Technoeconomic Analysis of a Hybrid Energy System for an Academic Building

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ABSTRACT

This work is mainly based on the optimal design of a standalone Hybrid Renewable Energy System (HRES) consisting of PV/diesel/battery systems, implemented in an academic building. Different hybrid system configurations such as PV-diesel generator-battery, diesel generator-battery, and PV-diesel generator are compared based on Net Present Cost (NPC) and Cost Of Energy (COE) to find out the best economically viable and environmentally friendly solution. Li-ion and lead-acid batteries were taken into consideration, and the optimization was done in HOMER PRO software. The PV-DG-Li-ion battery configuration emits approximately 2825387kg/year CO_2 whereas the conventional DG system emits 4565074kg/year. It is concluded that the PV-DG-Li-ion battery configuration provides the cleanest and most environment-friendly and techno-economically feasible solution.

Keywords-hybrid system; HOMER; NPC; COE; technoeconomical analysis

I. INTRODUCTION

Nowadays, clean Renewable Energy Sources (RESs) play an important role in fulfilling the increasing energy demands and environmental pollution issues, since most are not only abundant in nature, but also environment friendly. The PV system is considered as the most suitable among RESs due to several advantages like low cost, environment-friendly nature, and higher efficiency. But due to its intermittency nature, it is often used as sole distributed generation in residential buildings, offices, and academic buildings commonly integrated with storage systems to enhance the stability of the system and power quality issues [1-2]. Energy storage techniques such as Li-ion and lead-acid batteries were commonly providing services from small to large power applications [3]. Li-ion batteries have several advantages over the lead-acid batteries, such as fast charging operation, higher density in power and energy, and lower maintenance cost [3]. Different studies on battery energy storage systems reveal that the plays a major key role in energy generation power system when incorporated with RESs. Two key parameters, NPC and COE, are used for evaluating the performance of the battery storage system. The NPC of a Li-ion battery is relatively better than its counterpart lead-acid battery. Moreover, the life cycle of the Li-ion battery is more than five years longer than the lead-acid battery when it is interfaced with a solar PV system. The environmental effect along with the maintenance of Li-ion battery is also less [3]. Though the Li-ion battery wins over the lead-acid battery, but still for stationary applications, lead-acid batteries provide better efficiency. The energy storage system not only counter effects the unpredictability and variation in the output power produced by RESs but also increases the reliability and efficiency of the system [4-6].

A PV system can also be integrated with wind energy and a Diesel Generator (DG), in an installment also known as a Hybrid Energy System (HES) for efficient energy generation and enhanced reliability. If only the DG is operated for the generation of energy, then the overall maintenance and fuel cost will be much higher. HES has also several other disadvantages, such as a higher level of noise and emission of greenhouse gases. When the sources of the HES are integrated with the battery storage system, then the operational cost is drastically reduced. Moreover, the daily and seasonal variation demand affects the operational cost. During summer and winter seasons the fuel costs for weekends are higher compared to weekdays. Due to lower solar radiation, the use of conventional energy sources increases during winter. So, the variation of daily and seasonal energy demands changes is an important aspect as these affect the operational cost [7-8]. The reliability and compatibility of the PV solar system increases when it is integrated with other energy sources like DGs, wind farms, and battery. Such a system is called a HES. Presently, the HES powered by RESs is the most cost-effective and reliable.

Past works have mainly concentrated on the optimal sizing and the economic aspect of the designed hybrid system configuration either with solar PV- wind system, solar PV-wind-diesel generator system coupled with battery storage system [9-13]. Only a few published papers are available that consider the wind resource not adequately available in a particular location. Anyhow, the techno economic analysis and the optimal sizing of the hybrid system consisting of PV panels, DG, and a battery system consisting of Li-ion and Lead acid battery is not available in previous works. Since the wind energy resource is not abundantly available for the location under study, it is not considered for the present work.

In this paper, the technical and economic analysis of solar/ DG/battery storage HES implemented in an academic building is proposed. The proposed hybrid system consists of PVs, a DG, and a battery storage system consisting of Li-ion and/or lead-acid batteries. The techno-economic analysis of the hybrid system is carried out in HOMER (Hybrid Optimization Model for Electric Renewable) software based on NPC and COE and the results are compared regarding cost-effectiveness and efficiency. The optimal sizing of the system is estimated based on Total Energy Deficit (TED), NPC, and COE to meet the load demand of the system. The DG and battery bank are designed to compensate for the load demand during night time when the solar energy is not available. According to the developed methodology, the configurations suggested should ensure 0% TED. The optimal system is decided based on the minimum NPC and COE. The optimal hybrid system is designed and compared with other energy sources by using the solar radiation data and ambient temperature obtained from HOMER for the particular location under study [14-15].

The proposed configuration consists of a solar PV system, a DG along with a battery storage system, a converter, and an inverter system. The converter coverts the ac voltage produced by the DG to dc voltage and the inverter converts the dc voltage produced by the hybrid system into ac to meet the household load requirements.

II. SOURCE AND LOAD ASSESMENT

To develop an efficient hybrid system in a particular location, source and load assessment are essential for its techno economical analysis.

A. Site Location

The site under consideration is the academic institution KIIT Deemed to be University, located in the city of Bhubaneswar, Odisha, India. It consists of 5 academic blocks A, B, C, D, and E (Figure 1). Block A consists of 10 classrooms, 1 conference hall, 12 laboratories, and 5 washrooms. Block B contains the dean's office and 5 administrative offices. Block C consists of 12 classrooms, 5 laboratories, and 5 washrooms. Block D consists of 6 classrooms, 12 faculty cabins, and 6 washrooms. Block E consists of 20 classrooms, 4 laboratories, and 6 washrooms.

B. Source Assessment

The institute is located at 20.3555°N, 85.8161°E and solar radiation is plentifully available. During the summer season, the electrical load is quite high, so there is a necessity for grid independent hybrid RESs. For this location, solar power is abundantly available. Figure 2 shows the monthly variation of solar irradiance and Figure 3 shows the monthly temperature variation.

Fig. 1. Building blocks.

Fig. 2. Monthly solar irradiance.

Fig. 3. Monthly temperature variation.

C. Load Assessment

Maximum load occurs during the daytime hours, from 8 am to 8 pm when the academic activities are carried out. During night time, the load is minimal. During spring months the load is at its peak. During vacations the load is less. The total load demand of the institute is 10427.5kwh/day and the peak load is 1038.1kw. The proposed system is designed to satisfy all the demands economically. The system is designed to mitigate the peak load demand during summer and provide a reliable solution for all the existing energy problems. The hourly load demand and the monthly average solar global horizontal irradiance are plotted with variation of clearness index. With seasonal changes the temperature also varies, so the variation of daily temperature over one year is also plotted. Table I provides detailed load calculation of the institution under consideration. The hourly load profile is plotted in Figure 4 and the monthly load profile is plotted in Figure 5. The total load is maximum at 2pm, obtained from the daily load curve and the monthly peak is during May, i.e. during summer time.

III. RESOURCE ASSESSMENT

In this paper, PVs, DG, and batteries were considered as the resources for HOMER optimization. The location of the institute under study receives plenty radiation all over the year, so it is suitable for harnessing solar energy.

TABLE I. LOAD ASSESMENT

Campus 3, Block A	**Load (KW)**	**h/day**	**KWh/day**
Light load	12.072	8	96.576
Fan load	6.08	12	72.96
AC and laboratory load	320.234	5	3202.34
Total	338.386		3371.876
Campus3, Block B	**Load (KW)**		
Light load	2.357	8	18.856
Fan load	2.4	10	24
AC and laboratory load	40.16	5	481.92
Total	44.917		524.776
Campus 3, Block C	**Load (KW)**		
Light load	9.395	8	75.16
Fan load	4.56	12	54.72
AC and laboratory load	281.145	5	2811.45
Total	295.1		2941.33
Campus 3, Block D	**Load (KW)**		
Light load	7.087	8	56.696
Fan load	5.12	12	61.44
AC and laboratory load	120.639	5	1206.39
Total	132.846		1324.52
Campus 3, Block E	**Load (KW)**		
Light load	26.517	8	212.136
Fan load	24.56	12	294.72
AC and laboratory load	175.816	5	1758.16
Total	226.893		2265.01

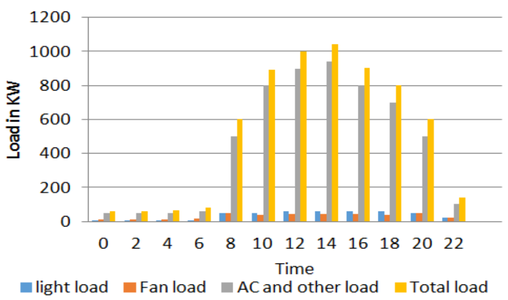

Fig. 4. Daily load curve.

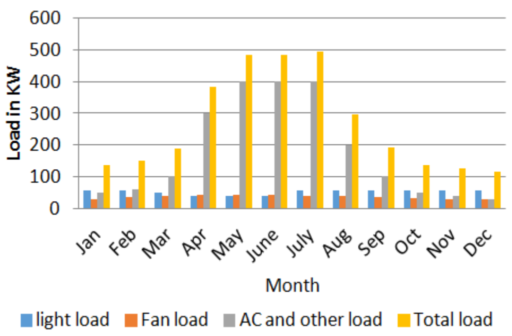

Fig. 5. Monthly load curve.

During summer the temperature can go as high as 45°C. Solar radiation is available for approximately 10-12 hours with longer sunny days during summer whereas during winter the radiation is available for almost 8-10hours with shorter sunny days. During the rainy season, it is hardly available for almost two months. The solar radiation data for this particular location are obtained from the site of NASA using the solar energy database from HOMER software. The annual average solar radiation is 4.81kWh/m^2/day with an average clearness index of 0.519. Figure 2 shows the monthly variation in daily radiation which indicates the ample solar radiation available. The energy generated by the PV panels can be expressed as:

$$E_{PV} = A \times \eta \times H \times PR \quad (1)$$

where E_{PV} is the total energy output of the PV panel, η is solar panel efficiency, A is the total panel area (m^2), H the average solar irradiance on a tilted panel annually (kWh/m^2/day), and PR the performance ratio of the panel

IV. SYSTEM DESCRIPTION AND COMPONENTS

The HRES can be designed consisting of a PV module, a DG, a power converter, and a battery bank consisting of lead-acid or lithium-ion batteries. In this configuration, the PV panels and the battery bank are connected to the DC bus system while the DG is connected to the ac bus system. The electrical load is connected to the ac bus system. The solar PV system generates the power to compensate for the electrical load demands and the excess generated power will charge the battery bank which can be used along with the DG during adverse weather conditions or during night time. The size of all the components used here is chosen such that there is no undue load on the system. The system configuration is given in Figure 6. If the energy generated by the hybrid system is more than what is required by the load, the excess energy is stored in the battery. If the energy generated is less than the load demand, then the battery bank will be used. In that scenario, the DG will operate and meet the deficit energy if the state of charge of the battery drops to the minimum value.

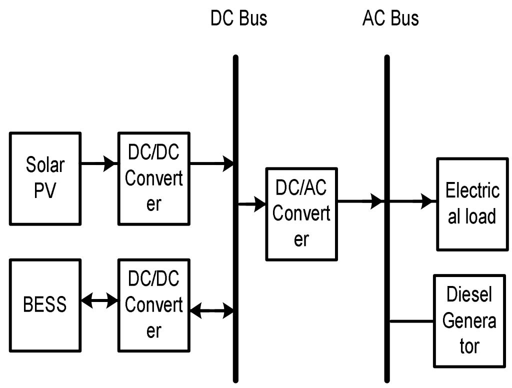

Fig. 6. System configuration.

A. PV Module

In India, there is ample scope for using solar energy which is a major RES. The generated power is DC in nature from which the maximum power can be extracted by using the MPPT technique. By changing the tilt angle of the solar panel the maximum solar radiation can be received according to the changing position of the sun. The PV power generated can be given by [16]:

$$P_{PV} = F_{PV}\, Y_{PV} \frac{I_T}{I_S} \quad (2)$$

where P_{PV} is the PV power (W), F_{PV} is the derating factor of PV which includes the effect of dust accumulation and temperature rise, Y_{PV} is the rated capacity of the PV panel, I_T is the incident solar radiation under operating conditions, and I_S is the incident solar radiation under standard operating condition (W/m^2).The details of the PV module are given in Table II.

TABLE II. DETAILS OF THE PV MODULE

VarioTrack VT -65	Value
Rated capacity	1000kW
Panel Type	Flat plate
Operating temperature	45°C
Efficiency	17.3%
Capital cost	602$/kW
Replacement cost	602$/kW
O&M cost	100$/kW

B. Diesel Generator

The DG gives the best possible combination for HESs incorporating solar RES with batteries. In the case of grid integrated systems, DGs provide an efficient backup during power shutdown periods. The capital cost of the DG is minimal but the operation and management cost is quite significant due to the fuel cost. The DG is incorporated into the system to evaluate its environmental impact. The details of the DG are given in Table III [17].

TABLE III. DETAILS OF THE DIESEL GENERATOR

CAT 1750	Value
Capital cost	500$/kw
Replacement cost	450$/kw
O&M cost	0.03$/hour
Lifetime	15000h
Efficiency	45%

C. Battery Bank

The energy produced by the solar PV system depends upon the intermittent solar irradiance. During night time or in bad weather conditions, it is not available. The main constraint of using RESs is that they are fluctuating in nature. So, in order to reduce the dependency on RES availability, battery energy sources are used in this study. In this work, both lithium-ion and lead-acid batteries were taken into consideration. The details of the battery bank systems are given in Tables IV-V.

Lead-acid batteries are used for residential applications for storing the energy produced by the solar PV system and to provide energy during adverse weather conditions and night time. These batteries have good reliability, low cost, and reduced discharge capacity. Despite all their advantages, they have reduced lifetime due to continuous loading and discharges. The lead-acid battery of the Surrette S-260 model with a nominal voltage of 12V and string size 2 is considered in this work. The initial state of charge of the battery is 100% and the minimum state of charge is 30%. The throughput of the battery is 1704kWh and its lifetime is 10 years. Its capital cost is 205$ and the operation and management cost is 50$/year [6].

TABLE IV. DETAILS OF LEAD-ACID BATTERY

Surrette S-260	Value
Nominal voltage	12V
Nominal capacity	3.12kWh
Maximum capacity	260Ah
Round the trip efficiency	80%
Capital cost	205$
Replacement cost	205$
O&M cost	50$
Lifetime	10years

TABLE V. DETAILS OF LITHIUM-ION BATTERY

Generic 1kWh Li-ion battery	Value
Nominal voltage	6V
Nominal capacity	1kWh
Maximum capacity	167Ah
Round the trip efficiency	90%
Capital cost	132$
Replacement cost	100$
O&M cost	10$
Lifetime	10years

Lithium-ion batteries can be used as alternatives because they have high efficiency and reliability and prolonged lifetime. Their only drawback is that they are quite expensive compared to the lead-acid batteries. The generic 1kWh Li-ion battery with a nominal voltage of 6V and string size 4 is considered in this paper. The initial and minimum state of charge is of 100% and 30%, the throughput is 3000kWh, and its lifetime is 10 years. Its capital cost is 132$ and the operation and management cost is 10$ [6].

The battery rating should be designed such that it can meet the load demand of the HES. The Wh capacity of the battery system is given by (3):

$$C_{Wh} = E_L \times AD \times \eta_{Bat} \times \eta_{Inv} \times DoD \quad (3)$$

where C_{Wh} represents the WH capacity of the load, E_L is the daily average load in kWh/day, AD is the autonomy of the battery, η_{Bat} and η_{Inv} are the efficiency of the battery and the inverter, respectively, and DoD is the battery Depth of Discharge.

D. Power Converter

The system consists of both AC and DC systems, so the power converters act as bridges that transfer power between these two systems. The solar PV produces DC power and the DG and the load are connected to the AC. So, power converters act as an interface between these two. The rating of the converter under consideration is 1725kW. The efficiency is 95% and the lifetime of the converter is 10 years. Its capital cost is 32189$ and its operation and maintenance cost is 8000$/year [18].

V. HOMER OPTIMIZATION

HOMER software is used to optimize the HES based on certain input parameters to provide the best possible combination in terms of techno-economical feasibility. The optimization aims to minimize the NPC and COE as objective functions. It also computes the size of the PV array, the number of batteries, and the size of the DG and the converter [19-20].

The NPC of the system includes all the installation, operational, and management costs minus the revenue generated over the period. The NPC is calculated by:

$$NPC = \frac{C_{Tot,annual}}{CRF(i,T)} \quad (4)$$

where $C_{Tot,annual}$ is the annual total cost of the system ($/year), i is the real interest rate annually (%), T is the time period of the project work (years), and $CRF(i,T)$ is the capital recovery factor.

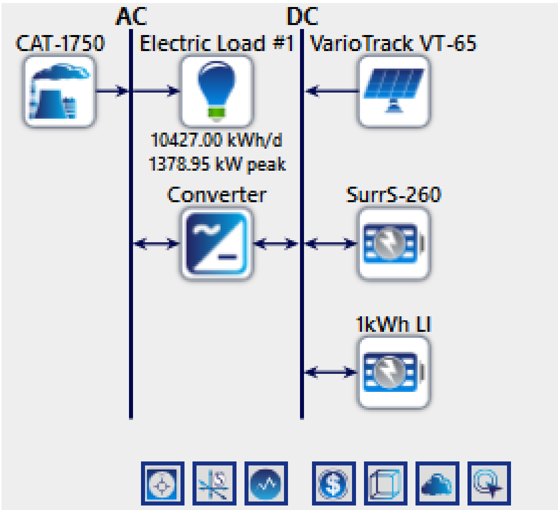

Fig. 7. Hybrid system configuration in HOMER.

COE represents the cost of the production of electricity by the HES under consideration on an annual basis. It is calculated by:

$$COE = \frac{C_{Tot,annual}}{E_s} \quad (5)$$

where $C_{Tot,annual}$ is the annual total cost of the system and E_s is the annual energy supplied.

The payback period (PBP) of the optimal system can also be calculated to ensure that the time period required for the recovery of capital or investment cost should be less:

$$PBP = \frac{Total\ Capital\ cost}{COE \times Annual\ Energy\ Consumption} \quad (6)$$

The proposed HES model developed in HOMER software is shown in Figure 7. The optimization is done based on the input data given in Tables II-V. The project lifetime is 25 years with an expected inflation rate of 2% and a nominal discount rate of 8%.

VI. RESULT ANALYSIS AND DISCUSSION

The simulation is carried out with the following configurations:

- PV-DG-battery (Li-ion and lead-acid)
- DG-battery
- PV-DG
- DG

The optimization is done on the above-mentioned configurations and the NPC and COE of these architectures are determined accordingly in HOMER. The first configuration is considered for two types of batteries, Li-ion and lead-acid. The result analysis shows the list of hybrid energy configurations based on the lowest NPC and COE. Table VI gives the optimal size of different possible hybrid energy configurations.

TABLE VI. OPTIMAL SIZE OF DIFFERENT CONFIGURATIONS

System configuration	PV (kW)	DG (kW)	No. of Li-ion battery strings	No. of lead-acid battery strings	Converter (kW)
PV-DG-Li-ion battery-converter	584	1400	274		670
DG- Li-ion battery-converter		1400	279		690
PV-DG-lead-acid battery-converter	2921	1400		304	604
DG-lead-acid battery-converter		1400		306	592
DG		1400			
PV-DG-converter	869	1400			172

The total NPC, the levelized COE, and the operating cost of all configurations are given in Table VII.

TABLE VII. COST ANALYSIS OF ALL CONFIGURATIONS

System configuration	NPC($)	COE($)	Operating cost ($)
PV-DG-Li-ion battery-converter	21.5M$	0.437$	1.65M$
DG- Li-ion battery-converter	21.58M$	0.438$	1.65M$
PV-DG-lead-acid battery-converter	22.91M$	0.465$	1.76M$
DG-lead-acid battery-converter	22.98M$	0.467$	1.76M$
DG	33.6M$	0.684$	2.603M$
PV-DG-converter	33.6M$	0.684$	2.603M$

From the above configurations, the PV-DG-Li-ion battery-converter system gives the most cost-effective solution. From Table VII, it can be observed that the above mentioned system has an NPC of 21.5M$, COE of 0.437$, and overall operating cost of 1.65M$. Out of the 6 system configurations, the system containing only DG has the highest fuel cost. Among the PV-DG-Li-ion battery-converter and the PV-DG-lead-acid battery-converter, the first one gives a better economical solution. Although the initial cost of a Li-ion battery is more, the life cycle cost is less compared to the lead-acid battery. So, the overall NPC, COE, and operating cost of the configuration containing a Li-ion battery is less compared to the total cost of a system with a lead-acid battery. The optimal system consists of a PV cell of 584kW capacity, a 1400kW DG, a 670kW converter, and 274 strings of Li-ion batteries. The highest amount of electricity is produced in April and May as the solar radiation is the highest during these two months. Until around 18:00hr, the PV and the DG of the HES meet the load demand of the system and the surplus energy is used to charge the battery system. But after that, the solar radiation decreases and it eventually becomes zero by 19:00hrs. During that time the DG alone can't meet the load demand so the battery will be utilized. The load demand decreases after 20:00hrs. Therefore, excess power is generated by the DG and the surplus energy is used to charge the battery. Figure 8 depicts the cost analysis of all 6 possible configurations in terms of NPC, COE, and operating cost. The PBPs of all possible configurations are estimated by assuming a project life period of 25 years with inflation rate and nominal discount rate of 2% and 8%, respectively. The PBP of the proposed optimal system consisting of PV-DG-Li-ion battery is calculated as 5.6 years which is sufficient to recover all the cost invested in the system.

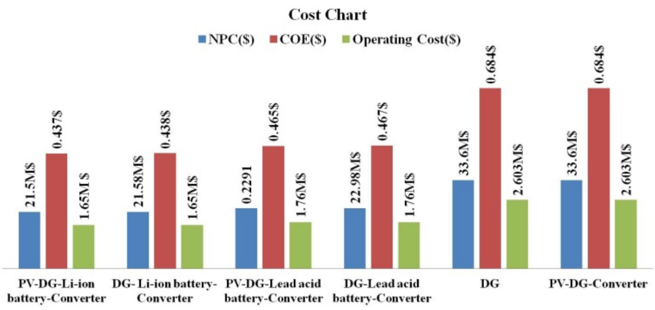

Fig. 8. Cost chart of various configurations of the hybrid system.

VII. ENVIRONMENTAL EFFECT

RESs produce clean and sustainable energy. Table VIII shows the emission of pollutant gases like carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons, sulphur dioxide (SO_2), and nitrogen oxide (NO) from the different configurations obtained from HOMER software. Compared to the conventional DG system which emits 4565 tons of CO_2, the optimal hybrid energy system emits 2825 tons which are quite less. This CO_2 emission reduction is due to the penetration of the RES in the system. The other pollutants are also reduced significantly. Figure 9 shows the graph of the emission of harmful pollutants by the 6 possible configurations under consideration and it can be observed that the PV-DG-Li-ion battery-converter system emits less pollutants than the other systems.

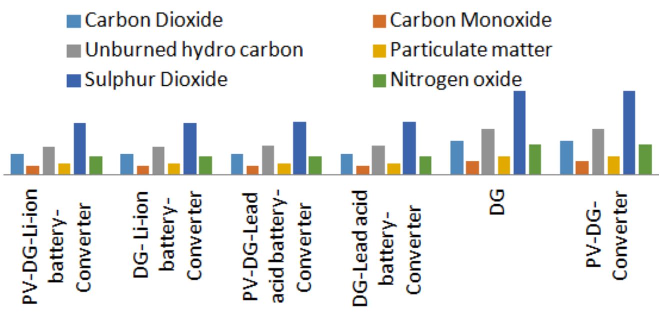

Fig. 9. Pollutant emissions.

TABLE VIII. POLLUTANT EMISSIONS

Emissions (kg/year)	System configurations					
	PV-DG-Li-ion battery-converter	DG-Li-ion battery-converter	PV-DG-lead-acid battery-converter	DG-lead-acid battery-converter	DG	PV-DG-converter
CO_2	2825387	2836377	2887232	2898694	4565074	4561485
CO	1187	1191	1213	1217	1917	1916
Unburned hydro carbons	385	386	393	395	622	621
Particulate matter	160	161	164	165	259	259
SO_2	7010	7037	7163	7192	11326	11317
NO	25389	25488	25945	26048	41022	40990

VIII. CONCLUSION

In this paper, the techno-economic analysis of a hybrid energy system in HOMER software for an educational institute is briefly discussed. The annual average solar radiation of the site under consideration is 4.81kWh/m^2/day with an average clearness index of 0.519. This is the potential location for the installation of PV/DG/battery system which gives the best economically viable solution by optimizing through HOMER software. The optimal system consists of a PV cell of 584kW capacity, a Diesel generator of 1400kW capacity, a 670kW converter, and 274 strings of Li-ion batteries with a nominal voltage of 6V and nominal capacity of 167Ah. The conventional Diesel generator system is not an economically viable solution due to its high fuel cost. It has also a hazardous effect on the environment due to its high level of emissions. In the present system, the hybrid energy system model is combined with the conventional DG system and the resulting system model gives the best possible result in terms of economy. The system not only reduces the number of operating hours of the Diesel generator and hence the fuel cost, but also reduces the emission of harmful gases. It is found that PV-DG-Li-ion battery system emits approximately 2825387kg CO_2 per year, when the conventional Diesel generator system emits 4565074kg/year. The PBP is calculated for the optimal system consisting of PV-DG-Li ion battery and it is found to be 5.6 years which is sufficient to recover all the costs invested in the system. Finally, the results obtained from this study can be successfully implemented in similar geographical location areas and the economy of these areas can be improved significantly along with the standard of living.

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