Sizing Analysis and Cost Optimization of Hybrid Solar-Diesel-Battery Based Electric Power Generation System Using Simulated Annealing Technique

Nitin Agarwala
Anoop Kumarb
Varun

ABSTRACT

An optimization model has been developed to determine specifications of a hybrid solar-diesel-battery based power generation system to maintain an optimum tradeoff between the life cycle cost and CO_2 emission from the system. The model has been solved by using the simulated annealing technique. The proposed method has been applied to a residential colony of 135 houses in Moradabad district, India. The optimum sizing process is verified by carrying out an appropriate sensitivity analysis. Simulation results shows that PV inclusion of 89% and diesel fraction of 11% with PV arrays of 1030 m^2, 477 batteries of 24 V and 150 Ah and three diesel generators of 5 kW each is the optimized configuration having minimum a life cycle cost (LCC) of $973000 for 25 yrs, CO_2 emission of 24193 kg/year and annual diesel consumption of 86212 liter. The model has been validated by comparing results with earlier research work.

Keywords: CO_2 Emission, Hybrid System, Life Cycle Cost, Optimization, Moradabad, Simulated Annealing, Solar-Diesel.

INTRODUCTION

Fossil fuel limited availability and CO_2 emissions from fossil fuels combustion are very rigorous harms that humankind needs to work out in the subsequent years (Zini et al., 2010). As a result the consump-

Nomenclature

A_D	Annual diesel consumption
A_m	Total area of PV modules (m^2)
DOD	Depth of discharge of the Battery
D_K	Diesel generator cost per kW (\$/kW)
D_{PG}	Diesel generator power (kW)
D_S	Diesel generator service cost (\$)
G_t	Total radiation on tilt surface (kWh/m^2/day)
K	Diesel cost per litre (0.93 \$/l)
LCC_{system}	Life Cycle Cost of hybrid power generation system (\$)
LCC_P	Life Cycle Cost of PV system (\$)
LCC_D	Life Cycle Cost diesel generator (\$)
LCC_B	Life Cycle Cost of battery bank (\$)
N	Life cycle period of the System
N_u	Number of units required per day (kWh/day).
P_{pv}	Hourly power output of solar PV modules (kW)
P_{BB}	Battery bank power (kW)
P_{DG}	Diesel generator power (kW)
P_D	Total power demand (kW)
U_{DG}	Number of units from diesel generator
n	Number of battery backup days.
n_b	Life cycle period of battery bank
r	Diesel generator service period
t_a	Ambient temperature (^{O}C)

Greek

η_b	Battery efficiency
η_{inv}	Inverter efficiency
η_C	Combined efficiency of inverter and battery.
η_{pv}	PV system efficiency
Φ	PV module tilt angle (28^0)

Abbreviations

HPGS	Hybrid power Generation System
RES	Renewable energy Sources
GHG	Green House gas
DG	Diesel Generator
PV	Photovoltaic
LCC	Life Cycle Cost
SOC	State of charge

tion of renewable energy sources (RES) for electricity generation has been rising around the world at an accelerating rate. They can develop diversity in energy supply markets, guarantee long-term sustainable energy supply, and reduce local and global Green house gas emissions (Ucar and Balo, 2009). The main disadvantage of RES is their reckless nature and dependence on weather and climatic conditions. As an effect, the variation of power generated by RES may not match with the time distribution of demand. Therefore, a hybrid power generation system (HPGS) integrating diesel generator (DG) with renewable energy options can be an excellent way out to this problem. The present study has been carried out to examine the role of Photovoltaic (PV)-diesel-battery based HPGS (Figure 1) in meeting the load requirements of a typical residential colony in Moradabad district of Uttar Pradesh, India.

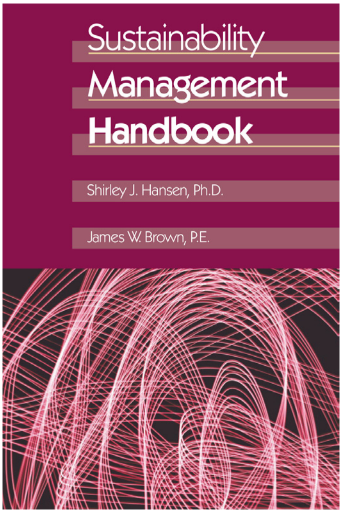
LITERATURE REVIEW

Significant research has been carried out on solar based hybrid energy systems with respect to performance, optimization and other related parameters of importance. A linear programming technique was used by Chedid and Rahman (1997) to optimally design a hybrid wind-solar energy system for either independent or grid-linked applications. The objective is to minimize unit cost of electricity while meeting the electricity load requirements in a reliable manner. Lazou and Papatsoris (2000) presented the life cycle cost (LCC) analysis of PV systems for electricity generation in residential houses of various Mediterranean and European countries. Techno-economic analysis of a hybrid PV-diesel system installed in a bungalow complex in Elounda, Crete, is performed by Bakos and Soursos (2002). Singal et al. (2007) assessed the potential of accessible non-conventional energy sources for power generation in Neil Island. A 50 kW solar power plant and 400 kW diesel generators are the obtainable supply of electric power in the island. They suggested that the existing power sources can be replaced by 100 kW biogas power plants, 150 kW biomass gasification plant and 200 kW PV systems, without any undesirable effect on the environment and socio-economic life of the habitants. Kamel et al. (2005) predicted the economics of hybrid power systems versus the present diesel generator technology in a desert agricultural area in Egypt by using optimization software. Lagorse et al. (2009) suggested a hybrid energy system involving a solar PV, a battery

10% Online Discount
Use Code JR10

SUSTAINABILITY MANAGEMENT HANDBOOK

Shirley J. Hansen, Ph.D., and James W. Brown, P.E.



Managing sustainability is THE challenge of our time. It's not just a technical issue and not just a green issue. It is a management issue. A strong sustainability program requires commitment, which in turn demands effective leadership. Such leadership must draw on a solid knowledge base, the ability to manage resources wisely, identify sustainability opportunities, make difficult choices, and accept the challenge to lead, influence and persuade colleagues. This book attempts to cut through the ever-present hyperbole to offer practical steps which can be taken now to protect the world around us. Rich in case studies, it addresses a range of critical stewardship issues. Growing out of a keen desire to protect the earth, the text is designed to help management transform important information and critical leadership skills into enhancing socially responsible operations. Authors Hansen and Brown have also included contributions from several additional leading experts in the field.

ISBN: 0-88173-644-9

6 x 9, Illus., 230 pp.
Hardcover, $135

ORDER CODE: 0648

CONTENTS

1 – Bringing Sustainability Down to Earth (Shirley J. Hansen)
2 – World Perspective on Sustainability (Bob Dixon)
3 – Packaging Sustainability (Shirley J. Hansen)
4 – Energy Supply Options (Shirley J. Hansen)
5 – Sustainable Facilities (Steve Roosa)
6 – Auditing in a Sustainable World (James W. Brown)
7 – Commissioning: at the Heart of Sustainability (James W. Brown)
8 – Green Insurance (Bob Sansone)
9 – LEED® (Nick Stecky)
10 – Master Planning for Sustainability (Shirley J. Hansen and James W. Brown)
Appendices
References
Index

BOOK ORDER FORM

① Complete quantity and amount due for each book you wish to order:

Quantity	Book Title	Order Code	Price	Amount Due
	Sustainability Management Handbook	**0648**	**$135.00**	
			Applicable Discount	
			Georgia Residents add 6% Sales Tax	
			Shipping Fees	**10.00**
			TOTAL	

② Indicate shipping address:

NAME (Please print) BUSINESS PHONE

SIGNATURE (Required to process order) EMAIL ADDRESS

COMPANY

STREET ADDRESS ONLY (No P.O. Box)

CITY, STATE, ZIP

MEMBER DISCOUNTS—A 15% discount is allowed to AEE members.
☐ **AEE Member (Member No.______________________)**

③ Select method of payment:
☐ CHECK ENCLOSED
☐ CHARGE TO MY CREDIT CARD
☐ *VISA* ☐ *MASTERCARD* ☐ *AMERICAN EXPRESS*

Make check payable in U.S. funds to:
AEE ENERGY BOOKS

CARD NO.

Expiration date *Signature*

④ Send your order to:
AEE BOOKS
P.O. Box 1026
Lilburn, GA 30048

INTERNET ORDERING
www.aeecenter.org/books
(use discount code)

TO ORDER BY PHONE
Use your credit card and call:
(770) 925-9558

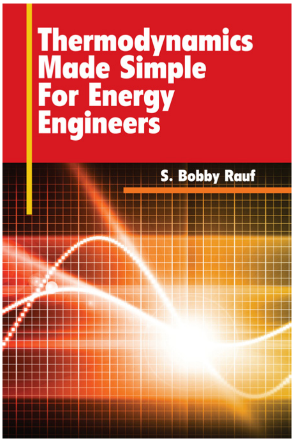
TO ORDER BY FAX
Complete and Fax to:
(770) 381-9865

INTERNATIONAL ORDERS
Must be prepaid in U.S. dollars and must include an additional charge of $10.00 per book plus 15% for shipping and handling by surface mail.

10% Online Discount
Use Code JR10

THERMODYNAMICS MADE SIMPLE FOR ENERGY ENGINEERS

S. Bobby Rauf, P.E., C.E.M.



Here is an overview of important principles and concepts in the field of thermodynamics, written in a fashion that makes this abstract and complex subject easy to comprehend. Intended to serve the needs and interests of energy-involved engineers, the content, concepts and principles are presented in a way which also will allow many non-engineering professionals with some math background to follow the material and gain useful knowledge. For those who may have been away from direct engineering practice for a time, this book can serve as a quick and effective refresher. Thermodynamic topics including enthalpy, entropy, latent and sensible heat, heats of fusion, and heat of sublimation are clearly presented. Also covered are phases of substances, the law of conservation of energy, SFEE, the first and second laws of thermodynamics, ideal gas law, and respective mathematical statements. Specific thermodynamic processes are examined, as well as heat and power cycles such Rankine, Carnot and the differences between them. Case studies illustrate various thermodynamics principles, and each chapter concludes with a list of questions or problems for self-assessment, with answers provided at the end of the book.

ISBN: 0-88173-650-3

6 x 9, 356 pp., Illus.
Hardcover, $125

ORDER CODE: 0661

CONTENTS

BOOK ORDER FORM

① Complete quantity and amount due for each book you wish to order:

Quantity	Book Title	Order Code	Price	Amount Due
	Thermodynamics Made Simple for Energy Engineers	**0661**	**$125.00**	

② Indicate shipping address:

NAME (Please print) BUSINESS PHONE

SIGNATURE (Required to process order) EMAIL ADDRESS

COMPANY

STREET ADDRESS ONLY (No P.O. Box)

CITY, STATE, ZIP

Applicable Discount	
Georgia Residents add 6% Sales Tax	
Shipping Fees	**10.00**
TOTAL	

MEMBER DISCOUNTS—A 15% discount is allowed to AEE members.
☐ **AEE Member (Member No.__________________)**

③ Select method of payment:
☐ **CHECK ENCLOSED**
☐ **CHARGE TO MY CREDIT CARD**
☐ *VISA* ☐ *MASTERCARD* ☐ *AMERICAN EXPRESS*

Make check payable in U.S. funds to:
AEE ENERGY BOOKS

CARD NO.

Expiration date *Signature*

④ Send your order to:
AEE BOOKS
P.O. Box 1026
Lilburn, GA 30048

INTERNET ORDERING
www.aeecenter.org/books
(use discount code)

TO ORDER BY PHONE
Use your credit card and call:
(770) 925-9558

TO ORDER BY FAX
Complete and Fax to:
(770) 381-9865

INTERNATIONAL ORDERS
Must be prepaid in U.S. dollars and must include an additional charge of $10.00 per book plus 15% for shipping and handling by surface mail.

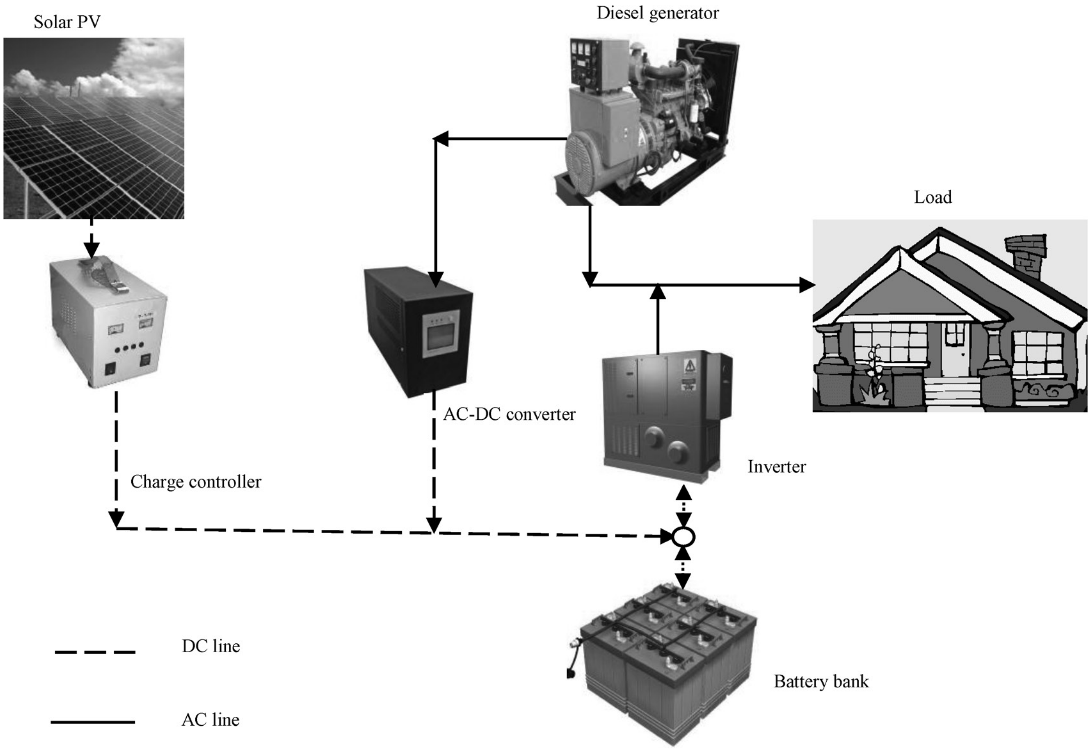


Figure 1. Hybrid Power Generation System (HPGS)

and a fuel cell to modify commercialized stand alone street lightening system consisting of PV cells and a battery. The objective is to determine the optimal configuration of the system at minimum cost.

Rehman et al. (2010) considered a hybrid system integrating solar PV-diesel generator and battery bank for a village being supplied electricity with standalone diesel generator, to displace part of the diesel by solar. The sensitivity analysis shows that at a diesel price less 0.6$/l, the hybrid energy system become more cost effective than the standalone diesel generator. Mbaka et al. (2010) compared standalone diesel generator, standalone PV and hybrid PV system using net present value method. A case study of remote village in Cameroon is considered for the calculation of energy costs and break even grid distance. They recommended that the most optimal size of hybrid system is attained at a renewable energy percentage in the range of 82.6-95.5%. An optimal design procedure based on an iterative technique is recommended by Kaabeche et al. (2011), to determine the optimum dimensions of different components of hybrid PV-Wind electricity system using a battery bank. The model takes into account the Deficiency of Power Supply Probability and the Levelized Unit Electricity Cost as the major design criteria. Rajkumar et al. (2011) presented the techno-economical analysis of hybrid PV-Wind-battery system using Adaptive Neuro-Fuzzy Inference System. The optimized system is also able to supply electricity without any renewable sources for a longer period, while acclimatizing the preferred loss of power supply probability.

In the literature discussed above, the optimal design of the HPGS is obtained by minimizing the system cost function. But, the environmental questions, like amount of Green House Gas (GHG) emissions from these systems have not been raised. Therefore in the present work a simulation model has been developed to obtain the optimum dimensions of different components of HPGS with an objective to maintain a favorable balance between the LCC and CO_2 emission from the system.

OBJECTIVE

The objective of present work is to explore the opportunity of using PV-battery-diesel based HPGS to gratify the electricity load requirements. Therefore, our first objective is to find out the optimum configuration of the hybrid system components that guarantee the energy autonomy of the location under consideration. Our second objective is to minimize life cycle cost and CO_2 emissions from the hybrid system. Hybrid system must be designed to ensure complete autonomy of demand. Therefore the following energy balance equation must be satisfied

$$P_D = P_{PV} + P_{DG} + P_{BB} \tag{1}$$

Where:

P_D = Power demand, kW

P_{PV} = Power generated by photovoltaic module, kW

P_{DG} = Power generated by diesel generator, kW

P_{BB} = Power from/to battery bank, kW (i.e. batteries can be an energy source or consumer)

Loss of load occurs when any the system fails to meet demand requirements. In that situation:

$$P_D > P_{PV} + P_{DG} + P_{BB} \tag{2}$$

Is this is the case, the system becomes unstable (voltage drops) or some electricity users are not served.

HPGS MODELING

Modeling HPGS components is very important to gain the maximum productivity from the system at minimum LCC. The major components of hybrid system considered in this article are solar PV modules, battery bank, inverter and diesel generator.

Photovoltaic generator model

Solar collectors are usually tilted at an angle to improve the amount of radiation captured and to minimize the reflection losses. The solar radiation data are generally available for horizontal surfaces and must be converted into tilted solar global radiation. An empirical model developed by Lin and Jordan (Kalogirou, 2009) is used in the present work to compute the incline solar radiation data. Figure 2 shows the solar radiation on inclined surface for Moradabad district (Agarwal, 2011).

The hourly power output of PV generator depends on the solar

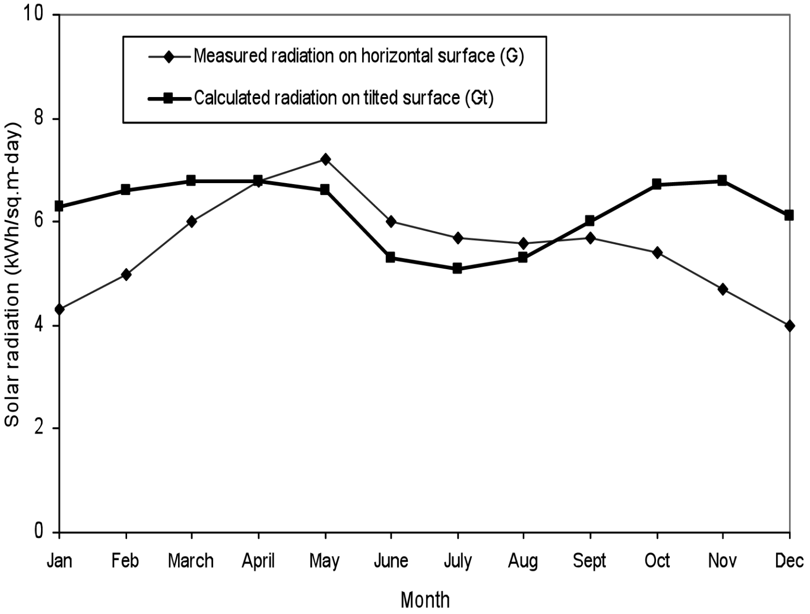


Figure 2. Monthly average daily solar radiation on horizontal and tilted surfaces at the latitude angle (28°)

irradiance G_t, the ambient temperature T_a and the PV module tilt angle Φ. It is calculated by the equation (Deshmukh and Deshmukh 2008):

$$P_g = \eta_{pv} \bullet A_m \bullet G_t \tag{3}$$

Where η_{pv} is PV generator efficiency and A_m is total area of PV modules. PV generator efficiency is given by Notton et al. (2010):

$$\eta_{pv} = \eta_{ref}\left[1 - \beta\left(T_{cell} - T_{cell,ref}\right) + \gamma \log\left(\frac{G_t}{G_{t,ref}}\right)\right] \tag{4}$$

Here η_{ref} is the reference module efficiency, $T_{cell,ref}$ is the reference cell temperature (25°C), $G_{t,ref}$ is the reference solar irradiance T_{cell} is the PV cell temperature, γ is the solar irradiance coefficient and β is the temperature coefficient. $T_{cell,ref}$, η_{ref}, β and γ are the data obtained by PV module manufacturer. β and γ depends on the material of PV module. Evans (1981) took $\beta = 0.0048/°C$ and $\gamma = 0.12$ for silicon cells. Based on the study of Bergene and Lovik (1995), Hegazy (2000) used the values of

β and γ as 0.004/°C and 0 respectively. T_{cell} can be calculated by using the following equation Notton et al. (2010).

$$T_{cell} = T_a + \left(\frac{NOCT - 20}{800}\right) G_t \tag{5}$$

Where NOCT is the normal operating cell temperature given by PV cell manufacturer.

Battery bank model

The battery bank capacity can be computed by the following equation:

$$\text{Battery Bank Capacity} = \frac{n \text{ x } N_u}{DOD \text{ x } \eta_c}$$

Where $\eta_c = \eta_b \text{ x } \eta_{inv}$

(6)

DC/AC inverter model

Inverters are chosen 10% higher than the total AC load to hold the maximum power. In this article a case study of 135 family houses is considered (see section 9), the AC load of each family house is 780 W, therefore rated power of inverter for one house is 858 W. Therefore the inverter specifications will be 858 W, 24 V_{DC} and 220 V_{AC}.

Diesel generator model

A quadratic equation is used to compute the rate of diesel consumption 'RF' by the diesel generated of rated power 'PDG'. The equation is given by:

$$RF = A \bullet P_{DG}^2 + B \bullet P_{DG} + C \tag{7}$$

Where A, B and C are constants and depends upon the rate of fuel consumption at zero load, half load and full load conditions which is provided by the manufacturer.

ECONOMIC ANALYSIS OF HPGS

The LCC of HPGS is the sum of LCC of all its components, which consists of initial capital cost of all the components, operation and maintenance costs, recurring costs like fuel cost, and non-recurring costs like battery replacement and diesel generator servicing cost (Bhuiyan et al. 2000). Therefore,

$$LCC_{system} = LCC_P + LCC_B + LCC_D \tag{8}$$

Life cycle cost of PV system

Life cycle cost of PV system is the sum of initial capital cost (P_{IN}), N_{PV} of operation and maintenance cost (P_{OM}) and system installation cost (P_{IS}) (Kolhe et al. 2002, Mbaka et al. 2010).

$$LCC_P = P_{IN} + P_{OM} + P_{IS} \tag{9}$$

Initial capital cost is the sum total of PV array cost (P_{PV}) and miscellaneous cost (P_M) which includes the cost of PV array support, cost of electric cables, nut, bolts etc.

$$P_{IN} = P_{PV} + P_M \tag{10}$$

Miscellaneous cost is considered as the percentage Z_1 (3%) of PV array cost (Ahmad 2001)

$$P_M = Z_1 \bullet P_{PV} \tag{11}$$

The NPV of annual operation and maintenance costs is taken as percentage Z_2 of initial capital cost and can be computed for a lifetime of *N* years using the following equation:

$$P_{OM} = Z_2 P_{IN} \times \sum_{i=1}^{N} \frac{(1+e)^{i-1}}{(1+d)^{i}} \tag{12}$$

Where e (5%) is the inflation rate and d (6%)is the discount rate. System installation cost (PS) is assumed as percentage Z3 (10%) of initial capital cost (Kolhe et al. 2002, Mbaka et al. 2010).

$$P_S = Z_3 \bullet P_{IN} \tag{13}$$

Life Cycle Cost of Battery Bank System

LCC of the battery bank is computed by the following relation.

$$LCC_B = CI_B + C_{CC} + C_{INV} + CR_B + COM_B \tag{14}$$

Where CI_B is the initial cost of battery bank, C_{CC} is cost of charge controller and C_{INV} is the inverter cost. The NPV of battery replacement cost (CR_B) is estimated by the following expression (Ahmad 2001) for a battery life n_b:

$$C_{RB} = CI_B \bullet Z_2 \left(\sum_{i=1}^{n_r} (1+e)^{n_b(i-1)} / (1+d)^{n_b i} \right) \tag{15}$$

Where n_r is the number of battery replacements in N number of years:

$$n_r = \mathrm{abs}[(N-n_b)/n_b]$$

The operation and maintenance cost of battery bank system is given by the equation

$$COM_B = Z_1 \bullet CI_B \left(\sum_{i=1}^{N} (1+e)^{(i-1)} / (1+d)^{i} \right) \tag{16}$$

Life Cycle Cost of Diesel Generator

LCC of diesel generator is computed by the method suggested by Mbaka et al. (2010) According to this method LCC of diesel generator is given by:

$$LCC_D = D_{IN} + D_{OM} + D_S + D_F \tag{17}$$

Where D_{IN} is the initial capital cost of the diesel generator and is given by: $D_{IN} = D_K * P_{DG}$

And D_{OM} is the NPV of annual operation and maintenance cost and is computed as:

$$D_{OM} = Z_4 D_{IN} \times \left(\sum_{i=1}^{N} \frac{(1+e)^{(i-1)}}{(1+d)^{i}} \right) \tag{18}$$

Here Z_4 (5%) is percentage of initial generator cost (given in Table 1). The NPV of diesel generator service cost is computed by the following equation.

$$D_S = Z_5 D_{IN} \times \left(\sum_{i=1}^{n_g} \frac{(1+e)^{r(i-1)}}{(1+d)^{ri}} \right) \tag{19}$$

Where:

n_g is the number of times the generator is serviced during the lifetime of N years calculated by n_g = abs(N/r)

$$n_g = \text{abs}\ (N/r) \tag{20}$$

r is the diesel generator service period and Z_5 is percentage of initial generator cost assumed as 15%.

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

$$D_F = K \bullet A_D \times \left(\sum_{i=1}^{N} \frac{(1+e)^{i-1}}{(1+d)^{i}} \right) \tag{21}$$

Where K is the diesel cost per liter and A_D is the annual diesel consumption. The cost parameters are summarized in Table 1.

Carbon-Dioxide Emission

The amount of kg of CO_2 emitted per liter from the diesel generator depends upon the characteristics of diesel generator and properties of the fuel used. This value normally falls in the range of 2.4 to 2.8 kg/l (Agustin et al., 2006). CO_2 emission from PV system depends upon the kind of solar cell material. In the present work monocrystalline silicon cells are considered whose CO_2 emission is taken as 30 g/kWh (Krauter and Ruther, 2004).

Table 1. Initial Costs. O&M Cost and System Lifetime

omponent	Initial cost	O&M cost per year	Lifetime
PV module	4.5 $/W	2% of initial cost	25 years
Diesel generator	2.0 $/W	20% of initial cost	12.5 years
Inverter	0.6 $/W	1% of initial cost	10 years
Battery bank	0.2 $/Wh	0.5% of initial cost	4 years

OPERATIONAL STRATEGY

The following operational strategy is prescribed for the HPGS:

(1) If the solar radiation is sufficient, PV power can be directly used to supply the electric load and excessive power can charge the batteries.
(2) If the solar radiation is not sufficient, the power is supplied by the batteries.
(3) If solar radiation is not sufficient and batteries state of charge is low, the power is supplied by the diesel generator.
(4) When the demand is lower than the supply, the diesel generator and PV arrays can be used to charge the batteries.

Figure 3 shows a flow chart of the system optimization process.

SIMULATED ANNEALING ALGORITHM

Simulated annealing (SA) technique was proposed by Kirpatrick et al. (1983), based on the pioneer efforts of Metropolis et al. (1953) to solve a variety of difficult combinatorial optimization problems.

Annealing is the metallurgical process of heating up a solid and then cooling it slowly until it crystallizes. The atoms of such materials have high-energy values at very high temperatures. This gives the atoms a great deal of freedom in their ability to restructure themselves. As the temperature is reduced, the energy levels of the atoms decrease. Ideally, the temperature should be reduced slowly to allow a more consistent and stable crystal structure to form, which will increase the metal's durability.

SA in statistical physics is based on the concept of thermal equilibrium at temperature T. The probability of a configuration of the system is determined by the Boltzmann factor

$$P\ (E) = \exp\ (E/k_B \bullet T) \qquad (22)$$

Where E is the energy of the configuration and k_B is the Boltzmann constant. At T = 0 the system is trapped at a minimum. At finite T, it can move around from one configuration to another. The various steps involved in optimization through simulated annealing process are presented in flow chart fashion in Figure 4.

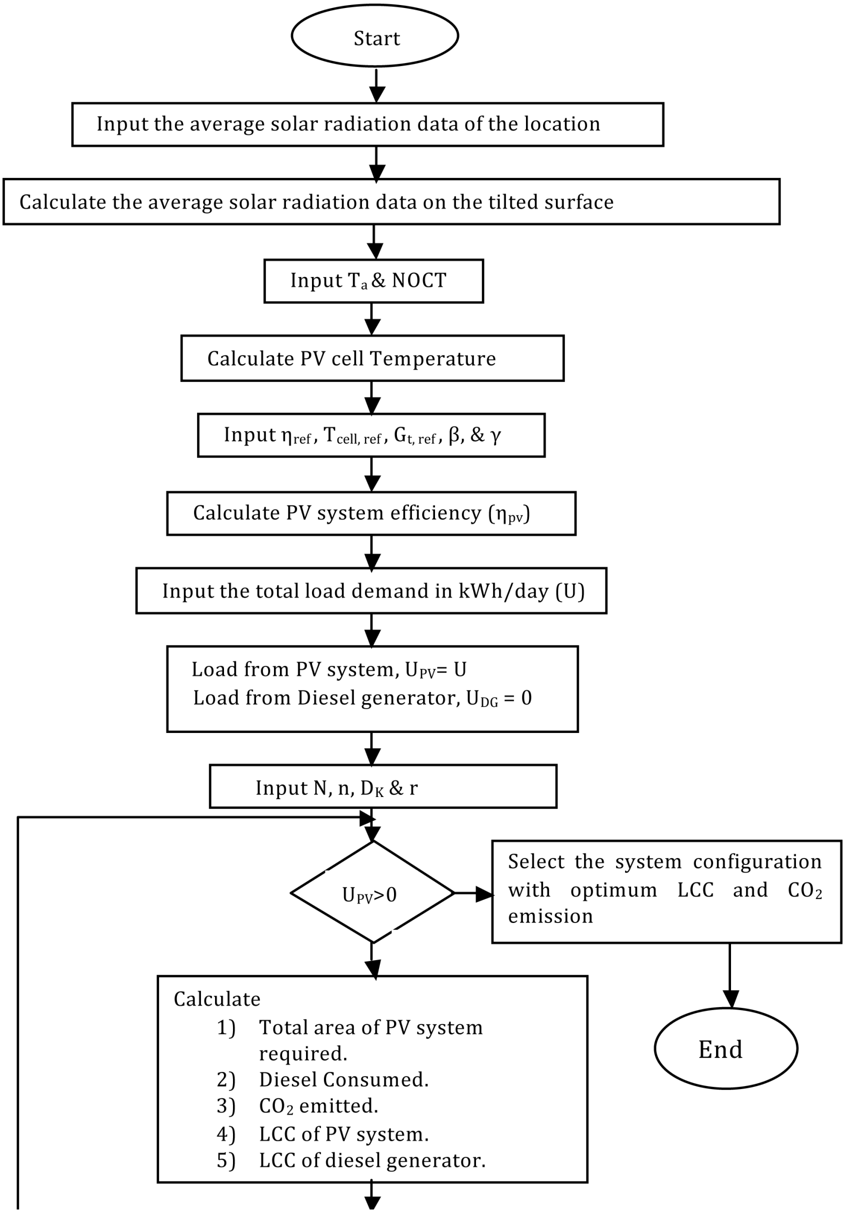


Figure 3. Flow Chart for the System Optimization Process

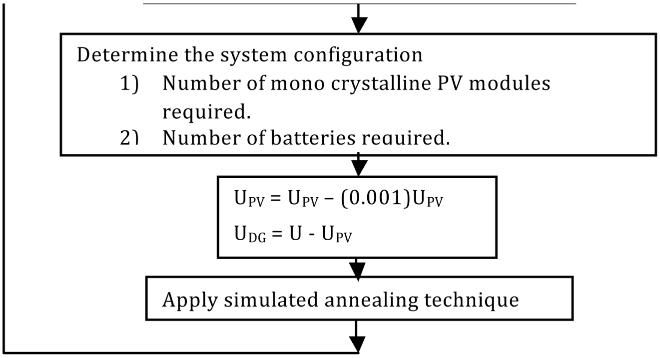


Figure 3 (*Cont'd*). Flow Chart for the System Optimization Process

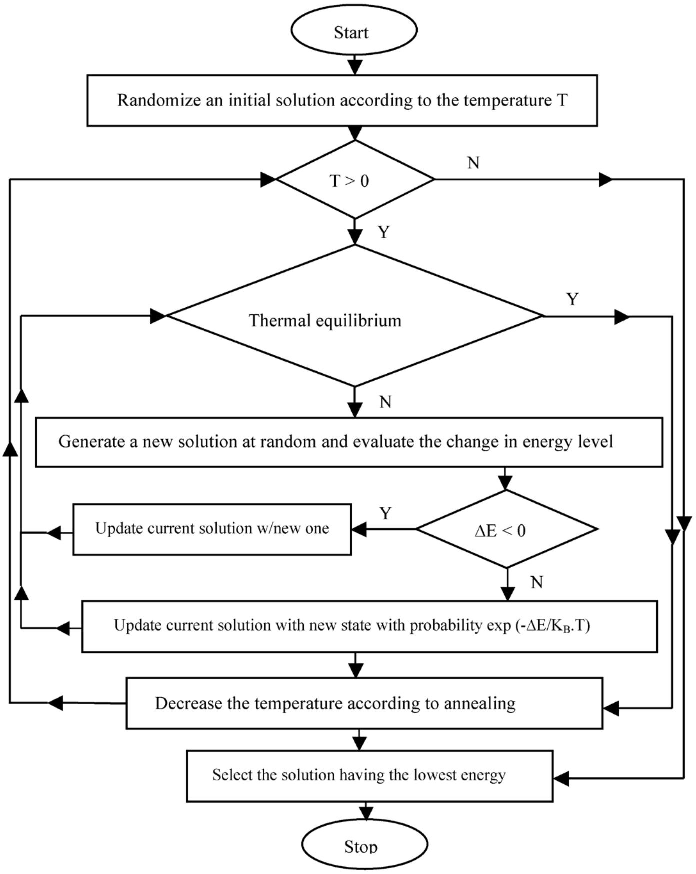


Figure 4. Flow Chart of Simulated Annealing Technique

The major advantage of SA over other methods is the ability to avoid being trapped in local minima. Moreover it guarantees a convergence upon running sufficient number of iterations. The convergence of optimum point in the following case study is reached at the 85th iteration with the optimum value of PV area 1030 m^2, DG power 15 kW and 477 batteries of 24V and 150 Ah. These results lead in a LCC of $ 973,00 and CO_2 emission of 86,212 kg/year.

CASE STUDY

A case study of residential colony of 135 family houses in Moradabad district of Uttar Pradesh is taken for analysis purpose. Each family consists of average 4-5 members with monthly income varying from $600 to $800.

There is electricity cut short of 9-12 hours every day from electricity grid due to deficiency. Therefore, it is assumed that 50% of the load demand is satisfied by the power supply from electricity grid and for the remaining 50%, a HPGS will be used in place of standalone diesel generator which is presently being used. The daily electric load demand for a typical family house is given in Table 2.

Based on climatic conditions (see Table 3) and the survey carried out in the colony, electricity load profile for complete year has been divided into four groups as shown in Figure 5. Area under each curve is obtained by Simpson's 3/8 integration rule to determine the number of units of electricity required per day as mentioned in Table 4.

RESULTS AND DISCUSSION

An optimization model is developed to determine the best of the solar-diesel-battery based hybrid power generation system so that the

Table 2. Daily Electric Load Requirements

Load Equipment	CFL Lamp	Refrigerator	TV	Washing machine	Electric fan
Units Required	4	1	1	1	3
Power (Watt)	4 x 20=80	200	80	300	3x40=120

Table 3. Climatic Conditions of Moradabad District

Environmental factors	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temperature	°F	56	62	74	84	92	91	87	86	84	78	69	60
Average morning relative humidity	%	83	78	71	55	50	61	82	85	81	76	78	82
Average evening relative humidity	%	41	35	30	22	24	36	61	64	51	33	31	38
Average precipitation	in	0.9	0.8	0.6	0.5	0.6	2.7	7.9	7.9	4.8	0.7	0.1	0.4
Average dew point	°F	44	46	50	52	57	66	75	75	71	60	51	44

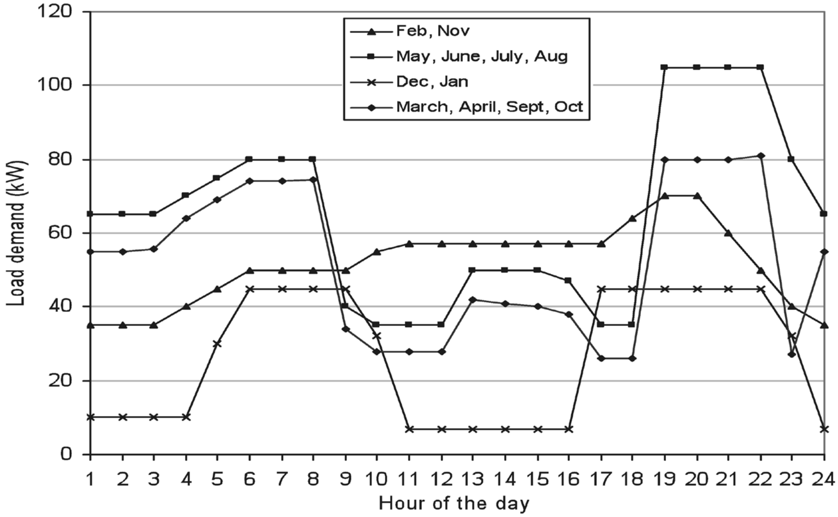


Figure 5. Typical Daily Load Demand of Family Houses Analyzed

most favorable balance is maintained between the life cycle cost and CO_2 emission from the system. The optimization model has been solved by simulated annealing technique to reduce the number of iterations, improve the accuracy of results and save computational time. A case study of a typical residential colony having 135 household is considered to test the applicability of the model. It can be observed from Table 4 that the electricity demand is peak in the month of May, June, July and August (Table 4).

Table 4. Units Required per Day during Different Months

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
No. of units required (kWh/day)	624.5	1198	1200	1200	1492	1492	1492	1492	1200	1200	1198	624.5

Figure 6 clearly indicates that the PV area less than 500 m^2 does not satisfy the load demands for all the months of the year. However, with PV area of 1400 m^2, the load demand is assured for about 10 months. Standalone PV system without any electricity shortage is acquired at an area of 1600 m^2. Figure 7 shows that the electricity shortage decreases as the incursion of PV is raised; hence the diesel consumption for electricity generation is reduced. Therefore with the increase in incursion of PV array diesel consumption is reduced and the emission of CO_2 in the atmosphere decreases (Figure 8).

Life cycle cost (LCC) analysis of the HPGS is presented in Figure 9. It can be seen that the total life cycle cost of the system reduces as the PV array area increases. At an area of 1030 m^2 and diesel generator power of 15 kW, total LCC is minimum ($973000) and average CO_2 emission is 24193 kg/year. In our previous research work on same case study [Agarwal, 2012] PV area of 1000 m^2 is selected as an optimum dimension of PV system. But, SA algorithm performs much closed analysis of LCC in between PV area of 1000 m^2 and 1100 m^2.

Figure 10 shows that a PV area of 1030 m^2 results in minimum LCC of $973,000. That is the advantage of using the SA technique over an iterative technique. Next, Figure 11 illustrates the electrical load variation during a typical day in the month of February. Same graph also shows the solar radiation and total electrical power from 1030 m^2 solar panels. When the power from PV is sufficient, it is used to supply the electric load and charge the batteries. When the PV power is deficient, power is supplied by the batteries to meet the load demand. If the power from PV and batteries are insufficient, demand is satisfied by 15 kW DGs.

A model suggested by Yang (2007) is used in this article to calculate the battery SOC. The range of SOC is assumed in between 0.4 to 0.7. Figure 12 shows the total load demand (including the battery charging), in the month of February. This much of load requirement will keep the battery SOC within the required limit of 0.4 to 0.7. It can be observed that after 18:00 pm, the power supply completely depends on battery

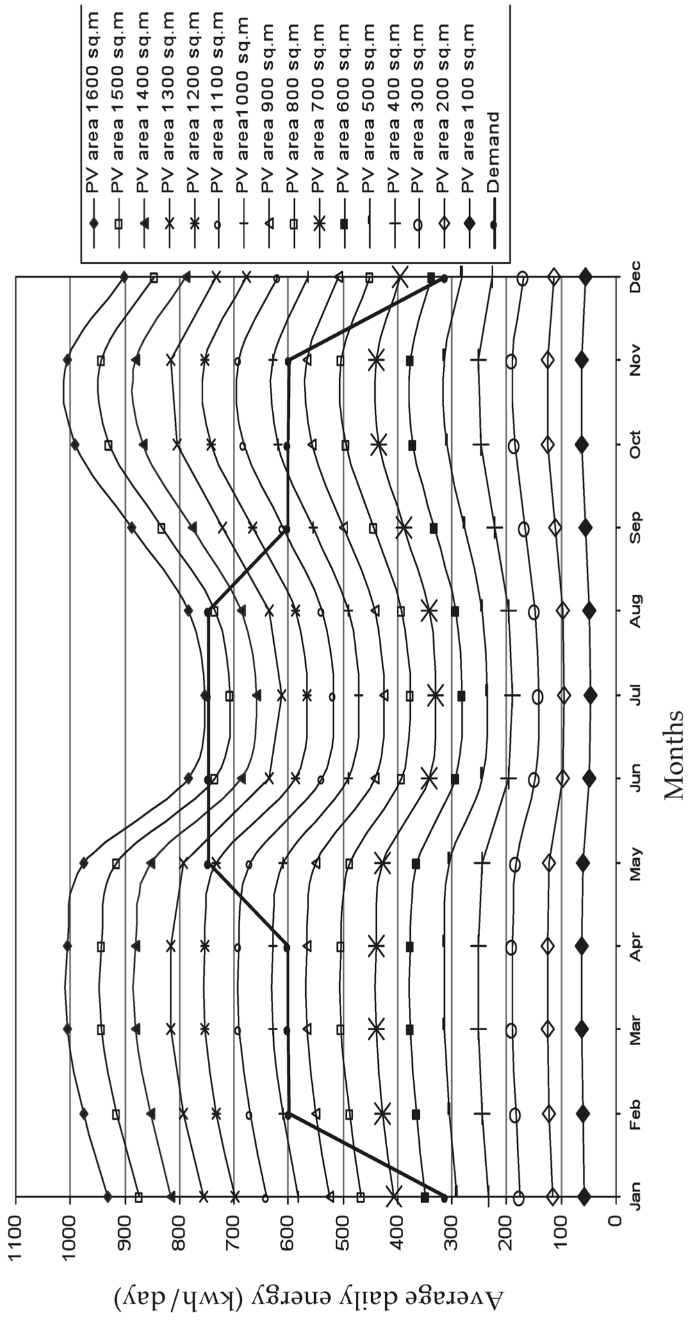


Figure 6. Energy Produced by PV Arrays of Different sizes

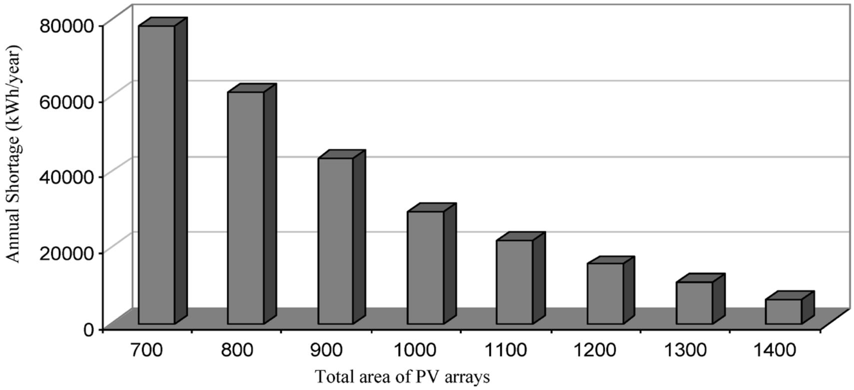


Figure 7. Annual Shortage for PV Arrays of Different Sizes

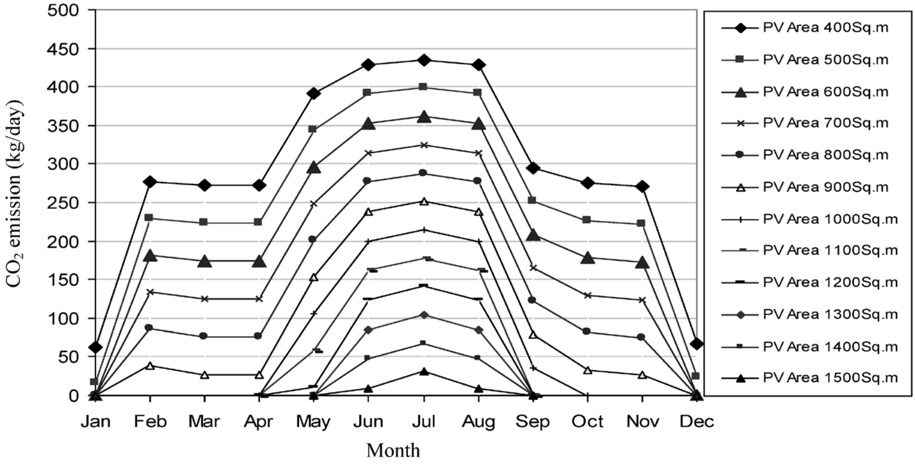


Figure 8. CO_2 Emission in a Month for PV Arrays of Different Dimensions

bank. After 1:00 am, the diesel generator is used to avoid any shortage so that no used remain unserved.

Therefore the optimum configurations of HPGS are PV area 1030 m^2, three DGs of 5 kW each, 477 batteries of 24V and 150 Ah. This arrangement of HPGS saves $ 319816 during the life cycle and reduces CO_2 emission of 144175 kg/year in comparison to standalone diesel generator system. If the area of PV system is further increased, the CO_2 emission is decreased but there is significant increase in lifecycle cost of the system.

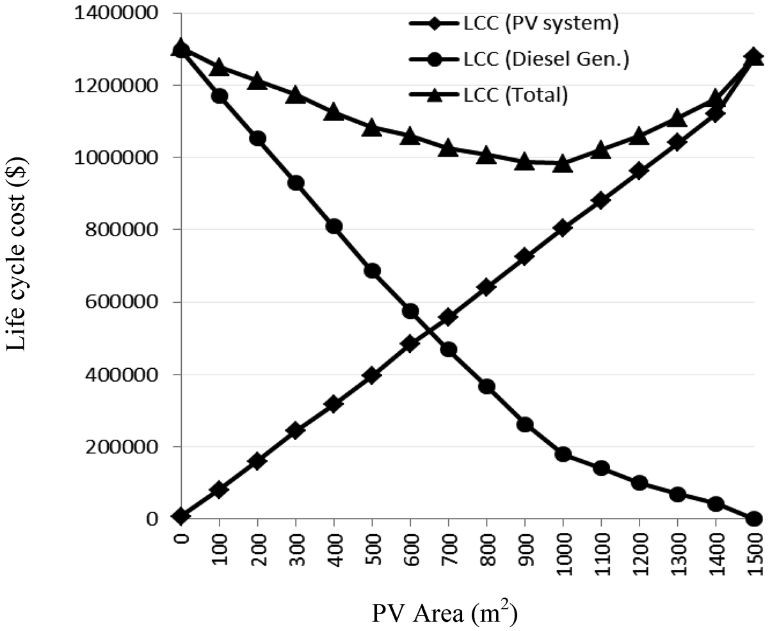


Figure 9. Life Cycle Cost of the System for Different Areas of PV Arrays

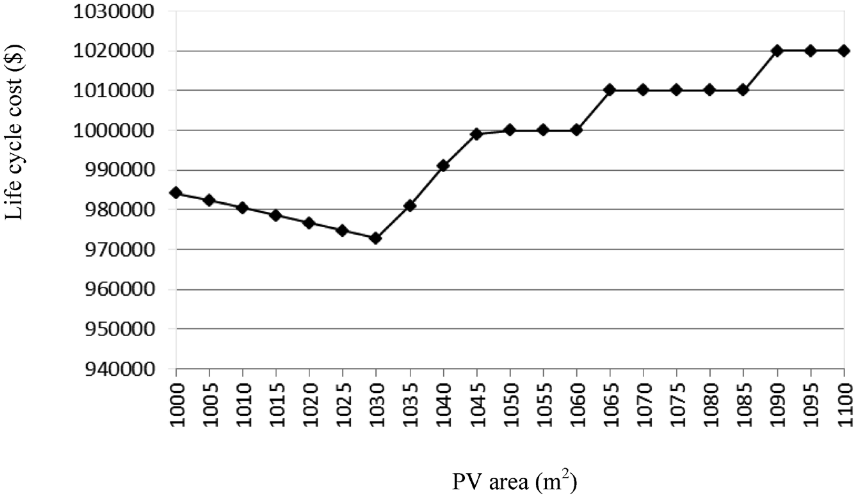


Figure 10. Close Analysis of LCC at PV Area between 1000m² to 1100

CONCLUSION

The aim of present work is to determine the optimum dimensions of solar-diesel based HPGS with battery storage. The objective is to maintain an optimum balance between the LCC and CO_2 emissions from the system. The decision variables incorporated in the optimization process are the total area of PV arrays, number of batteries of 24V and 150 Ah, diesel generator power (kW), and annual fuel consumption. The model has been applied to a residential colony of 135 family houses and is solved by using simulated annealing technique. The simulation result illustrate that the PV inclusion of 89% and diesel penetration of 11% gives the most optimized configuration with minimum LCC of $ 973000 and average CO_2 emission of 24139 kg/year. The dimensions of the most optimized design are 1030 m^2 PV area, 477 batteries of 24V and 150 Ah, 15 kW diesel generators and 86212 liter fuel consumption per year. If cost is not the major constraint, one can go for the configuration with higher incursion of PV system because in that case CO_2 emission will be appreciably lower. The simulation model developed can be used for optimal designing of PV-battery-diesel system for other locations having similar environmental conditions.

Our future work will take into account the effect of PV array tilt angle on the system effectiveness during different seasons of the year. It would also be an interesting research topic to consider the probabilistic performance analysis of the HPGS in combination with a system reliability assessment.

Acknowledgement

Authors are thankful to all the members of Ram Ganga Vihar colony, Moradabad, for their kind cooperation and participation in the survey.

References

Ahmad, G.E., 2001. Photovoltaic-powered rural zone family home in Egypt. Renewable Energy 26(3), 379-390.

Agarwal, N., Kumar, A., Varun, 2011. Optimal design of hybrid PV-diesel-battery system for power generation in Moradabad district of Uttar Pradesh, India. International Journal of Ambient Energy, 33(1), 23-34.

Agustín, B.J.L. and Dufo-López, R., Rivas-Ascaso D.M., 2006. Design of isolated hybrid systems minimizing costs and pollutant emissions. Renewable Energy, 31(14), 2227-2244.

Bakos, G.C. and Soursos, M., 2002. Techno-economic assessment of a stand-alone PV/hybrid installation for low-cost electrification of a tourist resort in Greece. Applied Energy, 73 (2), 183-193.

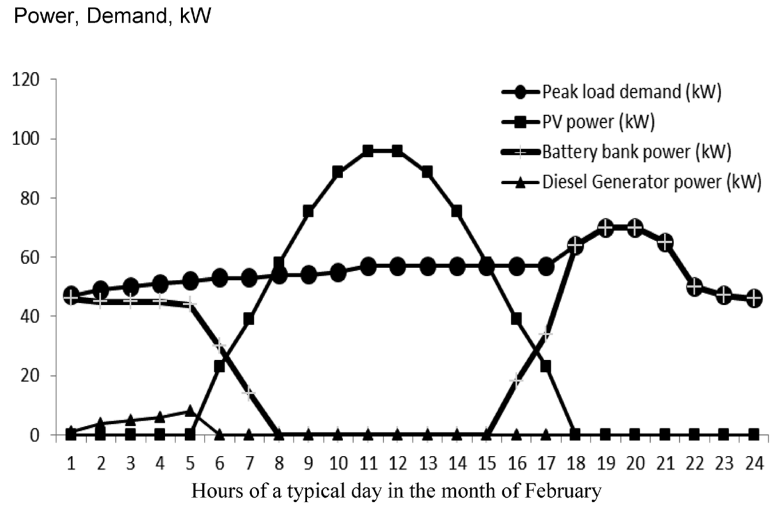


Figure 11. Peak Load Demand, Solar Radiation and Power from PV of a Typical February Day

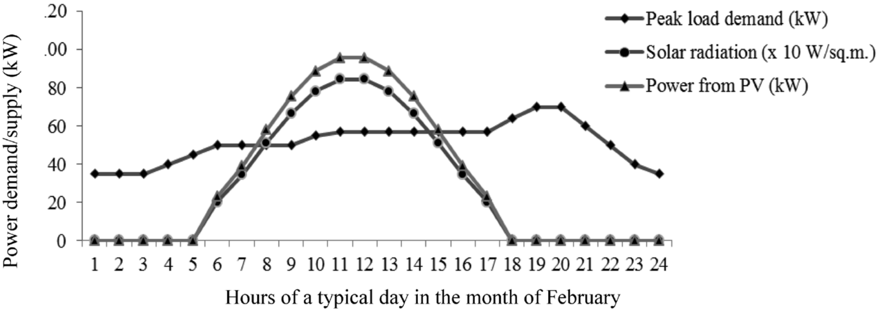


Figure 12. Power Demand/Supply for a Typical Day in February

Bergene, T. and Lovik, O., 1995. Model calculations on a flat-plate solar heat collector with integrated solar cells. Solar Energy, 55 (6), 453-462.

Bhuiyan, M.M.H., Sagar, M.A., and Mazumder, R.K., 2000. Economic evaluation of a standalone residential photovoltaic power system in Bangladesh. Renewable Energy, 21 (3-4), 403-410.

Chedid, R. and Rahman, S., 1997. Unit sizing and control of hybrid wind-solar power systems. IEEE Transactions on Energy Conversion, 12(1), 79-85.

Deshmukh, M.K. and Deshmukh, S.S., 2008. Modeling of hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 12 (1), 235-249.

Evans, D.L., 1981. Simplified method for predicting photovoltaic array output. Solar Energy, 27 (6), 555-560.

Hegazy, A.A., 2000. Comparative study of the performances of four photovoltaic/thermal solar air collectors. Energy Conversion and Management, 41 (8), 861-881.

Kaabechea, A., Belhamela, M. and Ibtiouenb, R., 2011. Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system. Energy, 36(2), 1214-1222.

Kalogirou, S., 2009. Solar energy engineering: processes and systems. 1st ed. Burlington, MA: Academic Press, 49-119.

Kamela, S. and Dahlb, C., 2005. The economics of hybrid power systems for sustainable desert agriculture in Egypt. Energy, 30(8), 1271-1281.

Kirkpatrick, S., Gellat, C.D. and Vecchi M.P., 1983. Optimization by simulated annealing, science. 220, 671.680.

Kolhe, M., Kolhe, S., and Joshi, J.C., 2002. Economic viability of stand-alone solar and photovoltaic system in comparison with diesel powered system for India. Energy Economics, 24 (2), 155-165.

Krauter, S., and Rüther, R., 2004. Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy. Renewable Energy, 29(3), 345-355.

Lagorse, J., Paire, D., and Miraoui, A., 2009. Sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery. Renewable Energy, 34 (3), 683-691.

Lazou, A.A. and Papatsoris, A.D., 2000. The economics of photovoltaic standalone residential households: a case study for various European and Mediterranean locations. Solar Energy Materials and Solar Cells, 62(4), 411-427.

Mbaka, N.E., Mucho, N.J., and Godpromesse, K., 2010. Economic evaluation of small-scale photovoltaic hybrid systems for mini-grid applications in far north Cameroon. Renewable Energy, 35 (10), 2391-2398.

Metropolis, N., Rosenbluth, A., Rosenbluth, M., Teller, A. and Teller, E., 1953. Equation of state calculations by fast computing machines. Journal of chemical physics, 21,1087.1092.

Notton, G., Lazarov, V., and Stoyanov, L., 2010. Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations. Renewable Energy, 35 (2), 541-554.

Rajkumar, R, K., Ramachandaramurthy, V.K., Yong, B.L. and Chia, D.B., 2011. Techno-economical optimization of hybrid pv/wind/battery system using Neuro-Fuzzy. Energy, 36(8), 5148-5153.

Rehman, S. and Al-Hadhrami, L.M., 2010. Study of a solar PV-diesel-battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. Energy, 35(12), 4986-4995.

Singal, S.K., Varun and Singh, R.P., 2007. Rural electrification of a remote island by renewable energy sources. Renewable Energy, 32(15), 2491-2501.

Ucar, A., Balo, F., 2009. Evaluation of wind energy potential and electricity generation at six locations in Turkey. Applied Energy 86(10), 1864-1872.

Yang H., Lu L., Zhou W., 2007. A novel optimization sizing model for hybrid solar-wind power generation system. Solar Energy 81(1), 76-84.

Zini, G., Tartarini, P., 2010. Wind-hydrogen energy stand-alone system with carbon storage: Modeling and simulation. Renewable Energy 35(11), 2461-2467

ABOUT THE AUTHORS

Nitin Agarwal is teaching for more than 10 years and currently working in the Department of Mechanical Engineering at Moradabad Institute of Technology, Moradabad. He has been graduated from GBPUAT, Pantnagar in 2000, and post graduated from MNNIT, Allahabad in 2003. Currently he is pursuing Ph.D. in the field of Hybrid Power Generation System form NIT, Hamirpur. His areas of interest are Renewable Energy modelling, Design of Hybrid Power Generation System, Life Cycle Cost Analysis etc.

Anoop Kumar is working at National Institute of Technology, Hamirpur for more than 23 years. He has been graduated and post graduated from Institute of Technology, Banaras Hindu University, Varanasi and completed his Ph.D. from IIT Delhi. His areas of interest are Computational Fluid Dynamics, Air-Pollution and Renewable Energy Modelling etc.

Varun, Mechanical Engineer, graduated from Rohilkhand University in 2002 and Post graduated from IIT Roorkee in 2004 and completed his Doctorate in 2010. He is teaching for more than 7 years and currently working as Assistant Professor in the Department of Mechanical Engineering at NIT, Hamirpur. His areas of interest include Renewable Energy, Heat Transfer, Life cycle Assessment etc.