GLOBAL JOURNAL OF ENGINEERING RESEARCH VOL. 3, No. 1 & 2, 2004: 9 - 15
 ISSN 1596-292X

COMPARATIVE LIFE-CYCLE COST ANALYSIS OF SOLAR PHOTOVOLTAIC POWER SYSTEM AND DIESEL GENERATOR SYSTEM FOR REMOTE RESIDENTIAL APPLICATION IN NIGERIA.

P. E. UGWUOKE and O. U. OPARAKU

(Received 25 July 2003; Revision Accepted 19 November 2003)

ABSTRACT

Many homes in Nigeria are in remote locations where grid electricity supply could not be extended. This paper attempts to present a concise life-cycle-cost comparison of diesel generator power supply system and photovoltaic power system for a remote rural application. In this comparative analysis, conceptual designs were developed for photovoltaic-power and diesel powered systems to meet the base-case load requirements. A case study for cost comparison of 3KW$_p$ photovoltaic home system and 3KVA diesel generator was considered. Financial evaluation of providing a 3KW$_p$ photovoltaic home system in remote location was carried out and compared with that of a 3KVA diesel generator. These two systems were compared using a 20-year life-cycle-cost analysis, to obtain the net present value (NPV) or "present worth" of the systems comprising of the total capital and operating costs over the period. Then sensitivity analyses were presented, which further explore system comparisons as certain base-case assumptions like capital cost, and diesel fuel costs are varied. The results show the photovoltaic system to be more cost-effective at low-power ranges of electrical energy supply.

KEY WORDS: Comparative life-cycle cost; PV Power System; Diesel Generator; Net Present Value.

INTRODUCTION

For every remote installation requiring electric power, there are several power supply alternatives such as grid-connected power supply, power supply from generator system, wind power, e.t.c. Life-cycle cost analysis is a form of economic analysis which allows a comprehensive evaluation of all the costs associated with installing and using a power system over a reasonable length of time, thus giving a realistic assessment of a system's life time costs. Because life-cycle cost analysis breaks out specific cost components (such as battery replacement) it gives a better analysis of the economic effect of using different components with different reliability factors.

Life-cycle cost comparison of 3KW$_p$ photovoltaic-powered system and diesel generator system of an equivalent size are presented here.

Economically, competitive ranges of photovoltaic systems relative to diesel generators for supplying reliable power depend on such factors as solar energy resource of the environment, load profile pattern, cost and level of maintenance needed for the system.

METHODOLOGY

In this comparative analysis, conceptual designs of photovoltaic powered system were developed to meet the base-case load requirements. This was compared with a 3 KVA diesel generator. Each base – case was intended to be representative of typical application for which PV systems might be used. These two base-case systems were compared using a 20-year life cycle cost analysis, to obtain the "present worth" (PW) or "net present value" (NPV) of the system, comprising of the total capital and operating costs over the 20-year period. The net present value (NPV) signifies that future costs must be presented in terms of their "present worth" or actual value today [PV Design Assistance Centre, 1998].

The life-cycle cost of each power system was calculated using the equation

$$LCC = C_{pw} + M_{pw} + E_{pw} + R_{pw} - S_{pw} \quad \ldots\ldots(1)$$

Where M = Operation and Maintenance cost

C = Initial capital cost of the system over the projected period.

E = Energy cost of the system.

R = Replacement & Repair costs.

S = Salvage value of the system (i.e. its worth in the final year of Life-cycle).

P. E. UGWUOKE, National Centre for Energy Research and Development, University of Nigeria, Nsukka - Nigeria
O. U. OPARAKU, National Centre for Energy Research and Development, University of Nigeria, Nsukka - Nigeria

The subscript PW signifies present worth or NPV. Some base-case assumptions unique to the household power application area were considered here.

These include Initial capital cost, salvage value of 20% of original capital cost, installation costs, operating labour cost, yearly inspection cost, diesel fuel cost at ₦26/litre, general inflation at 5%/year, nominal discount rate of 10% and net discount rate of 5% (i.e. nominal discount rate - general inflation)[Lasnier & Gan Ang, 1990].

Photovoltaic Power System Sizing

The method used here is the ampere-hour method. The daily ampere-hour load AH_L of each appliance in the home is calculated

$$\text{Thus } AH_L = \frac{Pr \times DDC \times WDC}{V_{ns} \times 7 \times \eta_{cp}} \quad \text{.......(2)}$$

Where Pr, DDC, WDC, V_{ns} and η_{cp} are the total power rating, daily duty cycle, weekly duty cycle, nominal system voltage and inverter power conversion efficiency factor respectively.

The basic approach in this load analysis is that the total power rating of all the appliances in the home must tally with the required load demand of the system.

Table 1 shows the list of appliances used for this evaluation and their ampere-hour load values calculated using equation 2. This list of appliances here is for a moderately sized four bedroom residence with about six inhabitants, inclined towards relatively moderate use of electricity in a remote Nigerian environment.

Array Sizing

In sizing the array, the above total ampere-hour load AH_L, is corrected to reflect the losses in the battery and wiring. A corrected ampere-hour load AH_c, is calculated thus;

$$AH_C = AH_L/\{\eta_W \times \eta_B\} \quad \text{.......(3)}$$

$\eta_W = 0.98$ and $\eta_B = 0.9$ are the wire and battery efficiency factors respectively. From equation 3, AH_C = 376AH/day

The system design current C_D is obtained from

$$C_D = AH_C/S_P \quad \text{.......(4)}$$

Where S_P = Peak sun hours per day. For the location under consideration S_P = 4.2 hours and so the design current equals 90A.

Table 1: Average Daily Load for the PV System

S/No	Load Description	Qty	Load Power (W)	Daily Duty Cycle (Hrs/day)	Weekly Duty Cycle (Days/week)	Inverter Power Conversion Efficiency Factor	Nominal system Voltage (V)	Calculated Ampere-hour load (AH/day)
1	Lighting points	10	110	4	7	0.9	24	20
2	Radio	1	99	4	7	0.9	24	18
3	Television (coloured)	1	200	4	7	0.9	24	37
4	Refrigerator	1	320	7	7	0.9	24	104
5	Water Heater	1	1200	0.7	7	0.9	24	39
6	Fans	5	575	3	7	0.9	24	80
7	Blender	1	400	0.5	7	0.9	24	9.0
8	Security lights	6	66	9.5	7	0.9	24	25
	Total		**2970**					**332AH/day**

Table 2: Life-cycle Cost Analysis for 3KVA Generator at Base-case Condition

S/No	Item	Single Present Worth Year	Uniform Present Worth Year	Amount (N)	Present Worth Factor	Present Worth Amount (N)
1	Capital Equipment and Installation	0	-	189,000.00	x 1	189,000.00
2	Operation and Maintenance					
	(a) Labour	-	20	90,000.00	x 12.46	1,121,400.00
	(b)Yearly Inspection	-	20	90,000.00	x 12.46	1,121,400.00
	(c) Insurance	-	-	-	-	-
3	Energy Cost					
	(a) Generator Fuel	-	20	99,658.00	x 12.46	1,241,739.00
4	Repair and Replacement					
	(a) Battery Bank	8	-	432,000.00	x 0.677	292,464. 00
	(b) Battery Bank	16	-	432,000.00	x 0.458	197,856.00
	(c) Generator Rebuild	5	-	75,000.00	x 0.784	58,800.00
	(d)Génerator Rebuild	10	-	75,000.00	x 0.614	46,050.00
	(e) Generator Rebuild	15	-	75,000.00	x 0.481	36,075.00
5	Salvage					
	(a) 20% Of Capital (Equipment Cost = N180, 000.00)	20	-	36,000.00	x 0.377	13,572.00
		Total Life-cycle (items 1+2+3+4 – 5)			=	N4,291,212.00

The number of modules in parallel M_P and in series M_S were obtained from the following equations.

$$M_P = C_D/\{C_{RM} \times M_{DR}\} \quad (5)$$

$$M_S = V_{ns}/V_{nm} \quad (6)$$

Where C_{RM} (3.1A), M_{DR} (0.9) and V_{nm} (12v) are the rated module current, module derate factor and module nominal voltage respectively.

From equations 5 and 6, M_P = 32 and M_S = 2. Therefore the total number of modules equals 64 (i.e. $M_P \times M_S$).

Battery Sizing

The battery selected for this sizing work, from manufacturer's guide, is type DP110DC which is rated to deliver 12 Volts and 110 ampere-hours when discharging and is designed for deep-cycle service with 80% maximum depth of discharge. A total of three days of storage was chosen.A temperature correction factor of 0.9 was assumed. The corrected battery capacity B_C is then calculated as: -

$$B_C = \{AH_C \times S_D\}/\{D_{max} \times T_F\} \quad (7)$$

vhich gives 1567AH

where S_D = storage days i.e. days of no sun

D_{max} = Maximum depth of discharge

T_F = Temperature correction factor.

The number of batteries in parallel:-

$$B_P = B_C/B_R \quad (8)$$

where B_R is the rated battery capacity = 110AH

The number of Batteries in series B_S is given by

$$B_S = V_{nS}/V_{nB} \quad \text{.....(9)}$$

where V_{nB} is the battery nominal voltage = 12V

Total number of batteries for the system B_T is given by

$$B_T = B_P \times B_S \quad \text{.....(10)}$$

= 28 batteries

Charge Controller Sizing

In order to determine the size of a charge controller needed for the PV system, the module short-circuit current and hence the array short-circuit current must be determined. The module short-circuit current here is taken to be 4.6 amps: -

$$A_{SC} = M_{SC} \times M_P \quad \text{.....(11)}$$

= 147 amps

where M_{SC} = module short-circuit current

M_P = modules in parallel

Then design controller capacity is calculated as

$$1.25 \times A_{SC} \quad \text{.....(12)}$$

= 184 amps

Three controllers of size 60A each will be adequate.

Inverter sizing

Inverter rating can be calculated thus:

$$INV_R = \{CD \times V_{nS}\}/1.25 \quad \text{.....(13)}$$

= 1728 watts

Table 3: Life-cycle Cost Analysis for a $3KW_P$ Photovoltaic System at Base-case Condition

S/No	Item	Single Present Worth Year	Uniform Present Worth Year	Amount (N)	Present Worth Factor	Present Worth Amount (N)
1	**Capital Equipment and Installation**	0	-	2,688,000.00	x 1	2,688,000.00
2	**Operation and Maintenance**					
	(a) Labour/Yearly Inspection	-	20	90,000.00	x 12.46	1,121,400.00
3	Energy Cost	-	-	-	-	-
4	**Repair and Replacement**					
	(a)Battery Bank	8	-	432,000.00	x 0.677	292,464.00
	(b) Battery Bank	16	-	432,000.00	x 0.458	197,856.00
5	**Salvage** 20% of Capital (Equipment Cost = N2, 560,000.00)	20	-	512,000.00	x 0.377	193,024.00
	Total Life-Cycle Cost = (item 1 + 2 + 3 + 4 - 5)					**N4, 106,696.00**

Table 4 : Life-cycle cost comparison of diesel generator and photovoltaic system as a function of variation of fuel cost from Base-case fuel condition

S/No	Item		Present Worth Amount for the Generator System (N)	Present Worth Amount For the PV System (N)
1	Capital Equipment and Installation		189,000.00	2,688,000.00
2	Operation and Maintenance			
	(a) Labour		1,121,400.00	1,121,400.00
	(b) Yearly Inspection		1,121,400.00	-
3	Energy Cost			
	(a) Diesel Fuel	at N10/litre	477,592.00	-
		at N15/litre	716,388.00	-
		at N26/litre	1,241,739.00	-
		at N40/litre	1,910,367.00	-
		at N80/litre	3,820,734.00	-
4	Repair and Replacement			
	(a) Battery Bank at 8th year		292,464.00	292,464.00
	(b) Battery Bank at 16th year		197,856.00	197,856.00
	(c) Generator Rebuild at 5th year		58,800.00	-
	(d) Generator Rebuild at 10th year		46,050.00	-
	(e) Generator Rebuild at 15th year		36,075.00	-
5	Salvage [illegible]0% [illegible]al Cost		13,572.00	193,024.00
6	TOTAL LIFE-CYCLE COST	at N10/litre	3,527,065.00	4,106,696.00
		at N15/litre	3,765,861.00	
		at N26/litre	4,291,212.00	
		at N40/litre	4,959,840.00	
		at N80/litre	6,870,207.00	

Therefore, a 1.5kw pure sine wave inverter can be adequately considered for the system **[Ruesel, 1984]**

Basic Parameters

The local cost of the PV system components were deduced from quotations of our local suppliers (Standby Power Systems Ltd and Eco-pal Electric System Ltd), while the cost of the diesel generator set was obtained from a major generator set supplier (Eloka Star Time Nig. Ltd). The discount rate of 5% used in the analysis is based on the average inflation rate in Nigeria (1970-1993) of 20%[Oparaku, 1997]

The single present worth discount factor DF_S and the uniform present worth discount factors DF_U used in the analysis were obtained from equations:

$$DF_S = 1/\{1 + DR\}^N \qquad (14)$$

$$DF_U = 1 - \{1 + DR\}^N/DR \qquad (15)$$

The total annual fuel consumption FC of the generator set was obtained from the equation:

$$FC = AOH \times FCR \times 365 \qquad (16)$$

Where AOH = average operating hours per day (i.e. daily duty cycle) and FCR = fuel consumption rate of the generator.

The total annual consumption of the generator at an annual average daily duty cycle of 7hrs per day and a fuel consumption rate of 1.18litres/hour is calculated to be 3015 litres. The installation costs in the two systems were assumed to be 5% of the original capital cost in each system[Lasnier & Gan Ang]

The operation and maintenance costs in each system include the cost for annual inspection (₦90,000) and wages (₦90,000) for a system operator in each case working for 8 hrs. per day on a wage of ₦ 7,500/month (Nigerian

Table 5: Life-cycle Cost Comparison of Diesel Generator and Photovoltaic System as a Function of Variation of Module Cost from Base-case Value.

S/No	Item	Present Worth Amount for Generator System (N)	Present Worth Amount for PV System (N)	
1	Capital Equipment and Installation	189,000.00	at 364/WP	1,345,344.00
			at 582/WP	2,151,072.00
			at 727/WP	2,688,000.00
			at 872/WP	3,222,912.00
			at 1091/WP	4,032,336.00
2	Operation and maintenance			
	(a) Labour	1,121,400.00	1,121,400.00	
	(b) Yearly Inspection	1,121,400.00	-	
3	Energy Cost (a) Diesel Fuel	1,241,400.00	-	
4	Repair and Replacement			
	(a) Battery Bank at 8th year	292,464.00	292,464.00	
	(b) Battery Bank at 16th year	197,856.00	197,856.00	
	(c) Generator Rebuild at 5th year	58,800.00	-	
	(d) Generator Rebuild at 10th year	46,050.00	-	
	(e) Generator Rebuild at 15th year	36,075.00	-	
5	Salvage (a) 20% of Capital Cost	13,572.00	at N364/WP	96,609.00
			at N582/WP	154,467.00
			at N727/WP	193,024.00
			at N872/WP	231,436.00
			at N1091/WP	289,560.00
6	Total life-cycle Cost	N4, 291,212.00	at N364/WP	2,860,455.00
			at N582/WP	3,608,325.00
			at N727/WP	4,106,696.00
			at N872/WP	4,603,196.00
			at N1091/WP	5,354,496.00

minimum wage).The repair and replacement costs of the system include the costs of replacing solar batteries every 8 years for each system and maintenance/repairs of generator set at about 41.5% of the original capital cost every 5 years for the generator system.

The salvage value is 20% of the original capital cost, excluding installation.The net present value (NPV) method or the present worth (PW) technique was adopted in this analysis. Equation 1 represents this technique as earlier stated. Tables 2 and 3 show the life cycle cost analysis for the 3 KVA diesel generator and 3 KW_P photovoltaic system respectively, both at base case conditions. Tables 4 and 5 show the final summary of the life cycle cost comparison of the diesel generator and PV systems.

Sensitivity Analysis

Sensitivity analysis demonstrates the effect of variation of certain parameters on the life cycle cost of the systems. The parameters discussed here are capital cost and diesel fuel cost. The sensitivity of LCC to diesel fuel cost was carried out at ₦10/litre, ₦15/litre, ₦26/litre, ₦40/litre and ₦80/litre.

Sensitivity to Diesel fuel

This analysis examines the effect of varying fuel cost from the base case value of ₦26/litre. Fig. 1 shows the impact of variation of fuel costs on the life-cycle cost analysis. It is observed that the diesel generator is financially

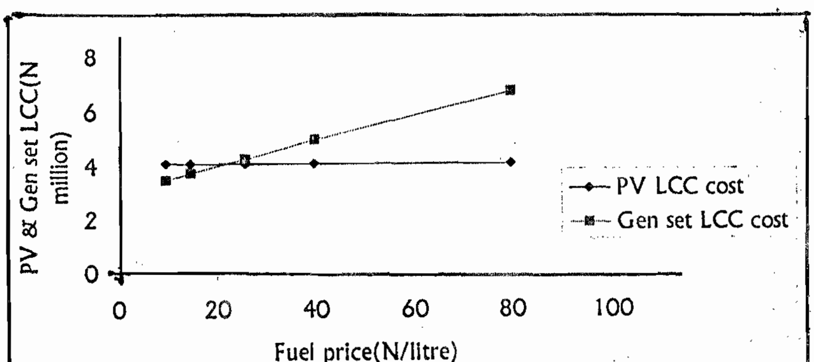

Fig. 1 Sensitivity of LCC to Diesel Fuel

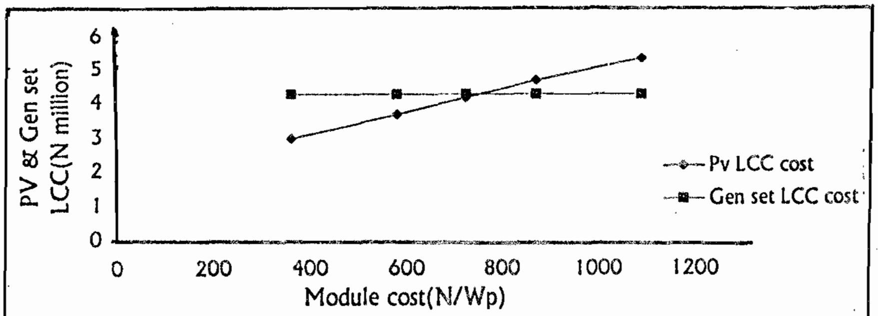

Fig.2 Sensitivity of LCC to Module cost

advantageous up to a fuel cost of ₦23/litre, but beyond this rate, the PV system becomes the more cost effective option on a life-cycle cost analysis.

Sensitivity to Module cost

Fig. 2 shows the sensitivity of LCC to module cost in ₦/W_p. Here the life cycle cost increases linearly with module cost per W_p. At a break-even point of ₦727/W_P, PV system is relatively comparable with a diesel generator. But however, at higher cost per W_p, PV system loses its cost effectiveness.

RESULT AND DISCUSSION

The life-cycle cost comparative analysis as shown in tables 4 and 5 and in figures 1 and 2 shows that photovoltaic system of comparable capacity with a diesel generator will cost relatively less than the diesel generator over an extended period of life-cycle. The photovoltaic system would require huge capital to acquire. The initial capital investment of the diesel generator used in this work is about 7.03% of its PV system counterpart. But on a 20-year life cycle cost comparison, the diesel generator LCC becomes higher by about 4.3% of its LCC. The base-case fuel cost of ₦26/litre was used and the result shows that PV is more advantageous at a high fuel cost. Since the Nigerian economy is dependent on the oil, Government has continued to embark on upward adjustment of fuel prices and the subsequent deregulation of the oil industry. It becomes necessary to look for an alternative and cost-effective option for energy generation such as development of photovoltaic systems. If the growth of photovoltaic systems are encouraged, it will facilitate the social and economic development of this country.

REFERENCES

Photovoltaic Design Assistance Centre, Sandia National Laboratories, Albuquerque, New Mexico, 1998. Stand-Alone Photovoltaic System – A Handbook of Recommended Design Practice.

Lasnier, F. and Gan Ang, T., 1990. Photovoltaic Engineering Hand Book. Published under the Adam Hilger imprint by IOP Publishing Company Ltd, England.

Ruesel, M .C., 1984. Residential Photovoltaic System Design Hand Book; Concord. Mass; MIT. Northeast Residential Experimental Station.

Oparaku, O.U., 1997. Electricity Supply to Rural Community in Nigeria – A Cost comparison of Photovoltaic Diesel/Gasoline Generator and Utility Power Supply Options. International Conference on Power Systems, Operation and Planning, Abidjan, Cote d'Ivoire – conference proceeding .235 –240.