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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