Optimization of 10 kW solar photovoltaic – diesel generator hybrid energy system for different load factors at Jaisalmer location of Rajasthan, India

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Abstract. Jaisalmer town in Rajasthan, India is having annual average solar insolation of 5.80 kWh/m²/day and 270 – 300 clear sky days in a year. A 10 kW off-grid hybrid energy system (HES) consisting of solar photovoltaic panels – diesel generator – bidirectional converter and batteries with zero percentage loss of load for Jaisalmer is designed using HOMER (version 3.4.3) software. Different system load factors of 0.33, 0.50, 0.67, 0.83 and 1 corresponding to fraction of running hours per day of the system are considered. The system is analyzed for all three aspects, namely, electrical, economic and emission point of view. Least levelized cost of electricity (LCOE) of Rs. 8.43/kWh is obtained at a load factor value of 0.5. If diesel generator alone (without Solar PV) is used to fulfill the demand for a load factor of 0.5 the value of LCOE is obtained Rs.19.23/kWh. Comparison of results obtained for HES and diesel generator are made for load factor of 0.5 and 1.

1. Introduction
Rural electrification is an important factor for socio-economic development and quality of life of rural population [1]. Rajasthan state is facing a major problem of rural electrification because of high transmission losses and difficult geographical location. In Rajasthan, approximately 24.65 lakhs rural households lack access to electricity. Around 53% of the non-electrified rural households are located in Jaisalmer, Jodhpur and Udaipur districts of Rajasthan [2]. Jaisalmer district with headquarters of Jaisalmer town is an arid desert region blessed with high solar insolation of 5.80 kWh/m²/day and 270 – 300 clear sky days in a year and situated along the international border on the western part of India. It lies between 26°01’ to 28°02’ North latitude and 69°29’ to 72°20’ East longitudes. According to CENSUS of India (2011) only 562 villages out of 799 villages of Jaisalmer district are electrified [3]. Government of India (GOI) and state governments are working in tandem for rural electrification under DeenDayal Gram JyotiYojna (DDGY). Various schemes in the past to address this problem are Remote Village Electrification Program (2003), Village Energy Security (2004), Rajiv Gandhi Grameen Vidyutikaran Yojna (2005) and Jawaharlal Nehru National Solar Mission (2010) [4]. Strategically Solar energy plays a vital role to produce power. However due to intermittent nature of solar power, a secondary source of energy is required to supply power continuously. Diesel generator is most preferable secondary energy source due to its ease of use as an off-grid standalone power generation [5]. In this study, a standalone HES combining solar Photovoltaic panels – diesel generator – bidirectional converter is used to fulfill the load demand with zero percentage loss of load. System is optimized using HOMER (Hybrid Optimization of Multiple Energy Resources, version 3.4.3) software that is developed by HOMER Energy LLC, USA.
2. Literature survey
Various researchers designed and analyzed the hybrid energy systems (HES) for rural electrification. They analyzed for different climatic conditions and studied the effect of various parameters. Rehman and Hadhrami [6] proposed HES for a non-electrified village located in the district Rafha of Saudi Arabia. They considered solar photovoltaic – diesel generator and batteries in the HES. They obtained 200 kW solar PV, four diesel generators of rated capacity 250 kW, 750 kW, 1250 kW and 2250 kW and 300 kW converter with 300 batteries for storage as an optimum combination. They obtained LCOE of 0.2 $/kWh and estimated a saving of 66,422 tons of emission of greenhouse gases into the local atmosphere. Ghasemi et al. [7] analyzed solar PV – diesel generator HES for remote village Khavar-E-Bala, located in north eastern part of Iran. When the electrical power demand is fulfilled by diesel generator the LCOE of 0.304 $/kWh was obtained. If the electrical power demand fulfilled by hybrid energy system, the LCOE of 0.430 $/kWh with 35 % of renewable fraction. Rezzouk and Mellit [8] developed solar PV – diesel generator HES for a research unit of Algeria. They obtained 75 kW diesel generator, 23 kW solar photovoltaic panels and 170 kWh battery storage system as optimum combination with least LCOE of 0.260 $/kWh. Hafez and Bhattacharya [9] proposed a HES to electrify a rural community. They found least LCOE of 0.278 $/kWh is given by a combination of diesel renewable optimum combination. Barzola et al. [10] proposed HES for a remotely located rural community. The optimum system is having 5.33 kW solar photovoltaic panels, 10 kW diesel generator, 7 wind turbines, 5.33 kW bi-directional converter and 48 storage batteries. They obtained least LCOE of 0.281 $/kWh for an optimum system. Kanase Patil [11-13] proposed HES model for seven unelectrified villages of Ranikhet tehsil located in Almora district of Uttrakhand, India. They optimized system using HOMER, LINGO 10 and C++ compiler software. They analyzed the system for various reliability index values of 0.95, 0.99, 0.999, and 1. As a source of power, they used micro hydro, biogas, wind turbines, solar PV, rice husk and wood based biomass gasifier.

3. Electrical energy demand
System is analyzed for 10 kW electrical load with zero percentage loss of load. Electrical load is calculated as shown in Table 1.

| S. No. | Electrical Load (kW) | Load Hours per day | Electrical Energy (kWh) | Load Factor |
|-------|----------------------|--------------------|-------------------------|-------------|
| 1.    | 10 kW                | 10.00 am to 6.00 pm = 8 hours | 80                      | 0.33        |
| 2.    | 10 kW                | 6.00 am to 6.00 pm = 12 hours | 120                     | 0.50        |
| 3.    | 10 kW                | 4.00 am to 8.00 pm = 16 hours | 160                     | 0.67        |
| 4.    | 10 kW                | 2.00 am to 10.00 pm = 20 hours | 200                     | 0.83        |
| 5.    | 10 kW                | 24 hours           | 240                     | 1.00        |

4. Solar radiation intensity
Annual average solar insolation and clearness index are 5.80 kWh/m²/day and 0.65 respectively as shown in Figure 1. Solar insolation and clearness index are taken from NREL using latitude of 26°54’94” N and longitude of 70°54’50” E for the location of Jaisalmer town, Rajasthan, India.
Figure 1. Monthly variation of solar insolation and clearness index for particular location of Jaisalmer, Rajasthan, India.

5. Economical and technical details of components
In this study, solar photovoltaic panels, diesel generator, bidirectional converter and batteries are considered in the HES to fulfill the load demand without any interruption. Schematic arrangement of HES is shown in Figure 2.

5.1. Photovoltaic panels
Photovoltaic panels are used to convert solar energy directly into electrical energy. By analyzing present market cost, capital and replacement cost of photovoltaic panel is considered as Rs. sixty thousand for 1 kWp. Operation and maintenance cost of solar PV system is considered Rs. six hundred per kilowatt per year. All costs are considered in Indian Rupees (1 $ = Rs. 66.98). Values of ground reflectance and derating factor are taken as 20 % and 80 % respectively and lifetime of solar Photovoltaic panel is considered as 25 years.

5.2. Diesel generator
Diesel generator is the most dependable and preferable secondary source of energy. So in this study, it is taken as a secondary source of energy. Capital cost of diesel generator is considered as Rs. twenty two thousand six hundred per kilowatt and replacement cost is considered as Rs.twenty thousand four hundred per kilowatt. Operation and maintenance cost is considered as Rs. 0.50 per hour per kilowatt. Lifetime of diesel generator is considered as 15, 000 hours [14].

5.3. Batteries
Batteries are used to store the solar photovoltaic panels output during the day time and to serve the load in the absence of solar energy. In this study, 12 V and 245 Ah capacity battery is chosen. Suggested life throughput of battery is considered as 3,550 kWh. Capital and replacement costs are
considered as Rs. thirty thousand per battery. 2 percent of capital cost per annum per battery is considered as operation and maintenance cost.

5.4. Bi-directional converter
A bidirectional converter is considered in this study to convert both AC and DC power. Capital and replacement costs are considered Rs. eighteen thousand per kilowatt while operation and maintenance cost is considered as Rs. one hundred eighty per year per kilowatt. Lifetime of the bi-directional converter is considered as 15 years with 90% inverter efficiency.

6. Result and discussion
HES is analyzed for different load factors of 0.33, 0.5, 0.67, 0.83 and 1 and results are given in Table 2. Results are discussed covering three major aspects:

6.1. Electrical analysis
This aspect covers total PV power generation, PV penetration, renewable fraction, excess electricity, capacity shortage and unmet load. As the load factor increases, total power generation by the system is continuously increases. Maximum excess electricity of 14,144 kWh/yr is obtained at a load factor of 0.33 after that it starts decreasing. At load factor of 0.67, minimum excess electricity of 9636 kWh/yr is obtained. Maximum renewable fraction of 96.58% is obtained at a load factor of 0.33 due to operation in only sunshine hours.

Figure 3. Total PV power generation and excess electricity for different load factors
Figure 4. Levelized cost of electricity and annualized cost for different load factors.

6.2. Economic analysis
This aspect covers LCOE, annualized and operating cost of the system. Least LCOE of Rs. 8.43/kWh is obtained for load factor of 0.5. LCOE at various load factors of 0.3, 0.5, 0.67, 0.83 and 1 are Rs. 8.90/kWh, Rs. 8.43/kWh, Rs. 10.21/kWh, Rs. 11.37/kWh and Rs. 12.19/kWh respectively. As load factor increases fraction of demand fulfilled by diesel generator increase so the various costs such as LCOE, operating cost and annualized costs are increased with increase in load factor. For load factor of 0.5, annualized cost, operating cost and LCOE are Rs. 369362, Rs. 38112 and Rs. 8.433/kWh respectively.

Table 2. Comparison of various parameters of hybrid energy system for different load factors.

| S. No. | Description | Components | 0.33 | 0.5 | 0.67 | 0.83 | 1 |
|--------|-------------|------------|------|----|------|------|---|
| 1.     | Capacity (kW) | Diesel Generator | 9 | 10 | 11 | 11 | 11 |
|        |              | Solar Photovoltaic | 25 | 32 | 40 | 49 | 59 |
|        |              | Converter | 11 | 11 | 11 | 11 | 11 |
|        |              | Batteries | 16 | 24 | 48 | 68 | 92 |
| 2.     | Production (kWh/year) | Total Electricity | 47374 | 61462 | 77807 | 96545 | 116509 |
|        |              | Excess Electricity | 14144 | 11491 | 9636 | 10211 | 11773 |
|        |              | Unmet Load | 7 | 0 | 0 | 0 | 0 |
|        |              | Capacity Shortage | 27 | 31 | 0 | 0 | 0 |
| 3.     | Renewable Fraction (%) | | 96.58 | 95.21 | 93.83 | 92.26 | 91.94 |
| 4.     | Cost | Annualized Cost (Rs./yr) | 259928 | 369362 | 596168 | 827532 | 1067893 |
|        |        | LCOE (Rs./kWh) | 8.90 | 8.43 | 10.21 | 11.37 | 12.19 |
|        |        | Operating Cost (Rs./yr) | 27736 | 38115 | 58310 | 76690 | 97799 |
| 5.     | Fuel | Fuel Consumption (L/yr) | 396 | 844 | 1353 | 2048 | 2520 |
|        |        | Hours of Operation (hrs/yr) | 257 | 507 | 609 | 820 | 949 |
| 6.     | Battery Life (years) | | 10 | 9 | 7 | 7 | 6 |
| 7.     | Emission | CO₂ (kg/yr) | 1044 | 2223 | 3562 | 5394 | 6637 |
|        |        | CO | 3 | 5 | 9 | 13 | 16 |

6.3. Emission analysis
This aspect covers operational hours of diesel generator, fuel consumption, battery life and emission of greenhouse gases. During sunshine hours, the power by solar photovoltaic panels is directly used to fulfill the demand and remaining portion of power is saved in batteries. Battery storage power is supplied during absence of solar energy and remaining demand is satisfied by diesel generator. For load factor 1, a major fraction of demand is satisfied by diesel generator which in turn increases operational hours of diesel generator, fuel consumption, greenhouse gases emission.

![Operational Hours of Diesel Generator and CO2 Emission for Different Load Factors](image)

**Figure 5.** Operational hours of diesel generator and CO2 emission for different load factors.

7. **Comparison between hybrid energy system and standalone diesel generator for a load factor of 0.5 and 1**

HES and standalone diesel generator are compared on the basis of LCOE, annualized cost, excess electricity, renewable fraction and CO2 emission. LCOE for HES and standalone diesel generator are Rs. 12.19/kWh and Rs. 19.12/kWh respectively. Annualized costs of HES and standalone diesel generator are Rs. 1067893 and Rs. 1675283 respectively. (Rs. 68 = 1 $ approx.)

HES produces total 116509 kWh/yr power out of which 11773 kWh/yr is excess energy that is neither directly used nor stored. Diesel generator produces 87600 kWh/yr power same amount of electrical load so zero excess electricity or capacity shortage.

Diesel generator consumes 29681 litre fuel per year by running 8760 hours per year and HES consumed only 2520 litre fuel per year. CO2 emission is proportional to the fuel consumption. As standalone diesel generator consumed more fuel. So, CO2 emission by standalone diesel generator (78160 kg/yr) is 91.51% more than the HES.

Similar comparison can be made for other values of load factor also. Table 3 shows the comparison between HES and standalone diesel generator for load factor values of 0.5 and 1.

**Table 3.** Comparison between hybrid energy system and standalone diesel generator for load factor values of 0.5 and 1

| S. No. | Description                  | Load Factor of 0.5 | Load Factor of 1 |
|-------|------------------------------|--------------------|------------------|
|       |                              | HES                | Diesel System    | HES              | Diesel System |
| 1.    | Capacity of components       |                    |                  |
|       | Diesel generator (kW)        | 10                 | 11               |
|       | Solar PV (kW)                | 32                 | -                |
|       | Converter (kW)               | 11                 | -                |                  |
| 2.    | Emissions                   |                    |                  |
|       | CO2 (kg/yr)                  | 2223               | 38768            |
|       | CO (kg/yr)                   | 5                  | 293              |
|       | CO2 (kg/yr)                  | 6637               | 78160            |
| 3.    | Production                  |                    |                  |
|       | Electricity (kWh/yr)         | 61462              | 43800            |
|       | Excess Electricity (kWh/yr)  | 11491              | 0.00             |
|       |                              | 116509             | 87600            |
| 4.    | Cost                         |                    |                  |
|       | LCOE (Rs./kWh)               | 8.43               | 19.23            |
|       |                              | 12.19              | 19.12            |
5. Fuel

|                | Annualized Cost (Rs.) |
|----------------|-----------------------|
| Fuel Consumption (L/yr) | 369362    |
| Hours of operation (hrs./yr) | 842267    |
|                | 1067893    |
|                | 1675283    |

6. Battery

|                | Expected life (yr) |
|----------------|-------------------|
|                | 9                 |
|                | -                 |
|                | 7                 |
|                | -                 |

### 8. Conclusions

Hybrid energy system analysis for a particular location of Jaisalmer town, Rajasthan, India shows that for different electrical load factors of 0.33, 0.5, 0.67, 0.83 and 1. Maximum and minimum excess electricity are 14144 and 9639 kWh/yr obtained for load factor of 0.33 and 0.67 respectively. Maximum renewable fraction is 96.58% obtained for load factor of 0.33, due to duration of electrical demand is in only sunshine hours. Least LCOE of Rs. 8.43/kWh is obtained at a load factor of 0.5. LCOE for load factors of 0.33, 0.5, 0.67, 0.83 and 1 are Rs. 8.90/kWh, Rs. 8.43/kWh, Rs. 10.21/kWh, Rs. 11.34/kWh and Rs. 12.19/kWh respectively. Maximum emission of greenhouse gases CO₂ and CO are 6637 kg/yr and 16 kg/yr respectively at a load factor of 1. Comparison of HES with standalone diesel generator covering all three aspects namely economic, electrical and emission for a load factor of 0.5 and 1 shows that HES performed better than standalone diesel generator.

### 9. References

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