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Energy and economic performance of small wind energy systems under different climatic conditions of South Africa

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ABSTRACT

Several studies have established the abundance of the wind resources in South Africa, which can position the country as a leader in wind power generation continentally if the resource is well harnessed. In acknowledging this, the government proposed 8.4 GW new-build installed wind capacity by 2030. While a significant percentage of the proposed capacity is to be realised from the large scale utility wind turbines, there was further recommendation for contribution from off-grid small wind technology. Presently, this off-grid technology is still at infancy in the country. Although public support policy programs have been recommended to promote the mass uptake of this technology, it is highly important to evaluate and provide information on the energy productivity of these technologies and the economics involved for informed policy development and successful application of such programs. This study specifically examines the energy productivity and economic viability of small-scale wind energy systems in different locations and regions of South Africa, as inefficiency and the low energy yield are some of the main reasons identified for the low growth of the technology.

1. Introduction

South Africa's electricity generation is primarily through coal, a resource abundantly deposited in the country. The national electricity provider, ESKOM, generates the nation's electricity from 90% coal, 5% nuclear energy, and 5% other sources [1]. However, similar to many other countries, energy price instability, insecurity of supply, climate change, and environmental pollution are concerns driving South Africa to redefine its energy portfolio and cultivate other sources of clean energy. These factors have motivated the nation to work towards generating more energy from renewable resources – resources that are free, localised, and environmental-friendly [2–4]. This redefinition of the country's expected energy mix by the South African government has resulted in institutional changes recognising the benefits of renewable energy, and specifically, the potentials of wind energy, a clean, environmental friendly, technologically matured, and comparatively low cost energy source [5,6].

A review of the research performed on South Africa's wind resources showed that several studies have been conducted to evaluate the country's wind energy potentials. These studies, including Diab's *Wind atlas of South Africa* [7], the *Strategic study of wind energy deployment in Africa* of Helimax Energie [8], and Hagemann's *Mesoscale wind atlas of South Africa* [9], clarified the magnitude of the wind resources and provided more accurate information concerning it. Being a nation with a wind power generation potential estimated at 80.54 TWh, and which could be realised with an installed capacity of about 30.6 GW [10], South Africa can become the continent's leading wind power producer.

In realising the new commitment of the government towards wind energy development, the Department of Energy in collaboration with other related stakeholders initiated a modelled energy scenario termed the policy-adjusted Integrated Resource Plan (IRP) 2010–2030 in November/December 2010. The, most recent, IRP proposed 8.4 GW new-build installed wind capacity for South Africa by 2030 [1]. While a significant percentage of this proposed capacity is expected to be

Abbreviations: AAWS, Average Annual Wind Speed; AEP, Annual Energy Production; AGL, Above Ground Level; AWEA, American Wind Energy Association; BWEA, British Wind Energy Association; Capex, Capital Expenditure; CoCT, City of Cape Town; DoE, South African Department of Energy; ESKOM, National electricity provider; FIT, Feed-In-Tariff; GHG, Greenhouse Gas; GW, Giga Watt; GWh, Giga Watt-hour; IC, Initial or Investment Costs;; IRP, Integrated Resource Plan; kW, Kilo Watt; LCOE, Levelised Cost of Energy; MW, Mega Watt; MWh, Mega Watt-hour; NPV, Net Present Value; PV, Solar Photovoltaic; R, Rand; RE, Renewable Energy; RSA, Republic of South Africa; SA, South Africa; SAWEA, South Africa Wind Energy Association; SAWS, South Africa Weather Service; SPP, Simple Payback Period; SWES, Small Wind Energy System; SWT, Small Wind Turbine; U.S. DOE, United States Department of Energy; WASA, Wind Atlas for South Africa; ZAR, South African Rand

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generated by large scale wind turbines, the IRP suggested contributions and further research in off-grid technologies and activities [1].

Presently, the off-grid small-scale wind technology is at infancy in South Africa, with very little development recorded [11–13], and if this technology is to contribute to the proposed GW, then the sector needs to be further researched and developed. Small wind energy systems (SWES) provide clean, renewable power for on-site application and reduce the burden on the power grid while providing energy security for households, businesses, communities, farms, public facilities, and remote locations in the developed and developing world [14]. Despite the fact that wind energy projects across the world had mainly been centred on wind farms comprising many large scale turbines, the small wind sector is experiencing expansion more recently [15]. Ackerman & Soder [16] noted that, in South Africa, the small-scale wind systems were identified to be in the range of less than 10 kW historically. The commonly used models are the 1.5 kW turbines [17]. Furthermore, Frost and Sullivan et al., [18] indicated that some policies do exist to promote small-scale wind generation in South Africa, and some manufacturers are active in the small and medium wind turbine market, with a relatively high degree of local content [11]. However, little or no known research has evaluated the way in which energy and economic performance have impacted the growth of small wind generation in South Africa [12,13].

Small wind turbines operate mostly in low and moderate wind speed areas, thus, their performance and durability need to be established, as a low energy yield is one of the major reasons responsible for continued low penetration [19–21]. Schwerin [22] expressed that, key factors which often caused the failure or underdevelopment of renewable energy projects include poor technology and maintenance capacities. Technological factors affecting the viability of distributed wind include scarcity of turbine choices, relatively poor productivity, siting, and burdensome interconnection rules [19]. The systems of today lean on the aerospace technologies, possessing advanced, though mechanically simple, robust designs, which enable reliable operations for a useful lifetime of between 20 and 30 years [23]. The simply structured, compactly designed, portable, little noise producing SWES are currently essential technological developments for the extraction of power from the wind in rural, suburban, and urban settlements where the installation of large scale turbines is restricted [24,25].

Public support policy programs are required to promote the growth of wind energy and influence the behaviour of developers and consumers. However, for the successful application of such programs, it is essential to evaluate and provide information on the energy productivity of installations, and the economics involved in all phases of the project [3]. Therefore, in seeking a development path for the small wind sector in South Africa, this study evaluates the techno-economic performance of small wind energy systems in a developing economy like South Africa and the effect on the viability and future growth of the sector. It specifically establishes new findings regarding the energy productivity and economic viability of the systems in different locations of the country. These findings constitute new information on parameters such as energy productivity, costs of small wind-generated electricity, and economic viability. Policymakers, investors, manufacturers, distributors, and academics need the abovementioned information for effective improved investment and performance design.

2. Methodology

This section describes the processes, methods, and designs adopted by the study for data collection, data analysis, and the results. Considering the variation in the wind resources of South Africa and the large expanse of the geographic area, this study categorised the country into four distinct regions. These regions were termed the Cape Peninsula, South-Eastern, Central, and Northern region [26]. Three locations were considered in each region of the country for the techno-economic evaluation. Purpose sampling was used for the selection of the twelve locations. The selection of these specific locations was based on sites with the most complete and available wind data in the different regions considered during the period under study. The Cape Peninsula region consisted of Cape Town, Oudtshoorn, and Worcester, while the South Eastern region included Port Elizabeth, Grahamstown and Richards Bay. De Aar, Bethlehem, and Potchefstroom were selected for the Central region. The Northern region consisted of Johannesburg, Nelspruit, and Polokwane.

The wind speed data of all the locations considered were collected from the South Africa Weather Service (SAWS) to determine the wind characteristics and probability distributions of the locations, using the Weibull distribution function, a mathematical model for analysing local wind load probabilities [27–29]. The average wind speed data were measured at an hour interval over a period of 5 years (2010–2014) at a height of 10 m above ground level (AGL). Thereafter, the amount of energy that could be produced by a small wind system in each site location was computed. Two commercially available small wind turbines (SWTs) were evaluated for each site location. They are the e300i (1 kW) and the e400n (3.5 kW) models manufactured by Kestrel Renewable Energy. The energy outputs of the selected turbines at all the sites were calculated by combining the wind probability distribution of each site with the power curves of the selected turbines [30,31].

The economic performances of the two selected SWTs were further evaluated for all the locations, and then compared with the average monthly consumption/demand of households in South Africa. The accurate evaluation of the economic feasibility of SWES is important, as it allows an end-user to measure the total expenditure and the system's payback period [32]. Basic economic models for evaluating electricity generating systems were used for the economic evaluation, and they include: Simple Payback Period (SPP); Net Present Value (NPV); and Levelised Cost of Energy (LCOE), in order to provide a balanced representation [2,33].

3. Energy performance

The objective here is to determine the energy productivity of small wind turbines in different locations of the country. Two differently rated small wind turbines were used for this process. Important parameters such as the wind speed distribution of all the site locations considered and the annual energy output of the small wind turbines in these locations were determined. The energy generated by a wind energy system at a given site during a related period of time is subjective to the power response of the system to different wind velocities, wind regimes and wind speed distribution [31]. The energy performance of a small wind energy system is affected mainly by the on-site wind resource and the accuracy of the turbine rating [34], and studies have shown that many small wind turbines are unable to deliver the rated power quoted by manufacturers [21,35].

3.1. Wind distribution

A potential site's wind characteristics are quite influential to determine the amount of energy produced by a turbine [31]. This section analysed the wind speed characteristics and probability distribution of some selected sites in South Africa for small wind generation using the Weibull distribution function. Wind speed varies across any country as it depends on the geographical characteristics of the different locations [4]. This wind speed variability can be defined by the Weibull distribution function, a standard mathematical model for analysing local wind load probabilities due to the appropriateness for the extensive collection of wind data [27–29,36–38].

The study made use of average wind speed data, measured at an hourly interval over a period of 5 years (2010–2014), and at a height of 10 m above ground level (AGL) in all the considered locations. The wind speed data are presented in Table 1. The average annual wind speeds (AAWS) of the respective locations for the period 2010–2014 are

Table 1
Annual Average Wind Speed (m/s) of selected sites at 10 m AGL (2010 — 2014).

Region	Site location	Lat.	Long.	HASL (m)	2010	2011	2012	2013	2014
Cape Peninsula	Cape Town	33.9630	18.6020	42	5.2	5.2	5.2	5.3	5.0
	Oudtshoorn	33.6000	22.1870	328	2.3	2.2	2.2	2.4	2.4
	Worcester	33.6630	19.4180	204	4.5	4.2	4.5	4.6	4.3
South Eastern	Port-Elizabeth	33.9860	25.6160	60	5.6	5.5	5.3	5.4	5.4
	Grahamstown	33.2900	26.5020	642	4.2	4.3	4.5	4.6	4.5
	Richards Bay	28.7370	32.0930	36	3.8	3.6	3.8	4.0	4.0
Central	De Aar	30.6650	23.9920	1286	4.6	4.4	4.6	4.8	4.7
	Bethlehem	28.2490	28.3340	1689	3.1	3.4	3.3	3.0	2.9
	Potchefstroom	26.7350	27.0750	1351	2.7	2.1	2.3	2.3	2.2
Northern	Johannesburg	26.1430	28.2340	1695	4.1	4.1	4.2	4.3	4.2
	Nelspruit	25.5030	30.9110	883	3.0	1.9	2.1	2.0	2.2
	Polokwane	23.8570	29.4510	1226	2.7	2.7	3.0	3.0	2.9

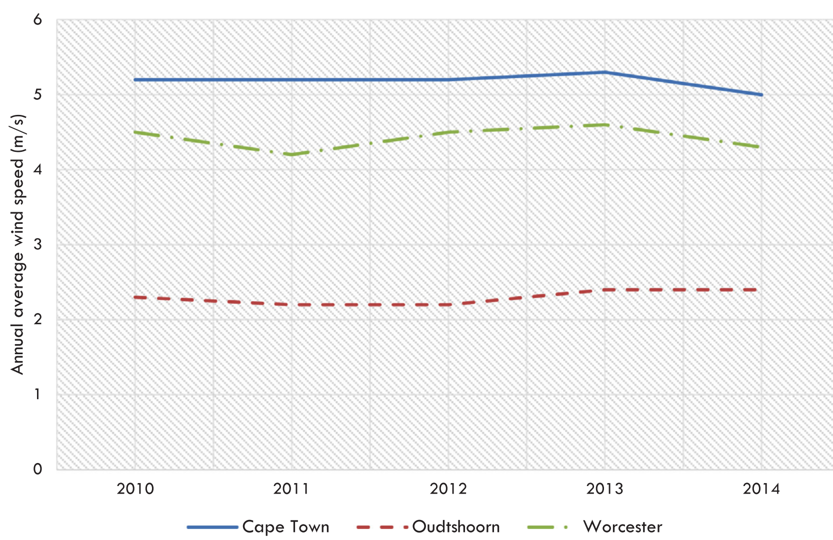

Fig. 1. AAWS of Cape Peninsula region from 2010 to 2014 at 10 m AGL.

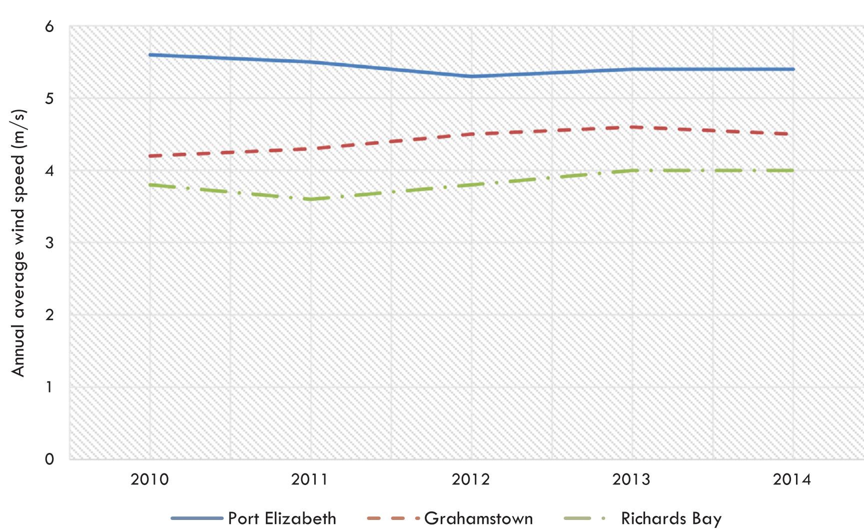

Fig. 2. AAWS of South Eastern region from 2010 to 2014 at 10 m AGL.

graphically illustrated in Figs. 1–4.

From the long-term wind data determined at 10 m AGL for the Cape Peninsula, Cape Town is the windiest among the three site locations considered in the region, with the highest AAWS of 5.3 m/s observed in 2013, while Oudtshoorn recorded the least with an AAWS of 2.2 m/s in 2011 and 2012. The South Eastern region has the site locations with the highest average annual wind speed in all the different regions, having an AAWS of 5.6 m/s throughout the measured period of 2010–2014. The highest AAWS in the region was recorded in 2011 in Port Elizabeth, while the least AAWS (3.6 m/s) occurred in 2011 in Richards Bay. For the Central region, De Aar is the windiest location. The highest AAWS (4.8 m/s) was recorded in De Aar in 2013, while Potchefstroom has the least AAWS (2.1 m/s) in that region in 2011. In the Northern region over the considered years, the AAWS ranged from 1.9 m/s to 4.3 m/s.

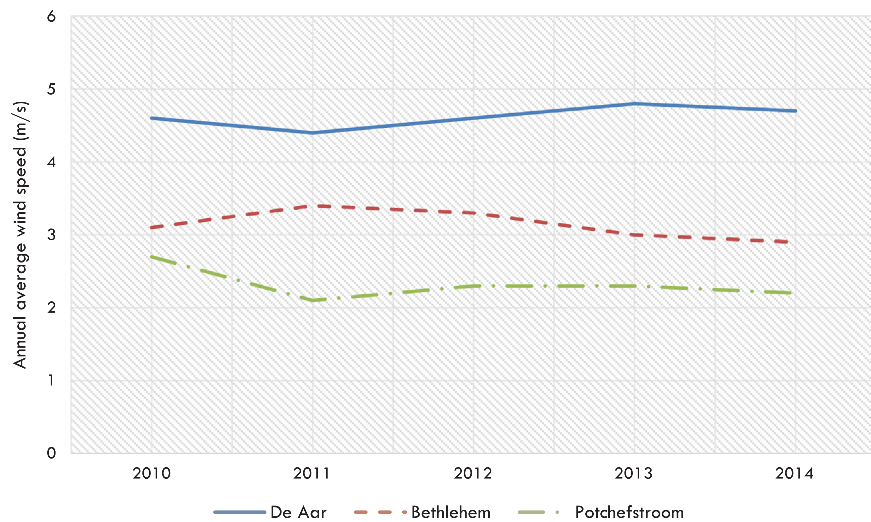

Fig. 3. AAWS of Central region from 2010 to 2014 at 10 m AGL.

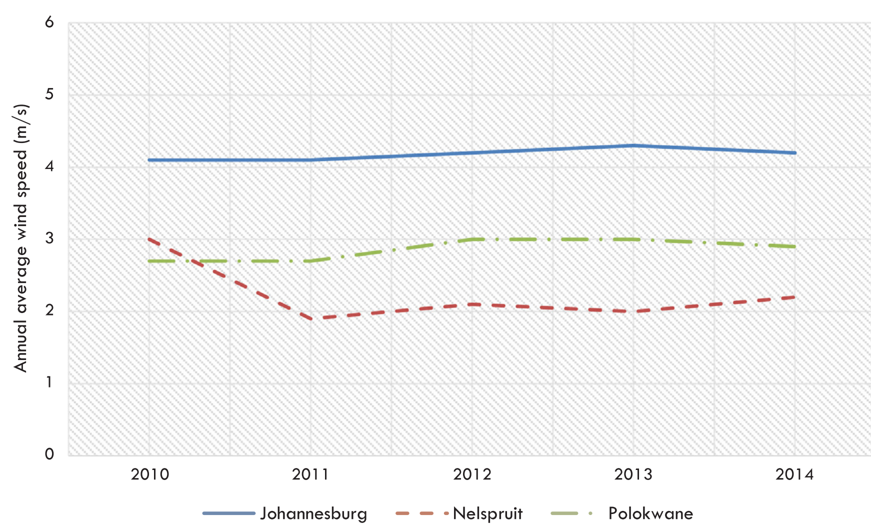

Fig. 4. AAWS of Northern region from 2010 to 2014 at 10 m AGL.

Johannesburg recorded the highest AAWS in 2013, while the least wind was recorded in 2011. Overall, it was observed that both the Cape Peninsula and South Eastern region experienced better wind resources in comparison to the Central and Northern regions over the years under consideration.

The wind variation for a normal site is generally described by the Weibull distribution, and it indicates the percentage of time a certain wind speed occurs in a given site [21,39,40]. The Weibull distribution is expressed by the equation:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k} \tag{1}$$

where $f(v)$ means the probability of wind speed (Weibull) distribution, v is the wind speed, k is the Weibull distribution shape factor, and c is the distribution scale factor.

The two factors, k (dimensionless) and c (m/s) are computed from the long-term wind data for a selected site, and they control the profile of the Weibull distribution curve [32]. The Weibull shape parameter k denotes the peak level of a potential site is, while the scale parameter c indicates the intensity of the wind available on the site [29,32,41]. These Weibull parameters can be determined through different methods in order to fit the Weibull distribution to the measured data at a given location [32].

Based on the suitability of the Weibull distribution for all the considered site locations in this study, the relationship between the shape factor k, scale factor c, and the average wind speed v_m is expressed by the following equations [6,29,32]:

$$k = 0.83 \quad {v_m}^{0.5} \tag{2}$$

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

These two Weibull parameters can be calculated when the average wind speed v_m and the gamma function Γ are known. Table 2 presents the Weibull shapes and scale parameters for all the sites under consideration. The computations for these parameters were based on the mathematical models above and the data from the SAWS. The probability distributions describing the variations in wind speed for the considered sites for the years 2010–2014 are shown in Figs. 5 to 8.

At 10 m above ground level, the shape and scale parameters ranged from 1.25 and 2.47 in Oudtshoorn, Potchefstroom, and Nelspruit to 1.92 and 6.09 in Port Elizabeth. Therefore, it can be inferred that Port Elizabeth is the windiest site (highest scale factor), while Oudtshoorn, Potchefstroom, and Nelspruit are the least windy sites, as the scale and shape parameters respectively signified the wind intensity and the peak level of a potential site [29,32]. The probability of observing higher wind speeds in the Cape Peninsula and South Eastern regions is greatest

Table 2
Wind speed characteristics for the different sites at 10 m AGL.

Region	Site location	AAWS whole year (2010–2014)	k	c (m/s)
Cape Peninsula	Cape Town	5.2	1.89	5.86
	Oudtshoorn	2.3	1.25	2.47
	Worcester	4.4	1.74	4.94
South Eastern	Port-Elizabeth	5.4	1.92	6.09
	Grahamstown	4.4	1.74	4.94
	Richards Bay	3.8	1.61	4.24
Central	De Aar	4.6	1.78	5.17
	Bethlehem	3.1	1.46	3.42
	Potchefstroom	2.3	1.25	2.47
Northern	Johannesburg	4.2	1.70	4.71
	Nelspruit	2.3	1.25	2.47
	Polokwane	2.8	1.38	3.07

in Cape Town and Port Elizabeth respectively. For the Central region, De Aar has a higher probability of recording high wind speeds than the other two sites in that region, while Johannesburg has the highest wind probability in the Northern region. This study confirmed that the Cape Peninsula and the South Eastern regions have higher probabilities of recording high wind speeds in South Africa when compared to the other regions.

3.2. Energy generation

The energy yield from a turbine is a function of the wind speed and wind distribution of the site [21], and this must be considered primarily with regards to the design and operation of the turbine as the probability density distribution of the wind speed significantly affects the performance of the turbine [32]. Manufacturers of small wind turbines generally provide rated power at different speeds, as turbines operate in different weather conditions with different wind speeds, hence their different specifications.

For any selected site, the energy yield of a wind turbine can be derived by combining the wind speed data of that particular site with that of the power curves of the selected turbine [30,31]. The wind turbine choice for any given site is determined based on the wind profile of the site [29]. For this study, two commercially available small wind turbines with different rated power, the e300i and e400n, were evaluated in all the selected locations in the country. The technical specifications of the selected turbines are presented in Table 3.

The e300i and e400n turbine models are three blade rotors designed to power a twin axial flux permanent magnet brushless alternator with good heat management. The turbines are fitted with a patented blade pitch control, making them to maintain their rated output in excess wind speeds with no cut-out wind speed. The blade pitch control is the system which monitors and adjusts the inclination angle of the blades and thus controls the rotation speed of the blades. At lower wind speeds, the pitching system leads to an acceleration of the hub rotation speed, and while at higher speeds, blade pitch control reduces the wind load on the blades and structure of the turbine.

Wind energy is a product of the power generated by a turbine at a wind speed v and time t at an investigated site [30,31]. Thus, the power P generated by the wind, expressed as a function of wind speed, can be calculated by [4,21,39]:

$$P = \frac{1}{2} C_p \rho v^3 A \tag{5}$$

where ρ is the air density, v is the wind speed, r is the radius of turbine rotor, C_p is the power coefficient of the rotor or the aerodynamic efficiency, $A = \pi r^2$ (swept area of the rotor), and the wind density ρ is assumed to be 1.225 kg/m^3 [21].

The power coefficient is the ratio between the energy extracted and the wind energy available, and has a Betz limit (maximum value) of 16/27 [32], or this limit is otherwise described as the usable energy of the wind, about 59%, which may be captured by the turbine according to the Betz law [21]. The actual power coefficient, however, is much lower than the Betz limit due to mechanical and electrical losses, thus the actual energy yield of the turbine is less than the usable energy [21,32]. Small wind turbines generally have a performance coefficient of less than 40% [35].

The captured amount of energy by a turbine is a function the power curve (power output against the wind speed characteristics) of the turbine and the Weibull distribution of the site [30,31]. Therefore, the energy yield E of a turbine over a time period T is expressed as [21,30,32]:

$$E = T \int P(v) f(v) dv \tag{6}$$

Also, when calculating the energy yield for a year, T becomes 8760 h. Thus, rewriting the equation, the annual energy yield is expressed as:

$$E = 8670 \quad \sum P(v) f(v) \tag{7}$$

Applying Eq. (7) to the power curves of the selected turbines and the wind probability distribution of the selected locations provides the annual energy yield of the small wind turbines in the respective locations, as presented in Table 4. The energy output results are graphically

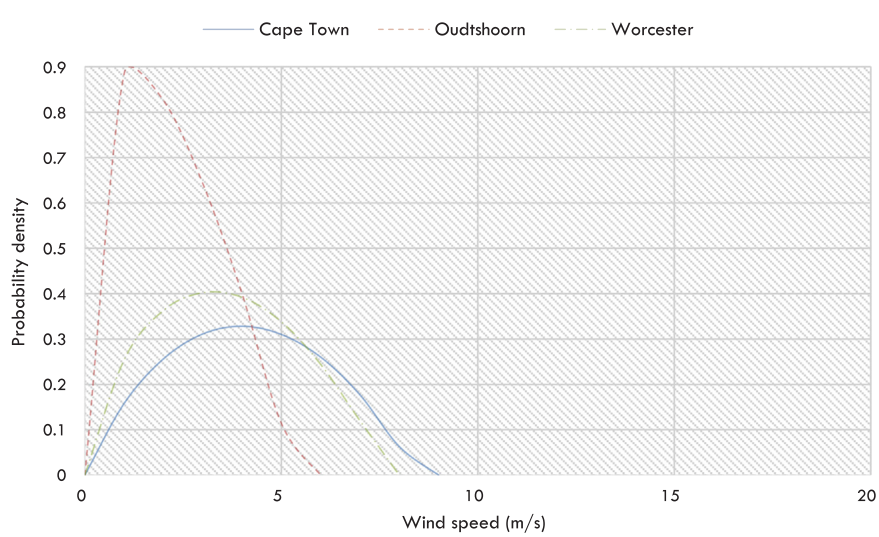

Fig. 5. Probability distribution for sites in Cape Peninsula region for the whole year (2010–2014).

Fig. 6. Probability distribution for sites in South Eastern region for the whole year (2010–2014).

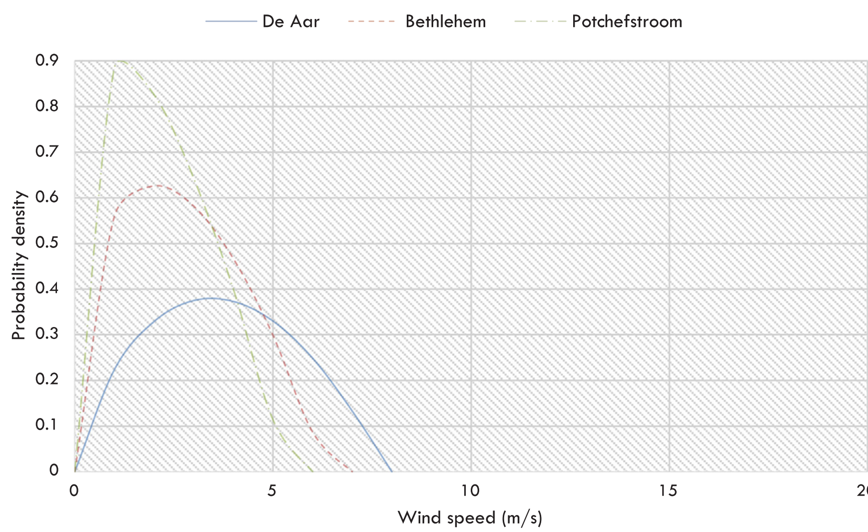

Fig. 7. Probability distribution for sites in Central region for the whole year (2010–2014).

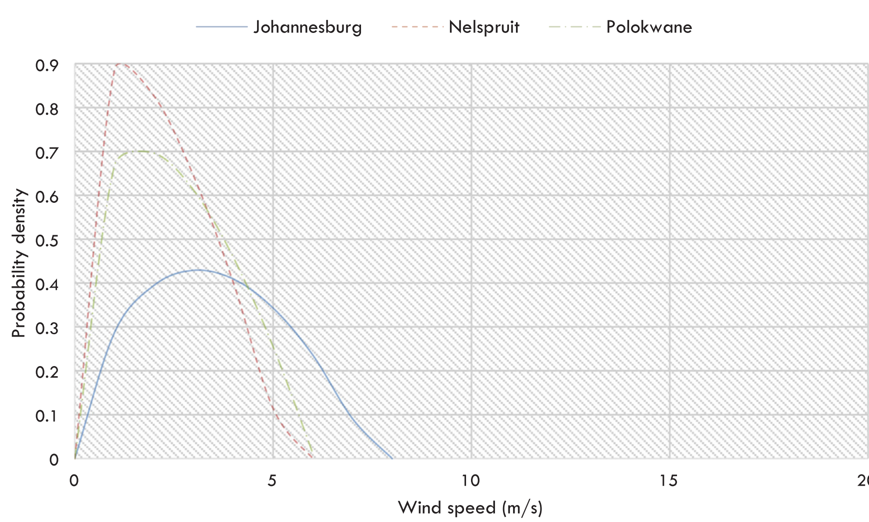

Fig. 8. Probability distribution for sites in Northern region for the whole year (2010–2014).

illustrated in Fig. 9.

From the annual energy production (AEP) calculated, Port Elizabeth demonstrated the highest energy production in all the considered locations for the two selected turbines. It has annual energy outputs of 2 160.69 kWh/yr. and 3 432.52 kWh/yr. for the e300i (1 kW) and e400n (3.5 kW) respectively, followed by Cape Town with 2 125.18 kWh and 3

Table 3
Technical specifications of selected small wind turbines.
Source: Kestrel Renewable Energy

Characteristics	e300i	e400n
Turbine type	HAWT	HAWT
Number of blades	3	3
Rotor diameter (m)	3	4
Rated power (kW)	1	3.5
Rated wind speed (m/s)	10.5	12
Cut-in speed (m/s)	2.5	4
Cut-out speed (m/s)	—	—

Table 4
Annual energy production of selected turbines at the different sites.

Region	Site location	e300i (1 kW) (kWh/year)	e400n (3.5 kW) (kWh/year)
Cape Peninsula	Cape Town	2125.18	3316.36
	Oudtshoorn	683.54	239.85
	Worcester	1758.22	2268.66
South Eastern	Port-Elizabeth	2160.69	3432.52
	Grahamstown	1758.22	2268.66
	Richards Bay	1482.19	1557.35
Central	De Aar	1487.79	2358.36
	Bethlehem	1132.49	847.18
	Potchefstroom	683.54	239.85
Northern	Johannesburg	1681.56	2056.58
	Nelspruit	683.54	239.85
	Polokwane	916.47	504.05

316.36 kWh. While Cape Town and Port Elizabeth had the highest annual energy production in their respective regions, De Aar generated the highest annual energy output in the Central region, and Johannesburg in the Northern region. De Aar exhibited 1 487.79 kWh (e300i) and 2 358.36 kWh (e400n), while the turbines in Johannesburg produced 1 681.56 kWh (e300i) and 2 056.58 kWh (e400n). The least annual energy output was produced in Oudtshoorn, Potchefstroom, and Nelspruit. The three locations demonstrated the same annual output of 638.54 kWh and 239.85 kWh for the e300i (1 kW) and e400n (3.5 kW) respectively. Interestingly, the turbine with the lower rated capacity, the e300i, seems more suited to sites with low wind speed characteristics than the one with the higher rating, as indicated in the sites with the least annual outputs. The e300i (1 kW) generated a larger annual output than the e400n (3 kW) in Oudtshoorn, Bethlehem, Potchefstroom, Nelspruit, and Polokwane.

With the monthly electricity consumption of the majority of low-income households below 50 kWh (600 kWh/year), and an average monthly consumption of 132 kWh (1584 kWh/year) by households throughout out SA [42], although expected to rise to approximately 350 kWh monthly (4 200 kWh/year) [43], the application of SWTs can meet the energy demand of some households in some environments in

Table 5
Capital costs of selected small wind turbines.
Source: Kestrel renewable energy

SWT model	Rated capacity (kW)	Specific cost (ZAR)
e300i	1	30,825
e400n	3.5	72,012

Table 6
The payback period of selected turbines at the different sites.

Region	Site location	e300i (1 kW) (year)	e400n (3.5 kW) (year)
Cape Peninsula	Cape Town	12	18
	Oudtshoorn	38	255
	Worcester	15	27
South Eastern	Port-Elizabeth	12	18
	Grahamstown	15	27
	Richards Bay	18	39
Central	De Aar	18	26
	Bethlehem	23	72
	Potchefstroom	38	255
Northern	Johannesburg	16	30
	Nelspruit	38	255
	Polokwane	29	121

Table 7
The Net Present Value of selected turbines at the different sites.

Region	Site location	e300i (1 kW) (ZAR)	e400n (3.5 kW) (ZAR)
Cape Peninsula	Cape Town	– 12,271.59	– 50,229.54
	Oudtshoorn	– 31,130.24	– 90,478.41
	Worcester	– 17,071.90	– 63,938.61
South Eastern	Port-Elizabeth	– 11,806.98	– 48,713.54
	Grahamstown	– 17,071.90	– 63,938.61
	Richards Bay	– 20,682.74	– 73,243.57
Central	De Aar	– 20,609.46	– 62,765.12
	Bethlehem	– 25,257.33	– 82,533.66
	Potchefstroom	– 31,130.24	– 90,478.41
Northern	Johannesburg	– 18,074.98	– 66,712.83
	Nelspruit	– 31,130.24	– 90,478.41
	Polokwane	— 28,083.27	— 87,022.33

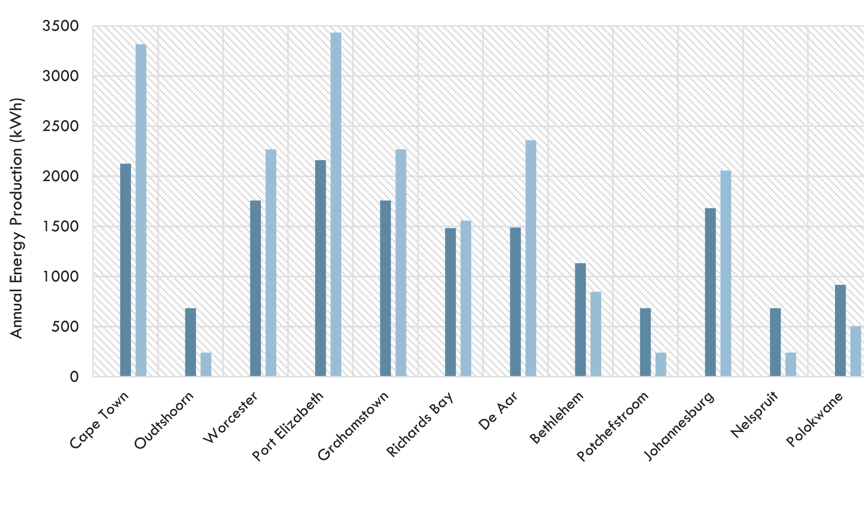

Fig. 9. Annual energy production of selected turbines at the different sites.

Table 8
The LCOE of selected turbines at the different sites.

Region	Site location	e300i (1 kW) (R/kWh)	e400n (3.5 kW) (R/kWh)
Cape Peninsula	Cape Town	5.03	7.54
	Oudtshoorn	15.65	104.21
	Worcester	6.08	11.02
South Eastern	Port-Elizabeth	4.95	7.28
	Grahamstown	6.08	11.02
	Richards Bay	7.22	16.05
Central	De Aar	7.19	10.59
	Bethlehem	9.45	29.50
	Potchefstroom	15.65	104.21
Northern	Johannesburg	6.36	12.15
	Nelspruit	15.65	104.21
	Polokwane	11.67	49.59

the country, or can be integrated with hybrid systems in several cases.

4. Economic performance

This section evaluates the economic viability of the small wind turbines with respect to the different selected locations in the country. These include analysing and determining the Simple Payback Period, Net Present Value, and Levelised Cost of Energy. The poor economic performance of renewable technologies, where the avoided cost of purchasing grid electricity is usually unable to repay the capital cost of the technology within its useful lifetime, is the foremost limitation to the mass installation of these technologies [2]. Analysing the economic viability of micro-generation technologies correctly is essential, as it enables a potential consumer to assess the final outlay and the payback period of such systems [32].

The cost of the electricity generated is the most important input parameter in the investment and economic analysis of electricity generating facilities [33]. If the small wind system can generate at a low cost, then the system has economic viability. However, several factors influence the unit cost of energy (expressed in terms of money per kW) that varies for respective sites in different countries [31]. Deriving the cost of wind-generated electricity and assessing its economic viability involve analysing economic parameters such as investment costs, operation and maintenance costs, energy production, turbine lifetime, interest rates, etc. [31,33]. Generally, the unit cost of energy is a fraction of the amount of energy generated of the total expenditures with respect to the given time interval, however, the economic viability of a small-scale generation system can be evaluated by several methods [2,4].

A few basic economic models for evaluating an electricity generating system were utilised in this study, including: Simple Payback Period (SPP); Net Present Value (NPV); and Levelised Cost of Energy (LCOE), in order to provide a balanced representation [2,4,31,33,44]. The initial costs (IC) or investment costs of the selected systems for this study include the specific price (capital cost) of the turbine system and the installation costs [31,45]. The specific (capital) costs of the selected systems include the costs of the turbine, stand, and battery, and are presented in Table 5 below.

The following assumptions were considered for the economic evaluation of the turbines:

1. The small wind energy systems are for off-grid generation.
2. The lifetime of the SWES is assumed to be 20 years [6].
3. The installation cost is 30% of the specific cost of the turbine system [46].
4. The discount rate is considered to be 10%.
5. Operation and maintenance (O&M) is 15% of the initial investment cost of the SWES.
6. The systems are assumed to generate equal amounts of energy outputs per year in its lifetime.
7. The average sales price of electricity in South Africa is R1.53/kWh [47].

4.1. Simple payback period (SPP)

The payback period is the time period (generally in years) in which a return is required from an investment or the amount of time it takes for the positive cash flow to exceed the initial investment, without concern for the time value of money [2,6]. It is important to know how quickly an investment might pay back, since it is the most straightforward and easiest of all economic models to comprehend by the general public. However, this model's disregard for the timing of cash flow, energy price escalation, and the cash flow beyond the payback period are its main shortcomings [2,48,49]. The SPP is an important determinant in investment considerations, as shorter payback periods are normally more desirable [6]. It is expressed as [6,45]:

$$\mathrm{SPP(years)} = \frac{\text{Initial Cost(R)}}{\text{Average Annual Revenue(AAR)}} \tag{9}$$

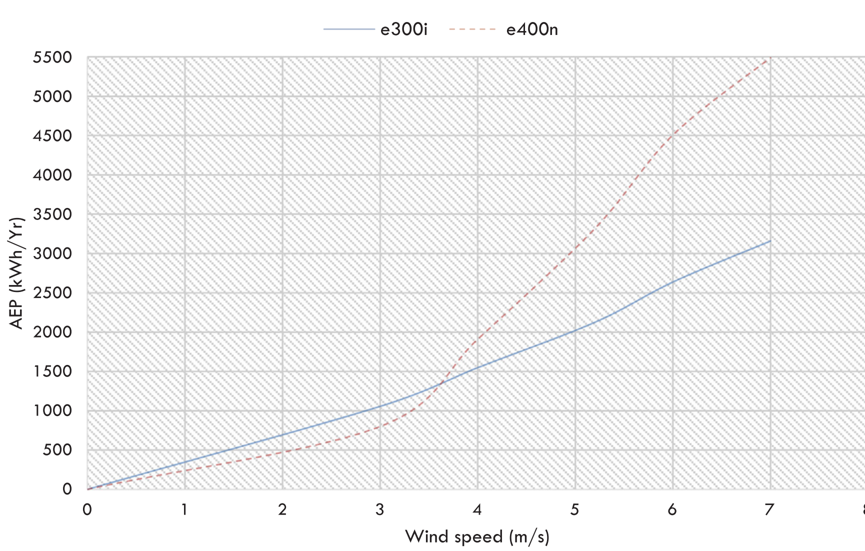

Fig. 10. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Cape Town.

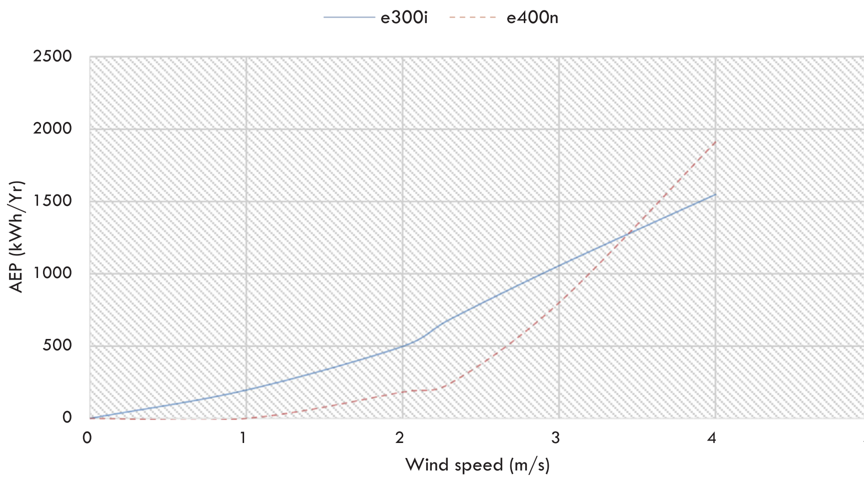

Fig. 11. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Oudtshoorn.

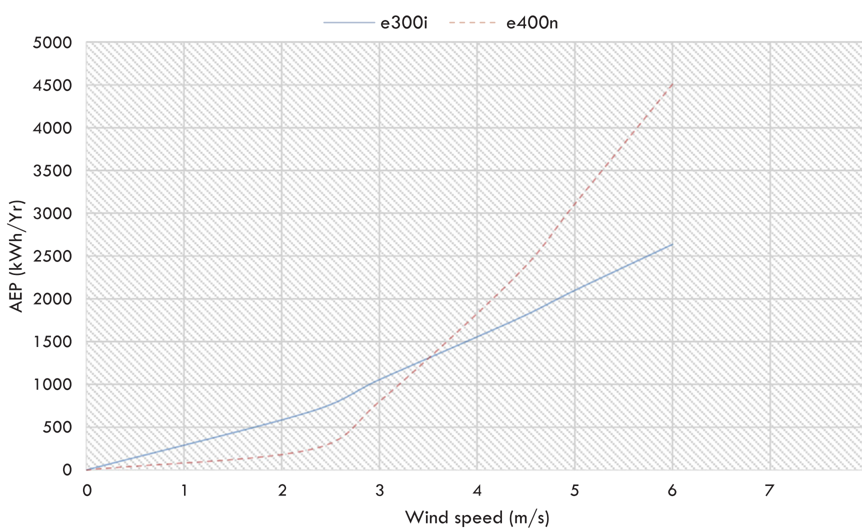

Fig. 12. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Worcester.

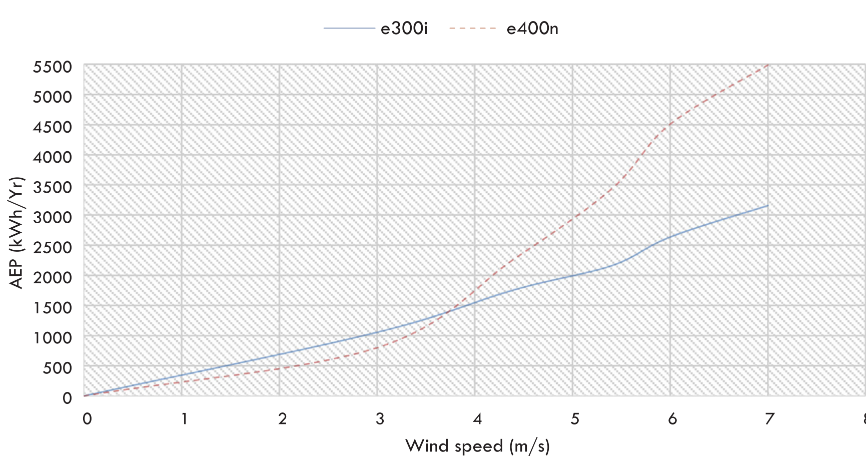

Fig. 13. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Port Elizabeth.

$$= \frac{\text{Initial Cost(R)}}{\text{Energy Output}\left(\frac{\text{kWh}}{\text{year}}\right) \times \text{Electricity Price}\left(\frac{\text{R}}{\text{kWh}}\right)} \tag{10}$$

where initial cost is the total price (Rand) paid for the small wind system and the installation, average annual revenue is based on hourly production, energy output is the amount of energy generated per year by the system, and electricity price is the tariff for energy from the utility (market retail price). The payback periods for the e300i and e400n turbines are presented in Table 6.

The payback periods for the e300i (1 kW) model are more than the useful lifetime of the turbines in Oudtshoorn, Bethlehem, Potchefstroom, Nelspruit, and Polokwane, hence, the initial investment

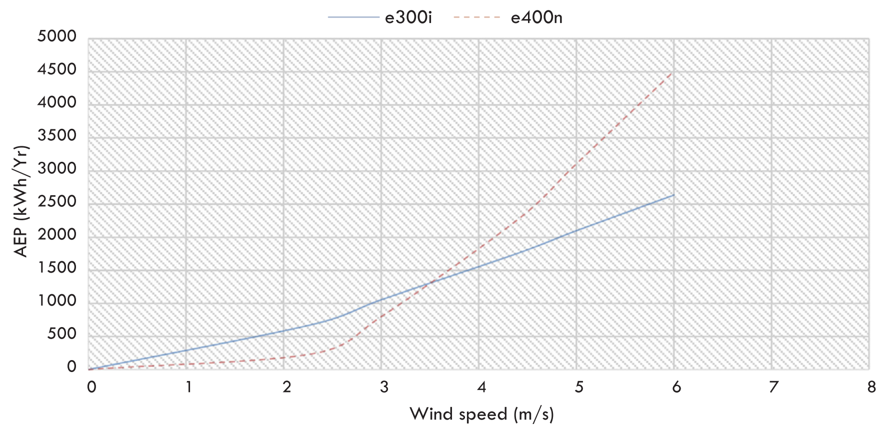

Fig. 14. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Grahamstown.

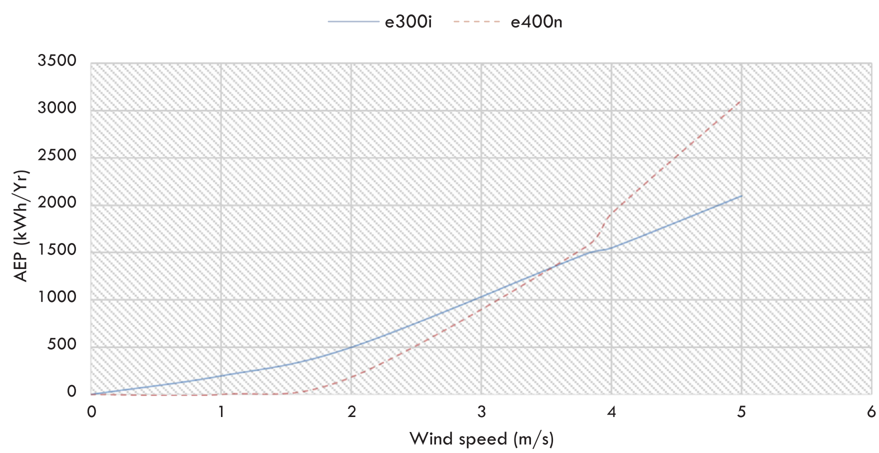

Fig. 15. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Richards Bay.

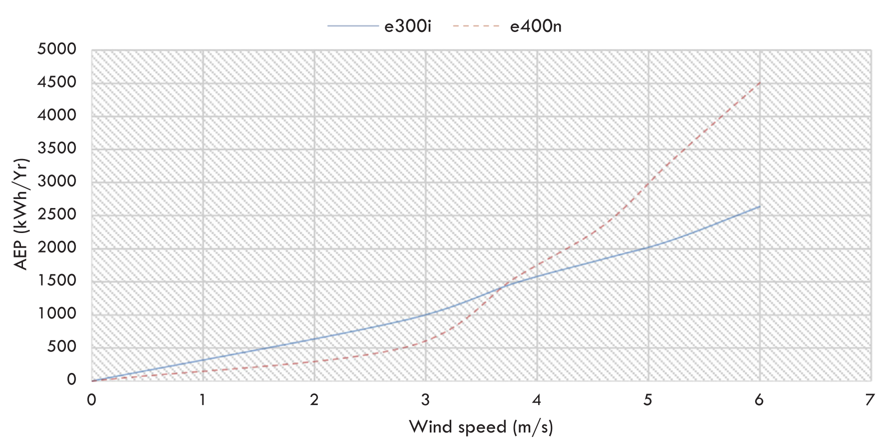

Fig. 16. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in De Aar.

may not be recovered in these locations before the end of the operating lifetime of 20 years of the turbine. For the e400n (3.5 kW), only Cape Town and Port Elizabeth have payback periods below the lifetime of the system. Cape Town and Port Elizabeth demonstrated the least amount of recovery years in the two categories of turbine models, with approximately 12 years and 18 years for the e300i (1 kW) and e400n (3.5 kW) respectively. The longest recovery years of 38 years and 255 years for the e300i (1 kW) and e400n (3.5 kW) turbine models were recorded in Oudtshoorn, Potchefstroom, and Nelspruit.

4.2. Net present value (NPV)

The Net Present Value (NPV) is a widely accepted economic method for evaluating investment projects and it applies to the principle of capital value over time [45,50]. The NPV operates on a concept of present value and calculates the difference between the present values of cash inflows and the present values of cash outflows, at a given target rate of return or cost of capital [2,45]. It is the sum of every discounted cash flow related to an investment project. A project is financially viable if the NPV is positive, while a negative value signifies an investment that is not viable [2,51]. For an energy project, the NPV is termed as the difference between the present value of the benefits and the

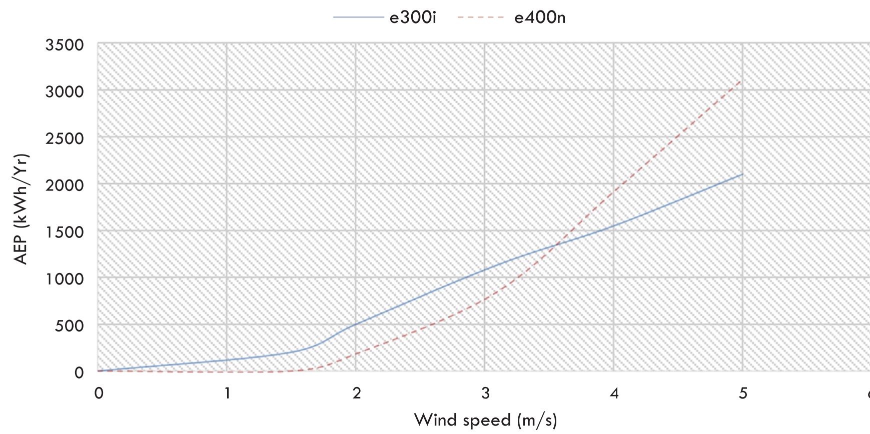

Fig. 17. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Bethlehem.

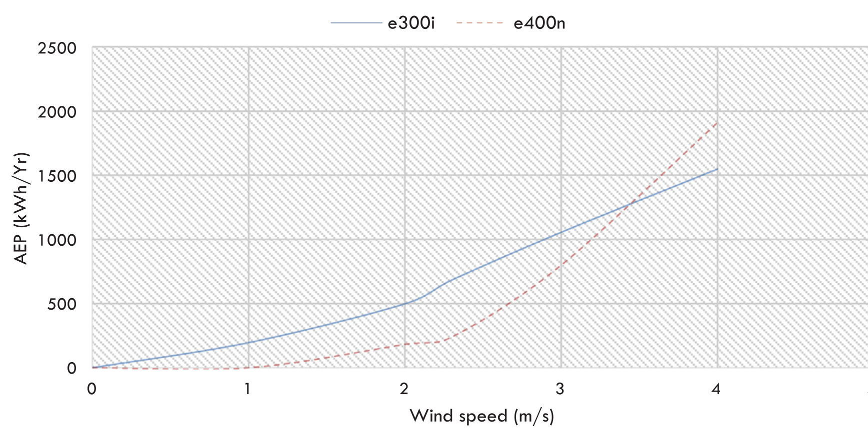

Fig. 18. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Potchefstroom.

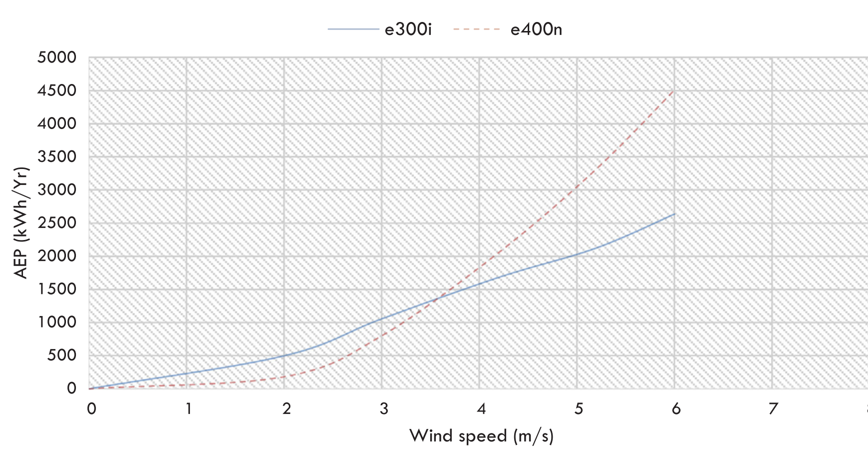

Fig. 19. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Johannesburg.

present value of the costs [45]. There are assumptions that the distribution of wind speed will be constant yearly, leading to an uniform amount of electricity being generated yearly, and that the annual revenue remains will also be uniform [45,52]. This cash flow uniform must be discounted, as it is a future occurrence. The NPV of a uniform cash flow is expressed as [45,52]:

$$NPV = AAR\left[\frac{(1+i)^n \quad -1}{i(1+i)^n}\right] - IC \tag{11}$$

where AAR is the Average Annual Revenue (based on hourly production), i is the discount rate, n is the lifetime of the turbine, and IC is the Initial Capital Cost (which is the present value of cost). The calculated NPVs for the e300i and e400n turbine models are illustrated in Table 7.

The analysis showed the two selected SWTs have a NPV of less than zero for all the location under consideration. Hence, the turbines are not economically viable for energy generation in all the locations.

4.3. Levelised cost of energy (LCOE)

The LCOE is probably the most important model for evaluating the economic performance of power projects such as wind energy [31]. The economic model calculates the unit cost of production of electricity over the economic life of the system project or the cost to produce one kWh of electricity, and it includes evaluating the total installation cost,

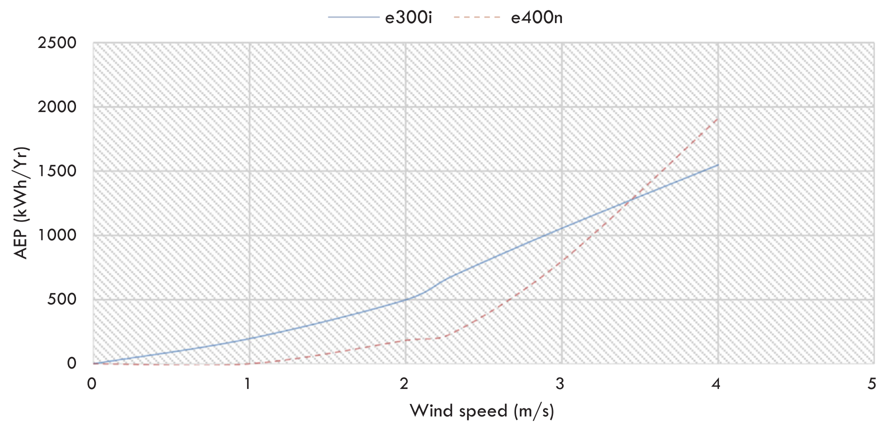

Fig. 20. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Nelspruit.

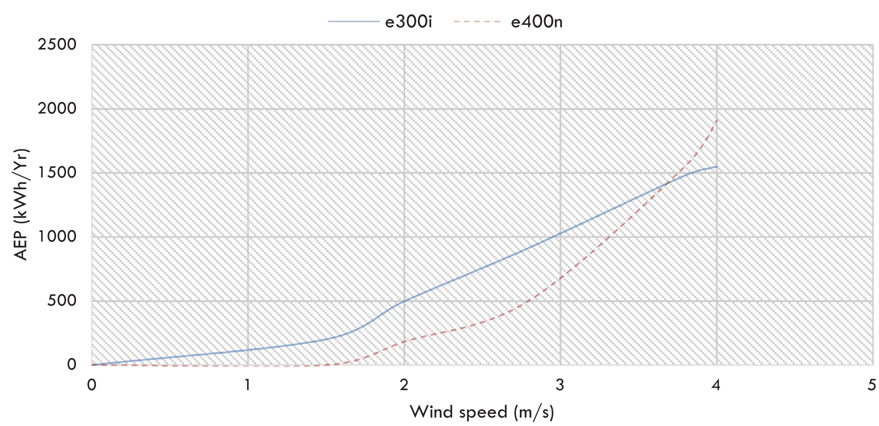

Fig. 21. Sensitivity of AEP to wind speed variations for e300i and e400n turbines in Polokwane.

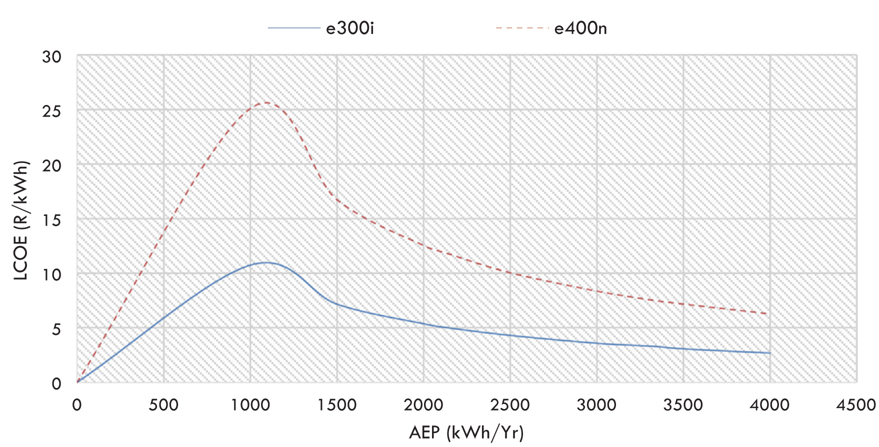

Fig. 22. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Cape Town.

financing costs, return on capital, etc. [31,45]. The result, which is expressed in cost per unit of energy output (e.g. R/kWh), has the interesting ability to create a comparison between different sources of generation [2]. Furthermore, according to Gross et al. [53], LCOE offers parameters for measuring the motivation for intervention in and informing policy.

The levelised cost for a wind energy system can be calculated as the ratio of the total annualised cost of the system to the annual electricity generated, and is expressed by [31]:

$$LCOE = \frac{(IC \times CRF) + O\,\&\,M}{Annual\ Energy\ Production} \tag{13}$$

where IC is the Initial Cost, $O\,\&\,M$ is the annual operations and maintenance cost, and CRF is the Capital Recovery Factor for the system. The Capital Recovery Factor for any given discount rate i and turbine lifetime n is expressed as [31]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n \quad -1} \tag{14}$$

The levelised costs for the e300i and e400n turbines in the different locations are presented in Table 8.

The analysis showed the LCOE of the two turbine models in all the locations are neither cost-competitive nor economically viable when compared with the electricity tariff offered by the national electricity

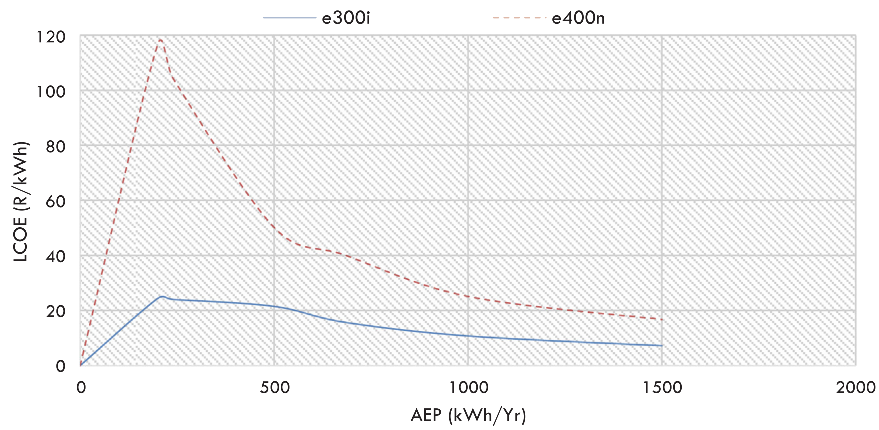

Fig. 23. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Oudtshoorn.

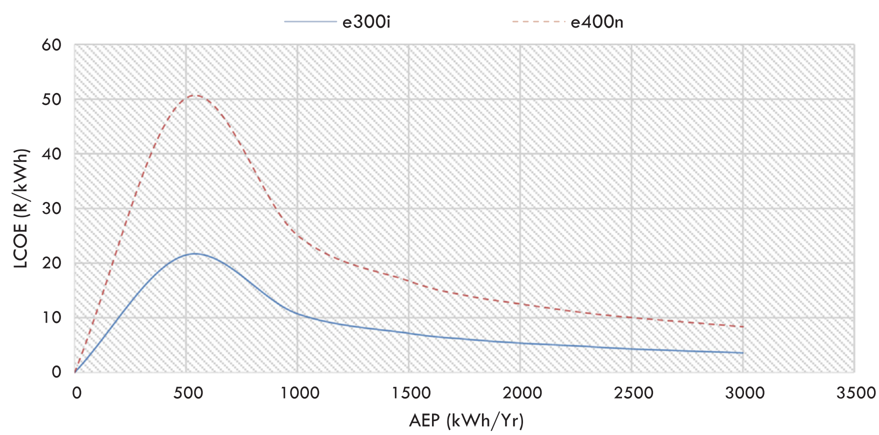

Fig. 24. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Worcester.

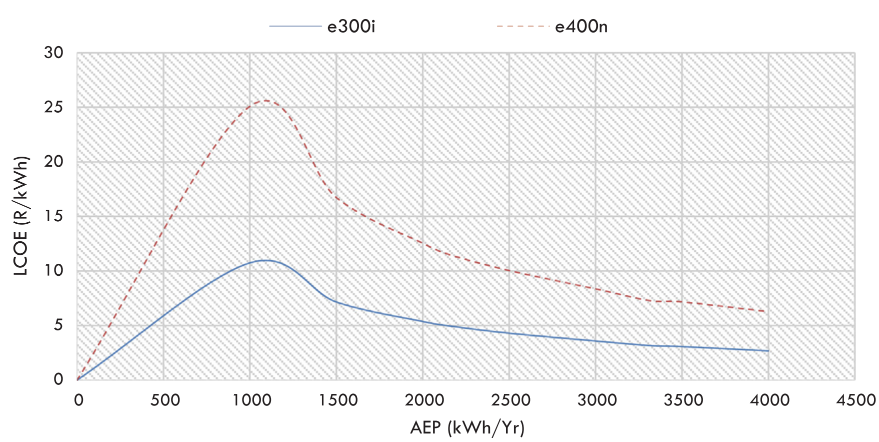

Fig. 25. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Port Elizabeth.

provider, Eskom. These uncompetitive high costs of electricity ranged between R4.95/kWh and R15.65/kWh for the e300i (1 kW) model, and R7.28/kWh and R104.21/kWh for the e400n (3.5 kW) model, as against the R1.53/kWh [47] of the conventional generation. The lowest costs were evident in Port Elizabeth, while the highest costs were found in Oudtshoorn, Bethlehem, Potchefstroom, Nelspruit, and Polokwane in the two categories of turbines. Cape Town has the lowest electricity costs in the Cape Peninsula region, De Aar in the Central region, and Johannesburg in the Northern region.

4.4. Sensitivity analysis

The development of a wind energy system involves a number of uncertain parameters. In this study, the behaviours of the Annual Energy Productions of the SWTs were tested by varying the wind speed parameters of the systems. Furthermore, the sensitivities of the techno-economic model (LCOE) of the SWTs were tested by varying the Annual Energy Production parameter around its base case values. The results of the sensitivity analysis for the different locations considered are described in Figs. 10–21 (wind speed against AEP) and Figs. 22–33 (AEP against LCOE) below. The deviation of the actual values of these parameters does affect the techno-economic performance of the SWTs.

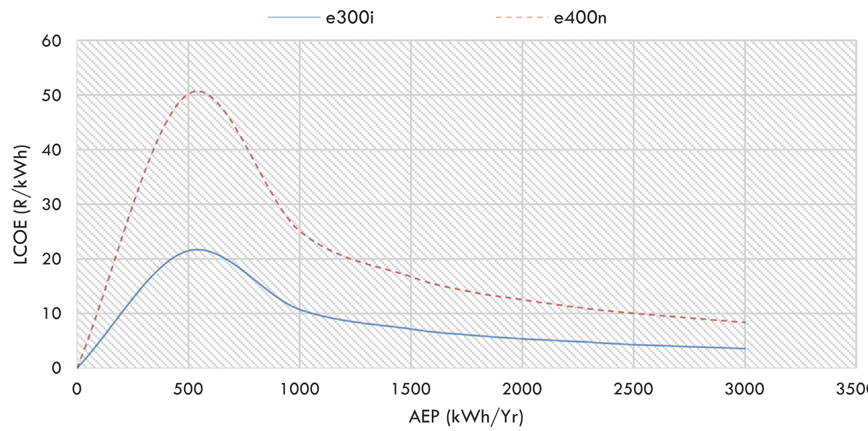

Fig. 26. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Grahamstown.

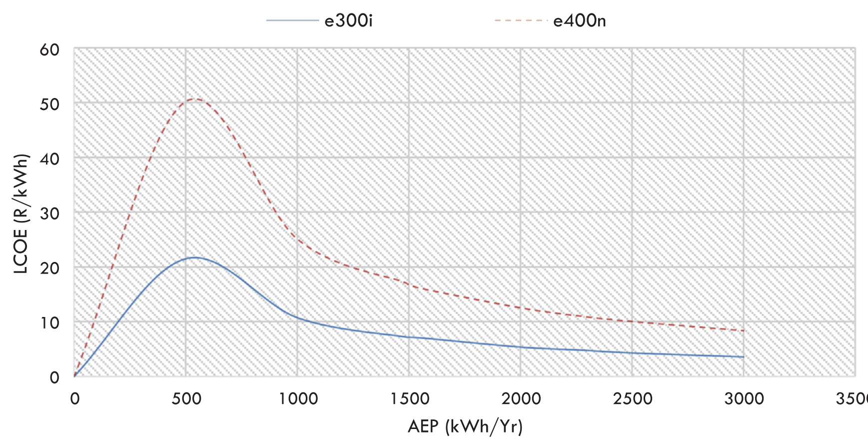

Fig. 27. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Richards Bay.

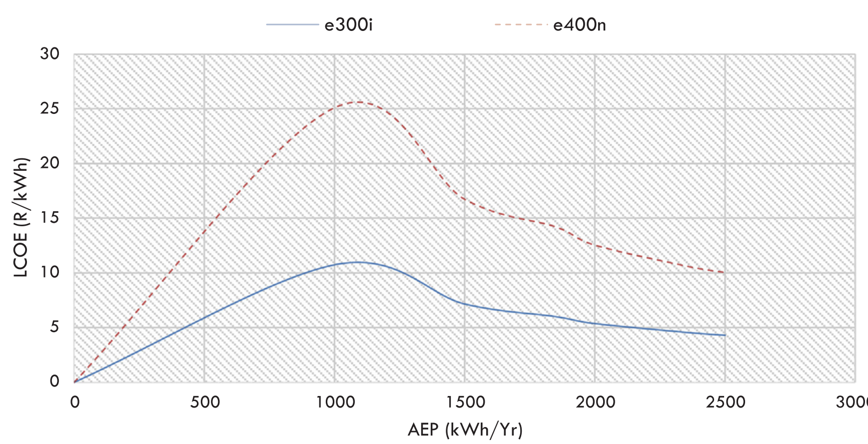

Fig. 28. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in De Aar.

5. Conclusion

This study contributes to research and establishes new findings regarding the energy and economic performance parameters of small-scale wind systems under different weather conditions in the country.

- The wind speed characteristics and distribution showed that Port Elizabeth is the windiest site, while Oudtshoorn, Potchefstroom, and Nelspruit represented the least windy sites. This study confirmed that the South Eastern and Cape Peninsula regions have higher probabilities of observing high wind speed in South Africa than any other regions.
- In the energy yield analysis for all the sites considered, Port Elizabeth produced the highest annual energy output for the two selected turbine models. The least AEPs were in Oudtshoorn, Potchefstroom, and Nelspruit.
- Importantly, with a monthly electricity demand below 50 kWh (600 kWh/year) by the majority of low-income households, and an average monthly consumption of 132 kWh (1 584 kWh/year) by households in South Africa, the installation of SWTs can meet the energy demand of a few households in some environments in the country.
- The SPPs for the e300i (1 kW) model are less than the useful life of the turbines in almost all the locations considered except

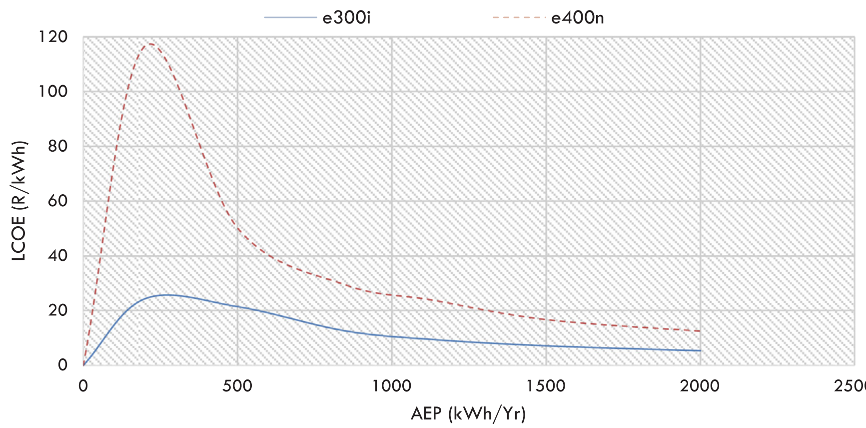

Fig. 29. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Bethlehem.

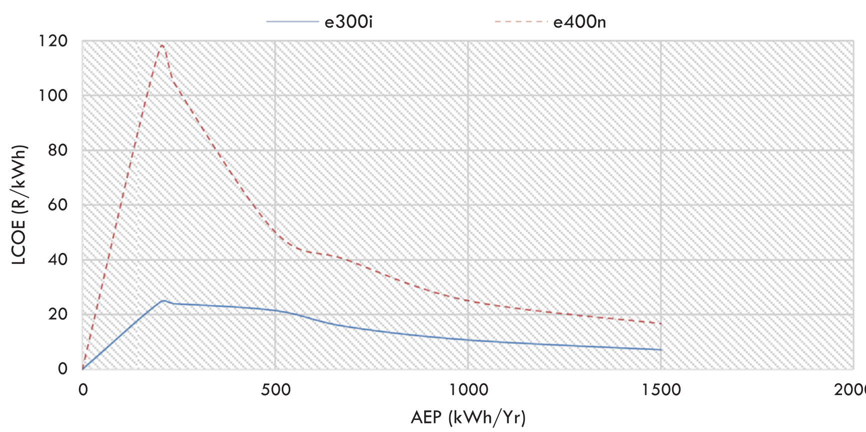

Fig. 30. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Potchefstroom.

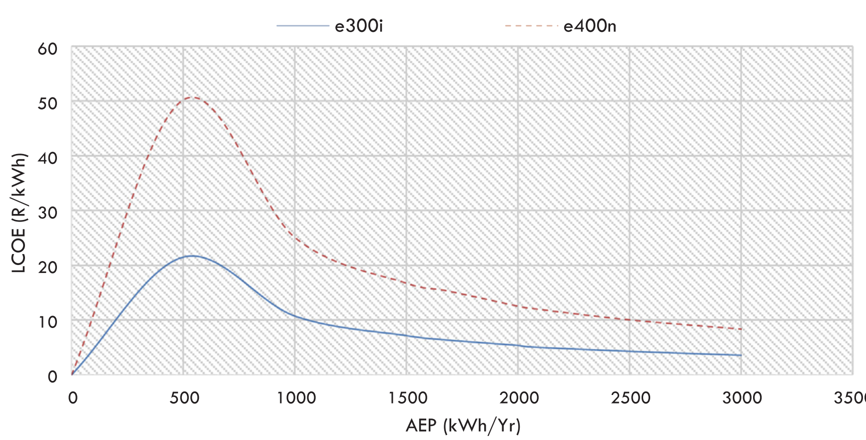

Fig. 31. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Johannesburg.

Oudtshoorn, Bethlehem, Potchefstroom, Nelspruit, and Polokwane. Only Cape Town and Port Elizabeth have SPPs that do not exceed the useful lifetime of the system for the e400n (3.5 kW).

- In the NPV analysis, the two turbine models evaluated have NPVs of less than zero in all the sites considered, thus, none of the turbines may be economically viable for investment in all the considered sites.
- For the Levelised Cost of Energy economic evaluation, the costs of electricity calculated for the two turbine models in all the sites considered are high and uncompetitive when compared with the average tariff of R 1.53/kWh offered by the national electricity provider, Eskom.
- The economic evaluation results revealed that SWTs are yet to be economically viable in South Africa under the present policies and assumptions considered.

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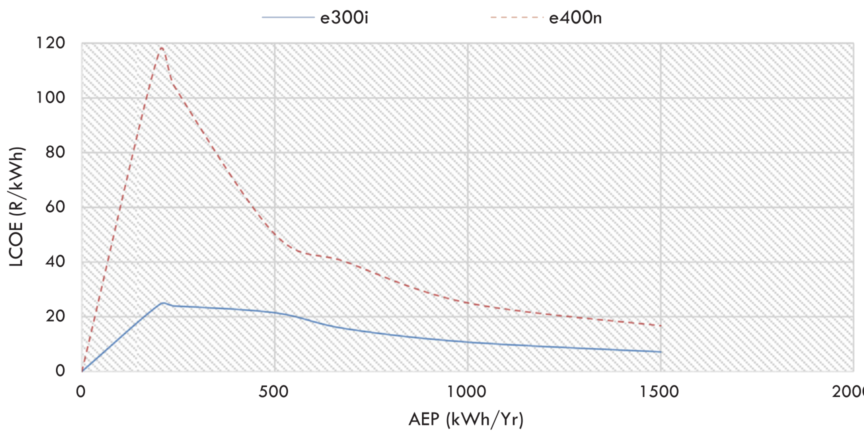

Fig. 32. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Nelspruit.

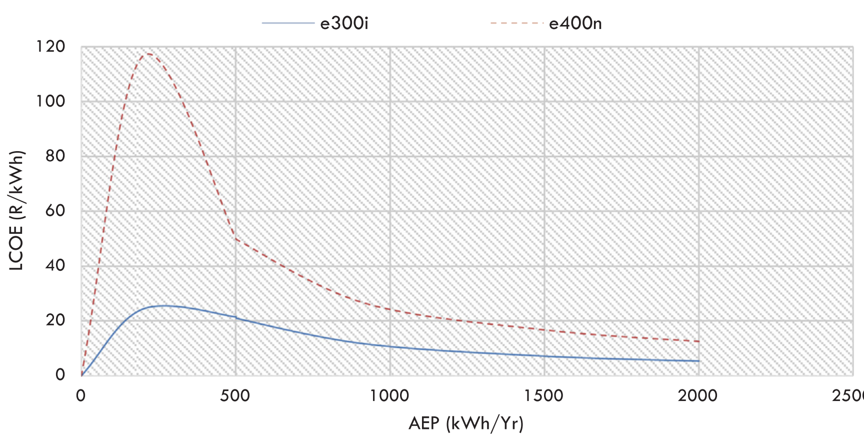

Fig. 33. Sensitivity of LCOE to AEP variations for e300i and e400n turbines in Polokwane.

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