Integrated renewable energy systems for off grid rural electrification of remote area

Renewable Energy 35 (2010) 1342–1349

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Technical Note

Integrated renewable energy systems for off grid rural electrification of remote area

A.B. Kanase-Patil*, R.P. Saini, M.P. Sharma

Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand 247667, India

ARTICLE INFO

Article history:
Received 27 April 2009
Accepted 7 October 2009
Available online 11 November 2009

Keywords:
Integrated renewable energy system
Optimization
Reliability index
Cost of energy
Off grid electrification

ABSTRACT

The off grid electrification by utilizing Integrated Renewable Energy System (IRES) is proposed to satisfy the electrical and cooking needs of the seven-uneletrified villages in the Almora district of Uttarakhand state, India. Four different scenarios are considered during modeling and optimization of IRES to ensure reliability parameters such as energy index ratio (EIR) and expected energy not supplied (EENS). The optimum system reliability, total system cost and cost of energy (COE) have also been worked out by introducing the customer interruption cost (CIC). The four different renewable energy scenarios have been compared for the considered study area using the LINGO software version 10. The fourth renewable energy scenario accounting 44.99% micro hydropower (MHP), 30.07% biomass, 5.19% biogas and 4.16% solar energy along with the additional resources of wind (1.27%) and energy plantation (12.33%) has been found to be the best among the different options considered. Furthermore, the optimal reliability for the fourth IRES system has been found to be 0.95 EIR at the optimized cost of Rs 19.44 lacs with estimated COE of Rs 3.36 per kWh. The COE obtained using LINGO software and HOMER software has also been compared and briefly discussed for all the four scenarios. In order to verify feasibility and cost of system for different biomass fuel prices, a sensitivity analysis has also been carried out and it has been found that the fourth scenario is more sustainable than the other considered options.

1. Introduction

A large proportion of the world's population lives in remote rural areas that are geographically isolated and sparsely populated. Such areas have very low power demand and are not connected to the grid. In a developing country like India, the majority of the population lives in remote rural areas with no utility grid and this seems to be the main obstacle to overall development. Electricity is one of the cleanest energy transfer option and is therefore the basis for the development of an area irrespective of the source of power. In recent years, from an environmental point of view, the renewable energy resources are being looked at as unlimited, inexhaustible, environment friendly and sustainable sources. Direct and indirect benefits of the electricity generation by renewable sources in rural areas include irrigation, food preservation, crop processing, cooling and small-scale industries which help in improving the living standard of the people. The availability of renewable energy sources is highly variable and site specific. The different areas have different types of energy sources available for electrification. The problem of variability of the output from these resources could be partially overcome by installing individual large renewable power plant or adding energy storage and reconversion facilities or developing integrated renewable energy system (IRES). The latter options have been adopted all over the world as the best options for energizing remote rural areas by electricity in decentralized mode.

The study area under consideration is located in Ranikhet reserve forest range of the Almora district of most populated and highly fertile Kumaon region of Uttarakhand state, India. The seven unelectrified villages are selected from this hilly region. The hilly terrain and dense forest are the obstacles in the extension of utility grid and could only be energized in decentralized mode using renewable energy sources. This paper presents the different possible renewable energy scenarios and suggests the best scenario on the basis of higher reliability and minimum cost of energy (COE) criteria.

2. Literature review

The concept of Integrated Renewable Energy Systems (IRES) was first proposed by Ramakumar [1–5] who evaluated the techno-economic aspects of a small-scale decentralized IRES for existing renewable energy sources in the rural areas of developing countries. These studies were carried out on the basis of the diverse

* Corresponding author. Tel.: +91 9927004300.
E-mail address: amarbkanase@yahoo.co.in (A.B. Kanase-Patil).

0960-1481/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2009.10.005

energy demands like cooking, irrigation, small-scale industries and electricity using *Cascaded* and *Tandem* approaches. Ahmed and Cohen [6] found that Integrated Renewable Energy Planning (IREP) requires consideration of utility systems like supply side, demand side, transmission and distribution. A knowledge-based approach was suggested by Ramakumar et al. [7,8] to minimize the capital cost using the concept of Loss of Power Supply Probability (LPSP). Gavanidou and Bakirtzis [9] used a trade off/risk method to compute the optimal sizes of solar photovoltaic (SPV) array and battery to minimize capital investment as well as for the minimum Loss of Load Probability (LOLP) requirement. Ramanathan and Ganesh [10] used seven energy sources to provide lighting in households using an integrated goal programming (GP) - Analytic Hierarchy Process (AHP) model. Ramakumar et al. [11,12] further employed a Linear Programming (LP) approach to design IRES, which involved the identification of various resources required for sizing of the devices. The objective functions of the optimization were to minimize the total annual cost per year subject to energy constraints. An Optimum Renewable Energy Model (OREM) was proposed by Iniyan et al. [13,14] for the effective utilization of renewable energy sources for lighting, cooking, pumping, heating, cooling and transportation in India for the period 2020–2021. A mathematical model was developed by Ramakumar and Chiradeja [15] for renewable energy system with distribution system models and power flow calculations. It was found that introduction of diesel generator can improve the system voltage profile and reduce the losses in electrical transmission line. Nakata et al. [16] used hybrid optimization modeling for integrating renewable energy systems to supply electricity and heat in rural Japan.

A hybrid energy system using different system components was developed by Ashok [17] to find an optimal combination of components for a typical remote village of Western Ghats in Kerala state of India. The optimization model was solved using non-linear constrained optimization techniques (Quasi-Newton algorithm) to get the combination of optimum sizes of components on the basis of minimum total life cycle cost. Katti and Khedkar [18] presented a decision support technique to optimize generation capacity of wind only, SPV only and integrated-SPV-wind power systems for stand-alone application using weather based model and a simple numerical algorithm. Fernandez et al. [19] used the optimal mix of renewable and conventional resources to fulfill the energy needs like lighting, cooking and space heating of a rural area of Kanvashram, situated in Pauri Garhwal district of Uttarakhand state, India. Akella et al. [20] formulated and optimized IRES model for Jaunpur block of Uttarakhand state, India. Electric Power Delivery Factor (EPDF) was used for the optimization of the system consisting of micro hydropower (MHP), biomass, solar and wind energy resources. It was found that the optimized IRES could provide feasible solution having EPDF range from 1.0 to 0.75. A deficit of EPDF less than 0.75 is the indication of a non-feasible model. Diaf et al. [21] developed an optimum sizing model with a new concept to supply wind power via uninterrupted power supply to Hybrid Photovoltaic/Wind System (HPWS). This model consists of submodels of system components, technical submodel based on LPSP and economical submodel based on Levelised Cost of Energy (LCE). Lagorse et al. [22] applied a new concept to supply electricity using a fuel cell in combination with SPV/battery stand-alone system throughout the year. They validated the proposed model with different optimization techniques such as genetic algorithm and simplex algorithm and obtained the optimal solution. Kaldellis [23] formulated a methodology to maximize SPV contribution and minimize the cost of electricity generation along with the best suitable storage devices available to the south- east Mediterranean Sea islands. The results indicated that the proposed system is more cost effective and reliable than the existing thermal power stations.

In view of the above literature review, it is revealed that very little work is available on the supply demand models and the main focus has been on energizing rural areas but not the individual village/cluster of villages. Further, no attempts have been made to extend the application of IRES to supply electricity to a community cold storage for processing the perishable vegetables and fruits apart from meeting power needs for domestic purposes. The present paper deals with the optimization of different options available in the study area considering the reliability worth and COE. The effect of sensitive prices of biomass fuel has been also discussed herein.

3. Methodology

3.1. Study area

Only 5.27% of the total villages are electrified in the hilly state of Uttarakhand, perhaps due to their remoteness and their location in dense forests. A cluster of seven unelectrified villages are selected from Ranikhet reserved forest range of Almora district for the present study. These villages located near to each other. These have a total of 267 households with a total population of 1437. The majority of the population is illiterate and agriculture is the only source of income. Fig. 1 shows the geographical location of the study area on the map. The study area has a latitude 29^0 38'' 21' N and longitude 79^0 29'' 56' E and is at a height of 1576 meters from mean sea level. The general information of the study area is given in Table 1 [24]. The extension of grid to these areas is not economically feasible and Uttarakhand Renewable Energy Development Agency (UREDA), a state nodal agency, is planning to electrify such villages by renewable energy resources such as MHP, biomass, solar and wind energy available in all the villages of the study area [25].

3.2. Resource assessment

In order to assess the potential of renewable energy resources, an extensive survey was conducted and information regarding the availability of biomass, insolation, hydrological and wind speed data were collected. The potential assessment has been carried out as per the methodology adopted by Mani and Rangarajan [26]. The data indicates that MHP resource is the maximum (293040 kWh/yr) followed by biomass including crop residues and forest foliage (198556 kWh/yr), solar energy (1837 kWh/m^2/yr) and wind potential (1270 kWh/m^2/yr). The small capacity (1 kW to 6 kW) MHP systems are proposed to be installed in the study area. Out of total 28 MHP systems, only 5 remain functional throughout the year and the other MHP systems are seasonal. The biomass gasifier requirement on daily basis varies from 6 to 8 h per day. A 40 kW rating biomass gasifier system is proposed to be used to generate energy from available resource throughout the year. The five-peak sun hours with 1 kW/m^2 daily irradiance observed and 1 kW SPV system is proposed for each village. The wind flow for given area is very low (2–15 m/s) and the small capacity wind turbines (3 kW) can be proposed as stand-alone system for electricity generation.

The villages have large number of domestic animals whose dung is available for biogas production and based on the quantity of dung available, a potential of 2,24,007 m^3 of biogas per year may be available. The 1,78,332 m^3/yr of biogas is proposed to be used to meet all cooking needs of the villages and the balance is proposed to be used to produce electricity with a potential of 34,256 kWh/yr. The details of the potential assessment of energy resources are given in Table 2, which indicates that the total potential of available renewable energy resource is about 5,38,715 kWh/yr. The unit COE as calculated using the standard procedures [27,28] is given in Table 3.

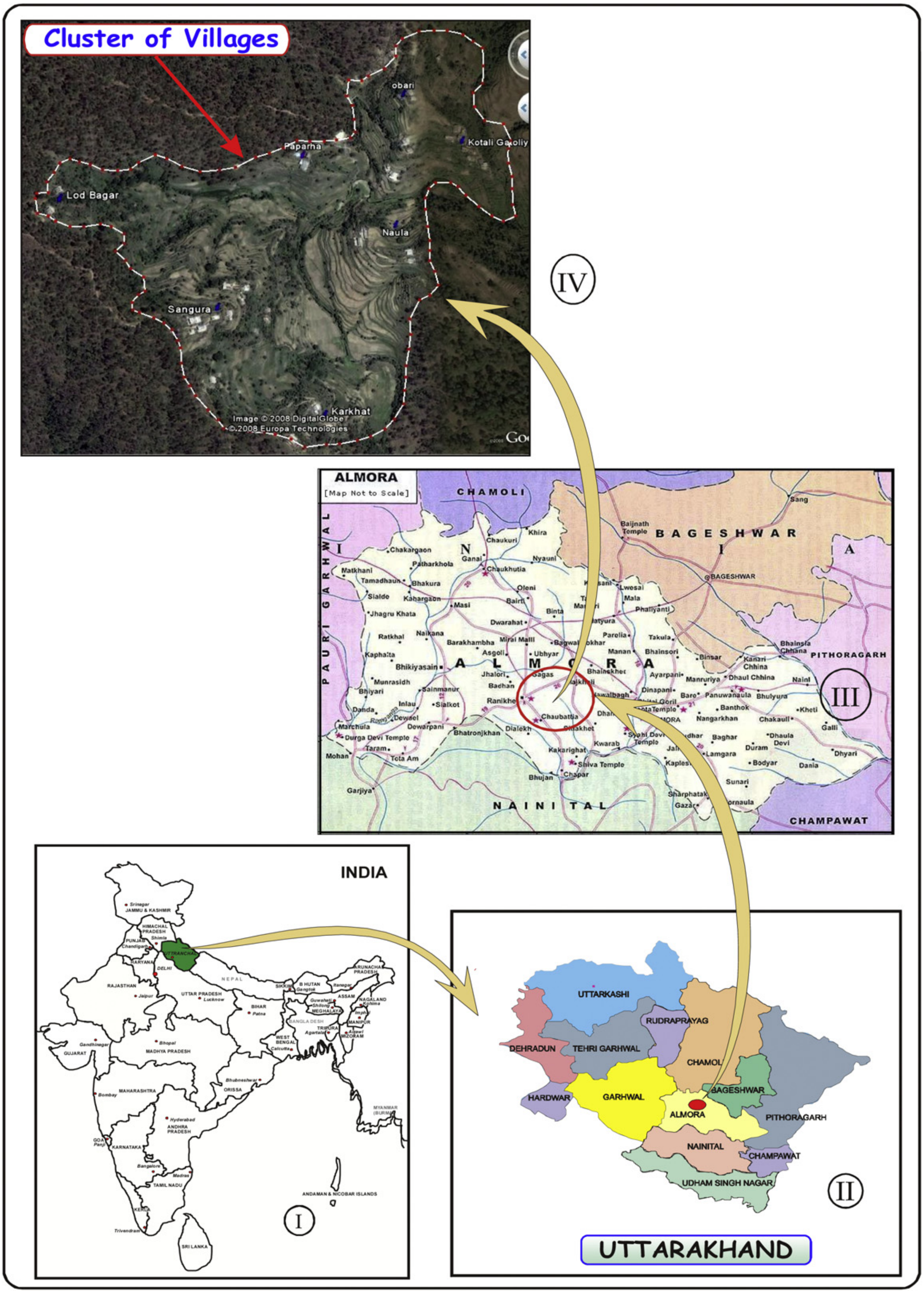

Fig. 1. Location of study area.

3.3. Load/demand assessment

The electrical energy demands of the area are classified as domestic, agricultural, community and rural industries. The domestic sector needs electricity for electrical appliances such as TV, fan and compact fluorescent lamps. The agricultural load includes fodder cutting and crop threshing machines. The community load includes schools and village *panchayat* offices. The rural industries such as milk storage and small-scale milk processing plants have been considered for these villages. The total

Table 1
General Information of study area [24].

Country	India
State/Province	Uttarakhand
Name of District	Almora
Name of Tehsil	Ranikhet
Name of Block	Tarikhet
Name of Panchayat	Tarikhet
Latitude	29^0 38" 21' N
Longitude	79^0 29" 56' E
Region (Hilly/Very High Altitude)	Hilly region
Elevation from Mean Sea Level	1576 MSL
Route to Reach Village	Foot Road (11 km)
No. of Uneletrified Villages	7
No. of Gharats	28
Total Population of Villages	1437

energy demand has been estimated as 5,61,273 kWh/yr and a classification of specific load is given in Table 4.

In order to energize the study area with optimum reliability is the main purpose of the present study. The COE is the economical constraint for implementation of these systems. Different scenarios are considered to optimize the available resources and minimize the COE generation. Different combinations of SPV, wind and energy plantation along with the base systems MHP, biomass gasifier and biogas-fired engines have been discussed.

3.4. Expected different scenarios

The available potential of MHP, biomass (crop residue and forest foliage) and biogas (used for electricity generation) has been estimated to be about 5,38,715 kWh/yr in the study area. A total electric load (demand) of 5,61,273 kWh/yr is calculated to meet out the demand. Since MHP and biomass resources have availability constraints, therefore, the only possibility of meeting the balance load can be based on SPV electricity. This results in considerable increase in the overall cost of IRES and makes the overall feasibility questionable. The overall cost can be reduced by incorporating wind and introduction of energy plantation. This can be a long-term possibility. Accordingly, four different scenarios have been considered as shown in Fig. 2 and compared on the basis of minimum COE and reliability. The four scenarios considered are discussed below.

3.4.1. Scenario 1: MHP-biomass-biogas-SPV

In the first scenario, MHP, biomass (crop residue and forest foliage) and biogas (used for electricity generation) are considered along with SPV system only. The wind and energy plantation are not considered here.

Table 3
Cost of Energy (COE).

Sr. No.	Parameters	Resources				
		MHP	SPV	BES	Biogas	WES
1	Energy Generation (kWh/yr)	233 040	1837	198 556	34 256	8890
2	System Rating (kW)	63	1	40	10	3
3	System Operating Hours (hrs/yr)	4535	1837	5100	3500	2975
4	Amortization Period (Year)	25	30	15	20	20
5	Capital Cost (Rs/kW)	70 000	225 000	30 000	20 000	80 000
6	O & M Cost (%)	2	2	2	2	2
7	Annual Interest Rate (%)	10	10	10	10	10
8	Fuel Cost (Rs/kWh)	–	–	3	2.99	–
9	Cost of Energy (Rs/kWh)	1.96	15.44	4.38	4.32	3.48

3.4.2. Scenario 2: MHP-biomass-biogas-wind-SPV

The wind potential, though in small quantity, has been added to scenario 1 as mentioned above. The small capacity wind turbines are proposed as stand-alone system for electricity generation.

3.4.3. Scenario 3: MHP-biomass-biogas-energy plantation-SPV

About 13 hectares of uncultivated land available in the study area can be used to raise energy plantations, which can be used to meet the additional demand in future. Preservation of forest, increase in biomass, checking of soil erosion and improvement of ground water table are the some of the added benefits associated with such plantations. A potential of 81,395 kWh/yr has been estimated to be available from these plantations.

3.4.4. Scenario 4: MHP-biomass-biogas-energy plantation-wind-SPV

In the last scenario, all the energy resources available such as MHP, biomass from crop residue and forest foliage, biogas (used for electricity generation), SPV along with wind and energy plantation are considered.

The purpose of using different scenarios is to avoid the use of diesel generation (DG) set, because it is difficult to transport limited and costly resources like diesel/kerosene to the remotely located study area.

Table 2
Estimated renewable energy resources in the study area.

Sr. No.	Name of Village	Area (ha)	HH	Population (No.)	Total Load (kWh/yr)	Resources				Additional Resources		Total Resources Available (kWh/yr)	Total resources that may be added (kWh/yr)
						MHP (kWh/yr)	Biomass (kWh/yr)	Biogas (kWh/yr)	SPV (kWh/m^2/yr)	Wind (kWh/m^2/yr)	Energy Plantation (kWh/yr)		
1	Naula	56.77	21	119	54 474	25 200	21 038	3156	1837	1270	10 803	51 231	12 073
2	Paparha	96.20	71	397	163 903	34 992	56 128	10 488	1837	1270	10 752	103 445	12 022
3	Lod Bagar	24.06	13	76	30 028	98 664	5548	2108	1837	1270	17 587	108 157	18 857
4	Kotli Gatoliya	24.38	47	273	100 571	15 672	28 105	5633	1837	1270	0	51 247	1270
5	Obari	16.50	14	83	31 071	71 808	15 969	1574	1837	1270	0	91 188	1270
6	Sangura	56.52	51	303	114 693	21 504	41 045	7447	1837	1270	22 477	71 833	23 747
7	Kharkhet	54.44	32	186	66 533	25 200	30 723	3854	1837	1270	19 776	61 614	21 046
Total		328.87	249	1437	561 273	293 040	198 556	34 256	12 859	8890	81 395	538 715	90 285

Table 4
Distribution of Electricity demands.

Energy Consumption Sector	Energy Demand (kWh/year)	Percentage Contribution (%)
Domestic Load	258 267	46.01
Agricultural Load	278 915	49.69
Community Load	5276	0.95
Rural Industrial Load	18 815	3.35
Total Demand	561 273	100.00

4. Model formulations

An IRES model has been developed to generate electricity as end product, which can be used in domestic, agricultural, community and small-scale rural industrial sectors. This model is based on linear programming approach and is given below:

$$\text{Minimize}: C_{\text{Total}} = \sum C_{ij} \times R_{ij}; \quad (1)$$

$$\text{Subject..to}: \sum R_{ij} = D_j;$$

$$\sum R_{ij}/\eta_{ij} \le S_j;$$

$$R_{ij} \ge 0;$$

where; C_{Total} is total cost of providing energy for end use (Rs in INR); C_{ij} is cost/unit of ith resource option (Rs/kWh); R_{ij} is optimal amount of ith resource option for jth end use (kWh); D_j is total energy for jth end use (kWh); S_i is availability of the ith resource option for jth end use (kWh); η_{ij} is conversion efficiency for the ith resource option for jth end use.

The model developed minimizes the total COE of the different IRES systems while accounting the reliability of the system, which is represented by the Energy Index Ratio (EIR) with minimum loss of Expected Energy Not Supplied (EENS) for the system considered.

5. Optimization of IRES systems

An optimization technique used for any system involves either maximization or minimization of an objective function and in order to achieve that objective function, numbers of attempts have been made to optimize the resources and unit COE. The system designed and suggested for the study area must be very reliable. However, it is true that more the reliability of the system, more is the COE generation. Therefore, an attempt has been made to design a system having required level of reliability ensuring the minimum COE generation. The model developed has been optimized with the linear programming techniques by considering the EENS as a probabilistic index used in reliability analysis of renewable energy systems. The EENS is the expected energy that will not be supplied under the conditions when the load exceeds the available generation [29–31]. The EENS can be expressed as:

$$EENS = L \times D/3600 \quad (2)$$

where; EENS is the Expected Energy Not Supplied (kWh); L is the average annual power load (kW); D is the duration of unavailability of load (seconds).

The EENS can be expressed in terms of energy index of reliability and expressed as:

$$EIR = 1 - \frac{EENS}{E_O} \quad (3)$$

where; EIR is the Energy Index Ratio (yearly); E_O is the total energy demand of the system (kWh).

In general, power planning for an area compares various alternatives available for the system development on the basis of ‘system cost’. The cost approach uses subjective and objective measures of customer “losses” arising from curtailments of the supply. This method has been applied extensively to the index EENS [32]. The unit cost of losses due to energy not supplied is a composite parameter based on the losses of various classes of customers affected by interruption. Cost of reliable and sustainable power i.e. reliability cost should be related to worth or benefit to the society. Since worth or benefit of reliability cannot be evaluated directly, the interruption cost can be used as a measure of reliability worth. To quantify reliability worth, it is necessary to relate a predicted reliability level with the customer interruption costs associated with that reliability level and can be achieved by following equation:

$$CIC = EENS \times IEAR \quad (4)$$

where; CIC is the Customer Interruption Cost (Rs); IEAR is the Interrupted Energy Assessment Rate (Rs/kWh).

The IEAR is an overall average value of COE of the system that is completely reliable. The relation between optimum reliability of the system and optimum total cost of the system has been predicted by Billinton and Allan [32]. EIR with CIC and EENS has been used to determine reliability of the system, which is then used to compute the optimal total cost and COE of the system.

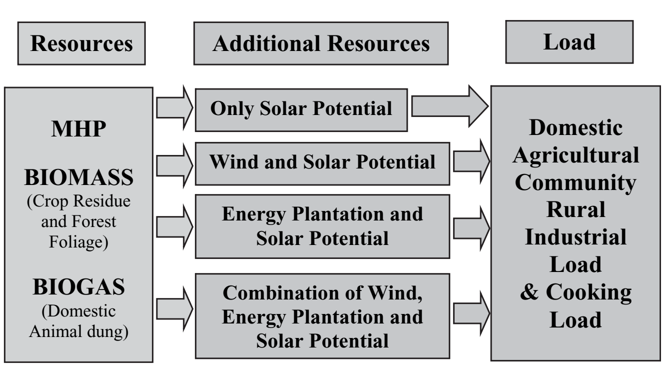

Fig. 2. Different scenarios considered for the study area.

6. Results and discussions

The developed model has been optimized for different EIR using LINGO software version 10 [33]. This model has been used to calculate COE and optimum system cost for different EIR. The variation in COE with EIR is shown in Fig. 3 for all the four scenarios considered in this study. The results indicate that the rate of decrease of COE for scenario 1 and 2 are higher than scenario 3 and 4 up to EIR of 0.8. This is due to dependence on solar energy in the scenario 1 and 2. After 0.80 EIR, all the systems show the constant decrease of COE upto 0.45 EIR and thereafter it becomes constant. The COE for a given reliability value can be predicted from Fig. 3 but it does not predict the optimum reliability and optimum system cost for that scenario.

In order to predict the optimum system reliability, all the systems are varied from 0.0 to 1.0 EIR. The EIR value of 0.0 is indicative of the system with no energy while the EIR value of 1.0 means system is capable of supplying 100% of the energy. For each value of EIR from 0.0 to 1.0, the system cost and COE are calculated. The different CIC of different scenarios are calculated from the EENS

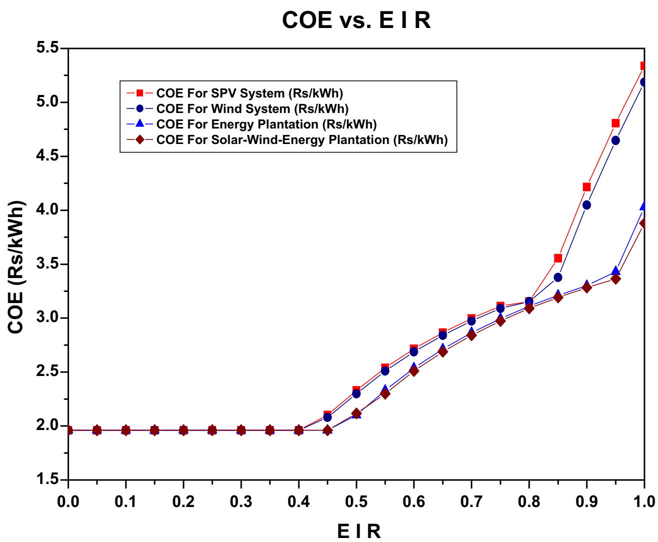

Fig. 3. Variation of COE with EIR.

and IEAR. The total system cost is the summation of system cost and calculated CIC. The part of the system cost with the reliability for all systems considered for different scenarios is shown in Fig. 4. Fig. 4 (a) depicts the relationship between the optimum reliability and the optimum system cost for scenario 1 while the relationships for the scenarios 2, 3 and 4 are shown in Fig. 4 (b), (c) and (d) respectively.

These results indicate that the optimum total cost for each scenario is different. The best system for the study area is the system that achieves higher reliability with optimum total system cost. The optimum total cost for scenario 1 has been found as Rs 19.91 lacs for the 0.82 EIR, which is the lowest reliability achieved among all the scenarios. Similarly for the scenarios 2, 3 and 4, the estimated optimal total system costs were found to be as Rs 19.78 lacs for 0.83 EIR, Rs 19.56 lacs for 0.94 EIR and Rs 19.44 lacs for 0.95 EIR respectively. The scenario 4, considering energy plantations and wind as additional resources, reduces the total system cost and offers highest reliability for the study area. The COE obtained by scenario 4 with this reliability (0.95 EIR) is found to be Rs 3.36 per kWh and COE for scenarios 1, 2, and 3 are Rs 4.81, Rs 4.65 and Rs 3.43 per kWh respectively for the same reliability. Hence, the COE for the scenario 4 is minimum and the system considering energy plantations and wind as additional resources has been designed and proposed for the study area.

The percentage contribution of each renewable energy resources for four different scenarios for EIR value of 1.0 are given in Table 5, which shows that implementation of resources even in small magnitude not only improves the reliability of the system but also reduces the COE. The COE of scenario 1, scenario 2, scenario 3 and scenario 4 for EIR value of 1.0 is Rs 5.34, Rs 5.19, Rs 4.03 and Rs

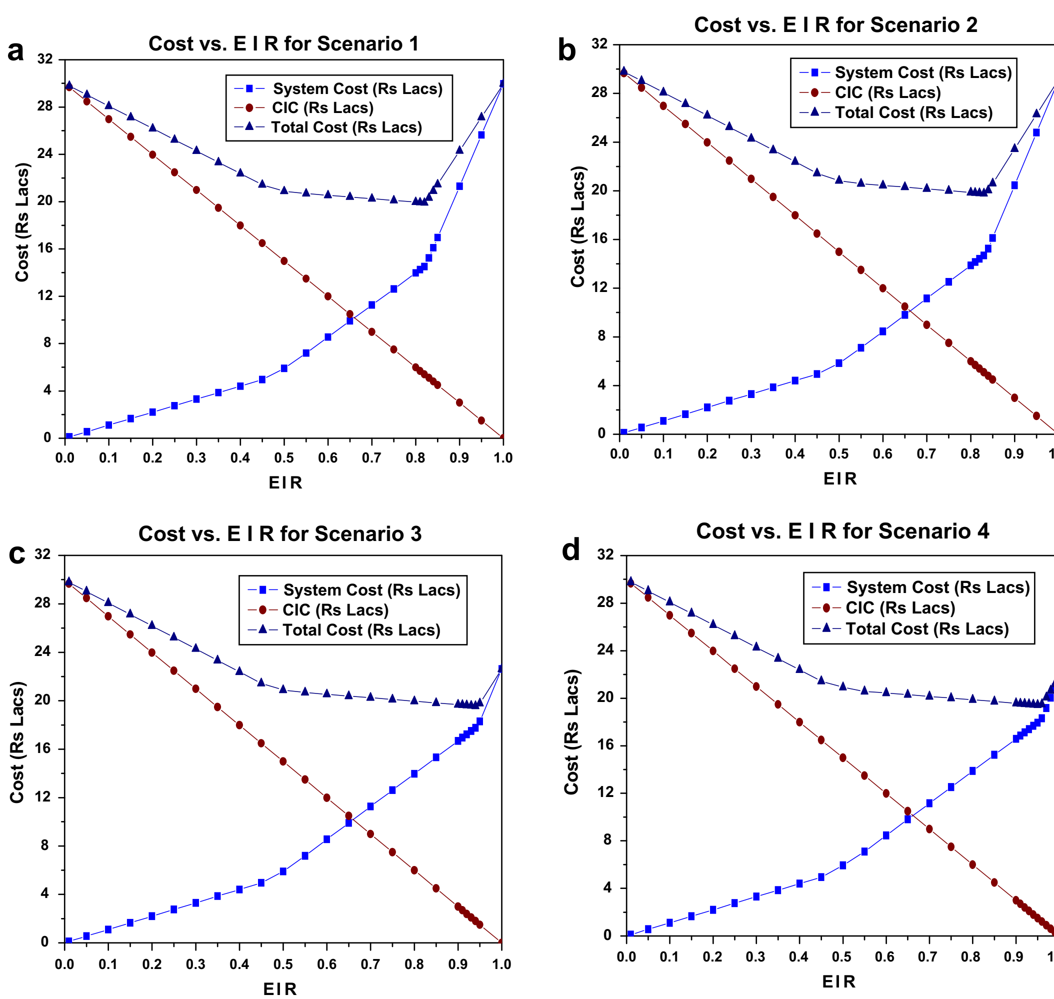

Fig. 4. Variation of cost of system with EIR.

Table 5
COE for all Scenarios for 1.0 EIR.

Scenario	Available Resources				Additional Resources		Optimum Cost of the System (Rs)	COE (Rs/kWh)
	MHP	BES	Biogas	SPV	Energy Plantation	WES		
1	263 736 (46.99%)	168 773 (30.07%)	29 117 (5.19%)	99 647 (17.75%)	–	–	2996 432	5.34
2	263 736 (46.99%)	168 773 (30.07%)	29 117 (5.19%)	92 535 (16.49%)	–	7112 (1.27%)	2911 373	5.19
3	263 736 (46.99%)	168 773 (30.07%)	29 117 (5.19%)	30 461 (5.43%)	69 186 (12.33%)	–	2262 080	4.03
4	263 736 (46.99%)	168 773 (30.07%)	29 117 (5.19%)	23 349 (4.16%)	69 186 (12.33%)	7112 (1.27%)	2177 312	3.88

3.88 per kWh respectively. The percentage reduction in COE for scenario 4, scenario 3 and scenario 2 over scenario 1 is 27.34%, 24.57% and 2.81% respectively. This implies that the energy plantation is the main resource that reduces the COE generation drastically and the scenario 4 is found to be the best among the other three scenarios considered on the basis of reliability and COE constraint.

7. Result verification

The results obtained using LINGO software version 10 has also been compared with the most preferable hybrid optimization software HOMER. The HOMER package is used to optimize off grid system with battery backup. Thus, the conversion and reconversion of energy decreases the system efficiency and adds more cost to the system. All four scenarios are compared and optimized in HOMER system and their COE are given in Table 6. The COE varies from Rs 3.88 to Rs 5.34 per kWh while that for hybrid systems varies from Rs 5.90 to Rs 12.40 per kWh. The cost of converter, local grid and battery added to hybrid HOMER systems increases the COE of the system while LINGO considers only the renewable energy resources on yearly basis for the study area. The comparative work suggests that there should be such an algorithmic code, which can consider the reliability parameters and optimizes the renewable energy resources in the study area. This code can be helpful to find out the sizes of renewable energy systems for the study area using IRES concept.

8. Sensitivity analysis of biomass fuel cost

Though the cost optimized function after adding wind and biomass (as growing energy plantations) either separately or combined definitely reduces the COE, but it should withstand the fluctuations in the price of biomass also. The application of IRES system improves the living standards of residents of villages considered either by employing the people or by paying the collection charges of biomass to the people. It will increase the cost of biomass. The system must therefore compensate for the price fluctuation of the biomass. The variation of the COE with respect to the cost of biomass fuel of the system is shown in Fig. 5. It can be observed that all the four systems are sensitive to biomass fuel prices. The slope of the lines associated with different scenarios considered, represent sensitivity of COE with respect to the cost of biomass. High value of slope line for a scenario indicates that COE increases/decreases sharply with variation in the cost of biomass fuel and vice-versa. Thus, it is concluded from Fig. 5 that the scenarios 3 and 4 are more affected by variation of biomass fuel prices as compared to that COE of the scenarios 1 and 2.

The contribution of biomass resources by energy plantation to the overall system is expected to be more sustainable as compared to only SPV dependent system and wind-SPV dependent system. The combined wind-energy plantation option and additional biomass system by energy plantation have been found to be more sensitive to biomass fuel price fluctuations and can still operate within acceptable prices. The scenario 4 appears to be effective and less costly than scenario 1 up to Rs 4.75 per kg, for scenario 2 up to Rs 4.50 per kg while that for scenario 3 up to Rs 2.75 per kg of biomass fuel price. The sensitivity analysis of biomass fuel price also reveals that the combined system can be more suitable to the study area, even if the biomass fuel price fluctuates with external circumstances.

Table 6
Hybrid system models and COE.

Sr. No.	Hybrid Model	COE (Rs/kWh)
1	MHP-Biomass-Biogas-SPV-Battery	12.40
2	MHP-Biomass-Biogas-Wind-SPV-Battery	11.75
3	MHP-Biomass-Biogas-Energy Plantation-SPV-Battery	6.05
4	MHP-Biomass-Biogas-Energy Plantation-Wind-SPV-Battery	5.90

9. Conclusions

Seven remote villages of the Almora district of Uttarakhand state, India have been considered for optimization of IRES system. The data collected from the study area have been used for the resource assessment and demand calculation. The unit COE of each system has been calculated for four different scenarios. The system considered in scenario 4 (MHP-Biomass-Biogas-Energy Plantation-Wind-SPV) is found to be the most reliable and cost effective among all the scenarios considered and has been proposed for the study area. The developed IRES model linearly optimized using LINGO software version 10 has a reliability of 0.95 EIR with optimum total cost of Rs 19.44 lacs. The COE for the scenario 4 is found to be lowest (Rs 3.36/kWh) followed by other systems for 0.95 EIR. The sensitivity analysis of the system has been conducted

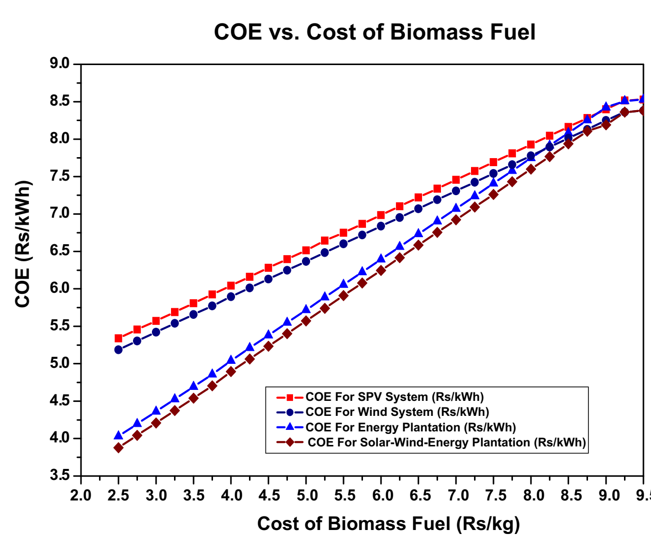

Fig. 5. Variation of COE with cost of biomass fuel.

on the basis of fluctuation of biomass fuel prices. The scenario 4 has been found the most feasible and sustainable than the other IRES system for fluctuating biomass fuel prices.

References

[1] Ramakumar R, Hughes WL. Renewable energy sources and rural development in developing countries. IEEE Trans Edu 1981;E-24(3):242–51.
[2] Ramakumar R. Renewable energy sources and developing countries. IEEE Trans Pow App Sys 1983;PAS-102:502–10.
[3] Ramakumar R, Butler NG, Podriguez AP. Economic aspects of advanced energy technologies. In: Proceedings of IEEE, 81; 1993.p. 318–32.
[4] Ramakumar R. Energizing rural areas of developing countries using IRES. IEEE Ene Con Engg Conf 1996;3:1536–41.
[5] Ramakumar R. Role of renewable energy in the development and electrification of remote and rural areas. IEEE Pow Engg Soc Gen Meeting 2004;2:2103–5.
[6] Ahmed BS, Cohen JM. Renewable energy sources: technology and economics. IEEE Int Conf Hum Info Tech 1994;3:2355–60.
[7] Ramakumar R, Abouzahr I, Ashenayi K. A knowledge-based approach to the design of integrated renewable energy systems. IEEE Trans Energy Convers 1992;7:648–59.
[8] Ashenayi K, Ramakumar R. IRES - a program to design integrated renewable energy systems. Energy 1990;15:1143–52.
[9] Gavanidou ES, Bakirtzis AG. Design of a stand alone system with renewable energy sources using trade off methods. IEEE Trans Energy Convers 1992;7:42–8.
[10] Ramanathan R, Ganesh LS. Energy alternatives for lighting in households: an evaluation using an integrated goal programming. Energy 1995;20:63–72.
[11] Ramakumar R, Abouzahr I, Krishnan K, Ashenayi K. Design scenarios for integrated renewable energy systems. IEEE Trans Energy Convers 1995;10:736–46.
[12] Ramakumar R, Shetty PS, Ashenayi K. A linear programming approach to the design of integrated renewable energy systems for developing countries. IEEE Trans Energy Convers 1996;EC-1:18–24.
[13] Iniyan S, Suganthi I, Jagdeesan TR. Renewable energy planning for India in 21st century. Renewable Energy 1998;14:453–7.
[14] Iniyan S, Sumathy K. An optimal renewable energy model for various end-uses. Energy 2000;25:563–75.
[15] Ramakumar R, Chiradeja P. Distributed generation and renewable energy systems, 37th Intersociety Ene Con Engg Conf (IECEC), IEEE paper no. 20027; 2002. p. 716–24.
[16] Nakata T, Kubo K, Lamont A. Design for renewable energy systems with application to rural areas of Japan. Energy Policy. 2005;33:209–19.
[17] Ashok S. Optimized model for community – based hybrid energy system. Renewable Energy 2007;32:1155–64.
[18] Katti PK, Khedkar MK. Alternative energy facilities based on site matching and generation unit sizing for remote area power supply. Renewable Energy 2007;32:1346–62.
[19] Fernandez E, Saini RP, Devdas V. Relative inequality in energy resource consumption: a case of Kanvashram village, Pauri Garhwal dist, Uttaranchal (India). Renewable Energy 2005;30:763–72.
[20] Akella AK, Sharma MP, Saini RP. Optimum utilization of renewable energy sources in a remote area. Renew Sustain Energy Rev 2007;11:894–908.
[21] Diaf S, Belhamel M, Haddadi M, Louche A. Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica Island. Energy Policy. 2008;36:743–54.
[22] Lagorse J, Paire D, Miraoui A. Sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery. Renewable Energy 2009;34:683–91.
[23] Kaldellis JK, Zafirakis D, Kaldelli EL, Kavadias K. Cost benefit analysis of a photovoltaic-energy storage electrification solution for remote islands. Renewable Energy 2009;34:1299–311.
[24] Economic and Statistics Department. Government of Uttarakhand, Janpath Ek Drusti Main - Almora, Almora; 2007.
[25] Ministry of New and Renewable Energy (MNRE). Government of India, Annual Report 2007-2008, <http://mnes.nic.in/list/snas.htm>.
[26] Mani A, Rangarajan S. Solar radiation over India. New Delhi: Allied Publication; 1992.
[27] Ashari M, Nayar CV, Keerthipala WWL. Optimum operation strategy and economic analysis of a photovoltaic-diesel-battery-mains hybrid uninterruptible power supply. Renewable Energy 2001;22:247–54.
[28] Markvart T. Sizing of hybrid photovoltaic-wind energy systems. Sol Energy 1996;57:277–81.
[29] Karaki SH, Chedid RB, Ramadan R. Probabilistic performance assessment of autonomous solar-wind energy conversion systems. IEEE Trans Energy Convers 1999;14:766–72.
[30] Stojkov M, Nikolovski S, Mikulicic V. Estimation of electrical energy not supplied in reliability analysis of distribution networks. Dubrovnik, Croatia: IEEE MELCON; 2004. p. 967–970.
[31] Tina G, Gagliano S, Raiti S. Hybrid solar/wind power system probabilistic modeling for long – term performance assessment. Sol Energy 2006;80:578–88.
[32] Billinton R, Allan RN. Reliability evaluation of power systems. Delhi: Springer Indian Edition; 2006.
[33] Website, <www.lindo.com>.