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FEASIBILITY OF HYBRID RETROFITS TO OFF-GRID DIESEL POWER PLANTS IN THE PHILIPPINES[1]

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Introduction

The Strategic Power Utilities Group (SPUG) of the National Power Corporation (NPC) in the Philippines owns and operates about 100 power plants, mostly fueled by diesel, ranging in energy production from about 15 kilowatt-hours (kWh)/day to 106,000 kWh/day. Reducing the consumption of diesel fuel in these plants, along with the associated financial losses, is a priority for SPUG. The purpose of this study is to estimate the potential fuel and cost savings that might be achieved by retrofitting hybrid power systems to these existing diesel plants. As used in this report, the term "hybrid system" refers to any combination of wind turbine generators (WTGs), photovoltaic (PV) modules, lead-acid batteries, and an AC/DC power converter (either an electronic inverter or a rotary converter), in addition to the existing diesel gensets.

The resources available for this study did not permit a detailed design analysis for each of the plants. Instead, the following five-step process was used:

1. Tabulate some important characteristics of all the plants.
2. Group the plants into categories (six classes) with similar characteristics.
3. For each class of system, identify one plant that is representative of the class.
4. For each representative plant, perform a moderately detailed prefeasibility analysis of design options.
5. Summarize and interpret the results.

The analysis of each representative plant involved the use of time-series computer simulation models to estimate the fuel usage, maintenance expenses, and cash flow resulting from various designs, and to search the domain of possible designs for the one leading to the lowest life-cycle cost. Cost items that would be unaffected by the retrofit, such as operator salaries and the capital cost of existing equipment, were not included in the analysis. Thus, the results are reported as levelized cost of energy (COE) *savings*: the difference between the cost of the existing diesel-only system and that of an optimized hybrid system, expressed in units of U.S. dollars per kWh (US$/kWh) of energy production.

This analysis is one phase of a study entitled "Analysis of Renewable Energy Retrofit Options to Existing Diesel Mini-Grids," funded by the Asia-Pacific Economic Cooperation (APEC) and the U.S. Department of Energy (DOE), and performed jointly by NPC, the U.S. National Renewable Energy Laboratory (NREL), and Sustainable Energy Solutions in New York, New York (Morris et al. 1998). A more detailed version of this paper is included in that report.

[1] Condensed from a longer version in Morris et al. (1998).

[2] Currently an independent consultant in Boulder, Colorado.

Features of Existing Systems

In order to get an overview of the existing plants, certain features of all the plants were tabulated. These features include:

- Hours per day of electrical service provided by the plant
- Average energy production in kWh/day
- Delivered fuel price at the plant, in Philippine pesos (PHP) per liter (1997 average prices)
- Use of a dump load to preclude the operation of the diesel generators at a loading of less than 40% of rated power.

Loads. The distribution of plant operating hours is shown in Figure 1. 43% of the plants provide 6-hour service, 36% provide 24-hour service, and 21% provide a variety of other service periods. Based on this distribution, 6-hour and 24-hour service are identified as the most significant groupings in terms of number of plants.

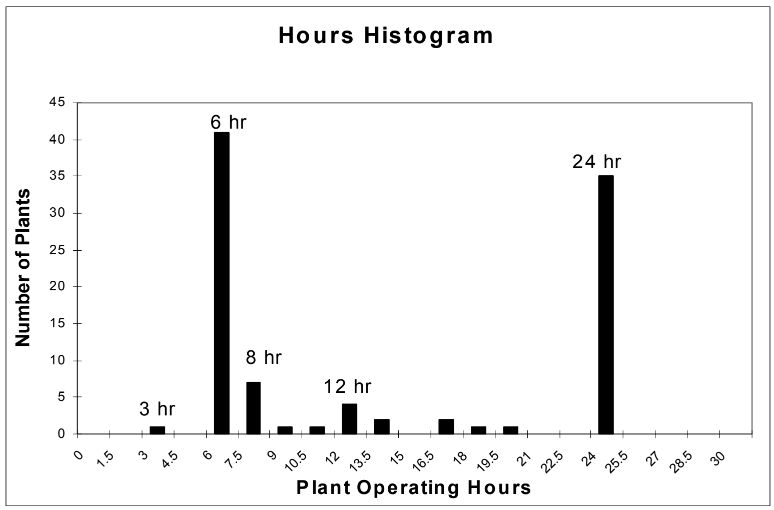

Figure 1. Distribution of plant operating hours

To gain further perspective on the loads, the daily energy production of the various plants was correlated to the hours of service. All of the 24-hour plants are grouped as Classes 1 through 4, depending on the daily energy production. Most of the 6-hour plants produce less than 500 kWh/day; these are grouped as Classes 5 and 6 according to whether or not a dump load is used. In the Class 6 systems, a dump load is used to prevent diesels from operating at less than 40% of their rated power; such low-load operation increases maintenance requirements. In the Class 5 systems, diesels may be permitted to operate at less than 40% of rated power; the increased maintenance costs resulting from this practice are not known and therefore are not included in this study. A summary of the six load classes identified in this manner is shown in Table 1. For each class, a representative example of a plant belonging to that class is also identified. These are the plants that were analyzed. The daily load profiles at these six representative plants are shown in Figures 2 and 3. These profiles are assumed to be constant throughout the year. (Significant seasonal variations in the load are not expected in this tropical climate.) Of the 99 plants owned by SPUG, 69 are encompassed by these six classes. The analysis of the six classes leads to some general conclusions that shed light on the other plants as well.

Table 1. Summary of Load Classes

Class	Service Hours	Daily kWh	Average Load, kW	Number of Plants	Example Plant
1	24	> 20,000	> 800	11	Tablas
2	24	10,000-20,000	400-800	10	Romblon
3	24	5,000-10,000	200-400	6	Cuyo
4	24	< 5,000	< 200	9	Kabugao
5	6 (No dump load)	< 500	< 80	21	Palanan
6	6 (Dump load)	< 500	< 80	12	Cagancillo
			Subtotal	69	
			Other	30	
			TOTAL	99	

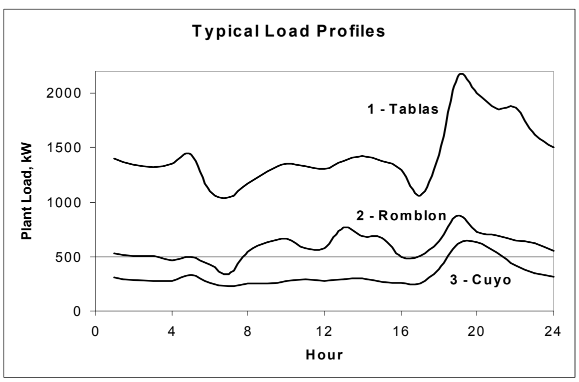

Figure 2. Load profiles for Class 1, 2, 3

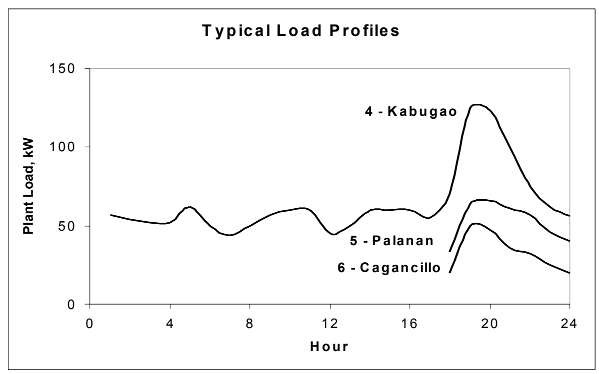

Figure 3. Load profiles for Class 4, 5, 6

Fuel Prices. The distribution of the delivered fuel prices at all the SPUG plants is shown in Figure 4, based on averages for the year 1997. Two significant groupings in the distribution are the range 4.0-8.5 PHP/L, with an average value of 6.5 PHP/L, and the range 8.5-12.0 PHP/L, with an average value of 9.9 PHP/L. At the 1997 average exchange rate of 29.5 PHP/US$, the average values of these two groupings are equivalent to US$0.22/L and US$0.34/L, respectively. One approach to the analysis would be to include the fuel price in the grouping of the plants into classes. However, it is believed that the fuel prices will

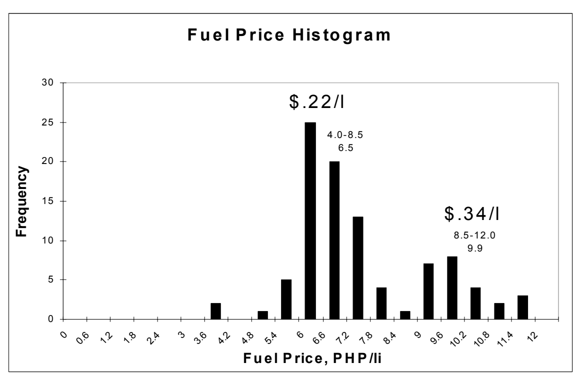

Figure 4. Distribution of delivered fuel prices at SPUG power plants

fluctuate in future years due to fluctuations in the world market price of fuel, the removal or reduction of subsidies affecting the fuel price incurred by NPC, privatization, and other factors. So that the results may be reinterpreted as fuel prices change, the fuel price is treated as a variable in the analysis. Values of US$0.22/L and US$0.34/L are used to represent the two main groupings in the distribution, as well as US$0.46/L to represent the possibility of increased fuel prices in future years. There is a trend that the largest plants have low fuel prices; however, fuel prices of about US$.30/L or more are seen at some plants producing as much as 20,000 kWh/day.

Resource Assessment

Wind. The role of wind turbines in an optimized hybrid design depends heavily on the wind resource in the vicinity of plant site. A wind atlas of the Philippines was recently completed at NREL (Elliott et al., in progress). However, at the time of this study, these results were not yet available. Therefore, the magnitude of the wind resource is treated as a variable in this analysis, so that the results may be interpreted as more information about the wind resource becomes available. Although this approach leads to conclusions that are less specific, it has the advantage that the results may be applied to a wider range of applications.

In a previous study (Barley et al. 1998), a one-year set of hourly wind speed data was obtained from Basco, in the northernmost province of Batanes. The annual average of this data set (adjusted for the estimated long-term average) is 6.13 m/s at a height of 12 m. Although some sites in the Philippines with a greater wind resource than this have been identified, it is generally true that the wind is strongest in the north. In order to represent a reasonable range of wind speeds in the analysis, the data from Basco were scaled to annual averages of 4.5 m/s, 5.5 m/s, and 6.5 m/s. This range serves to illustrate the sensitivity of wind power cost-effectiveness to the wind speed. The power densities corresponding to these three wind speeds are 98 W/m^2, 179 W/m^2, and 295 W/m^2, respectively. The seasonal profile of the wind resource, based on this data set, is shown in Figure 5. Of course, actual weather patterns vary throughout the country; therefore, hourly data measured at actual project sites will be used in further analysis of recommended retrofit projects.

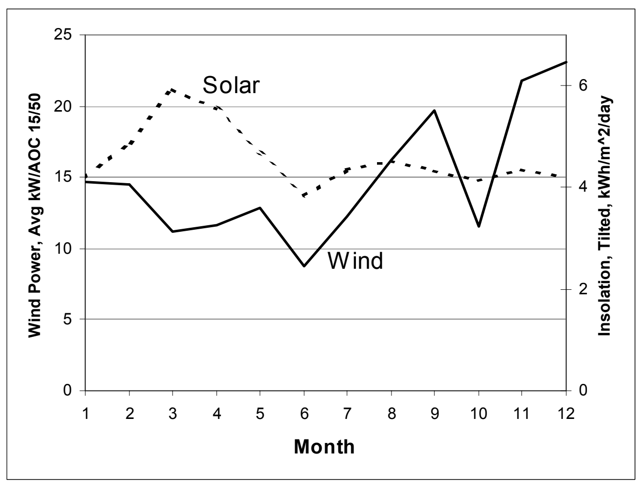

Figure 5. Seasonal profiles of the wind and solar resources

Solar. Site-specific estimates of annual average global insolation data for the Philippines were obtained from Bonjoc et al. (1985). The average value for all the sites is 4.01 kWh/m^2 /day. In addition, daily values of global insolation were obtained from the World Radiation Data Centre Web site (undated reference) for one site: Science Garden, in Manila. The long-term average of this data set is 4.50 kWh/m^2/day. For the analysis, hourly values were extrapolated from one year of daily values at Science Garden. (The most complete year of data, 1981, was scaled down from 4.86 kWh/m^2/day to the long-term average of 4.50 kWh/m^2/day.) Although Bonjoc et al. indicate some sites with a higher estimated solar resource, the value 4.50 kWh/m^2/day is above the average for all the sites. The approach in this analysis is to use a liberal estimate of the solar resource and a conservative estimate of the cost of PV modules. Then, if PV does not appear to be a cost-effective component in the optimized retrofit designs (which is in fact the result that is obtained), cases of lower resource or higher module costs are ruled out as well. If it is subsequently determined that a higher insolation or lower module cost would apply at a particular site, the analysis should be repeated for such a case.

The seasonal profile of this data set is shown in Figure 5, for comparison with the wind profile. Recalling that the seasonal load profile is assumed to be flat, the wind and solar resources are somewhat complementary. For example, the solar resource is strong during February through May, when the wind is relatively weak. However, the months of June and October are notably weak in combined resources.

Hybrid Designs

The system hardware configuration considered in this study includes wind turbines, batteries, and a rotary power converter, in addition to the existing diesels. Photovoltaics is also considered, although none of the optimized designs includes a PV component. A dump load component is used to stabilize the AC wind turbines. The rotary converter component, with higher available capacities, is replaced with an electronic inverter, with a higher conversion efficiency, in the smaller systems. The rotary converters are also less expensive per volt-ampere of capacity in the size range of the larger systems. In all cases, the wind turbines are connected to the AC bus, and all diesels are permitted to shut off when the power from other sources is adequate to meet the load. When the diesels are off, the reactive power requirements (volt-amperes reactive, or VARs) of the wind turbines and the village load are met by the power conversion device (inverter or rotary converter). The inclusion of a PV array and of batteries are options in the optimization procedure, except in the 6-hour plants (Classes 5 and 6), where the use of batteries is assumed. This type of hybrid system — AC wind turbines, with shutoff of all diesels allowed — is a relatively new technology with little field experience. In fact, some of the designs indicated in this analysis feature larger wind turbines than have previously been used in this configuration. Therefore, adequate technical support for such a venture would be especially important, and a recommended approach would be a turn-key installation by an experienced system integrator. Experience with this type of system will be gained in Wales, Alaska (Drouilhet, undated reference).

Component Costs

Installed costs of the various components featured in the hybrid designs are estimated as shown in Table 2. The installed cost of the large wind turbines is difficult to estimate because of the requirement of a crane for installation and the difficulty of moving a crane to the various Philippine islands and hilltop sites. In order to indicate the sensitivity of the results to this cost item, two different cost estimates were used, identified in Table 2 and in the results as sub-cases A and B. For a more accurate analysis in the design stage, this cost should be ascertained more definitively. A commercial installer of PV systems in the Philippines has estimated the installed cost of a PV array as about US$7.00/watt. Allowing for some economy of scale in a larger system, this cost is estimated as US$6.00/watt in this analysis. Battery life was computed on a case-by-case basis within the models, which are discussed below.

The hybrid system architectures assumed in this study feature wind turbines connected to the AC power bus and diesel gensets which may be shut off. In order to maintain a constant electrical frequency in such a system, a dump load is used. The dump load dissipates any power in excess of the load to avoid an increase in wind turbine speed and electrical frequency, and it is controlled using high-speed switching to maintain a stable frequency as the wind speed and the load vary. Such a dump load may have economic value, as in water heating, water pumping, or ice making. However, in order to vary the dump load quickly enough and in small enough increments to maintain a steady frequency, the use of a dump load component, featuring a bank of successively larger resistors (for at least a portion of the power dissipation) is assumed. The cost of this component, with associated controls, is assumed to be US$200/kW (Drouilhet 1998). The size of the dump load component is taken as the rated power of one wind turbine (or two wind turbines, in Class 3), under the assumption that any additional excess power could be utilized in a productive load or eliminated by shutting down some of the wind turbines.

The cost of existing diesel equipment is not included this analysis, because it would not be altered by a hybrid retrofit. However, the addition of more sophisticated diesel controls would be required, to enable automatic starting and stopping, synchronization, and load sharing in a hybrid system. The cost of these controls is assumed to be US$15,000 per diesel genset (Drouilhet 1998). In addition, combined maintenance and overhaul costs are estimated as US$7.00/run-hour for each diesel genset. This estimate is based in part on NPC maintenance records. It may be somewhat unrealistic to apply a maintenance cost that does not depend on the size of the machine. Thus, a more detailed accounting of maintenance costs should be performed in a subsequent analysis of recommended retrofit projects.

Table 2. Component Costs Assumed in the Analysis

Component	Model	Assumed Price	Comment
WTG	Bergey Excel	$24,000 ea.	10 kW, w/ 24-m tower, + 5% Inst.; Maint. 10%/10 yr
WTG	AOC 15/50	$75,000 ea.	50 kW, w/ 25-m tower, + 5% Inst.; Maint. 10%/10 yr
WTG	Zond Z40FS (A)	$600,000 ea.	550 kW, w/ 40m tower, installed; Maint. $50,000/10 yr
WTG	Zond Z40FS (B)	$825,000 ea.	550 kW, w/ 40m tower, installed; Maint. $50,000/10 yr
PV	Generic	$6,000/kW	
Battery	Trojan L-16	$110 ea.	+ 5% Inst., Maint. 5%/yr
Diesel controls	Generic	$15,000/dsl	
Dump load	Generic	$200/kW	with controls
Electronic inverter	~ AES	$1,000/kVA	+ 5% installation
Synchronous condenser	Small, generic	$100/kVAR	< 200 kVAR
Synchronous condenser	Large, generic	$60/kVAR	> 200 kVAR
Rotary converter	Generic	$20,000 + $200/kW	added to synchronous condenser cost

Financial Parameters

According to a SPUG economist, low-interest loans at an annual rate of 2.7% may be available for projects such as these. However, this analysis of least-cost designs is based on the standard interest rate of 15% for SPUG projects, so that the resulting designs will be most conducive to replication. It is assumed that income tax deductions do not apply to any of the expenses. Additional financial parameters are listed in Table 3.

Table 3. Financial Parameters Used in the Analysis

Parameter	Value
Annual discount rate	.12
General inflation rate	.07
Annual mortgage interest rate	.15
Period of mortgage, yr	20
Period of economic analysis = System life, yr	20
Annual rate of increase in fuel expense	.09
Annual rate of increase in battery replacement expense	.07
Down-payment fraction of first cost	.00
Fractional salvage value at end of equipment life	.00

Models

Two hybrid system computer models are used in this analysis. Both models are time-series simulation programs that were developed at NREL. HOMER (Hybrid Optimization Model for Electric Renewables) (Lilienthal 1995)[3] is simplified to run quickly, facilitating iterative computations to search the range of possible designs for the one leading to the lowest life-cycle cost. Hybrid2 (Baring-Gould et al. 1996) is a more sophisticated model which is used to verify the HOMER results and more accurately determine the fuel usage, maintenance requirements, and cash flow associated with the recommended design. In this analysis, both models are run for a period of one year using a one-hour time step.

Results

Results for Classes 1-4. The results of the analysis for Classes 1-4 are summarized in Figure 6. (Curve markings correspond to the system classes listed in Table 1.) The curves in this graph are based on visual interpolations and extrapolations of more detailed results, which are not included here due to the space limitation (Morris et al. 1998). For these 24-hour power plants, it is shown that hybrid retrofits could save both fuel and money, relative to the existing diesel-only systems, at wind speeds of about 5.5 m/s and higher and fuel prices above about US$0.20/L to US$0.25/L. For the cases studied, cost savings as high as about US$0.12/kWh and fuel savings as high as about 65% are predicted. Also, the amount of battery capacity recommended for the least-cost designs tends to increase as the size of the plant decreases and as the wind speed and fuel price increase. Some of the designs feature no storage component. Because the

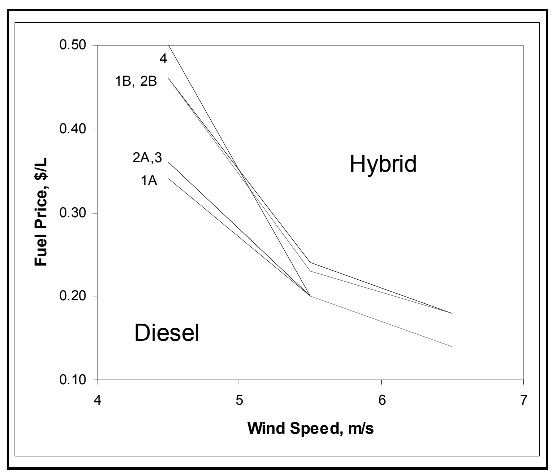

Figure 6. Approximate conditions needed for wind/diesel retrofit feasibility with 24 hour/day operation

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[3]Significant revisions of the HOMER model are not yet reported in the literature.

latter is less well-proven than the simpler wind/diesel technology, especially for the larger systems, a more detailed subsequent analysis of recommended designs should include a consideration of the trade-off between economics and simplicity for systems with and without energy storage.

In the example Class 4 system that was analyzed, adding one smaller diesel genset to the existing array has the effect of reducing the COE by about US$.04/kWh to US$.06/kWh in a diesel-only system, depending on the fuel price. This modified diesel array serves as the base case against which the hybrid designs are evaluated.

Results for Classes 5 and 6. For the 6-hour plants (Classes 5 and 6), the analysis indicates that hybrid retrofits are not cost-effective over the same ranges of wind speed and fuel cost. However, in each case, the addition of one smaller diesel genset yields considerable cost savings.

For Class 5. Adding a 90-kW diesel genset reduces the COE by:

Fuel Price US$/L	COE Savings US$/kWh
0.22	0.032
0.34	0.050
0.46	0.068

(Existing maintenance costs incurred due to running diesels below 40% of rated power are unknown, and thus are not included in these results.)

For Class 6. Adding a 70-kW diesel genset reduces the COE by:

Fuel Price US$/L	COE Savings US$/kWh
0.22	0.093
0.34	0.144
0.46	0.195

It is a general rule that hybrid retrofits are less likely to be economical in part-day diesel systems than in 24-hour systems, because:

- For the same average load, more of the energy from renewable sources needs to be stored. A larger power converter is needed to meet peak load. More energy is lost in power conversion and energy storage. The cycle life of the batteries is exhausted more quickly.

- For the same average load, the diesel-only base case features less diesel run time, so there is less money to be saved on maintenance by shutting off diesels.

Conclusions

This analysis shows that wind retrofits to the existing isolated power plants in the Philippines are most likely to be cost-effective for the plants providing 24-hour service, for wind speeds of approximately 5.5 m/s and greater, and for fuel prices above about US$0.20 to US$0.25/L, with some trade-off between the minimum wind speed and the minimum fuel price. Photovoltaics is not likely to be cost-effective in this application for a solar resource of 4.5 kWh/m^2/day or less and an installed module cost of US$6/watt or more. COE savings for the recommended designs range from about US$0.02 to US$0.12/kWh, with associated fuel savings ranging from about 30% to 65%. In the smaller systems studied, including the 6-hour plants and the smallest class of 24-hour plants, adding a smaller diesel to the existing equipment could save between US$0.04 and US$0.20 /kWh.

The primary trade-off determining the cost-effectiveness of hybrid retrofits is the cost of the hybrid equipment vs. that of the diesel fuel and maintenance saved. Because the hybrid equipment considered in this study would be imported, and because most of the diesel fuel used by SPUG is also imported, changes in the currency exchange rate would not be expected to have much effect on these results, with the exception that the diesel maintenance costs would shift relative to the other expenses.

Deferrable loads, also known as productive dump loads (such as water heating, water pumping, and ice making) can enhance the economic advantage of a hybrid power system by utilizing the excess wind energy that is occasionally available. This possibility was not considered in this study; however, it should be included in any subsequent analyses.

One of the objectives for this work was to develop a systematic approach for evaluating options for retrofitting diesel mini-grids with hybrid renewable technologies. The five-step approach outlined on the first page, in conjunction with the tandem use of the two computer models (HOMER and Hybrid2), proved to be an efficient and effective approach to developing an overview of the retrofit opportunities. Assembling the basic information about all of the power plants in Step 1 would not have been possible without the personal contact and cooperation of a SPUG engineer (co-author Rafael Abergas). This alone took about a week of two analysts' time. More specific recommendations would result from the study if the wind resource assessment had been completed in advance.

Since the NREL wind resource mapping of the Philippines has been completed, specific candidate sites have been identified through the use of the wind maps, existing mini-grid maps, topographic maps, and aerial photography. Anemometers will be installed at those sites to collect data for a more accurate analysis.

Some of the diesel power plants treated separately in this study are actually interconnected in a grid system. Subsequent analysis will involve treating the plants collectively. This will require a determination of the power capacity and the condition of these grids. Because the results are not very sensitive to the size of the plant, grouping the plants is not expected to make much difference in the results, except in cases where the interconnected grid passes through a higher wind resource than an individual plant grid.

Because the results of this analysis are presented with wind speed and fuel price shown as variables (Figure 6), the question may arise as to whether or not the same results would apply in another country. The aspects of this study that are specific to the Philippines are:

- The assumed flat seasonal profile of the load, based on the tropical climate
- The seasonal profiles of the wind and solar resources, shown in Figure 5
- The trade wind climate (in the northern part of the country, where the wind speed data were recorded), associated with a rather consistent wind resource
- The assumed level of solar radiation: 4.5 kWh/m^2/day (Because PV was ruled out in this study, only *higher* levels than this, on the tilted array plane, would contradict the assumption.)
- The component costs, shown in Table 2
- The financial assumptions, shown in Table 3.

Acknowledgments

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