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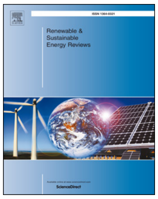

A qualitative review of empirical models for estimating diffuse solar radiation from experimental data in Africa

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A B S T R A C T

A good working knowledge of diffuse solar radiation (Hd) is of vital requirement for determining the gross primary productivity, net ecosystem, exchange of carbon dioxide, light use efficiency and changing colour of the sky. However, routine measurement of Hd is not available in most location across Africa. During the past 36 years in order to estimate Hd in the horizontal surface on hourly, daily and monthly mean basis, several empirical models have been developed for numerous location in Africa. As a result, numerous input parameters have been utilized and different functional forms applied. The empirical models so far utilized were classified into six main categories and presented based on the input parameters applied. The models were further re-classified into numerous main sub-classes (groups) and finally represented according to their developing year. In general, 301 empirical models, 58 functional forms and 28 groups were reported in literature for estimating Hd in Africa. The empirical and soft computing models developed within Africa and across the globe were examined in order to determine the best technique of estimation. The result revealed that soft computing models are more suitable for estimating Hd in Africa and other climatic zones across the globe. The authors equally identified and compared several photovoltaic (PV) stimulation tools and technologies often employed by PV system researchers for electrification purposes, as a direct application of the reviewed empirical models in this study. Thus, this review would provide energy researchers in terms of identifying the input parameters, functional forms, algorithms, PV stimulation tools and technologies which are widely applied up till now as well as recognizing their importance for estimating Hd and modelling PV systems respectively in numerous stations distributed in Africa and across the globe; so as to robust assess to smart energy that is eco-friendly in developed and developing countries.

1. Introduction

Since the beginning of 20th Century, Africa has been experiencing economic growth and energy consumption has increased by 45% [1]. However, the global energy systems are under-developed and incapable to meet the teaming populations' demand. Indeed, in spite of the fact that energy resources are more sufficient to meet domestic and industrial needs, access to modern energy services remains limited.

Africa not only has sufficient fossil fuels resources, but also abundant of renewable resources even if the resources are dispersed unevenly across the continent and are at differing stages of development, the regions is well-endowed with renewable energy types sufficient to meet the regional energy needs. In spite of the significant efforts made over the past years by researchers, government and non-governmental agencies to develop it, the renewable potential remain almost entirely untapped. Smart renewable energies (e.g. hydro, solar, wind, geothermal, and non-conventional solid biomass) still account for less than 2% of Sub-Saharan Africa energy mix. Amongst the renewable energies, hydropower potential is important, but remains untapped in the continent. As shown in Table 1, only 2% of the hydro potential in DR Congo, 5% in Ethiopia, and 12% in Congo have been developed so far [1].

Drawing from energy statistics in Africa, the inability of the continent to harness renewable energies to match or even exceed her conventional energy consumption and utilization can be one of the principal course of gloss poverty, under-development and spring up of fossils related diseases experienced in the region.

For instant, according to numerous researchers, adequate energy supply has been identified as a key prerequisite for economic, cultural and social development in complex societies [2–6]. In 1986, the United Nations General Assembly adopted its "Declaration on the Right to Development" [7], which established the right to development 'as an universal and inalienable right and an integral part of fundamental human rights', setting out of catalog of objectives for "equality of

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Nomenclature

PV	photovoltaics
SVM	support vector machine
WT	wavelet transform
CSP	concentrated solar power
RETSREEN	renewable energy technologies screen
SAM	system advisor model
HOMER	hybrid optimization model for electric renewables
ANN	artificial neural network
Io	hourly extraterrestrial solar radiation on the horizontal surface
C	monthly mean of the year
M	monthly mean of the year
a, b, c, d, e, f	regression constants
HB	hourly mean basis
DB	daily mean basis
MB	monthly mean daily basis
h	elevation in metres
Se	solar elevation in degrees
Tmin	monthly mean minimum temperature in °C
Tmax	monthly mean maximum temperature in °C
MBE	mean bias error
MPE	mean percentage error
RMSE	root mean square error
SSRE	sum of the square of relative error
MABE	mean absolute bias error
MAPE	mean absolute percentage error
NS	Nash Sutcliffe coefficient
U_{95}	uncertainty at 95%
IG	index of agreement
MAE	mean absolute error
GPI	global performance index
ANFIS	adaptive neural fuzzy inference system (ANFIS)
ARD	automatic relevance determination
ELM	extreme learning machines
GANN	generalized regression neural networks
RE	random forest
CANMET	energy diversification research laboratory
GHG	green house gases
Hd/Ho	diffuse coefficient
Hd/H	diffuse fraction
$kt = H/H_o$	monthly average clearness index (dimensionless)
H	global solar radiation on the horizontal surface
H_o	monthly extraterrestrial solar radiation on the horizontal surface
S_o	maximum sunshine duration (hrs)
n	number of days of the year
I_{SC}	solar constant in W/m^2
H_d	monthly mean diffuse solar radiation
T_{ave}	mean monthly maximum temperature (°C)
P	monthly mean atmospheric pressure at the site (hPa)
P_o	the standard atmospheric pressure at the sea level (1013 hPa)
S	monthly mean sunshine hours (h)
S/S_o	sunshine fraction (dimensionless)
T_d	monthly average dew point temperature
RH	monthly mean relative humidity (%)

Greek letters

ϕ	latitude (°)
δ	solar declination angle (°)
ω_s	sunset hour angle (°)
ω_1 and ω_2	the limit hour angle of an hour in which ω_2 is the larger in degrees
β	monthly mean atmospheric turbidity
θ	ratio of monthly mean minimum to maximum temperature

opportunity for all in their access to basic resources, education, health services, food, housing, employment and the fair distribution of income" [6]. Ultimately, energy, in its different forms, is necessary to drive all these goods and services linked to the achievement of human development target, playing a key role for overcoming poverty [6,8,9].

Several researchers have investigated the relation between the degree of development of a country and its energy use [4,10–21]. Some authors have found strong correlation between energy use and living standards at lower energy use levels ("developing countries"), and decoupling at higher levels ("developed countries"). Fig. 1 shows the relation between the per capita total primary energy demand and the human development index of a selected group of countries for the period 1995–2008. From the Fig. 1, it can be observed that while in highly developed countries variations in the use of energy fairly affect the level of development, in low and medium developing countries as well as in emerging economies (e.g. BRIIC countries: Brazil, Russia, India, Indonesia, China), changes in the use of energy translate into changes in the degree of development [6]. In the same order, human development index increases with the gross domestic product variation.

Table 1
Energy capacity and resources in Africa, 2015 [1].

	Africa	North Africa
	Capacity	
Crude oil refining capacity (bb1/ d)	3,739,500	1.991,100
Liquefaction capacity (LNG) (Mt/yr)	72	41
Installed hydroelectricity capacity (MW)	31,005	4907
Installed thermal electricity capacity (MW)	139,163	66,595
Installed electricity capacity from solar (MW)	2132	405
Installed geothermal electricity capacity (MW)	614	0
	Resources	
Crude oil NGL resources (mbl)	324,643	120,519
Natural gas resources (mcm)	83,275,000	45,170,000
Proved amount of coal in place (Mt)	122,572	91
Gross theoretical hydroelectricity resources (GW h)	3,855,300	150,000

However, the long-term knowledge of solar radiation at any particular locations on the face of earth is necessary for variety of areas such as agriculture, hydrological, ecological, solar energy applications and general robustness of the economy. Peers and researchers have proved that the abundant potential of solar energy can play an essential role to meet the ever-growing energy demand of the world at large [22–27]. Among different types of renewable resources, solar energy has attracted enormous attention of peers and researchers because not only it is sustainable, but also it is abundant, and as a key energy source for the future around the world with respect to the environmental issues associated with fossils as well as their limited reserves. Therefore, solar energy is the best substitute of fossils owing to the ever growing demand for energy globally. In fact, due to about 40 GW of solar photovoltaics (PV) capacity installed in 2014, the International Energy Agency [28] predicts that by 2050, photovoltaics (PV) as a renewable energy source (solar energy) may become one of the most promoting source of energy that will provide about 11% of global electricity production and would reduce 2.3 gigatonnes of CO_2 emission per year. As a result, more and more penetration of solar energy technologies to the world's energy sector is indeed appealing for supplying a notable part of electricity, heating, cooling, cooking, drying all types of things,