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RESEARCH ARTICLE

TECHNO-ECONOMIC ANALYSIS OF OFF-GRID AND GRID-CONNECTED SPV-WIND-DIESEL HYBRID ENERGY SYSTEMS

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ABSTRACT

In this study, two scenarios of hybrid energy systems are considered each contains a different combination of solar photovoltaic (SPV), wind turbine (WT), diesel generator (DG set), converter system and storage battery in off-grid mode and grid-connected mode. In this study, Hybrid Optimization Model for Electric Renewable (HOMER) software is used for financial and technical analysis of the system. The optimal size of off-grid and grid-connected hybrid energy system having SPV-wind-diesel-battery has been calculated based on solar radiation, hourly wind data and electricity demand for the site under study. The simulation results shows that in case of off-grid optimal hybrid system having a cost analysis as cost of energy (COE) of \$0.320/kWh, net present cost (NPC) of \$294028, operating cost of \$8014, and initial capital cost of \$190430 whereas for grid-connected system cost analysis are COE of \$0.108/kWh, NPC of \$99746, operating cost of \$7001, initial capital cost of \$9245. These costs are for energy demand of 195kWh/day and peak load of 28 kW for institutional loads. The results clearly indicate that the grid-connected hybrid system is best from an economic point of view and the off-grid system is suitable from the environmental point of view.

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INTRODUCTION

Energy is the important factor in the transformation phase towards modernization and development of any nation. Energy demand is increasing day by day due to enhancement in the living standards and growing population. Today the major challenge in energy sector is to fulfill this rising energy demand without fully exhausting the conventional resources (fossil fuel) and also avoid environmental degradation (Usman *et al*. 2017). At present, power generation in India is not enough to fulfill the energy demand. The conventional fossil fuel-based electric power generation is not sufficient to fulfill this huge demand of electrical energy. Therefore at present, there is a big gap between energy demand and supply of electrical energy in India. The reason is the less number of generating stations and availability of poor quality of coal, uranium, etc. Also, it is estimated that these fossil fuels could last around 200 years. There are number of harmful environmental effects of fossil fuel based electricity generation such as global warming, air pollution, acid rain, etc. (Imdadullah *et al*., 2006; Kumar *et al*., 2015). Renewable energy such as solar PV, wind, small/mini/micro hydro, biomass/ biomass waste, geothermal etc. could be the better and appropriate alternative to conventional sources. These renewables are clean, environment-friendly and unlimited. India has enormous potential of renewable energy such as solar PV has 20MW/sqkm, wind has 45,000MW, small/mini/micro hydro has 15,000 MW biomass has 19,500 MW and biomass waste has 1700 MW(Mohibullah, Imdadullah, 2006). The percentage share of electricity generation by renewable energy in India is presently only 14%, which is very low as compared to conventional sources and less percentage of their potential (Imdadullah, 2017). The energy supply and demand gap can be overcome by more generation of electrical energy from renewables. The power generation capacity can be increases in the form of small units called distributed generation (embedded generation) and among them in hybrid power systems (HPS). Hybrid power systems may be connected to the utility grid, but they can also work in off-grid mode feeding separate loads (several homes/farms, small-scale industry/ local communities). Grid-connected hybrid energy system provide electric power reserves and permit excess power to be fed back to the grid when hybrid energy system generate more power than load demand. The main target of hybrid energy system is to meet the energy demand reliably with reasonable cost to the remote, off-grid communities and also grid-connected area where grid supply is not regular. Hybrid energy systems are a good means to increase availability and

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reliability of power supply systems. This is realized by integrating different renewable energy and alternative energy, energy storage system, power electronic converter and controllers (Paska *et al*., 2009). It is obvious from the above discussion that hybrid renewable energy systems are cost-effective and reliable source of energy than conventional grid system. The main emphasis in this study is to meet the institutional load demand with grid-connected hybrid system and with isolated hybrid energy system (off-grid mode). To realize these goals, electrical load demand, solar radiation and wind speed data is used for techno-economic analysis using HOMER software (Shahzad *et al*., 2017).

MATERIALS AND METHODS

System and components

The pilot region, where the system has to be set up and the techno-economic optimization analysis would be done, has been selected as Zakir Hussain College of Engineering and Technology (ZHCET), Aligarh Muslim University (AMU), Aligarh, India. Based on the previous survey and calculation (Ahmad and Sadaf, 2012), the average daily load of lecture theaters has been calculated as 195 kWh for day time as well as for evening/night time (17:15-22:15 hours) since there are also evening courses. (https://www.amu.ac.in/ beoffice. jsp? did= 10114). In this study, the daily average load of 195.00kWh with random variation of 10% and peak load of 28.00 kW is used for *different configuration of hybrid energy system*. In general, due to intermittency in SPV and wind energy, they do not match the load profile. Therefore, battery storage system is used in the power systems to smoothen renewable energy (RE) generation and load profile (Türkay and Telli, 2011). In this study, diesel generator set is installed to avoid the problems of intermittent RE generation and supply with reliability in case of changing weather conditions.

Hybrid Energy System Configuration

The parallel AC and DC bus configuration permits the AC (alternative current) components/ac energy source/utility grid to directly connect to the ac bus and supply the ac loads whereas dc component/dc energy source connected to the dc bus through power electronics converter circuit and supply the dc load via converter if necessary. Moreover, some ac sources having their outputs variable voltage and variable frequency may be connected to the dc bus through converter circuit in order to feed constant dc power. The storage systems are also connected to the dc bus through bi-directional converter in order to maintain bi-directional power flow between storage system and dc bus depending upon the availability of power at dc bus. There is interconnection between ac and dc bus through ac-dc converter in order to maintain the reliable power supply to the load. This type of configuration is called hybrid-coupled hybrid energy system (Nehrir *et al*., 2011) as shown in Figure 1.

Wind Energy Resource

Wind energy is rich renewable energy with low GHG emissions than fossil fuel based energy and environmental friendly. To install a wind plant in a particular locality, analysis of wind speed data of that particular location is required (Ammari *et al*., 2015; Li *et al*., 2016). In this study, monthly average wind speed at 50-meter height over 10 year period (July1983- June1993) was taken from NASA surface meteorology and solar energy database for AMU, Aligarh. The Annual average wind speed at AMU, Aligarh is 3.15 m/s as shown in Fig.2.

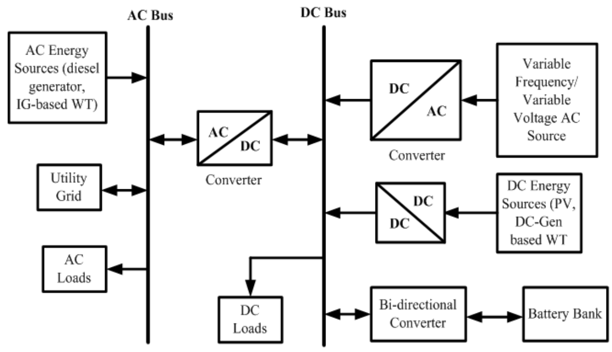

Fig. 1. Hybrid-coupled hybrid energy system

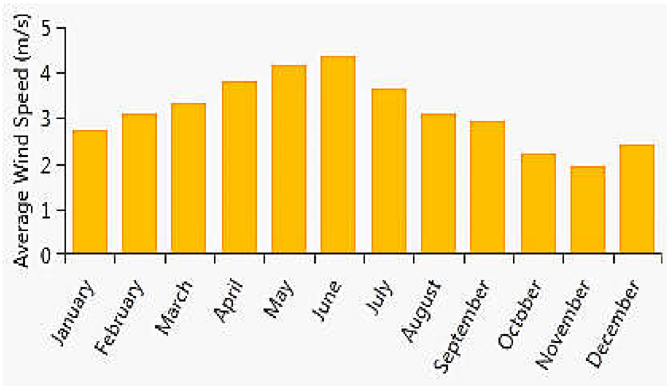

Fig. 2. Annual average wind speed at study area

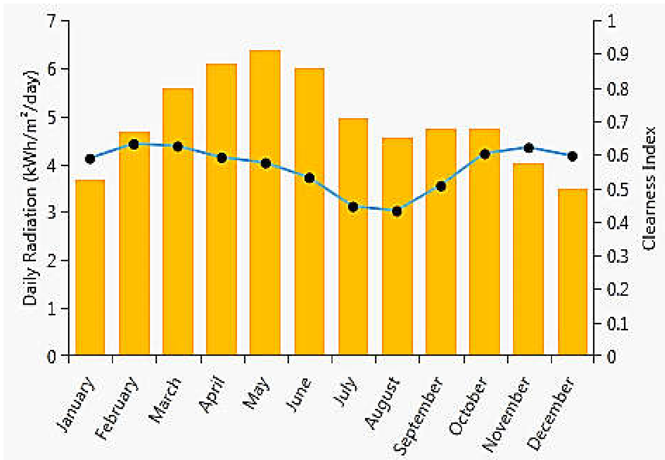

Fig. 3. Monthly average daily solar radiation and clearness index at selected site

The well-known equation of the power of the wind P(V) is given by (Ammari *et al*., 2015; Didane *et al*., 2017):

$$P(V)=\frac{1}{2}\rho A V^3 \quad (1)$$

Where,
V= velocity of the air (wind speed) (m/sec)
ρ= air density (kg/m^3)
A = area swept by the rotor blades (m^2)

Solar energy resource

Solar radiation data is necessary for design of SPV system an devaluation of its power generation capacity (Hossain *et al.*, 2017). The monthly average global horizontal solar radiation over 22 years for the period July 1983–June 2005 is collected from NASA surface meteorology and solar energy database for Zakir Hussain College of Engineering and Technology, Aligarh Muslim University, Aligarh (27°54.9'N, 78°4.6'E), India. The Annual average solar radiation in above site is 4.91kWh/m^2/ day. Fig. 2 shows monthly average solar radiation and clearness index of the site under study.

The electrical power output of a photovoltaic system can be estimated as follows(Maleki, Akbar, Rosen, Marc A. and Pourfayaz, 2017):

$$P_{PV}(t) = R_t \eta_{PV} A_{PV} \quad (2)$$

Where,

$$\eta_{PV} = \eta_r \eta_{pc} \left[1 - N_T \left(T_{air} + \left[\frac{NOCT-20}{800}\right] R_t\right) - T_{ref})\right] \quad (3)$$

Where,
A_{PV} = PV area,
η_{PV} =Efficiency of the PV panels,
R_t = Solar radiation on a tilted plane module,
η_{pc} = Power conditioning efficiency,
η_r = Reference module efficiency,
T_{air} = Ambient air temperature,
T_{ref} = Cell temperature at the reference conditions,
NOCT=Nominal cell operating temperature, and
N_T =Photovoltaic panel efficiency temperature coefficient.

Components assessment

In a hybrid energy system, a component can be used to generate, deliver, convert and store energy. In this analysis, the power sources solar PV, wind turbine, and the diesel generator are considered in off-grid mode and grid-connected mode whereas Batteries and Converter are used for storing and conditioning electricity respectively. Table 1 shows the capital cost, replacement cost and operation and maintenance cost of the hybrid energy components used in the design of the optimal system.

The power generated by solar PV is more than wind turbine due to good solar insolation at this site. The capital cost and replacement cost for a 1 kW Solar PV is shown in Table 1 which includes installation, logistics and dealer mark-ups. The output of Solar PV is a DC with a lifetime of 20 years. The de-rating factor of 80% is considered for each panel due to affects of temperature and dust on the panels. In this study, no tracking system has been considered. A Generic 10 kW (DC Gen based WT) DC output, having a hub height of 25 meter and a lifetime of 25 years, horizontal-axis wind turbine is selected. The amount of electricity generated by the wind turbine depends on the availability and variations in the wind speed (Sen and Bhattacharyya, 2014). The wind turbine (WT) may be induction generator (IG) based having an ac output as shown in Figure 1. The output of diesel generator is connected to an AC bus with a lifetime of 15,000 operating hours. The minimum load ratio of 30% of the capacity is considered. The total operating cost of the generator is calculated based on the amount of running time in a year. Batteries are used in the hybrid system as standby and to maintain a constant voltage during peak loads or during deficit in generation capacity. The Surrette 6CS25P battery is selected here. It has voltage of 6 V with a nominal capacity of 1156 Ah (6.94 kWh) and a lifetime throughput of 9,645 kWh (Sen and Bhattacharyya, 2014; Usman *et al.*, 2017). A power electronic converter is used for conditioning the ac/dc power based on the requirement. The inverter efficiency of 90% and rectifier efficiency of 85% with a lifetime of 15 years is considered. The lifetime of project is considered to be 25 years with an annual discount rate of 8% and expected inflation rate of 2 % (Imdadullah, 2017). In this study the grid used in HOMER as standard benchmark for comparing with the technical and cost parameters of the off-grid hybrid energy system. The grid power purchase cost is assumed as $0.100/kWh (https://www.homerenergy.com/).

HOMER model design

The hybrid energy system is designed with solar, wind, battery, converter, diesel generator and ac load as shown in Fig. 4. The input of HOMER model is hourly load data of one year, monthly average wind speed, ambient temperature and solar irradiance data of the site under study. In this hybrid energy system, the load of the site under study is coupled with AC bus, the diesel generator is connected to the AC side of the network and the Solar Photovoltaic (SPV), wind turbine and the batteries are connected to its DC side of the network. Generally, the conventional diesel generator (DG) is used as back-up to supplement the renewable energy system for peak loads and during poor resource periods. In this hybrid optimization, the outputs of solar and wind is considered 25% and 50% respectively. The carbon dioxide penalty cost is neglected. The financial parameters for SPV, wind turbine, converter, battery and diesel generator considered in this hybrid energy system design are shown in Table 1.

Table 1. Cost details of hybrid system components

Components	Capital cost ($/kW)	Replacement cost ($/kW)	O&M cost	Reference
Solar PV	2000	2000	10$/kW/year	(Hossain *et al.*, 2017)
Wind Turbine (Generic 10kW)	40,000	32000	200$/kW/year	(Sen & Bhattacharyya, 2014)
Diesel generator	370	296	0.05$/hour	(Rajbongshi, Borgohain, & Mahapatra, 2017)
Battery (Surrtte 6CS25P)	1295	1036	20$/year	(Rajbongshi *et al.*, 2017)
Converter	1000	800	0	(Rajbongshi *et al.*, 2017)

RESULTS AND DISCUSSION

Off-grid hybrid energy system

An Off-grid optimal hybrid energy system (HES) has been modeled in HOMER with large number of hourly simulations. HOMER simulates all probable combinations based on various input parameters and sorts out the optimization result from lowest Net Present Cost (NPC) to highest NPC.The Off-grid optimal system configurations includes system architecture, dispatch strategy, cost of energy (COE), NPC, operating cost and initial capital cost are shown in Table 2. The amount of GHG emissions including CO_2, CO, unburned hydrocarbon (UHC), particulate matter (PM), sulfur dioxide (SO_2) and nitrogen oxide (NO) in each Off-grid optimal hybrid system are shown in Table 3. The least cost Off-grid optimal HES architecture for this study is calculated as a 54.1 kW SPV, 31 kW diesel generator, 36 Surrette 6CS25P Batteries and 24.1 kW converter with a dispatch strategy of load following. The cost analysis of this least cost optimal HES are COE is $0.320/kWh, NPC of $294028, operating cost of $8014, initial capital cost of $190430 (see table 2).The renewable fraction (RF) and excess electricity (EE) for the least cost off-grid optimal hybrid energy system is 84.5% and 13.8% of total electricity production respectively as shown in Table 4. In this off-grid optimization system, the excess of electricity is 13390kWh/year (i.e., 13.80% of total electricity generated) goes unused due to low demand or may be used for other purpose. This shows that this system has the ability in meeting the future demand growth. It is clear from Table 4 that the power generated from SPV system is dominated the diesel generator because of mostly sunny days throughout the year at the site under study.

Grid-connected hybrid energy system

For present hybrid system configuration, grid is added to the previous hybrid energy system. In this study, grid is considered to be reliable and no power cut is considered for optimization of hybrid system. Although the significant renewable energy potential in the study region, there is low probability of implementation since the technology diffusion process is very much inclined by the component costs. When the system is connected to a grid, the optimal hybrid energy system is calculated as having the components of 3 kW PV, 2 Surrette 6CS25P Batteries, 50 kW grid supply and 0.658 kW converter and dispatch strategy of cycle charging.

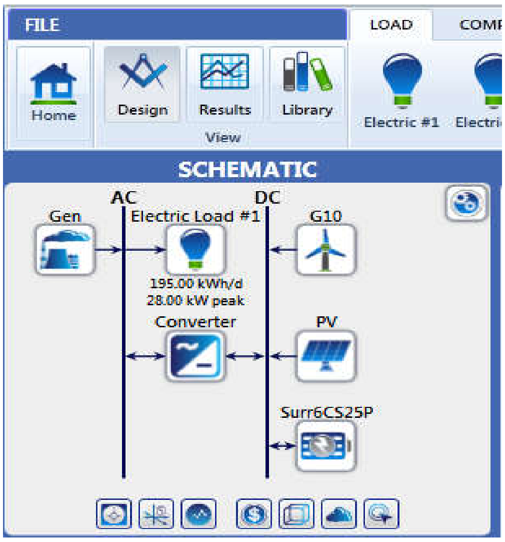

Fig.4. Off-grid hybrid energy system model in Homer

Table 2. Optimal off-grid hybrid energy system sorted based on NPC

	System Architecture						Costs			
Rank	PV (kW)	Wind (10kW)	Diesel Gen (kW)	Battery	Converter (kW)	Dispatch	COE ($/kWh)	NPC($)	Operating Cost ($/year)	Initial capital cost ($)
1	54.1	0	31.00	36	24.10	LF	0.320	294,028	8,014	190,430
2	54.0	1	31.00	36	23.80	LF	0.366	337,199	8,311	229,757
3	0	0	31.00	12	4.63	CC	0.375	344,938	24,235	31,643
4	0	1	31.00	12	5.29	CC	0.422	388,695	24,474	72,302
5	0	0	31.00	0	0	CC	0.518	476,577	35,978	11,470
6	91.1	0	0	158	30.50	CC	0.545	501,079	6483	417,268
7	0	1	31.00	0	0.257	CC	0.569	523,356	36483	51,727
8	95.0	1	0	150	31.10	CC	0.591	543,536	6,829	455,255
9	7.15	2	31.0	0	2.84	CC	0.627	576,952	36,229	108,605

Table 3. Emissions from different combination of off-grid optimal hybrid energy system

Rank	Emissions (kg/year)					
	CO_2	CO	UHC	PM	SO_2	NO
1	11,345	71.5	3.12	0.433	27.80	67.2
2	10,850	68.4	2.98	0.414	26.60	64.20
3	66,622	420	18.30	2.55	163	394
4	65,450	413	18.0	2.50	160	388
5	90,667	572	24.90	3.46	222	537
6	0	0	0	0	0	0
7	90,430	570	24.90	3.45	221	535
8	0	0	0	0	0	0
9	85,633	540	23.6	3.27	210	507

Table 4. Annual electricity generation and consumption by the optimal off-grid hybrid system

Production	kWh/year	%	Consumption	kWh/year	%
SPV	85,651	88.60	AC Primary Load	71,175	100
Diesel Generator	11,062	11.40	DC Primary Load	0	0
Total	96,712	100	Total consumption	71,175	100
			Excess Electricity	13,390	13.80
			Renewable Fraction		85.5

Table 5. Grid-connected optimal HES sorted based on NPC

System Architecture								Costs					
Rank	PV (kW)	Wind (10kW)	Diesel Gen (kW)	Batt.	Grid (kW)	Conv. (kW)	Dis.	COE ($/kWh)	NPC($)	Operating Cost ($/year)	Initial cap. cost ($)	RF (%)	EE (%)
1	3.00	0	0	2	50.0	0.658	CC	0.108	99,746	7,001	9,245	3.14	3.08
2	0.05	0	31.0	0	50.0	0.050	CC	0.110	101,416	6946	11621	0.10	0
3	3.00	0	31.0	2	50.0	0.658	CC	0.119	109,072	6,835	20,715	3.14	3.08
4	0	1	31.0	0	50.0	0.257	CC	0.151	138620	7,609	40,257	0.82	1.04
5	4.08	1	0	2	50.0	0.872	CC	0.161	147,814	7,440	51,632	4.83	5.36
6	4.08	1	31.0	2	50.0	0.875	CC	0.171	157,141	7,274	63,102	4.83	5.36
7	7.15	2	0	0	50.0	2.840	CC	0.210	192,941	7,411	97,135	13.0	5.01
8	0	2	0	4	50.0	2.840	CC	0.211	193,718	8,176	88,024	3.04	0.56
9	7.15	2	31.0	0	50.0	2.840	CC	0.220	202,268	7,245	108,605	13.0	13.8

Table 6. Annual electricity generation, consumption and EE by the grid-connected optimal HES

Production	kWh/year	%	Consumption	kWh/year	%
SPV	4, 747	6.44	AC Primary Load	71,175	100
Grid Purchases	68,943	93.6	DC Primary Load	0	0
Total	73,690	100	Total consumption	71,175	100
			Excess Electricity	2,267	3.08

Table 7. Major Contributors of GHG Emissions from different combination of grid-connected optimal HES

Rank	Emissions (kg/year)		
	CO_2	SO_2	NO
1	43,572	189	92.40
2	44,937	195	95.3
3	43,572	189	92.4
4	44,613	193	94.3
5	42,811	186	90.8
6	42,811	186	90.8
7	39,125	170	83.0
8	43,625	189	92.5
9	11,272	27.6	66.7

The costs for this configuration is calculated as COE of $0.108/kWh, NPC of $99746, operating cost of $7001, initial capital cost of $9245 as shown in Table 5. The renewable fraction (RF) and excess electricity (EE) for the least cost grid-connected optimal hybrid energy system is 3.14% and 3.08% of total electricity production respectively as shown in Table 5. The contribution of renewable source to load is 6.44% (solar PV only) and rest of the demand is met by the grid as 93.6% of the load (see Table 6). The Annual electricity generation, consumption, and EE by the optimal grid-connected hybrid system is shown in Table 6. Table 7 shows the emissions and their quantity for different optimization ranks. The amount-wise major contributors of harmful gasses are listed here in Table 7.

Conclusion

This study explores a technically achievable and economically sustainable hybrid energy solution for off-grid and grid-connected electricity supply to an institutional loads. It is found that for off-grid and grid-connected optimal hybrid energy solution SPV is available and it is a clean available source of energy to this locality. The following points may be noted.

- In the off-grid optimal hybrid energy system components calculated as a 54.1 kW SPV, 31 kW diesel generator, 36 Surrette 6CS25P Batteries and 24.1 kW converter with a dispatch strategy of load following having a cost analysis as COE of $0.320/kWh, NPC of $294028, operating cost of $8014 and initial capital cost of $190430.
- When the system is connected to a grid, the optimal hybrid energy system is calculated as the components of 3 kW PV, 2 Surrette 6CS25P Batteries, 50 kW grid supply and 0.658 kW converter and dispatch strategy of cycle charging. The costs for this configuration is calculated as COE of $0.108/kWh, NPC of $99746, operating cost of $7001, initial capital cost of $9245.
- It is clear that the cost of energy as well as system cost in grid-connected mode is cheaper than the off-grid mode. Although harmful gaseous emissions in grid-connected system are CO_2 of 43572kg/year, $SO_2$of 189kg/year and NO of 92.40 kg/year which is much greater than the off-grid emissions. This is due to grid power generation is mostly from fossil fuel based.

- The off-grid hybrid system is good option from environmental point of view since government of India is willing to cut the carbon emissions.

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