Comparison of Various Off–Grid Power System Models for a 10 kW Load at Jaipur in Rajasthan

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***Abstract*—A 10 kW hypothetical load is considered with zero percent loss of load for off – grid, Jaipur. Load is fulfilled with the help of possible combination of components such as solar PV, diesel generator, battery bank and converter. Four models are formed with the combination of components namely (a) only diesel generator (b) solar PV – converter – batteries (renewable system) (c) solar PV – diesel generator – converter (d) hybrid energy system consisting of solar PV - diesel Generator – battery bank and converter. All the models are simulated using HOMER software. Simulation results of models are compared on the basis of economic, electrical and emission aspects. From the simulation results of HOMER, hybrid energy system performs better in all the aspects. Sensitivity analysis is performed for hybrid energy system by varying (i) fuel price and (ii) global solar radiation.**

Keywords—solar PV; diesel generator; hybrid energy system; LCOE; sensitivity analysis

I. INTRODUCTION

A Hybrid Energy System (HES) is a combination of multiple sources of energy such as renewable energy and diesel generator and may also include energy storage such as battery. As an off grid power generation system, the hybrid systems are efficient and gives clean power that will in many cases be more cost effective than diesel systems. As a result, renewable energy options have become the preferred solutions for off grid power generation [1].

In this study, four models namely (a) only diesel generator (b) solar PV – converter – batteries (renewable system) (c) solar PV – diesel generator – converter (d) hybrid energy system consisting of solar PV - diesel Generator – battery bank and converter have been studied. The systems were studied assuming that they are located at Jaipur, Rajasthan.

Amutha and Rajini [2] designed a hybrid system for a small village kadayam in Tirunelveli district in the Tamilnadu, India. They performed the simulation for various possible (seven) configurations using solar PV, diesel generator, hydro generator, wind turbine and battery bank. By analyzing and comparing, they found that the best configuration was a combination of solar PV, wind turbine, hydro generator and battery bank with lowest levelized cost of energy of 0.111 $/kWh. Ankit Bhatt et al. [3] designed a Hybrid Energy System (HES) for five unelectrified villages of Almora district of Uttarakhand, India. They analyzed the system by using HOMER for an annual average load of 581 kWh/day or 55 kW peak load. They formulated four models namely (a) micro-hydro/SPV/biomass/biogas/diesel generator/battery, (b) SPV/ diesel generator/ battery (c) diesel/battery (d) SPV/battery. They found that the best combination was micro-hydro/SPV/biomass/biogas/diesel generator/battery with lowest Levelized Cost of Energy (LCOE) of 0.197 $/kWh and 94 % of maximum renewable fraction. Hafez and Bhattacharya [4] proposed a HES for a hypothetical load profile for a rural community. They considered annual average load of 500 kWh/day and thermal load is assumed 5 % of annual average load. They proposed four different cases including diesel only, a fully renewable based system, a diesel renewable combination and an external grid connected. They found diesel renewable combination as the best combination of HES with 53.08 % renewable fraction. Alireza et al. [5] designed a HES for three different locations of Colombia. They formed seven different models with solar PV, wind turbine, diesel generator and batteries. Two locations were having solar/diesel as the best combination and one having solar/diesel/wind as the best combination. All the three locations having only wind turbine and only diesel generator were least favorable option. Bahtiyar Dursun [6] proposed a HES for kavakli campus of kirklareli university, Turkey. They formed four different combinations of solar PV, fuel cell, diesel generator, grid connection and batteries common in all the system. They found grid and solar PV combination having least LCOE of 0.256 $/kWh. Abdirahman Mohamed Abdilahi et al. [7] designed a HES with a hypothetical annual average load of 1283 kWh/day for Hargeisa, Somaliland's major urban center. They analyzed and compared between hybrid system (PV/wind/diesel) and only diesel system. They found hybrid system is better with least LCOE of 0.288 $/kWh and they also performed sensitivity analysis for variation in solar radiation, wind speed, diesel fuel price and load demand.

In this study, simulation, optimization and sensitivity analysis has been done by using version 3.4.3 of HOMER software developed by National Renewable Energy Laboratory (NREL).

II. COST AND OTHER DETAILS OF COMPONENTS

The system is designed for a constant load of 10 kW (240 kWh/day) with zero percentage loss of load for a particular location of Jaipur, Rajasthan (India) using various available energy models such as only diesel generator, renewable

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system, solar – diesel system and hybrid energy system. Solar radiation intensity and clearness index are 5.43 kWh/m^2/day and 0.61 respectively taken form NREL using latitude and longitude of location as shown in Fig. 1.

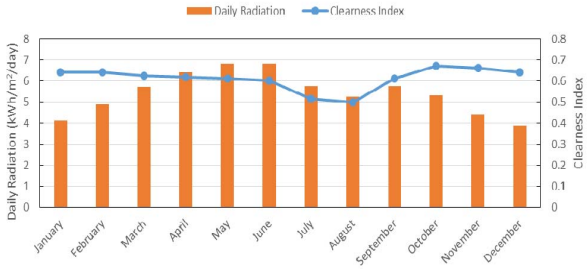

Fig. 1. Daily solar radiation and clearness index for Jaipur location.

A. Solar Photovoltaic System

In this study, solar PV is used as a renewable energy source. Capital cost of solar PV panel is taken as Rs. 60,000 /kW and operation & maintenance cost is taken as 1% of capital cost per annum. Life of solar PV system is taken as 25 years.

B. Diesel Generator System

In this study, a diesel generator with a life of 15,000 hours is used for continuous power supply in the absence of solar energy. Capital cost and replacement cost are taken as Rs. 22,600 and Rs. 20,400 per kW respectively. And operation & maintenance cost is taken as Rs. 0.50 per hour per kilowatt respectively [8].

C. Battery Bank System

In this study, battery bank is used for backup energy in the absence of both solar PV and diesel generator. Both capital and replacement cost of one battery is taken as Rs. 30,000. Operation & maintenance cost is taken as 2% of capital cost per annum per battery. The discover energy battery (12VRE – 3000TF-L) is taken into consideration which is having 245 Ah capacity and 12V voltage. Lifetime throughput of battery is taken as 3,550 kWh.

D. Converter System

Converter is used to convert the AC current to DC current and vice – versa. Both capital and replacement cost are considered Rs. 18,000 per kilowatt. And operation & maintenance cost is taken 1% of capital cost per annum per kilowatt.

After specifying the load demand, energy source, component details, global solar radiation and diesel price HOMER simulation optimized the capacity of energy source for each configuration which are as follows.

- For diesel only system a 11 kW diesel generator is required.
- For renewable system 98 kW solar PV and 11 kW converter and 272 batteries are required.
- For solar PV – diesel generator system 41 kW solar PV, 11 kW diesel generator and 11 kW converter are required.
- For HES 60 kW solar PV, 11 kW diesel generator, 11 kW converter and 92 number of batteries are required.

III. Only Diesel Generator System

In this system to fulfill the load, diesel generator is used as shown in Fig. 2. When the load is constant, then the diesel generator be a good option for power supply. Because at full load the diesel generator performance is better.

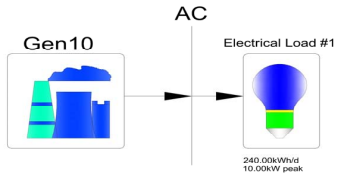

Fig. 2. System Configuration of only diesel generator system in HOMER.

A. Economical Analysis

For diesel generator system Levelized Cost of Energy (LCOE) is obtained as 19.12 Rs./kWh and annualized cost of energy is obtained as Rs. 16,75,283.

B. Electrical Analysis

The diesel generator produces 87,600 kWh/year electricity same as the demand of the system with zero excess electricity, unmet load and capacity shortage. As all the power produced by the diesel generator renewable fraction is zero.

C. Emission Analysis

Fuel consumption for diesel generator is 29681 Litre/year with 0.34 Litre/kWh specific fuel consumption. And the mean electric efficiency is 30 percent. CO_2 emission of the system is 78160 kg/year and emission of other parameters such as carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide and nitrogen oxides are 193 kg/year, 21 kg/year, 15 kg/year, 157 kg/year and 1722 kg/year respectively.

IV. Renewable Energy System

In this system load is fulfilled by a complete renewable system as shown in Fig. 3. Solar PV is used as a source which supply electricity to load and excess is used to charge the battery bank. In the absence of solar energy, battery bank is used to serve the load.

A. Economic Analysis

Levelized cost of energy and annualized cost of the system are 16.832 Rs./kWh and Rs. 14,73, 233 respectively.

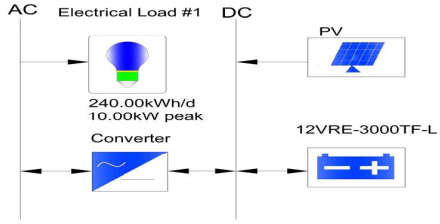

Fig. 3. System configuration of renewable energy system in HOMER.

B. *Electrical Analysis*

The system produces total 170894 kWh/year power out of which 64,424 kWh/year is excess electricity. And unmet and capacity shortage are 75 kWh/year and 87 kWh/year respectively. Mean output of PV system is 20 kW with capacity factor of 19.91 percent. Battery bank is having 56 hours autonomy. That means battery bank is capable to survive load till 56 hours.

C. *Emission Analysis*

The system is completely renewable system so the emission of greenhouse gases and other parameters are zero.

V. Solar PV and Diesel Generator System

In this system a combination of solar PV and diesel generator are used. The system demand is fulfilled by solar PV but in the absences of solar PV the load is fulfilled by diesel generator.

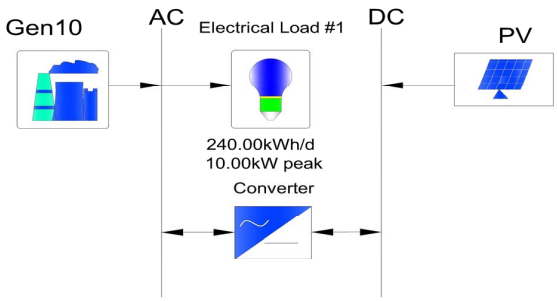

Fig. 4. System configuration of solar – diesel energy system in HOMER.

A. *Economic Analysis*

LCOE and annualized cost of the system obtained are 15.306 Rs./kWh and Rs. 13,40, 788 respectively.

B. *Electrical Analysis*

The system produces a total of 126457 kWh/year electrical energy out of which 71,496 kwh/year produced from solar PV system. System having 35,231 kWh/year excess energy with zero unmet load and capacity shortage. Solar PV produces 57 percent and diesel generator produces 43 percent of the total energy production. Rated capacity of PV system is 41 kW and mean output is 195.88 kWh/day with a capacity factor of 19.91 percent.

C. *Emission Analysis*

Diesel generator is secondary source of power so it will consume 19218 Litre/year fuel with operational hours of 6628 hours/year. And the CO_2 and CO emission are 50609 kg/year and 125 kg/year respectively.

VI. Hybrid Energy System

In the hybrid energy system two sources namely solar PV and diesel generator are used with energy storage in the battery bank.

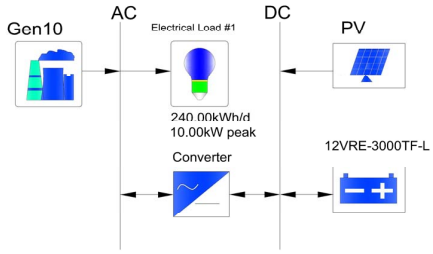

Fig. 5. System configuration of hybrid energy system in HOMER.

A. *Economic Analysis*

According to given input cost of components, the LCOE and annualized cost obtained are 12.681 Rs./kWh and Rs. 11,10,891.

B. *Electrical Analysis*

Total electricity generation by the hybrid energy system is 114600 kWh/year out of which 104629 kWh/year by solar PV system and remaining 9971 kWh/year is by diesel generator. System produces 10624 kWh/year excess electricity with zero unmet load and capacity shortage. Battery system having 19 hours autonomy. That means battery bank is capable to fulfill load till 19 hours.

C. *Emission Analysis*

In the hybrid system, emission of CO_2 gas is 9345 kg/year with 3549 Litre/year fuel consumption. And emission of other parameters such as carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide and nitrogen oxides are 23 kg/year, 3 kg/year, 2 kg/year, 19 kg/year and 206 kg/year respectively.

VII. Comparison of Results for Four Different Models

If a comparison made for various available models then the comparison is done mainly on the basis of economic, electrical and emission analysis.

A. *Economic Analysis*

When all the energy models are compared economically the HES gives least LCOE of 12.681 Rs./kWh. LCOE of diesel generator, renewable system, solar and diesel system are 19.124 Rs./kWh, 16.832 Rs./kWh and 15.306 Rs./kWh respectively. Annualized cost of the diesel system, renewable system, solar PV – diesel generator system, hybrid energy system are Rs. 16,75,283, Rs. 14,73,233, Rs. 13,40,788 and Rs. 11,10,891 respectively. Hybrid energy system is economically better than other models.

B. *Electrical Analysis*

If electrical point of view, all the models are compared then renewable system produces 170894 kWh/year electrical power which is more than the other models but it is also having 64424 kWh/year excess electricity. Only renewable system having unmet load and capacity shortage which are 75 kWh/year and 87 kWh/year respectively. Diesel generator system produces same energy as demand, so it is having zero excess electricity, unmet load and capacity shortage.

TABLE I. COMPARISON OF FOUR MODELS CONSIDERED

S. No.	Description		PV and Battery	Solar and diesel	HES	Diesel System
1.	Diesel generator (kW)		-	11	11	10
	Solar system (kW)		98	41	60	_
	Inverter (kW)		11	11	11	_
2.	Emissions (kg/ yr)	CO_2 (kg/yr)	-	50609	9345	78160
		CO (kg/yr)	-	125	23	193
3.	Production	Electricity (MWh/yr)	170.89	126.46	114.60	87.60
		Excess Electricity (MWh/yr)	64.42	35.23	10.62	0.00
4.	Cost	LCOE (Rs./kWh)	16.832	15.306	12.681	19.124
		Annualized Cost (Lakhs)	14.73	13.40	11.10	16.75
5.	Fuel	Fuel Consumption (L/yr)	-	19218	3549	29681
		Hours of operation (hrs./yr)	-	6628	1320	8760
6.	Battery	Energy in (kWh/yr)	62293	-	52967	-
		Energy out (kWh/yr)	53070	-	45215	-
		Storage depletion (kWh/yr)	36	-	178	-
		Losses (kWh/yr)	9186	-	7574	-
		Annual throughput (kWh/yr)	57563	-	49042	-
		Expected life (yr)	17	-	7	-

C. *Emission Analysis*

If systems are compared on the basis of emission point of view, then diesel generator emission is more than the other systems. Emission of CO_2 of diesel system, renewable system, solar PV – diesel generator system, hybrid energy system are 78160 kg/year, 0.00 kg/year, 50609 kg/year and 9345 kg/year respectively. Minimum generation of CO_2 (zero) is by renewable energy system. Emission of CO_2 increases in the order for the remaining three systems as follows; hybrid system, solar – diesel system and diesel generator system. Fuel consumption for Diesel generator, solar – diesel generator system and hybrid system are 29681 Litre/year, 19218 Litre/year and 3549 Litre/year respectively.

VIII. SENSITIVITY ANALYSIS

Sensitivity analysis is essential because it provides the information about the system behavior under the random changes in the system parameters. Sensitivity analysis is performed for the hybrid energy system because it gives better results as compared to other combinations. Sensitivity analysis is performed for variation in fuel price and global solar radiation.

A. *Effect of Fuel Price*

To know the effect of fuel price on the hybrid energy system, sensitivity analysis is performed. Analysis has been carried out for three fuel prices 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre. As the fuel price is increased the LCOE of the system is increased. The LCOE will become 12.681 Rs./kWh, 13.071 Rs./kWh and 13.438 Rs./kWh at fuel price of 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre respectively as shown in Table II.

TABLE II. EFFECT OF FUEL PRICE VARIATION ON VARIOUS ASPECTS OF SYSTEM

S. No.	Description	Fuel Cost (Rs./Litre)		
		50	60	70
1.	LCOE (Rs./kWh)	12.681	13.071	13.438
2.	Excess Electricity (kWh/yr)	10624	10003	9473
3.	Renewable Fraction (%)	91	92	92
4.	Operational hours of DG	1320	1236	1171
5.	Fuel Consumption (L/yr)	3549	3365	3211
6.	CO_2 emission (kg/yr)	9345	8860	8455

As the fuel prices are increased the LCOE of the system is increased but fuel consumption decreases. The fuel consumption is 3549 Litre/year, 3365 Litre/year and 3211 Litre/year at 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre respectively as shown in Fig. 6.

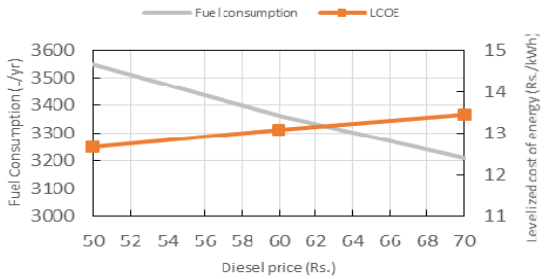

Fig. 6. Effect of diesel price variation on the fuel consumption and LCOE.

As the diesel prices increase the fuel consumption reduces consequently the CO_2 emissions reduces. CO_2 emissions at fuel price 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre are 9345 kg/year, 8860 kg/year and 8455 kg/year respectively. And excess electricity produced are 10624 kWh/year, 10003 kWh/year and 9473 kWh/year at fuel price 50 Rs./L, 60 Rs./L and 70 Rs./L respectively as shown in Fig. 7.

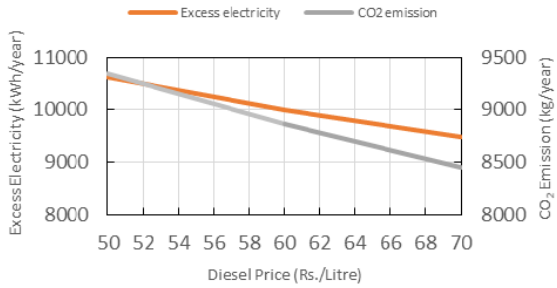

Fig. 7. Effect of diesel price variation on the excess electricity production and CO_2 emission.

B. *Effect of Global Solar Radiation*

The efficiency of solar PV panel depends on the intensity of solar radiation. When the solar radiation increases the power produced by the PV system increases and consequently utilization of diesel generator decreases. Thus, the contribution of solar energy in the hybrid system depends on the global solar radiation (GSR) received and captured on the surface of the PV panels. For sensitivity analysis, 7 different values of GSR is considered from a range of 5.0 kWh/m^2/day to 6.5 kWh/m^2/day with an interval of 0.25 kWh/m^2/day. The results are shown in the Table III.

As the solar radiation increases the LCOE of the system decreases because of better utilization of Solar PV panels. The least value of LCOE is 12.01 Rs./kWh at solar radiation level of 6.50 kWh/m^2/day.

TABLE III. EFFECT OF GLOBAL SOLAR RADIATION ON VARIOUS ASPECTS OF SYSTEM

S. N0.	Description	Global Solar Radiation (kWh/m^2/day)						
		5.0	5.25	5.50	5.75	6.00	6.25	6.50
1.	LCOE (Rs./kWh)	13.12	12.84	12.62	12.45	12.29	12.14	12.01
2.	Excess electricity (kWh/yr)	4590	7518	11639	13933	15920	15546	13796
3.	Renewable Fraction (%)	88	91	92	93	93	93	93
4.	Capacity Factor (%)	18.17	19.18	20.19	21.17	22.08	22.85	23.35
5.	Operational hours of DG	1660	1381	1271	1158	1069	1043	1032
6.	Fuel consumption (Litre/yr)	4427	3737	3420	3138	2904	2833	2800
7.	CO_2 emission (kg/yr)	11658	9841	9006	8263	7648	7460	7373

Global solar radiation is having effect on renewable fraction and CO_2 emission. Maximum renewable energy fraction of 93 % is achieved at a solar radiation level of 5.75 kWh/m^2/day. Renewable fraction is constant till 6.5 kWh/m^2/day beyond 5.75 kWh/m^2/day. CO_2 emission decreases with increase in global solar radiation as shown in Fig. 8.

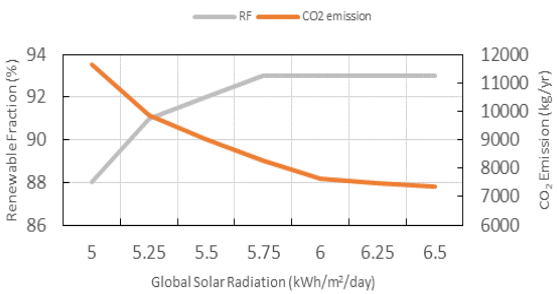

Fig. 8. Effect of global solar radiation variation on renewable fraction and CO_2 emission.

IX. CONCLUSIONS

I. For a 10 kW hypothetical load four different off grid energy models are designed and analyzed using HOMER software. By comparing four models it was found HES performs better and diesel only system is less favourable.

II. Composition of models are as follows, (a) only diesel generator system (b) renewable system (c) solar PV – diesel generator system and (d) hybrid energy system.
- LCOE obtained for models a, b, c and d are 19.124 Rs./kWh, 16.832 Rs./kWh, 15.306 Rs./kWh and 12.681 Rs./kWh respectively.
- Total electricity generated from models a, b, c and d are 87600 kWh/year, 170894 kWh/year, 126457 kWh/year and 114600 kWh/year respectively.
- And excess electricity from models a, b, c and d are 0.00 kWh/year, 64424 kWh/year, 35231 kWh/year, 10624 kWh/year respectively.
- Fuel consumption for models a, b, c and d are 29681 Litre/year, 0.00 Litre/year, 19218 Litre/year, 3549 Litre/year respectively.
- CO_2 emission for models a, b, c and d are 78160 kg/year, 0.00 kg/year, 50609 kg/year, 9345 kg/year respectively.

III. Sensitivity analysis is performed for fuel price 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre. LCOE at 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre are 12.681 Rs./kWh, 13.071 Rs./kWh and 13.438 Rs./kWh respectively.
- CO_2 emission at fuel prices 50 Rs./Litre, 60 Rs./Litre and 70 Rs./Litre are 9345 kg/year, 8860 kg/year and 8455 kg/year respectively.

IV. Sensitivity analysis is also performed for variation in global solar radiation in the range of 5.0 to 6.50 kWh/m^2/day.

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