Chapter 22
Performance Analysis of Hybrid Renewable Energy System for Twenty-Seven Different Locations in India

S. K. Saraswat and K. V. S. Rao

Abstract Due to the escalation of the world's population and economic growth electricity demand is continuously rising. Primary sources of electricity generation are the fossil fuels available all over the world. Due to fossil fuels depletion and global warming issues, renewable energy sources became a more reliable and adaptable option. In India, rural electrification is a major problem, and to overcome this problem Government of India (GOI) is focusing on renewable energy sources. To minimize line losses and economic power supply, the Government of India is promoting off-grid and grid-connected power generation sources with various incentives and subsidies. An off-grid standalone solar PV-diesel hybrid energy system for a base load of 10 kW (240 kWh/day) with zero percentage loss of load is designed in HOMER software. Twenty-seven different locations in India have been selected to analyze the feasibility and found to be the most suitable locations for generation using a hybrid energy system. Feasibility has been analyzed by covering economic, energy, and emission aspects. Among all the 27 locations, Jaisalmer has been found to be the most favorable, and Itanagar is found to be the least favorable location in all three aspects. Here, Jaisalmer has the largest share of renewable energy in the total generation (91.94%), while Itanagar has the lowest share (68.78%). Sensitivity analysis has been performed for fuel price, discount rate, inflation rate, annual capacity shortage, and project life span.

Keywords Hybrid energy system · Rural electrification · Solar PV · HOMER · India

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22.1 Introduction

Energy is a basic need of human life to live comfortably for enhanced healthcare, education, and economic growth. A measure of a country's development is gross power production and per capita energy consumption. Fossil fuels are the primary fuels for power production. According to International Energy Agency (IEA), the world's total power production was 28,115 TWh, out of which 20,215 TWh (71.9%) was from nonrenewable energy sources [1]. India produces 1328 TWh of power through nonrenewable energy sources, which is 79.6% of total power generation [2]. In fossil fuels, coal is a key cornerstone of India's energy supply. In India, 52% of installed power capacity and nearly 70% of electricity are generated by coal [2]. India has limited reserves of coal to fulfill its demand. There is a necessity to think about alternatives to primary fossil fuels because of the depletion of fossil fuels at a faster rate.

With fossil fuels, there is another major problem of greenhouse gases emission due to combustion. According to International Energy Agency (IEA), in 2021, global CO_2 emission was 36.3 billion tons, with the highest-ever increase rate of 6%. The significant portion of emissions is from the world's ten countries China, the United States, India, Russia, Japan, Germany, Iran, South Korea, Canada, and Indonesia [3]. In 2021, India's total CO_2 emission was 2251 million tons (Mt) which is the third largest in the world. India emits 1065 $MtCO_2$ for power production, which is 47.31% of total CO_2 emission [3]. Due to global warming and fossil fuel depletion, the world has turned to develop renewable energy sources [2]. The government of India is more concerned about climate change and global warming, so there is more focus on developing renewable energy sources. Accordingly, the name of the Ministry of Forest and Environment has been changed to the Ministry of Environment, Forest and Climate Change government of India has also signed the climate change accord of the United Nations held in Paris in 2015.

India is facing another major problem of rural electrification. About 289 million people are not having electricity [3]. Due to uneconomic grid extension, high transmission losses, and less reliability, the Indian government is trying to implement rural electrification through off-grid standalone or grid-connected renewable energy systems. Mainly two organizations, the Ministry of Power (MOP) and the Ministry of New and Renewable Energy (MNRE) are promoting and funding the rural electrification schemes. The Indian government announced various policies to electrify the villages [4].

- Electricity Act of 2003
- Remote village electrification program, 2003 by the Ministry of Non-Conventional Energy Sources (now known as Ministry of New and Renewable Energy)
- Village Energy Security Program, 2004 by MNRE
- Rajiv Gandhi Grameen Vidyutikaran Yojana in 2005 by the Government of India
- Decentralized Distributed Generation (DDG) scheme under the MOP in 2009

- Jawaharlal Nehru National Solar Mission (JNNSM) in 2010 by the Government of India
- Remote Village Electrification (RVE) operated with JNNSM by MNRE in 2011.

Currently, the Indian government announced Deen Dayal Upadhyaya Gram Jyoti Yojna (DDUGJY) in 2015 to electrify 5.98 crore un-electrified households. Power Finance Corporation and Rural Electrification Corporation of India allocated a fund of ₹756 billion to electrify 18,452 villages barring Maoist-infested areas and rugged terrains. Various incentives, funds, and subsidies are given under the different schemes of the central and state government of India for rural electrification. The above discussed problem can be reduced/mitigated by using renewable energy resources for power generation applications by both off-grid and grid-connected power systems [5].

Hybrid Energy System is studied and explained by various authors. They covered the analysis of HES for different locations, including remote location applications, other electrical loads, other power system models, software, and sensitivity analysis. Dekker et al. [6] proposed HES for a remotely located residential load and simulated it for six different locations Cape Town, East London, Pretoria, Nelspruit, Bloemfontein, and Upington of South Africa. It was found that Upington was the most suitable location and East London was the least suitable location. Suresh and Manoharan [7] analyzed SPV–diesel–battery HES for six different locations Chennai, Nagapattinam, Ooty, Kanyakumari, Salem, and Rameswaram of Tamil Nadu, India. The authors found Kanyakumari was the most suitable place for HES in Tamil Nadu, with the highest renewable fraction of 56% and the least net present cost of INR 85,436.

Olatomiwa et al. [8] investigated the techno-economic feasibility of different power-generating configurations within the six different geo-political zones of Nigeria. Sandwell et al. [9] analyzed HES for three different locations, Barmer, Ladakh, and Dhemaji of India in terms of both Levelized cost of energy (LCOE) and emission. Panapakidis et al. [10] analyzed four different locations in the Greek region by considering solar PV, wind turbines, diesel generators, and fuel cells as a source of energy. From an environmental point of view, authors found wind turbine–fuel cells perform better. Thomas et al. [11] proposed a multi-component renewable energy model for the electric vehicle charging station in New Delhi, India. As a result, authors suggested a grid-tied solar PV system as the most economically viable and feasible solution for electric vehicle charging applications.

As the literature discussed, hybrid energy systems will become a keystone for rural electrification because rural electrification is a significant problem in developing countries. Various authors [12, 13] designed HES for remotely located locations, coastal areas, remotely located hospitals, and technical colleges. Therefore, the aim of the present study is to propose a hybrid renewable energy system for off-grid base load applications in different geographical regions of India.

In the present study, Hybrid Optimization Model for Electric Renewables (HOMER) is used, which was developed by National Renewable Energy Laboratory (NREL) in 1993 and used for both on-grid and off-grid power applications [14].

HOMER performs three principal tasks, i.e., simulation, optimization, and sensitivity analysis. HOMER requires climatic data (solar radiation intensity, clearness index, wind speed), electrical energy demand, system component details, and their associated costs such as capital, operation and maintenance, and replacement cost.

22.2 Electrical Energy Demand

The system is analyzed for a 10 kW (240 kWh/day) hypothetical electrical load with zero percentage loss of load. Particularly 10 kW base load is chosen because it covers the load of domestic, community load, telecom load, small-scale industries, agriculture pumping load, army base camps, remotely located research station, and especially for those places which are not possible to connect through the grid. The main aim of the work is to make these applications independent from the grid. Systems are economical, electrical, and emission point of view discussed and compared for all 27 different locations. Sensitivity analysis is performed for fuel price, discount rate, inflation rate, annual capacity shortage, and project lifetime for a particular location of Jaisalmer, Rajasthan, India.

22.3 Methodology

The methodology of the present study deals with the assessment of the LCOE, total annualized cost, annual real interest rate, renewable fraction, excess electricity, capacity factor, and battery throughput. The brief details of important factors are as follows.

- The LCOE is the ratio of annualized system cost the producing electricity to the total useful electric energy generation by the system. LCOE is calculated by using Eq. (22.1).

$$LCOE = \frac{Total\ Annualized\ Cost}{E_{AC} + E_{DC}} \tag{22.1}$$

where LCOE is calculated in ₹/kWh, E_{AC} is the AC primary load served (kWh/year), and E_{DC} is the DC primary load served (kWh/year).

- The total annualized cost of the system is the sum of the annualized capital cost, replacement cost, and operation and maintenance cost of all components of the system. The total annualized cost is calculated by using Eq. (22.2)

$$TAC = C_{annz-cap} + C_{annz-rep} + C_{annz-maint} \tag{22.2}$$

where TAC is the total annualized cost, $C_{annz\text{-}cap}$ is the annualized capital cost, $C_{annz\text{-}rep}$ is the annualized replacement cost and $C_{annz\text{-}maint}$ is the annualized operation and maintenance cost.

The annual real interest rate (i) is the function of the discount rate and inflation rate, as shown in Eq. (22.3)

$$i = \frac{i' - f}{1 + f} \tag{22.3}$$

where i is the annual real interest rate, i' is the discount rate, and f is the inflation rate.

- The renewable fraction is the fraction of the energy delivered to the load generated from renewable power sources. HOMER calculates the renewable fraction using the following Eq. (22.4)

$$f_{ren.} = 1 - \frac{E_{nonren.}}{E_{Served}} \tag{22.4}$$

where f_{ren} is the renewable fraction, $E_{nonren.}$ is the energy delivered by the nonrenewable energy sources, and E_{served} is the electrical demand.

Excess electricity is surplus electrical energy that must be dumped because it cannot be used to serve a load or charge the batteries. Excess electricity fraction (f_{excess}) is the ratio of total excess electricity and total electricity production, as shown in Eq. (22.5).

$$f_{excess} = \frac{E_{excess}}{E_{Prod.}} = \frac{Total\ excess\ electricity(kWh/yr)}{Total\ electricity\ production(kWh/yr)} \tag{22.5}$$

- The capacity factor is the ratio of the average power output of the PV array (kW) and the rated power (kW) of the PV array. It is specified in percentage.
- The battery throughput is the average number of energy cycles that the battery bank undergoes in its life span.

22.4 Hybrid Energy System Description

The hybrid energy system under study consists of PV modules, diesel generators, batteries, and a bi-directional power converter. Figure 22.1 shows the structure of the hybrid energy PV-diesel-battery system.

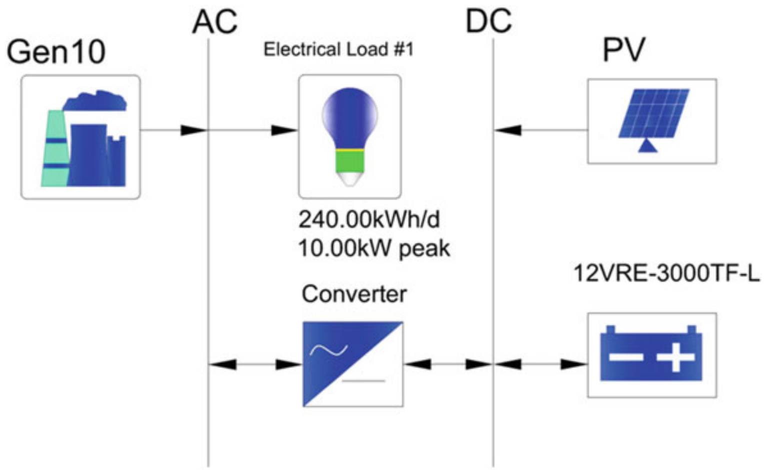

Fig. 22.1 System configuration of the hybrid energy system in HOMER software

22.4.1 Photovoltaic Modules

A photovoltaic module (Canadian solar, type: CS6P-235P) is a device that is used to convert solar energy directly into electrical energy. The cost of a PV module includes the cost of PV panels, charge controllers, and cables. By analyzing the present market cost, the cost of panels is taken ₹60,000 for 1 kW_P generation [15]. Operation and maintenance cost is considered ₹600 per kW per year, and the cost is considered in Indian rupees. The lifetime of a solar PV module has been taken 25 years. Values of the derating factor and ground reflectance are taken as 80% and 20%, respectively. The PV panel system is a fixed one, and no tracking is provided. The tilt angle is considered the same as the latitude of their location.

22.4.2 Battery Bank

The battery bank is used to serve the required load in the absence of both solar PV and diesel generators. The battery bank is used to store the solar PV output during daytime. If the battery bank charging reaches 20%, then the diesel generator starts supplying the load. The Battery (Type: 12VRE-3000TF-L) from Discover Energy has been chosen in the study from the list provided by HOMER. The battery bank bus voltage is 48 V, so 4 batteries are connected in series to form bus voltage. The capital and replacement cost of the battery is considered ₹30,000 per battery. Operation and maintenance cost is considered as ₹600 per battery per year [15].

22.4.3 Diesel Generator

A diesel generator is used to fulfill the load demand when the load is not satisfied by the solar PV power system or when the batteries are discharged. Capital cost for diesel generator is considered as ₹22,600 per kW while replacement and operation and maintenance costs are ₹20,400 per kW and ₹0.50 per hour per kilowatt, respectively [15]. The generator lifetime is considered for 15,000 h, and the fuel curve slope and intercept are taken as 0.2860 and 0.0480, respectively. The Diesel Generator (Type: KG1-5AS) from Kirloskar Brothers Ltd. has been chosen in the study [15].

22.4.4 Power Converter

Any system that contains both AC and DC power requires a bi-directional power converter. A bi-directional power converter is required in a hybrid solar, diesel, and battery bank power system to maintain the flow of energy between DC and AC power components [15]. Capital and replacement costs are both considered ₹18,000 per kW. Operation and maintenance cost per year is considered as ₹180. Lifetime is taken as 15 years with inverter efficiency of 90% and rectifier efficiency of 85% [15].

22.5 Climatic Data

For the optimization process, the present study assesses the important climatic data of solar radiation and clearness index through the National Renewable Energy Laboratory (NREL), USA. The complete details regarding the geographical and radiation intensity at the selected locations are provided in Table 22.1.

22.6 Results and Analysis

For all 27 locations in India, the solar-diesel hybrid energy system is optimized using HOMER software. Results are analyzed in three different categories as Economic analysis, Electrical analysis, and Emission analysis. In the economic analysis, the system is compared on the basis of the LCOE and annualized cost. In the electrical analysis, total power produced by solar PV and diesel generators, excess electricity, and renewable fraction are analyzed. In the emission analysis, operational hours of diesel generator and greenhouse gases emission are analyzed.

Table 22.1 Geographical and radiation intensity at the selected locations

S. no	Location	State	Solar radiation (kWh/ m^2/day)	Clearness index
1	Agartala	Tripura	4.54	0.509
2	Aizawl	Mizoram	4.83	0.541
3	Aurangabad	Maharashtra	5.20	0.562
4	Barmer	Rajasthan	5.74	0.640
5	Bengaluru	Karnataka	5.12	0.528
6	Bhuj	Gujarat	5.36	0.589
7	Bhubaneswar	Odisha	4.81	0.519
8	Bongaigaon	Assam	4.43	0.508
9	Darjeeling	West Bengal	4.65	0.535
10	Dehradun	Uttarakhand	5.22	0.608
11	Guwahati	Assam	4.43	0.504
12	Imphal	Manipur	4.46	0.505
13	Indore	Madhya Pradesh	5.24	0.579
14	Itanagar	Arunachal Pradesh	3.95	0.455
15	Jaisalmer	Rajasthan	5.80	0.650
16	Jodhpur	Rajasthan	5.67	0.635
17	Lucknow	Uttar Pradesh	5.06	0.573
18	Mangalore	Karnataka	4.98	0.517
19	Mumbai	Maharashtra	4.75	0.514
20	New Delhi	–	5.13	0.586
21	Punji	Goa	5.41	0.559
22	Andaman and Nicobar	–	4.42	0.567
23	Raipur	Chhattisgarh	5.21	0.569
24	Siliguri	West Bengal	4.55	0.520
25	Tezpur	Assam	4.27	0.492
26	Tirupati	Andhra Pradesh	5.45	0.562
27	Vadodara	Gujarat	5.22	0.574

22.6.1 Economic Analysis

Optimization of the solar-diesel hybrid energy system is done by using HOMER software. On comparing the results for different locations, it is found that Jaisalmer is the most suitable location for a hybrid energy system followed by Barmer, Jodhpur, Dehradun, and so on. Economically the least favorable location is Itanagar as shown in Table 22.2.

For the Jaisalmer location, the optimum system consists of 59 kW solar PV, 11 kW diesel generator, and 11 kW converter with 92 batteries. The annualized

Table 22.2 Comparative analysis of simulation result

S. No	Location	LCOE (₹/kWh)	Annualized cost (₹/yr)	Production (kWh/yr)	Excess electricity (kWh/yr)	Renewable Fraction (%)	Capacity Factor (%)	Operational hours of DG	Fuel consumption (L/yr)	CO_2 Emission (kg/yr)	CO Emission (kg/yr)
1	Agartala	14.19	1,243,099	107,277	6087	76.39	16.48	2693	7337	19,321	48
2	Aizawl	13.68	1,198,137	109,128	6863	81.09	17.61	2141	5866	15,447	38
3	Aurangabad	13.37	1,171,068	111,815	8998	83.27	18.49	1917	5204	13,705	34
4	Barmer	12.31	1,078,324	117,439	12,808	91.42	20.91	999	2677	7050	17
5	Bengaluru	13.72	1,202,316	109,700	7699	80.06	17.55	2259	6189	16,298	40
6	Bhuj	12.99	1,138,097	113,677	10,303	85.99	19.29	1603	4355	11,469	28
7	Bhubaneswar	13.90	1,217,983	107,613	5827	79.10	16.99	2362	6483	17,071	42
8	Bongaigaon	14.26	1,249,334	106,456	5240	76.43	16.33	2641	7299	19,220	47
9	Darjeeling	13.85	1,213,666	108,399	6412	79.78	17.25	2284	6273	16,518	41
10	Dehradun	12.86	1,126,939	114,374	10,744	87.12	19.62	1473	4003	10,542	26
11	Guwahati	14.32	1,254,329	106,497	5522	75.46	16.17	2810	7632	20,097	50
12	Imphal	14.5	1,248,409	106,900	5879	75.78	16.30	2754	7522	19,808	49
13	Indore	13.17	1,153,775	113,080	9913	84.81	18.98	1738	4724	12,440	31
14	Itanagar	15.18	1,330,023	103,184	3718	68.78	14.43	3534	9688	25,511	63
15	Jaisalmer	12.19	1,067,893	116,509	11,773	91.94	21.18	949	2520	6637	16
16	Jodhpur	12.39	1,085,541	115,469	11,061	90.41	20.72	1121	2994	7884	19
17	Lucknow	13.25	1,160,858	111,160	8121	84.57	18.58	1750	4791	12,615	31
18	Mangalore	13.90	1,218,078	109,303	7643	78.46	17.21	2416	6673	17,571	43
19	Mumbai	14.13	1,237,885	108,434	6876	77.61	16.90	2499	6930	18,248	45
20	New Delhi	13.09	1,147,093	112,307	9076	85.36	18.93	1683	4556	11,997	30

(continued)

Table 22.2 (continued)

S. No	Location	LCOE (₹/kWh)	Annualized cost (₹/yr)	Production (kWh/yr)	Excess electricity (kWh/yr)	Renewable Fraction (%)	Capacity Factor (%)	Operational hours of DG	Fuel consumption (L/yr)	CO_2 Emission (kg/yr)	CO Emission (kg/yr)
21	Panaji	13.16	1,152,911	112,324	9241	84.67	18.82	1765	4773	12,569	31
22	Port Blair	14.86	1,301,940	104,308	4380	71.03	15.02	3272	8987	23,665	58
23	Raipur	13.27	1,162,782	112,324	9241	83.81	18.70	1765	4773	12,569	31
24	Siliguri	14.07	1,232,277	107,279	5692	78.01	16.75	2484	6820	17,960	44
25	Tezpur	14.53	1,273,265	105,654	5081	73.69	15.72	2976	8162	21,493	53
26	Tirupati	13.21	1,157,315	111,753	8818	84.25	18.64	1817	4906	12,918	32
27	Vadodara	13.27	1,162,537	112,898	9931	84.00	18.82	1825	4970	13,088	32

cost of each component, solar PV, diesel generator, battery bank, and converter is ₹303,450, ₹155,383, ₹586,786, and ₹22,276, respectively. Annualized cost for the overall system is ₹1,067,893.

22.6.2 Electrical Energy Analysis

For the proposed solar PV–diesel hybrid energy system, HOMER calculates the power production by solar PV and diesel generator. Power generated by solar PV is used to supply the load, and surplus power is used to charge the battery bank after a full charging of the battery bank the power is the excess power that is dumped. Barmer has 117,439 kWh/year maximum total power production with 12,808 kWh/year highest excess energy. Similarly, Itanagar is having minimum (103,184 kWh/year) of total power production and a minimum (3718 kWh/year) of excess energy, as shown in Table 22.2. The renewable fraction shows the demand fulfilled by solar PV in percentage. Jaisalmer has the highest (91.94%) renewable fraction. Itanagar is having minimum (68.78%) renewable fraction. Barmer is having highest PV penetration and is followed by Jodhpur, Bhuj, and Jaisalmer.

For the Jaisalmer location, total power production is 116509 kWh/year, out of which 11,773 kWh/year is excess electricity. In total power generation, PV penetration is 94%, and only 6% is by the diesel generator. Jaisalmer location has a 59 kW PV array, which produces 109,448 kWh/year of power with a capacity factor of 21.18%. Operational hours of the PV array are 4372 per year. The diesel generator operates 949 hours per year with 155 starts per year.

22.6.3 Emission Analysis

In the proposed solar-diesel hybrid energy system, demand that is not fulfilled by the solar PV system and battery bank is supplied by the diesel generator. A diesel generator is a source of emission of greenhouse gases emission in HES. The emission of greenhouse gases depends on fuel consumption which depends on the operational hours of diesel generators. Itanagar has the highest (3534 h) operational hours of diesel generator, which consumes 9,688 L/year fuel, and emissions of CO_2 and CO are 25,511 kg/year and 63 kg/year, respectively, as shown in Table 22.2.

Due to the better utilization of solar PV in the Jaisalmer location, there is very less utilization of diesel generators, and it will only consume 2520-L fuel per year with a mean electrical efficiency of 28%. The specific fuel consumption of a diesel generator is 0.36 L/kWh. Emissions of CO_2 and CO are 6637 kg/year and 16 kg/year, respectively. Emission of other parameters such as unburned hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxides are 16 kg/year, 2 kg/year, 1 kg/year, and 13 kg/year, respectively. Other suitable locations are Barmer and Jodhpur.

22.7 Sensitivity Analysis

Sensitivity analysis is performed to know the effect of various parameters on system performance. Here, the sensitivity analysis is performed for the eleven fuel prices, five inflation rates, twelve discount rates, six capacity shortages, and eleven project lifetime factors at the most feasible location of Jaisalmer, Rajasthan. Here, Optimization is performed in various phases because of the large number of simulations and forty-five cases of sensitivity analysis. The graphical details of the sensitivity analysis are shown in Fig. 22.2.

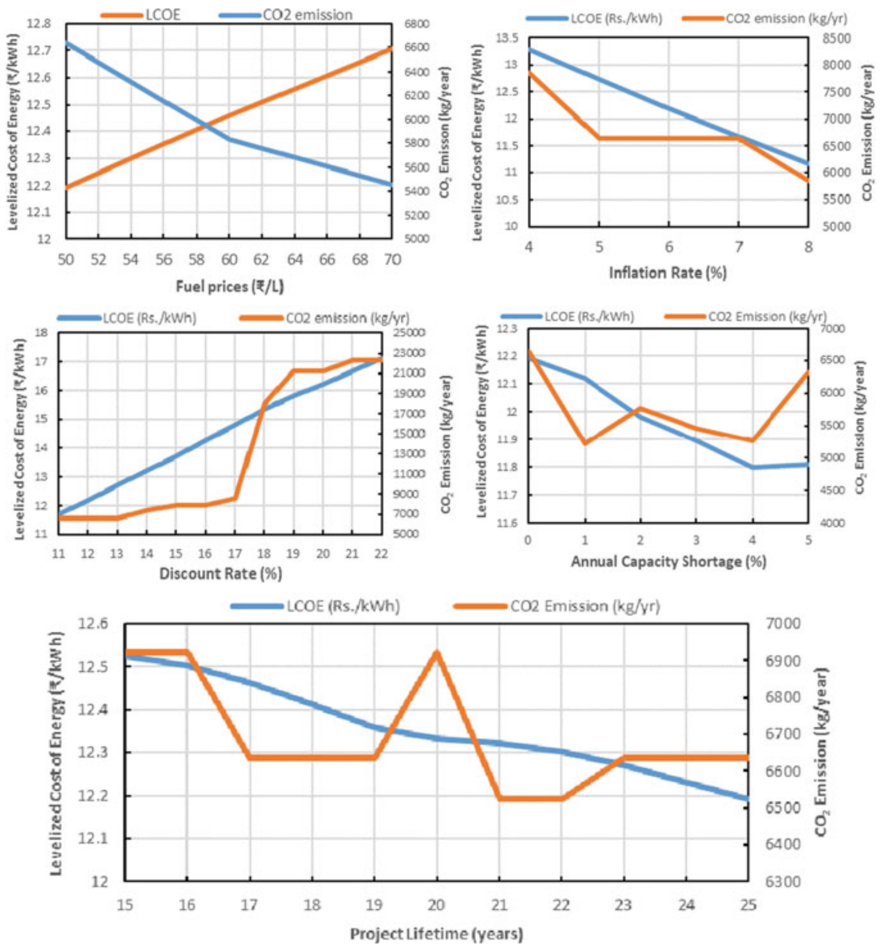

Fig. 22.2 Sensitivity analysis of LCOE and CO_2 emission for fuel price, inflation rate, discount rate, annual capacity shortage, and project lifetime

22.8 Conclusions

This study is mainly done for those applications which are remotely located and independent of the grid connection. Solar PV and diesel generators are considered primary and secondary sources of power generation because of the high solar radiation intensity throughout the country and the diesel generator is a more reliable and dependable standalone secondary source of energy. At all 27 locations, the most suitable location is found by comparing three aspects that are economical, electrical, and emission. These three aspects cover LCOE, annualized cost, total power production, excess electricity, renewable fraction, operational hours of diesel generators, and greenhouse gas emission. By comparing these aspects, the results are as follows.

- Jaisalmer location is found to be the most suitable location with the least LCOE of ₹12.19/kWh and the highest renewable fraction of 91.94%, and Barmer, Jodhpur follows the order.
- Itanagar is found to be the least favorable location, with the highest LCOE of ₹15.18/kWh and a minimum renewable fraction of 68.78%. Port Blair and Tezpur have LCOEs of 14.86 ₹/kWh and 14.53 ₹/kWh, respectively, which is better than Itanagar.

Sensitivity analysis is performed for fuel price, discount rate, inflation rate, annual capacity shortage, and project lifetime. The system behavior is obtained for different parameters, which are as follows.

- As the fuel price increases, the LCOE of the system also increases, but CO_2 emissions will reduce.
- If the discount rate is increased, both the LCOE and CO_2 emissions are increased.
- If the inflation rate is increased, both LCOE and CO_2 emissions are reduced.
- If an annual capacity shortage is considered to be increasing from 0 to 5%, then LCOE decreases, but CO_2 emission will show both increasing and decreasing trends depending on the value of the capacity shortage.
- As the life span of the project is increased, then both LCOE and CO_2 emission decreases.

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