Renewable Energy 90 (2016) 377–385

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Empirical and numerical analysis of small wind turbine aerodynamic performance at a plateau terrain in Kenya

David Wafula Wekesa [a], [b], *, Cong Wang [a], Yingjie Wei [a]

[a] Institute of Dynamics and Control of Spacecrafts, School of Astronautics, Harbin Institute of Technology, Harbin City, PR China
[b] Department of Physics, Jomo Kenyatta University of Agriculture & Technology, Nairobi City, Kenya

ARTICLE INFO

Article history:
Received 28 February 2015
Received in revised form
3 November 2015
Accepted 1 January 2016
Available online 15 January 2016

Keywords:
Aerodynamic performance
SWT
CFD
WPD

ABSTRACT

Kenya's energy depends on fossil fuels and the country is yet to embrace alternative sources that are environmentally friendly. In this paper, empirical and computational approaches are presented to investigate aerodynamic performance of Small Wind Turbine (SWT) operation at arid rural Mwingi-Kitui plateau region, Kenya. We used empirical statistics to represent wind resource, and Computational Fluid Dynamics (CFD) to address SWT aerodynamic performance at the site. The numerical simulations, employing Transition Shear Stress Transport (SST) model and fully mesh resolved rotor, were performed and results obtained compared with empirical methods. From the Wind Power Density (WPD) values, 44.50–85.48 W/m^2 between turbine hub heights 20 and 60 m, the site corresponds to wind class ≈ 1; hence unsuitable for grid-connected power generation. In addition, the numerical findings give useful insights to SWT aerodynamic performance with respect to empirical approach at a plateau terrain wind regime.

1. Introduction

Energy remains the major resource to transform a developing country into a developed one [1–4]. Kenya is a developing country, with energy mainly derived from woody biomass (68%), Petroleum fuels (22%), and electricity (9%) [5]. These competing energy sources have impacted negatively on the environment. In addition, electricity, which is mainly hydro-power driven, is highly unreliable. This is attributable to persistent droughts with consequential drying of water reservoirs [5]. Despite the country's struggle to solve energy challenges, like establishing plants driven by geothermal and diesel generators, energy cost continued to rise in the last decade.

On average, National surveys have revealed that almost 90% of Kenyans rely on traditional fuels such as biomass, charcoal, and dung to meet their heating and cooking needs. Dependence on firewood in the rural areas as the main source of cooking fuel is on the rise, with more than 80% of households relying on firewood for cooking compared to 10% of urban households. Charcoal is the second most popular type of cooking fuel used by 13.3% of households, while Kerosene is the third and frequently utilized among 44.6% of urban dwellers [6].

To reverse the trend of over dependence on fossils fuels, as well as enhance access to cheap and reliable energy, there is need for the country to diversify its energy sources. In addition, new technologies to harness local resources should be embraced to generate energy. This will support economic development and promote self-sufficiency in energy needs with emphasis to the rural poor population [5]. Wind energy is the latest veritable alternative energy source that is renewable for power production over the last decade, and offers the potential for CO$_2$ emissions reduction in power generation [7–9]. For global CO$_2$ emissions reduction to be realised, power generation should strongly depend on utilizing renewable energy systems, especially in the developing countries.

However, effective use of wind energy requires precise wind energy resource assessment. Precise wind speed measurements plays an important role for estimating the wind energy potential of a target site. Generally, wind resource assessment includes [10–12]: onsite wind conditions measurement; correlations between onsite meteorological towers to fill in missing data; correlations between long-term weather stations and short-term onsite meteorological towers; analysis of the wind shear and its variations; modelling of the distribution of wind conditions, and

---

* Corresponding author. Institute of Dynamics and Control of Spacecrafts, School of Astronautics, Harbin Institute of Technology, Harbin City, PR China.
E-mail addresses: dwekesahit@gmail.com (D.W. Wekesa), alanwang@hit.edu.cn (C. Wang), weiyingjie@gmail.com (Y. Wei).

http://dx.doi.org/10.1016/j.renene.2016.01.004
0960-1481/© 2016 Elsevier Ltd. All rights reserved.

prediction of the available energy at the site.

In Kenya, there is need for prospective and utilization of wind energy resource as a solution to provision of sustainable, reliable and cost effective power to the rural areas and urban poor. One of the main challenge to exploitation of wind energy resource can be attributed to non-availability of the wind resource data in the rural areas where the bulk of the country's population (84%) resides [13]. Currently, the country has 34 national meteorological stations centred in national airports and airstrips in urban areas [14]. However, their data is gathered at meteorological height of 10 m and is intended for agro-meteorology and civil aviation and hence not specific for harnessing wind as a source of energy [5,14]. Thus, in order to supply the increasing demand for the production of electricity especially for remote application, SWTs have an effective role [15].

Based on the 6 years data collected from four meteorological stations in Hong Kong, He et al. [16] investigated a surface wind characteristics with different terrain conditions. Wind turbulent characteristics under different terrains were compared based on long-term field measurements. From the study in Ref. [16], wind characteristics which determine wind energy potential of a site, can be significantly affected by surrounding terrains or topographies. Therefore, different upwind terrain or topographical conditions may result in remarkably varied distributions of local wind resource and hence wind energy potential of a region. Similar observations have been made in related studies in Refs. [1,17–24].

Using empirical methods, Mukulo et al. [5] and Kamau et al. [25] have analysed the wind energy potential for Marsabit and Mwingi-Kitui plateau, respectively, both Eastern regions of Kenya. Despite the empirical methods being prone to many statistical errors, with limitation in both time and cost, the studies results are very useful to wind energy technology stakeholders [26]. However, unsteady phenomena in the plateau terrains due to SWT rotational aerodynamics cannot be investigated by classical tools, such as empirical and Blade Element Momentum (BEM) methods.

Therefore, in the present study, we seek to employ both empirical and CFD approaches to evaluate aerodynamic performance of SWT operation at a remote power-starved population in rural Kenya. The results presented in this paper show that turbine hub height elevation has a very predictable influence on SWT aerodynamic performance through its effect on air density and kinematic viscosity. In addition, the numerical results provides detailed understanding of CFD application and its added value in evaluating SWT aerodynamic performance with respect to empirical approach at a plateau terrain.

2. Methodology

2.1. Experimental techniques

Following the empirical study by Mukulo et al. [5], wind speed measurements were performed at a tower height level of 20 m, located at the Mwingi-Kitui plateau, Kenya. The plateau terrain site is geographically located at an altitude of 0517 m above sea level on latitude 1.00^0 S and longitude 38.01^0 E. Wind speed data were measured every 10 s and averaged at intervals of 10 min for storage in a data logger. The 10 min averaged wind speed data were further averaged over an hour and stored sequentially in a permanent memory for a period of 12 months. Furthermore, the wind speed at higher heights of 40 m, 60 m, 80 m, and 100 m could be calculated using the power law (Eq. (1)). The annual mean wind speeds for turbine hub heights were used as U_{mean} of fluctuating wind, while respective standard deviations (σ_s) averages as fluctuation amplitude U_{amp} to represent the wind characteristics of the site [27].

The wind profile power law is a relationship between the wind speeds at one height, and those at another. It is often used in wind power assessments where wind speed data at various heights must be adjusted to a standard height prior to use. The wind power law was used to convert the measured wind speed at 20 m elevation to higher heights as in the case of an empirical study in Ref. [5]. The power law is expressed as:

$$v_z = v_1 \left(\frac{z}{z_1}\right)^{\alpha}, \tag{1}$$

where v_z is the wind speed at height z and v_1 is the reference wind speed at the reference height z_1. The exponent α is an empirically derived coefficient that depends on such factors as surface roughness and atmospheric stability [28]. The value of the empirical exponent varies from less than 0.10 for very flat land, water or ice to more than 0.25 for heavily forested landscapes and typical value of 0.14 for low roughness surfaces [2]. The value of 0.20 for exponent has been chosen to describe the actual nature of ground cover at the site. The empirical power law exponent of 0.20 fits within the description of the American Wind Energy Association (AWEA) for a site with short grass, hedges and few trees which best describes the plateau terrain at the site [5].

2.1.1. Optical encoders

An optical encoder transducer was used to generate coded reading of measurement. Shaft encoders were used for measuring angular displacement and velocity. The anemometer and wind vane sensors in this study were developed using the incremental and absolute encoders, respectively, to generate digital signals. Advantages of digital transducers over analogue ones include high resolution, high accuracy, and relative ease of adaptation in digital control systems. Details of the experimental setup involving calibration of wind sensors have been discussed in previous wind assessment studies by the authors in Wekesa et al. [28,29].

2.1.2. Measuring wind speed and direction

The wind sensors were clamped on a horizontal metallic support masked on a strong metallic vertical stand 20 m above the surface. The wind sensors were separated well enough to avoid the flow disturbance due to the blowing wind. The signals from both anemometer and wind vane sensors were fed to CR 10 Campbell microcontroller-based data logger. Wind data was measured and stored in the Electrically Erasable Programmable Read-Only Memory (EEPROM). Reading of wind speed was done at interval of 3 times a day alongside conventional instruments at the meteorological station for comparison. The language used by the data logger is C which is a general-purpose programming language that can work on any Automatic Voltage Regulator (AVR) microcontrollers. Detailed description of the software design and high resolution data logging instrumentation system for wind speed and direction measurement can be found in Wekesa et al. [28,29]. The data logging system flow chart is as shown in Fig. 1.

2.1.3. Accuracy of measurements

A linear regression fit chart was used to test and establish a correlation between the wind speed data by Mukulo et al. [5] meteorological anemometer with calibrated mast-mounted optical anemometer. The results of the comparison between two anemometer measurements are displayed in the time series and scatter diagram shown in Fig. 2. The figure shows a very good correlation between the data obtained by Mukulo et al. [5] meteorological anemometer with those of the experimental mast-mounted optical anemometer. Therefore, Mukulo et al. [5]