NREL/CP-440-23116 • UC Category: 1210 • DE97050809

Sizing Wind/Photovoltaic Hybrids for Households in Inner Mongolia

C. Dennis Barley
Debra J. Lew
Lawrence T. Flowers

Presented at Windpower '97
Austin, Texas
June 15-18, 1997

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Work performed under task number DO059620

June 1997

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling 423-576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Printed on paper containing at least 50% wastepaper, including 10% postconsumer waste

SIZING WIND/PHOTOVOLTAIC HYBRIDS FOR HOUSEHOLDS IN INNER MONGOLIA

C. Dennis Barley, Debra J. Lew[1], and Lawrence T. Flowers
National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, CO 80401 USA

ABSTRACT

Approximately 140,000 wind turbines currently provide electricity to about one-third of the non-grid-connected households in Inner Mongolia. However, these households often suffer from a lack of power during the low-wind summer months. This report describes an analysis of hybrid wind/photovoltaic (PV) systems for such households. The sizing of the major components is based on a subjective trade-off between the cost of the system and the percent unmet load, as determined by the Hybrid2 software in conjunction with a simplified time-series model. Actual resource data (wind speed and solar radiation) from the region are processed so as to best represent the scenarios of interest. Small wind turbines of both Chinese and U.S. manufacture are considered in the designs. The results indicate that combinations of wind and PV are more cost-effective than either one alone, and that the relative amount of PV in the design increases as the acceptable unmet load decreases and as the average wind speed decreases.

1. INTRODUCTION

There are more wind turbines installed in Inner Mongolia, China, than in any other region of the world. These 140,000 wind turbines, in conjunction with low-cost batteries, provide electricity to about one-third of the non-grid-connected households in this region. However, these households often suffer from a lack of power during the low-wind summer months. The addition of photovoltaic arrays (PV) could provide a more reliable source of rural electrification for these areas. This report details an analysis of hybrid wind/photovoltaic systems, using batteries but not using engine generators, for individual households in Inner Mongolia. The sizing of the major components – wind turbine generators (WTG), PV, and batteries – is based on a subjective trade-off between the cost of the system and the percent unmet load. Two models are used to delineate this trade-off: (1) the simplified time-series model of Barley and Winn (Barley 1996a, 1996b; Barley and Winn 1996) is used to determine designs that are approximately least-cost for various levels of unmet load; (2) the more sophisticated Hybrid2 model (Green and Manwell 1995) is then used to more accurately determine the performance (unmet load) and cost of energy in each of these designs. For these computations, actual resource data (wind speed and solar radiation) from the region are processed so as to best represent the scenarios of interest. Small wind turbines of both Chinese and U.S. manufacture are considered in the designs. The results indicate that combinations of wind and PV are more cost-effective than either one alone, and that the relative amount of PV in the design increases as the acceptable unmet load decreases and as the average wind speed decreases.

2. RESOURCE ASSESSMENT

The models used in this analysis require hourly values of wind speed and solar radiation, preferably for a period of one year, so as to capture seasonal effects, diurnal cycles, storm cycles, and stochastic variations. For this project, monthly wind speed distributions at a 10 m hub height were provided for two scenarios (tentative specifications of the wind and solar resources). The corresponding average wind speeds and best fits to a two-parameter Weibull distribution are shown in Table 1. (v_c is the wind speed normalizing factor, and k is the shape factor in the Weibull wind

---

[1] Current address: International Institute for Energy Conservation, 8 Sukhumvit Soi 49/9, Bangkok, 10110 Thailand.

speed distribution; see Eggleston and Stoddard 1987.) In addition, a set of data measured at three-hour intervals was obtained for nearby Jurh, for the years 1977-1979. In order to combine the weather *pattern* information contained in the three-hour data with the more site-specific *magnitude* information contained in the monthly distributions, the following procedure was used:

- Hourly data were generated from the three-hourly data using the method of linear interpolation between bracketing values.
- These hourly data were then scaled to match the annual average derived from the wind speed distribution for each scenario.

Table 1. Summary of Wind Speed Data, Measured at 10 m

Site	**Elevation (m)**	**Average Wind Speed (m/s)**	**v_c (m/s)**	***k***
Scenario A	900	4.9	5.2	1.7
Scenario B		3.6	3.7	1.4
Jurh, 1977	1280	6.0	~6.6	~2.2
Jurh, 1978		5.8		
Jurh, 1979		5.9		

(Note: v_c and k are parameters of the Weibull wind speed distribution; see text for reference.)

In remote areas, it is common for average measured wind speeds to decrease as a function of time (Schwartz and Elliott 1995). This may be due to lack of proper anemometer maintenance, construction of buildings near the anemometers, or the growth of trees near the anemometers. It is evident in Table 1 that the three-hour Jurh data indicate a stronger resource than do the (more site-specific) monthly data for the two scenarios. Thus the wind speeds used in these computations – 3.6 and 4.9 m/s – may be considered conservative estimates of the wind resource for the two scenarios. The seasonal profile of the wind energy produced by one WTG (model FD200) in Scenario A is shown in Figure 1.

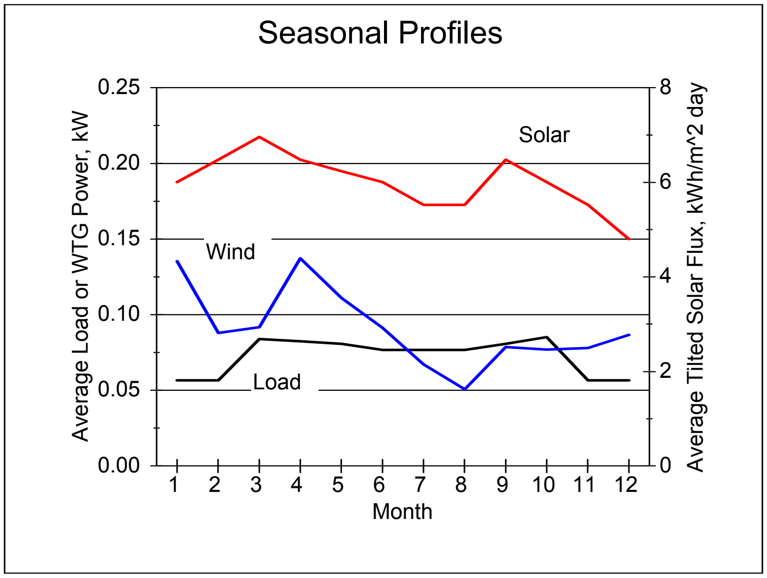

Figure 1. Seasonal profiles for the load, wind power, and solar power (Scenario A)

Solar radiation data were provided in two forms:

- Profile data: Hourly global horizontal insolation was provided for a typical day and a peak day in each month. A data set of 8760 hourly values was constructed by repeating the typical day profile for each day of each month. This method yields averages of 4.92 kWh/m^2·day on a horizontal surface and 6.54 kWh/m^2·day on the tilted surface.

- Daily data: Daily global horizontal insolation was provided for an entire year. A data set of 8760 hourly values was constructed by assuming a smooth, symmetrical profile within each day (per Duffie and Beckman, 1991, Sec. 2.13). This method yields averages of 4.61 kWh/m^2·day on a horizontal surface and 5.99 kWh/m^2·day on the tilted surface.

Of the two methods, the daily data set is selected for the computations reported in this paper. The advantages of using this data set are (1) correct total radiation for each month, (2) correct day-to-day variations, and (3) correct day-to-day correspondence of horizontal radiation with sun's seasonal position (used in conversion to the tilted surface). The disadvantage is that weather patterns within the day (such as the occurrence of cloudiness in the morning or the afternoon) are not represented. The daily data set is also the more conservative estimate of the solar resource. The seasonal profile of the monthly average solar radiation on the tilted surface is shown in Figure 1.

3. LOAD ASSESSMENT

A survey of current household loads in Inner Mongolia shows two general levels of electricity consumption: *high demand* households average 1075 kWh/yr and *low demand* households average 166 kWh/yr. In these analyses, a *medium demand* household of 633 kWh/yr is also modeled. The high demand households generally have a continuous refrigerator load and may also have washing and drying machines, while the low demand household is assumed not to include a continuous load such as a refrigerator. A household load profile was derived from a community load in Inner Mongolia of 51 households which is currently served by a wind/diesel system. We scaled this profile to 166, 633, and 1075 kWh/yr for the low, medium, and high demand households, respectively. The high and medium demand household loads were assumed to include refrigeration during the warmer months. The results presented in this paper are for the medium load of 633 kWh/yr. The hourly profile of this load is shown in Figure 2, and the seasonal profile in Figure 1. Unmet load typically occurs in the summer months of August and early September.

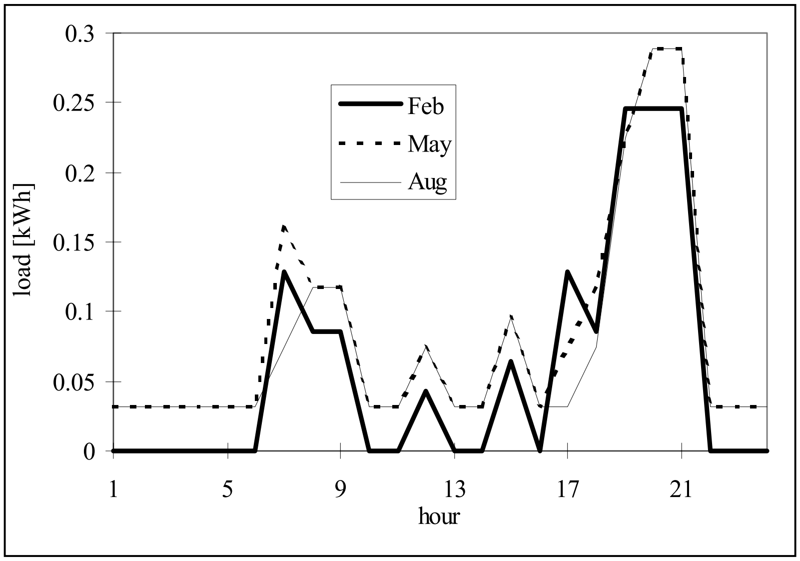

Figure 2. Household load profile used in the analysis

4. COMPONENT SPECIFICATIONS

The wind turbines modeled in this analysis include four Chinese turbines, three U.S. turbines and one German turbine. The annual output for each wind turbine in the Scenario A wind resource is listed in Table 2. The lower turbine outputs due to the lower air densities found at these altitudes are taken into account in this calculation. The most cost-effective turbines, in terms of total installed cost per annual output, are the Chinese 200 W and 2 kW turbines. The Chinese turbines tend to have low hub heights (less than 10 m) and have been designed to accommodate the low wind speeds found at these heights. Figure 3 compares the power curves, normalized to the peak power for each turbine, of the turbines listed in Table 2. The Chinese power curves tend to rise more rapidly so that power can be generated at the low wind speeds which are found at the low hub heights of 6-10 m. Results presented in this paper are for the FD200 and Air 300 models; as shown in Table 2, these are the most cost-effective models of Chinese and U.S. manufacture, respectively, in the size range that matches the household load.

Table 2. Comparison of Small Wind Turbines from China, the United States, and Germany, in Scenario A [Byrne 1996b]

Turbine	Peak Power [W]	Hub Height [m]	Rotor Diam. [m]	Annual Output [kWh]	Total Installed Cost [$]	Total Installed Cost per Annual Output [$/kWh]
China						
Shangdu Livestock Machinery Works (SLMW)						
FD1.5-100	180	5.0	1.5	460	241	0.52
FD200	290	6.0	2.5	730	362	0.50
FD300	480	7.0	2.5	860	518	0.60
FD5.6-2000	2800	8.5	5.6	7000	2891	0.41
United States						
Air 300	380	6.0	1.1	280	542	1.94
BWC 850	1050	26.0	2.4	1690	3930	2.33
BWC 1500	1700	24.0	3.0	2750	8184	2.98
German						
German Wenus 5kW	6200	12.0	6.0	8900		

(Note that the Chinese tend to rate their turbines much more conservatively than is done internationally.)

The photovoltaic modules are assumed to be of 50 watts rated power, with an installed cost of $321.50 and a service life of 20 years, and mounted at a slope of 44 degrees (equal to the latitude). The inverter is assumed to be rated at 575 W, with an installed cost of $440 dollars and a service life of 10 years. The batteries (of Chinese manufacture) are assumed to have a charge capacity of 1.26 kWh, a service life of 150 equivalent full cycles, and an installed cost of $142 each.

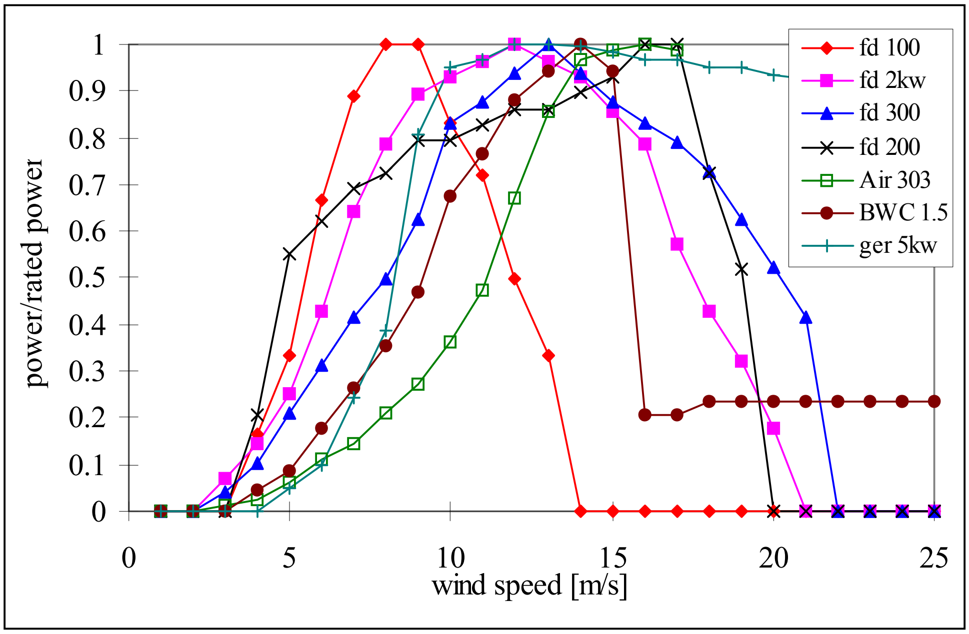

Figure 3. Comparison of scaled power curves from small wind turbines manufactured in China, the United States and Germany (Note that the turbines from China are designed for the lower wind speeds that are present at low hub heights.)

5. MODELING AND OPTIMIZATION PROCEDURE

In hybrid systems that feature an engine generator, the usual approach to optimization of the design is to minimize the life-cycle cost (LCC), which includes both equipment costs and fuel costs. In hybrid systems that do *not* feature an engine generator, there is no fuel expense involved. Instead, it is typical that a portion of the load will go unmet. Meeting 100% of the load with renewables and batteries would require an investment in the equipment needed to generate and store enough energy to withstand the longest doldrums (calm/cloudy weather); such equipment is excessive most of the time. In many cases, such an investment is not justified. Thus the component sizing problem involves a trade-off between the system cost and the unmet load (UL). If there is a definite economic cost associated with unmet load, a least-cost design can be determined mathematically. Otherwise, the trade-off between cost and unmet load is subjective. The following procedure is used here in determining optimal designs:

a. Assign an arbitrary cost to unmet load, C_{UL}, in \$/kWh.

b. Define the augmented life-cycle cost (LCC_{aug}) as the sum of the equipment costs, O&M costs, and unmet load cost.

c. Size the components to minimize LCC_{aug}.

d. Repeat steps a through c for various values of C_{UL}, plotting the results. (Higher values of C_{UL} drive the optimization to higher equipment costs and lower unmet loads.)

e. Make a subjective judgement of the most appropriate design.

Two different models are used to perform these computations. First, a simplified, quasi-steady-state time-series model (Barley 1996a, 1996b; Barley and Winn 1996) is used to determine approximate least-cost designs. This model has the advantage of fast computation time and an efficient search algorithm for determining the least-cost component sizing (numbers of WTG, PV modules, and batteries) in step c above. Then the more detailed, stochastic model Hybrid2 (Green and Manwell 1995) is used to more accurately determine the cost of energy (COE) and unmet load for each of the designs indicated by the simple model. In this analysis, the COE is defined as:

$$\text{COE} = \text{LCC} \times F_L / (\text{Load} - \text{Unmet load}) \qquad (1)$$

where:

COE = Cost of energy, \$/kWh
LCC = Life-cycle cost, present worth dollars (not including C_{UL})
F_L = Levelizing factor, which converts a present worth to a uniform annual expense (based on a 20 year system life and a 12% discount rate)
Load = Household load, kWh/yr
Unmet load = Load that cannot be met by the system, kWh/yr

6. RESULTS

The procedure outlined above (steps a-d) has yielded the series of design options plotted in Figures 4-6, for the following cases:

Figure 4: Scenario A (average wind speed = 4.9 m/s), with the Chinese FD200 WTG.

Figure 5: Scenario B (average wind speed = 3.6 m/s), with the Chinese FD200 WTG.

Figure 6: Scenario A (average wind speed = 4.9 m/s), with the Southwest Air 300 WTG.

Each point on these graphs represents a design which has been determined as approximately least-cost for the corresponding level of unmet load. The graphs clearly illustrate the trade-off between COE and unmet load. In these results, the calculated COE values are higher than values calculated for existing systems in Inner Mongolia [Byrne *et al.* 1996a], partly due to the use of higher priced system components, and partly due to the fact that excess energy in this analysis is not utilized and is considered to have zero value.

Case	**Wind (W)**	**Solar (W)**	**Battery (kWh)**
A	400	0	1.26
B	400	0	2.52
C	400	50	3.78
D	400	50	6.30
E	400	150	6.30
F	400	200	7.56

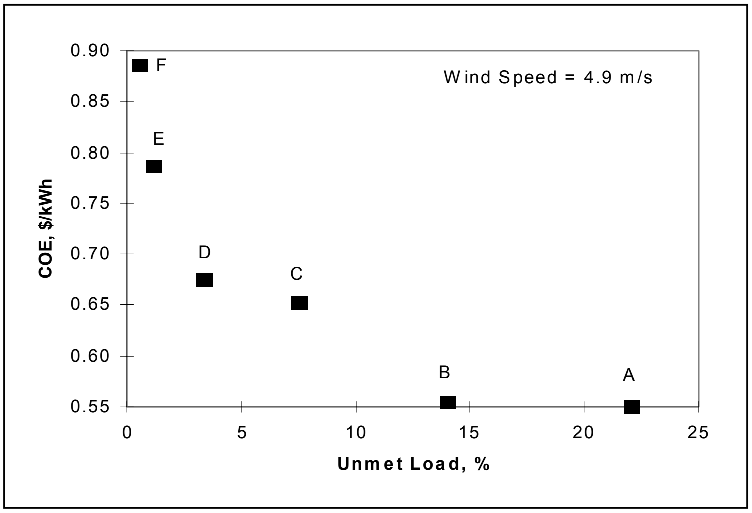

Figure 4. Results for Scenario A, with the Chinese FD200 WTG

Case	Wind (W)	Solar (W)	Battery (kWh)
G	400	100	2.52
H	400	150	3.78
I	400	250	3.78
J	400	250	5.04
K	400	250	6.30
L	200	350	6.30

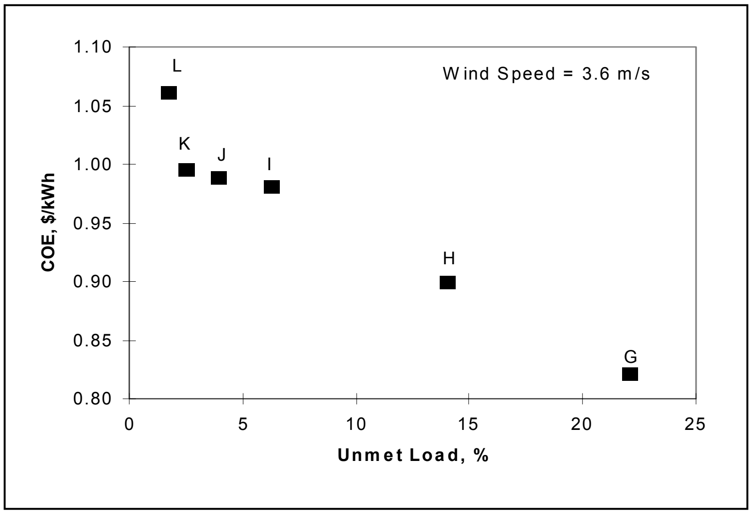

Figure 5. Results for Scenario B, with the Chinese FD200 WTG

Case	Wind (W)	Solar (W)	Battery (kWh)
M	300	250	2.52
N	300	300	3.78
O	300	350	5.04
P	300	350	6.30
Q	300	400	5.04
R	300	400	6.30

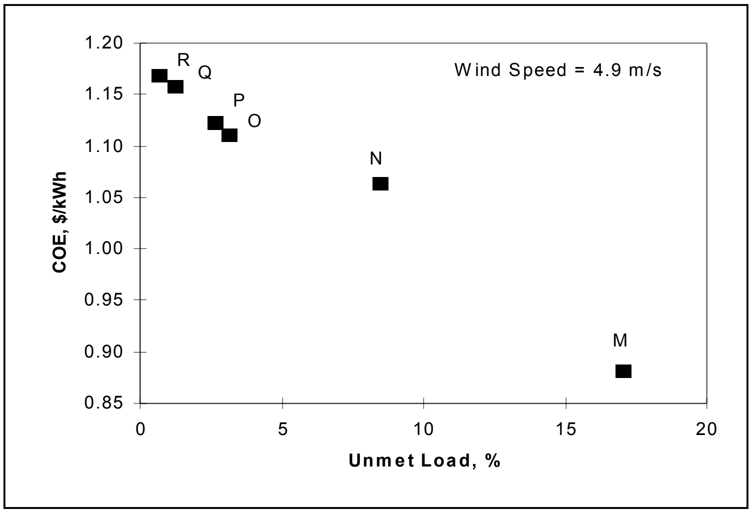

Figure 6. Results for Scenario A, with the Southwest Air 300 WTG.

The addition of PV helps to meet demand during the low wind summer months for a low incremental cost of energy. Due to the large uncertainties in the wind resource, computations for Scenario A were performed for both 4.9 m/s and 6.0 m/s average wind speeds. This illustrates the effect of estimating the resource incorrectly or of large interannual variations in the wind resource. The effect of this increase in wind speed on the wind-only systems is to reduce the unmet load by a factor of four. Reliability remains a problem in the summer months. The increased wind speed reduces the unmet load by a factor of 8 for selected wind/PV hybrids. Note that while the resource has a large effect on the amount of unmet load, it has little effect on the COE. For the case of 300 W wind, 200 W PV and 8.4 kWh batteries in the 6.0 m/s average winds (not shown in Figures 4-6), a large amount of excess energy would be generated. This energy could be used for optional loads such as a water pump or heating element; however, to simplify this analysis, it has been assumed that excess energy is not utilized. In the 4.9 m/s average winds, this configuration is capable of generating about 870 kWh wind power and 460 kWh solar power, 520 kWh of which would be excess energy.

Larger amounts of PV are indicated for household systems in Scenario B due to the poor wind resource. It is likely that wind resource variation will have a lesser effect on these systems. For the case of 200 W wind, 400 W PV and 8.4 kWh batteries (not shown in Figures 4-6), about 400 kWh of wind power and 850 kWh of solar power could be generated. Approximately 400 kWh of this generation would be of excess energy.

7. CONCLUSIONS

In the type of hybrid systems studied here, which do not include fueled engine generators to provide back-up power, alternative designs are compared based on unmet load as well as cost. The relative importance of these two criteria is a subjective judgement; thus we have presented our results so as to illustrate the trade-off and provide some options. The use of the two models (the fast, simplified model to search for least-cost designs, and the slower, more precise model to verify performance) worked well. Between the two models, differences in the prediction of unmet load are consistently less than 2.5 percentage points for the cases shown; larger differences in the cost of energy result from differences in the prediction of battery life, which is considered to be only an estimate even in the more sophisticated Hybrid2 model. Based on the component specifications that were provided, the Chinese wind turbines are much more cost-effective than those of U.S. manufacture, at the wind speeds considered. Because the seasonal profiles of the wind and solar resources are somewhat complementary in this region (i.e., months of higher solar resource correspond to some of the months of lower wind resource, as shown in Figure 1), combinations of wind and solar perform better than either wind or solar alone. Between cases B and D in Figure 4, for example, the addition of PV to the wind-only system (in conjunction with an increase of battery capacity) reduces the unmet load from 14% to 3.3%, with a cost increase of only 22%. The relative amount of PV in the indicated designs increases as the acceptable unmet load decreases and as the average wind speed decreases.

The greatest uncertainties in this analysis are the wind speed data and the battery data (price and cycle-life). Future work includes the design of wind/PV/battery/engine hybrid systems for villages in these regions.

8. ACKNOWLEDGMENTS

We would like to gratefully acknowledge the contributions of John Byrne and Bo Shen of the Center for Energy and Environmental Policy at the University of Delaware, and the Chinese Academy of Sciences for providing information for this analysis. William Wallace, NREL, played a key role in leading this project. Peter Lilienthal, NREL, gave helpful suggestions regarding the presentation of the results. Funding for this work was provided by the U.S. Department of Energy through NREL under contract number DE-AC36-83CH10093.

9. REFERENCES

Barley, C.D. (1996a). *Modeling and Optimization of Dispatch Strategies for Remote Hybrid Power Systems*. Ph.D. dissertation, Ft. Collins, CO: Dept. of Mechanical Engineering, Colorado State University.

Barley, C.D. (1996b). *Hybrid Power Design Handbook (with Software*). http://www.earthnet.net/~dbarley.

Barley, C.D., Winn C.B. (1996). "Optimal Dispatch Strategy in Remote Hybrid Power Systems." *Solar Energy,* Vol. 58, No. 4-6.

Byrne, J. *et al*. (1996a). *Levelized Cost Analyses of Small-Scale, Off-grid Photovoltaic, Wind and PV-Wind Hybrid Systems for Inner Mongolia, China, Volume 1*. Newark, DE: Center for Energy and Environmental Policy, University of Delaware.

Byrne, J. (1996b). Personal communication.

Duffie, J.A., Beckman, W.A. (1991). *Solar Engineering of Thermal Processes*. New York, NY: John Wiley & Sons, Inc.

Eggleston, D.M., Stoddard F.S. (1987). *Wind Turbine Engineering Design*. New York: Van Nostrand Reinhold Co.

Green, H.J., Manwell, J. (1995). "HYBRID2 - A Versatile Model of the Performance of Hybrid Power Systems." *Proceedings of American Wind Energy Association Windpower 1995, Washington, DC, 26-30 March*. Washington, DC: American Wind Energy Association.

Schwartz, M., Elliott, D. (1995). "Mexico Wind Resource Assessment Project." *Proceedings of American Wind Energy Association Windpower 1995, Washington, DC, 26-30 March*. Washington, DC: American Wind Energy Association.