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Development of optimal integrated renewable energy model with battery storage for a remote Indian area

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ABSTRACT

Over the past few years, renewable energy has come to be seen as a possible solution to the energy problems of people. The present work focuses on optimal sizing of an integrated renewable energy system (IRES) considering locally available different renewable energy sources namely micro hydro, solar, wind, biomass and biogas with battery system for electrification of a remote area in Karnataka state in India. Genetic algorithm (GA) has been used to minimize the total net present cost (TNPC) and cost of energy (COE) of the developed IRES model considering the three decision variables-total active sunshine area occupied by the SPV modules, total swept area required to install wind mills and state of charge (SOC) of battery system. Scenario based results of optimal sizes, TNPC and COE have been obtained based on suitable device types and time schedule of biomass generator. Based on optimization results, three IRE scenarios are proposed for the study area. Of the three, scenario-S1 for zone 2 and zone 3. While, scenario-S2 for zone 1 and zone 4 are found to be most feasible for the study area. Further, optimal time schedule, resource combination and device type for all zones have also been determined.

1. Introduction

Rural electrification plays an important role in the growth of a nation and living standard of its citizens. Grid based electricity supply to remote regions has proved unfeasible due to challenges involved in connecting the grid to these areas [1,2]. Diesel generator based power supply proves costly due to high fuel prices and more importantly, they increase green-house emissions. Renewable energy resources are clean and may be good alternatives to conventional fuel for meeting the electrical load demand of remote rural areas. However, due to the random nature of renewable energy resources, it is preferable to use integrated renewable energy (IRE) systems to increase system reliability [3,4]. An IRE system utilizes two or more locally available renewable energy resources and has the potential to provide a cost effective solution to meet the variety of energy needs in off grid applications [5-7]. Renewable energy systems generally entail high capital costs, low operation and maintenance (O&M) costs and fuel costs, due to which an economic analysis required to determine the optimum cost and benefit ratio, to arrive at the least possible unit price of the system. In order to utilize the available renewable energy resources efficiently and economically, optimal models need to be developed. However, the modeling of an IRE system is a complicated task which requires the development of mathematical models for each component [8]. Such modeling requires optimal designing of system components to minimize the total annual cost of the IRE system. As an example for a typical case the optimum designing process includes estimation of the appropriate number of wind turbine, SPV panels and batteries so that the load demand is satisfied at minimum possible total net present cost [9]. Yang hongxing et al. [10] recommended an optimal model for designing hybrid system employing battery storage system. They considered five decision variables such as wind turbine number, wind turbine installation height and battery numbers in order to obtain the power supply for a telecommunications relay station. Koutroulis et al. [11] investigated optimal number and type of system components for 20-years using genetic algorithm. The objective was to minimize the total system cost subjected to the constraint that the load power with zero load rejection. Total system cost was compared with the system cost obtained through conventional optimization methods. Askarzadesh and Leandro dos [5] developed three grid independent hybrid renewable energy systems for electrification of a small load area in Kerman Iron. Optimal model of hybrid system was achieved based on the integer variables of system components such as total active

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Nomenclature

A_{SPV}	area of SPV (m^2)
A_{WTG}	swept area of wind turbine (m^2)
BGG	biogas generator
BMG	biomass generator
CN	runoff curve number for hydrological sail (CN = 40–58 for dense forest)
BS	battery system
COE	cost of energy ($/kWh)
Com	combination
C_b	initial capacity of battery system
CRF	capital recovery factor
CD	cow dung (ton/yr)
C_P	power co-efficient
C_{NPV}	net present capital cost
CS	converter system
DE	dump energy (%)
D	duration of unavailability of load (hour)
DOD	depth of discharge
E_{BGG}	annual energy output of BGG (kWh)
EENS	expected energy not supplied (kWh)
EIR	energy index ratio
E_{MHP}	annual energy output of MHP (kWh)
E_{BMG}	annual energy output of BMG (kWh)
E_{WTG}	annual energy output of WTG (kWh)
E_{SPV}	annual energy output of SPV (kWh)
E_{gen}	annual energy (kWh)
E_O	total energy demand (kWh)
FC_{NPV}	net present fuel cost ($/ton)
g	acceleration due to gravity (m/s^2)
h_{net}	net head (m)
It	solar radiation availability (W/m^2)
I	monthly rainfall (mm)
L	average annual power load (kW)
Lw	length of the watershed (m)
MHG	micro hydro generator
N_{SPV}	solar panels (Nos.)
N_{WTG}	wind turbine (Nos.)
N_{BS}	battery system (Nos.)
OM_{NPC}	net present O &M cost ($/yr)
Pr	rated output power of wind turbine (kW)
P_{SPV}	power output of SPV system (kW)
P_{MHG}	power output of MHG (kW)
P_{BGG}	power output of BGG (kW)
P_{WTG}	power output of WTG (kW)
P_{BMG}	power output of BMG (kW)
Q	discharge (m^3/s)
Qd	direct surface runoff depth (mm)
R_{NPV}	net present replacement cost
SPV	solar photovoltaic panel
S	maximum potential retention (mm)
S1, S2 and S3	three scenarios of IRE models
TS1 and TS2	time schedules of the biomass generator
TNPC	total net present cost ($)
UL	unmet load
Vr	rated speed of the wind turbine (m/s)
WTG	wind turbine generator
$	US Dollar
η_{MHP}	efficiency of micro hydro generator (%)
η_{BGG}	efficiency of biogas generator (%)
η_{BMG}	efficiency of biomass generator (%)
η_{SPV}	efficiency of SPV panel (%)
η_{WTG}	efficiency of wind turbine generator (%)
η_{inv}	efficiency of inverter system (%)
η_{RECT}	efficiency of rectifier system (%)
η_{BC}	battery charging efficiency (%)
η_{BD}	battery discharge efficiency (%)
σ	hourly self discharge rate
ρ_w	density of water (kg/m^3)
α_{BMG}	capital cost of BMG ($/kW)
α_{BGG}	capital cost of BGG ($/kW)
α_{MHG}	capital cost of MHG ($/kW)
α_{SPV}	capital cost of SPV ($/kW)
α_{WTG}	capital cost of WTG ($/kW)
α_{BS}	capital cost of battery system (per battery)
α_{CONV}	capital cost of bi-directional converter (per converter)
β_{BMG}	maintenance cost of BMG ($/yr)
β_{BGG}	maintenance cost of BGG ($/yr)
β_{MHG}	maintenance cost of MHG ($/yr)
β_{SPV}	maintenance cost of SPV ($/yr)
β_{WTG}	maintenance cost of WTG ($/yr)
β_{BS}	maintenance cost of BS ($/yr)
β_{CS}	maintenance cost of bi-directional converter ($/yr)
ρ_W	density of water (kg/m^3)
γ	interest rate (%)
μ	escalation rate (%)
λ_{AFC}	average bio-generators fuel price ($/ton)
τ	project life time

area panels, total swept area of the wind turbine blades and number of batteries using PSO based approach. They found that PV/WT/battery hybrid system was most cost effective and reliable for meeting the energy demand of the proposed area. Koutroulis et al. [12] proposed genetic algorithms based optimization function to minimize the sum of the capital and maintenance costs occurring during the desalination system's life period. Ramakumar et al. [7] developed a knowledge-based system design tool IRES-KB and reported scenarios based models for typical remote rural village in India. The objective of the study was to minimize the total capital cost at a pre-selected reliability level. Optimal sizes of energy storage systems have been found to fulfill the energy requirements at the desired reliability level. Subho and Sharma [13] proposed a particle swarm optimization based hybrid model with the cycle charging strategy for a remote area demand of 7 un-electrified villages of Dhauladevi block of Almora district, with an account of the available resources of solar, hydro, biomass and biogas energy, along with the addition of diesel generator. In Refs. [14], developed suitable hybrid energy model for the same area with different three energy management strategies of cycle charging, load following and peak shaving strategy. Minimum total net present cost and cost of energy was achieved through three different optimization techniques (genetic algorithm, particle swarm optimization and biogeography based techniques) with considered same strategy. They also found twelve different device type combination of hybrid system and compared, out of that 10th combination was found to be most feasible and suggested for the same study area. Ismail et al. [15] proposed a hybrid system comprises solar PV panel and battery system of for a small rural community. Based on the investigation, the system has been found extremely beneficial compared to utility grid. Rajanna and Saini [16] developed scenario based integrated renewable energy models with least net present cost and cost of