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Performance assessment of hybrid power generation systems: Economic and environmental impacts

Abdullah Al-Sharafi [a,*], Bekir S. Yilbas [a,b], Ahmet Z. Sahin [a,b], T. Ayar [c]

[a] Mechanical Engineering Department, KFUPM, Dhahran 31261, Saudi Arabia
[b] Center of Research Excellence in Renewable Energy, Mechanical Engineering Department, KFUPM, Dhahran 31261, Saudi Arabia
[c] Industrial & Systems Engineering, KFUPM, Dhahran 31261, Saudi Arabia

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ABSTRACT

This article aims to introduce a double-step performance assessment tool for the hybrid power generation systems. As a case study, a hybrid system comprising PV array, wind-turbine, battery bank and diesel engine is incorporated in hourly based simulations to meet power demand of a residence unit at Dhahran area, Kingdom of Saudi Arabia. Different indicators related to economical and environmental performance assessments of the hybrid system have been considered. In the economic related assessment case, cost of electricity, energy excess percentage, and operating life cycle indicators have been considered and combined to develop the first overall performance index. Renewable contribution, renewable source availability and environmental impact indicators have been considered for the environmental assessment case and they are combined in the second performance index. For either economical or environmental cases, the optimum configuration of the system is achieved by maximizing the first and second overall performance indicators. This innovative optimization tools gives the designer the freedom to assign suitable weights associated with economical aspect, environmental impact, governmental regulations and social impact, for the first and second overall performance indicators, and combine them in the total performance index. The optimum system configuration is at the point where the total performance index is maximized.

1. Introduction

In recent decades, world population and human activities have grown dramatically which led to increase, energy consumption, industrial activities [1] while conveying social and economic related developments and improve human modern life style. In this regard, International Energy Agency (IEA) reported that world energy requirements would increase by 65% and CO_2 emissions by 70% between 1995 and 2020 [2]. The excessive dependency on the fossil fuels creates an adverse impact on the environment [3] since the energy sector still strongly depends on the low cost fossil fuels resources which increase the greenhouse effect and global warming phenomena. It will ultimately lead to significant changes in the Earth's climate [4]. Moreover, industrial wastes related to energy production represent major contribution to air pollution and environmental degradation. However, the optimal use of renewable energy will play important role to reduce this effect while meeting the increasing energy demand. Nowadays, renewable energy resources meet about 14% of the world energy requirements [5] and their contribution is expected to increase and reach up to 80% in 2100 [6]. In general, buildings consume about 40% of the total world annual energy production while harming the environment [7]. In this regard, Balaras et al. [8] studied the environmental impact of energy consumption due to heating of European apartment buildings. Based on the statistical data of 193 buildings in Europe, they demonstrated that 38% of these buildings had high annual heating requirements, about 30% of the buildings had higher airborne emissions, and 23% of these buildings had higher solid waste emissions comparing with the European averages. Biesiot and Noorman [9] studied the long-term environmental effects of residential house power requirements using energy consumption and CO_2 emissions indices. CO_2 emissions, Gross Domestic Product (GDP) growth and energy consumption were analyzed by Ramanathan [10]. Soytas et al. [11] investigated carbon emissions in the United States. They demonstrated that growth of income had no impact on carbon emissions, but energy use did, and the income growth is not a solution to environmental problems. Cristóbal-Monreal and López [12] inves-

* Corresponding author.
E-mail address: alsharafi@kfupm.edu.sa (A. Al-Sharafi).

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Nomenclature

C_B	the charge capacity of battery bank (W h)
COE	levelized cost of energy ($/kW h)
C_{inv}	cost of inverter
C_{run}	annual running (or operating) cost
C_{tot}	the total cost of the system ($)
C_{wind}	the sum of present value of capital and maintenance costs of the wind turbines
DOD	maximum depth of discharge of the battery
EI	Environmental impact
EXC	energy excess percentage (%)
i_{pv}	module optimum operating point current at arbitrary conditions (A)
i_{sc}	module short circuit current (A)
i_{mp}	module maximum power current (A)
I_T	total radiation incident on tilted plane (kW/m^2)
I_{st}	standard light intensity (1000 W/m^2)
LPS	loss of power supply (kW h)
$LPSP$	loss of power supply probability (%)
N	the lifetime of the hybrid system in years
N_c	total number of the hybrid system components
n_{batt}	number of batteries
n_{deisel}	number of hours that the diesel engine is used in the whole year
n_{pv}	number of PV modules
n_{solar}	number of hours that the solar radiation is available in the whole year
$n_{Total.}$	number of the hours in the whole year (8760)
n_w	number of wind turbines
n_{wind}	number of hours that the wind speed of the installation location is more than the cut in wind speed of the wind turbine (3 m/s) in the whole year
OLC	operating life cycle
P_T	the total energy generated by PV array and wind turbines (kW)
P_L	load demand at the time (t) (kW)
P_{pv}	the energy generated by the PV module (kW)
P_w	the output power of wind turbine at a local wind speed (kW)
RC	Renewable contribution
RSA	Renewable source availability
T_A	the ambient temperature at arbitrary conditions (K)
T_{st}	the standard temperature (298 K)
T_{cell}	the cell temperature (K)
ΔT	the deference between the cell temperature and the standard temperature (K)
V_{pv}	module optimum operating point voltage at arbitrary conditions (V)
V_{oc}	module open circuit voltage (V)
V_{mp}	module maximum power voltage (V)
ΔV	the difference between module optimum operating point voltage at arbitrary conditions and module maximum power voltage (V)
v	wind speed at hub height (z) (m/s)
v_o	wind speed at the reference height (z_o) (m/s)
v_c	cut-in wind speed of the wind turbine (m/s)
v_f	cut-off wind speed of the wind turbine (m/s)
v_1, v_2	intermediate wind speed levels used to improve the accuracy of curve fitting
WE	Wasted energy (kW h)

Greek symbols

α	the sum of the present value of the capital cost and maintenance of the PV modules ($)
α_o	module current temperature coefficient (A/K)
β_c	the summation of present value capital cost of the battery and the cost of replacements ($)
β_o	module voltage temperature coefficient (V/K)
γ	the ground surface friction coefficient
η_{inv}	the efficiency of inverter
η_{Batt}	the charging efficiency of battery bank

tigated the use of PV-battery-diesel system to supply electricity to mobile facilities where the weight as well as the cost of the system are important parameters. Their optimization was carried out taking into account three cases: minimization of the weight of the system, optimization of the cost, and optimization of both weight and cost. They concluded that, in the cases of more than 90 percent, photovoltaic (flexible crystalline silicon panels)-diesel-battery is the solution that minimizes the weight. Hydrogen production via using renewable energy recourses represent excellent alternative for better sustainability. In this regard, Ferrari et al. [13] used 1 MW of photovoltaic panels to produce the required electricity for the hydrogen production using 42 kW pressurized alkaline electrolyzer. Due to the variability of the solar radiation, they carried out a time-dependent hierarchical thermo-economic analysis to evaluate the optimal size of the system. Their findings revealed that use of PV panels is not an economically viable solution for the high investment costs and, therefore, they suggested that the system should be connected to the grid when the solar energy is not sufficient. Sayedin et al. [14] studied the impact of climate conditions on the optimal size and operating conditions of a photovol taic–electrolyzer system. Solar power generation is unpredictable due to the random nature of the solar radiation. In this regard, Mehrabankhomartash et al. [15] used Monte-Carlo simulation method to determine the optimum battery size of a PV-battery system used to meet the power requirements for a commercial building. Their results showed that a 196.8 kW battery system should be used to cover the load without outages.

On the other hand, many researchers studied integration of biomass materials in renewable energy hybrid systems and using the agricultural bio-waste materials for re-cycling and activated carbon production. In this regards, Yahya et al. [16] presented a wide range of activated carbon derived from agricultural waste materials. They showed that relatively inexpensive and locally available agricultural residues could be used for producing activated carbon for many applications. Feasibility study of using PV-wind-biomass-battery hybrid system to meet the electrical load demand of a small area was carried out by Singh et al. [17]. They introduced swarm based artificial bee colony (ABC) algorithm. They concluded that the hybrid energy system is reliable, economical and suitable source of electricity.

Solar and wind renewable energy resources have great potentials to meet power demands of buildings, however; to achieve high performance utilizing renewable energy resources, it is essential to have an efficient storage system which increases the cost of the power generated [18]. Furthermore, solar energy is not available at the nighttime hours and wind speed at such location is random and may be less than the cut in wind speed of such wind turbine at which it starts to produce electricity. An innovative idea to reduce the size of the storage system is to integrate solar and wind resources in one hybrid system via photovoltaic (PV) array