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ANALYSIS OF THE ECONOMICS OF PHOTOVOLTAIC-DIESEL-BATTERY ENERGY SYSTEMS FOR REMOTE APPLICATIONS

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ABSTRACT

Computer simulations were conducted to analyze the performance and operating cost of a photovoltaic energy source combined with a diesel generator system and battery storage. The simulations were based on the load demand profiles used for the design of an all photovoltaic energy system installed in the remote Papago Indian Village of Schuchuli, Arizona. Twenty year simulations were run using solar insolation data from Phoenix SOLMET tapes. Total energy produced, energy consumed, operation and maintenance costs were calculated. The life cycle and levelized energy costs were determined for a variety of system configurations (i.e., varying amounts of photovoltaic array and battery storage). The system configuration producing the minimum levelized energy cost was determined. Results are presented for three sets of economic assumptions and for two different photovoltaic module efficiencies representative of standard and high density (high frame efficiency) modules. Effects of reducing photovoltaic module costs on the levelized energy cost results are examined. Implications of the study on the design of power system for remote applications are discussed.

1. INTRODUCTION

The NASA-Lewis Research Center has for the last several years managed the Department of Energy's Stand-Alone Photovoltaic Applications System Project. The objectives of this project are to conduct research and development for non-grid connected photovoltaic energy systems and to conduct field tests to demonstrate and verify the technology. Because of the wide-spread electrification of the continental United States, most of the initial applications for stand-alone photovoltaic systems have been in remote areas of the developing regions of the world where photovoltaic systems are more likely to be cost-competitive with traditional sources of energy. This is based on the fact that the real cost of supplying small amounts of power dependably to remote areas is extremely high when one determines true costs of traditional energy sources based on transmission and distribution line installation or diesel generator installation, operation and maintenance. Studies, conducted for NASA-Lewis by the Aerospace Corporation (1) have shown that for relatively small yearly energy demands, (<5800 kwh/year), a stand-alone photovoltaic system (comprised of PV array, battery storage and controls) is less costly on a levelized energy cost basis than a diesel generator set in regions of the world where delivered fuel costs are \$3.00 per gallon and expected to escalate in price over the 20 year system life assumed. Although the PV system has been determined to be more economical than a diesel generator, costs per kwh still are quite high (greater than \$2/kwh) because of the high capital cost of the photovoltaic system, especially the battery storage subsystem.

While continued progress in reducing costs of the photovoltaic arrays has been made and is anticipated to continue, the cost of battery storage has actually increased in the last few years with little prospect for significant near term price reductions envisioned. Projections made for NASA-Lewis for future prices of modular stand-alone photovoltaic systems show storage costs dominating the total system costs, approaching nearly 50-60 percent of the initial capital cost and 70-75 percent of the life-cycle cost (2). These realizations gave impetus to the need to study alternative photovoltaic-hybrid systems which couple a diesel generator set with a photovoltaic array with only a minimum of battery storage. It was expected that a hybrid configuration of this sort could supply electrical energy for small demand applications at a lower life-cycle cost than a photovoltaic-battery system or a diesel generator alone.

To determine the economic viability of the photovoltaic-diesel-hybrid system, a series of computer simulations of various photovoltaic-battery-diesel configurations were performed by the Aerospace Corporation for NASA-LeRC (3). A schematic diagram of the system analyzed is presented in Fig. 1. The simulations determined the operating and maintenance costs from which the life cycle costs and levelized energy costs were estimated for various systems sized to provide energy for a typical application, a remote village power system.

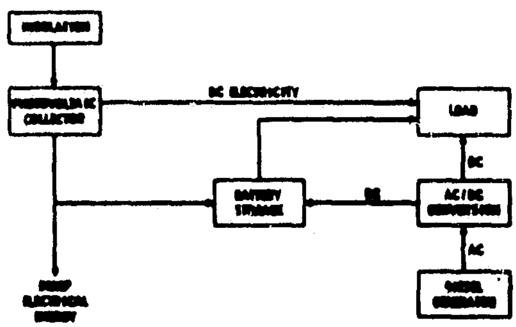

Figure 1. System Concept: Photovoltaic/Battery Plus Diesel

2. METHODOLOGY

Fig. 2 illustrates the analytical approach used in the study. Additional details are described in (3). An hour-by-hour computer simulation of the operation of each photovoltaic-diesel-battery configuration over a twenty year time period (1953-1972)

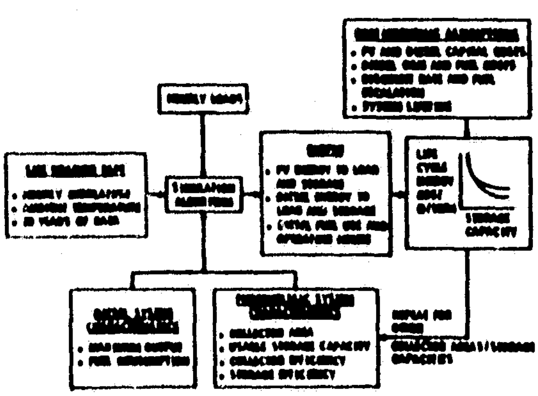

Figure 2. Combined Photovoltaic/Diesel Study Outline

was conducted. The load profile used in the simulation was that used for the design of an all photovoltaic system for the remote Papago Indian Village power system in Schuchuli, Arizona, Fig. 3. (The total annual demand is 6716 kWh and the peak

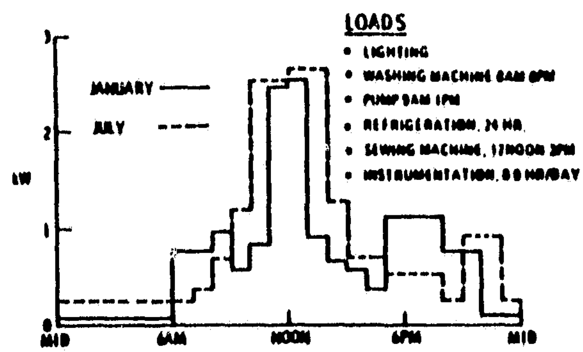

Figure 3. Schuchuli Village Power System Design Load Profile

load 2.6 kW. The day/night energy usage ratio is approximately 70/30.) Hourly insolation and temperature data from Phoenix, Arizona SOLMET tapes were used. The diesel generator assumed in the study was a commercial 4 kW unit. Capital cost, operating and maintenance characteristics (e.g., fuel usage) of the diesel generator assumed in the study were based on manufacturer's data. The costs and technical characteristics of the batteries and the photovoltaic modules were taken from specifications and price quotes for commercially available hardware. The "balance of system" hardware costs were taken from (4), and included costs for site preparations, array structure, field wiring, fencing, lightning protection, battery and controls housing and maintenance equipment.

Using the input data above, the hourly energy delivered to the load by each system component (i.e., PV array, diesel generator, battery) was calculated. The simulation maintained a record of the electrical energy delivered by the PV array to the load and the battery, the energy drawn from the battery and the number of hours of operation and fuel consumed for the diesel. When photovoltaic-generated D.C. electricity is available, the energy is delivered to the load, with excess going to the battery. If the battery is in a full state of charge, the excess power is assumed to be "dumped". If the load demand exceeds the PV output, the difference is applied by the battery. If the combined PV-battery output cannot satisfy the load, the diesel is turned on. Any diesel-generated energy in excess of the load demand is delivered to the battery.

At the conclusion of the 20 years of hourly simulations, the records generated along with the assumed costs and economic

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parameters (e.g., discount rate) were used to compute the levelized life cycle and levelized energy generation costs for the particular configuration under study. The life cycle and levelized energy costing computations are described in detail in (3) and are based on the basic net present value methodology. The life cycle and levelized energy costs were calculated for three different sets of economic parameters (Table I) which were chosen to provide applicability of the results to a diverse number of potential application regions.

alone for a total diesel system would then be $24,744, $34,533 or $37,801 depending upon the use of the economic assumptions 1, 2 or 3, respectively.

Combining a photovoltaic array with the diesel without storage effects some reductions in fuel consumption, dropping it to 20,140 gallons. However, it is not until some battery storage is added to the configuration, that a drastic drop in fuel consumption is achieved. Adding as little as 2.5 kWh of battery storage reduces fuel

TABLE I

ECONOMIC PARAMETERS USED FOR LIFE CYCLE AND LEVELIZED ENERGY COSTS CALCULATIONS

	Assumption 1	Assumption 2	Assumption 3
Real Discount Rate, %	10	15	5
First Year Diesel Fuel Cost, $/Gal.	1.25	3.00	1.25
Fuel Escalation Rate, %	3	0	3
System Life, Yrs	20	20	20
Inflation Rate	0	0	0

2.1 Results

As shown in (1), fuel costs dominate the life cycle costs for all diesel generator systems. By utilizing the PV-hybrid approach, the simulation data show significant reductions in fuel consumption are realized. Fig. 4 presents a plot of fuel usage over the 20 years of the simulation as a function of photovoltaic collector area and for varying amounts of battery storage. An all diesel system operating continuously to supply the entire load profile would consume 36,780 gallons of fuel during the 175,200 hours of operation. The life cycle cost of the fuel

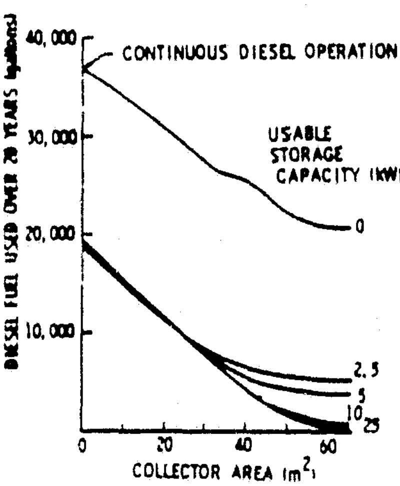

Figure 4. Diesel Fuel Use for Photovoltaic-Diesel System vs. Collector Area for Several Amounts of Battery Storage

usage to 5040 gallons at 65 m^2 of collector area. Life cycle fuel costs for this configuration are $3395, $4738 and $5186 for assumptions 1, 2 and 3. Corresponding to the drop in fuel consumption is a marked drop in diesel operations and maintenance (O&M) costs which are a direct function of hours of operation. Life cycle O&M costs for the all diesel system ranged from $41,391 to $60,593 depending upon economic assumptions. These O&M costs dropped to between $3,662 to $5,360 for 2.5 kWh of storage at a collector area of 65 m^2. The sharp reductions in fuel and O&M costs must be contrasted, however, against the added costs of the battery storage and array collector area when these elements are included in the system. For example, the cost of the 65 m^2 of array collector area and 2.5 kWh of battery storage are estimated to have a life cycle cost of $54,664 which is independent of economic assumptions because all the expenses associated with the photovoltaic array and battery are initial and not recurring costs. An exception might be for battery replacement, which likely would be done at 10 years; however, the additional life cycle cost for the replacement batteries is a minimal amount when contrasted to total system life cycle cost and thus is ignored. (For example, to replace 10 kWh of battery storage capacity after 10 years adds $308 to $767 to the life cycle cost for 15 and 5 percent discount rates, respectively.)

The total life cycle costs for the various photovoltaic-battery-diesel systems analyzed are given in Table II.

TABLE II

LIFE CYCLE COST OF VARIOUS PHOTOVOLTAIC-BATTERY-DIESEL SYSTEMS, $

Collector Area (m^2)	Storage Capacity (kWh)	Economic Assumption 1	2	3
0	0	77,978	76,275	111,340
	2.5	37,267	38,392	50,822
	5	33,393	37,374	47,960
	10	36,018	37,999	48,585
	25	37,893	39,874	50,460
20	0	90,148	88,206	117,315
	2.5	50,417	50,714	58,202
	5	48,907	49,655	55,844
	10	49,521	50,268	56,452
	25	51,394	52,140	58,323
30	0	91,673	89,803	116,375
	2.5	52,795	52,140	58,495
	5	50,882	51,125	55,521
	10	50,736	50,896	54,988
	25	52,609	50,892	56,860
40	0	91,111	89,422	112,340
	2.5	57,852	57,742	62,803
	5	55,624	55,666	59,345
	10	53,232	52,945	55,446
	25	54,788	54,464	56,841
50	0	95,383	93,759	115,419
	2.5	64,024	63,887	68,776
	5	61,675	61,660	65,135
	10	58,696	58,285	60,353
	25	59,959	59,481	61,311
65	0	104,002	102,410	123,507
	2.5	73,564	73,405	78,156
	5	71,118	71,059	74,372
	10	68,139	67,683	69,589
	25	69,538	69,032	70,752

Calculations based on: standard module (efficiency 6.8%), module cost $9/Wp, battery cost $125/kWh.

The levelized energy costs (LEC) are determined by multiplying the corresponding life cycle cost (LCC) by the capital recovery factor and dividing by the yearly annual energy usage.

$$LEC = \frac{LCC \cdot \dfrac{k}{1-(1+k)^{-n}}}{6716\ \text{kWh}}$$

Where k is the discount rate and n is the system life in years.

For $k = .15$, $LEC = 2.37\times10^{-5}$ LCC/kWh
$k = 0.10$, $LEC = 1.74\times10^{-5}$ LCC/kWh
$k = 0.05$, $LEC = 1.19\times10^{-5}$ LCC/kWh

The maximum levelized energy costs, regardless of economic assumption, occur for a PV-diesel configuration consisting of 65 m^2 of collector area with no battery storage. These are $1.81/kWh, $2.42/kWh and $1.47/kWh for assumptions 1, 2 and 3. This maximum occurs because of the excessive amount of diesel running time (102,260 hours) which still accumulates to meet the loads during transient cloudy and nighttime conditions.

For all cases, the minimum LEC occurs for zero collector area but with 5 kWh of battery storage. These LEC's are $0.61/kWh, $0.89/kWh and $0.57/kWh for the three assumptions. The photovoltaic-diesel-battery hybrid approaches competitiveness with the minimum LEC cost diesel battery system only for economic assumption 3. In this case, a PV-diesel-battery hybrid consisting of 30 m^2 of collector array and 10 kWh of storage has a LEC of $0.65/kWh in contrast to the $0.57/kWh for the diesel-battery system. This near-competitiveness occurs as a result of the relatively low (5%) discount rate assumed.

The data in Table II was derived based on a standard photovoltaic module (efficiency 6.8 percent) and a cost of $9 per peak watt. It was determined to be of interest to ascertain the effects on the LEC of using high density (high frame efficiency) modules with an efficiency of 11.4 percent to affect reductions in area-related systems costs (e.g., array structure). The LCC and LEC for hybrid systems utilizing the high density (efficiency) modules were thus calculated (5). Module costs were assumed to be $15 per watt peak. Some results are shown in Table III. The collector area for the high density (efficiency) module is in parenthesis and the approximate amount of high density-based collector area which will produce the same energy as the standard module photovoltaic array.

TABLE III

EFFECTS OF MODULE EFFICIENCY ON LEVELIZED ENERGY COSTS, $/KWH

Collector Area (m^2)	Storage Capacity (kWh)	Module Efficiency, % 6.8	11.4
40	0	1.58	1.87
(25)*	2.5	1.01	1.31
	5	0.97	1.27
	10	0.93	1.22
	25	0.95	1.25
65	0	1.80	2.29
(40)*	2.5	1.28	1.76
	5	1.24	1.71
	10	1.18	1.66
	25	1.21	1.69

For Economic Assumption number 1.

*Approximate equivalent high density collector area.

The results of this analysis indicate that the use of the high density (efficiency) module provides no economic advantage, in fact, at the assumed purchase price of $15 per watt peak the levelized energy costs are higher for every case examined.

The analysis indicates that the most economical configuration on a levelized energy cost basis for all three economic assumptions is the diesel-battery without any photovoltaic component for the photovoltaic system costs assumed. The question that arises is at what module cost will the photovoltaic-hybrid be a better economic choice than the diesel-battery system? To answer that question, the photovoltaic module cost was determined at which, for each configuration analyzed, the photovoltaic-hybrid system levelized energy cost would be equal to the diesel-battery system. This module cost is termed the breakeven module cost and is shown for the number 1 economic assumption in Fig. 5 as a function of collector area and for several amounts of battery storage. The data shows that the highest allowable breakeven module cost occurs for 10 kWh of storage and for a collector area of 40 m^2. Similar curves generated for the other economic assumptions also show the maximum point occurring for 40 m^2 of collector area (25 m^2 for the high efficiency modules) and 10 kWh of storage.

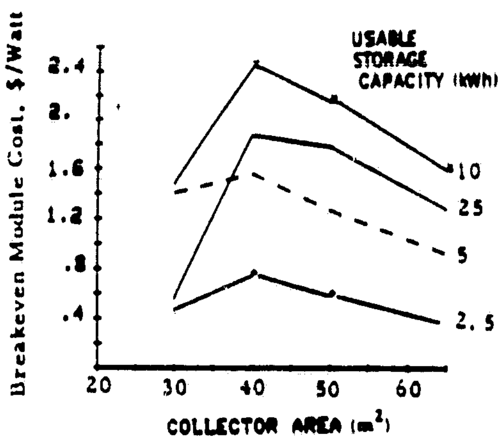

Figure 5. Standard Photovoltaic Module Breakeven Costs vs. Collector Area for Several Amounts of Battery Storage (Economic Assumption 1)

The maximum breakeven module costs for the three assumptions and for both the regular and high density (efficiency) modules are given in Table IV.

TABLE IV

PHOTOVOLTAIC-HYBRID MAXIMUM BREAKEVEN MODULE COSTS, $/Wp

	Economic Assumption 1	2	3
Standard Module	2.44	3.28	6.25
High Density Module	2.71	3.52	6.41

The breakeven-module maximum costs range from a low of $2.44/Wp for the standard

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module under economic assumption 1 to a high of $6.41/Wp for a high efficiency module under assumption 3. When the cost of photovoltaic modules drops to or below this level, the photovoltaic-hybrid will be economically advantageous over the diesel-battery system. The prospects for price reductions to the levels required are considered fairly probable.

3. SYSTEM DESIGN IMPLICATIONS

For situations where a small amount of reliable power is desired, and for basic economic conditions similar to those used in this study, a photovoltaic-hybrid system, while a better economic choice than a diesel generator alone is not the best choice. However, considering only system economics may not be sufficient in order to best choose among energy options. Since the areas of applications of these systems are in general remote locations, non-quantifiable factors must be considered. First is the availability of fuel at the site. How reliable is the fuel source and how difficult is it to deliver the fuel to the site? Is the site difficult to access due to the terrain, lack of infrastructure or weather? Even though fuel may be relatively inexpensive, fuel availability and delivery logistics are an important consideration. Secondly, diesel systems require regular maintenance which is in direct relation to running time. How will the maintenance be performed and by whom? Are there sufficient replacement parts and trained personnel available to conduct the maintenance? While yet to be shown by accumulated experience, photovoltaic-hybrids do appear to offer some prospects for minimizing both fuel delivery and maintenance concerns.

Additionally, the issue of reliability must be considered. With an all diesel system or with a diesel coupled with a small amount of storage, electrical power can be totally lost if there is a malfunction of the diesel. With a photovoltaic-hybrid, even with a diesel failure, some power could still be supplied by the photovoltaic component, for example, for those loads viewed as most critical until repairs could be made to the diesel.

4. CONCLUSIONS

Based on computer simulations of photovoltaic-diesel-battery hybrid energy systems supplying power for a specific remote village load profile and for the specific economic and technical assumptions used in this study, the following conclusions were determined:

1. Photovoltaic-diesel-battery hybrids can produce power more cost effectively on a levelized energy cost basis than an all diesel system for a yearly demand of 6716 kWh at current photovoltaic costs and efficiencies.

2. The lowest levelized energy cost system configuration occurs for a diesel-battery system without a photovoltaic component.

3. High density (efficiency 11.4 percent) photovoltaic modules appear not to be economically advantageous over standard (efficiency 6.8 percent) modules for use in photovoltaic hybrid systems at the assumed price of $15 per watt.

4. Photovoltaic-diesel-battery hybrids will be the best economic choice for small power applications only when module prices decrease from those assumed in the study. The reductions that must occur range between 30-70 percent depending upon fuel costs and economic conditions.

5. Choice of system configuration for remote applications should consider factors typically not quantified in an economic analysis such as fuel supply uncertainty, spare parts and maintenance personnel availability, and overall system reliability.

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