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Hourly Simulations of Hybrid Renewable Energy Systems for San Cristobal/Santa Barbara, Guatemala

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HOURLY SIMULATIONS OF HYBRID RENEWABLE ENERGY SYSTEMS FOR SAN CRISTOBAL/SANTA BARBARA, GUATEMALA

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ABSTRACT

This paper presents the results of a conceptual systems analysis comparing alternative, renewable energy-based, hybrid power systems to a conventional diesel genset for a remote, non-electrified village in Guatemala. A time-series computer simulation model, HYBRID1, was used to calculate the performance of the various systems; a separate analysis was used to determine the life-cycle cost of energy for each system. Detailed hourly simulation computer models, such as HYBRID1, are necessary to properly account for the time-varying loads, renewable resources, performance of the generators, and battery state of charge, as well as accommodating alternative system architectures and control/dispatch strategies. The analysis considers several anticipated load profiles for the village, to account for the possibliiites of productive and water pumping loads in addition to the base load of household lighting and communications. For this particular site, the lowest cost of energy would be supplied by a wind-diesel-battery system, with a control strategy that operated the diesel in a backup (switched) mode.

INTRODUCTION

The neighboring Guatemalan communities of San Cristobal and Santa Barbara in the district of Comapa are considering the installation of a hybrid renewable energy system for the supply of electrical power. Diesel generators have a poor reputation in Guatemala, primarily because of low reliability; hence, it is hoped that diesel-generated power can be partially or completely replaced by power generated from a wind turbine and/or photovoltaic (PV) panels.

The purpose of this paper is to compare hybrid renewable energy systems (i.e., various combinations of wind, PV, and/or diesel power with battery storage) with conventional stand-alone diesel systems using the results of HYBRID1/Version 1.11 (Refs. 1-5) simulations for a Guatemalan village. The cost of energy for the different systems is compared using a standard life-cycle cost approach. HYBRID1 is a computer model that was originally developed for analyzing wind/diesel systems and was subsequently modified to include other system configurations. At present, HYBRID1 is not able to model all system configurations and dispatch strategies that may be of interest to a system designer.

The systems examined in the present study are: (i) diesel-only (DO); (ii) diesel-battery/parallel (DB/P), (iii) wind-diesel-battery/parallel (WDB/P); (iv) wind-diesel-battery/switched (WDB/S); (v) wind-PV-battery (WPVB); and (vi) wind-battery (WB). All systems deliver power to a mini-grid that distributes 120V power to households and businesses in the community.

Estimates of the absolute magnitude of the life-cycle cost of energy (COE) presented in this paper have a degree of uncertainty because of the many variables involved (e.g., operation and maintenance (O&M) costs); however, estimates of the relative costs of energy of the different alternatives are more certain and may be used to evaluate system alternatives. Although the HYBRID1 simulations were used to determine which energy system is the most cost-effective, comparing systems purely on the basis of life-cycle cost neglects many other important factors not focused on in this paper, such as level of service and adaptability to load growth.

VILLAGE DESCRIPTION

The neighboring communities of Santa Barbara and San Cristobal are typical of remote villages in Guatemala. Extension of power lines to this area would be extremely expensive because of the long distance to the utility grid, and is not considered. There are approximately 50 serviceable buildings between the two villages, mostly houses, one school, several stores, and a community meeting center. In general, the houses are tucked into protected pockets that are sheltered by trees and the surrounding terrain. There are a few exposed locations including a ridge that nearly divides the population in half. The initial estimate was that electricity use would average about 10 kWh per household per month. Uses are basic lighting and entertainment (i.e., TV and radio) and some limited refrigeration. Although there is little potential for large productive use of electricity in the near term, it is expected that productive uses will emerge after the power system is installed.

MODEL INPUTS

The following sections describe the inputs that were used in the HYBRID1 simulations. Because of the large number of inputs required by HYBRID1, not all inputs are discussed.

Load Profiles

Six different load profiles were developed for the present study. These profiles were orginally based on the 10 kWh per household per month estimate, and the expectation that the load is primarily due to lighting and will, consequently, occur in the early morning and evenings. This results in an average village load of 16 kWh per day. Because of the expectation of immediate load growth after system installation, this load was never actually used in any of the simulations; instead, the load was doubled in magnitude and called load A. Load A peaks at about 9.5 kW and consumes an average of 32 kWh per day. The second load used in the simulations, load A1, simply adds a baseload of 1 kW to load A. This baseload results from a limited refrigeration need in the villages. Load A1 consumes an average of 50 kWh daily. The average daily profiles for loads A and A1 are shown in Figure 1 below.

The next two loads, B and B1, add productive daytime uses to loads A and A1, respectively. The productive uses occur between the hours of 11:00 am and 7:00 pm at a constant level of 6 kW. The evening uses in load B are identical to those in load A. Just as with load A, load B1 is simply load B plus the 1 kW baseload. The average daily energy consumed by loads B and B1 is 79 and 91 kWh/day, respectively. Loads B and B1 are shown in Figure 2.

The final two loads, A1d and B1d, are the same as loads A1 and B1 except that a deferrable water pumping load has been added. The deferrable load is the same in both cases. It is based on pumping 5,000 gallons of water per day, overcoming a 164 foot (50 m) net head. The water pump is assumed to have a constant efficiency of 35% and a rated power of 1 kW. The energy required every day to meet these pumping requirements is 7.4 kWh. Because of the rated power of 1 kW, the pump must operate at least 7.4 hours a day to meet this load.

Wind and Solar Resource Data

Hourly wind speed data from Copalapa, Guatemala, were used in the simulations. Wind data were obtained for the time period beginning in January 1993 and ending January 1994. The average wind speed for the entire year was 14.5 mph (6.5 m/s). Significant seasonal variations are evident. The lowest winds occurred in May and June. The average wind speed for that period was 8.2 mph (3.7 m/s). The data most closely resemble a k = 2.0 Weibull distribution, which is reasonable for the location under study.

Solar data from the vicinity of San Cristobal and Santa Barbara were used in the simulations. Because only 1 month of data was available, the year of data was composed of 12 identical months. The solar data reflect the 4.0 kWh/m^2 average daily insolation for this area.

Battery Bank

The battery bank was configured from 6 V, flooded, deep-cycle lead-acid batteries. Because a 120-V system was desired, the battery bank capacity grew in units of 20 batteries in series. Capacity (amp-hours) versus current (amps) data are input into a HYBRID1 preprocessor, known as the Kinetic Battery model (Refs. 6 and 7), and the data are fitted to a non-linear curve.

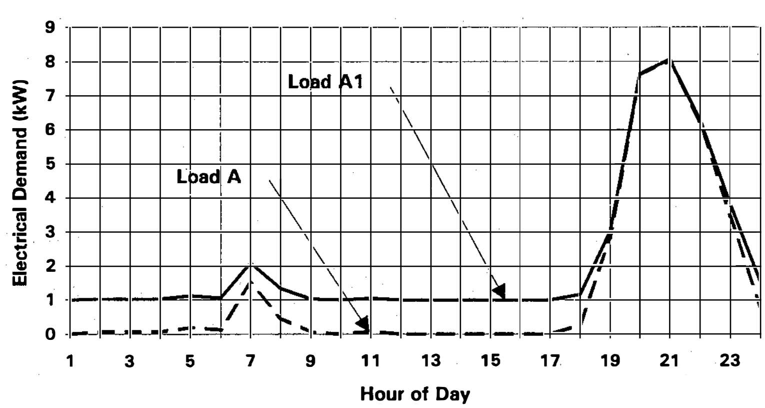

FIGURE 1. AVERAGE DAILY PROFILES OF LOADS A AND A1

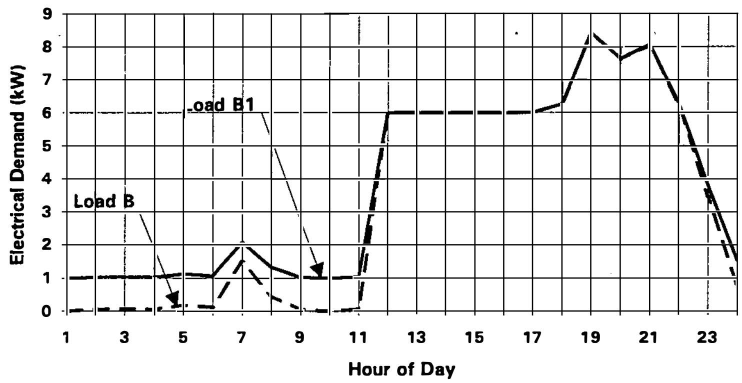

FIGURE 2. AVERAGE DAILY PROFILES OF LOADS B AND B1

Because detailed battery voltage data were not available, approximate voltage characteristics were input into HYBRID1. The internal voltage (open circuit) was assumed to vary from 6 V (full) to 5.5 V (lowest allowable). By combining this voltage drop with the current-capacity data and the internal resistance voltage drop, approximate voltage characteristics were generated for the batteries. The C/8 discharge capacity (300 Ah per 6 V battery) was used to size the battery bank. For the systems described in this report, the battery storage capacity varied from about 1 to 6 load-days.

Wind Turbine Power Curve

The wind turbine power curves used in the simulations are similar to those of commercially available, variable-speed small wind turbines. For both the 10 and 1.5 kW rated wind turbines, the cut-in, rated, and cut-out wind speeds were assumed to be 7 mph (3.1 m/s), 29 mph (13 m/s), and 34 mph (15.2 m/s), respectively.

Diesel Generator

A 10 kW diesel generator was used as the prototype for all simulations. The performance parameters for this diesel generator are given in Table 1 below. For simplicity, the cases requiring a 5 kW diesel genset used the same specifications as in Table 1, multiplied by a factor of 0.5.

TABLE 1. DIESEL GENERATOR PERFORMANCE PARAMETERS

Rated Power of Diesel	10 kW
Minimum Allowed Diesel Power	1 kW
Rated Fuel Consumption	1.05 gal/hr
No-Load Fuel Consumption	0.35 gal/hr

System Configuration and Power-Conditioning Losses

One of the main limitations in using HYBRID1 is the system configuration. The system modeled by HYBRID1 is centered around an AC bus in which the load can be met simultaneously by the wind turbine generator (WTG) and the diesel genset. (This is typical of large wind-diesel systems.) However, the systems examined in this paper were not of this type. For the systems analyzed in this paper, the load can only be met by the inverter and diesel genset, as shown in Figure 3. The WTG either charges the battery or, if the battery bank is nearly 100% charged, it can meet the load directly via the inverter. The same applies to the PV panels. The diesel can charge the battery only if the inverter is capable of parallel operation. Currently, only a few of these inverters are commercially available. These configuration differences made it difficult to exactly model the losses from the power-conditioning equipment (i.e., the inverter, rectifier, and battery charger) with HYBRID1. However, losses were modeled as best as possible by altering some of the component efficiencies, so as to compensate for the inaccuracy in the system configuration being modeled. Although this introduces a margin of error into the calculations, it was estimated to be within the uncertainty of the *relative* COE comparisons.

ECONOMIC ANALYSIS

A spreadsheet analysis was used to calculate the life-cycle costs. This analysis accounts for the lump-sum capital costs and the variable operating costs of each system. Capital costs are covered in the following section. The assumed O&M costs for the diesel generator and wind turbine are summarized in Table 2. These values compare favorably with those found in other sources (Ref. 8). The assumed financial parameter values are summarized in Table 3. Bank loans are not considered because of the uncertainties involved and, consequently, all systems are assumed to be paid off in the first year of operation.

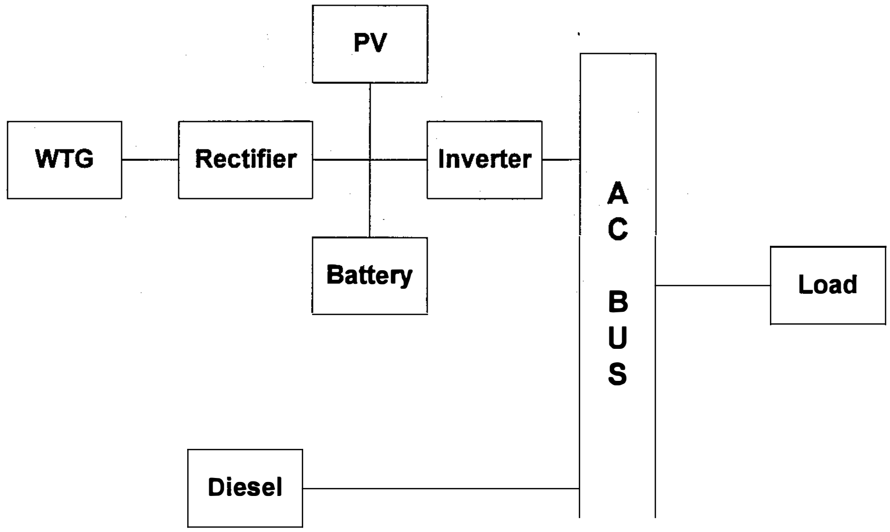

FIGURE 3. SYSTEM CONFIGURATION

The price of diesel fuel used was $1.75 per gallon. The dumped power was given no value. The battery banks were assumed to need replacement every 5 years. (The battery life routine in HYBRID1 was not used because of the lack of suitable data.)

TABLE 2. O&M COSTS AND PARAMETERS

Description	Diesel Generator	Wind Turbine
Overhaul Cost	$350/kW	$100/kW
Overhaul Period	10,000 hours of operation	7.5 years
O&M Rate	$0.05/kWh	$0.02/kWh

TABLE 3. FINANCIAL PARAMETERS

Description	Value
General Inflation Rate	5%
Fuel Annual Inflation Rate	6%
Discount Rate	4%
System Economic Life	15 years

SYSTEM DESCRIPTIONS AND COSTS

In order to simplify the presentation of the costs for the different systems analyzed, all capital costs are given in terms of a unit cost per kW; costs for a given system can be calculated by multiplying the unit cost by the capacity (i.e., kilowatts) of the different components of a system. (For example, to estimate costs for a 10 kW diesel system, multiply the unit costs for the system components, a diesel and balance of diesel costs, by ten and then add them together.) Table 4 shows the unit costs for the different equipment used in the various systems. Because of the variation in cost with size, different unit costs are given for the different size wind turbines and towers. The battery costs are the only costs not given on a per kW basis; they are given on a per battery basis. The alternative systems analyzed, together with their system costs, are described below.

Diesel-Only System

The diesel-only (DO) system is the standard by which all renewable energy systems are compared when considering installations in developing countries. The system is very simple, consisting only of a diesel genset, the control equipment, a housing, and the fuel tank. The cost for a 10 kW diesel system, based on the costs given in Table 4, is $15,500.

The only appropriate loads (of the ones described previously) for a 10 kW DO system are A and B. Loads Aland B1, which have a baseload of 1 kW, are not appropriate, because diesels are not typically run at 10% capacity because of wear on the diesel and poor fuel efficiency at such low loads. Loads A and B require that the diesel be started once or twice a day, run for a few hours, and then be shut off. For the remainder of the day, the village is without power. One of the advantages of renewable energy systems is that they can provide power 24 hours a day. This is an important consideration when refrigeration loads are present.

TABLE 4. UNIT COSTS FOR SYSTEM COMPONENTS

Description	Unit Cost ($/kW)
Diesel Generator	650
Balance of Diesel Costs for Diesel System (structure, construction, misc. electrical, shipping, training, and fuel tank)	900
Stand-Alone Inverter	750
Paralleling Inverter	2,400
1.5 kW Wind Turbine w/ Controller	2,860
Tilt-Up Lattice Tower for **1.5 kW** Turbine (includes raising kit, jack stand, and wiring)	1,750
10 kW Wind Turbine w/ Controller	1,600
Tilt-Up Lattice Tower for **10 kW** Turbine (includes raising kit, jack stand, and wiring)	1,042
Balance of Wind Turbine Costs (installation, misc. electrical, shipping, and training)	660
Photovoltaic Array (MPPT included)	6,500
Deep-Cycle Batteries **(Cost given is for each 6 V battery)**	150

Diesel-Battery/Parallel System

The diesel-battery/parallel (DB/P) systems consist of a 5 kW diesel generator and associated balance-of-system (BOS) requirements, a 5 kW paralleling inverter, and forty or eighty 1.8 kWh batteries. This system takes advantage of the capability that some new inverters can be switched onto the AC bus simultaneously with the diesel generator, allowing the inverter to augment the diesel power or the diesel to charge the battery bank. One of the most important advantages of this inverter is that the diesel size can be reduced, which can have the favorable side effect of increased diesel efficiency. On the downside, the inefficiencies of the battery storage may offset the efficiency gains on the diesel side. From an economic viewpoint, the additional cost of the paralleling inverter far exceeds the savings from going to a smaller diesel genset. The cost of the batteries (which have to be replaced every few years) also contributes to a higher capital cost. The capital cost of the DB/P system with 40 batteries is $25,750, and with 80 batteries is $31,750.

The operating strategy for this system, as modeled by HYBRID1, can be explained in the following four rules: (1) the diesel runs whenever there is a load; (2) the inverter augments the diesel when the load increases above 5 kW and there is sufficient battery power available; (3) the diesel generator must run for at least 4 hours after each start and, during this time, if there is no load, the diesel runs at minimum power (i.e., 0.5 kW); and (4) when the battery charge decreases below 35% of the maximum (i.e., $Q <= 0.35*Qmax$) the diesel runs at rated power until the battery bank is charged to $0.95*Qmax$, and during that time the inverter is not used.

Wind-Diesel-Battery/Parallel System

The wind-diesel-battery/parallel (WDB/P) system is the same as the previously described system, except that a 1.5 kW wind turbine is added for more battery charging. The estimated cost of this system with 40 batteries is $33,325, and with 80 batteries is $39,325. The operating strategy is exactly the same as the DB/P system except for the following: (1) the wind power reduces the load and if there is excess the batteries are charged provided that they are not already fully charged; and (2) the minimum diesel run time is 2 hours.

Wind-Diesel-Battery/Switched System

The wind-diesel-battery/switched (WDB/S) system is a very important one because it has been used in a number of remote locations where power is needed. This system uses an inverter that cannot meet the load simultaneously with the diesel generator, but can run alone (also referred to as stand-alone operation). Therefore, a switching mechanism is necessary to ensure that the inverter and diesel generator are not switched onto the load simultaneously. Although this system requires a reserve diesel that can meet the peak load, the inverter is much less costly than the one for the parallel systems. The WDB/S systems considered for this study consist of a 10 kW wind turbine, tower, and BOS, a 10 kW stand-alone inverter, a 10 kW diesel system (including BOS), and either forty or eighty 1.8 kWh batteries. The capital costs for these systems are $59,800 and $65,800, repectively.

The operating strategy that was modeled for this system adheres to the following set of rules: (1) the wind power meets the load first and then charges the batteries if there is excess; (2) the inverter meets the remainder of the load whenever there is enough battery power; (3) if the load cannot be met by the inverter then the diesel meets the load; and (4) when the battery charge decreases below 35% of the maximum the diesel runs at rated power until the battery bank is charged to 95% of maximum capacity, and during that time the inverter is not used.

Wind-PV-Battery System

The wind-PV-battery (WPVB) system consists of a 10 kW wind turbine, tower, and BOS, a 10 kW stand-alone inverter, a 6 kW PV array, and 160 1.8 kWh batteries. This is an important system to consider for villages in developing countries because reliance on diesel engines is completely eliminated. Fuel does not have to be transported and diesel maintenance is not needed. However, this system is expensive, having an initial cost of $101,300.

The operating strategy for this system is very straightforward because there are no diesels involved. All solar and wind energy is first used to meet the load, then to charge the batteries, and, if the batteries are fully charged, the excess is dumped.

Wind-Battery System

The wind-battery (WB) system consists of two 10 kW wind turbines, two towers, and two BOS, a 10 kW stand-alone inverter, and 160 1.8 kWh batteries. The total cost of this system was estimated to be $93,100. Because the wind resource is good (i.e., average annual wind speed of 6.5 m/s) and the solar resource is marginal (i.e., 4 kWh/m^2 per day), the chance that a WB system would be more cost-effective than a PV-battery system seemed likely. However, while these systems will initially be cheaper than the PV-battery system, it should be remembered that battery charging by wind will cause fluctuations in charging current that will lead to higher I^2R losses than the smoother PV charging. The operating strategy is the same as that described for the WPVB system.

SIMULATION RESULTS

Twelve cases were simulated with HYBRID1. Each simulation was run for 6696 consecutive hours, which served as the basis for the 1-year performance estimates. In the life-cycle cost analysis, each year's performance is assumed to be identical in the 15-year economic lives of the systems. For the systems that were primarily diesel systems (i.e., DO, DB/P, WDB/P), only loads A and B were applicable. For the renewable energy systems (i.e., WDB/S, WPVB and WB), the 24-hour and deferrable loads were applicable (i.e., loads A1, B1, A1d, and B1d).

The HYBRID1 results are summarized in Table 5 at the end of this report. Each case is identified by the system type abbreviation followed by a hyphen and the load designation. The economic results are summarized in Figure 4 (also at the end of the report). Each case is divided into the incremental COE due to (1) the capital cost, (2) the diesel operation costs, and (3) all other operation costs. COE is defined as the present value of all fixed and variable costs divided by the total useful energy produced in the 15 years of operation. The units for COE are in 1994 dollars per kWh.

The hybrid diesel systems (DB/P and WDB/P) did achieve somewhat higher diesel fuel efficiencies than the DO system. However, the higher capital and nondiesel operating costs for these systems resulted in higher COEs than for the DO systems. The WDB/S system, on the other hand, benefitted from significantly reduced diesel operating costs. Consequently, the COE for this system is as much as $0.08/kWh less than that for the DO system. While completely eliminating the diesel costs, the stand-alone renewable energy systems (WPVB and WB) suffer from extremely high capital costs. The COEs for these systems are as much as $0.17/kWh higher than those for the DO systems.

Some of the simulations showed that the modeled systems could not meet the load a significant fraction of the time (sometimes as much as 16% of the load could not be met). Despite this fact, the level of service of the hybrid systems is still superior to that of the DO systems.

CONCLUSIONS

This study demonstrated the comparative analysis of some of the current renewable energy-based, hybrid systems for providing power to remote villages. While the base case was a diesel genset using nominal costs for Guatemalan diesel fuel, further analysis is required to incorporate the actual economic costs of operating and maintaining diesels in remote villages.

Of the systems and operational strategies studied, the least cost option for this site and load profile is the WDB/S option, providing water pumping as a deferrable load. For small systems, on the order of 5 to 10 kW peak power, parallel operating strategies and system architectures are less cost-effective; these systems seem to be better suited, economically, for meeting larger loads. It is important to analyze alternative load profiles so that the potential system user/investor can evaluate future economic development possiblilites (i.e., productive uses of electricity) and their impact on system architecture and control strategy.

The study demonstrated the value of using a simulation that accounts for all the key system variations, the alternative control/dispatch strategies, the load profiles, the resource information, and the economic parameters. This project highlighted a number of operational shortcomings in the current version of HYBRID1 that will be rectified in HYBRID2.

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TABLE 5. SUMMARY OF PERFORMANCE RESULTS

#	Case ID	Total Useful Energy Prod. (kWh)	Load Not Met (kWh)	Diesel Fuel Use (gallons)	Diesel Runtime (hours)	Diesel Energy Production (kWh)	Wind Turbine Energy Prod. (kWh)	Diesel Efficiency (kWh/gal)
1	DO-A	11,606	6	1,516	2,013	11,606	0	7.656
2	DO-B	28,969	14	3,637	4,604	28,969	0	7.965
3	DB/P-A	11,239	373	1,426	3,383	11,912	0	8.353
4	DB/P-B	26,503	2,480	2,983	6,041	27,505	0	9.221
5	WDB/P-A	11,333	279	1,142	2,568	9,898	2,348	8.667
6	WDB/P-B	27,254	1,729	2,792	5,553	25,996	2,348	9.311
7	WDB/S-A1d	21,047	0	1,047	997	9,966	15,656	9.519
8	WDB/S-B1d	35,828	0	2,467	2,350	23,497	15,656	9.525
9	WPVB-A1	16,491	1,868	0	0	0	15,656	n/a
10	WPVB-A1d	17,861	3,186	0	0	0	15,656	n/a
11	WB-A1	16,115	2,244	0	0	0	31,313	n/a
12	WB-A1d	17,699	3,348	0	0	0	31,313	n/a

Nomenclature: DO - diesel only; DB/P-A - diesel-battery/parallel system; WDB/P - wind-diesel-battery/parallel system; WPVB - wind-PV-battery system; WB - Wind-battery system; A and A1 - load A (no base load) and A1 (base load) - both do not include productive uses; B and B1 - load B (no base load) and load B1 (base load) - both include productive uses.

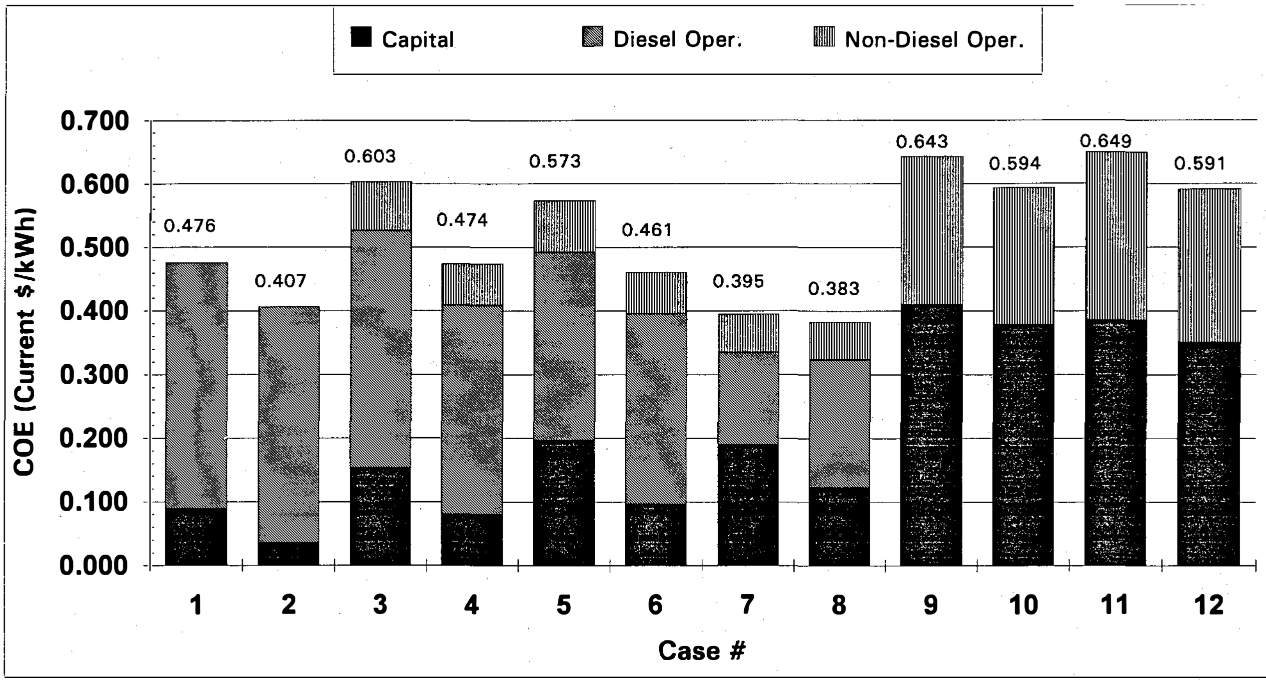

FIGURE 4. SUMMARY OF ECONOMIC RESULTS