Technical and Economic Assessment of solar PV/diesel Hybrid Power System for Rural School Electrification in Ethiopia

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Abstract- This paper proposes the most feasible configuration of solar PV system with diesel generator as back up for hypothetical rural school electrification around Arbaminch town(6.0333° N, 37.5500° E) in the southern region of Ethiopia. Integration of PV systems with the diesel plants is being disseminated worldwide to reduce diesel fuel consumption and to minimize atmospheric pollution and the proposed simulation has been done to assure that the PV-Diesel hybrid system is Economically and technically feasible for Ethiopia as well. The proposed system can supply the daily energy demand of 50kWh / day with 11kW peak for 24 hours. Technical and economic analysis of the optimum system has been done to compare the economic viability of solar photovoltaic (PV)/ gen/battery hybrid power system with that of a standalone diesel generator only system. For analysis purposes HOMER simulation software has been used and meteorological data of solar insolation of the site have been taken from Online data from NASA. To incorporate uncertainty in solar radiation and diesel fuel price , both are taken as a sensitivity variable in the simulation. The costs of components are taken from the online site of manufacturing and equipment suppliers and adjusted to an Ethiopian price value. The result of simulation shows that solar PV system with Generator backup is more cost effective and environmental friendly over the conventional diesel generator alone system with in life time of the project.»

Keywords- HOMER, Photovoltaic, Diesel Generator, Hybrid power system

1. Introduction

In Ethiopia rural schools are geographically highly dispersed and electrifying these schools by using an extension of the national grid is not economically feasible. In a highly fragmented areas, the decentralized approaches to electrify schools and other institutions by local supply can become competitive due to lower investments and maintenance costs compared to large-scale electrification by expanding interconnected grids. Different technological options are in practice, most commonly diesel generating sets and renewable energies [1].

Small diesel-power generating sets (diesel gensets) have been the traditional way to address the problem. They provide a simple solution and can be designed for different capacities, being adapted to the needs of the consumers. In cases security of supply is not of major importance, single diesel gensets can be applied for electrification, accepting that no electricity can be supplied at times the genset is out of commission, i.e. due to repair or maintenance. However, diesel gensets have problems with short durability, which is due to the fact that they work very inefficiently when running just at fractions of their rated capacity. Moreover, frequent startup and shutdown procedures decrease their lifetime as well [2].

One of the basic problems for the application of diesel generating systems in rural school electrification in Ethiopia is a problem related to infrastructure, maintenance and covering running costs of the generator. Many rural schools are far away from towns where the diesel fuel exists so that the regular supply with diesel fuel becomes a logistical problem and an important financial burden .

The solution for the above problem is the use of renewable energy such as solar photovoltaic and wind energy as an energy source for remote areas. However, one of the main problems of standalone system such as solar as well as wind energy is the fluctuation of energy supply, resulting in intermittent delivery of power and causing problems if supply continuity is required. This can be avoided by the use of standalone hybrid systems. A hybrid power system can be defined as a combination of different but complementary energy generation system based on renewable energy or mixed renewable energy source- with a backup of Liquefied Petroleum Gas (LPG)/diesel/gasoline gen_set).

Shaahid and El Amin [3] performed techno-economic evaluation of PV/diesel/battery hybrid power system for rural electrification in Saudi Arabia. They analyzed solar radiation of Rafa to asses' techno-economic feasibility of PV/diesel/battery hybrid system for a typical remote village of Rawdhat Bin habbas , which has electrical energy demand of 15,943MWh. The Simulation has been done by using HOMER software and the result indicates that PV/diesel/battery hybrid system is technically and economically feasible with levelized cost of energy of 0.170 $/kWh. The Study also indicates that the initial cost of Hybrid system is higher than stand alone diesel generator system. The PV cost covers 78% of the total initial cost of the system. The increase in PV penetration decreases the operating hour of diesel generator which further augmented by including battery storage in the system. The running cost of diesel generator only system is much higher than that of hybrid system due to continuous cost of diesel fuel.

Eyad S.Hrayshat [4] has performed a detailed techno economic analysis of hybrid PV-diesel -Battery system by using HOMER simulation and Optimization software to meet the load demand of off grid house located in the remote Jordanian settlement. The hybrid system is economically feasible for diesel fuel price above 0.15$/liter . The optimum system reduced the operating hour of diesel generator by 19.3% , diesel consumption by 18.5 % and 18% reduction of emission of green house gases in comparison with the diesel only situation. Two control strategies have been used in simulation. The first is load following energy dispatch strategy on which whenever the diesel generator starts it produce only enough power to cover the load and lower priority loads such as charging battery bank left to renewable power source. The second dispatch strategy used is cyclic charging on which whenever the generator operates it operate at full output power and the excess electricity charges the battery bank if it is not full or go to low priority load such as water pumping. Otherwise, the excess electricity dumped in the dump load. In this study the diesel generator brought on line at the time when PV fails to satisfy the load and when the battery storage is depleted.

Chaurey and TC Kandpal [5] presented a techno economic comparison of rural electrification based on solar home system (SHS) and PV micro grid in India. Techno economic comparison of the two options has been done to facilitate a choice between the two systems. A comparison was based on annualized life cycle cost (ALCC) for the same type of load and load pattern for varying number of household and varying length and cost of the distribution network. The study analyzed the viability of the two options from the perspective of the user, the energy Service Company and the society. For purposes of analysis they have selected two types of load with daily energy consumption of 72Wh/ day and 144Wh/day. The result of the study shows that a micro grid is financially more attractive option for the user, the energy Service Company and the society, if the village has a large number of households, densely populated and lies in a geographically flat terrain. Whereas, the SHS is a better option for rough terrain and if the community is small and sparsely populated

Benjamin O. et al. [6] Analyzed life cost of diesel-photovoltaic hybrid power system for off grid residential building in Enugu Nigeria. The main aim of analysis is to compare the Life Cycle Cost (LCC) hybrid system with that of single stand alone photovoltaic system and stand alone diesel generator options. The life cycle cost analysis of the systems has been done by comparing the Net Present Value(NPV)and the Internal Rate of Return (IRR) of the three options.the result shows that the diesel/photovoltaic hybrid system has small LCC when compared to that of stand alone single source Photovoltaic and diesel generator options. Moreover, apart from the economic gain ,the hybrid system is also environmentally friendly because of the reduced emission of greenhouse gasses and other pollutants associated with diesel

In this paper PV/ diesel hybrid system is used to electrify hypothetical rural school near Arbaminch town in the southern region of Ethiopia. Optimization and economic analysis have been done by using HOMER optimization software [7] which is the optimization model for electric renewable. The proposed hybrid power system typically relies on renewable energy to generate 95% of total energy . The large share of renewable makes this system almost independent and lowers the energy prices over the long term, and the diesel generator is used as a backup to assist during periods of high loads or low renewable power availability and covers only 5% of total energy need.

2. Objective

The main objective of this paper is to analyze technical and economical viability of PV/Diesel hybrid system for rural school electrification in Ethiopia. The analysis has been done by using HOMER software. Economic comparisons regarding present worth, annual worth, return on investment and simple payback period has been done with the base case system (standalone diesel generator) and optimal hybrid PV/diesel gen/ battery case.

3. Methodology

In order to design PV/Diesel hybrid power system by using HOMER optimization software , one has to provide some inputs such as hourly load profile, monthly solar radiation value for a PV system, the initial cost of each component(renewable energy generators, diesel generators ,battery ,converter), cost of diesel fuel, annual real interest rate project lifetime, etc. The solar radiation data of Arbaminch were taken from online data of NASA meteorological department. The capital cost of each equipment taken from solarbzz site and adjusted to local value by including transportation and other costs [8]. The load profile of the school determined by using the wattage and hour of use of equipment considered as explained in subsequent section. To get hourly load profile of the school Excel spreadsheet program is used.

HOMER simulates the operation of a system by making the energy balance calculation every hour for each of the 8760 hours in a year. It displays a list of configurations sorted based on the Total Net Present Cost (TNPC). The total net present cost represents the life cycle cost of the system. The calculation assesses all costs occurring within the project lifetime, including initial set-up costs, component replacement cost, maintenance and fuel cost. However, the system configuration based TNPC is varied depending on the sensitivity variables that have been chosen by the designer. Therefore, the software repeats the optimization process for every selection of sensitivity variables. In this paper monthly solar radiation and diesel fuel price has been used as sensitivity variables. The final optimal solution of a hybrid renewable energy system is referring to the lowest TNPC. However, the designer can select a different optimal value depending upon the expected degree of reliability of the system [9].

4. System Architecture

The configuration hybrid power generation systems can be divided into three classes according to bus bar forms, including pure AC bus bar system, pure DC bus bar system and hybrid AC-DC bus bar system. The three class system has different features [10]. In this paper AC configuration is used due to its compatibility with SMA solar Inverters which are well designed for on grid and off grid electrification [11].

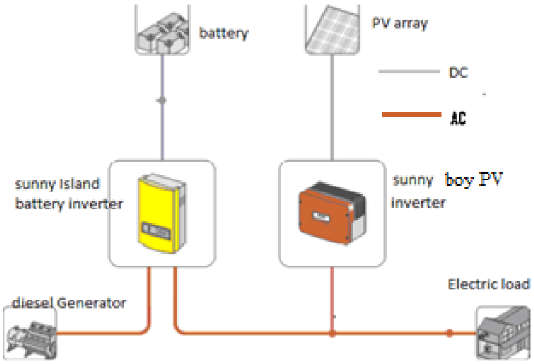


Fig. 1. AC coupled hybrid configuration.

AC-coupled systems where all loads and generators are coupled independently on a common AC-bus is currently evolving as a standard due to numerous advantages [12]:

- Standardized coupling of different components (AC-coupling)
- Off-the-shelf grid components can be used
- Simplified design and operation of island grids
- Compatibility with existing grids
- Reduction of system costs
- Increased reliability of supply
- Expandability

5. System Description

5.1. Load Profile of the School

The selected hypothetical school consists of six blocks building each having five classes. The design also includes teacher's home of one building with 8 classes. The school has 1-8 grades with approximate number of regular students are 1500 and extension student of 200. To eradicate literacy it is assumed that adult schools are also conducted during the night time since they are busy during the daytime in agricultural and social works. It is also assumed that the school can generate income by using supplied electricity for instance by opening barber shops, mobile phone charging station and etc. The daily and monthly load profile of the school is shown in the figure 2 and 3.

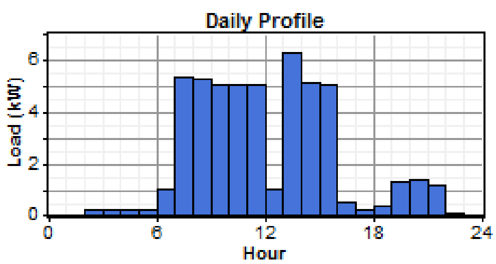


Fig. 2. Daily Load profile.

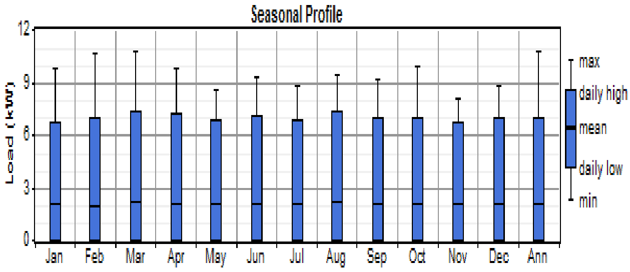


Fig. 3. Monthly Load profile »

5.2. Solar resource and photovoltaic system

Main electrical generator of the proposed system is photovoltaic panel which converts solar irradiation directly into Electricity. Since the solar radiation varies daily, hourly and seasonally the electricity produced by the PV array vary accordingly. Since the selected site has very good solar irradiation throughout the year and battery storage and diesel generator are incorporated in the system to handle this variability, the system can supply grid quality electricity for 24 hours. However, in order to capture the maximum amount of energy from the solar photovoltaic panel the following factors should be considered during and after the design of the system:

- Total size of solar PV array
- Type of module /array used
- The orientation of the module/array
- The angle from Horizontal
- Anything that shades the array
- The local minimum and maximum ambient temperature and etc.

The proposed design accounts for the decrease in PV efficiency panels with the ambient temperature. The average daily radiation of the site is 5.32 kWh/m^2/day, providing 1700kWh/ kW$_p$. The array slope angle is set to 15 degrees and the array azimuth is 0 degrees which are referring to the South direction. The lifetime of this PV array system is 25 years with de-rating factor of 90% and ground reflectance is 20%. Fig.4 shows the average monthly solar radiation data on the site where maximum radiation occurs in the month of January.

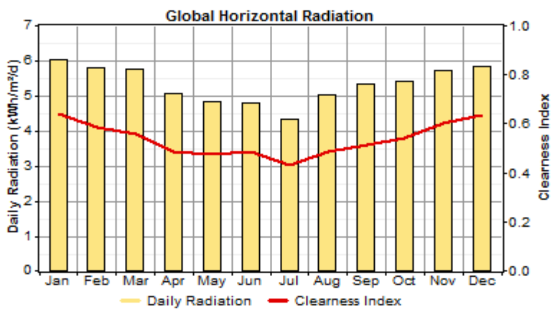


Fig. 4. Average Monthly solar radiation of the site

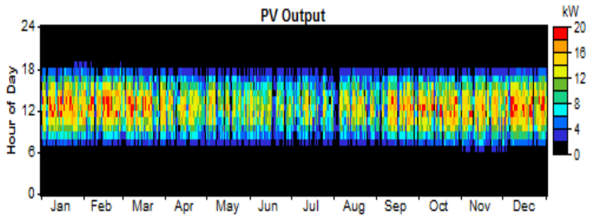


Fig. 5. PV output of PV/gen7battery hybrid optimal system

5.3. Battery storage

The key difference between a grid-connected system and an off-grid system is the need for a battery bank. Since sunlight is not available at night, and since we are most likely to require electricity at night for lights, entertainment devices , and so on, batteries are indispensable to any off-grid system. Unfortunately, batteries are also often the most problematic and costly part of a system. Renewable energy systems, deep cycle batteries provide the energy storage for the system . Unlike car battery, deep cycle batteries that are used in renewable energy applications are meant to be discharged and recharged (cycled) repeatedly. To maintain healthy batteries and prolong battery life, most manufacturers suggest limiting the depth of discharge to about 20%. There is a different type of solar batteries. The most common one is flooded lead acid (FLA) batteries and sealed batteries (AGM or Gel cell). Flooded Lead Acid batteries require a bit of maintenance, however, they generally last longer than their sealed counterparts [9].

The type of battery used for the proposed system is Surrette 4KS25p model (AGM type) with a rating of 4V, 1900Ah, 7.6 kWh with life time throughput 10,569kWh. The cost for one battery is assumed $1400 with the replacement cost of $1300. The battery stack is containing several numbers of batteries and 12 batteries per string with bus voltage of 48V. The Figure below shows the properties of the Surrette 4KS25p battery..

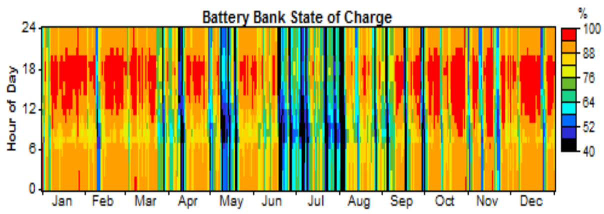
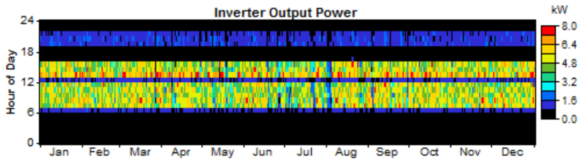


Fig. 6. Battery State of Charge of optimal PV/gen/battery hybrid power system .

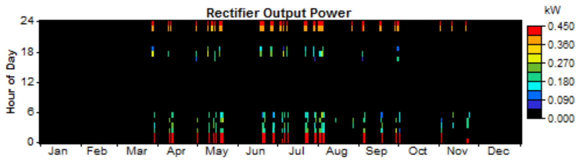
As shown in Fig. 6 the state of charge of battery is higher in all months except Jun, July and August which are the raining seasons of the site with low solar radiation. The battery is almost full during day time since the load is directly covered by the power out of the PV system without discharging the battery.

5.4. Power converter

The power electronic converter is used to maintain the flow of energy between AC and DC components .The optimal size of power converter used in this system is 9 kW. The lifetime for one unit of converter is 10 years with the efficiency of 95%. The system uses two types of converters. One is Sunny boy inverter which converts DC (direct current) electricity from PV array to AC (Alternating current) with bus voltage of 240V, 50 Hz. The other converter is Sunny Island battery inverter as shown in fig 1, which is an energy manger of the overall system. It converts DC electricity from Battery into AC electricity with the same voltage and frequency of the bus. It is a bi-directional inverter with the capability of converting Ac to DC and vice versa. The overall controlling detailed will be explained in next consecutive section.



a.



b.

Fig. 7. Output of power converter a). Inverter output b.) Rectifier output

Figure 7 reveals that the inverter working intensively during day time to convert DC power from the PV system to AC power needed by the load. At 12:00-13:00 which is lunch time , no consumption of power and the inverter output is very small since it reduces the power from the PV system by increasing system frequency. Otherwise it charges the battery if it is not full. Figure 7b shows that the diesel generator charges the battery rarely during the year. It charges the battery during the raining season and seasons with low solar radiation.

5.5. Diesel generator

The diesel power plant of 1 kW is used in an optimal configuration. The diesel price with three discrete values of 1$/L, 1.2$/L and 1.5$/L are used for the sensitivity variables. At present, the diesel price is about 1$/L in Ethiopia. The lower heating value is 43.62MJ/kg, the density. The main advantage of using a Sunny Island inverter is, it controls the energy flow to the load and it prolongs the life of battery which is the main fragile component in the system. As far as enough power is available to power the load from the solar array, the inverter directly supplies the load totally PV without discharging the battery or starting the backup diesel generator. If the load requirement is greater than the capacity of the power system including battery and generator the inverter sends signal to load relay to shed some non critical loads.

6. Descriptio Energy management and control scenario

The sunny battery inverters monitor and control the whole system automatically by calculating the state of charge (SOC) of the batteries and controlling the power via bus frequency (50Hz). The sunny Island battery inverter forms the AC grid of the hybrid power system [13]. At the same time it controls the voltage and frequency on the AC side.

When the Photovoltaic array produces more energy than being consumed, the energy is used to charge the battery bank if the battery is in a low state of charge otherwise it increases the bus frequency and automatically reduces the power feed from a photovoltaic array to the buss. If, on the other hand, the photovoltaic array generates less energy than being used, the batteries provide the needed margin. The Sunny Islands continuously monitor the SOC of the batteries. If the SOC decreases below 60 %, the sunny battery inverter automatically starts the generator. The generator will be disconnected at 90 % SOC. With commissioning, the Sunny Island inverter configuration was set to default, requesting the diesel generator to run between 40 % to 90 % SOC. This was changed to avoid deep cycling of the batteries and thus to increase the lifetime of the batteries.

In order to enable the parallel operation of the AC coupled voltage source without involving any communication the so called droop mode is used. This method uses active and reactive power statics as a basis for coordinating the performance of the various coupled converters. To achieve optimum power flow , the grid parameters voltage and frequency are specifically influenced.

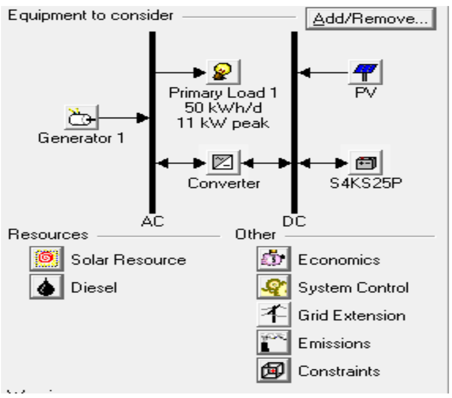


Fig. 8 Schematic of hybrid PV–diesel–battery power system.

7. Sensitivity Analysis

Two sensitivity variables have been chosen to take into accounts the variation of these variables in the future. The chosen variables are amount of solar radiation of the site and the price of diesel fuel. It is assumed that these two variables highly affect the cost of the system. The output of sensitivity analysis is shown as graph as shown in Fig 9 . As seen from fig 9, PV/Gen/battery system is optimal until the solar radiation will reach 5.88 kWh/m^2 and less sensitive to the price change of the fuel. The current diesel fuel price in Ethiopia is around 1.2 $/liter . When the diesel price sore beyond 1.5 $/litter PV/battery hybrid system is more economical. Since the optimal system incorporates all the subsystems it is feasible to install generator as back up and use solar energy and battery to cover base loads. Of course the energy management system in the battery inverter always prioritizes energy from solar energy followed by batteries and finally the backup diesel generator.

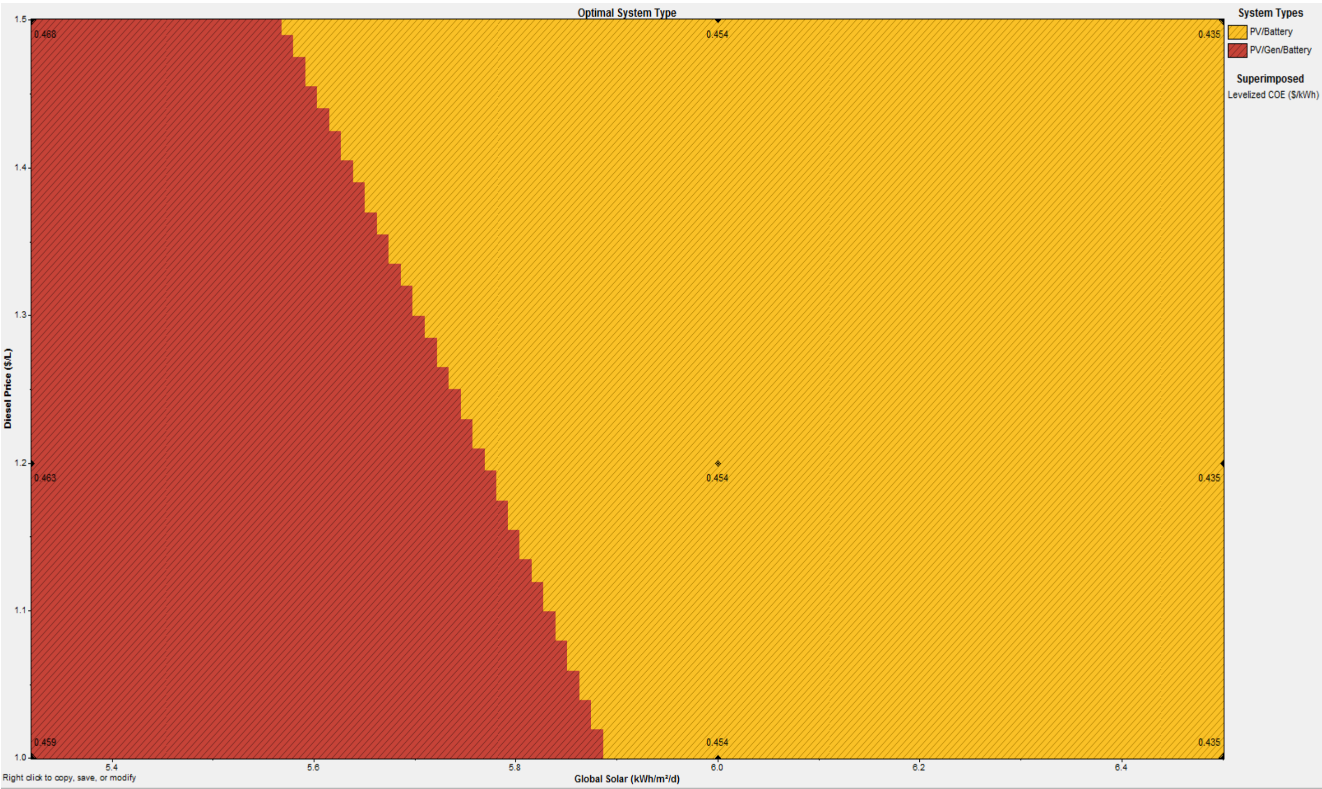


Fig. 9. Graphical Result of sensitivity analysis between Diesel fuel price and Solar radiation value for optimal Hybrid system

8. Economic comparison of Diesel only system and PV/Diesel/battery hybrid system

The fig 9 below shows economic comparison of the diesel only system , which is base case, with that of PV/Gene/battery system. The important variables are displayed in the table with corresponding value and here only the meaning of the variables will be explained to avoid repetition. The metrics (present worth, Annual worth, return on investment etc.) show the value of the difference between the two options(base case and current system) taking into account the Lifecycle costs of both systems [14]. The system summary table (Fig 9) shows the component sizes, capital cost and net present cost of the base case system and current systems.

- The *present worth* is the difference between the net present costs of the diesel only system and the PV/diesel/battery hybrid system. A positive value indicates that the PV/diesel/battery system saves money over the project lifetime compared to the diesel only system which is equivalent to $ 206,562

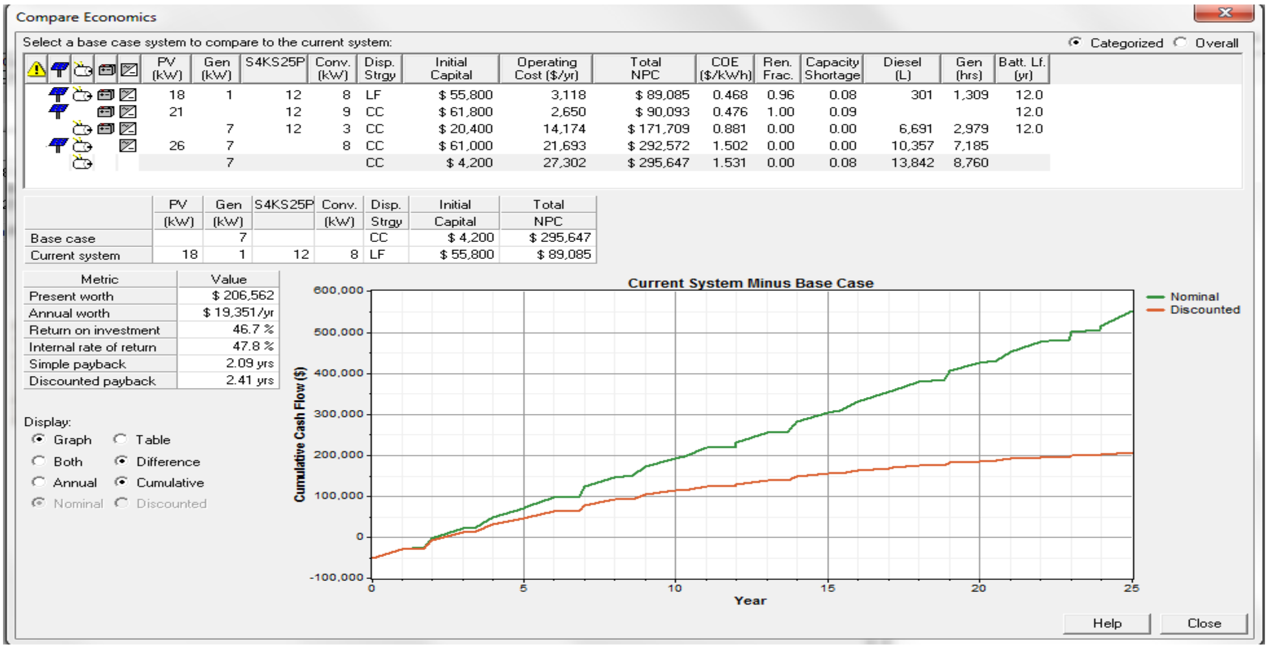


Fig. 10. Economic comparison of PV/gen/Battery system with that of Diesel generator only system

- The *annual worth* is the present worth multiplied by the capital recovery factor. The capital recovery factor (CRF) is given by

$$CRF\,(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$

Where

i= real interest rate in our case 8%

N= number of years, in our case 25 years which are the lifetime of the project

- *Return On Investment (ROI)*, is the concept of an investment of some resource yielding a benefit to the investor. A high ROI means the investment gains compare favorably to investment cost. In purely economic terms, it is one way of considering profits in relation to capital invested. It is calculated as

$$ROI = \frac{(payback\ - Investment)}{Investiment} \times 100$$

In our case it is 46.7 % which shows good business case.

- *Payback* is the number of years at which the cumulative cash flow of the difference between the current system (PV/diesel/battery) and base case system(diesel only) switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system. In our case it takes 2.09 years to pay back the investment. The simple payback is where the nominal cash flow difference line crosses zero. The discounted payback is where the discounted cash flow difference line crosses zero.

- *Internal rate of return (IRR)* is the discount rate at which the base case and current system have the same net present cost

Therefore the PV/diesel/battery hybrid system is economically feasible compared to that of diesel generator only case. With good solar radiation of the site the day load can be completely covered by Pv generator and the night load with battery and diesel generator backup.

9. System Description Result and Discussion

Several simulations have been made by considering different PV , Battery , converter and Diesel generator. The PV capacity has been allowed to vary from 0 to 20kW , the diesel generator from 0 to 10kW , battery from 0 to 5 string and converter from 0 to 12kW. It can be noticed from the result(see Table 1) PV/ diesel gen./ battery system is the optimum system with the total net present cost of $89,085 and with the cost of energy 0.468$/kWh . However , the diesel only system has a total net present cost of $295,647 with the cost of energy 1.531$/kWh which is much higher than hybrid system.

The optimum system contains all the generators hence increases the reliability of the system. The economic comparison clearly shows that the hybrid system has economic as well as technical advantages over a stand alone diesel system. The system pays back its investment cost within two years and saves a huge amount of money. The main advantage of hybrid system involving SMA battery inverter is that it can deliver the required amount of energy directly from PV without discharging the battery as far as enough solar radiation on the site. This increases the lifetime of the battery and also prevents the frequent start and stop of diesel generator consequently saves the fuel cost of the system. From the result of the simulation it is concluded that PV/Diesel/battery hybrid power system is feasible in terms of economics as well as technically. It has also less greenhouse gas emission (see Table2) and therefore reduces negative externality of diesel generator. Figure 11 and 12 shows cash flow summary of hybrid and stand alone diesel generator system. As seen from the hybrid system has a high initial capital cost and low operating and fuel cost. Whereas the stand alone diesel system has a low capital cost and high operating and fuel cost.

Table.1. Categorized result of simulation

Calculate — Simulations: 11088 of 11088 Progress:
Sensitivities: 9 of 9 Status: Completed in 16:26.

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.32 Diesel Price ($/L) 1.5

Double click on a system below for simulation results.

PV (kW)	Gen (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen (hrs)	Batt. Lf. (yr)	
18	1	12	8	LF	$ 55,800	3,118	$ 89,085	0.468	0.96	0.08	301	1,309	12.0	**PV-diesel gen hybrid system**
21		12	9	CC	$ 61,800	2,650	$ 90,093	0.476	1.00	0.09			12.0	
	7	12	3	CC	$ 20,400	14,174	$ 171,709	0.881	0.00	0.00	6,691	2,979	12.0	
26	7		8	CC	$ 61,000	21,693	$ 292,572	1.502	0.00	0.00	10,357	7,185		
	7			CC	$ 4,200	27,302	$ 295,647	1.531	0.00	0.08	13,842	8,760		**Diesel Gene only system**

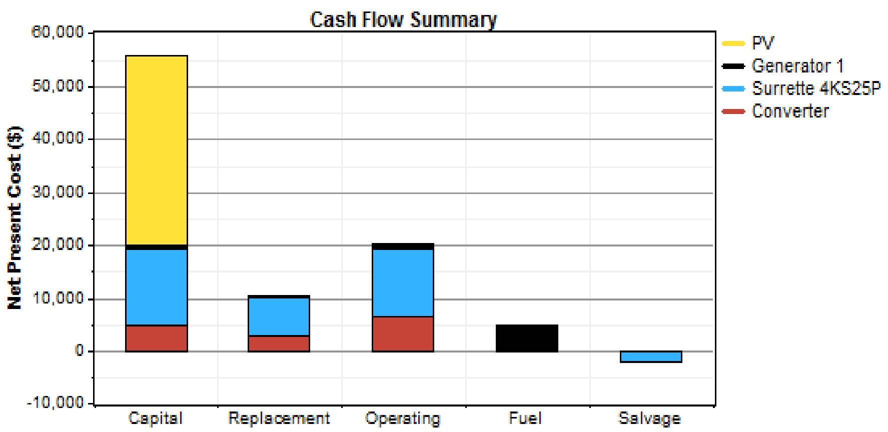


Fig. 11. Cash flow summary of PV/Gen/ battery hybrid system by cost type

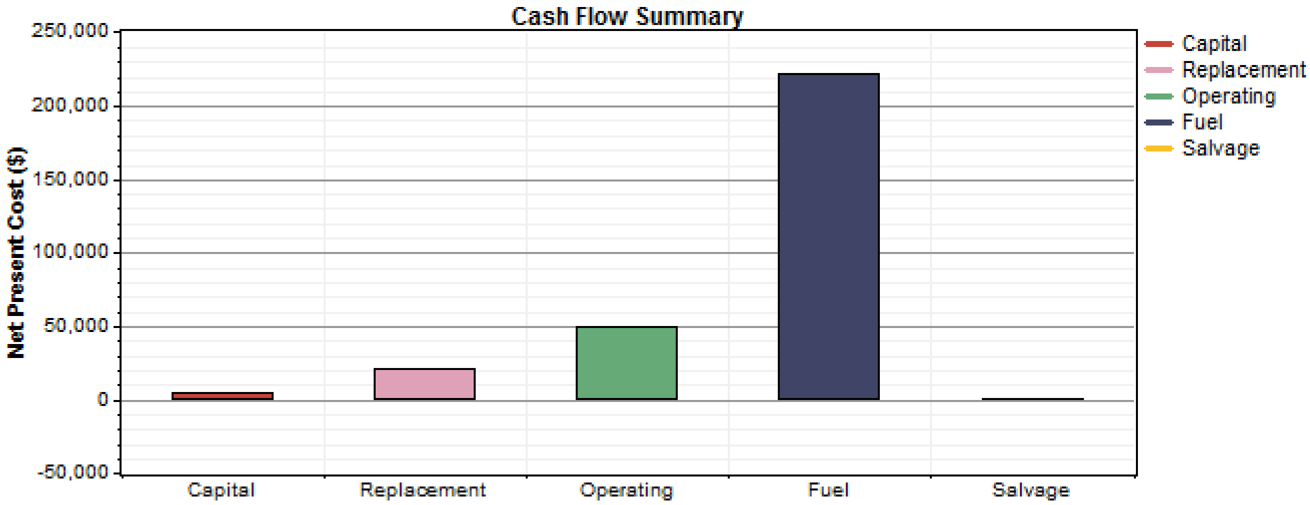


Fig. 12. Cash flow summary of diesel generator only system by cost type

Table 2. Comparison of greenhouse gas emission

Pollutant	**PV/Gen/battery Hybrid system Emission Kg/yr**	**Diesel Generator only system Emission Kg/yr**
Carbon dioxide	584	36,450
Carbon monoxide	1.44	90
Unburned hydrocarbons	0.16	9.97
Particulate matter	0.109	6.78
Sulfur dioxide	1.17	73.2
Nitrogen oxides	12.9	803

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Appendix

Technical data and cost information of components used in the HOMER simulation software

PV Array	**DC**
Capital cost	4000$/kW
Replacement cost	3000$/kW
O& M cost	$0
Efficiency	15%
Lifetime	25
Tracking system	No tracking
Diesel Generator	**AC**
Capital cost	600$/kW
Replacement cost	500$/kW
O& M cost	0.075$/hour
Lifetime	15000hr
Battery	**DC**
Technology	Surrette 4KS25P
Capacity	7.6 kWh
Nominal Capacity	1900Ah
Voltage	4V
Min. state of charge	40%
Capital cost	$1300
Replacement cost	$1200
O& M cost	100$/year
Efficiency	80%
Lifetime	12year
Converter	**AC/DC/AC**
Capacity	9kW
Capital cost	$700/kw
Replacement cost	$700/kw
O& M cost	70$/year
Efficiency	90%
Lifetime	10 year