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Feasibility study and energy conversion analysis of stand-alone hybrid renewable energy system

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ABSTRACT

There is a great interest in the development of renewable power technologies in Algeria, and more particularly hybrid concept. The present paper has investigated the performance of hybrid PV–Wind–Diesel–Battery configuration based on hourly measurements of Adrar climate (southern Algeria). Data of global solar radiation, ambient temperature and wind speed for a period of one year have been used. Firstly, the proposed hybrid system has been optimized by means of HOMER software. The optimization process has been carried out taking into account renewable resources potential and energy demand; while maximizing renewable electricity use and fuel saving are the purpose. In the second step, a mathematical model has been developed to ensure efficient energy management on the basis of various operation strategies. The analysis has shown that renewable energy system (PV–Wind) is able to supply about 70% of the demand. Wind power has ranked first with 43% of the annual total electricity production followed by diesel generator (with 31%) while the remaining fraction is being to PV panels. In this context, 69% of the fossil fuel can be saved when using the proposed hybrid configuration instead of the diesel generators that are currently installed in most remote regions in Algeria. Such a concept is very promising to meet the focus of renewable energy program announced in 2011.

1. Introduction

According to the International Energy Agency (IEA) the global energy consumption will increase by 37% to 2040 [1]. Furthermore, it has been expected a significant raise in the world electricity demand by 80% over the period 2012–2040 [1]. As a result, fossil fuel prices are projected to move forward in the next 20 years to reach $215/barrel in 2035 [2]. Nowadays, current energy policies are focusing on the concept of energy efficiency gains and low carbon fuels [1]. The penetration of low-carbon technologies in recent years and the enhancements in the efficiency of energy conversion systems have just slowdown the demand growth. It is worthy to note that the energy prices are strongly related to the turmoil in parts of the Middle East and North Africa (MENA). Therefore, the fluctuations in fossil fuels prices in the last decade together with the coming shortage and depletion have heighten concerns over future energy supply security. To this end, advanced energy policies, in many countries, have been based on the development of renewable and sustainable energy resources [3–7].

Following this approach, Algeria has announced, in March 2011, a very promising program to develop and expand the use of renewable energies in order to move from the fossil fuels era to the green energy era by 2030 [8]. Algeria is aimed through this program to be a pioneer in the production of electricity from solar photovoltaic and concentrating solar thermal power (CSP). Therefore, solar energy is the major focus of the Algerian renewable energy program and it is expected to supply about 37% of the national electricity need by 2030 [8].

Day than day, the use of both CSP and photovoltaic technologies around the world, particularly in Spain, Germany and the US, has shown a significant cost reduction through efficiency improvements and scaling up [9,10]. Whereas CSP options are more preferred at large scale applications, the photovoltaic has proven their performance at small scale and off-grid use in remote regions. The competitiveness at small scale applications, easy maintenance and installation, and lower energy cost in regions where electrical grid is not available are the most important advantages of solar photovoltaic technology [11].

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Nomenclature

A_c	PV panels receiving area
C_{bat}	capacity of the battery at time (t)
C_{batmax}	maximum capacity of the battery
DOD	deep of discharge
E_s	global solar irradiation
N_{mod}	number of PV modules
P_{cha}	power demand
P_f	full module factor
P_{ge}	power produced by the diesel generator
P_n	nominal power
P_{pvs}, P_{Ws}	electricity produced by PV and wind generators respectively
P_w	power produced by the wind turbine
T_C	cell temperature
V_c	cut-off wind speed
V_d	cut-in wind speed
$V(H)$	wind speed measured at the hub height
V_n	rated wind speed

Greek symbols

α	wind speed power law coefficient
η_{gen}	efficiency of PV generator
η_{mod}	efficiency of the PV module
η_{ref}	efficiency reference of PV generator
$\eta_{dc/ac}$	converter efficiency
η_{decha}	efficiency of battery discharging process

For the case of Algeria this latter advantage is of a particular interest because of its large area and lower density of population. For instance, the population density in the part of Sahara is less than one people per one square kilometer. Covering such a wide region with power grid is an expensive investment. Even, if it were be, the cost of electricity will be higher than actual average values. In such a context, photovoltaic panels would be the best solution for both population and government. In order to do so, the ministry of energy and mines has planned to install several solar photovoltaic projects with a total capacity of 800 MW by 2020 as a part of the program highlighted above. Moreover, other projects with an annual capacity of 200 MW are planned between 2021 and 2030 [8]. At this year, the electricity from PV should be competitive to the state-of-the-art power generation options. Recent studies have indicated that about a half in the cost reduction can be achieved though scaling up while the other half is the concern of R&D activities [9].

To this end, most recent R&D activities worldwide are focusing on the combination of solar photovoltaic with other sources of energy as it is the only alternative to overcome the issue of higher electricity cost up to now. Many countries are now showing an increasing interest in the development of hybrid solar PV power systems. Emerging Markets such as China, India, Indonesia, Tunisia, Algeria, and Saudi Arabia are excellent examples. For China, Li et al. [12] have investigated the feasibility of a hybrid PV–Wind with storage system to electrify a household in the region of Urumqi. When compared with only PV and only Wind power plants, the proposed configuration has shown a reduction in the total net present cost by about 9% and 11% respectively. Rehman et al. [13] have interested on the feasibility of a modifying a diesel generator into hybrid PV–wind–diesel plant in Rafha, Saudi Arabia. They have found that at a diesel price of 0.6 $/L the hybrid system become cost competitive. With regard to the efficiency and system reliability, Daud and Ismail [14] have designed and analyzed a PV–wind–diesel hybrid system for a family house in Palestine. Taking into account the actual energy resources map in Tunisia, Colantoni et al. [15] have developed a mathematical program to find the optimum dimension of hybrid PV–Wind power system. The authors have highlighted the potential of hybrid fossil renewable power plants to reduce fossil fuels import in Tunisia. Celik [16] have introduced a novel sizing methodology for hybrid Wind–PV system based on the monthly variation in the required size of the renewable energy converters. Kumar and Manoharan [17] have dealt with the feasibility of implanting hybrid PV–Diesel plant in Tamil Nadu, India. The economic analysis based on the net present cost, fuel consumption and renewable electricity fraction have indicated that the interior climatic zone is the most suitable for hybrid photovoltaic–wind power generation plants. Hafez and Bhattacharya [18] have analyzed the potential of installing hybrid PV–wind–diesel system in Johor Bahru, Malaysia. Akms et al. [19] and Hoque et al. [20] have been interested on the PV–wind–diesel generator hybrid power system under Bangladesh climates. The former investigated the performance of the hybrid system under Martin Island climatic conditions whereas the latter has considered a small village in Comilla. Lal and Raturi [21] have carried out an economic assessment of PV–Wind–Diesel hybrid power system for a remote location on the island of Vanua Levu.

In Algeria there is also an increasing interest on the development and investigation of hybrid photovoltaic systems, particularly after the introduction of the renewable energy program in 2011. Khelif et al. [22] have proposed the combination of PV panels with an existed diesel generator under operation in AFRA (southern Algeria). The authors have developed a mathematical program to predict the hourly performance of the proposed hybrid plant including voltage, current, fuel consumption, battery state of charge and electricity production. The model is also capable to perform an economic assessment to evaluate the profitability of the power system. They have concluded that the profitability of the proposed hybrid system is strongly related to fossil fuel cost and beyond a 0.34 €/l of fuel the project is cost-effective. Rezzouk and Mellit [23] have interested in the feasibility of powering a research unit (UDES) located in the north of Algeria with a hybrid PV–Diesel–battery system. HOMER program has been applied and various configurations as a function of PV penetration including a stand-alone diesel generator and stand-alone PV system were considered. The authors have found that a hybrid power plant with 25% electricity production from PV panels is the optimum configuration that ensures high stability with the lowest electricity cost. Himri et al. [24] have proposed the combination of an existing diesel generator with wind turbine to feed a remote region in the southern of Algeria. They have used HOMER program to evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction of the proposed Wind–Diesel power system. The simulation has shown that the hybrid system becomes feasible at a wind speed of 5.48 m/s with a fossil fuel price of 0.162 $/L or more. Aissou et al. [25] have experimentally and numerically studied the performance of small scale PV–Wind power system under coastal climate in Bejaia, Algeria. The hybrid plant consists of six photovoltaic panels of 175 W each connected in parallel, 1 kW wind turbine, batteries, inverter, and sensors for measurements. The hybrid plant control and power management have been evaluated. The design and modeling of the components have been carried out using Matlab/Simulink while the power control strategy is