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Unit Sizing and Cost Analysis of Renewable Energy based Hybrid Power Generation System - A Case Study

Nitin AGARWAL[1,*], Anoop KUMAR[2] and Varun GOEL[2]

[1]Department of Mechanical Engineering, Moradabad Institute of Technology, Moradabad, Uttar Pradesh 244001, India
[2]Department of Mechanical Engineering, National Institute of Technology, Hamirpur, Himachal Pradesh 177005, India

([*]Corresponding author; e-mail address: nitin23757@yahoo.com)

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Abstract

A simulation model is developed for optimal sizing and analysis of a PV-diesel-battery based hybrid power generation system with the objectives to minimize life cycle cost and CO_2 emission, while maintaining the desired system autonomy. A case study of a boy's hostel in Moradabad district is taken for analysis purposes. It has 91 rooms with a capacity of 3 boys in each room. The decision variables included in the optimization methodology are total PV area, number of PV modules of 600 Wp, diesel generator power, fuel consumption per year and number of 24 V and 150 Ah batteries. The simulation result shows that the PV percentage of 86 % and diesel penetration of 14 % gives the most optimized solution with minimum LCC of \$110,547 and average CO_2 emission of 28 kg/day. The developed model has been validated by comparing its results with earlier research work.

Keywords: Hybrid power, optimization, life cycle cost, CO_2 emission, Moradabad

Introduction

Solar energy is likely to play a very important role in accomplishing electrical energy demands throughout the world in the near future. Now, due to global policy and fear on environmental issues (Copenhagen climate summit, Kyoto Protocol, European Directive on renewable energy sources etc.), production of electrical energy by means of renewable energy sources (RES) has enhanced awareness, and turn out to be one of the most attractive and ecological friendly technical solutions.

Immense research has been carried out on solar PV based hybrid power generation systems with respect to reliability, cost optimization and other related significant parameters. Nfaha *et al*. [1] developed a PV-diesel-battery based hybrid energy system to generate electricity for rural households and schools in remote areas of a far north province of Cameroon. Techno-economic studies of a hybrid PV-diesel system with battery storage mounted in a bungalow in Elounda, Crete was carried out by Bakos and Soursos [2]. Kamel *et al*. [3] computed the economics of hybrid energy systems versus a diesel generator system in a desert area of Egypt by using optimization software. Mellit *et al*. [4] presented a technique based on spatial interpolation for optimal sizing of PV system for Algeria. Egido and Lorenzo [5] developed an analytical model for calculating the capacity of PV arrays and battery storage. Rehman *et al*. [6] performed feasibility analysis of wind energy incursion into a diesel based plant of a village in Saudi Arabia. They suggested that the hybrid system is economically practicable if the carbon tax is considered and subsidy is eliminated. Rajkumar *et al*. [7] performed the techno-economical analysis of PV-Wind-battery based hybrid system using Adaptive Neuro-Fuzzy Inference System. The optimally designed hybrid system can supply electricity renewable for a longer period, while acclimatizing the desired loss of power supply probability. An optimal design methodology based on an iterative optimization technique was suggested by Kaabeche *et al*. [8], to find out the optimal configuration of different components of hybrid PV-Wind power generation system using a battery bank. The method takes into account the levelised unit cost of electricity and the deficiency of power supply probability as the major design parameter.

India has been facing enormous electricity deficiency in spite of major growth in electricity generation. The peak load demand of electricity during 2009-10 was 126,951 MW while the availability was only 111,533 MW, a shortage of 12.1 %.

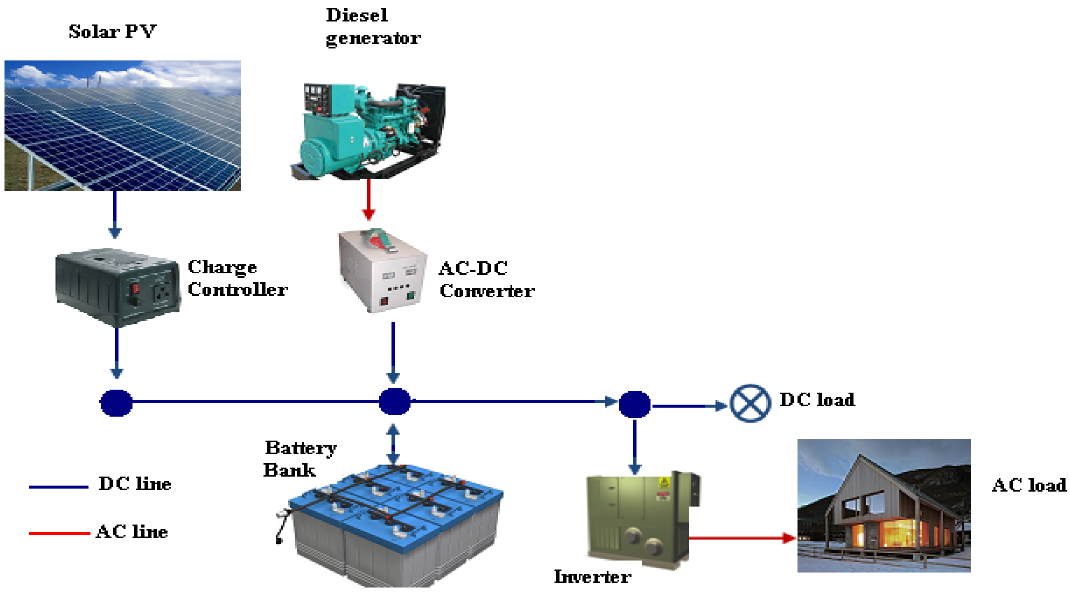

Figure 1 Hybrid power generation system.

Uttar Pradesh, one of the most densely populated states in India has a peak load demand of almost 13.974 GW and facing the scarcity of just about 20 %. As an effect there is an electricity slash of 6 - 9 h in the cities and villages of the state. Since Uttar Pradesh is blessed with high solar radiation levels, a considerable part of its energy requirements can be harnessed from solar energy. The present analysis is concentrated on a boy's hostel of an engineering college in Moradabad district of Uttar Pradesh. The purpose of this analysis is to explore the opportunity of using a PV-battery-diesel based hybrid power generation system (as shown in **Figure 1**) to fulfill the electricity load requirements. Thus, our primary objective is to determine the optimal configuration of the hybrid system components that guarantee the energy autonomy of a typical boy's hostel. Our secondary objective is to minimize the CO_2 emissions and life cycle cost of the hybrid system. This paper is structured as follows;

- Electric load profile
- Solar radiation on tilted surface
- PV system components modeling
- Life cycle cost analysis
- System reliability analysis
- Results and discussions
- Conclusion

Table 1 Climatic conditions of Moradabad district.

Environmental factors	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temperature	°F	57	62	73	84	91	91	87	86	84	78	69	60
Average morning relative humidity	%	83	78	71	55	49	61	82	85	81	76	78	82
Average evening relative humidity	%	41	35	30	21	24	36	61	64	51	33	31	38
Average precipitation	in	0.9	0.8	0.6	0.4	0.6	2.7	7.9	7.9	4.8	0.7	0.1	0.4
Average dew point	°F	44	46	50	51	57	66	75	75	71	59	51	44

Electric load profile

Moradabad is located in a western part of Uttar Pradesh in India, between 28°-21′ to 28°-16′ N and 78°- 4′ to 79° E [9]. The boy's hostel studied in this paper consists of 91 rooms having a capacity of 3 boys per room. Presently diesel generators are the only source of electricity. Based on climatic conditions shown in **Table 1** and the survey carried out in the hostel, the electric load profile for the entire year has been divided into 4 groups of months as shown in **Figure 2**. This Figure clearly shows that the demand of electricity is highest in the months of May, June, July and August. The area under each curve has been determined using trapezoidal integration rule to obtain the number of units required per day which is shown in **Table 2**.

Table 2 Units required per day during different months of the year.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
No. of units required ($kWh\ day^{-1}$)	71	81	157	157	205	205	205	205	157	157	81	71

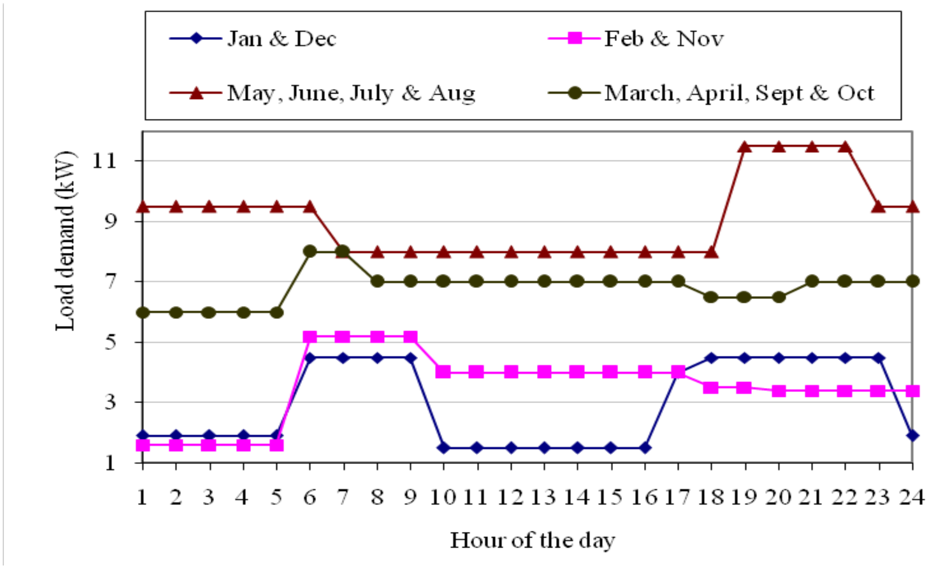

Figure 2 Typical daily load demand of the boy's hostel under study.

The design parameters of different components of the HPGS are given below.

Photovoltaic system

G_{dsr}	Diffuse solar radiation (kWh/m^2-day)
G_T	Total solar radiation (kWh/m^2-day)
G_{esr}	Monthly average daily extraterrestrial insolation on horizontal surface (kWh/m^2-day)
K_I	Clearness index
G_{tsr}	Daily average solar radiation on the tilted surface (kWh/m^2-day)
T	Monthly total radiation tilt factor
β	Tilt angle of flat plate collector (30°)
ε	Ground reflection
L	Latitude of the location (degree)
δ	Sunset hour angle (degree)
δ'	Sunset hour angle for a tilted surface (degree)
η_{pv}	PV system efficiency
A_t	Total area of PV modules (m^2)
Ta	Ambient temperature (°C)
Tcell	PV cell temperature (°C)
Φ	Solar irradiance coefficient
θ	Temperature coefficient
NOCT	Normal operating cell temperature (°C)
LCC_{PV}	Life cycle cost of PV system ($)
C_{PV}	PV array cost ($)
N	Lifetime of the PV system (considered as 25 years)
C_{In}	Initial capital cost ($)
C_{SI}	System installation cost ($)
C_{POM}	Present value of operation and maintenance cost ($)
C_M	Miscellaneous cost ($)

Battery Bank

DOD_b	Depth of discharge of the battery
η_b	Battery efficiency
η_{inv}	Inverter efficiency
η_C	Combined efficiency if inverter and battery
N_b	Number of battery backup days
U	Number of units required per day (kWh/day)
C_{BB}	Cost of battery bank ($)
C_{PBR}	Present value of battery replacement cost ($)
C_{CC}	Cost of charge controller ($)
C_{INV}	Inverter cost ($)
N_B	Battery lifetime (4 years)
N_R	Number of battery replacements

Diesel Generator

P_{DG}	Diesel generator power (kW)
N_S	Diesel generator service period (4 years)
N_{DG}	Number of times the generator is serviced
LCC_{DG}	Life cycle cost of Diesel generator ($)
C_D	Diesel cost per liter ($0.91 /litre)
A_D	Annual diesel consumption (liter/year)

C_{AF}	Annual fuel (diesel) cost ($)
C_{IDG}	Initial cost of the diesel generator ($)
C_K	Diesel generator cost per kW ($)
C_{DGS}	Diesel generator service cost ($)
C_{DOM}	Annual operation and maintenance cost ($)

Solar radiation on tilted surface

Solar collectors are generally tilted at an angle to increase the amount of solar radiation captured and to reduce the reflection losses. The solar radiation data are generally obtainable for horizontal surfaces and must be changed into tilted solar radiation. A mathematical model developed by Lin and Jordan [10] is used in this paper for this purpose. It is easiest of all the methods and assumes that all diffuse radiation is homogeneously scattered over the sky dome. The relationship between the ratio of diffusion to total solar radiation for a horizontal surface and monthly clearness index K_I is given by;

$$\frac{G_{dsr}}{G_T} = 1.390 - 4.027\ K_I + 5.531\ K_I^2 - 3.108\ K_I^3 \tag{1}$$

$$K_I = \frac{G_T}{G_{esr}} \tag{2}$$

The average solar radiation per day on an inclined surface is given by;

$$G_{tsr} = TG_T \tag{3}$$

where T is the monthly total radiation tilt factor and can be computed by the following equation [16];

$$T = \left(1 - \frac{G_{dsr}}{G_T}\right) F_B + \frac{G_{dsr}}{G_T}\left(\frac{1+\cos\beta}{2}\right) + \varepsilon\left(\frac{1-\cos\beta}{2}\right) \tag{4}$$

β is the inclination angle of flat plate collector taken as 30°. The ground reflectivity ε is taken equal to 0.2 and F_B is the ratio of average beam radiation on incline PV surface to that on horizontal surface and can be calculated as [10];

$$F_B = \frac{\cos(L-\beta)\cos(\varphi)\sin(\delta') + (\pi/180)\delta'\sin(L-\beta)\sin(\varphi)}{\cos(L)\cos(\varphi)\sin(\delta) + (\pi/180)\delta\sin(L)\sin(\varphi)} \tag{5}$$

Sunset hour angle for horizontal and inclined surface can be computed by following equations;

$$\delta = \cos^{-1}[-\tan(L)\tan(\varphi)] \text{ and } \delta' = \min\{\delta, \cos^{-1}[-\tan(L-\beta)\tan(\varphi)]\} \tag{6}$$

Here φ is solar declination in degrees. Using the above equations the solar radiation on an inclined PV surface is calculated and a curve is plotted as shown in **Figure 3**.

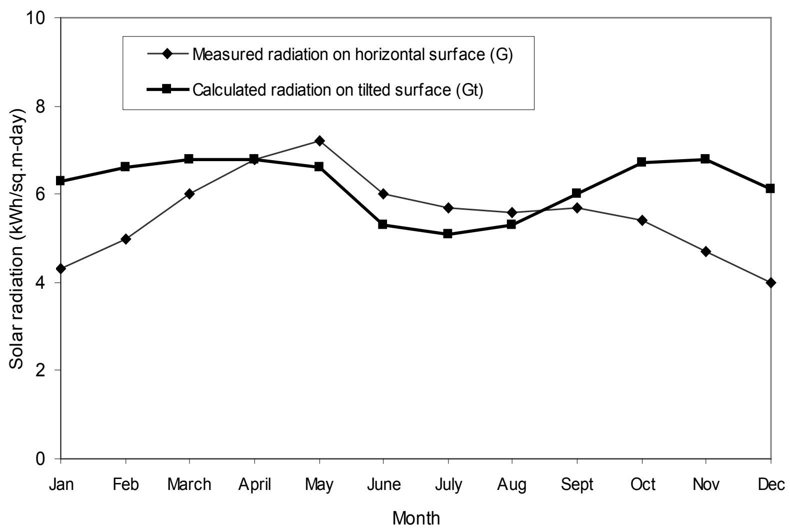

Figure 3 Monthly average daily solar radiation on horizontal and tilted surfaces at the latitude angle.

PV system components modeling

PV system components' modeling is exceptionally important to find out the optimum dimensions of HPGS. The key components are the PV modules, the battery bank and the inverters. The different steps involved are as follows.

PV module efficiency

The output power from the solar PV modules depends on the solar irradiance, the ambient temperature and the PV module inclination angle. The hourly power output of the PV system is given by the following equation [11];

$$P_{pv} = \eta_{pv} \,.\, A_t \,.\, G_{tsr} \tag{7}$$

PV system efficiency is given by [12];

$$\eta_{pv} = \eta_{ref}\left[1 - \theta\left(T_{cell} - T_{cell,ref}\right) + \Phi \log\left(\frac{G_{tsr}}{G_{t,ref}}\right)\right] \tag{8}$$

where $G_{t,ref}$ is the reference solar irradiance (1000W/m^2), T_{cell} is the PV cell temperature, η_{ref} is reference module efficiency, $T_{cell,ref}$ is the reference cell temperature (25 °C), θ is the temperature coefficient and Φ is the solar irradiance coefficient. θ and Φ depend on the material of PV module. $T_{cell,ref}$, η_{ref} , θ and Φ are the data specified by the PV manufacturer. Evans [13] took θ = 0.0048 /°C and Φ = 0.12 for a silicon cell. T_{cell} can be calculated using the equation [12].

$$T_{cell} = T_a + \left(\frac{NOCT - 20}{800}\right) G_{tsr} \tag{9}$$

where NOCT is the normal operating cell temperature specified by the PV cell manufacturer.

Battery bank capacity

The battery bank capacity can be estimated as follows;

$$\text{Battery Bank Capacity} = \frac{N_b \times U}{DOD_b \times \eta_c} \tag{10}$$

where $\eta_c = \eta_b \times \eta_{inv}$

DC/AC inverter

The inverter must be competent enough to grab the maximum power of AC loads [14]. Therefore capacity must be 10 % higher than the required AC load. Since the required total AC load of the hostel is 11.78 kW, hence thirteen inverters of rated power 1000 W are adequate to bear the load. So the inverter specifications will be 1000 W, 24 V_{DC} and 220 V_{AC}.

Life cycle cost analysis

Life cycle cost (LCC) analysis of HPGS is done using the Net present value method (NPV). Numerous researchers have used LCC as the main cost criteria for design and analysis of hybrid systems [14-16]. The LCC of the hybrid PV- battery- diesel system is the sum total of the LCC of all its elements which includes the initial capital cost of all the elements, recurring costs like diesel cost, operation and maintenance costs and non-recurring costs like diesel generator servicing costs and battery replacement costs [17]. Therefore;

$$LCC_{system} = LCC_{PV} + LCC_{DG} \tag{11}$$

Life cycle cost of PV system (LCC_{PV})

LCC of a PV system is the sum total of the initial capital cost , system installation cost, net present value of operation and maintenance cost and net present value of battery replacement cost [18].

$$LCC_{PV} = C_{In} + C_{SI} + C_{POM} + C_{PBR} \tag{12}$$

Initial capital cost is the summation of PV array cost, cost of battery bank, inverter cost, cost of charge controller and miscellaneous costs like the cost of electric cables, cost of PV array support, nuts, bolts etc.

$$C_{In} = C_{PV} + C_{BB} + C_{INV} + C_{CC} + C_M \tag{13}$$

Miscellaneous cost is assumed as the percentage K_1 (3 %) of the PV array cost [19];

$$C_M = K_1\, C_{PV} \tag{14}$$

The NPV of annual operation and maintenance costs is taken as percentage K_2 (2 %) of the initial capital cost and can be computed for a lifetime of N years using the following equation.

$$C_{OM} = K_2 C_{In} \times \sum_{i=1}^{N} \frac{(1+e)^{i-1}}{(1+d)^i} \tag{15}$$

where d (6 %) is the discount rate and e (5 %) is the inflation rate. System installation cost is considered as percentage K_3 (10 %) of the initial capital cost [19];

$$C_{SI} = K_3\, C_{In} \tag{16}$$

To determine the cost of battery replacement, first we have to find out the number of times the battery is replaced in the lifetime of N years. If N_r is the number of battery replacements, then;

$$N_r = abs\left(\frac{N - N_b}{N_b}\right) \tag{17}$$

where N_b is the battery lifetime. The NPV of battery replacement cost can be estimated by the following equation [19];

$$C_{PBR} = C_{BB}\, K_3 \sum_{i=1}^{N_r} \frac{(1+e)^{N_b(i-1)}}{(1+d)^{N_b i}} \tag{18}$$

Life cycle cost of diesel generator

The life cycle cost of the diesel generator is evaluated by the method explained in ref. [19]. According to this method the LCC of a diesel generator is specified by;

$$LCC_{DG} = C_{IDG} + C_{DOM} + C_{DGS} + C_{AF} \tag{19}$$

C_{IDG} is the initial cost of the diesel generator and is calculated by;

$$C_{IDG} = C_K P_{DG} \tag{20}$$

The NPV of annual operation and maintenance cost and can be estimated by the equation;

$$C_{DOM} = \mathrm{K}_4 C_{IDG} \times \sum_{i=1}^{N} \frac{(1+e)^{i-1}}{(1+d)^{i}} \tag{21}$$

where K_4 (5 %) is the percentage of the initial generator cost. The NPV of the diesel generator service cost depends on the number of times the generator is serviced (n_g) during the lifetime of N years. If N_s is the diesel generator service period, then C_{DGS} can be calculated as;

$$C_{DGS} = K_5 C_{IDG} \times \sum_{i=1}^{N_{DG}} \frac{(1+e)^{r(i-1)}}{(1+d)^{ri}} \tag{22}$$

In the above equation K_5 (15 %) is the percentage of the initial generator cost. N_{DG} is the number of times the generator is serviced in the lifetime of N years;

$$N_{DG} = abs\left(\frac{N}{N_s}\right) \tag{23}$$

The NPV of annual diesel cost can be computed by the equation;

$$C_{AF} = C_D A_D \times \sum_{i=1}^{N} \frac{(1+e)^{i-1}}{(1+d)^{i}} \tag{24}$$

where C_D is the diesel cost per liter and A_D is the annual diesel consumption.

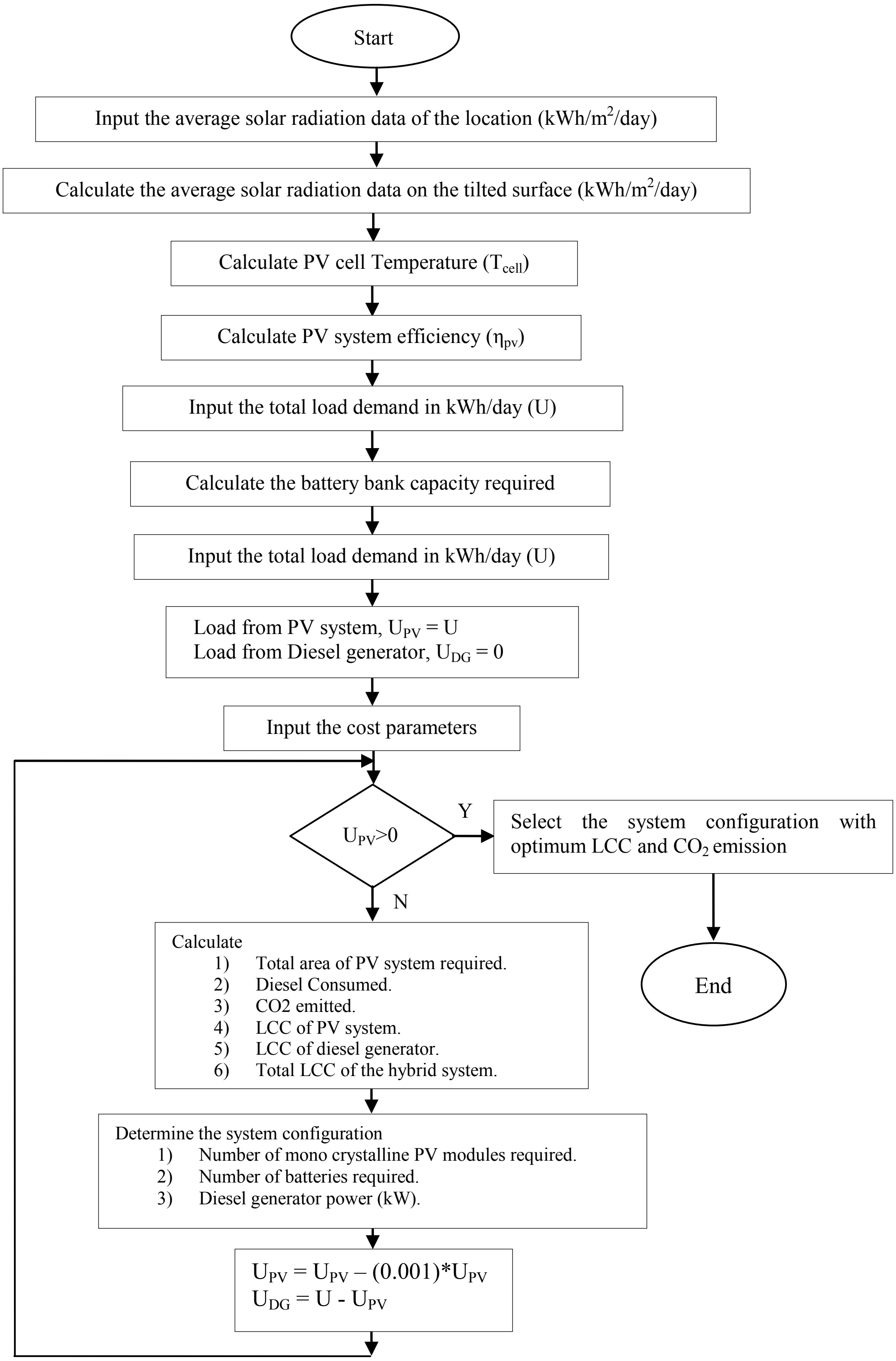

Figure 4 Flowchart for the optimization process.

System reliability analysis

In the current analysis, the reliability of the HPGS is articulated in terms of System Autonomy (*SA*). SA is defined by the following equation [20];

$$SA = 1-(h_l/h_t) \tag{25}$$

Here h_l is the total hours during which loss of load takes place and h_t is the total hours of operation. Using the above equations, different dimensions of the system components that satisfy the reliability requirements can be obtained and the optimal design can be selected on the basis of minimum LCC and CO_2 emissions.

Results and discussions

The current analysis is applied to a boy's hostel of 91 rooms in Moradabad district of Uttar Pradesh, India. A standalone diesel generator is the only source of electricity in the hostel which causes massive CO_2 emissions in the atmosphere. The unit cost of electricity from the diesel generator is estimated as Rs. 12 per kWh. For that reason an analysis is carried out to determine the best possible dimensions of the HPGS so that an optimum trade-off can be maintained between the life cycle cost and CO_2 emission from the system. The developed model has an input data of the number of kg of CO_2 emitted per liter of diesel consumed by the generator. This value depends upon the characteristics of the diesel generator and properties of the fuel, and it generally falls in the range of 2.4 - 2.8 kg/l [21].

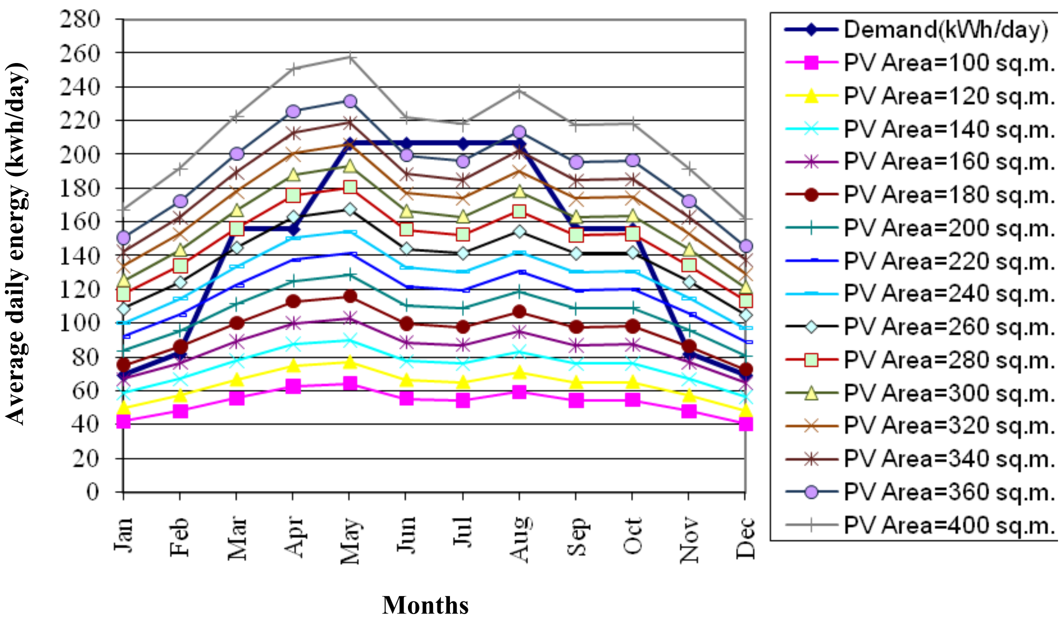

Figure 5 Electricity produced by PV arrays of different sizes.

Figure 4 illustrates the flow chart of the model developed for the design and analysis of the HPGS. The daily average load demand is shown in **Table 2**. The electric demand appears to peak in the months of May, June, July, and August. It is clear from **Figure 5** that a PV area less than 160 m^2 does not fulfill the load demands for all the months of the year. However, if the PV area is 340 m^2, the demand is satisfied for about 10 months. A standalone PV system that utterly satisfies the demand can be obtained at an area of 400 m^2.

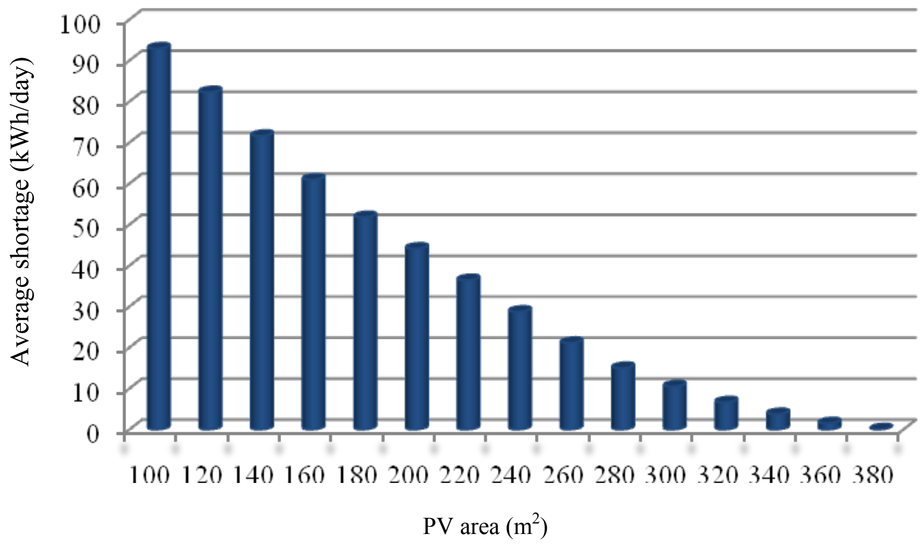

Figure 6 Average electricity shortage per day for different PV areas.

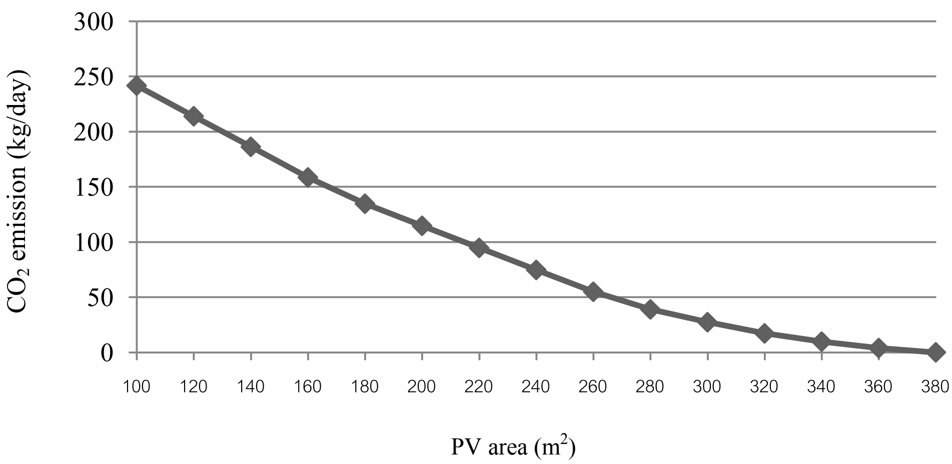

Figure 7 Average CO_2 emissions per day for different PV areas.

Figure 6 clearly shows that the electricity shortage decreases as the area of PV is increased; as a result the fuel consumption for electricity is reduced. Hence with the enhancement of PV modules, the CO_2 emissions also decrease (**Figure 7**). CO_2 emissions are high in the peak months of the year since more diesel is burned during these months to meet the electricity shortage.

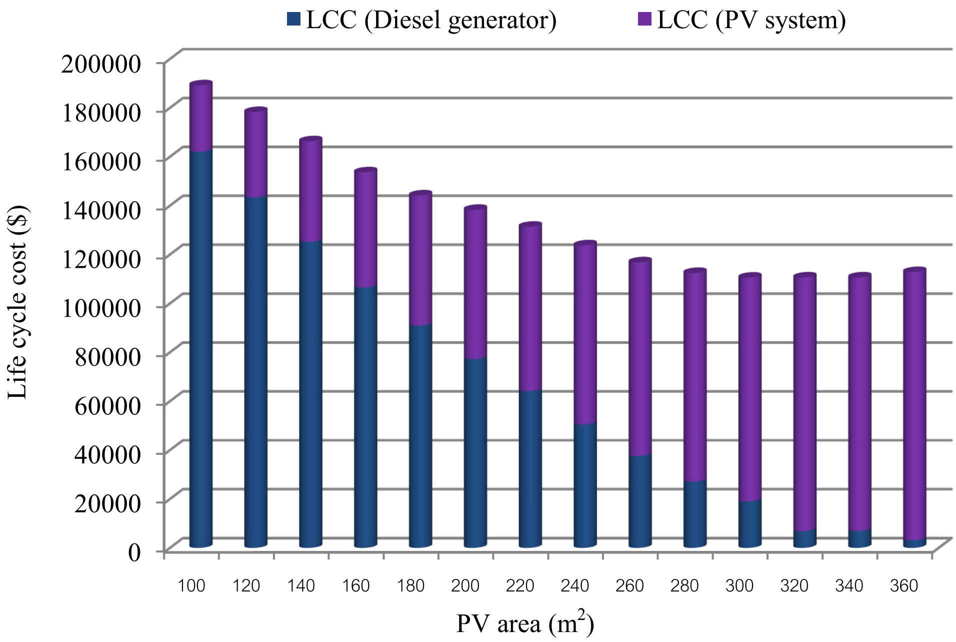

Figure 8 Life cycle cost of the system for different areas of PV arrays.

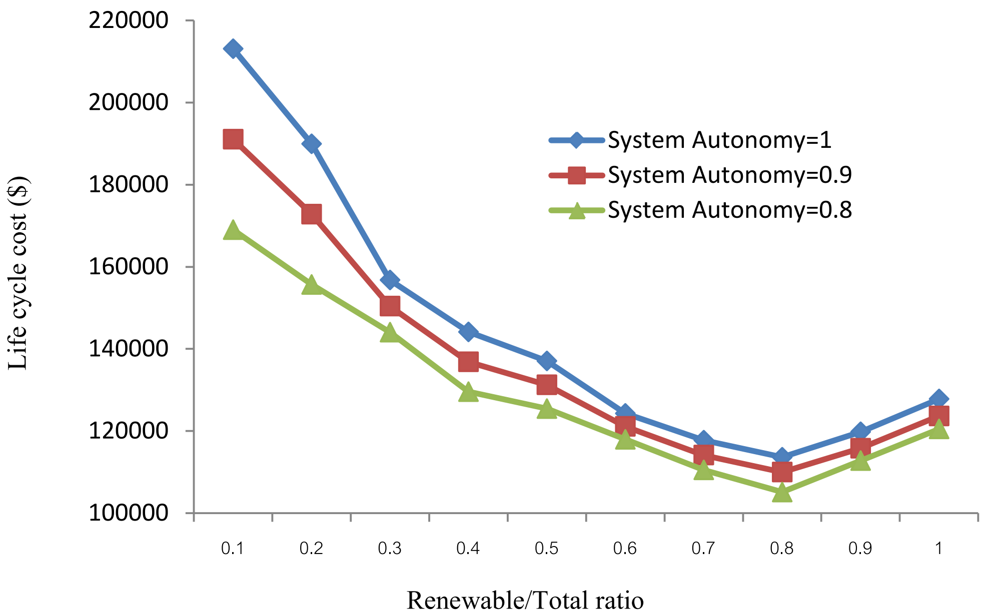

Figure 9 Life cycle cost of the system at different system autonomy.

LCC analysis of the HPG is shown in **Figure 8**. It can be clearly seen that the LCC of the system decreases as the PV array area increases. The minimum LCC is \$110,547 obtained at a PV area of 300 m^2 and diesel generator power of 5 kW. This configuration emits 27.5 kg of CO_2 per day. This configuration of HPGS saves \$89,626 during the life cycle and reduces CO_2 emission by 345.6 kg/day when compared with a diesel only generator system. If the PV area is further increased, the CO_2 emission is reduced but there is a considerable increase in LCC of the system. It is noticeable that the diminution in system autonomy will reduce the LCC of the system. This drift in reduction of LCC is shown in **Figure 9**.

Conclusions

The analysis of an HPGS system identifies Moradabad district as a potential candidate for the use of solar based hybrid system for electricity generation for hospitals, schools, hostels, hotels etc. The objective of this analysis is to determine the optimum dimensions of different elements of the PV-diesel-battery based hybrid system so that the LCC and CO_2 are minimized while maintaining the desired system autonomy. A case study of a boy's hostel in Moradabad district was considered for analysis purposes. The simulation result indicates that a PV percentage of 86 % and diesel penetration of 14 % gives the most optimized solution with a minimum LCC of \$110,547 and average CO_2 emission of 28 kg/day. The dimensions of the fully autonomous optimized system are 303 m^2 PV area, 61 PV modules of 600 Wp, 10 kW diesel generator, 1,156 liter fuel consumption per year and 162 batteries of 24V and 150 Ah. The computer program developed for the analysis of the HPGS can be used for optimal sizing of PV-battery-diesel system in other locations having similar environmental conditions.

Acknowledgement

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