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Techno-economic optimization based approach for energy management of a stand-alone integrated renewable energy system for remote areas of India

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ABSTRACT

In recent years, sustainability receives greater attention due to increasing demands and limited resources worldwide. The Indian state of Uttarakhand is rich in the availability of renewable energy resources such as solar, micro hydro, biomass, wind etc. Optimum utilization of these resources in stand-alone mode has been recognized as an economical and efficient option compared to grid extension for electrification of remotely located rural households. This paper presents a combined techno-economic optimization and energy management of a stand-alone solar-micro hydro-biomass-wind based IRES (Integrated Renewable Energy System) to meet the electrical energy demand of cluster of village hamlets of Uttarakhand state. A load shifting based DSM (demand side management) strategy has been suggested in the paper for energy management of the considered IRES. Further, optimization results without and with DSM strategy have been presented and compared. Finally, a sensitivity analysis has also been performed to evaluate the impact of different parameters on the considered system.

1. Introduction

Energy has been universally recognized as one of the most important parameters for economic growth and human development. Globally, power sectors mostly depend on conventional energy resources (coal, oil, gas etc.) for its electricity requirements. However, the use of conventional energy resources leads to environmental and social problems such as global warming, acid rain, health problems to human beings etc. Renewable energy resources (solar, wind, biomass, micro hydro etc.) offer enormous economic, environmental and social benefits. The utilization of renewable energy can provide a sustainable access to electricity to users in rural areas for the crop processing, irrigation, food preservation, cooling and small scale industries [1–11].

Kanzumba Kusakana [12] modeled and simulated hybrid energy system comprised of hydrokinetic turbine, photovoltaic panels, wind turbine, diesel generator and battery for possible energy access in rural areas of South Africa. Also, various feasible configurations of hybrid energy system were presented and compared in the paper based on NPC (net present cost) and COE (cost of energy). Paliwal et al. [13] determined reliability constrained optimal resource mix for an autonomous hybrid power system consists of diesel generator, photovoltaic, wind and battery storage. They optimized seven considered configurations of hybrid system using PSO (Particle Swarm Optimization) to fulfill techno-socio-economic criterion for a place located in Jaisalmer, Rajasthan, India. Ismail et al. [14] proposed an optimal design of a PV/micro turbine/battery based hybrid system using genetic algorithm for rural communities of Palestine. They considered different types of batteries, PV modules and micro turbines available in market. Finally, they minimized the COE of production of different combinations of hybrid system for zero LLP (loss of load probability).

Most of the previous works were focused on electrification of a small area using locally available energy sources [15–18]. Clustering of villages has not been considered by the researchers. Further, little works have been reported in literature that considered energy management of integrated renewable energy system for rural areas [19–25].

The present paper is focused on the combined techno-economic analysis and energy management of an IRES (Integrated Renewable Energy System) for remote rural areas of Indian state of Uttarakhand. A load shifting based DSM (demand side management) strategy has been suggested in the paper. Further, techno-economic

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Nomenclature

A	swept area of wind turbine rotor (m^2)
B	binary variable for shiftable loads
C	cost of system ($)
CFL	Compact Fluorescent Lamp
CRF	capital recovery factor
CV	calorific value of biomass (kcal/kg)
E	energy (kWh)
f	inflation rate
G	solar radiation incident on PV array (kW/m^2)
H	head available for power generation in MHP system (m)
LCOE	levelized cost of energy ($ per kWh)
m	number of shiftable loads at any hour
MAWS	mean annual wind speed (m/s)
MHP	Micro Hydro Power
n	lifetime (yr)
N	number of component
NPC	net present cost ($)
P	power (kW)
Q	discharge availability in water streams (m^3/s)
r	interest rate (%)
RT	range of time interval
S	salvage value of component ($)
SPV	solar photovoltaic
V	wind speed (m/s)
Y	rated capacity (kW)

Greek letters

η	efficiency
ρ	density (kg/m^3)

Subscripts

a	air
a,cap	annualized capital
a,fuel	annualized fuel
AL	average load
a,maint	annualized maintenance
ann,tot	total annualized
a,rep	annualized replacement
Batt	battery
BMGS	biomass gasifier system
CHG	charging
cs	capacity shortage
D	demand
DCHG	discharging
INV	Inverter
l	type of shiftable load
MHPS	micro hydro power system
net	net value
nom	nominal
PEL	permanent load
PRL	priority load
proj	project
PV	photovoltaic array
REC	rectifier
SL	shiftable load
SPVS	solar photovoltaic system
STC	standard test conditions
w	water
WES	wind energy system
WT	wind turbine
BM	biomass

optimization of the considered IRES without and with DSM strategy has been carried out. Finally, a sensitivity analysis has also been conducted that allows detecting to which parameters the considered IRES is more sensitive.

2. Methodology adopted

Methodology adopted for the present work includes identification of study area, demand assessment of various energy consumption sectors, resources assessment, mathematical modeling, problem formulation, DSM strategy and optimization. Important steps of methodology are discussed as:

2.1. Step I — identification of study area

A cluster of 12 numbers of un-electrified village hamlets of Dewal block of Uttarakhand state (India) has been considered as the study area. The total population of the study area is 774 with the total households of 189 [26]. This area has a latitude of 30°8′ N and longitude of 79°37′ E and is located at the height of 1611 m from the mean sea level. Location of the study area on map is shown in Fig. 1 and general information of study area is discussed in Table 1.

2.2. Step II — demand assessment

The electrical energy demand of the study area has been classified as domestic, commercial, agricultural and community. Domestic sector includes electricity for CFL (Compact Fluorescent Lamp), fan, TV and radio for each HH (household). Community sector incorporate fan and lighting for hospitals, schools, community hall etc. Agricultural loads include water pumps and crop thrashing machines and commercial loads consist of shops and flourmill.

Rating and number of appliances required in different energy consumption sectors as discussed in Table 2. Hourly electrical energy demand of the study area without DSM strategy has been worked out and given in Table 3. The shiftable loads (water pump, crop threshing machine, flourmill, water heater) and street lights considered in the study are high rating appliances and operated for short duration. This causes the sudden changes in load profile of the area. An attempt has been made to verify the predicted load profile through primary data collected from the local people.

2.3. Step III — resource assessment

The study area is rich in renewable energy resources such as biomass (pine needles, firewood) and water streams. In Dewal block, ‘Ghes’ stream is identified for power generation as this stream has perennial discharge of around 150 l/s. The net head of 20 m has been estimated at this site. Firewood and pine needles are the major sources of biomass in the study area and estimated as 32 tons/yr [27]. The mean annual wind speed and annual average daily solar radiation of study area have been estimated as 5.11 m/s and 5.37 kWh/m^2/day respectively [28]. Availability of renewable energy resources in the study area have been discussed in Table 4.