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The solar energy assessment methods for Nigeria: The current status, the future directions and a neural time series method

Chigbogu Godwin Ozoegwu

Department of Mechanical Engineering, University of Nigeria, Nsukka, Nigeria

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ABSTRACT

By the virtue of her geography, demography and premature status of industrialization, Nigeria holds an immense promise to be the future hub of solar energy economy. Full assessment of Nigerian solar energy resource was thus imperative. The five decades of research efforts - on assessment and quantification of the solar energy resource - are extensively reviewed and the subsisting gaps highlighted. As a case study, a number of the Nigerian solar energy correlations, acclaimed for high accuracy and availability of fully-defined regressors, are re-calibrated and comparatively tested using recent data for Enugu metropolis sourced from the Nigerian Meteorological Agency (NIMET). An adaptation (Eq. (18b)) of an existing model performed best amongst the compared models. Results seemed to suggest that when data is available for a relatively short duration and when such data set is further degraded by issues of some months of missing data, it is better to use sunshine models and mixed-weather parameter models that include sunshine as one of the regressors. It is found that Nigerian solar assessment study suffers from very narrow application of artificial intelligence and time-series approaches. As a contribution towards bridging this gap, the first application of artificial neural networks in time series analysis of the solar energy is demonstrated. The neural time series is verified with One-way ANOVA to have a capacity to predict a current Nigerian solar energy value from the past values. Also, the capacity of neural time series for up to one-year forecast of solar energy of the studied locations is verified with One-way ANOVA. This is a point of superiority over the empirical models which already abound for Nigerian locations. This work could serve as a handy source of information to policymakers, scientists, engineers and technologists building solar technologies targeted at Nigeria.

1. Introduction

1.1. The future relevance of solar energy to Nigeria

Solar is the mother renewable energy (RE) resource with relative superiority over the other RE resources. The superiority is hinged on its universal availability (and fairly uniform endowment to all human-inhabited regions), its almost-zero environmental impact on utilization and its risk-free supply facilities (that is, free from natural disasters, human vandalism and local/international politics). For this reason, solar energy is normally accorded higher penetration levels than the other RE resources in the long-term RE targets of countries. It is thus not surprising that Scientists, Engineers, Technologists, Policymakers and Investors have paid a great deal of attention to its scientific understanding, quantification (theoretical, empirical and experimental), storage, utilization, trade and policy. As a result of the intense research and evolving policy landscape (which has improved cost of manufacture and operational efficiency of solar devices), the price of PV panels lowered from US$ 30/W about 30 years ago to below US$ 1/W in 2013 and the current global market for solar PV technologies is increasing at a rate of more than 35% yearly [1].

Nigeria is a country with demographics and 'geographics' that are profitable (economically and environmentally) for the adoption of renewable/sustainable energy and power technologies. According to the World Bank [2], Nigeria is the seventh most populated nation in the world after China, India, USA, Indonesia, Brazil and Pakistan. The population of Nigeria in the year 2006 was 140,431,790 and the population growth rate is 3.2 per annum [3]. Then, the population in 2015, 2020 and 2030 are respectively projected to be 186458724, 218263539 and 299073661. Current Nigeria's population growth favours declining *dependency ratio* because most growth lies with the people in the working ages; between ages 15 and 64 [4]. This means that Nigeria is set for demographic dividends if the Government can reduce the dependency arising from massive unemployment residing with the working ages. Nigeria has a landmass of 923,768 km^2 and an impressive solar energy resource in the range 3.5–7.5 $kWh/m^2/day$

E-mail addresses: chigbogug@yahoo.com, chigbogu.ozoegwu@unn.edu.ng.

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(145.83–312.50 Wm^{-2}) [5]. Thus, being sited near the equator, Nigeria's solar energy resource range is much more above than below the global average of 170 Wm^{-2} that is reported in [1]. With all its well-posed demographics and geographics, Nigeria is still at a very low level of industrialization. Therefore, building an industrialized Nigeria, that is driven by RE (especially solar), is a veritable way to secure - for the posterity - reduced greenhouse gas (GHG) emission and a massive trade hub for emission credits like the Certified Emissions Reductions (CERs) under the *Clean Development Mechanism* and the Emission Reduction Units (ERUs) under *Joint Implementation*. More on carbon market can be found [6].

1.2. Overview of solar energy assessment methods

Weather conditions, which are random in nature, are the predictors (regressors) of terrestrial solar radiation. Thus, in absence of exact theoretical models, terrestrial solar radiation are usually given as empirical or evolutionary functions of the random weather conditions. The empirical models are classified as sunshine-based, cloudiness-based, temperature-based and hybrid [7]. Hybrid models are based on combinations of sunshine, cloudiness, temperature and other meteorological parameters like precipitation, relative humidity, dew point temperature, soil temperature, evaporation and pressure. The sunshine-based models seem to be the most popular and are largely built on the pioneering Angstrom-Prescott model [8,9].

The Prescott's form of the model is linear as follows;

$$\frac{H}{H_0} = A_0 + A_1\frac{S}{S_o} \tag{1}$$

where H is the average global solar radiation, H_0 is the average extraterrestrial radiation on a horizontal surface, S is average sunshine hours and S_o is the average day length. Instead of H_0, the Angstrom form of the model uses the terrestrial radiation on a horizontal surface on a completely clear day. It is seen that the Angstrom-Prescott model is a linear polynomial. Glover and McCulloch [10] found that the slope A_1 of the Angstrom-Prescott model is effectively constant while the intercept is a function of latitude (l) and thus modified to $A_0\cos l$. A few other models do not agree with the constancy of A_1; for example, Zabara [11] correlated A_0 and A_1 with cubic polynomials in S/S_0, Gopinathan [12] considered them as bivariate linear polynomial functions in S/S_0 and Z (elevation) and Togrul et al. [13] correlated them with linear to quartic polynomials in S/S_0. Ogelman et al. [14] suggested extending the Angstrom-Prescott model to a polynomial of quadratic order and they calibrated/validated their quadratic model with a three-year data of Adana and Ankara, Turkey. Samuel [15] further extended the Angstrom-Prescott model to a polynomial of cubic order. Other general models that are built on the Angstrom-Prescott model include the linear-logarithmic model of Newland [16], the model of Louche et al. [17], the power models of Coppolino [18], the models of Elagib and Mansell [19], the exponential model of Almorox and Hontoria [13,20], the models of Jin et al. [21], the model of El-Metwally [22], the model of Rensheng et al. [23], the model of Sen [24], the linear exponential model of Bakirci [25]. In recognition of the part played by the elevation (Z) of a location in influencing the availability of solar radiation, the linear univariate Angstrom-Prescott model was extended by Sayigh [26] to linear bivariate model

$$\frac{H}{H_0} = A_0 + A_1\frac{S}{S_o} + A_2 h, \tag{2}$$

The temperature-based models are also quite popular. The bulk of available temperature-based models are built on the pioneering Hargreaves and Samani model [27]. The Hargreaves and Samani model is given as follows;

$$\frac{H}{H_0} = A_1(\Delta T)^{0.5} \tag{3}$$

where $\Delta T = T_{max} - T_{min}$, is the difference between the average daily maximum and the average daily minimum temperatures. The model has inspired other models [28–32]. Another pioneering temperature based approach is the exponential model of Bristow and Campbell [33] which is given as follows $H/H_0 = A_1(1 - \exp(-a_1\tau^{\alpha_1}))$,where τ is the daily range of air temperature given as $\Delta T = T_{max,i} - (T_{min,i} + T_{min,i+1})/2$, i refers to the current day and $i + 1$ refers to the next day. Bristow and Campbell [33] may have inspired other similar models [32,34,35]. Very recently, Hassan et al. [36] established seventeen new temperature-based models which are calibrated and validated for different locations around Egypt.

A number of the available cloudiness-based models were pioneered by Black [37]. The Black's quadratic model is

$$\frac{H}{H_0} = 0.803C{-}0.340C{-}0.458C^2 C{\le}0.8 \tag{4}$$

where C is mean total daytime cloud cover in octa. Subsequently, Badescu [38] proposed linear, quadratic and cubic polynomial models of H/H_0 in C and calibrated the models for estimation of monthly mean daily solar global irradiation over Romania. Another line of cloudiness-based models was pioneered by Paltridge and Proctor [39] for estimation of hourly beam and diffuse radiation. And, their contribution inspired few other works which includes [40,41]. The methods reviewed so far can be classified as empirical models which are based on maximum likelihood regression. More on the survey of empirical models for solar energy assessment can be found in many dedicated reviews. The most recent of them, which covered the historical and the key contributions, include [7,42,43].

According to Inman et al. [44], the empirical models ignore the short term stochastic characteristics and the dependence of observation sequences of solar radiation and, thus, are clearly deficient. This shortcoming justified application of stochastic regression methods for forecasting solar energy since the 1970s. Two approaches to stochastic regression are popular in solar energy forecasting; the AutoRegressive Moving Averages (ARMA) and the AutoRegressive Integrated Moving Averages (ARIMA). ARMA has been applied in the following representative works [45–53] while ARIMA has been applied in the following representative works [54–57].

Artificial intelligence (AI) techniques were inspired by the ability of life to adapt and evolve. AI has found application in modeling and forecasting of solar energy. Typical AI techniques that have been applied include artificial neural network (ANN) [58–70], fuzzy logic [71,72], adaptive neuro fuzzy inference system (ANFIS) [69,70,73,74], Support Vector Machines [69,70,72] and hybrid methods [75,76]. ANN with the multilayer layer perceptron (MLP) architecture is the most popular amongst the AI methods in solar modeling/forecasting [77]. ANNs run on the electrical analogy of biological neural process in the human brain to adaptively solve complex problems. A recent dedicated review of the application of artificial intelligence in solar radiation forecasting can be found [78].

Another class of models of solar energy are the independent models which estimate horizontal global solar radiation with astronomical parameters like day number. In such models, neither the target (the solar energy) nor the meteorological predictors are needed for estimation of solar energy. Bulut [79] proposed a sine wave model in day number for daily global solar radiation and calibrated the model for Istanbul using longterm measured data. Bulut and Büyükalaca [80] numerically validated the applicability of the sine wave model to other locations over Turkey. Kaplanis and Kaplani [81] proposed a cosine wave model in day number for daily global solar radiation and calibrated the model for six climatic zones of Greece. Li et al. [82] proposed an improved model, which is an additive combination of sine wave and cosine wave models, for estimating daily global solar radiation on a horizontal surface by the day of the year. A Gaussian day of the year model has been proposed and shown to be more accurate than the harmonic models [83]. Such studies, which are not quite many, have