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Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India

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Abstract

The economic viability of a stand-alone solar photovoltaic (PV) system with the most likely conventional alternative system, i.e. a diesel-powered system, has been analysed for energy demand through sensitivity analysis using a life-cycle cost computation. The sensitivity analysis allows estimation of the comparative viability of PV against a conventional alternative system based on particular country-specific parameters. The overall PV best and worst case viability, as compared to a conventional diesel-powered system, have been obtained from sensitivity analysis of the energy demand. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Terrestrial solar photovoltaic (PV) systems are presently economical for many remote applications, where the cost of other alternatives, such as extending utility power lines or transporting fuel, are very high. The PV Program Plan (1991–1995) stated that since the start of the development of PV for terrestrial use in 1972,

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module prices have dropped from \$500/W peak to approximately \$4–5/W peak in 1990, contributing to a substantial decrease in PV electricity prices. MNES (1996) has reported that in India, over 80 000 villages remain to be electrified; among them, 10 000 villages are in difficult areas and approximately 70 million homes are without electricity and 4 million diesel pump-sets are to be energised. In the year 1995–1996, PV module production was approximately 8 MW in India, which was approximately 12% of world output and the second largest in the world.

Wagdy et al. (1985) and Haas (1995) have stated that realistic economic analysis of PV systems is difficult to translate into an accurate long-term cost projection because of the number of complex factors involved. A life-cycle cost analysis is needed to compare the ultimate delivered cost of technologies with different cost structures. The economic viability of a stand-alone PV system and the most likely conventional alternative, i.e. a diesel-powered system, have been analysed for energy demand through sensitivity analysis for different parameters, such as discount rate, diesel cost, diesel system life time, fuel escalation rate, solar insolation, PV array cost, reliability, etc., for Indian conditions.

2. Life-cycle cost analysis of the solar PV system

The life-cycle cost of a solar PV system consists of the initial capital investment (C_0), the present value of operation and maintenance costs ($\mathrm{OM}_{\mathrm{pv}}$) and the present value of battery replacement cost (R_{pv}):

$$\mathrm{LCC} = C_0 + \mathrm{OM}_{\mathrm{pv}} + R_{\mathrm{pv}} \tag{1}$$

The initial capital investment C_0 is the sum of the investments of each part of the PV system, i.e. PV array, DC/AC converter (maximum power-point trackers), storage batteries, electronic control and battery charger, miscellaneous (electric cables, outhouse, etc.), packaging, transportation and installation, etc. These investments depend on the peak power rating of the PV array.

2.1. Operation and maintenance costs

Operation and maintenance costs includes taxes, insurance, maintenance, recurring costs, etc. It is generally specified as a percentage (say m) of the initial capital cost. All operating costs are escalated at a rate e_0 and discounted at rate d. The life-cycle maintenance for a lifetime of N years is:

$$\mathrm{OM}_{\mathrm{pv}} = \mathrm{OM}_0 \left(\frac{1 + e_0}{d - e_0} \right) \left[1 - \left(\frac{1 + e_0}{1 + d} \right)^N \right] \quad \text{if} \quad d \neq e_0 \tag{2a}$$

$$\mathrm{OM}_{\mathrm{pv}} = \mathrm{OM}_0 * N \quad \text{if} \quad d = e_0 \tag{2b}$$

where OM_0 is taken as:

$$OM_0 = m(C_0) \tag{3}$$

2.2. Battery replacement costs (non-recurring costs)

The battery replacement cost (R_{pv}) is mainly a function of the number of battery replacements (v) over the system lifetime, without taking the salvage value of replaced batteries. It is given by:

$$R_{pv} = C_b B_e \sum_{j=1}^{v} \left(\frac{1+e_0}{1+d} \right)^{Nj/v+1} \tag{4}$$

The battery life, i.e. N_R (cycles), in real operation is dominated by the daily depth of discharge (DOD_d) and depends on its specific characteristics, i.e. average life (N_A cycles) at a specified DOD_0 (usually $DOD_0 = 0.8$) and the battery coefficient (B_c), which is given by Soras and Makios (1988) as 0.02–0.03 for flat-plate batteries and 0.01–0.02 for tubular batteries:

$$N_R = 0.5 N_A \exp(-B_c 100(DOD_d - DOD_0)) \tag{5}$$

where

$$DOD_d = \frac{1}{12} \sum_{m=1}^{12} \left(\frac{L - E_D}{B_r} \right) \tag{6}$$

The number of battery replacements (v) is computed as:

$$v = \mathrm{INT} \frac{N}{(N_R/365)} \tag{7}$$

The cost annuity method aims to convert all the net cash-flow life-cycle costs (LCC) with an investment project into a series of annual payment of equal amounts. The conversion takes place by multiplying LCC by CRF (i.e. capital recovery factor). The levelled energy cost (LEC) from the PV system is given by:

$$LEC = \frac{LCC * CRF}{\sum_{m=1}^{12} N_d L_m} \tag{8}$$

where N_d is the number of days per month, L_m is monthly daily energy supplied by the PV system and CRF is given by:

$$\mathrm{CRF} = \frac{d}{1-(1+d)^{-N}} \tag{9}$$

The conventional solution for remote rural electrification is to extend the existing grid, and where that is not feasible, to establish a mini-grid based on diesel-powered systems. Diesel systems are independent of natural cycles, whereas PV systems are highly dependent on natural cycles.

3. Life-cycle cost analysis of a prime diesel generator system

It is difficult to compare PV and diesel-powered system technologies fairly, since their cost structures are entirely different. A diesel system has a low initial cost, while a PV system is significantly more expensive for the same energy demand. However, the PV system uses no fuel and has very low maintenance costs, while the diesel generator requires constant purchase of fuel and maintenance on a regular basis.

3.1. Sizing of a diesel system

The required diesel generator set capacity can be given by:

$$\text{Diesel gen-set size} = \frac{\text{max energy demand}}{(\text{max operating hours/day}) * \mathit{max} \text{ load factor}} \tag{10}$$

The generator set must also be capable of meeting the maximum peak demand (MPD). Thus, the larger value of the two (the calculated generator set size or MPD) has been used. The fuel consumption is given by:

$$\text{Fuel consumption} = \mathrm{AOH} * \mathrm{FCR} * 365 \quad \text{l/year}$$

where AOH (h/day) is the average generator-set operating hours over the year and FCR (l/h) is the fuel consumption rate, which is a function of diesel generator-set size and load factor. Eskenazi et al. (1986) have given a continuous curve of capital cost of diesel generation-sets over the size range given in Fig. 1 and the fuel consumption rates at different load factors given in Fig. 2. The lifetime of the diesel generator set has been assumed to be 6 years.

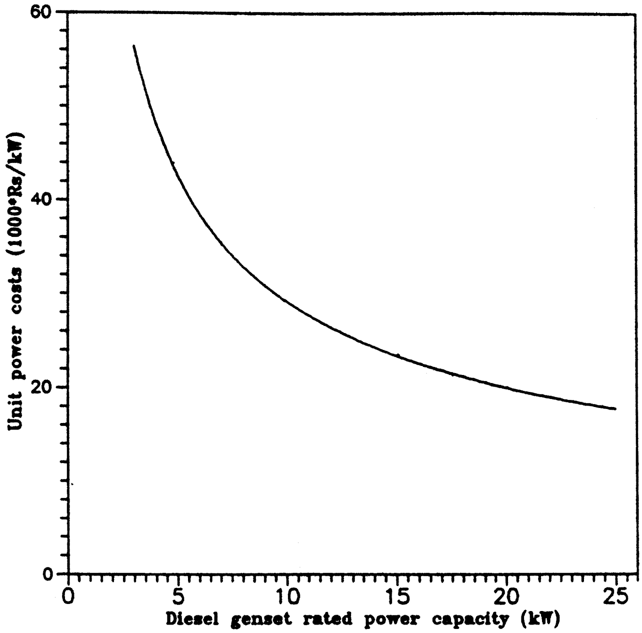

Fig. 1. Diesel generation-set costs.

3.2. Recurring life-cycle costs of a diesel system

Most prime diesel plants operate at an average load factor within 12–25%. In the present analysis, the load factor for a diesel-powered system is assumed to be 25%. An operating manual (e.g. Siemens, 1996) lists the following different levels of diesel maintenance requirements, which are the recurring costs.

i. Oil and filter change: oil and filter changes can be performed at a frequency of 250 h of operation. This also includes inspection of air and fuel filters, fuel systems, starter battery and system electrical connections. It costs approximately Rs 875–3500 per event. In the economic analysis here, it has been taken as Rs 1750 per event.
ii. Decarbonisation: in addition to oil change tasks, replacement of the air and fuel filters, cleaning the cylinder head, nozzles, gaskets, etc. can be performed at a frequency of 1500 h. This costs approximately Rs 8750–17 500 per event. Here, it has been taken as Rs 8750 per event of decarbonisation.
iii. Engine overhaul: in addition to the tasks listed above, a full engine overhaul can be performed after 6000 h of operation. Replacement of the crankshaft, bearings, valves, valve springs, injectors, fuel pumps, piston, piston rings, starter battery, etc. should be carried out. This costs approximately Rs

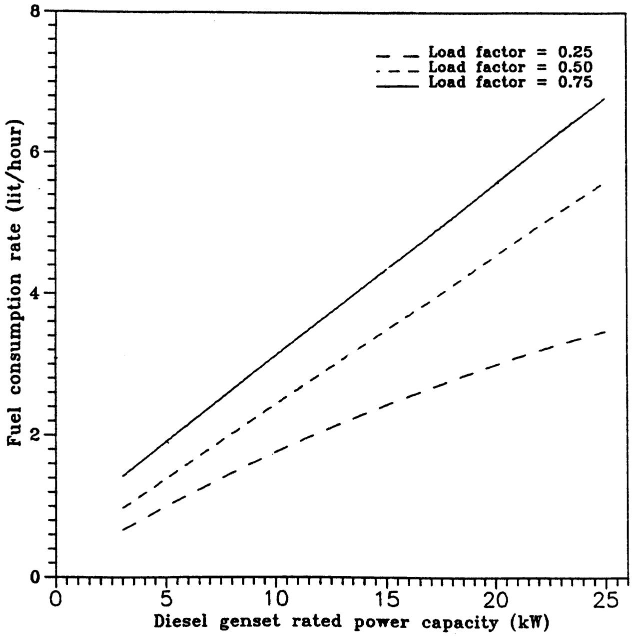

Fig. 2. Fuel consumption rates of diesel generation sets.

50 000–100 000 per event. Here it has been assumed the engine overhaul cost of Rs 50000 per event.

For a diesel engine set that is continuously running, the sample maintenance schedule listed above would require 35 oil changes, 6 decarbonisations and 1.5 overhauls per year.

The life-cycle cost of recurring fuel can be calculated as:

$$\text{LCC(fuel)} = \text{annual fuel cost} * \left[\left(\frac{1+\text{FE}}{d-\text{FE}} \right) * \left(1 - \left(\frac{1+\text{FE}}{1+d} \right)^N \right) \right], \quad d \neq \text{FE} \tag{11}$$

where FE represents fuel escalation.

The life-cycle cost of recurring maintenance is given by:

$$\text{LCC(maintenance)} = \text{annual maintenance cost} * \left[\left(\frac{1+e_o}{d-e_o} \right) * \left(1 - \left(\frac{1+e_o}{1+d} \right)^N \right) \right] \tag{12}$$

where annual maintenance cost is the annual non-fuel expenditure and e_o represents general escalation.

3.3. Non-recurring life-cycle costs of diesel system

These include replacements of engines/generator and replacement of system batteries, etc. Non-recurring costs are given by

$$\text{LCC(replacement)} = \sum_{j=1}^{v} \left[\text{item cost} * \left(\frac{1 + e_o}{1 + d} \right)^{Nj/v+1} \right] \tag{13}$$

where item cost is the non-recurring expenditure in the present day and v is the total number of replacements over a life period of N years.

The total life-cycle cost is the sum of capital cost, LCC of fuel cost, LCC of maintenance cost and LCC of replacement cost. Sensitivity analysis should be used to evaluate the effects of uncertainty on the system. The various parameters used in the economic evaluation are given in Table 1.

4. Life-cycle cost comparison of PV-powered system with diesel-powered system

A life-cycle cost comparison of PV powered systems and diesel-powered system has been carried out to give a first-order indication of when a PV system should be considered for application. Sensitivity analysis has been given to explore the system comparisons with base-case assumptions. The graphic presentation of the sensitivity analysis allows estimation of the comparative viability of PV vs. a diesel system based on Indian condition parameters. The analysis has been carried out for the energy demand for different key parameters, such as discount rate, diesel fuel cost, diesel system lifetime, fuel escalation rate, solar insolation, PV array cost, reliability, etc.

4.1. Sensitivity to discount rate

It has been found that a PV system is economical compared to a diesel-powered system up to an energy demand of 58 kW h/day with a 10% discount rate as base. At discount rates of 15 and 20%, PV-powered system are economically advantageous up to an energy demand of 40 and 30 kW h/day, respectively. This shift in the crossover occurs because of the nature of the PV and diesel cash flows, in terms of recurring vs. capital costs. The base-case PV cash flow, on the other hand, is less affected by cost escalation. The PV system also has recurring costs due to battery replacements, so the LCC is sensitive to the discount rate.

4.2. Sensitivity to diesel fuel cost

It has been observed that a PV system is economical up to an energy demand of

Table 1
The economic parameters and cost of components for the base case

PV array cost (C_p)	Rs 150/W_p
Battery cost (C_b)	Rs 4000/kW h
Battery DOD_0	0.8
Battery average life (N_A cycles)	1200
Battery coefficient (B_c)	0.02
Cost of each DC unit (C_{dc})	Rs 7000/kW
Cost of battery charge controller	Rs 350/kW h
Miscellaneous cost (wiring, panels, etc.) (C_m)	Rs 70 000/kW_p
Packing, transportation, etc. costs (C_s)	Rs 100 000/kW_p
Economic evaluation period (N)	20 years
General inflation rate (i)	7.5%
Discount rate (d)	10%
Escalation rate (e_0)	7.5%
Annual fixed charge rate of expenses (m)	1.0%
Diesel cost	Rs 30/l
Fuel escalation rate (FE)	5%
Life period of diesel set	6 years
O & M costs of diesel engine	
Oil & filter change	Rs 1750/event
Frequency of oil & filter change	250 h of operation
Decarbonisation	Rs 8750/event
Frequency of decarbonisation	1500 h of operation
Engine overhaul	Rs 50000/event
Frequency of engine overhaul	6000 h of operation

Rs is the Indian currency, i.e. Indian rupees (INR).

53 kW h/day for a diesel cost of Rs 30/l, which is shown in Fig. 3. At a diesel cost of Rs 20/l, the crossover occurs at an energy demand of 38 kW h/day, and at Rs 10/l, the PV is cost-effective only up to 28 kW h/day. In India, the cost of diesel is highly subsidised; if the Indian government were to remove the subsidy at the consumer end, the cost of diesel would increase and the PV system would become more attractive. In remote areas, the transportation cost of fuel doubles or even triples the cost of diesel.

4.3. Sensitivity to diesel system lifetime

The lifetime of diesel-powered systems varies widely with the quality and frequency of maintenance. The effect of diesel system lifetime on energy costs shows that the PV system is economical up to an energy demand of 48 kW h/day for a diesel system lifetime of 6 years. For a diesel system life of 3 years, the PV is economical up to 60 kW h/day, and for 9 years, up to 42 kW h/day.

4.4. Sensitivity to fuel escalation rate

It has been found that if the fuel escalation rate is 3% and above, the PV is

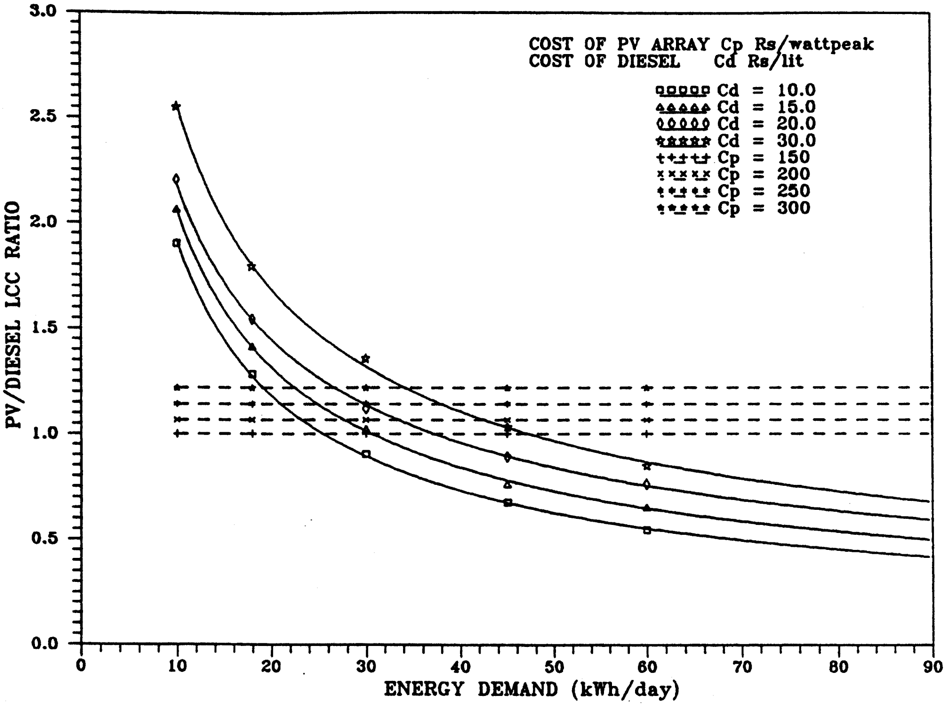

Fig. 3. PV and diesel system life-cycle cost comparisons for different PV array and diesel cost as a function of energy demand.

more favourable for the base-case assumptions. Fuel escalation mainly depends on the international price of diesel, reserved foreign exchange of the country, etc.

4.5. Sensitivity to solar insolation

The comparison of life-cycle costs of PV- and diesel-powered systems over a range of energy demands for different solar insolation shows that for solar insolation of 4 kW h/m^2 day, the PV system remains cost-effective up to an energy demand of 53 kW h/day. For solar insolation of 6 kW h/m^2 day, the PV is competitive up to 77 kW h/day. If the solar insolation increases by 66%, the LCC of PV decreases by 30%. In India, solar insolation varies between 4 and 7 kW h/m^2 day.

4.6. Sensitivity to PV array cost

The life-cycle costs of PV- and diesel-powered systems have been compared over a range of energy demands as a function of PV array cost and are shown in Fig. 3.

It has been found that for a PV array cost of Rs 150/W peak, the PV is economical up to an energy demand of 50 kW h/day, and for Rs 300/W peak, up to 35 kW h/day.

4.7. Sensitivity to reliability of PV system

The reliability of a PV system mainly depends on its application. A comparison of life-cycle costs of PV- and diesel-powered systems over a range of energy demands for different reliability levels has been carried out and showed that PV is economical up to 43 kW h/day for 99.5% reliability of the PV system; for 95% reliability it is economical up to 72 kW h/day. The LCC of a PV system is highly sensitive to its reliability.

Finally, the overall PV best- and worst-case viability as compared to a diesel-powered system over the energy demand range have been obtained by compounding the extremes of the sensitivity parameters and a graph is plotted in Fig. 4. For the best-case PV viability, a curve was generated using a low discount rate of 10%, a high fuel diesel cost of Rs 30/l, a short diesel system lifetime of 3 years and solar

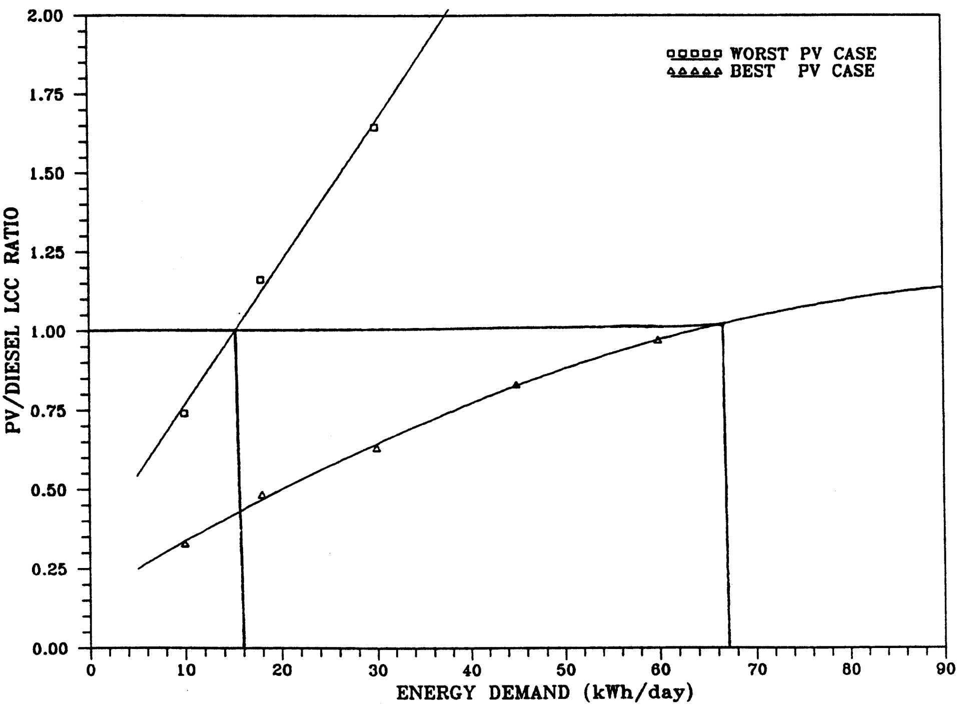

Fig. 4. Sensitivity to PV and diesel system life-cycle costs to the best and worst PV conditions as a function of energy demand.

insolation of 6 kW h/m^2 day. The worst-case curve was developed using the other extremes of the ranges, i.e. a discount rate of 20%, diesel cost of Rs 10/l, a diesel system lifetime of 9 years and solar insolation of 4 kW h/m^2 day. The area between the two curves represents a reasonable range of economic assumptions.

5. Conclusion

The economic viability of a stand-alone PV system in comparison to the most likely conventional alternative system, i.e. a diesel-powered system, has been analysed for energy demand through sensitivity analysis. The analysis shows that PV-powered systems are the lowest cost option at a daily energy demand of up to 15 kW h, even under unfavourable economic conditions. When the economic parameters are more favourable, PV-powered systems are competitive up to 68 kW h/day. These comparisons are intended to give a first-order indication of when a stand-alone PV system should be considered for application. As the cost of PV systems decreases and diesel costs increase, the break-even points occur at higher energy demand.

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