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Research Article

Design and Optimization of Photovoltaic-Diesel Generator-Battery Hybrid System for off-grid areas

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Abstract

A hybrid system based on photovoltaic array integrated with diesel generator and battery is considered an effective option to electrify remote and isolated areas where transmission of the grid is not possible. In the design of a photovoltaic array-diesel generator-battery hybrid system, selection of a suitable size, blending of the photovoltaic array, diesel generator and battery storage with the optimum mix of energy delivered by diesel generator, battery and obtainable from photovoltaic is an important issue in such hybrid systems. This paper presents the development and application of a simple spreadsheet modeling software based on time series simulation methodology. Results show that the optimal configuration of an autonomous system is 50% of the annual energy demand is met by diesel generator, while the remaining 50% is delivered by the photovoltaic integrated with a battery and minimum cost of energy will be 13.1 Rs/kWh (assuming diesel fuel price of 60 Rs/L). Photovoltaic array – diesel generator system integrated with battery system has been analyzed for energy demand through sensitivity analysis using life cycle cost calculated and system sizing under resource uncertainty with the help of probabilistic approach. The investigation also examines the effect of different diesel generator loading on optimum photovoltaic penetration and cost of energy. System sizing and optimization to minimize the operational hours of diesel generator with an increase in photovoltaic capacity with the help of battery storage.

Keywords: *Photovoltaic array – diesel generator – battery hybrid system optimal sizing, Photovoltaic penetration, Sensitivity analysis, Uncertainty of resource.*

1. Introduction

Rural areas of developing countries lack options for supply of electricity due to poor distribution of financial resources to aid grid extension. The development of modernized energy system for developing countries especially in rural areas is constantly a considerable problem to energy utilities. The progressive use of diesel generators in rural areas as main source of electrification is continuously becoming unsuitable because of the following reasons; the diesel generator requires the fuel at every single second of operation and the maintenance of every time is needed and it is very important to worry about the instability of power generated by those generators and the accessibility of fossil fuels is still a challenge for some communities. Another option of electricity generation is standalone photovoltaic array or wind system. The amount of power produced by renewable energy devices such as photovoltaic array cells varies significantly on an hourly, daily and seasonal basis due to the variation in the availability of the solar radiation. Therefore, in order to cater to instantaneous uncertainty of power from photovoltaic panels, provision of a battery bank becomes absolutely necessary. Although a battery bank is expensive and has its own charging and discharging losses by using battery storage, dump energy is minimized, reduces fuel consumption, minimizes hours of part load operation of diesel generator and reducing the number of start and stop of diesel generator. Major issue with this system is economic optimum in the mix of energy delivered by each component such as photovoltaic array, diesel generator and battery.

Economic and technical assessment of off-gird photovoltaic array—diesel generator—battery system was performed by Shaahid *et al*., 2007. The techno economic viability of utilizing a hybrid power system which compromises of 80 kW photovoltaic array system including 175 kW diesel generator together with battery storage of 3 h of autonomy with photovoltaic array penetration of 26% was reported at cost of Rs 8.94 per kWh with daily total load carried out 1689 kWh. Shaahid *et al*., 2009 used HOMER software to find an optimal design of photovoltaic array—diesel generator battery hybrid system for supping remote village. The study examines the effect of photovoltaic array battery penetration on the cost of electricity. The result shows that 27% photovoltaic array penetration with % of fuel saving in photovoltaic

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array—diesel generator—battery system is 27% less than a diesel only system. Nema *et al*., 2012 gives the design idea for sizing of hybrid systems with 95% covered by photovoltaic array, 4% of diesel generator 1 and remaining 1% by diesel generator 2 by using HOMER software. Solar photovoltaic array – diesel generator sizing analysis and cost optimization has been widely investigated by Agarwala *et al*., 2013. The simulation result shows that photovoltaic array penetration of 89% and diesel generator covered about 11% with minimum life cycle cost (LCC) by using simulated annealing technique.

Suryoatnojo *et al*., 2014 studied optimal sizing of photovoltaic array—diesel generator—battery system using PSO method. They concluded that the diesel generator unit produces energy about 69%, Photovoltaic array 28% and battery bank with 3%.

Roy *et al*., 2015 investigated the feasibility of photovoltaic array—diesel generator hybrid system without energy storage. They achieved an optimum mix of energy delivered by diesel generator and photovoltaic array on the basis of cost of energy. They concluded that 70% of annual energy demand is met by diesel generator and remaining 30% is met by photovoltaic array with minimum cost of energy by using deterministic approach.

In this paper, a complete design of hybrid system consisting of photovoltaic array panels, a diesel generator as a backup power source and a battery system supplying a hospital in Pune, Maharashtra is demonstrated. The proposed sizing method for this hybrid systems using simple time step simulation based model is used.

2. Methodology

The mathematical modeling of photovoltaic array hybrid system comprising of diesel generator and battery power systems is essential for sizing the system. Methodology for modeling of photovoltaic array, diesel generator and battery bank as well as system modeling, configuration with energy balance are described in this the section. The overall project is designed for drying of fruits and perishable based on the area below the collector and tilt angle of the collector on south facing.

2.1 Modeling of photovoltaic array

The performance of solar photovoltaic array is needed to produce power in an efficient way as much as possible,

The power output from the photovoltaic array at given time step is the function of the panel efficiency, area and the radiation incident (I_t). The photovoltaic array output power can be found by the following equations;

$$P_{pv} = \eta_{pv} \times A \times I_t \quad (1)$$

It is the radiation incident on the tilted surface of the photovoltaic array (W/m²) at that time step, and A is the total photovoltaic array area (m²). Incident solar radiation on the tilted surface of photovoltaic array w.r.t inclination angle is calculated as (Sukhatme *et al*., 2006),

$$I_t = (I_g - I_d)r_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I_d\left(\frac{1-\cos\beta}{2}\right) r \quad (2)$$

Where I_g is global solar radiation for time step of one hour (W/m²), I_d is diffuse radiation (W/m²), r_b is the tilt factor, r is the ground reflectance and β is the angle of inclination.

2.2 Modeling of diesel generator

A diesel generator is required to supply the load when the generator energy from the photovoltaic array-battery system is insufficient. If diesel generator is directly attached to the load, then the rated capacity of the diesel generator must be at least equal to the maximum load. A relation to selecting the rating of the diesel generator is given by (Kolhe *et al*., 2000);

$$P_{dgr} = max\left(Peak\ DG\ demand,\ \frac{Energy\ Demand}{\frac{Hrs}{day} \times Load\ Factor}\right) \quad (3)$$

The fuel consumption of the diesel generator depends on the rated power of the generator and the actual power output supplied by it. The fuel consumption of the diesel generator is (FC_{DG}) in (l/h) is given by following Eq.

$$FC_{DG} = A_G \times P_{DG} + B_G \times P_{dgr} \quad (4)$$

Where P_{DG} is the output power and P_{dgr} is rated power of diesel generator. A_G and B_G are coefficients of the consumption curve in (l/kWh) where A_G = 0.2088 l/kWh and B_G = 0.01841 l/kWh for the diesel generator (Arun *et al*., 2008).

2.3 Photovoltaic array-diesel generator-battery hybrid system configuration and energy balance equation

The layout of a parallel hybrid system configuration is given in Fig. 1.

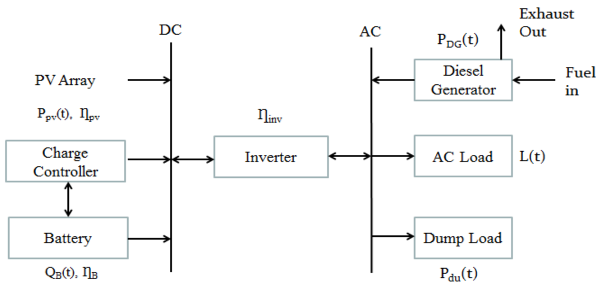

Fig.1 Schematic layout diagram of photovoltaic array – diesel generator-Battery hybrid system

The system components include diesel generator, photovoltaic array, battery and bidirectional inverter. Parallel mode of operation allows the photovoltaic array and the diesel generator to supply a portion of the load directly. The energy generated by photovoltaic array panels and stored in the battery bank when power from photovoltaic array is greater than the required load. Photovoltaic array and battery have preference to supply the load. When the battery is discharged to its minimum level, the diesel generator as a backup source is switched on to fulfill the demand of electricity. Charge controller prevents the overcharging and discharging of the battery.

In some cases where generated energy exceeds the load requirement and the battery bank is fully charged in sunshine hours, this extra energy is consumed by the dump load. It affects the hourly energy flow sequence in the power supply system, the variation of battery sizing, diesel generator sizing and the amount of usable photovoltaic array energy at any given time. This model includes a time series simulation approach based on the overall energy balance of the system. The net power generated is represented as the difference between the total power generated by the photovoltaic array ($P_{PV}(t)$) after taking inverter efficiency and power required by the load (L(t)) and dumped power when there is excess generation of energy.

$$\frac{dQb}{dt} = \left(L(t) - (Ppv \times \eta pv) - Pdu(t)\right) \times f \qquad (5)$$

Where f shows the efficiencies associated with the charging and discharging process.

$f = \eta_c$ whenever $P_{PV} \geq L(t)$
$f = \eta_d$ whenever $P_{PV} \leq L(t)$

Above equations related to the rate of change of energy of the battery storage with the input power, demand power and the power convertible efficiencies in charging or discharging. The stored energy Q_B over a time period of Δt may be expressed as follows:

$$Q_B(t + \Delta t) = Q_B(t) + [\, L(t) - (P_{pv} \times \eta_{pv}) - P_{du}(t) \,] \times f\Delta t \qquad (6)$$

If $P_{PV} + Q_B(t) \leq L(t)$ then $P_{deficit}(t)=(P_{DG})$

η_{inv} shows efficiency of the inverter. In the system operation over the time period Δt, whenever the energy supplied by the generator is greater than the demand ($P_{PV} > L(t)$), the energy added is used for charging the battery. If the dispatch of diesel generator is such way, the energy delivered by the generator is lower than the load, and then battery meets the deficit level. It is assumed that the charging and discharging take place with an efficiency that remains constant over time. The self-discharge loss for the battery bank is assumed to be negligible. Modeling of charge controller is not considered in this paper.

The minimum required generator rating and the corresponding battery storage capacity, for meeting the required load may be obtained by solving (Eq. 6) over the entire time duration. To solve energy balance equation, required inputs are the expected load curve over a specific time interval. To obtain the minimum battery rating, a numerical search is performed that satisfies the energy balance with the following conditions:

$$Q_B(t) \geq 0 \; \nabla t \qquad (7)$$

The battery energy level is always non negative as per Eq. 7.

$$Q_B(t = 0) = Q_B(t = T) \qquad (8)$$

Eq. 8 represents the repeatability of battery state of energy over the time period. The required battery bank capacity is obtained by Eq. 6. The battery capacity can be calculated from the following expression
Required battery capacity,

$$B_r = \frac{Max\ battery\ energy\ storage}{Depth\ of\ Discharge} \qquad (9)$$

$$B_r = \frac{max(QB(t))}{DOD} \qquad (10)$$

High DOD decreases the battery life. Modeling of batteries for real time analysis of hybrid system must account for the dependence of battery bank parameters on state of charge of battery, storage capacity of battery, rate of charge and discharge and self-discharge of battery. In hybrid renewable energy system, the mode of operation of battery i.e. the charging or discharging is dependent on the photovoltaic array power source availability and the load demand.

The flow chart of Fig. 2 shows the method of selecting the rating of Photovoltaic array, diesel generator and battery rating.

3. System Optimization

The designer needs to choose an optimum system configuration based on the required objective.

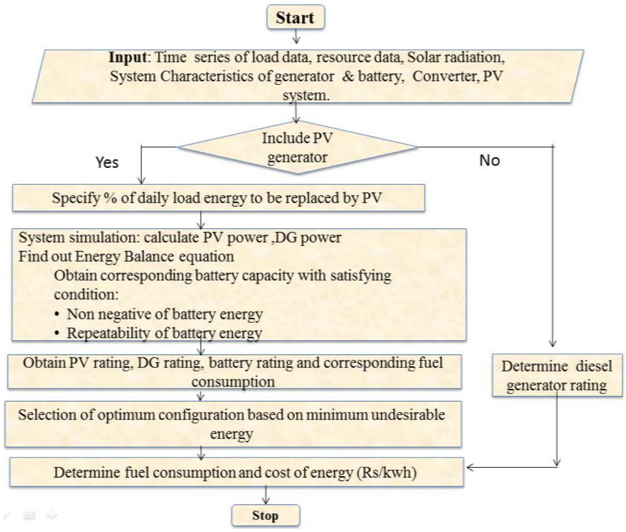

Fig.2 Sizing procedure of photovoltaic array - diesel generator-battery hybrid system sizing flowchart

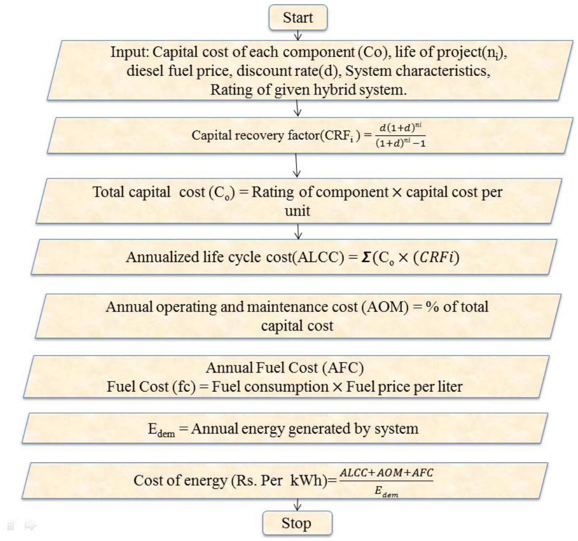

Fig.3 Flowchart showing the optimization procedure of photovoltaic array - diesel generator - battery hybrid system

In this section, the procedure for choosing optimum system configuration is discussed. The cost of energy (COE) is most important factor which accounts for the capital cost and the operating cost and fuel cost combined with the system, is chosen as an appropriate economic parameter to estimate and to optimize the system configuration. Fig. 3 shows the system optimization process step by step. CRF is the capital recovery factor for the system component, and it is a function of the discount rate (d) and life of the component (n_i).

4. System sizing under resource uncertainty

The above methodology used for sizing of system with the help of deterministic approach. In this section probabilistic approach is used for system size under resource uncertainty. In this, the hourly values of power available from power resources are assumed as random variables, i.e. solar radiation and power coming from the photovoltaic array. The load is thus assumed to be deterministic over the time step. The resource uncertainty is shows the probabilistic constraint. The system has to meet the required deterministic demand with probability greater than a required value. The chance constraint method relating the probability of the demand, D(t) being met by the system is:

$$Prob[P_S(t) \geq P_D(t)] \geq \alpha \tag{11}$$

Where $P_S(t)$ is power from resource, $P_D(t)$ is required demand and a is specific reliability of system. In this case power from photovoltaic array is resource i.e. above equation becomes

$$Prob[P_{pv}(t) \geq P_D(t)] \geq \alpha \tag{12}$$

Combine equation of energy balance (Eq. 6) and above equation (Eq. 12), the Chance constraint may be expressed as

$$P\left[\frac{Qb(t)\Delta t}{f(t)\Delta t} - \frac{Qb(t)}{f(t)\Delta t} + P_D(t)f(t) + P_{du}(t)\right] = \mu_{Ppv} - \sigma_{Ppv}Z\alpha \tag{13}$$

Where $Z\alpha$ is the inverse cumulative normal probability distribution corresponding to reliability with mean as zero and unity of standard deviation. Following equation shows the equivalent in terms of battery energy values for any step we get,

$$Q_B(t+\Delta t) = Q_B(t) + [\mu_{Ppv} - \sigma_{Ppv} Z\alpha - P_D(t) - P_{du}(t)] \times f(t)\Delta t \tag{14}$$

It may be noted that the deterministic energy balance Eq. 6 and the probability energy balance Eq. 14 are same. As random variable $P_{pv}(t)$ and in stochastic case is represented by its deterministic equivalent of the methodology developed to find out system sizing under resource uncertainty.

5. Illustrative examples

An illustrative example for sizing and optimizing of the integrated system is presented in this section. The hourly load profile and the key technical and economic aspects in the following subsection.

5.1 Selection of load

The low energy demand for rural areas does not compensate the cost of long-range transmission lines from the national grid. The solar resource data and electrical demand data for a remote hospital located in Pune in the state of Maharashtra, India have been considered. Fig.4 shows the hourly average solar radiation on typical day at Pune, Maharashtra for the month of January (Mani and Rangarajan,1980). For a representative day, the hourly variation in the electrical demand for the hospital daily energy requirement is 3467 kWh. The electrical demand is considered to be constant over the time step of 1 hour. The average and maximum electrical demands are 145kW and 182.35 kW respectively. The power demand profile with hourly time includes heating, cooling as well as electrical appliances are represented in Fig 5.

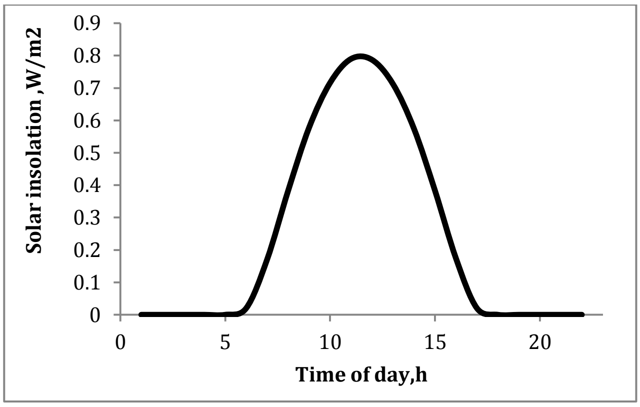

Fig.4 Hourly average solar radiation on typical day at Pune for month of January (Mani and Rangarajan, 1980)

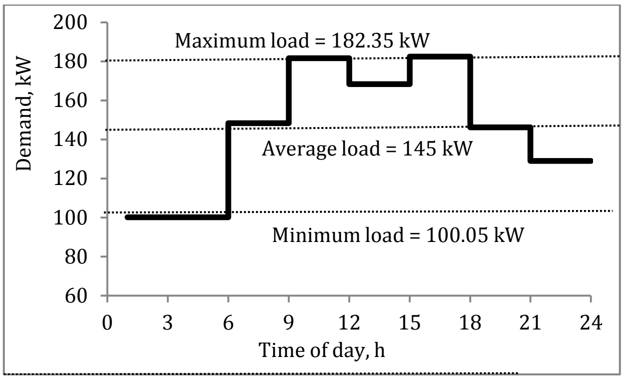

Fig. 5 Load profile on a representative day for a remote hospital in Pune, Maharashtra

5.2 Photovoltaic array sizing and penetration

The energy requirement (L_o) in Wh/day determine when f % of daily required energy is catered by photovoltaic array system for example, 10% of total energy is to be replaced by photovoltaic array, so f is taken as 0.1 in following equation.

$$L_0 = \text{Total load in 24 hr} \times f \tag{15}$$

Where f is energy penetration of photovoltaic array system i.e. (10 %, 20%, 30% ....etc.) System energy balance Eq. 6, energy stored for each and every time step Δt determined the energy contribution of photovoltaic array power, excess dump power and according to this, determine the energy contribution of diesel generator. In this photovoltaic array-diesel generator-battery hybrid system, firstly calculate photovoltaic array area according to % of photovoltaic array penetration to fulfill the demand.

5.3 Result and discussion of case study

Choose that combination of system size when all parameters should be satisfied objective function for every time step. With increasing in photovoltaic array penetration, increase the photovoltaic array rating and contribution of diesel generator, the power is then minimize simultaneously. In sunshine period, due to high solar radiation produced maximum energy from photovoltaic array and that excess generation by photovoltaic array will need to be dumped. Energy from diesel generator and dumped energy are undesirable. Total undesired energy is the addition of energy generated by diesel generator entire time period and amount of energy dumped in 24 hr. time period. Following relation shows the total undesirable energy is the function of total energy required for diesel generator and total dumped energy (Roy *et al.*, 2015);

Total undesirable energy =

$$\sum_{n=1}^{24} Pdg(t)\Delta t \; + \sum_{n=1}^{24} Pdu(t) \tag{16}$$

Table.1 System sizing and optimization input parameters

S. No	Parameter	Value
1	Photovoltaic system efficiency, %	15
2	Charging efficiency, %	85
3	Discharging efficiency, %	85
4	Inverter efficiency, %	92
5	Depth of discharge, %	70
6	DG fuel curve coefficients	
	A_G(l/kwh)	0.01841
	B_G(l/kwh)	0.2088

Table.2 photovoltaic array, diesel generator and battery Size as a function of percentage of photovoltaic array penetration for remote hospital in Pune for typical day

PV penetr-ation	PV rating	DG rating	Battery rating	FC rating (DG only)	FC rating (PV-DG)	Energy dump ed
%	kWp	kVA	kWh	%	%	kWh/day
0	0.0	182.4	0.0	0.0	0.0	0.0
10	67.5	182.4	0.0	9.7	0.0	0.0
20	132.8	182.4	0.0	19.6	0.0	0.0
30	199.5	182.4	0.0	29.4	0.0	0.0
40	242.8	182.4	0.0	34.2	0.0	0.0
50	305.0	182.4	252.6	45.2	12.3	80.6
60	366.0	182.4	255.3	45.5	10.2	408.9
70	427.1	182.4	246.7	48.6	13.4	654.9
80	488.0	182.4	202.6	48.6	12.4	998.1
90	549.0	182.4	158.5	48.6	11.4	1354.8
100	609.9	182.4	114.4	48.6	10.4	1716.5

The selected photovoltaic array penetration should be such that the total undesired energy is minimized. That point is called as the technically optimum penetration point where undesirable energy is minimized and battery rating getting reduces from that point. As photovoltaic array penetration increases, photovoltaic array rating also increases while rating of diesel generator remains same for entire photovoltaic array penetration because diesel generator provides the maximum load during no sunshine hours. From 50% photovoltaic array penetration battery introduced with some amount of energy dumped.Battery getting charged when photovoltaic power is greater than the load requirement. Below 50% battery cannot store the amount of energy because of the less photovoltaic array area or insufficient photovoltaic array rating for stored energy. At 50% penetration, the photovoltaic array rating is 304.95 kW and battery rating is 252.58 kWh with minimum dumped energy is 80.61kWh/day. After 48% battery rating reduces because of the increase in photovoltaic array power with photovoltaic array penetration so no need of extra energy which is stored in battery and that energy should be dumped. For given load profile optimum photovoltaic array penetration about 48% which shows in Fig. 6. The results of simulation for January month are presented in Table 2. However it is need to verify the economic point of view for proposed technical optimum size.

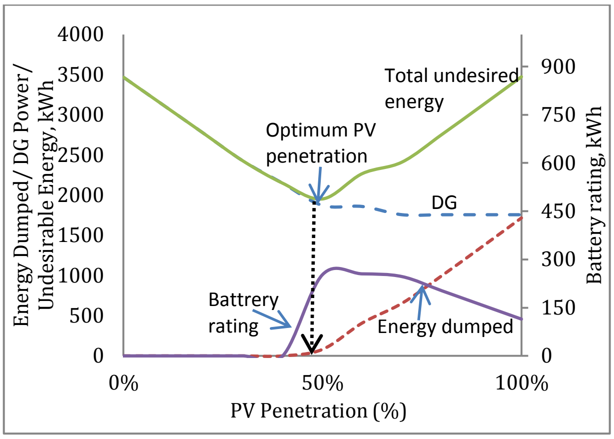

Fig. 6 Technical Optimum photovoltaic array penetration for the month of January

5.4 Results of system sizing and optimization from economic point of view

In this section, photovoltaic array –diesel generator-battery hybrid system sizing is analyzed on the basis of less cost of energy. Following section shows the specified photovoltaic array penetration value, size of diesel generator and battery were calculated. As discussed earlier, system sizing under uncertainty in the system, optimum photovoltaic array penetration never gets changed i.e. 50% photovoltaic array penetration is constant, but required photovoltaic array area increases so photovoltaic array rating also increases.

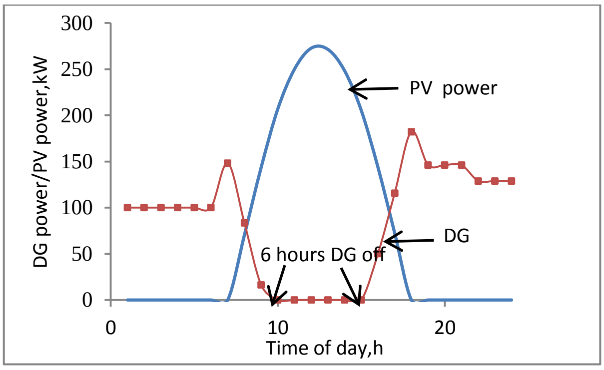

Fig. 7 Hourly energy flows for month of January at 50% photovoltaic array penetration for photovoltaic array–diesel generator hybrid system

Fig. 7 and Fig. 8 show the difference between operational hours of photovoltaic array-diesel generator and photovoltaic array-diesel generator-battery system by using deterministic approach. In photovoltaic array-diesel generator-battery hybrid system, diesel generator is shut-off 9 hours in sunshine period and rest because of the power provided by photovoltaic array and battery while photovoltaic array-diesel generator hybrid system, diesel generator is shut-off 9 hours at 50% penetration with minimum dumped.

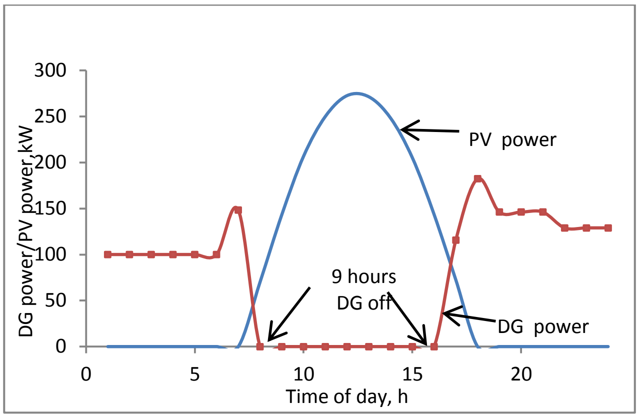

Fig. 8 Hourly energy flows for month of January at 50% photovoltaic array penetration for photovoltaic array-diesel generator-battery hybrid system

Its clearly shows that decrease the no. of operational hours on diesel generator with the help of storage battery. Diesel fuel saving with diesel generator only system is 45.15% and photovoltaic array-diesel generator hybrid system is 12.5%.

5.5 Cost optimization results

The annual operating and maintenance cost of the system has been taken as 4% and 1% of the of the capital cost for diesel generator and photovoltaic array respectively. Fuel cost calculated based on the optimum dispatch of the diesel generator. Moreover, battery replacement cost as well as inflation rate and cost of emissions related with diesel generator exhaust is also not considered in the analysis of system. Fuel consumption is calculated by Eq. 4.

Table.3 System optimization input parameters

Parameter	Value
Discount rate (d%)	14
Diesel generator life (years)	10
Photovoltaic array system life (years)	25
Battery bank life (years)	10
Inverter life (years)	10
Cost of diesel generator (Rs/kVA)	20000
Cost of photovoltaic array system (Rs/kW)	100000
Cost of battery bank (Rs/kWh)	5440
Cost of charge controller (Rs/KWh)	350
Cost of inverter (Rs/kW)	18000
Operating and maintenance cost of photovoltaic array as a % of total capital cost	0.01
DG as % of total capital cost	0.04

The variation of annualized life cycle cost, annualized cost of photovoltaic array, annualized cost of diesel generator and annual fuel cost (AFC) are depends as functions of % photovoltaic array penetration in Fig. 9. Fig. 10 shows the Contribution of various system components to annual cost at 50% penetration in the form of breaking sections.

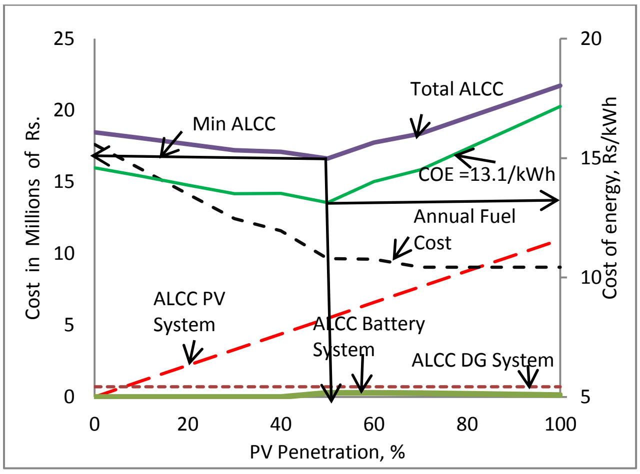

Fig. 9 Variation of ALCC of total system, photovoltaic array of annualized cost, diesel generator, battery and annually fuel cost and COE with photovoltaic array penetration for the month of January

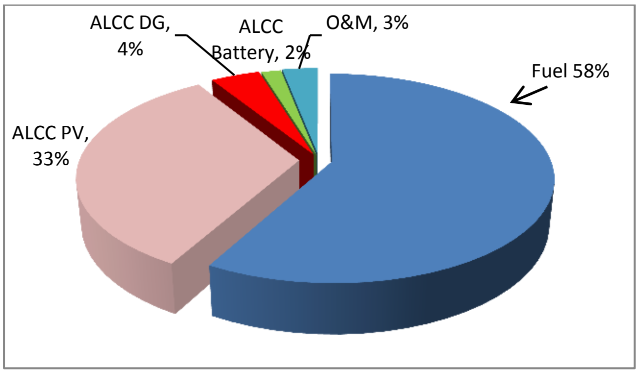

Fig. 10 Various system components contribution to annual cost at 50% penetration

About 58 % of annual spending is due to diesel fuel cost whereas 33% of ALCC of photovoltaic array cost while only 2% of ALCC of battery and 3% and 4% contribute the OM cost and diesel generator cost respectively. To demonstrate numerically, for given load profile, the cost data for the economic analysis is considered given in Table 3. As photovoltaic array contribution increases, photovoltaic array of annual cost increases but annual fuel cost decreases. Annualized cost curve describes the minimum point which is best compromise between reduction in fuel cost and increase in cost of the photovoltaic array as well as decreasing battery cost with minimum ALCC of system is at 50 % photovoltaic array penetration. Cost of energy found 13.1 Rs/kWh for present case study of the hospital.

5.6 Result of uncertainty

Fig. 11 represents deterministic a probabilistic required photovoltaic array area. It shows that photovoltaic array area is higher than deterministic approach in uncertainty case. In this case, the reliability is considered as 0.7.With help of this methodology, optimum never gets changed, but the required photovoltaic array area is increasing and photovoltaic array rating is also increases. In this scenario, reliability is considered as 0.7.

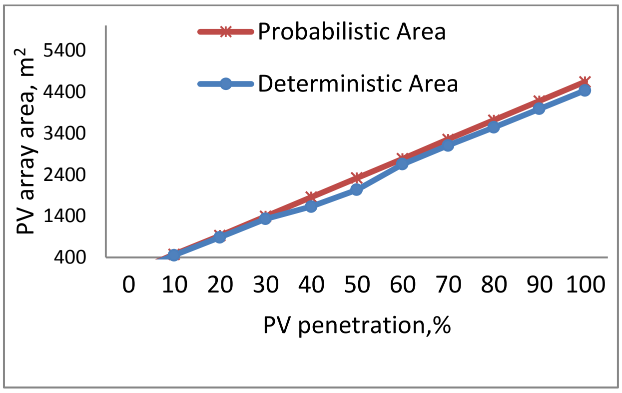

Fig.11 Variation between deterministic and probabilistic photovoltaic array area

6. Sensitivity analysis

In photovoltaic array-diesel generator-battery system, Annual fuel cost and photovoltaic array cost is mostly influenced the optimum penetration. The analysis has been proceed out for the energy demand for different parameters, like photovoltaic array cost, discount rate, diesel fuel price, battery bank cost, variation of different load profile which is coinciding with profile of solar radiation as well as fraction of diesel generator loading effects the optimum penetration. These factors affect the optimum and cost of energy. Sensitivity of these parameters is discussed in next section.

6.1 Sensitivity to photovoltaic array cost

Photovoltaic array is more costly component than the others system component such as battery, diesel generator etc. Considering the diesel cost is 60 Rs./liter and the original case with photovoltaic array cost is 100 Rs/Wp, cost of photovoltaic array is sensitive to optimum penetration of photovoltaic array which clearly shown in Fig. 12. The straight line indicates the cost of energy of only diesel system. The optimum photovoltaic array penetration is 0% when photovoltaic array cost is Rs.150 per W, and the COE is nearby same as a diesel generator only system. Similarly when photovoltaic array cost is Rs.130 per W power, a hybrid photovoltaic array-diesel-battery system gives benefits at the optimum photovoltaic array penetration of 30%. As decreasing the photovoltaic array cost to 100 to 50 Rs/W, the optimum photovoltaic array penetration replaced to 50% along with decrease in the cost of energy to 13.1 and 11.2 Rs/kWh respectively. This result is described that the optimum photovoltaic array inclusion is not much sensitive to photovoltaic array cost. Moreover, when the photovoltaic array cost is less than Rs 150 per W, it gives the photovoltaic array-diesel generator-battery system is always a feasible option with respect to the only diesel generator system.

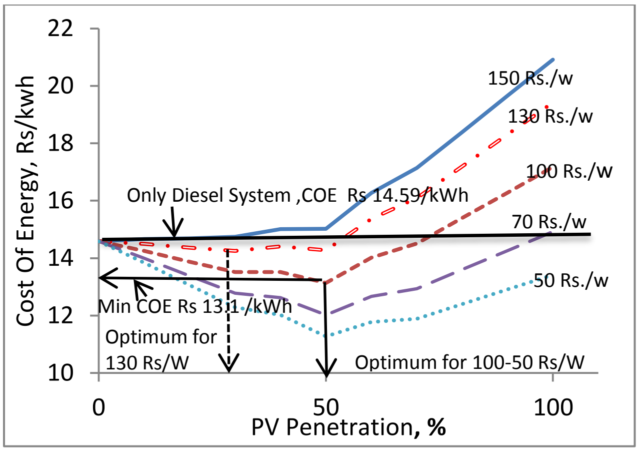

Fig.12 Sensitivity of photovoltaic array cost on optimum penetration

6.2 Sensitivity to diesel fuel price

We need to analyze the effect of diesel price on cost of energy which is directly related with annual fuel cost because, diesel price is invariantly fluctuates in current situation. Fig. 13 describes the effect of fuel price on optimum photovoltaic array penetration and COE. As increase in diesel fuel price, cost of energy also increases from the original case value of Rs.100 per W power having COE is 13.1Rs/kWh. Optimum never get changed, i.e. 50% penetration is constant all diesel fuel price, but tremendous increment in the cost of energy. Cost of energy at Rs 100 per lit. is 18.25 /kWh.

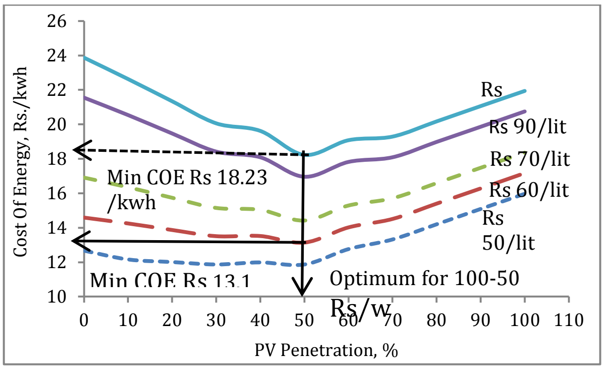

Fig. 13 Sensitivity of diesel cost on optimum photovoltaic array penetration

6.3 Sensitivity to load profile

Solar radiation profile and load profile plays an important role in determining the optimum photovoltaic array penetration. If the total load is covered in sunshine hours (Fig. 14), the diesel generator may be eliminated and increasing optimum penetration level with the help of battery storage to fulfill load demand. The modified load profile and the profile of solar radiation must coincide with same total energy requirement i.e.3467.4 kW/day belongs to month of January. Simulation results shows in Fig. 15 for modified profile curve and found that the optimum photovoltaic penetration can be maximum as much as 100%. It means that when the load profile curve perfectly matches with the solar radiation profile, there is no need of diesel generator i.e. a photovoltaic array and battery system of 609.9 kWp with minimum dumped energy of 0.38 kWh respectively can fulfill to the total demand. Sensitivity of the cost of energy to the photovoltaic array cost is shown in Fig. 16 for this changed load profile.10.4 is the minimum cost of energy in Rs/kWh for original case value. Result shows that when optimum at the 100% photovoltaic array penetration, there is no need of fuel. When photovoltaic array cost is raised to 150 Rs/W and 130 Rs/W, photovoltaic array penetration optimum is at 80% and COE is Rs.13.7 per kWh and Rs.12.5 per kWh respectively.

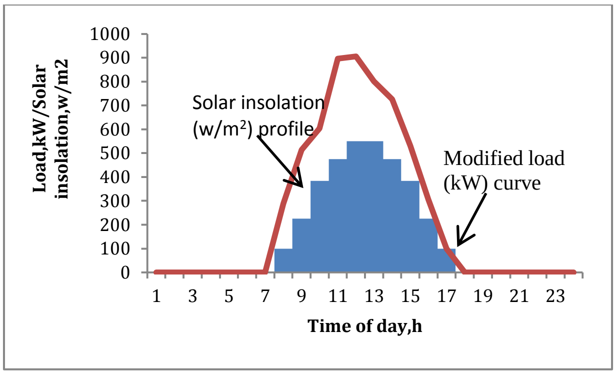

Fig.14 Change of load profile curve for the same case of remote hospital

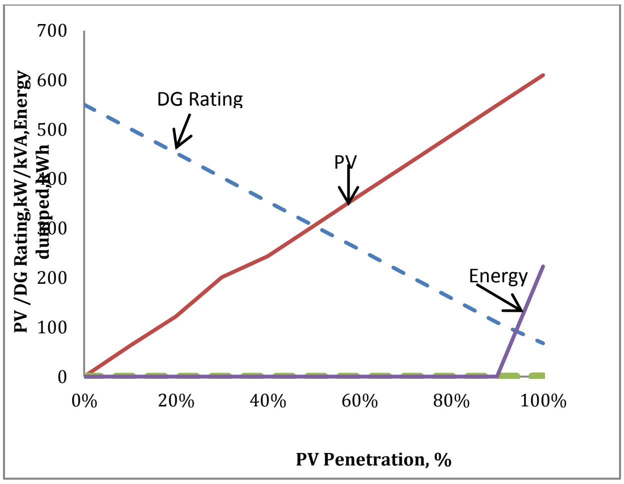

Fig. 15 DG size and photovoltaic array size along with the dumped energy and different photovoltaic array penetration levels for changed load profile case.

In present case study above system sizing considered 0.5 fraction of diesel generator loading. As a diesel generator loading increases, optimum gets changed because of battery storage capacity.

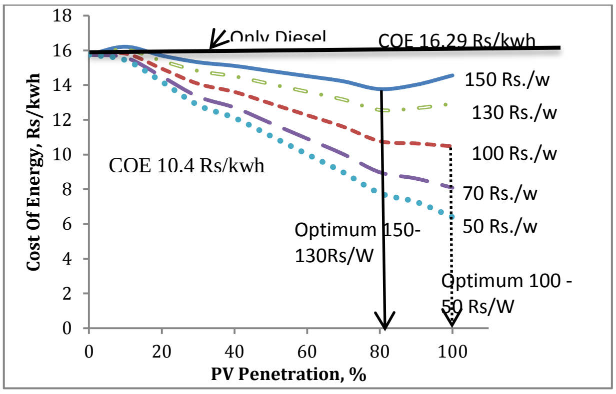

Fig. 16 Cost of energy variants with photovoltaic array penetration for changed load case

For illustrative case study of hospital, it is found that when fraction of diesel generator loading 0.7 required fuel consumption is less as compared to other parameters with photovoltaic array penetration 80% while at 0.6 fraction of diesel generator loading more fuel required than 0.7 at same photovoltaic array rating with minimum dump 185.72 kWh. Cost of energy 12.65 Rs/kWh. Table 4 shows the variation of diesel generator loading on optimum and cost of energy. COE mainly influenced with photovoltaic array rating and fuel consumption. Fig. 17 shows the variation of effect of diesel generator loading on optimum and cost of energy for present case study with representative month of January.

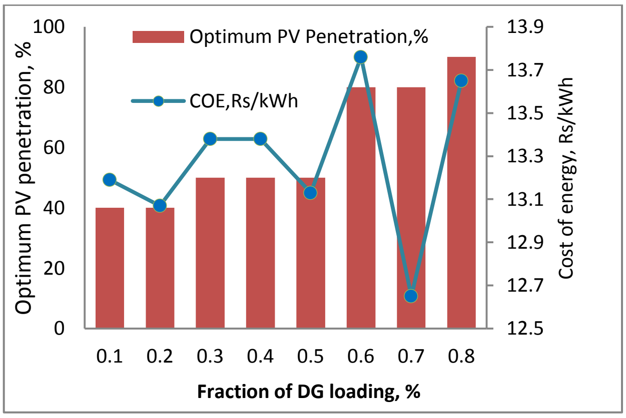

Fig. 17 Variation of fraction of diesel generator loading on optimum penetration and cost of energy

Table 4. Effect of fraction of diesel generator loading on optimum and COE

Fraction of Dg loading	Optimum PV Penetration,%	COE, Rs/kWh	Battery rating	PV rating	Dump	Fuel consumption	fuel saving (DG only) %	Fuel saving (PV-DG) %
0.1	40	13.2	29.1	243.9	43.0	508.7	34.2	3.9
0.2	40	13.1	78.4	243.9	207.8	499.2	34.2	5.7
0.3	50	13.4	112.0	305.0	180.5	462.1	42.6	8.1
0.4	50	13.4	112.0	305.0	196.4	462.1	42.6	8.1
0.5	50	13.1	252.6	305.0	80.6	441.3	45.2	12.3
0.6	80	13.8	1211.5	488.0	185.7	268.3	66.1	43.2
0.7	80	12.7	1211.6	488.0	185.7	204.3	66.7	43.2
0.8	90	13.7	1817.8	549.0	7.2	177.4	78.0	62.0

6.5 Effect of different months of year

Sensitivity with various parameters are discussed till now were especially for the representative day of January month, but system sized for entire year is not considered. Due to monthly climate variations, a level of the solar radiation varies. Fig. 18 represents the optimum configurations with different months of the year considered as the representative month for the whole year (Mani and Rangarajan). It is found that, optimum never get changed with different months in photovoltaic array-diesel generator-battery system and the minimum cost of energy 12.5 Rs/kWh is obtained for April and May and maximum cost of 15.22 Rs/kWh is obtained for July because of solar radiation availability with respect to month.

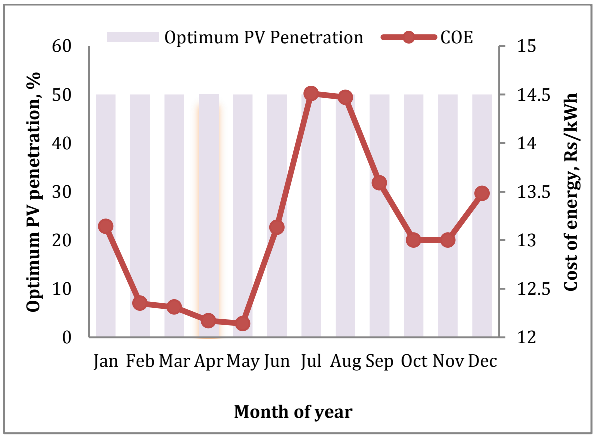

Fig.18 Variation in optimum photovoltaic array penetration and cost of energy for different months

Conclusions

In this study, we analyzed the technical and economic analyses for photovoltaic array systems along with battery storage. The parameter chosen for viability is cost of energy (COE) in Rs/kWh. The photovoltaic array penetration is the pre-specified fraction of demand to be replaced by the photovoltaic array. The relationship between the photovoltaic penetration and the COE is plotted with various sensitive parameters like load profile, solar radiation availability at a certain location, photovoltaic array cost, diesel fuel price, battery cost and discount rate. For the case study, we considered a remote hospital in the district of Pune; Maharashtra, India was chosen to determine the cost of energy and the optimum photovoltaic penetration. Following conclusions can be obtained from the results.

- A photovoltaic array-diesel generator-battery system is always economically feasible compared to diesel generator only and photovoltaic array-diesel generator system at a photovoltaic array cost of less than 150 Rs/Wp.
- Optimum diffusion of the photovoltaic array is 50% for the considered illustrative case study and

the corresponding minimum cost of energy is 13.1 Rs/kWh.

- The optimum is a weak function of the photovoltaic array cost, diesel fuel cost, battery cost and discount rate.
- The Optimum is influenced strongly by load profile, fraction of diesel generator loading and the solar radiation availability.
- The optimum is also influenced by fraction of diesel generator loading. When fraction of diesel generator loading is 0.7 with minimum fuel consumption for 80% photovoltaic array penetration at least cost 12.65 Rs/kWh for illustrative case study.
- Optimum load profile is one which exactly matches the solar radiation variability over a day and corresponds to photovoltaic array only system with a cost of energy of Rs. 10.4 /kWh with base case.

A deterministic model as well as probabilistic model of the photovoltaic array as well as system sizing under resource uncertainty has been presented in this work.

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