Technoeconomic Feasibility and Sensitivity Analysis of Off-Grid Hybrid Energy System

Sumit Sharma, Yog Raj Sood, and Ankur Maheshwari

Abstract This paper aims to analyze and configure the optimal configuration of a hybrid renewable energy system to fulfill the electric load requirement of unelectrified rural areas in Chamarajanagar district, Karnataka (India). The renewable energy sources available at the location are solar, wind, and biomass with pumped hydro storage used for the energy-storing purpose. This research paper identified the best-suited design to satisfy the village load demand of a hybrid renewable system in a variety of combinations. Different case studies are compared and evaluated based on the cost of energy (COE), total net present value (NPV), initial capital value (ICV), and operating cost. Also, the behavior of different cost patterns is studied with the variable inputs; therefore, sensitivity analysis is presented in this study.

Keywords Renewable energy sources (RES) · Solar photovoltaic (SPV) · Pumped hydro storage · Diesel generator

Nomenclature

$Cost_{TNP}$	Total net present value
$Cost_{Tann}$	Total annualized value
CRF	Capital recovery factor
rate	Annual interest rate (%)
life	Plant life (years)
T_{Load}	Total load served (kWh/year)
P_S	Solar rated capacity (kW)
D_S	Solar derating factor (%)
I_r	Solar radiation in present time (kW/m^2)
$I_{r,STC}$	Solar radiations at standard conditions (1 kW/m^2)
α_T	Temperature coefficient (%/°C)

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T_S Solar cell temperature in present time (°C)
$T_{S,STC}$ Solar temperature under standard conditions (25 °C)

1 Introduction

The usage of renewable energy sources (RES) has been increasing in recent times because of the electricity problem that arises in remote communities, where grid-connected electricity is not possible. A hybrid energy system is characterized as an independent and organized cluster of various RES. In modern society, the energy is put next to the fundamental humanities necessities, such as food, clothes, and shelter. The electricity produced from conventional energy sources is costly and creates a lot of environmental problems. Many researchers across the world studied the working of the hybrid energy system (HES) in rural communities and observed that HES would be the best solution for electricity supply in remote areas. Kumar S. et al. presented the cost assessment and sizing estimation of the HES in the western Himalaya region in Himachal Pradesh, India [1]. Different types of control methodologies used in the evaluation of HES are discussed by Subho Upadhyay [2]. As RES are available for electricity production, but mainly the solar, wind, hydro, and biomass are available in abundance and generally used for electricity production. There are different storage technologies like batteries, pumped hydro storage, hydrogen fuel cell, etc. R. Singh et al. discussed the different storage technologies and system architecture of the HES [3]. Among all the storage technologies, batteries are mostly used because of their availability, but there is a lot of drawbacks of batteries. In this research paper, the technology used for storing the electrical energy is pumped hydro storage. Sambeet Mishra et al. focused on the benefits and advantages of HES in comparison with an islanded system [4]. Due to the dependency on fossil fuels by the majority of the population, a stage arises of higher electricity costs and maximum environmental problems. Therefore, there will be a need to go on renewable energy sources for electrical energy production. Bagul, A. D et al. discussed the benefits of HES in electricity generation in rural areas [5]. In [6], the author discussed the sensitivity analysis using the various types of storage systems. Sharma S., et al. focused on the technoeconomic assessment of green microgrid systems in the simulation atmosphere [7]. Moreover, the reader may refer to [8–15] for other applications of technoeconomic feasibility and sensitivity analysis of off-grid hybrid energy system.

This paper presents the cost assessment and sizing analysis of a hybrid system with the available resources, i.e., solar, wind, biomass, and converter with a pumped storage system for storing purposes. Section 2 presents the input parameters and resource variables data used in the study. Sections 3 and 4 present the economic modeling and results of this research paper.

2 Input Parameters and Resource Variables

In view of the electricity requirements of the village cluster, the electrical load demand of the selected location has been calculated. The location chosen for the study is a cluster of three unelectrified villages situated in district Chamarajanagar, Karnataka (India) [16]. The majority of the population is living in the hilly areas and forests where the electricity supply is not feasible. RES available at the location are solar, wind, biomass, and pumped hydro storage. The daily load demand for the selected location is present in Fig. 1. The electrical load in kWh per day is approximated as 724.80 kWh/day, with a peak load demand of 108.60 kW.

The electrical energy produced from the solar photovoltaic is due to solar rays. The solar system generated the DC power output but the load is AC electrical; therefore, a bidirectional converter is used in the system for the conversion of DC electrical output into AC electrical power. A good amount of wind speed is necessary at the site for electrical energy generation. To avoid emission problems diesel generator is replaced by the biomass generator. Table 1 shows the value of resource components, i.e., solar radiations (kWh/m^2/day), wind speed (m/s) and available biomass (tonnes/day). Figures 2 and 3 present the block diagram of different components and flowchart describing the purposed analogy in HES, respectively.

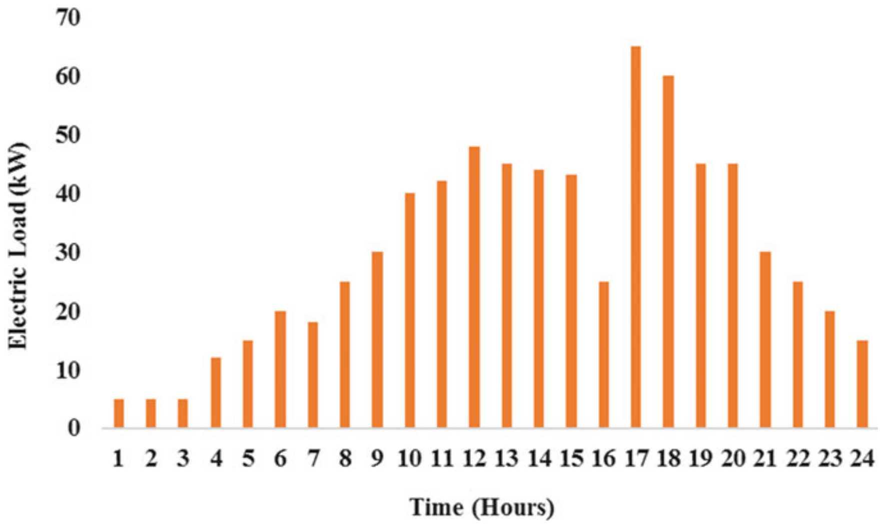

Fig. 1 Electric load profile for 24 h

Table 1 Resource parameters values of solar, wind, and biomass

Months	Solar radiations (kWh/m^2/day)	Wind speed (m/s)	Available biomass (tonnes/day)
Jan	5	2.8	3
Feb	5.8	2.7	4
Mar	6.5	2.6	5
Apr	6.4	2.5	6
May	6.3	2.7	7
Jun	5	3.4	8
Jul	4.8	3.2	8
Aug	4.9	3	7
Sep	5	2.4	6
Oct	4.9	2.2	5
Nov	4.8	2.3	4
Dec	4.9	2.8	3
Annual average value	5.36	2.72	5.50

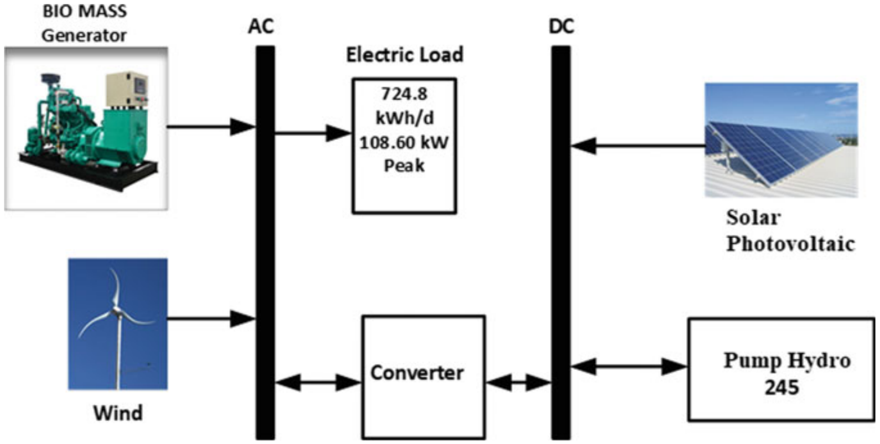

Fig. 2 Block diagram of hybrid energy system containing solar, wind, biomass generator, pumped storage, and converter

3 Economic Modeling

The simulation model is constructed using the net present value which corresponds to the total installation and operation costs of the system over its lifetime. The total NPV contains many costs like replacement, maintenance, fuel, and capital costs. The net present cost is expressed as [17]

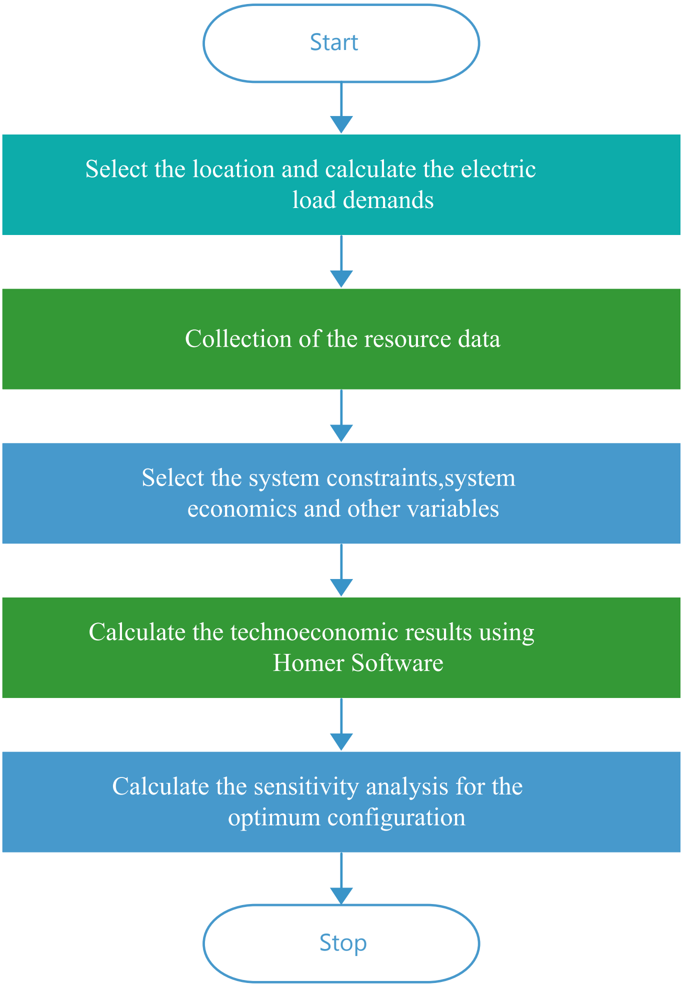

Fig. 3 Flowchart describing the purposed analogy

$$\mathrm{Cost}_{\mathrm{TNP}} = \frac{\mathrm{Cost}_{\mathrm{Tann}}}{\mathrm{CRF(rate, life)}} \tag{1}$$

Levelized COE is calculated as the average cost per kWh of energy generated by the system. CRF is dependent on the project life and annual interest rate and is expressed as [18]

$$\mathrm{COE} = \frac{\mathrm{Cost}_{\mathrm{Tann}}}{\mathrm{T}_{\mathrm{Load}}} \tag{2}$$

$$\text{CRF} = \frac{\text{rate}(1 + \text{rate})^{\text{life}}}{\text{rate}(1 + \text{rate})^{\text{life}} - 1} \tag{3}$$

SPV is generating electrical energy from the sun's rays. The mathematical equation used for the solar power output is [19]

$$P_{SPV} = P_S D_S \left(\frac{I_r}{I_{r,STC}} \right) \left[1 + \alpha_T \left(T_s - T_{S,STC} \right) \right] \tag{4}$$

4 Results and Discussion

The HES developed for the chosen site consists of the SPV, wind turbine, biomass gasifier generator, pumped hydro storage, and converter. The input parameters and cost assessment of different components are taken from [4]. Different combinations have been obtained from the simulation as shown in Table 2. There are many results obtained from the Homer software; only nine combinations have been shown here because of close comparisons and observed that from the different combinations, case 8 has the minimum cost of energy, i.e., 26.65 ₹/kWh. Therefore, it can be said that case 8 would be the optimal solution for the electrification of rural communities. As has been found, the optimal solution consists of 238 kW of SPV, 9 units of pumped storage, and 106 kW of converter. There are no wind turbine and biomass gasifier generators in the optimal solution obtained for rural areas. Table 3 shows the cost summary of the different components in HES.

As we know, the electrical energy generated from renewable energy resources are weather-dependent. In the proposed hybrid energy system, there is only SPV, pumped storage, and converter; therefore, the more sensitive parameter is solar radiations. Table 3 shows the sensitivity analysis of HES. As seen from the table that as the value of solar radiation increases, the cost values decrease. Therefore, it can be concluded that for the higher solar radiations there will be very less cost of electricity, and vice versa (Table 4).

5 Conclusion

This paper examines the technoeconomic aspects of renewable energy hybrid systems in order to find an ideal solution for fulfilling a rural community's demand for electrical loads. After the evaluation, it was found that on the basis of available local resources, SPV and biomass gasifier-based generators along with pumped hydro storage system are selected for providing electricity. Along with sizing optimization, the sensitivity analysis has been done and observed that with the increase in the sensitive parameters, levelized COE, total NPC, OC, and ICC decrease, and vice

Table 2 Different combinations obtained for the hybrid energy system

S. no.	PV (kW)	Wind (kW)	Biomass generator (kW)	Pumped storage (Quantity)	Converter (kW)	COE (₹/kWh)	NPV (₹$*10^6$)	OC (₹/year)	ICV (₹$*10^6$)
1	187	1	500	5	114	48.99	174.21	765572.43	164.54
2	199	4	500	5	120	51.74	177.19	608333.40	169
3	189	8	500	5	121	52.19	178.68	734675.56	169
4	185	3	500	5	132	52.49	179.43	1070446.41	166.02
5	242	13	0	9	105	29.18	99.76	1684363.59	78.17
6	181	15	500	6	130	55.02	188.36	1198947.63	172.72
7	187	21	500	6	111	55.17	188.36	928022.99	176.45
8	238	0	0	9	106	26.65	91.57	1614678.11	69.98
9	239	3	0	9	99.1	27.17	93.06	1626962.41	72.22

Table 3 Cost summary of different components in the proposed hybrid energy system

S. no.	Component	Capital cost (₹)	Replacement cost (₹)	Operation and maintenance cost (₹)	Salvage value (₹)	Total (₹)
1	Generic 245 kWh pumped hydro	14,741,100	475927.581	17324165.09	34395.9	32506796.77
2	Generic flat plate PV	53227563.68	0	2293667.512	0	55521231.19
3	System converter	2365268.311	1003521.229	0	188872.9495	3179917.334
4	System	70333931.99	1479449.554	19617832.6	223268.8495	91208312.07

Table 4 Sensitivity analysis of hybrid energy system with the change in solar radiations

S. no	Sensitive variable solar radiation	PV (kW)	Pumped storage (Quantity)	Converter (kW)	COE (₹/kWh)	NPV (₹$*10^6$)	OC (₹/year)	ICV (₹)
1	5.36	238	9	106	26.6531	91.5735	1614671.6	70333957.3
2	7	211	8	103	23.74955	81.1505	1439937.45	62481194.65
3	8	187	8	118	22.1861	75.939	1,430,929	57421274.85
4	9	189	7	112	21.21825	72.2165	1276147.45	56096437.1
5	10	174	7	129	20.3993	69.2385	1274956.25	53134816.1
6	12	169	6	106	18.7614	64.027	1104912.45	49962650.5
7	15	166	5	104	17.49575	59.56	948641.9	47563871.5

versa. One major finding of this study is the usage of biomass and pumped hydro storage in electricity generation, which brings a pollution-free environment into the system. This current proposal can improve living standards and boost the economic activity of rural communities in the state of Karnataka, India.

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