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Economic & Environmental Analysis of Remote diesel generator with photo-voltaic cogeneration

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Abstract - The burning of depleting fossil fuels for power generation has detrimental impact on human life and climate. In view of this, Renewable energy sources are being increasingly exploited to meet the energy needs. In order to handle intermittent nature of renewable energy source, hybrid energy systems can be applied instead of standalone system. These systems use different energy generators in combination, by this maintaining a stable energy supply in times of shortages by one of the energy resources.

This paper discusses the design, simulation, systematic techno-economic and environmental analysis of autonomous hybrid systems i.e. PV-Diesel energy system with battery storage for rural electrification is suitable to achieve both ecological and socio-economic objectives, since Hybrid systems are an environmental sound technology.

MATLAB Simulink is used for Simulation performed for three cases: 1) diesel only; 2) diesel-battery; and 3) PV with diesel-battery using a one-year time period. The results of the simulations are used to perform an economic analysis and predict the environmental impacts of integrating a PV array into diesel-electric power systems for remote villages. The economic part of the model calculates the fuel consumed, the kilowatt-hours obtained per gallon of fuel supplied, and the total cost of fuel. The environmental part of the model calculates the CO_2, particulate matter (PM), and the NOx emitted to the atmosphere. The investigation also examines the effect of PV/battery penetration on COE, operational hours of diesel gensets. In this study exhibits that the operational hours of diesel generators decrease with increase in PV capacity.

Keywords: Diesel Generator, Battery, Simulation, Hybrid Energy System, Matlab Simulink, PV, bidirectional inverter, Environmental impact

1. INTRODUCTION

Electrification of isolated or remote areas has been a subject of consideration ever since electricity started to affect human activities. In these areas the geographic adverse conditions and/or the increased cost to expand the utility grid usually lead to the implementation of autonomous power energy systems [1–3]. In previous decades the relatively low cost of operation and maintenance (O&M) of a diesel generator (DG) based mainly on the low prices of fuel, along with the high initial cost for PV generators (PVGs) and the required power electronics, resulted in extended use of DGs to supply power to meet load demand in remote areas [4–7]. The conducted steady and systematic Research and Development (R&D) of PVs and their related Balance of System (BOS) have caused a significant decline in the associated prices. On the other hand, the constant increases in energy demand and the related utilization of natural resources have caused enormous increase in fuel prices. These factors have made the renewable energy sources (RES) a viable supplement and perhaps a main alternative to be used in remote areas where the cost of O&M and the fuel cost of DGs are relatively high [8].

The advantages *wrt* Implementing PVs in an autonomous system are several [9], but there is a real disadvantage concerning limited system reliability when there is no solar irradiation for a longer period than the one being considered by the designer for storage capacity of the system. In such a case, the energy stored in the battery bank due to economic reasons cannot meet fully the load requirements [10]. On the contrary, the non constant yearly energy production of the PVG may lead to over design and thus to a more expensive PVG with relatively greater battery storage capacity in order to meet the load requirements. The unnecessarily larger size of PVGs and ratings of the needed inverter can be avoided by using a combination of a conventional energy source to supply power, especially when the peak load demand is much higher than the capacity of the PVG. In such cases the use of a DG to supply the required load power, while it simultaneously charges the battery, results in providing the necessary reliability and cost effectiveness characterizing the overall hybrid power system (HPS) [11].

This paper presents three competing power systems, with equal capacity, serving the same load, which were proposed, developed and tested for their reliability, efficiency and cost effectiveness. These three investigated systems were: 1) a DG one, 2) a DG-battery one, and 3) a PV with DG-battery one. The operating requirements and associated costs of the examined three power systems (PSs) were used to perform the desired economic analysis.

2. LOAD ESTIMATION AND MATEROLOGICAL DATA

The meteorological Annual and other data *wrt* a site i.e. Town *Gilibili*, Ballarpur, Dist. Chandrapur, State. Maharashtra, India at Latitude -19.96, Longitude -79.30 is obtained from website [w7]. Daily and Annual Load Demand Estimated by interviewing number of villagers using Energy Need Assessment Questionnaires.

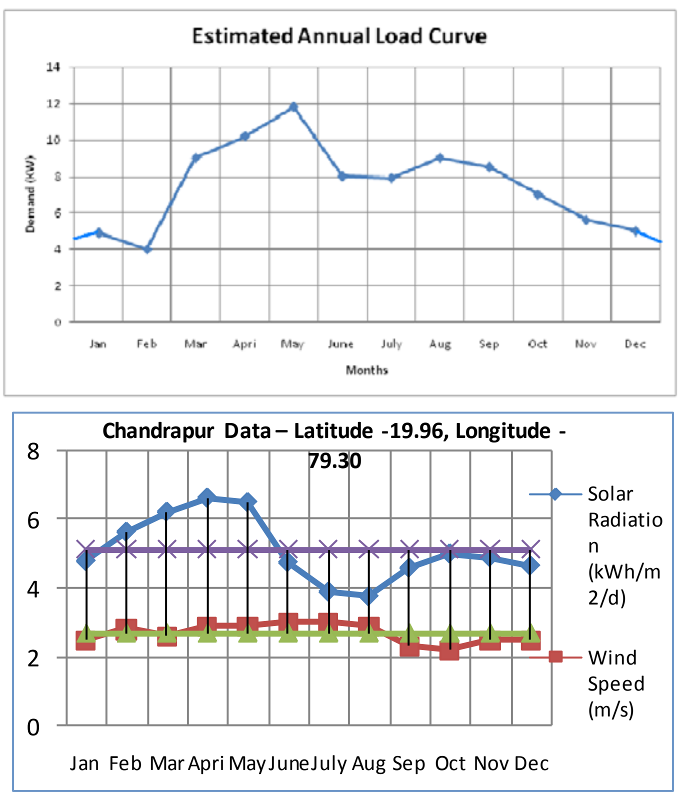

Fig.(a) Load curve & (b)Metrological data for location

3. MATLAB / SIMULINK SOFTWARE

MATLAB is powerful in matrix or vector programming; it is also a brilliant tool in working with matrix for numerical and engineering applications. It has the ability to be programmed to solve several tasks at one time using the idea of matrix. In MATLAB, there are toolboxes of special collections of functions and scripts. Script is a program without input and output, which is actually a collection of MATLAB statement in one file. Function block accepts variable inputs and allows variable outputs [9].SIMULINK has a wide selection of dynamic systems for modeling, analyzing and simulating. It also offers a graphical user interface for creating block diagram models. A system is configured in terms of block diagram representation from a library of standard components. In the middle of a simulation, algorithms and parameters can still be changed to get intuitive results, thus providing the user with a ready access learning tool for simulating many of the operational problems found in the real world. It also provides immediate access to the mathematical, graphical, and programming capabilities of MATLAB [13]

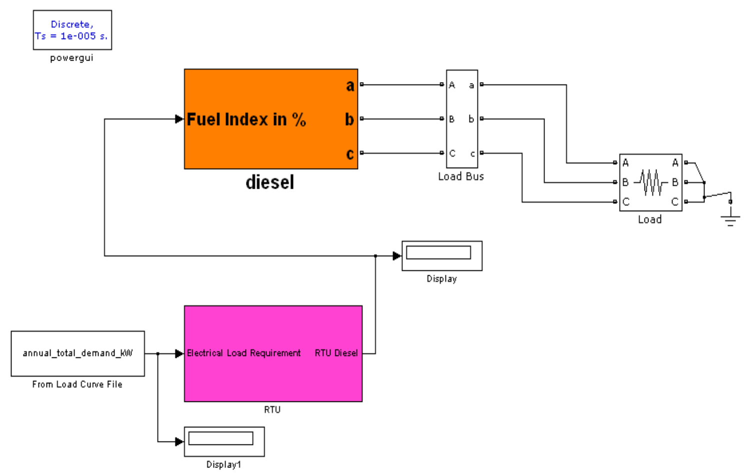

Fig. (a) Diesel Generator only Simulation Circuit

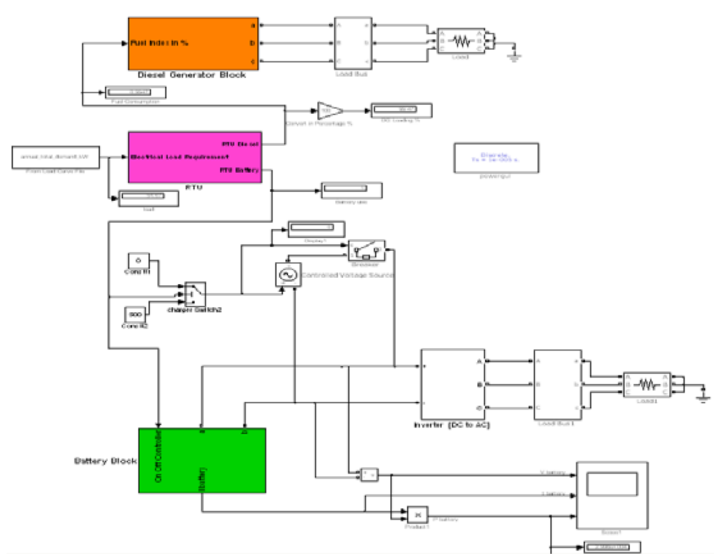

Fig.(b) Matlab simulation of Diesel + Battery Circuit

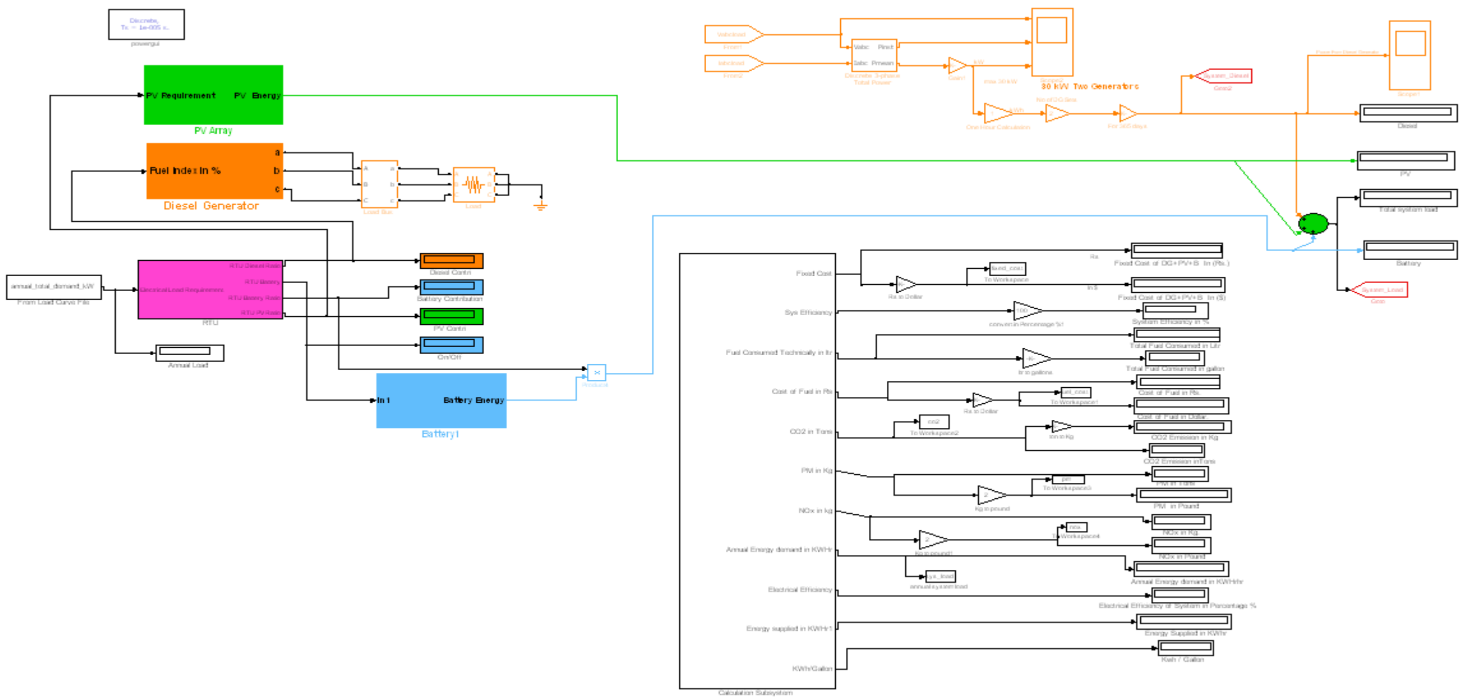

Fig. Matlab Simulation Model of 3 different model (a) Diesel Only (b) Diesel + Battery (c) PV + Diesel + Battery

4. OVERVIEW OF AUTONOMOUS POWERS OPERATION

4.1 PV Array Modeling

PV arrays are built up with combined series/parallel combinations of PV solar cells, which are usually represented by a simplified equivalent circuit model such as given in Fig. 1 and by equation(1).

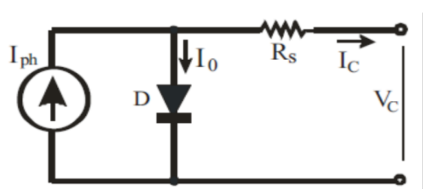

Fig.1. Simplified equivalent circuit of Photovoltaic Cell

$$V_C = \frac{AkT_C}{e}\ln\left(\frac{I_{ph}+I_0-I_C}{I_0}\right)-R_S I_C \qquad (1)$$

Where,
e: electron charge (1.602 × 10-19 C), k: Boltzmann constant (1.38 × 10-23 J/oK), Ic: cell output current,
Iph: photocurrent, function of irradiation level and junction temperature (5 A) , I0: reverse saturation current of diode (0.0002 A), Rs: series resistance of cell (0.001 Ω), Tc: reference cell operating temperature (20 °C), Vc: cell output voltage, V.

Energy production by the PV

Typical and mostly used integration of global irradiation is the monthly daily mean irradiation, $(G_d)m$, given
by [12]

$$(G_d)_m = \frac{1}{(m2 - m1)}\sum_{N=m_1}^{m_2} G_d$$

Where, G_d in W/m^2 is the daily global irradiation, m1 is the first day of the examined month, and m2 is the last day of the examined month. Cell temperature Tc in ◦C is another parameter which alters the performance of a PVG. An increase of Tc causes associated increase of the PVG's current, but also associated noticeable decrease in PVG's voltage and power. If the meteorological station provides only the ambient temperature and the global solar irradiation, then the cell temperature can be approximated by [13].

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$$Tc = Ta + 0.02G \quad (3)$$

where, Ta is the ambient temperature. When the ambient temperature and irradiation levels change, the cell operating temperature also changes, resulting in a new output voltage and a new photocurrent value. The solar cell operating temperature varies as a function of solar irradiation level and ambient temperature. The variable ambient temperature Ta affects the cell output voltage and cell photo current. Furthermore, if the wind speed u in m/s is given at the actual site, then Tc can be better approximated by [14]:

$$Tc = 3.12 + 0.899Ta + 0.025G - 1.3u \quad (4)$$

If G and Tc are known, then [15-16]:

$$P(G, Tc) = P_{STC} \frac{ISC(G, T_c)Voc(G, T_c)}{ISC_{STC}\, Voc_{STC}} \quad (5)$$

Where, P(G, Tc), ISC(G, Tc) and Voc(G, Tc) are the power, the short-circuit current and the open-circuit voltage of the PV module at (G, Tc) conditions, respectively; production by the PVG The energy being produced by the PVG is proportional to the global irradiation. It is also related to the temperature of the cell and the air mass.

Simulation of PV Array

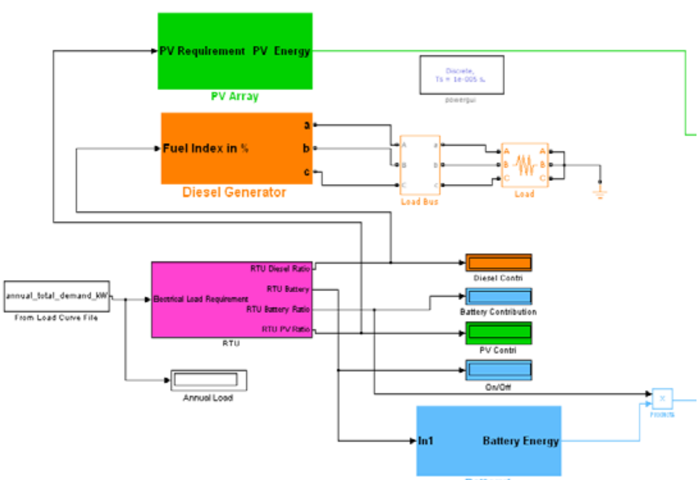

Fig.(d) PV+ diesel+ Battery Matlab simulation model

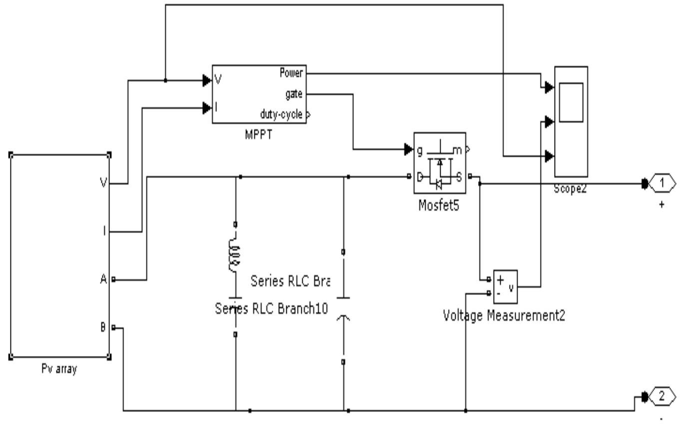

Fig. (e) PV Array Simulation

4.2. Energy production by the Diesel Generator

The power which may be supplied to an autonomous system by the DG is equal to the total load demand. If not given by the manufacturer of the DG, the fuel consumption (FC) vs the supplied load (SL) curve should be established as follows

$$FC = a \times SL + b \quad (6)$$

The coefficients a and b can be calculated using the least square method for a number of experimental measurements as follows.

$$a = \frac{N\sum(SLi \times FCi) - \sum SLi \sum FCi}{N\sum SL^2 i - (\sum SLi)2} \quad (7)$$

$$b = \frac{\sum FCi - a \sum SLi}{N} \quad (8)$$

where, i is the examined measurement (i.e. 1, 2,…,N), SLi is the load being supplied and FCi is the fuel being consumed by the DG when it supplies load SLi . The above mentioned curve is of significant importance for the economic assessment of every PS for possible use. Similarly, the efficiency η_{DG} of the DG is strongly dependent on the load it supplies and is given by,

$$\eta_{DG} = \frac{P_{out}}{P_{in}} = \frac{SL}{MCV \times FC} \quad (9)$$

$$\eta_{DG} = \frac{Pout}{Pin} = \frac{SL}{MCV\,(a \times SL + b)} \quad (10)$$

If the load to be supplied is less than 30% of the DG rating capacity, the DG operation should be prevented not only due to its low performance, but mainly due to the damage the machine may suffer, which will limit its useful life [19]. In such a case, either the load should be supplied by the battery or the charger itself should have enough rated power to charge the battery (without causing damage to it) and the total load being served should be rated close to 70-80% of the DG nominal power output [19].

4.3 Battery bank

A mathematical model of battery bank storage is necessary to predict the state of charge (SOC) of battery at each hour of simulation period. It is difficult to predict the exact SOC of battery for uncontrolled charge /discharge cycles in standalone systems. Load will not be satisfied when the power generated by PV system is insufficient and storage is depleted and its state of charge has fallen below a predetermined minimum value. Energy is stored in battery bank when power generated by PV system exceeds the load. On the contrary, energy is taken from the battery bank when power generated is less than the load demand. The SOC of battery bank at any time t1 depends upon state of charge in the previous moment t0 and the sequence of generated power and load demand levels in the time interval t1- t0.System controller (not shown in block diagram) starts/stops charging batteries when SOC of battery bank reaches to its predefined minimum/maximum charge quantity. System controller disconnects the load when SOC falls below a minimum charge quantity. The SOC of battery bank storage at any hour t can be obtained by monitoring the charge/discharge energy to/ from the battery as given by following expressions:

$$E_{batt}(t) = \min [ChargeLim, (E_l(t)/\eta_{inv} - E_g(t)) / \eta_{batt}] \quad (11)$$

$$E_{batt,in}(t) = \min [ChargeLim, (E_g(t) - E_l(t)/\eta_{inv})\eta_{batt}] \quad (12)$$

$$E_b(t)=E_b(t-1) (1-\delta)-E_{batt} (t)+E_{batt,in} (t) \quad (13)$$

Where, $E_b(t)$ and $E_b(t -1)$) are SOC of battery at the time t and (t -1) respectively; δ is the hourly self discharge rate of bank taken as 0.009 for this study; $E_{batt,in}$ (t) and E_{batt} (t) are the charge and discharge quantities of battery storage; $E_l(t)$ is load demand; $E_g(t)$ is the total energy produced by both PV at time t; η_{inv} and η_{batt} are the efficiency of inverter and charge/discharge efficiency of battery storage respectively; ChargeLim is the maximum allowable charge/discharge energy to/from the battery, assumed to be equal to 10/20 percentage of total battery bank storage capacity. In this paper, the charge/ discharge efficiency of battery is assumed to be the same and equal to the round trip efficiency of battery storage.

The battery bank combined with the inverter's output power should support as much of the load demand as possible in order to avoid frequent (unnecessary) use of the DG. When designing a hybrid PV–DG system the selection of the battery is a significant factor, since its capacity determines not only the energy it can supply but also the peak load that can be served by the battery-inverter sub-system (due to the voltage drop of the battery, which is a function of the supplied load and at the same time is the input voltage of the inverter). In general the capacity of battery is calculated as follows [17].

$$E_{batt} = \frac{E_{L\text{-}BAT}\, d}{\eta_{inv}\, V_s\, \eta_c\, \eta_t\, DOD\, \eta_{bat}} \quad (14)$$

where, E_{batt} is the required battery capacity in Ah, $E_{L\text{-}BAT}$ is the daily supplied energy to the load by the battery in Ah/d, d is the number of days the battery can supply the load, η_{inv} is the efficiency of the inverter, V_s is the system voltage on the DC side in V, η_c is the cable efficiency, η_t is the temperature efficiency, DOD is the used depth of discharge, and η_{bat} is the efficiency of the battery.

4.4 Bidirectional Inverter (Inverter-Charger)

The inverter nominal output power specifies the peak load that can be supplied. In a hybrid PV-DG power system an inverter with nominal power output less than the peak load demand can be used when the peak load is directly supplied by the DG. In most cases, when the base load and the peak load of the PS do not have significant fluctuations, it is preferable to implement an inverter that can supply the peak load, which results in a PS fully controlled by the inverter, and thus decreasing significantly the other related time intervals (eg DG startup period etc) where no load can be served. When the DG is in operation the bidirectional inverter becomes a charger of the battery and all the load is supplied by the DG.

5. ECONOMICAL CRITERIA

The economic analysis part of the simulation model involves calculation of the simple payback time (SPBT) for the PV module and calculation of energy payback time (EPBT) for the PV array. In most of the remote villages, battery banks are used as back-up sources for power. Therefore, the PV with diesel-battery system is compared to the diesel-battery system in the analysis of SPBT. The SPBT is given as:

$$SPBT = \frac{\text{Excess Cost of PV system}}{\text{Rate of saving}} \quad (15)$$

Economics plays an integral role in both, in simulation process wherein it operates the system so as to minimize the total life cycle cost, and in its optimization process, wherein it searches for system configuration with the lowest total life cycle cost. The life cycle cost calculation includes the initial cost of construction, component replacement, maintenance and fuel cost and miscellaneous cost such as emission /penalty cost resulting from pollutant emission / load unmet. In this study, the life cycle cost (LCC) calculation is done only for those system configurations that satisfy customer desired reliability criteria. Therefore, initially the unit sizing program is run to get these combinations, and thereafter the program is extended to evaluate the LCC of such combinations. The LCC of system without any other miscellaneous cost is calculated as [17]:

$$LCC = \frac{ACC}{CRF} \quad (16)$$

$$ACC = CC + OMC + RC + FC \quad (17)$$

Where, ACC is the annual cost of configuration, CRF is the capital recovery factor, ACC is the sum of annual capital costs (CC), operation & maintenance (OMC), replacement cost (RC), and fuel cost (FC) of all system components. The annual cost can be found by multiplying the initial cost by the capital recovery factor (CRF). Where ir, is the annual interest rate, ny is the life of the system. Following expressions are used for the calculation of annual fuel cost(FC) and replacement cost (RC) in equation.

6. POLLUTANT EMISSION COST

When the fuel combustion takes place in diesel generator, numbers of emission (gases) are produced. Percentage of carbon dioxide (CO_2) is largest amongst these emissions. Due to this reason the amount of carbon dioxide production only is considered to find emission cost in this study. The CO_2 emission cost is calculated on the basis of price of tradable renewable certificate using following equations:

$$CO_2weight = (Ccontent.PDG) / 1016.04 \quad (20)$$

$$CO_2tax = (PTRC / Ccontent) * 1016.04 \quad (21)$$

$$Ec = CO_2weight * CO_2tax \quad (22)$$

Where, Ec is the cost of emission, Ccontent is the carbon content taken as 0.6078 Kg per KWh, PTRC is the price of tradable renewable certificate (US$/KWh). CO_2weight is taken in tons, and CO_2 tax has been calculated in terms of US dollars per ton. Finally this cost of emission is also added in the annual cost to the customer (ACC) to calculate LCC of system.

7. SIMULATIONS AND RESULTS

After performing the simulations for the three cases, it was observed that case 3 provided superior results in terms of fuel consumption for the diesel generator and the greenhouse emissions. It was observed that the diesel generator operates most efficiently for case 3, while the diesel-battery system in case 2 has the highest kilowatt-hours per gallon. In case 1, the entire load was supplied without the PV array and the battery bank, leaving the load to be supplied by the diesel generator. Since the diesel generator operates with the lowest load for the diesel-only system, it is the least efficient system and has the lowest kilowatt-hours per gallon. In case 2, when the battery bank is discharged, the diesel generator is used to charge the battery bank, so eventually, the entire load is supplied with the help of the diesel generator. In case 3, part of the load was supplied using the PV array. As a result, there is substantial saving in the fuel consumption by the diesel generator due to use of the battery bank and the PV array with the diesel-only system.

The study exhibits that for a given hybrid configuration, the number of operational hours of diesel generators decreases with increase in PV capacity. It has been found that the for a given PV–diesel hybrid system, the decrease in diesel run time is further enhanced by inclusion of battery storage. The percentage fuel savings by using hybrid PV–diesel–battery system (60 KW diesel system, 1 h storage, 22% PV penetration) is 22% as compared to diesel-only situation. The percentage decrease in carbon emissions by using the above hybrid system has been found to be 21% as compared to the diesel-only scenario. More importantly, with the use of the above hybrid system, about 17615 Kgs/year of carbon emissions can be avoided entering into the local atmosphere. The hybrid PV–battery–diesel configuration (by virtue of a high degree of flexibility) offers several advantages such as: diesel efficiency can be maximized; diesel maintenance can be minimized; and a reduction in the capacities of diesel and battery (while matching the peak loads) can occur. The present investigation shows that the potential of renewable energy option of solar energy cannot be overlooked. A fraction of Gilbili energy demand may be harnessed by deployment of PV systems. The observations of this study can be employed as a benchmark in designing/sizing of hybrid PV–diesel–battery systems for other locations having similar climatic and load conditions. Over dependence on fossil fuels is alarming. Hence, investments in solar energy are imperative to mitigate energy crisis in foreseeable future.

System Cost can vary as per selection of equipments, transportation, installation, etc.

Sr.No.	**Parameter**	**Diesel Only**	**Diesel – Battery System**	**PV with Diesel-Battery System**
1.	System Cost ($)	$ 71363.6	$ 120261.8	$ 171802.72
2.	System Cost (Rs)	Rs. 3925000	Rs. 6614400	Rs. 9449150
3.	System Mechanical Efficiency (%)	26.22 %	29.9 %	29.9 %
4.	KWhr / Gallon (KWhr)	10.61	12.1	12.1
5.	Fuel Consumed (Gallons)	8409.22	7322.36	6584
6.	Fuel Consumed (Liters)	31828.9	27715.16	24921.086
7.	Total cost of Fuel ($)	28935.38	25195.6	22655.5
8.	Total cost of Fuel (Rs.)	1591445.48	1385758.4	1246054.26
9.	CO2 Emitted (Kg)	81163.72	70673.6	63548.77
10.	CO2 Emitted (tons)	81.16	70.67	63.55
11.	PM Emitted (tons)	36.12	31.46	28.28
12.	PM Emitted (pounds)	72.24	62.9	56.55
13.	NOx Emitted (pounds)	3462.6	3015	2711
14.	NOx Emitted (Kg)	1731.3	1508	1356
15.	Annual Energy demand (KWhr)	89221	89221	89221
16.	Annual Energy Supplied	101516	100186	89530
17.	Electrical Efficiency of DEG (%)	87.89	89.06	90.03

Table : Comparison of Results of all 3 PMS cases

8. Conclusion

The preliminary results reported here demonstrate that the integration of a PV array into a diesel-battery stand-alone hybrid power system reduces the operating costs and the greenhouse gases and particulate matter emitted to the atmosphere. The Simulink model can be used to study the performance of any PV with diesel-battery hybrid power system if the operating characteristics of the power system are known. With few modifications, the model can be extended to incorporate other renewable energy sources. The incorporation of additional renewable sources of energy, such as wind turbines in this system, could

further reduce fuel consumption. The dynamic performance and the control system strategy of the power system can also be incorporated into the model.

Although there is a significant capital investment to purchase a PV system for this application, the PV system may have acceptable 16 to 20-yr LCCs for many remote locations. Furthermore, over its life cycle, the PV hybrid power system will consume less fuel and emit less CO_2, NOx and PM than the diesel-only system. If the external costs associated with these emissions are taken into account, the PV system discounted payback period will further decrease. Hybrid energy systems, which result in more economical and efficient generation of electrical energy, would not only enhance the capability of automated and precision generation systems, but would also help to extend the life of nonrenewable energy sources.

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