kWh)	0.67	0.39	0.48	0.36	0.29	0.45	0.32	0.30	0.27	0.28	0.38
	C_{H_2}($/kg)	38.65	22.99	21.64	13.01	8.82	10.85	6.86	3.84	2.61	1.91	1.84
S12	C_{lec}($/kWh)	2.64	1.43	1.96	1.00	0.72	1.35	0.77	0.68	0.51	0.55	0.72
	C_{H_2}($/kg)	152.13	84.91	87.95	36.07	21.61	32.88	16.60	8.68	4.97	3.79	3.52
S13	C_{lec}($/kWh)	2.72	1.46	2.02	0.84	0.71	1.13	0.66	0.59	0.42	0.45	0.53
	C_{H_2}($/kg)	157.22	86.89	90.46	30.26	21.35	27.57	14.27	7.50	4.17	3.08	2.57
S14	C_{lec}($/kWh)	0.77	0.44	0.57	0.40	0.31	0.51	0.34	0.32	0.28	0.29	0.38
	C_{H_2}($/kg)	44.64	25.98	25.43	14.39	9.37	12.50	7.28	4.09	2.70	2.00	1.87
S15	C_{lec}($/kWh)	1.47	0.80	1.10	0.60	0.46	0.80	0.48	0.44	0.34	0.37	0.45
	C_{H_2}($/kg)	84.97	47.64	49.15	21.48	13.99	19.56	10.30	5.59	3.31	2.50	2.22

Effect of wind turbine operating parameters on hydrogen production and economic

The effect of wind turbine operating parameters (cut-in, cut-out, rated wind speeds and turbine hub height) on the possible hydrogen yield is carried out to gain insight into the possible influence of these parameters on hydrogen production and its economic gains or burdens. To achieve this, Servion SE MM100 wind turbine (i.e. turbine T9) was selected for this purpose. This is because this turbine presents the highest *Cf* across all the sites. Wind speed of one of the cities i.e Noupoort (S9) was selected to complete the study. There was no particular reason for selecting the city for the sensitivity analysis as wind characteristics of any of the cities could be used. In order to allow fair comparison across various dependent variables, percentage changes were used as a measure of variation in the sensitivity analysis. This will allow fair judgement on how the input variables (v_{ci},v_r, v_{co} and H_h) affect the dependent variables of interest (i.e hydrogen production, cost of hydrogen, capacity factor and cost of energy from wind turbine). Each of the input parameters were varied from 0 to 100% to view the response of the dependent parameters. When one input variable is varied, others are kept constant.

Impact of change in cut-in wind speed

The results presented in Fig. 5 depict the influence of variation in cut-in wind speed on the hydrogen production, cost of hydrogen, capacity factor and cost of electrical energy. Fig. 5(a) shows that an increase in cut-in wind speed decreases the hydrogen production. A 25, 50, 75 and 100% increase in cut-in wind speed will reduce the hydrogen production by about 1.5, 3.4, 5.6 and 8.2%, respectively. This will increase the cost of hydrogen as depicted in Fig. 5(b) by about 1.4, 3.7, 6 and 8.8%, respectively. Fig. 5(c) revealed that a gradual 25% increase of cut-in wind speed up to 100% will reduce the capacity factor by 1.5, 3.4, 5.6 and 8.2%, respectively. This causes a corresponding increase in the cost of electricity generation by 1.5, 3.5, 6.0 and 8.9%, respectively.

Impact of change in rated wind speed

In a similar manner, the effect of change in rated wind speed was observed on the hydrogen production, cost of hydrogen, capacity factor and cost of electrical energy. The result is presented in Fig. 6. The figure revealed that a 25% gradual increment up to 100% in the rated wind speed causes reduction in hydrogen production as seen in Fig. 6(a) by about 22, 30, 53 and 63%, respectively. This results into the increase in the cost of hydrogen by about 27, 64, 112 and 173%, respectively as

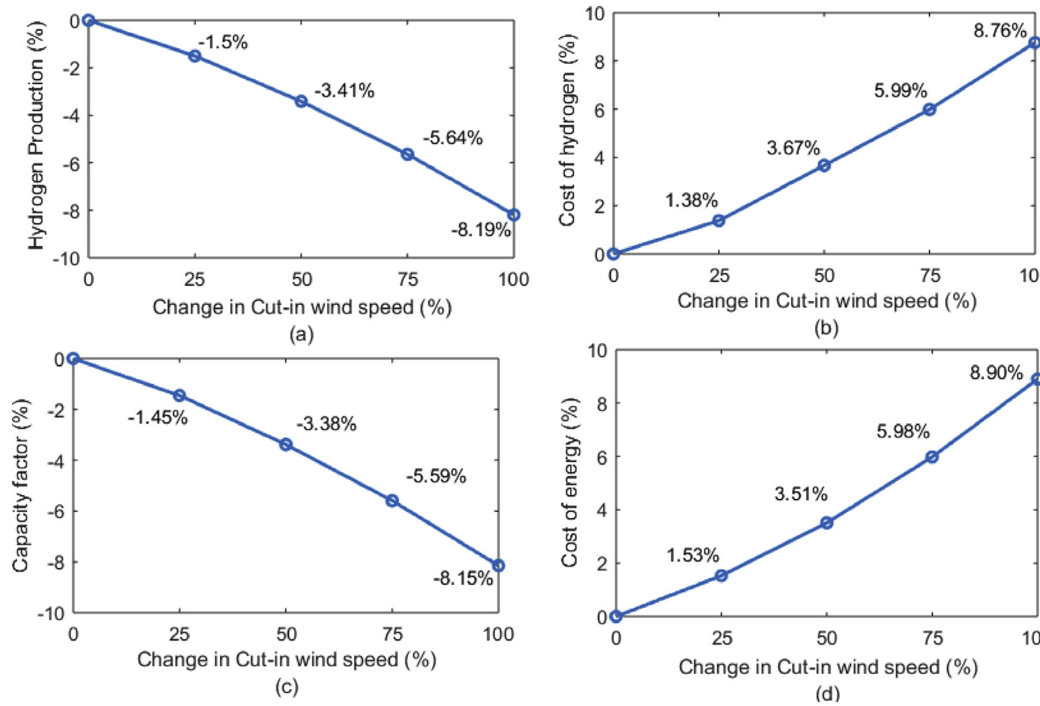

Fig. 5 – Effect of change in cut-in wind speed on the (a) hydrogen production (b) cost of hydrogen (c) Capacity factor and (d) cost of energy.

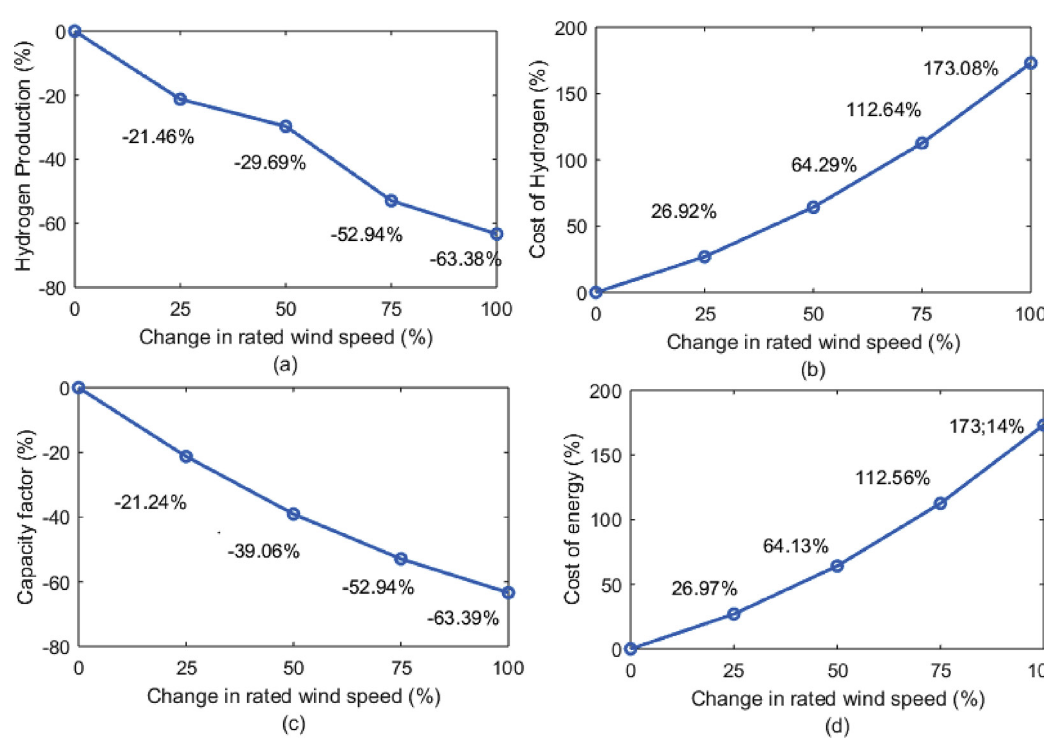

Fig. 6 – Effect of change in rated wind speed on the (a) hydrogen production (b) cost of hydrogen (c) Capacity factor and (d) cost of energy.

depicted in Fig. 6(b). These high changes in responses show that rated wind speed affects hydrogen production to a greater extent and therefore wind turbines should be selected in such a way that the rated wind speed matches well with the wind regime of the intending site. Fig. 6(c) and (d) showed the exponential decrease in wind turbine capacity factor and corresponding increase in the cost of energy.

Impact of change in cut-out wind speed

The effect of cut-out wind speed on the hydrogen production, cost of hydrogen, capacity factor as well as the cost of electricity from wind turbine was also explored and the results are presented in Fig. 7. The results generally revealed that cut-out wind speed has negligible impact on the hydrogen production as well as its economic viability (less than 0.6%). Hence matching of cut-out wind speed to the local wind regime is not much of a worry for electricity generation or hydrogen production.

Impact of change in wind turbine hub height

The possible responses of hydrogen production, capacity factor, cost of energy as well as the cost of energy due to change in turbine hub-height were also investigated and the results are presented in Fig. 8. The figure clearly revealed that change in turbine hub height has significant impact of hydrogen production and its associated economic viability. A gradual 25% change in hydrogen production up to 100% correspondingly increase the hydrogen production as well as the capacity factor by about 4%–12%. This decreases the cost of hydrogen and electricity by about 4%–10%, respectively.

Impact of exponential shear on hydrogen production

Exponential shear (m) is one of the parameters that distinguish one site from the other, it directly affects the distribution of wind speed based on the site terrain. Its possible influence on the hydrogen yield as well as its economic implications on hydrogen production was explored using using Servion SE MM100 wind turbine (i.e. turbine T9) and wind regime of site S9 (Noupoort). The exponential shear of site S9 was varied gradually by 25% up to 100% and the possible effect on hydrogen production, cost of hydrogen, wind turbine capacity factor as well as the cost of electricity from wind turbine were determined and the results are presented in Fig. 9. The Fig. 9(a) and (c) revealed that a linear increase in the exponential shear causes a corresponding linear increase in the hydrogen production and capacity factor. For example, a 25% increase in exponential shear will increase the hydrogen production by about 2.7%and capacity factor by about 2%. Also an increase by 50% increases the hydrogen production as well as the capacity factor by 3.98 and 3.94%, respectively. Fig. 9(b) and (d) showed that if the exponential shear increases, the cost of hydrogen as well as the cost of energy decreases in a similar proportion. A 25, 50, 75 and 100% increase in exponential shear will cause a corresponding decrease in the cost of hydrogen by about 1.94, 3.78,

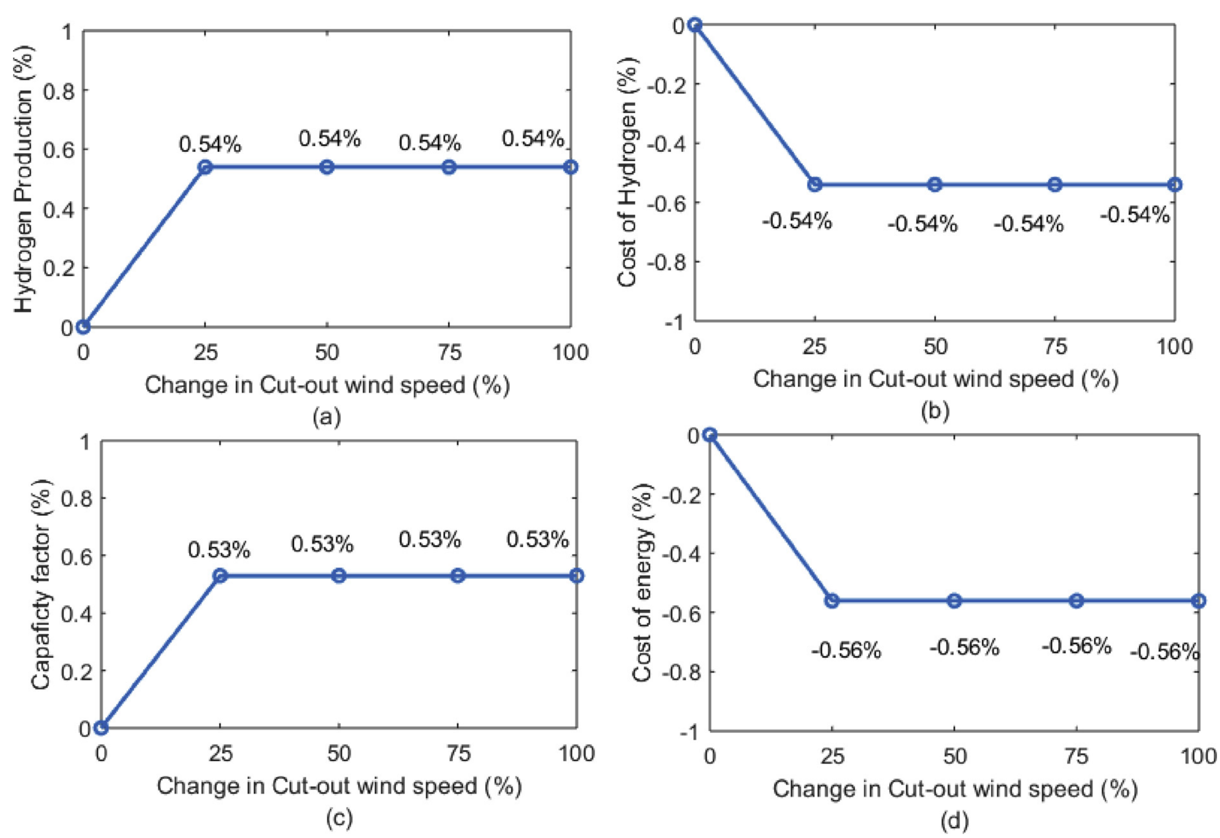

Fig. 7 – Effect of change in cut-out wind speed on the (a) hydrogen production (b) cost of hydrogen (c) Capacity factor and (d) cost of energy.

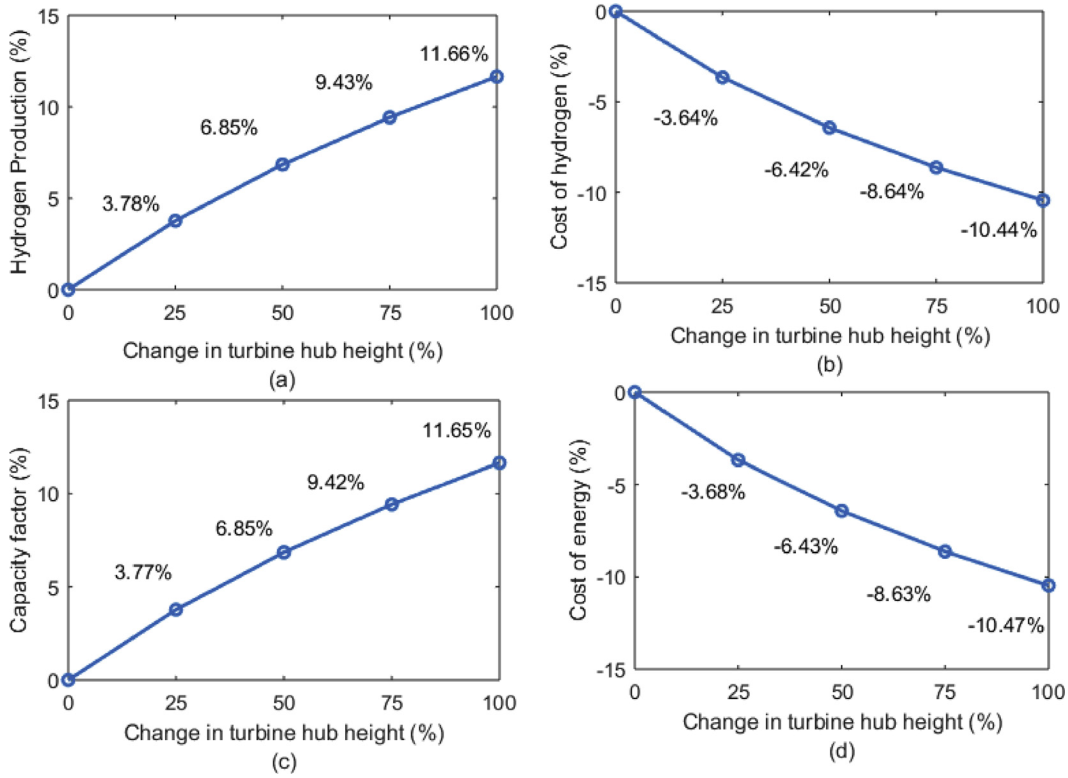

Fig. 8 – Effect of change in wind turbine hub-height on the (a) hydrogen production (b) cost of hydrogen (c) Capacity factor and (d) cost of energy.

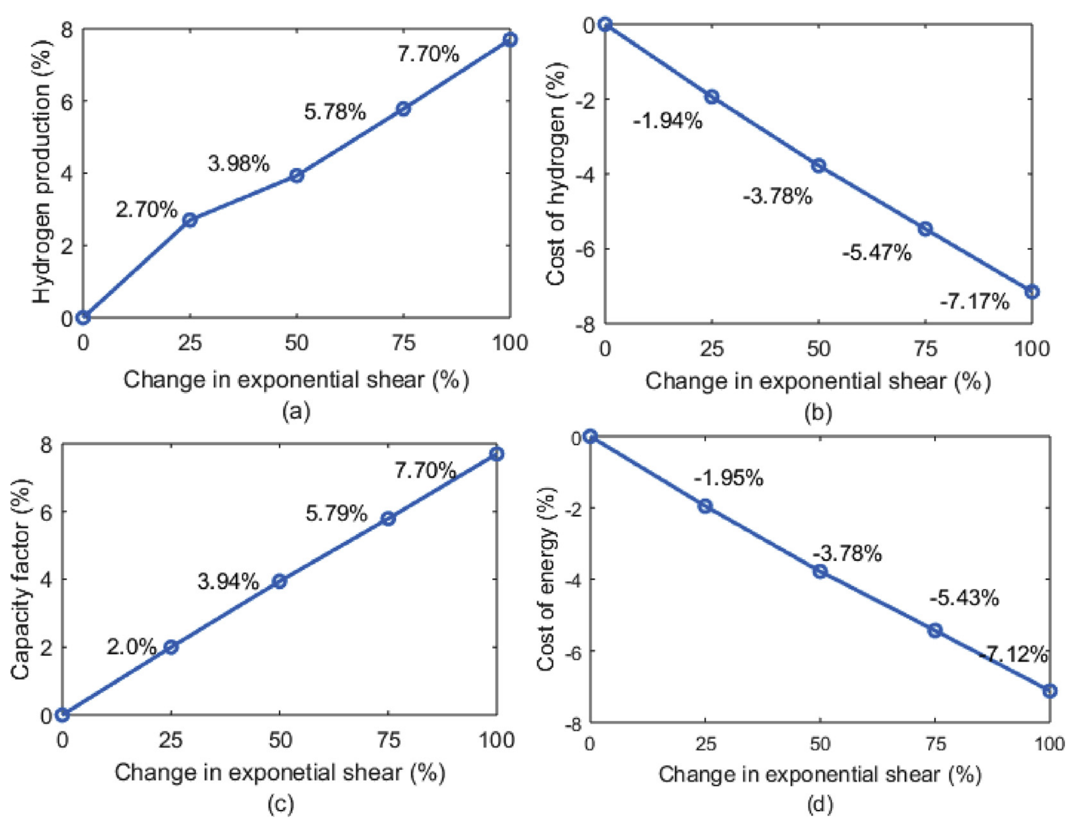

Fig. 9 – Effect of exponential shear on the (a) hydrogen production (b) cost of hydrogen (c) Capacity factor and (d) cost of energy.

5.47 and 7.17%, respectively. In the same vein, the costs of electricity from the wind turbine are reduced by about 1.95, 3.78, 5.43 and 7.12%, respectively.

Conclusion

The potential and economic viability of green hydrogen production from wind energy resources for 15 sites cutting across 5 provinces of South African have been investigated. The possible impact of variation in the turbine operating factors, the effect of exponential shear characteristics on renewable hydrogen production as well as its economic gains/burdens have also been explored. From the results of the studies, the followings are concluded:

i. The mean wind speed (V_m) of the fifteen (15) different sites under study varies from 5.07 m/s in Eston (S12) to 8.10 m/s in Napier (S5), hence site Napier is the windiest of all the sites.
ii. The exponential shear (m) varies from 0.033 in Calvinia (S2) to 0.251 in Jozini (S13) indicating that wind speed in Jozini varies significantly with height suggesting a higher hub-height wind turbine is the most preferred at this site.
iii. Wind turbine WT_9 (ServionSE MM100) with rated wind power of 2 MW, cut-in wind speed of 2 m/s, rated wind speed of 11 m/s, cut-out wind speed of 22 m/s and turbine hub-height of 100 m has the highest capacity factor (Cf) across all the sites. The turbine has Cf that ranges from 24.04% in Eston (S12) to 54.55% in Napier.
iv. Site S5 has the highest electricity generation potential across all categories of wind turbines which ranges from 390.73 GW h per annum with turbine WT_1 to 13609 GW h per annum with turbine WT_{11}
v. Site S5 presents the best hydrogen production potential with annual hydrogen production that ranges between 6.51 metric-tons with turbine WT_1 and 226.82 metric-tons of hydrogen with turbine WT_{11}. Also the annual storable compressed hydrogen was found to be between 171.85 m^3 to 5986 m^3 of hydrogen, respectively
vi. Wind turbine WT_9 has the least cost of electricity generation ranging from 0.23$/kwh at site S5 to 0.42 $/kwh at site S13. Also, the cost of hydrogen is lowest at site S5 and ranges between 39.55 $/kg using wind turbine WT_1 and 1.4 $/kg using wind turbine WT_{11}.
vii. The sensitivity analysis conducted revealed that rated wind speed affects hydrogen production and its associated viability significantly. Hence, wind turbines should be selected in such a way that the rated wind speed matches well with the wind regime of the intending site.

Future research will look into the technical, economic and environmental impact assessment of using the produced hydrogen for meeting the energy needs of rural communities in South Africa using Fuel Cell. The payback of wind-hydrogen project for meeting the local loads in comparison to the use of diesel generator will be investigated.

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