EVOLVING OPTIMAL INTEGRATED RENEWABLE ENERGY SYSTEM MODEL FOR STAND-ALONE APPLICATIONS

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY
in
ALTERNATE HYDRO ENERGY CENTRE

by
ANURAG CHAUHAN

ALTERNATE HYDRO ENERGY CENTRE
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247667 (INDIA)
DECEMBER, 2015

ABSTRACT

In the current energy scenario, small scale power generation at the end user facility has received considerable attention for use in remote and rural areas because of high cost and complexity associated with the grid extension. Therefore, the development of suitable stand-alone systems using locally available energy resources has become a preferred option in order to meet the energy demand. With increased emphasis on eco-friendly technologies and high fuel cost associated with conventional energy generation, the use of renewable energy resources such as small hydro, biomass, solar photovoltaic (SPV) and wind energy are being explored.

Renewable energy (RE) resources are highly stochastic and site-specific in nature. Therefore, single technology based scheme such as stand-alone solar photovoltaic system, stand-alone windmill based system or stand-alone Micro Hydro Power (MHP) system may fail to supply energy to rural areas with high reliability. However, integrated utilization of different renewable energy resources may overcome the drawbacks of single technology based system and helps in increasing power reliability with the reduction of system cost and amount of energy storage.

In Integrated Renewable Energy System (IRES), energy demand of a remote rural area, far away from the utility grid, matches with the potential of locally available renewable energy resources. In IRES, resources are utilized in appropriate and cost effective manner based on the resource availability and energy demand of the area. Therefore, IRES offers energy conservation and high energy efficiency resulting from the combination of renewable energy resources.

Based on the extensive literature review carried out, it is observed that most of the studies were focused on solar/battery, wind/battery and solar/wind/battery based integrated system. However, solar/wind/battery based integrated system along with Micro Hydro Power/biomass/biogas systems is still quite limited in literature. Further, in most of the studies, electrical energy demand of rural area is normally kept fixed for year round application during size optimization of IRES. The seasonal variations in electrical energy demand were not accounted in many studies. The possible combinations of different manufacturer specified sizes of system components available in market were not

considered in most of the studies. The demand side management (DSM) during size optimization of IRES has also not been considered in many studies.

Keep this in view, the present study was planned with the following objectives:

(i) To identify and consider an un-electrified area having sufficient resources of renewable energy.

(ii) To estimate the potential of available renewable energy resources and estimate the seasonally varying demand of various energy consumption sectors of the selected area.

(iii) To consider different resource scenarios of IRES for the study area in order to select a suitable resource scenario to meet electrical and cooking energy demands of the study area at minimum cost for specified value of power reliability index.

(iv) To consider different possible combinations of manufacturer specified sizes of system components and suggest the best combination that meets the energy demands of the study area at minimum cost for different values of power reliability.

(v) To perform a sensitivity analysis in order to investigate the impact of different sensitive parameters on the costs of considered system.

(vi) To suggest demand side management strategy based on energy consumption scheduling of appliances for the considered IRES.

In order to fulfill the above mentioned objectives, the present study has been carried out for a selected remote area. In Uttarakhand state of India, most of the rural households have no access of electricity due to uneconomical gird extension in remote hilly terrain and dense forest. Energy access in remote rural areas can help in improving agricultural condition, per capita income, poverty level, education, health conditions and living standard of the nearby population.

Keeping this in view, a cluster of 48 numbers of un-electrified village hamlets of Chamoli district of Uttarakhand state of India has been selected as the study area based on the different selection criterion. The selected village hamlets are rich in the availability of renewable energy resources such as MHP, biomass, solar and wind energy. Accordingly, the present study proposes a stand-alone Integrated Renewable Energy System for the fulfillment of electrical and cooking energy demands of the study area.

The proposed system is designed to integrate MHP system, biogas digester system, biomass gasifier system (crop residue and forest foliage biomass based), solar photovoltaic system and wind energy conversion system along with battery bank storage system. In the study area, biogas generated from cattle dung is proposed to be utilized to meet cooking energy demands of the rural households first and thereafter, the surplus biogas available is used for the electricity production while other renewable energy resources are directly used for electricity production.

An extensive field survey was conducted for collecting the information regarding the availability of biomass, water flow rate (discharge), solar radiation and wind speed data through site visits. It has been observed that the potential of MHP resource in the study area is found maximum (328800 kWh/y) followed by biomass (135608 kWh/y), solar energy (1969 kWh/m^2/y) and wind energy (1349 kWh/m^2/y). Based on the availability of dung in the study area, a sufficient amount of biogas of 401500 m^3 per year is estimated to be generated that may be utilized for cooking and electricity production.

Out of the total biogas, 265516 m^3 biogas per year is proposed to be utilized for cooking while the surplus biogas of 135984 m^3 per year will be utilized for electricity generation in the selected area. Further, electrical energy demand of cluster of village hamlets has been estimated by carrying out a primary survey. The electrical energy demand of the study area has been classified as domestic, commercial, agricultural and community. The electricity consumption of 424544 kWh/y of domestic sector is found to be highest among all the considered sectors followed by community sector as 218561 kWh/y, commercial sector as 43558 kWh/y and agricultural sector as 14600 kWh/y.

A year is divided into two seasons of six months each based on the energy requirements and energy consumption pattern. Accordingly, an hourly electrical energy demand is proposed for the study area whose daily load varies as per the seasonal variation.

The objective of the present study is to develop an optimal Integrated Renewable Energy System model in stand-alone mode through optimal sizing of system components. As system operation strategy plays a vital role in optimal sizing of IRES, it is therefore, an optimal system operation strategy has been developed considering several factors such as electrical energy demand, energy generation, resource allocation, operating limits of energy generating systems, storage limits of battery bank and specified value of reliability.

Among different resources available in the study area, MHP and biogas resources have availability constraints, therefore, the only alternative of meeting the remaining demand can be based on incorporating biomass gasifier, wind and solar energy along with battery bank storage system. Therefore, four different resource scenarios are considered under the present study as given below:

- Resource scenario 1: MHP-biogas-solar-battery based IRES
- Resource scenario 2: MHP-biogas-wind-solar-battery based IRES
- Resource scenario 3: MHP-biogas-biomass-solar-battery based IRES
- Resource scenario 4: MHP-biogas-biomass-wind-solar-battery based IRES

The considered resource scenarios of IRES have been optimized using improved harmony search (IHS) algorithm in MATLAB. The model developed was used to calculate the levelized cost of energy for reliability value of 0% LPSP. It is observed that the system considering resource scenario 4 (MHP-biogas-biomass-wind-solar-battery based IRES) is found to be the most reliable and cost effective option among all the considered resource scenarios. Also, this resource scenario requires the minimum battery storage among different resource scenarios to achieve the power reliability of 0% LPSP.

Further, based on the manufacturer specified sizes of system components available in market, a total of 24 possible combinations of system components were considered during size optimization of MHP-biogas-biomass-wind-solar-battery based IRES. The considered combinations have been investigated to select the best combination that meets the energy demand of study area at minimum net present cost (NPC) for different values of power reliability by considering 0%, 5% and 10% LPSP cases.

Sensitivity analysis of MHP-biogas-biomass-wind-solar-battery based IRES has been performed for 0%, 5% and 10% LPSP for different sensitive parameters such as electrical energy demand, wind turbine cost, battery cost, discount rate, biomass price and part load operation of biogas generator. Based on the analysis carried out, the most sensitive parameter of the system has been determined.

As discussed above, an optimal model of IRES has been developed through optimal sizing of system components for an estimated demand. However, day ahead forecasted electrical energy demand was not optimized which results into the high net present cost of the system along with the large size of battery bank storage system. Therefore, using integer linear programming (ILP), a demand side management strategy based on energy consumption scheduling of appliances has also been considered. The considered DSM strategy was modeled in order to minimize the peak hourly energy consumption of the study area through the consumption scheduling of appliances.

In order to investigate, the MHP-biogas-biomass-wind-solar-battery based IRES with DSM strategy has also been studied and optimized for 0%, 5% and 10% LPSP cases. Further, optimization results of IRES with DSM strategy have been compared with the results of system without DSM strategy. It has been observed that significant amount of savings in system sizes and costs are obtained with DSM strategy compared to system without DSM. For 0% LPSP, a saving of INR 2.39 million in total NPC has been obtained with DSM strategy. It has also been observed that savings of INR 0.27 per kWh in LCOE, 70.2 kWh in battery bank storage, 1.17 kW_p in PV array size and 5 kW in converter size are obtained with DSM strategy in comparison of the system without DSM.

Based on the study carried out, the optimum size of IRES with DSM strategy has been recommended for the study area which comprises a 50 kW MHP system, 50 kW biogas system, 40 kW biomass gasifier system, 12 numbers of 4.2 kW rated small wind turbine, 17 numbers of 235 W_p rated PV module, 89 numbers of 150 Ah rated battery and 50 kW converter for reliability value of 0% LPSP. The total NPC of this configuration is found to be as INR43.60097 million at the estimated LCOE of INR 4.86 per kWh for a total land use of 21472 m^2.

Summarizing, an optimal Integrated Renewable Energy System model consisting of MHP, biogas, biomass, wind and solar energy along with battery bank storage system has been developed in order to meet electrical and cooking energy demands of cluster of village hamlets considered in Uttarakhand state of India. The results obtained under the present study may be useful for the development of IRES in stand-alone mode for the electrification of other similar remote rural areas.