Evaluation of wind resources potential and economic analysis of wind power generation in South Africa

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Abstract. The presence of adequate renewable energy resources and the rapid development of wind projects in South Africa have led to mapping out of the country's wind capability. In view of this, the economic prospects of utilizing wind energy as a potential energy alternative in South Africa are examined and discussed from the perspectives of green energy strategies for sustainable energy development. This research work is designed to investigate the economic effects of using the wind turbine (WT) in ten locations in South Africa based on the grid planning and power sector reform. The HOMER application software is utilized in this study to assess the wind resources on provincial and national scales, along with estimating the annual energy generation of the selected locations. The wind energy potential of South Africa is analysed by utilizing the capacity factor (CF), wind penetration and mean output of the WT for various locations in South Africa. The results obtained from the study indicate that the selected sites fall within the range of Class 1V of IEC wind classifications with the annual average wind speed of 4.04 m/s for Pretoria and 6.39 m/s for Cape Town at 50m hub heights. The economic assessment of the WT for electric power generation is carried out by using some key performance indicators (KPIs) such as net energy purchased, energy sold, revenue, grid energy purchased, annual utility bill savings, net present cost (NPC) and cost of energy (COE). It is established from the study that Cape Town is the most suitable location for installation of the WT by utilizing the same load profile and system configuration. The output of this research work can be used by the renewable energy development agencies as inputs to harness the potential of wind resources for strategic planning of the power sector reform and industrial development.

Keywords: Battery storage system, economic, energy purchased, energy sold, net energy purchased.

Introduction

The global industrial revolution, rapid population growth and increase in the world standard of living have increased the power demand in proportion to the rates that have ever been witnessed in the history of human civilization. The availability of electric power supply plays a critical role in commercial, industrial and agricultural sectors as well as expanding the global economy [1]. This has made many countries in the world to depend on fossil fuels for power generation, domestic applications and transportation. The imminent energy crises that arise from the global depletion of fossil fuel, political instability in the oil-producing countries and the failure of the local refinery capacity to meet domestic fuel consumption will expose many countries to economic risk and insecurity. In spite of naturally gifted large deposit of renewable energy resources in many countries in the world, over 1.1 billion people do not have access to electricity owing to one constraint or another [2]. The utilization of renewable energy resources is a roadmap to support the global economy with a teeming population of about 7.7 billion people. This has prompted many countries to allow the private sectors to actively participate in the power sectors by utilizing numerous resources to meet the power demand of their citizens. With the deregulation of power sectors in the UK, Canada, France, Sweden, Italy, Finland, Norway, Belgium, Spain, US, Germany and Ireland, the power utilities have changed their operations from vertically integrated mechanisms to open market systems. The fundamental reasons for the global power deregulation are the increasing environmental concerns of petroleum products and their impacts on the climate as well as the capability of many countries to develop their own distributed generation (DG) technologies for commercial power generation [3]. The open market mechanism allows competitors to enter multiple global markets with the integration of DGs into their networks. Due to the facts that DGs contribute both technical and economic benefits to the optimal operation of the electric power system and deregulated open market. The DG is defined as electric storage and electric generation components that are connected to the grid or customer side of the meters [4]. The DGs are designed by the manufactures with the range of 3 kW to 10 MW based on the specifications of the customers and utilities and are generally connected to the utility grid at the selected points or operate as islanded power systems. The DGs typically consist of non-renewable energy and renewable energy sources such as small hydro, wind energy conversion system, photovoltaic, geothermal, biogas, biomass and battery storage system [5]. The DGs can be coordinated and managed within the utility grid with the application of the smart-grid features or power management facilities.

The sudden escalation of the global power consumption due to the population growth, over-dependence on fossil fuels for power generation and environmental effects of petroleum products have made the power utilities and researchers to look for a better alternative that can alleviate the negative effects of using conventional generating units [6]. The power generations in some countries such as Denmark, Germany, Sweden, Iceland, United Kingdom and China have shifted from conventional technologies that operate with the greenhouse gas (GHG) emissions to renewable energy technologies (RETs) that have numerous technical, economic and environmental benefits. The RETs have shown some remarkable growth in the last two decades, this has tremendously increased the global installed capacity of the WTs. The cumulative installed capacity of the WT in China alone, is approximately 99% more than the total installed capacity of the power stations in South Africa, being 19.7 GW at end of 2017 [7]. Similarly, the sizes, power ratings and diameters of the WTs have drastically improved based on recent advances in the technology. The South African power sector is mainly dominated by the coal-fired power plants, this demonstrates that approximately 77% of South Africa's power demand is sourced from coal and 23% from low carbon content sources. Currently, 81% of the coal consumed domestically in South Africa goes towards electricity production. The current lifetime of coal deposit that is left in South Africa is about 40 years, this has made the Department of Energy and other government agencies to design a blueprint for utilization of RETs as the alternative to conventional generation technologies. Besides depleting of coal in South Africa, global warming, acid rain, smog, soil degradation, public health impacts and GHG emissions have become serious challenges for the people that live within the areas where coal-fired power plants are located in South Africa. The coal-fired power plants are typically situated in Limpopo and Mpumalanga owing to the presence of rich coal deposit concentration in the provinces. The large percentage of power generation stations have been installed in the North-East of the country and transmitted at a high voltage to the Southern provinces over long distances as shown in Fig. 1. With the integration of the WTs into the grid, the power generation will not only be distributed among the nine provinces to reduce transmission distances and the associated losses but also save some costs.

According to the recent report by the World Bank, many people have been reported to be living in the underdeveloped and developing countries where access to electricity has become a serious crisis owing to financial and technical barriers [6]. Similarly, an average of 20% of the South African Development Community (SADC) countries' population do not have access to power supply, only 5% of remote communities in the region have access to power supply [8]. The region is facing a major challenge in the development of its power infrastructures due to under-utilization of renewable energy resources for power generation and many financial constraints. This has hindered the economic growth and regional integration activities that are vital for the development of SADC countries. As a result of this, the SADC Renewable Energy Initiatives has embarked on several remarkable renewable energy projects that are mainly designed as pathways to motivate the policy makers in the government agencies, power sector and investors for a large-scale utilization of renewable energy resources to increase the power generation capacity of the region. The access to a reliable and affordable electricity can be used to improve the standard of living of South Africans and eradicate poverty to a certain extent. In order to achieve this objective, South Africa Department of Energy has recently made available 2018 integrated resources plan (IRP) for public comments so that it can be gazetted. The IRP is a program designed to accomplish the present and future power requirements of South Africa by identification of the essential investments in the power sector to maximize the national interest. This allows good investment decisions to be made by the government agency so that the nation can meet the projected power demand with the minimum operating costs. One of the goals of the IRP is to meet the energy needs of South Africa and design a blueprint that can support and upgrade the existing power infrastructures for the socio-economic objective. This requires an increase in the capacity of South Africa power generation and reduction in the GHG emissions for environmentally sustainable energy with the integration of low carbon sources into the grid. The plan is designed to achieve 46% of power from coal, 10 % of power from solar CSP and solar PV, 16% of power from gas, 15% of power from wind and 6% of power from hydropower by 2030 [9].

The wind resources have been projected to play a proactive role in global energy requirements, especially in developing and undeveloped nations. The possibility to deliver electric energy from renewable energy resources in South Africa has essentially become more prominent based on the combined effect of wind and solar energy resources in the country [10]. South Africa is a country that is situated in the Southern part of Africa, its coastline extends by more than 2,500 km from the border it shared with Namibia on the Atlantic coast. The coastline of South Africa stretches to the North-East where it shared a border with Mozambique that is located on the Indian Ocean [11]. The country has an excellent capability for the large-scale wind farms in the Western Cape, Free State and Eastern Cape provinces. The large availability of renewable energy resources in the country has made some provinces to be viable for the large-scale grid connected and standalone power systems. The combination of wind resources and other renewable energy resources can be economically used to meet a large percentage of South Africa's power demand. The country has a feasible potential for the application of wind energy that ranges from small to large scale microgrid power systems. The windiest place in South Africa is Beaufort West that can be found in Western Cape province, the town encounters just 2% of all hours in the year with quiet conditions. The average wind speed of the town is approximately 6.9 m/s with 42.1% of the wind speeds more prominent than 8 m/s [6]. In spite of the wind capability of South Africa, wind energy is yet to be fully harnessed in the country' energy mix. This demonstrates that the application of the WT is only limited to small and medium scale power systems in South Africa. This has justified the domination of South Africa power sector with a number of coal-fired power plants. In light of this, this work is designed to (i) present the status of wind energy development in South Africa, (ii) assess the potential of wind resources in some locations in South Africa and (iii) carry out the economic analysis of wind resources in South Africa.

Several studies have been carried out on the economic feasibility of the microgrid systems with the integration of renewable energy resources. Umer et al. [12] have proposed an algorithm for optimal sizing of hybrid components such as WT, photovoltaic (PV) and battery storage system (BSS). The methodology proposed in the work is to prevent over and under sizing of the significant segments of a microgrid system. Ogunjuyigbe et al. [13] have proposed the capacity optimization technique for optimal operation of the PV, WT, BSS and diesel generator hybrid system. The algorithm is applied to optimize the carbon dioxide (CO_2) emissions, life-cycle cost and dump energy. Yang et al. [14]

have presented an approach for capacity optimization of renewable energy resources and BSS in a hybrid system with the aim of optimizing the initial investment and operation and maintenance (O&M) costs of the proposed power system. Ahmadi et al. [15] have presented the optimal sizing of the WTs, PV and BSS for minimization of total present cost of the power system. Atia et al. [16] have proposed a methodology to determine the optimal capacities of the major components of a microgrid system designed for residential facilities by reducing the annualized cost. Wang et al. [17] have carried out a comparative analysis study on the demand side management of a commercial building that utilizes a microgrid system with the integration of the PV, BSS and Electric Vehicle (EV). The application of the EV in a microgrid system can be used to minimize the overall operation cost of the building. In the aforementioned literature review, the objective functions considered by the authors are overall operating cost, annualized cost, total present cost, CO_2 emissions, initial investment cost, life-cycle cost, dump energy and O&M costs. However, a few research works have indicated a feasible location for wind resources in South Africa. This paper proposes the HOMER tool to achieve the aim of this research work owing to the following benefits: It can estimate the best option that would give the best energy efficiency, the optimization analysis provided by the HOMER alleviate many problems that are associated with achieving optimal solutions and configurations, it is fast to run with a combination of numerous resources, flexible and efficient and it provides detailed results for analysis and evaluation of a microgrid system. The objectives considered in this paper are the simultaneous optimization of the net energy purchased, energy sold, revenue, grid energy purchased, annual utility bill savings, NPC and COE with the application of the WT and BSS.

In this research work, a methodology for optimization of wind resources in ten locations in South Africa is proposed with a grid-connected microgrid system. The procedure for finding the best location for installation of the WT in this work is based on the location that has the most optimized KPIs and availability of wind speeds. Similarly, the availability of wind resources is considered in this work, since it is one of the factors that determine the power output of the WTs. The ten locations that are selected for this reach work spread across nine provinces in the country, the locations are as follows: Bhisho (Eastern Cape), Bloemfontein (Free State), Johannesburg (Gauteng), Polokwane (Limpopo), Nelspruit (Mpumalanga), Kimberly (North Cape), Pietermaritzburg (KwaZulu-Natal), Mafikeng (North West), Cape Town (Western Cape) and Pretoria (Gauteng). The novelty of this work lies on the fact that it assesses net energy purchased, energy sold, revenue, grid energy purchased, annual utility bill savings, NPC, COE, capacity factor, mean output power of the WTs and annual energy produced by the WTs to determine the optimal solution for the proposed power system. The assessment of wind resources potential and the economic analysis of the WTs integration into the utility grid is implemented based on the aforementioned KPIs. The methodology proposed in this research work is based on the hourly wind speed and load profile of some towns and cities in South Africa. A detailed comparison based on the results obtained from different locations indicate the proposed approach is efficient to assess the economic feasibility and capability of wind resources in South Africa.

The remaining part of this paper is arranged as follows. Section 2 presents the potential of wind resources for power generation in South Africa, Section 3 presents the mathematical modelling and components of a microgrid system, Section 4 presents the economic metrics that be used to analyse the optimal performance of a microgrid system, Section 5 discusses the grid rates, Section 6 presents the proposed methodology for optimization of the proposed system and results and discussions are presented in Section 7 while the conclusion is drawn in Section 8. This paper provides a lot of information that will be helpful to wind energy designers, government at different levels and private sectors that are occupied with wind energy improvement. The results of this study can be used by government agencies, investors and utilities for a large-scale exploitation of wind resources for power generation.

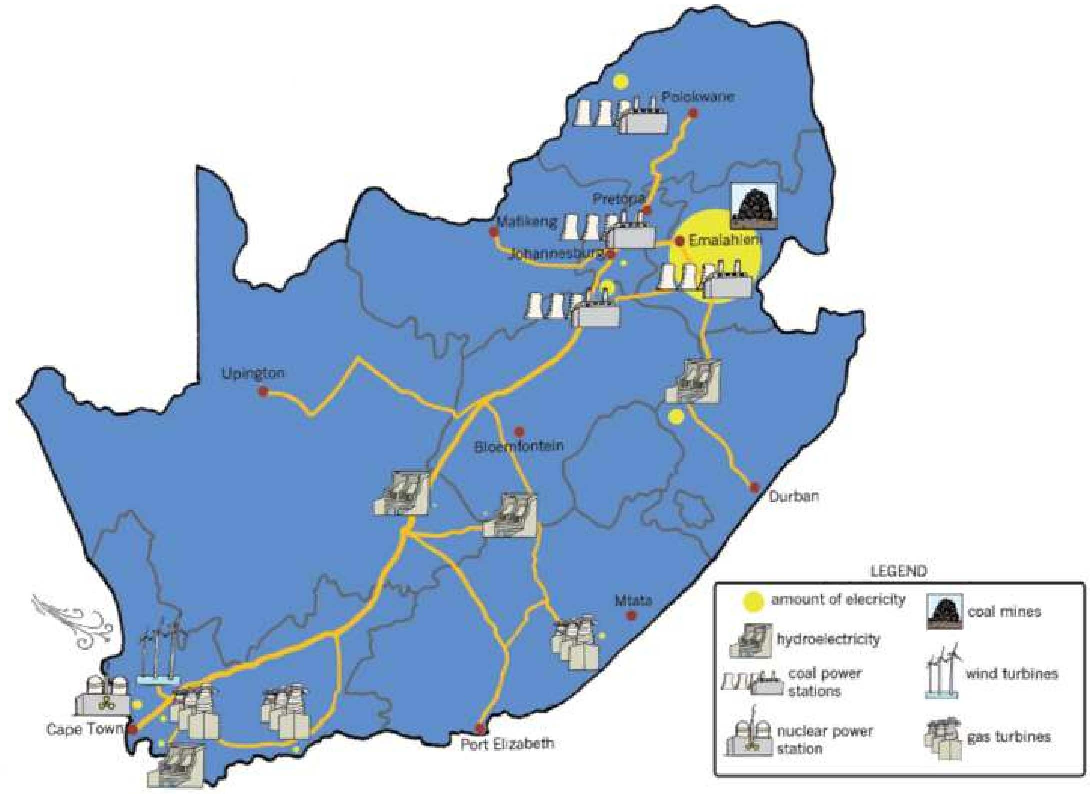

Fig. 1: Eskom power stations in South Africa [18]

Potential of wind resources for power generation in South Africa

The renewable energy assessment that is recently carried out in South Africa shows that the country has the potential to generate 30,000 MW and 12,000 MW from wind and solar resources based on the results obtained from 18 solar and wind sites [19]. This indicates that wind resources have the capability to generate enough electricity that can meet the power specifications of South Africa' commercial, industrial and residential sectors as shown in Fig. 2. The abundance of renewable energy resources in some locations has increased the potential of the nation to generate more than 62% of South Africa' electricity needs from wind resources [20]. This demonstrates that if wind farms were to be constructed in every location in the country except in exclusion areas, approximately 6700GW that is sufficient to meet the global electricity demand will be generated conveniently [21]. As a measure to generate South Africa total electricity demand that is approximated to be 250 TWh/yr, about 0.6% of the land mass of the country will be committed to wind farms with the installed capacity of 75 GW. Moreover, it has been reported by CSIR that over 80% of South Africa' land mass has sufficient wind resources for the optimal and techno-economic operations of wind farms with a very high annual load factor of approximately 30% [10]. The potential of wind energy resources can be utilized to stimulate the power sector and the economic activities by enhancing the percentage of wind energy in the energy generation mix of the nation. Some renewable energy projects that worth about R58 billion were recently signed in South Africa as a measure to create about 13,000 job opportunities and add 2305 MW to the energy mix of the country. The projects are anticipated to harness the technical, economic and environmental benefits that associated with shifting from using only conventional power technologies to the mixture of renewable energy and fossil fuel based power generation system [22]. The wind energy resources have been extensively used by some organizations for grid and off-grid power applications across the country. Some of the wind energy projects in South Africa are listed in Table 1.

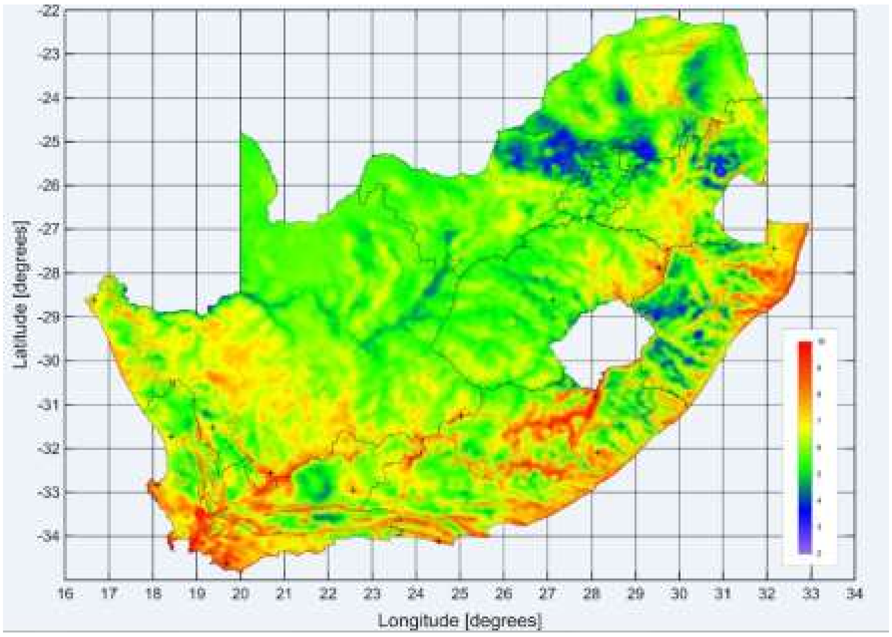

Fig. 2: Wind resources map for South Africa [23]

Table 1: Wind energy projects in South Africa [24-26]

Project	**Capacity**	**Turbine model**	**Project cost**	**Province**	**Start of commercial operations**
Cookhouse Wind Farm	135.8 MW	Suzlon S88	R2.4 billion	Eastern Cape	March, 2014
Gouda Wind Farm	135.5MW	Acciona	(R2,7 billion)	Western Cape	September, 2015
Jeffreys Bay Wind Farm	135.11 MW	Siemens	(R2.9 billion)	Eastern Cape	July, 2014
Amakhala Emoyeni Wind Farm	131.05 MW	Nordex N117 / 2,400	R3.94 billion	Eastern Cape	July, 2016
Enel's Gibson Bay Wind Farm	108.25 MW	Nordex	R2 billion	Eastern Cape	May, 2017
Darling wind farm	5.2 MW (13.2 MW)	Fuhrländer	R75 million	Western Cape	2008
Sere wind farm	50/46MW	Siemens SWT-2.3-108	R2.689 billion	Western Cape	October, 2014
Dassiesklip wind farm	27 MW	Sinovel SL3000	N/A	Western Cape	2014
Oyster Bay wind farm	80 MW	Nordex N90/2500	R18 billion	Eastern Cape	2015

Motivations and constraints of wind energy application and development in South Africa

The power demand of South Africa has increased tremendously as a result of rising in socio-economic activities and population growth. To meet South Africa's growing power requirements, the Department of Energy has rolled out some sustainable energy development programs. The programs projected a gradual increase in renewable energy capacity of South Africa from the current 5% to 9% by 2030. The contribution of wind energy resources to mix energy of South Africa has been anticipated to be 16134 MW installed capacity and 42.4 TWh generation capacity by 2030 [27]. This indicates that the government has planned to increase the generation capacity with the integration of more RETs into South Africa's energy mix. The wind energy projects can act as drivers to major socio-economic development in the rural communities that have not been connected to the grid owing to one constraint or another. The development of wind resources for power generation is being motivated by many factors such as ownership by the local communities, high energy demand and energy security, job creation, access to electricity in rural areas, reduction of GHG emissions, local content, power sector reform, management control, preferential procurement, enterprise development and socio-economic development [27]. However, the development of wind energy development is subjected to many challenges such as intermittent characteristics of wind resources, high capital cost, government policies that have not supported the utilization of wind resources in recent years, land use barriers, ineffective power quality control and lack of proper information on the technical and economic benefits of using the WT for power generation.

Microgrid system

A microgrid system consists of the demand management facilities, battery storage system (BSS), loads and distributed generation technologies such as diesel generator, microturbines, gas turbines, PV, WT and biomass generator. It is designed to operate autonomously of the utility grid or in parallel with the utility grid as shown in Fig. 3. The microgrid systems are designed to operate with the existing power infrastructures and must be able to feedback the excess power into the grid during the times of power outages that are associated with the grid failure [28]. The main purpose of utilizing the microgrid systems is to guarantee a reliable and affordable power supply at the load points [29]. Beside this, it can also provide power solutions for commercial, industrial and residential consumers. The application of the microgrid systems extends the following benefits to the utilities and customers: reduce GHG emissions, reduce congestion of the transmission and distribution lines, automatic self-healing operations, cost- effective, efficient, allow integration of the smart grid features, improve the incorporation of RETs into the grid, improve customer participation in the power generation and enhance the reliability and quality of power supply [30].

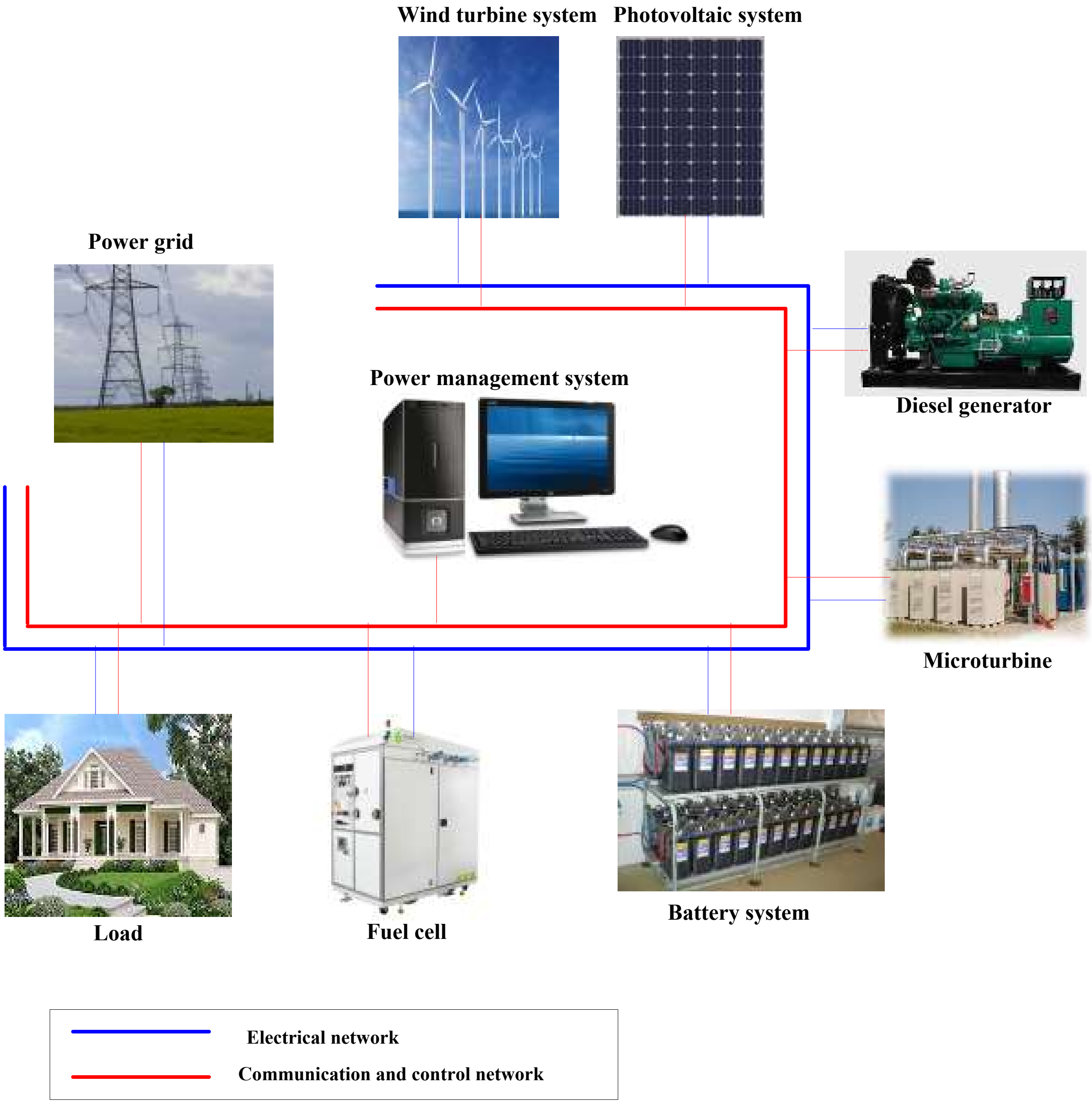

Fig. 3: Microgrid system with the integration of wind and battery system

Wind turbine system

The basic function of the WT is to convert the wind energy to electrical energy with the application of the air flow provided by the wind speed. The choice and installation of the WT in a particular location or site is a function of meteorological data, load demand, maximum installed capacity, environmental constraints, noise sensitivity to the residents of the site, set back from the road, minimum WT spacing and constraints that are associated with the interference of communication signals [31]. This enables the independent power producers or utilities to maximize the power generation and minimize the capital cost, risk and operating costs of the WT within the constraints of the sites. Moreover, the power output of the WT is modelled by considering the following factors: wind speed, air density, blade diameter, energy conversion efficiency, height tower, wind shear exponent, annual valid operating period and installed height [32]. These factors affect the performance and the annual energy output of the WTs based on the range of the cut-in speed and cut-out speed specified by the manufacturers [12]. The correlation between the power generated by the WT and wind speed is presented in Fig. 4.

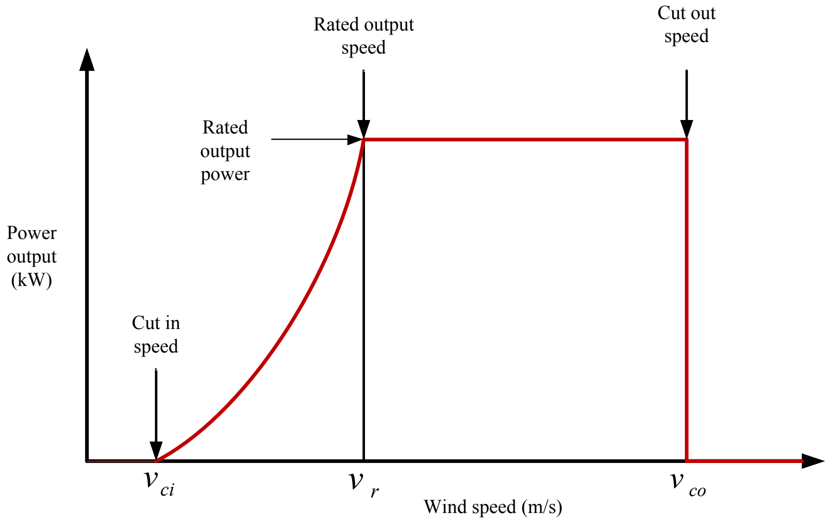

Fig. 4: Wind turbine power curve

The wind speed at the hub height of the WT can be estimated by utilizing the power law equation presented in equation (1) [33] :

$$V_{hub}(t) = V_r(t)\left(\frac{H_{hub}}{H_r}\right)^{\alpha} \tag{1}$$

where $V_r(t)$ is the wind speed at reference height (H_r), $V_{hub}(t)$ is the wind speed at the hub height (H_{hub}) and α is the power law exponent that signifies the ground surface friction co-efficient. The general expression to calculate the output power of the WT is presented in equation (2) as [34]:

$$P_{WECS}(V_{hub}(t)) = \begin{cases} P_r\left(\dfrac{V_{hub}^{k}(t) - V_{ci}^{k}(t)}{V_r^{k}(t) - V_{ci}^{k}(t)}\right) & ,\left(V_{ci}(t) \le V(t) \le V_r(t)\right) \\ P_r, & \left(V_r(t) \le V(t) \le V_{co}(t)\right) \\ 0, & \left(0 \le V_{ci}(t)\ and V(t) \le V_{co}(t)\right) \end{cases} \tag{2}$$

where $V_{hub}(t)$ is the wind speed at the hub height, P_r is the rated power of the WT, k is the Weibull shape parameter, $V_{ci}(t)$ is the cut-in wind speed, $V_{co}(t)$ is the cut-out wind speed and $V_r(t)$ is the rated wind speed.

Weibull distribution function

The Weibull distribution function gives a suitable illustration of the wind speed information for wind energy computation purposes [13, 14]. It has been reported in some research works that wind speed can be modelled by using the Weibull distribution function. The analysis of the measured data demonstrates that the wind speed in a region is bound to obey the Weibull distribution and the probability density function. The two parameters of the wind speed are described in this subsection. The probability density function ($f(v)$) is given in equation (3) as [35]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{3}$$

where v is the wind speed (m/s), k is the Weibull shape factor and c is the Weibull scale parameter (m/s).

The cumulative distribution function $F(v)$ can be expressed as [36]:

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{4}$$

The Weibull shape factor and Weibull scale parameter are related with the average speed as presented in equation (5) [35].

$$V_m = c\Gamma\left(1 + \frac{1}{k}\right) \tag{5}$$

where Γ is the gamma function.

The gamma function is represented in equation (6) as:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t}\, dt \tag{6}$$

The gamma function can be approximated by using equation (7) [37]:

$$\Gamma(x) = \left(\sqrt{2\Pi x}\right)\left(x^{x-1}\right)\left(e^{-x}\right)\left(1 + \frac{1}{12}x + \frac{1}{288}x^2 - \frac{139}{51840}x^3 + \ldots\ldots\ldots\ldots\ldots\ldots\right) \tag{7}$$

1.1.1. Power generated by the wind turbines and capacity factor

The WTs can produce maximum power in a situation where the wind speed frequency distribution for the site meets the wind requirements specified by the manufactures. This indicates that the WT will operate efficiently, provided the wind regime of the site is suitable for the model of the WT. However, in some circumstances, it is not technically feasible to design a WT that can operate optimally in a particular location owing to the intermittent nature of wind speed. In view of this, the power utilities must select their WTs based on the wind regime that matches the specified rated wind speed, cut-in wind speed and cut-out wind speeds [12]. The performance of the WT for a period of time can be assessed by using mean output power, total energy output and capacity factor. The mean output power (P_m) produced by a WT can be expressed as [38]:

$$P_m = P_r\left\{\frac{e^{-\left(\frac{v_{ci}}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_{ci}}{c}\right)^k} - e^{-\left(\frac{v_{co}}{c}\right)^k}\right\} \tag{8}$$

where v_{ci} , v_{co} and v_r are the cut-in, cut-out and rated wind speeds.

The capacity factor is a ratio of an actual power output of a generating unit over a given period of time to its rated power output. It is presented in equation (9) as [39]:

$$CF = \frac{P_m}{P_r} \tag{9}$$

The annual energy produced by the WT can be expressed as [39]:

$$E_{annaul} = P_m \times 8760 \tag{10}$$

Battery storage system

The BSS is widely utilized as a backup unit in the microgrid systems to reduce the congestion of the grid during the peak periods [6]. This guarantees the optimal operation of the grid by using the BSS as a backup unit that prevents a sudden power outage that associated with some scenarios such as peak periods, scheduled maintenance and unscheduled shut down owing to components failures. There are diverse sorts of battery technologies that can be used for the microgrid operations, these include Lead acid batteries, Li-on batteries, Redox flow batteries, Nickel-cadmium batteries, Sodium sulphur batteries, etc. The ability to choose a suitable battery for the power system operation depends on some factors such as cost, charging cycle, discharging cycle, maintenance, environmental effects, depth of charge, etc. These factors are essential for the optimization of the operating costs of the renewable energy project, increase the performance of the microgrid systems, minimize the maintenance costs and maximize the financial return of the power system. The battery system is purposely integrated into the microgrid systems as a measure to smooth out the effect of stochastic characteristics of renewable energy resources. The battery system is designed to be charged after the load demand has been met and there is an excess power supply. During the peak periods when the cost of energy is expensive, the stored energy in the BSS can be used to meet the load demand [6]. The power that flows from the WTs, load and grid can be used to determine the state of charge (SOC) of a battery system at time t [40]. The SOC of a battery system is expressed in equation (11) as [6]:

$$SOC(t) = SOC\,(0) + \eta_c \sum_{\tau=1}^{\tau} P_{in}\,(\tau) - \eta_d \sum_{\tau=1}^{\tau} P_{out}(\tau) \tag{11}$$

where P_{in} and P_{out} are the power entering and leaving the battery at time t and η_c and η_d are the coefficient of charging and discharging efficiency of the battery system [41].

$$SOC^{\min} \leq SOC(t) \leq SOC^{\max} \tag{12}$$

$$SOC^{\min} \leq SOC\,(0) + \eta_c \sum_{\tau=1}^{\tau} P_{in}\,(\tau) - \eta_d \sum_{\tau=1}^{\tau} P_{out}(\tau) \leq SOC^{\max} \tag{13}$$

where SOC^{max} is the maximum capacity of the battery and SOC^{min} is the minimum acceptable battery SOC.

The battery storage system can be modelled based on the SOC and depth of discharge (DOD) limits as presented in equation (14) [6]:

$$SOC^{\min} = (1 - DOD)SOC^{\max} \tag{14}$$

The state of charge is one of the significant parameters that can be utilized to define the residual capacity of a battery system. The state of charge of a battery system can be estimated by using the following [42]:

Battery charging

$$SOC(t) = SOC(t-1)(1-\sigma) + \left[\frac{E_{gen}(t) - E_{load}(t)}{\eta_{inv}}\right] \times \eta_{bat} \tag{15}$$

Battery discharging

$$SOC(t) = SOC(t-1)(1-\sigma) + \left[\frac{E_{load}(t)}{\eta_{inv}} - E_{gen}(t)\right] \times \eta_{bat} \tag{16}$$

where $SOC(t)$ and $SOC(t-1)$ are the battery at the initial and the battery energy at the end of interval t respectively, $E_{load}(t)$ is the energy demand at the time t, $E_{gen}(t)$ is the energy generated by the WT at time t, η_{inv} is the inverter efficiency, η_{bat} is the battery efficiency and σ is the self-discharge factor.

The required battery storage capacity B_{cap} (Ah) can be expressed as [43], [44]:

$$B_{cap} = \frac{E_{L(Ah)} D_A}{DOD_{\max} \eta_{temp}} \tag{17}$$

where D_A is battery autonomy, $E_{L(Ah)}$ is load consumption (Ah), η_{temp} is the battery temperature correction factor and $DOD_{\max}$ is the maximum battery depth of discharge.

Storage energy cost

The storage energy cost depicts the average cost that is expended to charge the battery storage system in a microgrid system. The storage energy cost can be expressed as [45]:

$$BC_{be,n} = \frac{\sum_{i=1}^{n-1} BC_{cc,i}}{\sum_{i=1}^{n-1} BE_{cc,i}} \tag{18}$$

where $BC_{be,n}$ is the storage energy cost in time step n (R/kWh), $BC_{cc,i}$ is the cost of cycle charging the storage in time step i ($) and $BE_{cc,i}$ is the amount of energy that went into the storage bank in time step i (kWh).

Economic metrics of the proposed microgrid system

The lifetime of the proposed microgrid system is 25 years with the annual interest rate of 2 % and the discount rate of 8%. The optimal operation of a power system is based on the optimization of investment indicators such as net energy purchased, energy sold, energy purchased, annual utility bill savings and operating costs. The accurate estimation of the costs that involved in generating energy from a microgrid system over the lifespan of the project is imperative for its financial feasibility and to generate electric power at a low operating cost [46]. The viability of a microgrid system can be evaluated by using the economic components that are briefly explained as follows:

Annualized cost of the system

The annualized cost of the system (ASC) is a summation of the annualized capital and O&M costs of a project minus the salvage value [45]. The COE and NPC are the functions of the ACS. This indicates that the ACS needs to be estimated as a measure to evaluate the financial feasibility of a microgrid system project [6].

$$ACS_{total} = CRF(i, \mathrm{Proj}) \times NPC, i \tag{19}$$

where *Proj* is the lifetime of the microgrid system components, NPC is the net present cost and CRF is the capital recovery factor.

The ACS is the sum of costs of all the components of a microgrid project as presented in equation (20) as:

$$ACS_{total,i} = \sum_{i=1}^{n}\left(ACS_{wind,i} + ACS_{batt,i} + ACS_{inverter,i} - S_i\right) \tag{20}$$

where ACS_{wind}, ACS_{batt} and $ACS_{inverter}$ are annualized cost of WT, battery and inverter while S is the salvage values at end of the project.

The overall system annualized cost comprises of the annualized costs of the components such as capital, replacement, O&M and salvage value [47]. Hence, the value of ACS is expressed as the sum of the aforementioned operating cost parameters for each component that constitutes a microgrid system.

$$ACS_{total,comp,i} = \sum_{i=1}^{n}\left(ACS_{cap,i} + ACS_{rep,i} + ACS_{O\&M,i} - S_i\right) \tag{21}$$

where $ACS_{cap,i}$, $ACS_{rep,i}$ and $ACS_{O\&M,i}$ are the annualized capital cost, annualized replacement cost and annualized operation and maintenance cost respectively.

Capital recovery factor

The capital recovery factor is generally utilized by the independent power providers (IPPs) to estimate the present value or amount of annuity of their microgrid systems. It is expressed in equation (22) as [6]:

$$CRF(i, \mathrm{Proj}) = \frac{i(1+i)^{\mathrm{Proj}}}{(1+i)^{\mathrm{Proj}} - 1} \tag{22}$$

where *i* is the real discount rate.

Net present cost

The NPC of a microgrid system is the present worth of all the costs of installation and O&M that it incurs over the lifespan of the project, minus the present worth of all the profits that it makes over its lifespan [45]. The NPC is one of the economic performance indicators that can be used for the optimization of a microgrid system. The NPC of a microgrid project can be expressed as [6]:

$$NPC = \frac{ACS_{total}}{CRF(i, \mathrm{Proj})} \ \text{(R/yr)} \tag{23}$$

Cost of energy

The COE is the average cost per kWh of electricity produced by a microgrid system [45]. The cost of producing electrical energy can be assessed by utilizing the COE as a benchmark to compare the variety of the WTs based on differences in wind resources and locations or sites. The COE is used in this study to carry out the economic analysis of the selected WT. The value of the COE is a function of investment cost, O&M cost, average wind speed, the lifespan of the project, interest rate and discount rate [6].

$$COE = \frac{ACS_{total}}{E_{served}} \tag{24}$$

$$E_{served} = E_{grid} + E_{as} \tag{25}$$

where ACS_{total} is the annual cost of the system (R/yr), E_{served} is the electrical load served (kWh/yr), E_{grid} is the amount of electricity sold to the grid by a microgrid system (kWh/yr) and E_{as} is the value of electrical energy that the microgrid system actually served (kWh/yr).

Renewable fraction

The renewable fraction (RF) is the portion of the electrical energy that originated from renewable energy sources and delivered to the load points. The renewable electricity production is the aggregate sum of electrical energy generated annually by the renewable energy components of the microgrid systems. The RF can be estimated by utilizing the following equation [45]:

$$RF = 1 - \frac{Energy_{nonren}}{Energy_{served}} \tag{26}$$

where $Energy_{nonren}$ is the electrical energy generated from the non-renewable sources (kWh/yr).

Grid rates

The renewable energy resources can only be connected to the grid based on the permission from the utilities. The cost of the grid connection is dependent on the size of the WT and its location on the grid. In some cases, the cost of grid connections will be paid by the utilities, but it will be captured in the power purchase agreement (PPA) between the utilities and the IPPs as a debt that will be paid by the government agency as a measure to improve energy mix. The grid connection can also be designed in such a way that it will be deducted from the net profit of the IPPs. It is mandatory to install smart meters to quantify the sale and export of excess energy to the grid. This will enable the utilities and IPPs to estimate the net energy purchases based on the PPA. The grid rates depict the prices related to purchasing electrical energy from the utility grid and selling electricity to the grid [45]. The grid rate of energy provides by Eskom is assumed to be R 1.0918/kWh and the energy sold price in the grid by the IPPs is assumed to be R 0.9577/kWh with the value added tax. The grid rates comprise of the grid power price, grid sell back price, net purchases estimated monthly or annually and net metering [45].

Energy Charge

The total annual energy charge can be estimated on a monthly basis in a situation where the net metering does not apply by using the following equation [45]:

$$EC_{grid,energy} = \sum_{i}^{rates}\sum_{j}^{12} EC_{grid\ purchsased i,j} \times P_{grid,i} - \sum_{i}^{rates}\sum_{j}^{12} EC_{gridsales,i,j} \times P_{sellback,i} \tag{27}$$

where $EC_{grid\ purchsased i,j}$ is the amount of energy purchased from the grid in month j during the time rate i applied (R/kWh), $EC_{gridsales,i,j}$ is the amount of energy sold to the grid in month j during the time rate i applied (R/kWh), $P_{grid,i}$ is the grid power for rate i (R/kWh) and $P_{sellback,i}$ is the sellback rate i (R/kWh).

The net generation can be calculated on the monthly basis in a situation where the net metering is applicable by using the following equation [45]:

$$EC_{grid,energy} = \sum_{i}^{rates}\sum_{j}^{12} \begin{Bmatrix} EC_{netgrid\ purchsased i,j} \times P_{grid,i} & ,If\ EC_{netgrid\ purchsased i,j} \geq 0 \\ EC_{netgrid\ purchsased i,j} \times P_{sellback,i} & ,if\ EC_{netgrid\ purchsased i,j} < 0 \end{Bmatrix} \tag{28}$$

$EC_{netgrid\ purchsased i,j}$ is the net grid purchases in month *j* during the time that rate *i* applies (kWh).

The net generation can be estimated on the annual basis where the net metering applies by using the following equation [45]:

$$EC_{grid,energy} = \sum_{i}^{rates} \begin{Bmatrix} EC_{netgrid\ purchsased i,j} \times P_{grid,i} & ,If\ EC_{netgrid\ purchsased i,j} \geq 0 \\ EC_{netgrid\ purchsased i,j} \times P_{sellback,i} & ,if\ EC_{netgrid\ purchsased i,j} < 0 \end{Bmatrix} \tag{29}$$

Demand charge

The demand charge is the scheme that allows each consumer to sell power to the grid based on the PPA between the IPPs and the utilities. The total annual grid demand charge can be estimated by using equation (30)[45].

$$EC_{grid,demand} = \sum_{i}^{rates}\sum_{j}^{12} P_{grid,peakhour,i,j} \times P_{grid,demand,i} \tag{30}$$

where $P_{grid,demand,i}$ is the grid demand rate for rate I (R/kW/month) and $P_{grid,peakhour,i,j}$ is the peak hourly grid demand in month j during the time that rate i applies (kWh).

Optimization process of a microgrid system

The microgrid system is designed by the utilities by considering some factors such as technical, economic and environmental benefits [48]. These factors are subject to the operational constraints of the power system and many physical barriers that are detrimental to the development of renewable energy technologies [49]. The optimal configuration of a microgrid system is a function of the mixture of the component that constitutes the system and the dispatch strategy applied by the operators of the power system [50]. The objective of the proposed microgrid system is to carry out the economic analysis of a grid-connected microgrid system and wind potential of South Africa based on the location that has the optimal values of the net energy purchased, energy sold, energy purchased, annual utility bill savings, cost of energy and net present cost among the ten selected sites in South Africa. The overall objective of the study is achieved by using wind resources of different sites in South Africa and identify the site that has the optimal KPIs based on the same system configurations and technical constraints. The results are sorted out to compare and select the most feasible location for the installation of the WT. The proposed microgrid system is presented in Fig. 5 while the critical and non-critical load profiles for the proposed microgrid system are presented in Fig. 6a-b.

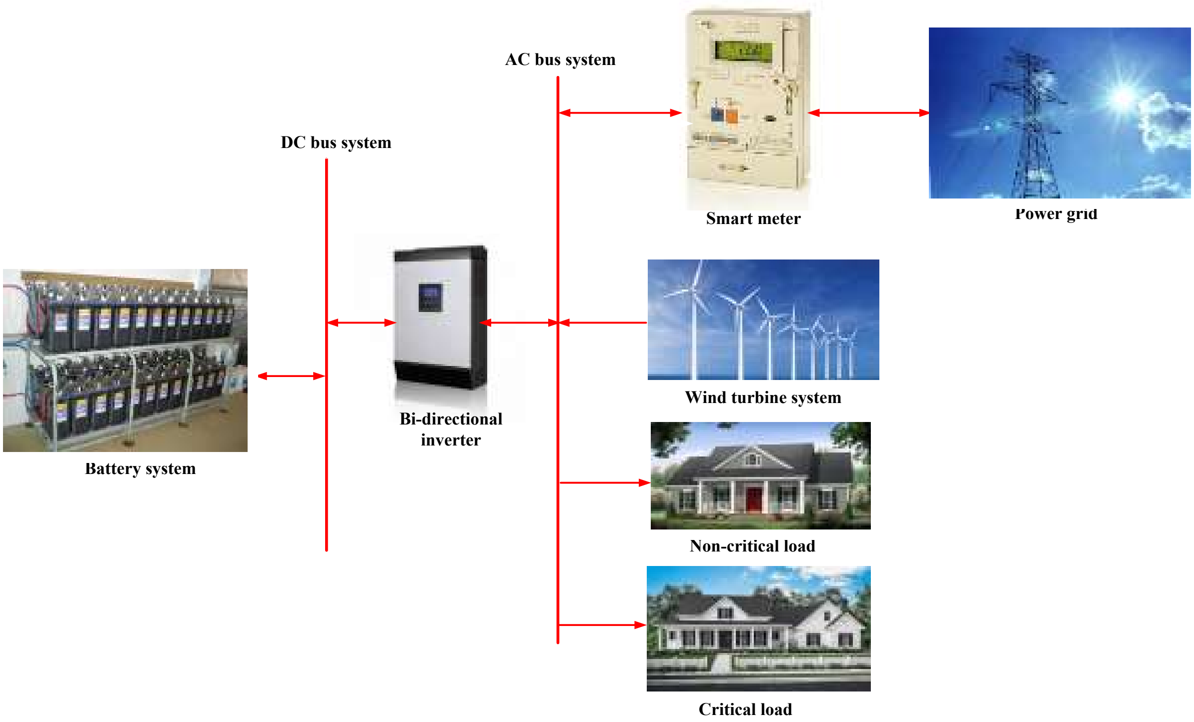

Fig. 5: Proposed grid connected microgrid system

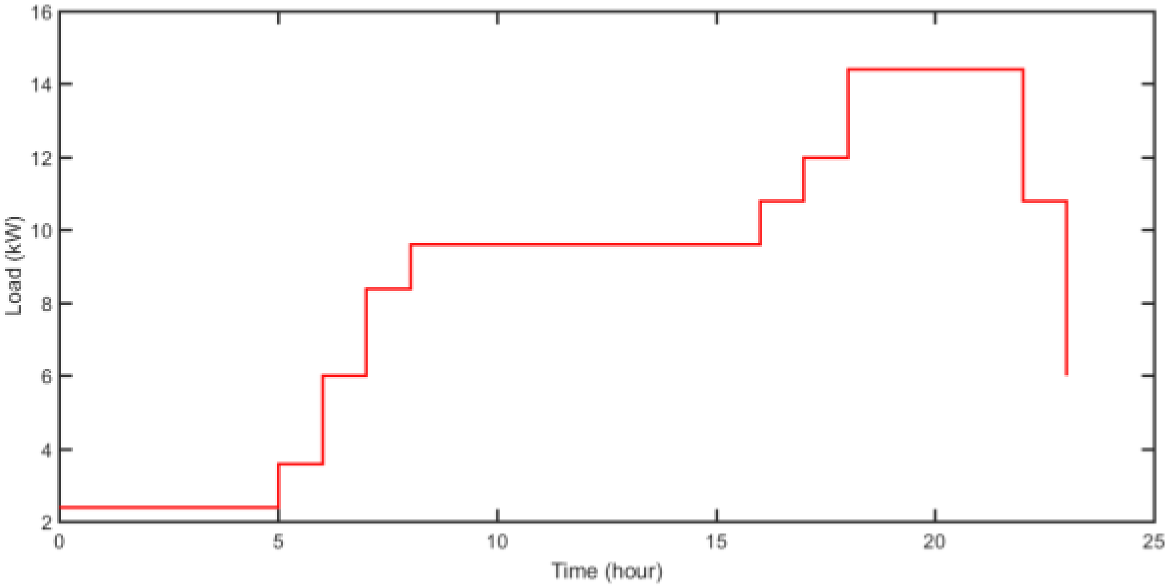

Fig. 6a: Critical load prolife for the proposed power system

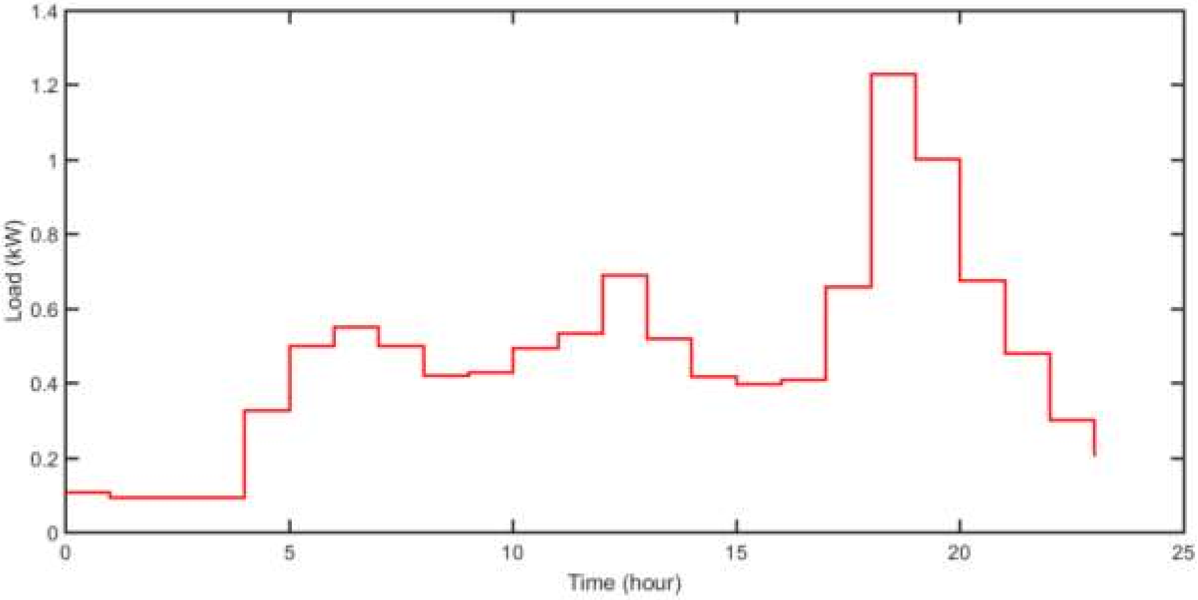

Fig. 6b: Noncritical load prolife for the proposed power system

Analysis of a grid connected microgrid system

The economic feasibility of a microgrid system is subjected to its capability to produce electrical energy at a low operating cost. Owing to this, it is mandatory for the utilities to estimate the total costs incurred in generating electrical energy over the lifespan of the microgrid project [36]. The financial viability of a microgrid project can be assessed by considering the capital cost, the lifetime of the component that constitutes the microgrid system, O&M costs, replacement cost, energy production, average wind speed, discount rate and interest rate. These parameters depend on the availability of wind resources that vary from one location to another. This indicates that the availability of wind resources is one of the significant factors that can be used to determine the appropriate site for the installation of the WT. The cost-effective of a microgrid system can be accomplished by picking the right location since the optimal operation of the WT depends on the wind conditions of a particular site. This study is designed to investigate the economic impacts of the WT in the grid-connected power system by using the technical details of each component of the proposed microgrid system as presented in Table 2.

Table 2: Characteristics of the selected components of the proposed microgrid system

Characteristics of WT		**Characteristics of battery**		**Characteristics of inverter**	
Description	WT	Description	Battery	Description	Inverter
Model number	AWS HC 5.1 kW	Model number	Generic lead acid	Model number	System converter
Rated Capacity	(5.1x10) 51 kW	Nominal capacity	1 kWh	Rated power	20 kW
		Maximum capacity	513 Ah		
Other technical details of WT		**Other technical details of battery**		**Other technical details of inverter**	
Cut- wind speed	2.7 m/s	Initial SOC	100%	Rectifier input	
Rated wind speed	11 m/s	Minimum SOC	40%	Relative capacity	100%
Cut- out speed	55 m/s	Degradation limit	20%	Efficiency	95%
Rotor diameter	5.24 m	Maximum operating temperature	55 °C	Inverter input	
Swept area	21.4 m^2	Minimum operating temperature	-20°C	Efficiency	95%
Number of blade	3	Operating lifetime	5 years	Operating lifetime	15 years
Operating lifetime	20 years	Capacity ratio	0.611		
Hub height	50m	Maximum charge current	167A		
Insulation Class	H	Maximum discharge current	500A		
Capital cost (R)	25,000	1200		12,000	
Replacement cost (R)	25,000	1200		12,000	
O&M cost (R/yr)	250	50		120	

Results and discussions

The study is implemented with the application of the HOMER software for the economic analysis of the proposed microgrid system. The operating parameters of all the components of the proposed microgrid as presented in Table 2 are used in conjunction with the wind speed of each location selected in this study to investigate the effects of utilizing wind resources in a power system. The aim of this research work is to maximize the benefits of utilizing wind resources in South Africa as shown in Table 3 with ten case studies. This can be accomplished by determining the best location for the installation of the WT based on the KPIs that have been earlier discussed in the paper. The wind speed for each location is used in this work to assess the potential of wind resources and carry out techno-economic analysis of the WT in South Africa. The average wind speed provided by the National Aeronautics and Space Administration (NASA) from its wind resources database is used in the proposed power system. The wind speed is reported for all the ten locations that have been taken into consideration in this research work. The grid-connected microgrid system designed for this study considered the technical specifications of each component to obtain feasible solutions.

Table 3: Ten case studies for the investigation of the economic impacts of wind resource

Case study	Province	Capital cities	Longitude	Latitude
1	Eastern Cape	Bhisho	27°26.5'E	32°51.0'S
2	Free State	Bloemfontein	26°9.6'E	29°5.1'S
3	Gauteng	Johannesburg	28°2.8'E	26°12.2'S
4	Limpopo	Polokwane	29°26.9'E	23°53.8'S
5	Mpumalanga	Nelspruit	30°58.2'E	25°28.5'S
6	Northern Cape	Kimberley	24°45.0'E	28°43.7'S
7	KwaZulu- Natal	Pietermaritzburg	30°22.8'E	29°36.0'S
8	North West	Mahikeng	25°38.4'E	25°51.4'S
9	Western Cape	Cape Town	18°25.4'E	33°55.5'S
10	Administrative head of South Africa	Pretoria	28°13.8'E	25°44.9'S

Wind potential analysis of different case studies

In this sub-section, the comparative analysis of different case studies is carried out to determine the financial and technical feasibility of investing in the renewable energy project in some locations in South Africa. The monthly average wind speed for the selected locations for the study is presented in Table 4. The following locations are selected for the potential and economic assessment of wind resources in South Africa, i.e. Bhisho, Bloemfontein, Johannesburg, Polokwane, Nelspruit, Kimberly, Pietermaritzburg, Mafikeng, Cape Town and Pretoria. The most attractive locations for the installation of the WT in South Africa are coastal areas like Cape Town, the mountainous areas in Eastern Cape, Free state and Northern Cape provinces of South Africa. The mountainous terrain of Lesotho that is a few kilometres from Bloemfontein and Kimberley has contributed to a significant generation of power from wind resources in the areas. The inland hilly areas of the Eastern Cape such as Bhisho is another attractive location for installation of the WT in South Africa. The peak wind speeds are experienced in all the locations, starting from June to November, expect the coaster town of Cape Town that has the peak winds from January to December. The annual energy production from each site ranges from 18,295 kWh in Pretoria to 49,462 kWh in Cape Town with the average wind speed of 4.041 m/s obtained in Pretoria and 6.387 m/s obtained in Cape Town. The maximum monthly average wind speeds obtained in Bhisho, Bloemfontein, Johannesburg, Polokwane, Nelspruit, Kimberly, Pietermaritzburg, Mafikeng, Cape Town and Pretoria are 6.58 m/s, 5.72 m/s, 5.03 m/s, 5.19 m/s, 4.84 m/s, 6.14 m/s, 5.77 m/s, 5.6 m/s, 6.69 m/s and 4.95 m/s. However, the minimum monthly average speeds for the aforementioned locations are 5.49 m/s, 4.65 m/s, 3.34 m/s, 3.55 m/s, 3.49 m/s, 5.1 m/s, 4.41 m/s, 3.95 m/s, 5.98 m/s and 3.37 m/s.

This indicates that South Africa has the potential to generate energy that can meet the local power demand from wind resources. Based on the minimum and maximum values of the wind speeds presented above, it can be established that Cape Town is the most favourable place among the locations considered in this study for installation of the WT being a coastal city with the capacity factor of 22.1% and wind penetration of 76.8% while Pretoria is the least wind locations among the ten cities or towns selected for this research work with the capacity factor of 8.19% and wind penetration of 28.4% as shown in Tables 5 and Fig. 7. The capacity factor has a positive influence on the power produced by the wind system. The average speed, operating hours of the WT and maximum and mean output power of the WT as shown in Table 5 have demonstrated the wind potentiality of each location or site. The results presented in Table 5 has indicated that capability of Cape Town to operate optimally with the application of the WT with the following results: average wind speed = 6.39 m/s, operating hours of the WT = 7,471 hr/yr, maximum power output = 31.8 kW and mean output power = 5.65 kW respectively. The average wind speed, operating hours of the WT, maximum output of the WT, mean power output of the WT, capacity factor and wind penetration estimated in Cape Town are 58.17%, 20.17%, 29.27%, 170.33%, 169.89% and 170.422% more than the same parameters estimated in Pretoria.

Table 4: Monthly average wind speed data

locations	Bhisho	Bloem-fontein	Johanesburg	Polokwane	Nelspruit	Kimberly	Pieterm-aritzburg	Mahikeng	Cape Town	Pretoria
Month	wind speed (m/s)	Wind speed (m/s)	wind speed (m/s)	wind speed (m/s)	wind speed (m/s)	wind speed (m/s)	wind speed (m/s)	wind speed (m/s)	wind speed (m/s)	wind speed (m/s)
Jan	5.87	4.97	3.49	4.46	3.71	5.63	4.73	4.71	6.27	3.62
Feb	5.75	4.7	3.34	4.34	3.6	5.3	4.41	4.5	6.43	3.5
Mar	5.62	4.65	3.36	3.94	3.49	5.15	4.43	4.15	6.14	3.37
Apr	5.49	4.67	3.53	3.83	3.63	5.21	4.56	4.17	5.98	3.54
May	6.09	4.8	3.87	3.55	3.86	5.1	4.63	3.95	6.2	3.74
Jun	6.53	5.15	4.27	3.55	4.1	5.33	5.23	4.21	6.69	4.04
Jul	6.58	5.26	4.41	3.67	4.27	5.51	5.25	4.29	6.9	4.18
Aug	6.37	5.61	4.77	4.77	4.76	5.96	5.48	5.13	6.49	4.74
Sep	6.35	5.72	5.03	4.94	4.84	6.13	5.77	5.44	6.36	4.95
Oct	6.36	5.5	4.68	5.19	4.65	6.14	5.47	5.6	6.68	4.73
Nov	5.98	5.24	4.11	5.11	4.29	5.95	5.07	5.35	6.32	4.31
Dec	5.59	5.02	3.65	4.56	3.83	5.89	4.7	4.95	6.18	3.77
Average	6.048	5.108	4.04	4.326	4.09	5.608	4.978	4.704	6.387	4.041

Table 5: Wind characteristics of the selected locations

Case study	Capital Cities	Average speed (m/s)	Operating hours (hr/yr)	Maximum output (kW)	Mean Output (kW)	Capacity factor (%)	Wind penetration (%)
1	Bhisho	6.05	7,400	31.6	5.15	20.2	70
2	Bloemfontein	5.11	7,009	31.7	3.71	14.6	50.5
3	Johannesburg	4.04	6,194	27.4	2.11	8.27	28.7
4	Polokwane	4.33	6,486	30.8	2.45	9.61	33.3
5	Nelspruit	4.09	6,287	24.9	2.13	8.36	29.0
6	Kimberley	5.61	7,256	32.3	4.48	17.6	60.9
7	Pietermaritzburg	4.98	6,934	30.8	3.48	13.6	47.3
8	Mahikeng	4.70	6,832	30.7	3.00	11.8	40.8
9	Cape Town	6.39	7,471	31.8	5.65	22.1	76.8
10	Pretoria	4.04	6,217	24.6	2.09	8.19	28.4

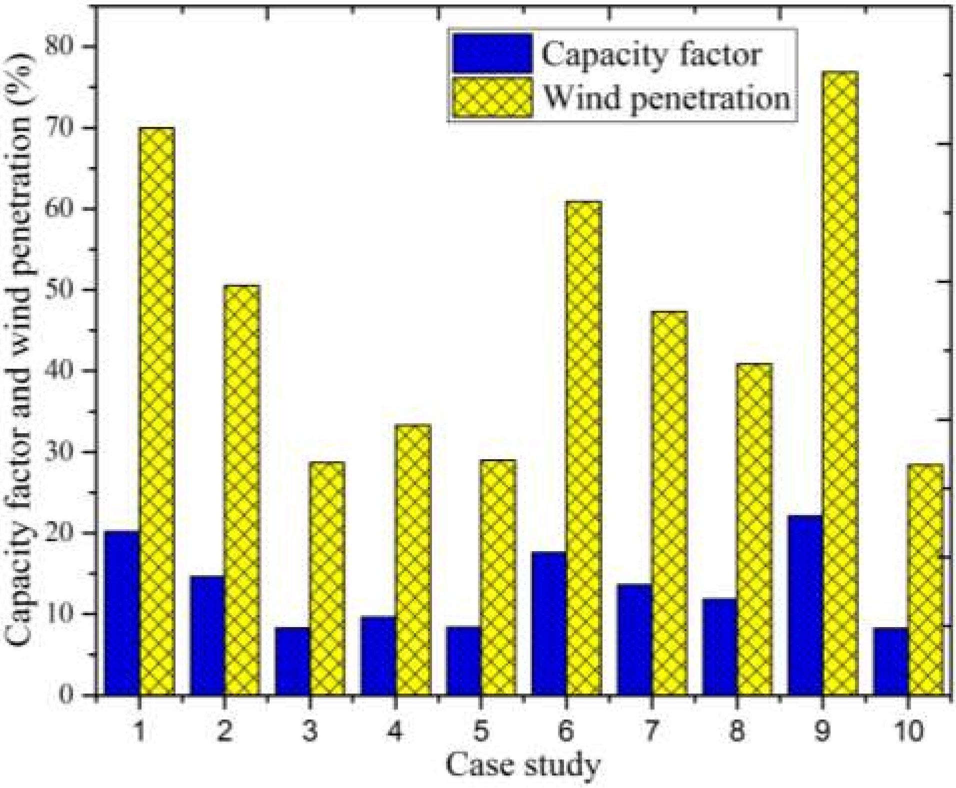

Fig. 7: Capacity factor and wind penetration for each selected location

Economic analysis of different case studies

The price of crude oil in the international market has increased to the extent that it threatens the economy of the countries that rely on fossil fuels for power generation. The need for a potential alternative power source is imminent, owing to the reduction of over-dependence on crude oil and the economic risk that is associated with the fluctuation of fossil fuel price. South Africa has abundant wind resources that need to be harnessed for generation of energy. In view of this, the economic analysis of wind energy resources that has become a global interest is presented in this subsection. This paper introduces some KPIs such as COE, ACS and NPC to analyse the economic impacts of the WT in a microgrid system. The integration of the WTs into the Eskom distribution and transmission systems will reduce over-dependence on coal for power generation in South Africa and enhances the security of power supply because of the economic and environmental benefits. Moreover, one of the objectives of this study is to optimize the COE, ACS and NPC of the proposed microgrid system. It can be established from Fig. 8 that the value of the COE has been reduced with the application of the WT from R 1.0918/kWh to R 0.260/kWh in Cape Town and from R 1.0918/kWh to R 0.799/kWh in Pretoria. This indicates that there is 76.19% and 26.82% reduction in the COE in Cape Town and Pretoria. Similarly, Cape Town has the least value of ACS when compared with other locations as shown in Fig. 9 and Table 6. This shows that wind resources have many economic impacts on the optimal operation of a power system based on the location and availability of suitable wind speed in accordance with the requirements of the wind turbine's manufactures.

The financial feasibility of a microgrid project depends on the interest rate, discount rate, availability of wind resources, capital cost, O&M costs and government policies. In view of this, the effects of wind resources on the and NPC are presented in this subsection. The financial analysis of the WT in Cape Town demonstrates that NPC is R270,970.00 as shown in Fig. 10 and Table 6. A microgrid system can generate utility bill savings revenue of R1026850 thorough out the lifetime of the project when installed in Cape Town. The estimated value of NPC for Pretoria is R 686,509.10. The project can generate utility bill savings revenue of R392725 throughout the project lifetime that is estimated to be 25 years. The utilization of wind resources leads to COE, ACS and NPC reduction and make a wonderful contribution to the energy mix. The integration of the WT into the utility grid has numerous financial benefits, include lower electricity tariff when compared with Eskom tariff. This makes the electricity produced from the renewable energy resources to be more worthy than conventional generating units, where the fuel cost alone is more than 70% of the total operating costs. Moreover, the license to operate as independent power producers with the utilization of renewable energy resources is not stringent to obtain in South Africa when compared with other countries. Apart from this, South Africa government can introduce some policies in terms of incentives to increase integration of wind energy projects into the grid. This will motivate many private organizations and individuals to increase their investments in renewable energy projects. The integration of wind energy into the utility will reduce ozone layer depletion, soil degradation and global warming. It will also increase the global green energy generation. The results obtained from this work show the potentiality of South Africa for renewable energy production.

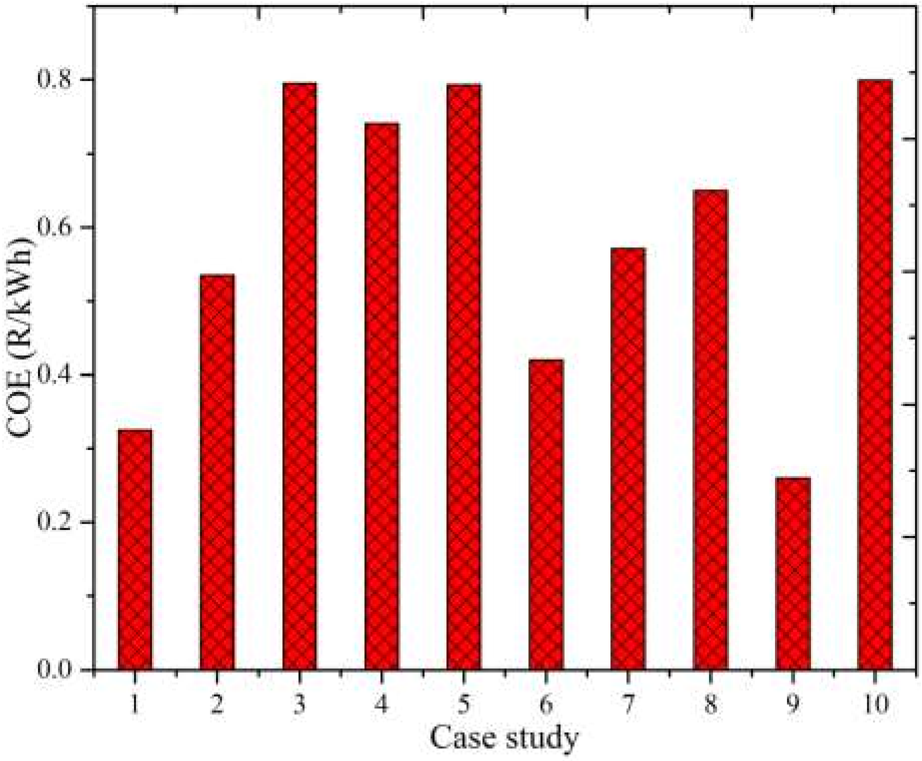

Fig. 8: COE for each location in South Africa

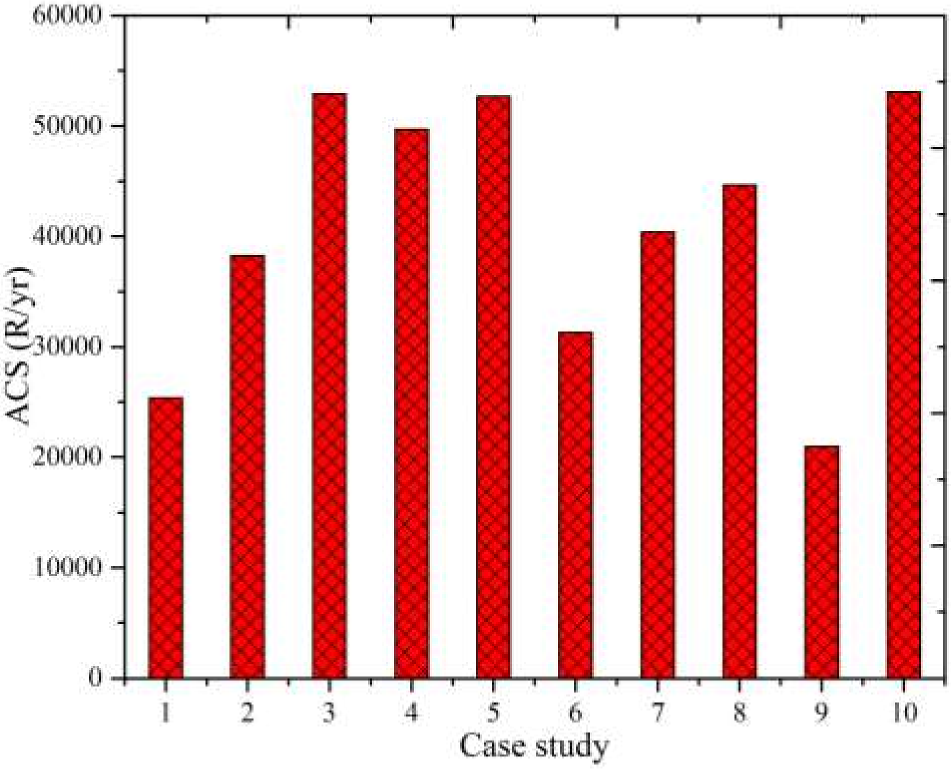

Fig. 9: ACS for each location in South Africa

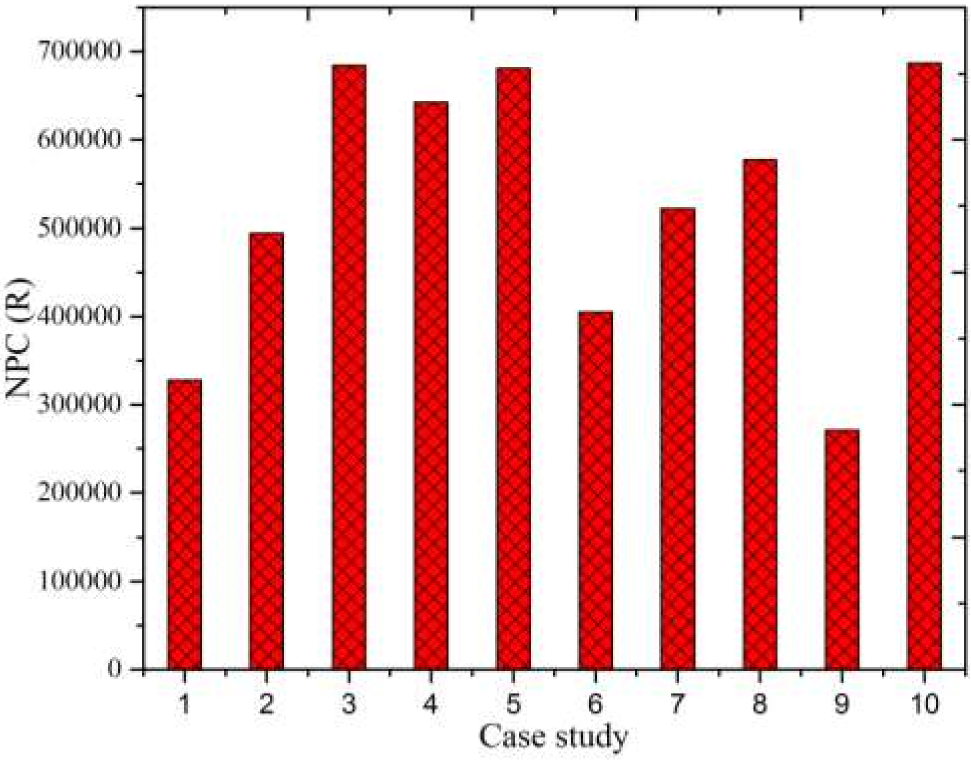

Fig. 10: NPC for each location in South Africa

Table 6: Economic analysis of each location in the nine provinces of South Africa

Case study	Capital cities	COE (R/kWh)	ACS (R)	NPC (R)
1	Bhisho	0.325	25,368	327,950.90
2	Bloemfontein	0.535	38,242	494,375.50
3	Johannesburg	0.795	52,936	684,329.10
4	Polokwane	0.741	49,721	642,765.10
5	Nelspruit	0.793	52,689	681,133.90
6	Kimberley	0.420	31,325	404,953.80
7	Pietermaritzburg	0.571	40,368	521,855.50
8	Mahikeng	0.650	44,648	577,188.30
9	Cape Town	0.260	20,961	270,970.00
10	Pretoria	0.799	53,104	686,509.10

Similarly, the same trend is observed in energy sold to the grid, energy purchased from the grid and net energy purchased as shown in Table 7. It can be validated from the results presented in Fig. 11 that Cape Town has the least energy purchased from the grid and highest energy production, followed by Bhisho, Kimberly and Bloemfontein, based on the availability of wind speed in each location. This is due to the offshore or coastal wind energy in Cape Town and mountainous terrains in Bhisho, Kimberly and Bloemfontein and neighboring country like Lesotho. The highest values of grid purchases are recorded in Pretoria, Johannesburg and Nelspruit being less windy inland areas when compared with other locations in the study as presented in Fig. 12. It can also be observed from Fig. 13 that the highest values of annual utility savings and energy charge are obtained in Cape Town, Bhisho, Kimberly and Bloemfontein owing to the values of capacity factor, wind penetration and mean output power obtained in the respected locations. However, Pretoria, Johannesburg and Nelspruit have the least values of annual utility savings and annual energy production in the study. Moreover, Cape Town has the least energy charged as shown in Fig. 13 owing to the high values of capacity factor and wind penetration. This will lead to a huge economic benefit that can accrue from wind resources in the location. The monthly summary of the energy sold, energy purchased, energy charge and net energy purchased for the ten selected locations in South Africa based on the availability of wind resources are presented Tables 8-17. The results obtained in this work can be used by the utilities as standards to conduct the technical and economic assessment of alternative energy sources in the microgrid systems. This work provides investors with clean energy decision capabilities and how to invest in renewable energy resources. It improves the capability of the utilities, managers and decision-makers by presenting the performance indicators that can be used to implement sustainable energy development and enhances the efficiency of energy demand management in the alternative power systems.

Table 7: Overall results for different selected locations in South Africa

Case study	Capital cities	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Annual utility bill savings (R)	Energy charge (R)
1	Bhisho	32,973	13,663	19,311	37,606	22,916
2	Bloemfontein	38,954	7,038	31,915	27,473	35,789
3	Johannesburg	48,156	2,187	45,970	15,840	50,483
4	Polokwane	45,616	2,648	42,968	18,399	47,268
5	Nelspruit	47,793	2,031	45,762	16,041	50,236
6	Kimberley	35,385	10,193	25,193	32,927	28,872
7	Pietermaritzburg	40,255	6302	33,953	25,792	37,915
8	Mahikeng	42,365	4,238	38,127	22,416	42,195
9	Cape Town	31,050	16,073	14,978	41,074	18,508
10	Pretoria	48,164	2,019	46,145	15,709	50,652

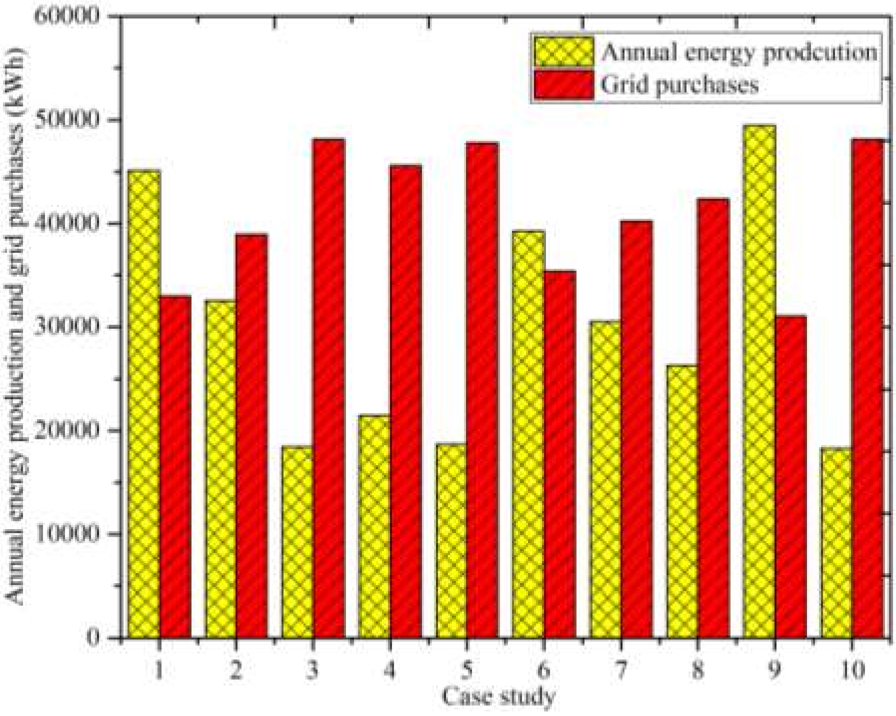

Fig. 11: Annual energy output of the WT in the selected locations and grid purchases

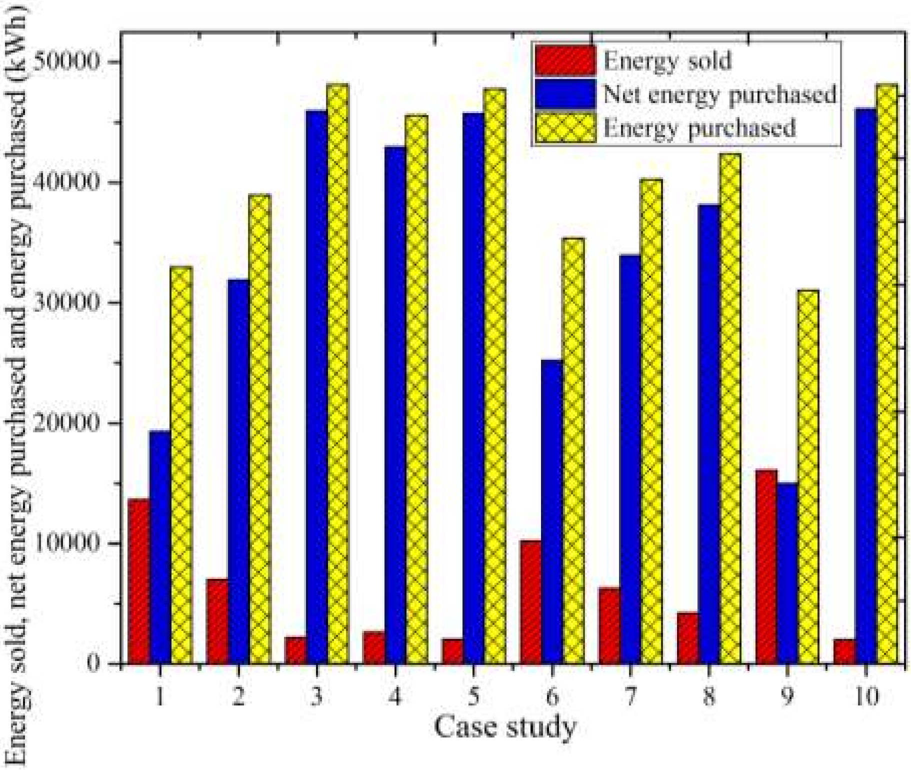

Fig. 12: Net energy purchased, energy purchased and energy sold

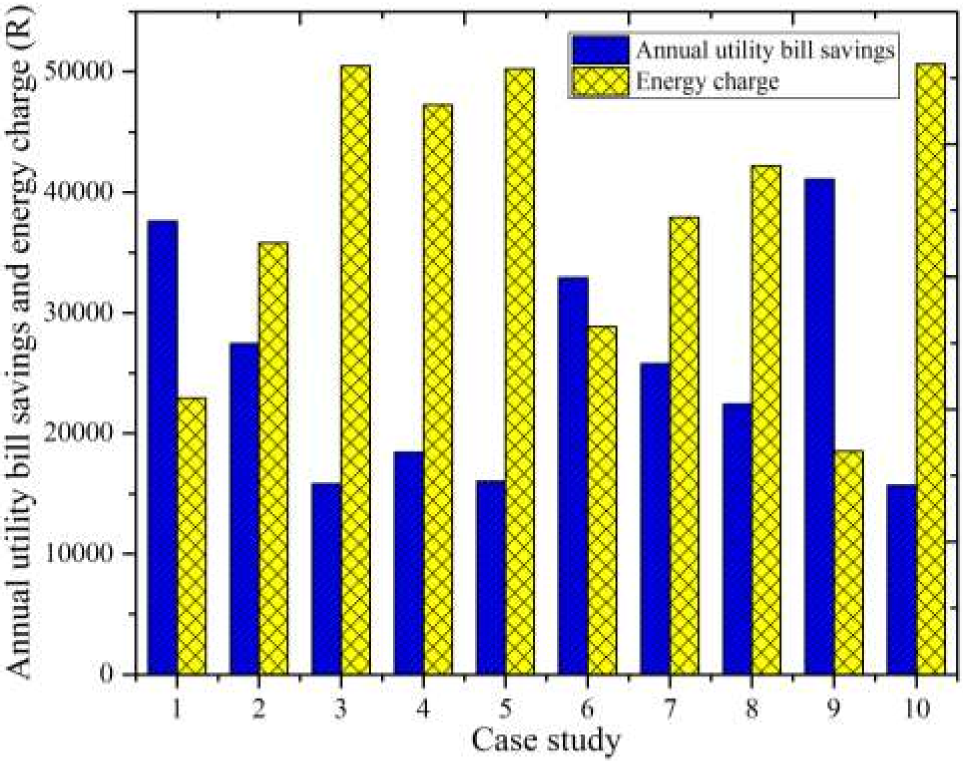

Fig. 13: Annual utility bill savings and energy charge

Table 8: Utility monthly summary for Bhisho

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	3,642	779	2,862	3,230
February	3,123	676	2,443	2,763
March	3,594	736	2,858	3,219
April	3,032	751	2,281	2,591
May	2,305	1,309	996	1,263
June	1,996	1,798	198	456.88
July	1,760	1,830	-70	168.96
August	2,045	1,453	591	840.66
September	2212	1,441	770	1,034
October	2,522	1,337	1,185	1,474
November	3,003	857	2,147	2,459
December	3,740	696	3,044	3,417
Annual	32,973	13,663	19,311	22,916

Table 9: Utility monthly summary for Bloemfontein

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	4,268	335	3,932	4,338
February	3,811	245	3,566	3,926
March	4,263	298	3,966	4,370
April	3,551	365	3,187	3,528
May	2,974	516	2,459	2,753
June	2,582	868	1,713	1,987
July	2,188	818	1,370	1,606
August	2,320	934	1,387	1,728
September	2,451	990	1,461	1,728
October	2,974	756	2,218	2,523
November	3,360	506	2,954	3,293
December	4,110	408	3,702	4,097
Annual	38,954	7,038	31,915	35,789

Table 10: Utility monthly summary for Johannesburg

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	5,468	24.3	5,444	5,947
February	4,798	18.9	4,779	5,221
March	5,264	32.9	5,231	5,715
April	4,344	30.9	4,313	4,713
May	3,651	126	3,524	3,865
June	3,011	246	2,765	3,052
July	2,825	346	2,475	2,749
August	2,864	141	2,449	2,730
September	2,830	470	2,360	2,640
October	3,528	302	3,225	3,562
November	4,331	104	4,226	4,628
December	5,244	67.2	5,176	5,661
Annual	48,156	2,187	45,970	50,483

Table 11: Utility monthly summary for Polokwane

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	4,690	140	4,550	4,986
February	4,094	121	3,972	4,354
March	4,842	99.6	4,742	5,191
April	4,128	57.4	4,070	4,452
May	3,885	62.4	3,833	4,182
June	3,525	76.9	3,448	3,775
July	3,333	113	3,220	3,531
August	2,879	401	2,477	2,759
September	2,901	408	2,493	2,776
October	3,183	537	2,647	2,962
November	3,618	400	3,218	3,567
December	4,538	231	4,303	4,734
Annual	45,616	2,648	42,968	47,268

Table 12: Utility monthly summary for Nelspruit

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	5,297	35.7	5,261	5,749
February	4,624	36.2	4,588	5,014
March	5,172	43.8	5,128	5,605
April	4,271	38.1	4,233	4,627
May	3,664	121	3,543	3,885
June	3,140	187	2,953	3,249
July	2,927	284	2,644	2,924
August	2,882	401	2,481	2,762
September	2,959	368	2,591	2,879
October	3,553	288	3,265	3,603
November	4,199	145	4,054	4,446
December	5,106	84.6	5021	5,494
Annual	47,793	2,031	45,762	50,236

Table 13: Utility monthly summary for Kimberley

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	3,812	611	3,201	3,577
February	3,417	438	2,979	3,311
March	3,915	499	3,415	3,797
April	3,192	632	2,561	2,880
May	2,793	671	2,121	2,406
June	2,491	1,041	1,490	1,761
July	2,087	976	1,111	1,343
August	2,167	1,211	957	1,207
September	2,288	1,264	1,024	1,287
October	2,640	1,165	1,475	1,766
November	3,016	865	2,152	2,465
December	3,567	860	2,707	3,071
Annual	35,385	10,193	25,193	28,872

Table 14: Utility monthly summary for Pietermaritzburg

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	4,456	242	4,213	4,633
February	4,029	168	3,860	4,237
March	3,634	239	4,193	4,610
April	3,109	334	3,300	3,648
May	2,566	408	2,701	3,003
June	2,223	883	1,683	1,956
July	2,404	760	1,463	1,699
August	2,450	828	1,575	1,831
September	2,450	981	1,469	1,735
October	3,000	727	2,273	2,579
November	3,589	452	3,137	3,486
December	4,364	279	4,084	4,497
Annual	40,255	6302	33,953	37,915

Table 15: Utility monthly summary for Mahikeng

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	4,479	204	4,275	4,695
February	3,978	128	3,850	4,221
March	4,680	142	4,538	4,973
April	3,866	115	3,750	4,110
May	3,597	146	3,451	3,788
June	3,053	225	2,828	3,118
July	2,904	298	2,606	2,885
August	2,620	606	2,104	2,281
September	2,587	721	1,867	2,135
October	2,925	759	2,166	2,467
November	3,445	525	2,920	3,259
December	4,230	369	3,861	4,264
Annual	42,365	4,238	38,127	42,195

Table 16: Utility monthly summary for Cape Town

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge
January	3,402	1,036	2,366	2,722
February	2,830	1,001	1,829	2,131
March	3,301	996	2,305	2,650
April	2,764	1,060	1,704	2,003
May	2,271	1,348	923	1,189
June	1,950	1,905	45.3	304.89
July	1,705	2,083	-379	-133.86
August	1,993	1,579	414	660.83
September	2,392	1,451	757	1,021
October	2,392	1,534	858	1,143
November	2,834	1,058	1,777	2,081
December	3,400	1,022	2,378	2,733
Annual	31,050	16,073	14,978	18,508

Table 17: Utility monthly summary for Pretoria

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Energy charge (R)
January	5,370	30.3	5,304	5,834
February	4,694	29.0	4,665	5,097
March	5,259	33.4	5,225	5,709
April	4,339	31.3	4,807	4,707
May	3,744	97.7	3,647	3,995
June	3,173	174	2,999	3,298
July	2,979	257	2,722	3,006
August	2,888	397	2,492	2,774
September	2,885	423	2,463	2,745
October	3,496	320	3,176	3,510
November	4,185	149	4,036	4,426
December	5,153	78.4	5,074	5,551
Annual	48,164	2,019	46,145	50,652

Conclusion

In this research work, a techno-economic analysis of a wind/battery microgrid system has been carried out based on the designed load profile and daily average wind speed. In view of this, this paper presents the comparative studies of a grid-connected microgrid configuration based on some key performance indicators. The study is implemented by utilizing the HOMER software is a very effective tool for the economic analysis of the proposed microgrid system. The HOMER simulation software is observed to be highly useful for the microgrid planning and operation. Moreover, the prospects of penetrating the WT into the grid are analysed effectively with the application of the tool. The application of renewable energy resources is the most preferred power solution to the problem of load shedding in the SADC countries, due to the fact that renewable energy is environmentally friendly with no carbon footprint and operates with low COE and NPC. The optimization of a wind/battery microgrid is conducted in this work to compare the technical and economic benefits of using wind resources for a medium-scale electricity production in some sites in South Africa. The selected locations for the potential and economic assessment of the WT in South Africa include Bhisho, Bloemfontein, Johannesburg, Polokwane, Nelspruit, Kimberly, Pietermaritzburg, Mafikeng, Cape Town and Pretoria. The results obtained from the study reveal that Cape Town has the lowest values of COE, NPC, energy purchased from the grid, net energy purchased and energy charge and highest value of energy sold and annual utility bill savings when compared with other selected locations in the study. Moreover, it is observed from the analysed results that Cape Town is the most economically favourable site for installation of the WT owing to the wind potential of the site. This research work is designed to investigate the wind potentiality of some locations in South Africa. In this direction, this paper presents the feasibility study of a microgrid system with some key performance indicators that independent power providers and other investors should be utilized as a measure to obtain the optimal operation of their power systems. It demonstrates the cost-effectiveness of a microgrid system and the prospect of decreasing coal dependence of South Africa's power sector. The output of this research work can be used by the renewable energy development agencies as inputs to harness the potential of wind resources for strategic planning of the power sector reform and industrial development. The potential of wind resources and economic assessment of the WT in selected locations across South Africa as presented and discussed in this paper are summarised as follows:

i. The annual energy production that ranges from 18, 295 kWh to 49, 4962 kWh are recorded in Pretoria and Cape Town by using AWS HC 5.1 kW wind turbine. The highest value of energy production is obtained in Cape Town among the selected locations owing to the presence of the wind speed that falls within the specifications of the manufacturer.
ii. The minimum COE is obtained in Cape Town as 0.233 R/kW at a hub height of 50m and the maximum value of COE is obtained in Pretoria, 0.233 R/kW.
iii. The NPC has the least value in Cape Town as R 270,970 with a giving WT at a hub height of 50m, while the highest is obtained in Pretoria as R 686,509.10 with the same WT that has the model number AWS HC 5.1 kW.
iv. The costs of energy of all the selected location in the study are considerably less than the utility tariff. This indicates that grid-connected microgrid system has many economic prospects when compared to using the power supply from the grid alone.
v. There are substantial annual utility bill savings when compared with using only utility grid to meet the load demands.
vi. The proposed microgrid system is a pathway for sustainable development that leads to R 41,074 and R 15,709 annual utility bill savings in Cape Town and Pretoria.
vii. It is observed from the results obtained from the study that the microgrid system operates satisfactorily with the wind speed that ranges from one location to another based on the availability of wind resources and increases the electricity production.
viii. Cape Town, Bhisho and Kimberly are found to be more profitable for grid-connected microgrid system owing to the key performance indicators utilized in the study.
ix. The selected locations have the average wind speeds that are above 3.37 m/s. Maximum average wind speed value of 6.69 m/s is obtained in June at Cape Town and a minimum value of 3.397 m/ s is obtained in March at Pretoria.
x. The maximum values of grid purchases are obtained in Pretoria, Johannesburg and Nelspruit with the same model of the WT owing to low capacity factor and wind penetration.

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