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Modeling of integrated renewable energy system for electrification of a remote area in India

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ABSTRACT

Over the years, renewable energy based power generation has proven to be a cost-effective solution in stand-alone applications in the regions where grid extension is difficult. The present study focused on the development of models for optimal sizing of integrated renewable energy (IRE) system to satisfy the energy needs in different load sectors of four different zones considered in Chamarajanagar district of Karnataka state in India. The objective of the study is to minimize the total cost of generation and cost of energy using genetic algorithm (GA) based approach. Considering optimization power factor (OPF) and expected energy not supplied (EENS), optimum system feasibility has been investigated. Based on the study, it has been found that IRES is able to provide a feasible solution between 1.0 and 0.8 OPF values. However, power deficit occurs at OPF values less than 0.8 and the proposed model becomes infeasible under such conditions. Customer interruption cost (CIC) and deficit energy (DE) for all zones were also computed to quantify the reliability of the systems.

1. Introduction

In a developing country like India, majority of the population resides in remote rural areas and number of small isolated communities in such areas live without access to electricity from the power grid [1]. Extension of power grid based supply to these remote regions is not cost-effective or feasible. Moreover, conventional solutions proved by diesel generators are costly due to high cost of fuel and maintenance and have drawbacks such as loud noise and more importantly, emissions of green-house gases. Renewable energy sources are clean and may prove to be good alternative solutions for supplying the required electrical load. Due to the uncertainty in the availability of renewable energy resources, it is preferable to use an integrated renewable energy (IRE) system to increase system reliability [2]. An IRE system utilizes two or more locally available renewable energy based systems and may be a cost effective solution to meet the energy demand of remote areas. Further, such IRE systems are non-polluting, reliable and reduce the total operating and maintenance cost [3]. In order to utilize the available renewable energy resources efficiently and economically, optimal models are required to be developed to meet the demand through these resources. However, the modeling of an IRE system is a very complex task which requires the development of mathematical models for each components [4].

The optimization of integrated renewable energy systems has been addressed in number of studies. Ramakumar et al. [5] developed a linear programming (LP) approach to design IRES model by utilizing various renewable energy resources. They minimized the total annual cost under the constraints of availability of power and energy requirements. Joshi et al. [6] proposed a decentralized energy planning for three villages in Nepal. The optimization aimed at minimizing cost function considering mix of energy resources and conversion devices. Akella et al. [7] formulated an optimal size of IRE system for Jaunpur block of Uttarakhand state of India. They used electric power delivery factor was used for optimization problem to calculate cost of energy from different energy resources contribution for the considered area. Ashok [8] developed a numerical iterative algorithm to optimal sizing of a PV-wind-micro-hydro hybrid system for the electrification of rural areas in Western Ghats (Kerala), India. Iniyan et al. [9] developed an optimal renewable energy model (OREM) for renewable energy allocation in India for the year 2020–21. They minimized the ratio of cost and efficiency. Ferrer et al. [10] used integer or binary variables to define for location and size of the equipment. Khatod et al. [11] developed systematic analytical approach to minimize the production cost of small autonomous power system. The study carried out on

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Nomenclature

A_{SPV}	area of SPV (m^2)
BGG	biogas generator
BMG	biomass gasifier system
COE	cost of energy (Rs/kWh)
CIC	customer interruption cost (Rs in thousands)
CN	curve number
CRF	capital recovery factor
Cumecs	cubic meter per second
D	duration in which load is not meet out (hour)
D_E	total energy demand (kWh)
DIE	deficit in energy (kWh)
E_{BGG}	annual energy output of biogas generator (kWh)
EENS	expected energy not supplied (kWh)
E_{MHP}	annual energy output of micro hydro generator (kWh)
E_{BMG}	annual energy output of biomass generator (kWh)
E_{WTG}	annual energy output of wind turbine generator (kWh)
E_{SPV}	annual energy output of solar photovoltaic system (kWh)
E_O	total energy production (kWh)
FC	fuel cost (Rs)
g	acceleration due to gravity (m/s^2)
OTC_G	optimal total cost of generation (Rs in thousands)
h_{net}	net head (m)
H_T	solar radiation availability (W/m^2)
IEAR	interruption energy assessment rate (Rs/kWh)
INR	Indian rupee
IR	interest rate (%)
k_{BGG}	annual capacity factor for BGG
k_{BMG}	annual capacity factor for BMG
k_{MHG}	annual capacity factor for MHP
k_{SPV}	annual capacity factor for SPV
k_{WTG}	annual capacity factor for WTG
L	average annual power load (kW)
Lw	length of the watershed (m)
LCE	levelized cost of energy (Rs/kWh)
MHG	micro hydro generator
N	life of the plant (yr)
O&M	operation and maintenance cost (Rs/kWh)
OPF	optimization power factor
Pi	capital cost (Rs)
P_{SPV}	power output of solar photovoltaic system (kW)
P_{MHP}	power output of micro hydro generator (kW)
P_{BGG}	power output of biogas generator (kW)
P_{BMG}	power output of biomass generator (kW)
P_{WTG}	power output of wind turbine generator (kW)
Q	discharge (m^3/s)
SPV	solar photovoltaic system
TC_G	total cost of generation
WTG	wind turbine generator
η_{MHG}	efficiency of micro hydro generator (%)
η_{BGG}	biogas conversion efficiency (%)
η_{BMG}	biomass conversion efficiency (%)
η_{SPV}	Conversion efficiency of SPV (%)
P	density of water (kg/m^3)
ρ_w	density of water (kg/m^3)

uncertainties associated with solar irradiance, wind speed, demand and outages of various generating units for the period of one year. Ramakumar et al. [12] developed a design tool IRES-KB based on the knowledge-based system and reported scenarios based models for typical remote rural village in India. They minimized the total capital cost for the proposed IRE system at a pre-selected reliability level. They also found optimal sizes of energy storage systems to fulfill the energy requirements at the desired reliability level. Koutroulis et al. [13] investigated optimal number and type of system components for 20-years using genetic algorithm. They minimized the total system cost subject to the constraint of the load power with zero load rejection. Also they compared the total system cost with conventional optimization methods.

Hakimi andTafreshi [14] developed a particle swarm optimization (PSO) based intelligent method applied to the problem of sizing in a hybrid power systems for residential area. They optimized the net present cost of all the systems. Fatemeh and Rihy [15] formulated optimized cost function to minimize the net present cost of hybrid generation system operation over 20 years under the economic and technical constraints. They computed reliability index from components failure, including wind turbine, PV array, battery and inverter failure using PSO algorithm. Deshmukh and Ramakumar [16] proposed two probabilistic models for wind electric conversion system. The first one was based on wind speed distribution while the other was on Markov approach model. They discussed the influence of the major parameters involved on the overall system reliability when operated in parallel with conventional utility grid. Maleki and Fathollah [17] used reliability concept to maximize the allowable loss of power supply probability (LPSP max) for the hybrid system. Also, they proposed cost effective hybrid system and system rank for different LPSP values (0%, 0.3% and 1%) and found the most cost effective hybrid system for the LPSP value of 5%. Amer et al. [18] proposed a hybrid renewable energy system to satisfy the load demand through searching algorithm for reducing the levelized cost of energy with a satisfactory range of the production. Alireza and Leandro [2] developed three grid independent hybrid renewable energy systems for electrification to a small load area in Kerman Iron. They found PV/WT/battery hybrid system is most cost effective and reliable for meeting the energy demand of the proposed area.

Venkat and Mccalley [38] presented scenario based national-wide transmission overlay planning over 40-years through NETPLAN co-optimization tools. They evaluated net benefits in terms of total investment and production cost system. Further, various end effect mitigation models were also used to simulate a 40-year long-term infrastructure planning problem at yearly time steps [39]. Trishna Das et al. [40] demonstrated the generic bulk energy storage dispatch model for production costing simulation and assess the economic viability of storage system under different system scenarios.

Further, levelized cost of energy and levelized unit electricity cost were considered as an economic sub model for the economic assessment of IRE systems [19–22]. Similarly loss of power supply probability, expected energy not supply, loss of load deficiency and loss of load expectation were considered as reliability sub models for the analysis of IRE system reliability [23–26].

Based on the literature review, it is found that, a few studies have been carried out to develop modeling of off-grid integrated renewable energy system by combining resources such as micro hydro, solar, wind, biomass and biogas. The models developed so far mainly focus on one or two resources such as solar and wind, and with battery system for meeting load demand of individual