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Analysis of hybrid energy systems for application in southern Ghana

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A B S T R A C T

Due to advances in renewable energy technologies and increase in oil price, hybrid renewable energy systems are becoming increasingly attractive for power generation applications in remote areas. This paper presents an economic analysis of the feasibility of utilizing a hybrid energy system consisting of solar, wind and diesel generators for application in remote areas of southern Ghana using levelized cost of electricity (LCOE) and net present cost of the system. The annual daily average solar global radiation at the selected site is 5.4 kW h/m^2/day and the annual mean wind speed is 5.11 m/s. The National Renewable Energy Laboratory's Hybrid Optimization Model for Electric Renewable (HOMER) software was employed to carry out the present study. Both wind data and the actual load data have been used in the simulation model. It was found that a PV array of 80 kW, a 100 kW wind turbine, two generators with combined capacity of 100 kW, a 60 kW converter/inverter and a 60 Surrette 4KS25P battery produced a mix of 791.1 MW h of electricity annually. The cost of electricity for this hybrid system is found to be \$0.281/kW h. Sensitivity analysis on the effect of changes in wind speed, solar global radiation and diesel price on the optimal energy was investigated and the impact of solar PV price on the LCOE for a selected hybrid energy system was also presented.

1. Introduction

It is well known that access to energy is an essential pre-requisite for development of any kind: human development; economic development, and social development. In fact, access to electricity is fundamental in advancing the well-being of any society and promoting economic growth as well as employment opportunities for young people [1].

Like most countries in sub-Saharan Africa, access to electricity in Ghana is low compared to more advanced countries. The country's electricity supply is primarily from hydro and thermal power plants. It has a total installed electricity generation capacity of 2280 MW in 2012 [2]. This is made up of 1180 MW from hydro power (∼52%) and 1100 MW from thermal power (∼48%). In the same year (i.e., 2012) the electricity consumed was 9258 GW h, out of which 2931 GW h constituted residential use (∼32%). Unfortunately, there still remains close to 28% of households that do not have access to electricity in Ghana [3]. With its current per capita electricity consumption of only 357.5 kW h [3], Ghana is considered energy poor. To put that figure in perspective, South Africa has a per capita energy consumption of 4532 kW h [4]. Ghana's strategic goal is to dramatically increase its electricity generation from the 12,024 GW h in 2012 up to 32,915 GW h in 2020 [5].

A convergence of factors such as global decline in fossil fuel reserves, damaging effects of global warming, and rising energy demand due to increasing population are forcing a shift to low-carbon sources of energy. As a tropical country Ghana has abundant solar energy resources. However, until recently the country did not produce significant electricity from solar energy. In 2013, it completed a 2 MW solar power plant, which is the largest in mainland West Africa [6]. Although, a conservative estimate suggests that over 1000 km^2 of land area exists with moderate-to-excellent wind resource potential in Ghana [7], the country is not considered a player in the wind energy sector. In fact, it does not currently produce any significant amount of wind power. Nonetheless, there are plans to generate additional 150 MW from wind power and 14 MW from solar energy by 2015 [6].

The problem with solar and wind energy sources is that they are unpredictable and can be unreliable. A stand-alone solar energy system cannot provide electricity around the clock throughout the year if there are cloudy days when there is no sunlight. Similarly a stand-alone wind energy system may not produce usable energy for considerable portion of time during the year due to relatively high cut-in wind speed [8]. One way to remove or minimize the

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weaknesses of these renewable energy systems is through the use of hybrid energy systems, which employ two or more complementary sources of energy. For example, a diesel conventional generator can be combined with a wind energy system or a solar energy system or both. Feasibility, reliability and economic analyses conducted in a number of studies showed that hybrid power systems are more reliable and cheaper than single source energy systems [9–12]. In fact, a number of studies on renewable hybrid energy systems have been performed in different parts of the world. For example, a hybrid power system based on wind, diesel and battery was modelled by Nfah and Ngundam [13] for power supply to remote areas in Cameroon using 4 years wind data for validation. The results indicate that hybrid systems are a better approach to increase access to electricity in the remote areas of Cameroon without expensive grid extension. Later, a method for optimal design of small grid-connected hybrid energy systems consisting of solar and wind sources in Chile was reported by Caballero and Yanine [14]. The objective was to minimize the life cycle cost of the system without compromising reliability using simulation. The results indicate that the hybrid system minimizes the cost of electrical power and size of grid. Yanine et al. [15] also reported a technique for the control of grid-connected hybrid micro-generation systems without energy storage in Chile. Their theoretical framework based on homeostatic control principles was assessed via a simulation analysis. The results confirmed the study's hypothesis that sustainable energy systems are completely achievable. In addition, Ismail et al. [16] performed a techno-economic analysis and designed a hybrid system consisting of photovoltaic panels, a battery system and a diesel generator for a typical Malaysian village household. The results showed that the hybrid system developed was optimal. Furthermore, an economic feasibility analysis of investments in hybrid systems in different climatic zones of Tamil Nadu (India) based on net present cost was conducted by Kumar and Manoharan [17]. It was observed that government subsidies hold the key to attracting investments in renewable energy utilization in these zones because renewable energy systems are initially capital intensive in nature. More recently, Adaramola et al. [18] reported an assessment of the wind energy potential in the coastal regions of Ghana. However, there are no analyses of hybrid energy systems for Ghana in the open literature.

The objective of this article is to study an economic analysis of a hybrid energy system consisting of solar, wind and conventional diesel generators for application in rural areas of southern Ghana. It is believed that this information will broaden the scope of options available to policy makers and all stakeholders in the energy sector as the country seeks to make critical investments in energy.

2. Load and energy resources

The renewable resource data used in this study are for Adafoah in the Greater Accra region of Ghana. This site is located on latitude 5°47′N and longitude 0°38′W and at an elevation of about 2 m above sea level. The solar energy and wind energy resources at the selected site as well as the cost of diesel (to fuel the generator) and electrical loads are presented in this section.

2.1. Electrical load

The electricity consumed per capita in Ghana from 2001 to 2012 is presented in Fig. 1. The figure shows that there is general increase in annual electricity consumption per capita between 2007 (288.8 kW h/capita) and 2012 (357.5 kW h/capita). The amount of electricity consumed per day per capita in 2012 can be estimated as 0.9795 kW h. The average household size in Ghana

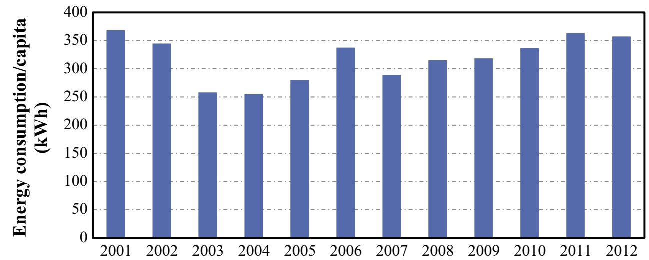

Fig. 1. Electricity consumption per capita in Ghana from 2001 to 2012 [3].

is 4.4 [19] and hence, the average electricity consumption per household can be determined as 4.31 kW h per day. For the analysis carried out in this study, each household is therefore assumed to require electrical load of 5 kW h/day.

Technical and economic assessment of a hybrid energy plant for a mini-grid system is simulated for a small community that consists of 400 households in this study. This community would require a power plant that can produce 2000 kW h of electricity per day with a peak load of about 83 kW. It is expected that there will be daily, monthly, seasonal variation in electricity consumption pattern in this community. To account for these variations, hourly and daily variations in the electrical loads are assumed to be 10%.

2.2. Solar radiation data

The solar radiation data for the selected location were obtained from the Ghana Energy Commission. The monthly daily averaged global solar radiation is presented in Fig. 2. As expected, monthly and seasonal variations in global solar radiation and the monthly energy output from solar energy conversion systems would vary from one month to another as well as from one season to another. The annual averaged daily global solar radiation is 5.41 kW h/m^2/day. The monthly clearness index, which is defined as the fraction of solar radiation at the top of the atmosphere that reaches a particular location on the earth surface varied between 0.495 (in August) and 0.586 (in October) with an annual average of 0.543. The clearness index provides information on the level of availability of solar radiation at the surface of the earth as well as changes in atmospheric conditions [20,21] and the weather condition at a site. Based on the range of values of the clearness index, the weather conditions in Adafoah can be classified as partly overcast. A range of values of global solar radiation are used to investigate the effect of changes in the solar radiation on the energy system

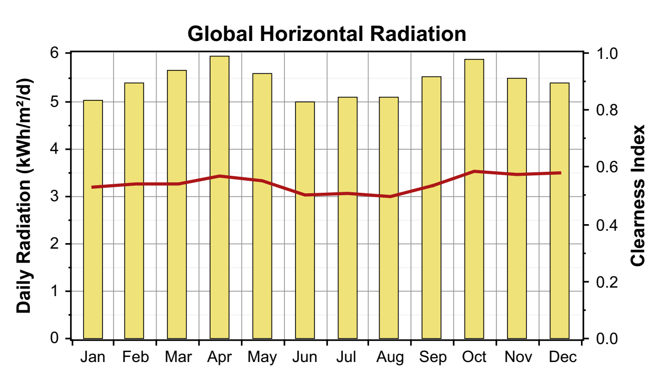

Fig. 2. Monthly daily averaged global solar radiation and clearness index for Adafoah [22].