ASME/AIAA 99-0058

WIND/HYBRID OPERATION WITH BIODIESEL*

R. Nolan Clark
Eric D. Eggleston
USDA - Agricultural Research Service
Bushland, Texas

Abstract

Wind/hybrid operations data were collected with two fuels at the USDA Agricultural Research Service, Wind/Hybrid Research Laboratory, located in Bushland, TX. The hybrid system included a single diesel generator set, an AOC 15/50 wind turbine, motor loads, a resistive load bank, custom controls, and a simulated village load. The configuration was high penetration, no storage, without allowing diesel generator shut down. Data show that both #2 diesel fuel and biodiesel (vegetable oil) adequately powered the electrical generating system and had equivalent fuel usage. The AOC wind turbine provided 45% of the power, but only a 19% fuel savings was obtained with the engine running continuously.

Introduction

Many farms and communities exist on islands or other remote places that will never be connected to large utility girds. They depend on costly diesel power to generate electricity and many are required to store enough diesel fuel for an entire year. Reducing this fuel expense by using local energy sources is the reason for our wind/hybrid electric generation research and development program.

One way to reduce diesel fuel usage is to add wind turbines to the existing diesel grid which reduces the demand on the diesel generator sets, and saves fuel.[1] Wind plants that produce a large percentage of the electrical load have more potential for fuel savings, but require additional controls for voltage and frequency.

Constructing a hybrid system that works, developing the necessary controls, and evaluating its performance were our primary objectives. We were interested in using biodiesel fuel in the generator engine to see for ourselves what were the environmental benefits, engine issues, and performance affects. In addition we wished to see how well the Hybrid2 modeling code predicted actual performance based on data available to designers at the beginning of such a project.

Some explanation of biodiesel fuel is necessary. The first successful diesel engine invented by Rudolf Diesel ran on peanut oil. Since then, diesel engines have become optimized for combustion of relatively small molecules provided by petroleum based fuels. The raw, large vegetable oil molecules can be used, but they coke injectors and gum up the engine components works after a short time. The vegetable oil molecule is composed of a "backbone" with three fatty-acid chains (esters) attached. A simple chemical cracking process, known as transesterification, breaks off the backbone and frees the smaller esters, which have been shown in much pervious research and field testing to work well as a straight, or blended, substitute for petroleum based diesel fuel.[2]

Biodiesel can be made from just about any vegetable oil by the following a general recipe. Thirty liters of oil are filtered into a tub, 6 liters of alcohol and a dash (1.5% of the amount of oil) of sodium hydroxide, a catalyst, are then added. After stirring vigorously for two hours, let settle for 20 hours. The backbone combines with the alcohol to form glycerol, which settles to the bottom. The glycerol phase is then drained, yielding about 30 liters of biodiesel.[3] Biodiesel is non-hazardous and a good solvent. While it can be used to wash greasy parts without abusing your hands, it tends to soften natural rubber hoses and is more prone to winter fuel gelling problems. Teflon or metal fuel lines and clean fuel tanks are required. The

*Contribution from the USDA-Agricultural Research Service in cooperation with the National Renewable Energy Laboratory, National Biodiesel Board, and the Alternative Energy Institute of West Texas A&M University.

biodiesel used in this tests was provided by the National Biodiesel Board and was manufactured from soybean oil.

The Hybrid2 logistical modeling code, developed by the National Renewable Energy Laboratory (NREL) and the University of Massachusetts,[4] uses data provided on the diesel engine and it's dispatch strategy, wind turbine, and time series wind and load data to perform an energy balance over each time step of the model run. From these data, energy flows are determined. Different system components are examined to determine the optimum energy flow. But in the real world, data available at the beginning of a hybrid project may not be representative, reliable, or even exist. We wished to know how close the model came under these real world circumstances and sample it's merit.

Test Configuration

The test configuration consisted of an AOC 15/50 wind turbine** with a rated power of 50 kW, a Caterpillar 3304PCNA, 49 kW diesel generator, motor loads, and a dual-duty load bank for village load simulation and controlled dumping of excess wind power as shown in Figure 1. The AOC 15/50 wind turbine is a three-bladed, down wind machine with fixed pitch and induction generator. The wind turbine control was not modified for this study. The diesel generator operated at 1800 rpm, was naturally aspirated, and had a mechanical governor for speed control. The motor loads consisted of two water pumps and a blower and the load bank consisted of resistance heaters that are switchable in 1-kW increments.

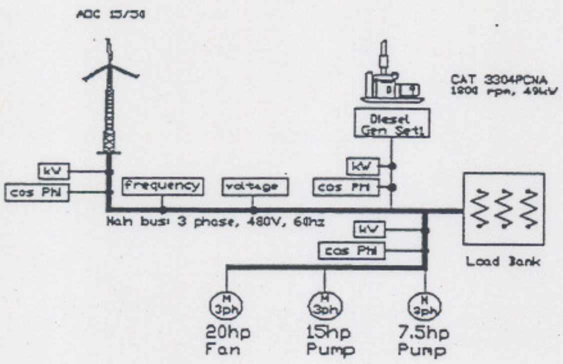

Figure 1 Schematic of test configuration.

The village load could be set to any constant level within the design limits of the system or programed to follow a predetermined load profile. For this study, a constant load of 40 kW was chosen to represent the village due to the nearly constant nature of the loads in many remote villages where spacing heating and industry loads are not included. The village load can be configured to include resistance heaters, pump motor and fan motor loads.

The wind/hybrid controller maintains the appropriate frequency by increasing or decreasing the load on the hybrid system. The sum of the diesel power and wind power always equal the variable load (village plus dump load). The control logic was describe earlier by Eggleston and Clark.[5]

When running a 40 kW constant village load, installed wind penetration was 125% (wind power/village load). Instantaneous penetration was measured as high as 200% because the wind turbine output exceeded 80 kW for short periods. The diesel ran continuously and only shut down for operator commands or system errors.

This wind/diesel test configuration was run a total of 1027 hours. The test configuration is described as an AC bus, high penetration, no storage, with the diesel engine running continuously.[6] Testing was performed in three stages: shake down, wind/biodiesel tests, and wind/#2 diesel fuel tests. System shake down and commissioning took 253 hours of operation. Biodiesel fueled the system for 346 hours. And a further 428 hours of data were collected while operating on #2 diesel fuel.

Results

During the 253 hour shake down period, the engine consumed far too much oil and excessive carbon caked the exhaust pipes, and the hour meter had to be replaced. The engine came to this project from an irrigation pumping project and showed more wear than the hour meter had suggested and some signs of starting fluid abuse. As a result, the engine was overhauled after the shake down period. Two of the four pistons had broken rings and scored liners. The head was reconditioned and the injection pump overhauled, while the pistons, rings, liners, injection nozzles, and hour meter were replaced. With the engine out, other problems were remedied. Vibration caused the failure of an engine mount, several broken power wires and contactors, and cracked

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**The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

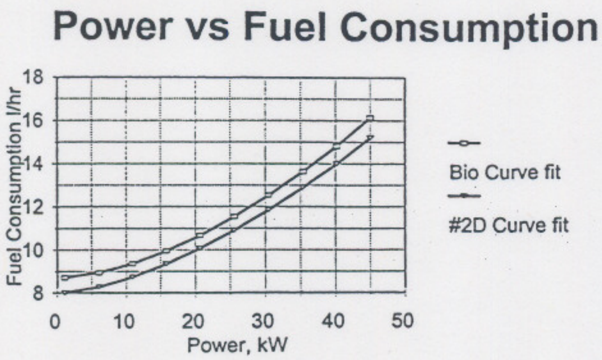

Figure 2 Fuel consumption of diesel generator as a function of power production.

generator feet. Incorrectly adjusted vibration isolators accounted for most of these problems. The vibration isolators were adjusted and most of the electrical equipment was removed from the engine skid and mounted on a wall nearby. The two bearing generator and clutch were removed and a single bearing generator installed in it's place. After these changes, our diesel generator was very near the construction of an off-the-shelf generator set that is similar to ones currently found in many villages.

The nearly 800 hours of testing were accomplished in seven non-stop runs, the longest being 222 hours. There were four error shut downs, mostly due to control problems associated with a slow frequency transducer in high, gusty winds. The frequency transducer provided a signal every 5 sec which did not properly indicate the true frequency or frequency change of the system when operating above 18 m/s wind speed. One error shut down was caused by blown fuses in one step of the balancer load. Another was caused by an AOC 15/50 wind turbine tip brake problem.

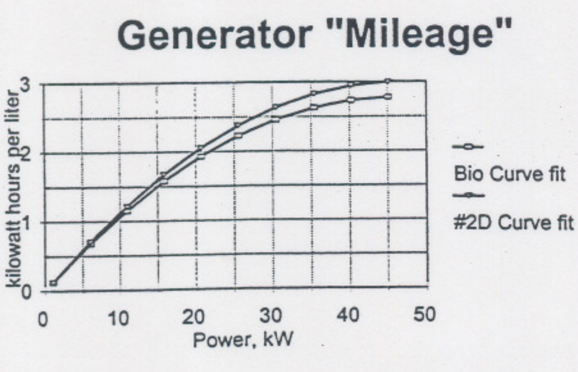

Figure 3 Energy production per unit of fuel consumed as a function of power produced.

Engine performance was evaluated with the two fuels and show the engine consumed about 0.7 liter/hr more biodiesel than #2 diesel at any power level, as shown by least squared error curve fits in Figure 2. This curve is often shown in manufacturers' literature as a straight line and plotted as percent load instead of actual load. The major difference in our curve and a manufacturers' curve is that our data contains data from all load combinations, not 5 to 10 set operating conditions. Actually the data available from the engine manufacturer agrees with the #2 diesel curve, thus we feel these data are correct and confirm our test instrumentation. The volume of biodiesel consumed per kilowatt hour production averaged 5.4% higher than for #2 diesel fuel as shown in Figure 3. This increased use of biodiesel is caused because the biodiesel has a slightly lower heat value than #2 diesel. This variation was predicted and was not a surprise to us.

The frequency control of a diesel generator was controlled by the governor. The response of the governor to changes in load is called the droop. Surprisingly, the frequency droop using biodiesel fuel was significantly improved because it had less frequency changes with equivalent changes in power. The system had better power quality and frequency stability when using biodiesel fuel, as shown in Figure 4. These differences in fuel performance appear to be due to the inherent design of the diesel engine and it's fuel injection subsystem when burning a fuel with slightly reduced energy content per unit volume. While no qualitative data were taken on exhaust emissions of the two fuels, operating with biodiesel eliminated all visible exhaust even in a fully loaded condition. We were very impressed with biodiesel's clean exhaust. Also, engine oil samples sent for analysis showed nothing anomalous.

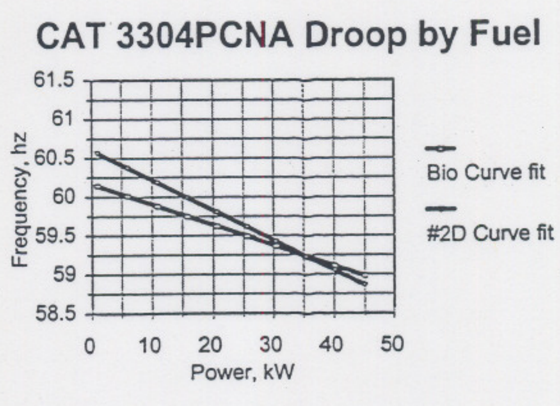

Figure 4 Frequency regulation of a diesel generator as a function of power produced.

Energy production, energy consumption, and fuel savings were compared to non-hybrid operation and are presented in Table 1. The village load for all runs was a constant 40 kW. In each run, the wind turbine provided a significant portion of the system power at 45% for biodiesel and 40% for #2 diesel fuel. Even at these power levels, the fuel savings was modest at 19% and was almost identical for both runs. These data clearly show that engines must be stopped to provide significant fuel savings.

Table 1: Energy Summary

	Biodiesel		#2 Diesel	
Run hours	346.4		428.3	
Production				
Diesel kWh	8225	54.7%	10982	59.9%
Wind kWh	6800	45.3%	7339	40.1%
Consumption				
Village kWh	13856	92.2%	17126	93.5%
Dump kWh	803	5.4%	897	4.9%
Aux kWh	366	2.4%	299	1.6%
Fuel	4133.43	liters	4788.74	liters
	11.93	l/hr	11.18	l/hr
Engine@40kW	14.72	l/hr	13.75	l/hr
Fuel savings	2.79	l/hr	2.56	l/hr
	18.95%		18.69%	

Auxiliary loads such as the radiator and balancer load bank fans accounted for only 2% of the entire system energy consumption. Energy dumped for control purposes accounted for 5% of the total, which was low and desirable. However, system control was limited to long response times by the slow frequency transducer; resulting in some short term back-driving of the diesel and/or dumping of diesel energy. We feel this portion of the control system could be improved and the 5% dumped power could be further reduced and most back-

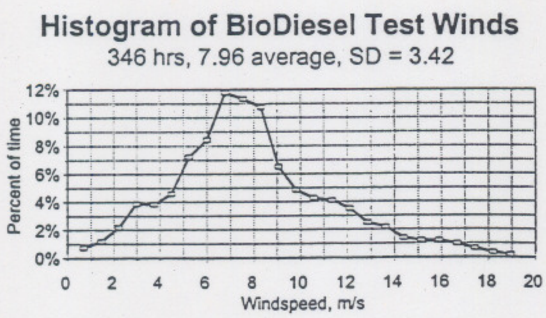

Figure 5 Wind speed histogram for the period of biodiesel testing.

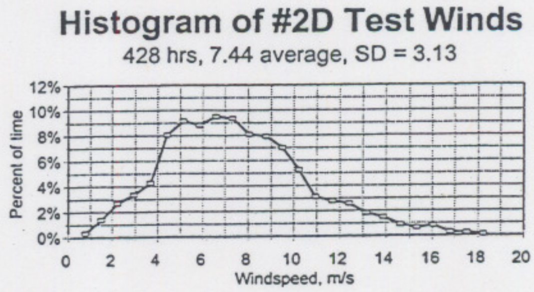

Figure 6 Wind speed histogram for the period of #2 diesel testing.

driving and dumping of diesel energy avoided.

Histograms of five minute average wind data are shown in Figures 5 and 6. These histograms indicate that the two test were conducted in similar winds; therefore, the wind turbine should show similar results and the wind power contribution should be similar.

AOC 15/50 power curves from five minute average, hub height wind data are shown in Figures 7 and 8. During biodiesel testing there were several winter storms which caused some icing. Also, our anemometer lost a cup for a short period which distorted low wind speed measurements (data clustered above the curve in the 3-7 m/s range), but apparently not high wind measurements.

Our AOC wind turbine controller (prototype #1, unique, and since altered) tended to allow too much motoring and freewheeling of the turbine in light winds, consuming diesel power and fostering upwind operation of the machine and causing reduced output. Seven upwind excursions occurred during biodiesel tests: 4 manually curtailed, and 3 naturally corrected while personnel were absent. Upwind operation is seen in the power curves as a mini spur curve that reaches a maximum of about 9 kW

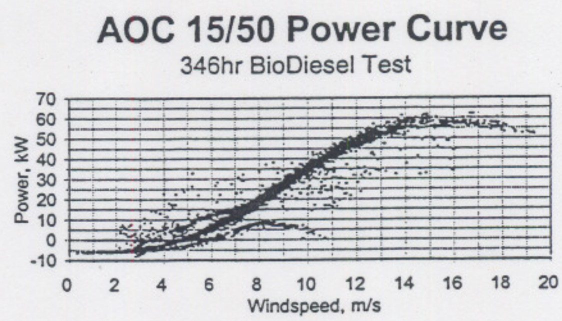

Figure 7 Power curve measured during the period of biodiesel testing.

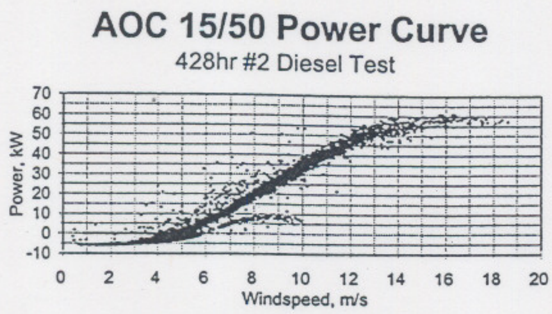

Figure 8 Power curve measured during the period of #2 diesel testing.

in a 9 m/s wind. Six upwind excursions were recorded during the #2 diesel tests: 4 manually curtailed, and 2 naturally corrected. The AOC is prone to flip upwind while freewheeling or motoring in winds below 5 m/s. Two modes of flipping back downwind have been observed: violently when winds exceed 10 m/s (perhaps 90% of all cases), or the exact reverse of flipping upwind -- freewheeling in winds below 5 m/s. As indicated earlier, the wind turbine controller has been modified since these test runs to reduce the upwind operation.

The penetration histogram shown in Figure 9 has some interesting features. Penetration was determined as the measured wind power divided by the village load. Partial integration of this histogram shows that the turbine motored (penetration less than zero), consuming up to 6kW for 8-14% of the time. In addition, the diesel engine idled (penetration greater than 100%) 14-18% of the time when wind power was able to cover the entire load alone. These data indicate that improvements in fuel saving might be realized with a wind turbine controller that prevents motoring and upwind operation. An improved hybrid system control to allow the diesel to be shut down when stable penetration exceeds 100% could also provide significant fuel savings.

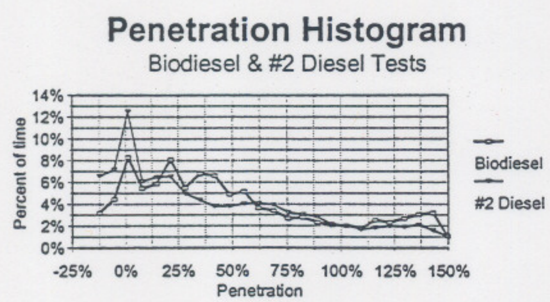

Figure 9 Penetration histogram for biodiesel and #2 diesel testing.

These test were compared to the results of HYBRID2 modeling. For the hourly wind data, actual 5-min wind data was reduced to hub height and the hourly average determined. Inputs to the HYBIRD2 model were hourly wind data, manufacturer's performance of an AOC 15/50 wind turbine, one generic 49 kW diesel, and a constant 40 kW load. These are typical data that might be available prior to building a hybrid system. The total energy consumption predicted by HYBRID2 was very similar to actual data measured. However, HYBRID2 over-predicted wind energy production by 26%. Some of the over-prediction may be due lower wind turbine performance because of motoring and upwind operation of the wind turbine during the testing. No modeling was done using actual biodiesel fuel consumption figures, so the same mis-predictions were exaggerated further. Tables 2 & 3 summarize the comparisons between test data and HYBRID2 results.

Table 2: #2 Diesel Test Data vs. Hybrid2

#2 Diesel Test	Data	Hybrid2	Change
Run Hours	428	428	
Diesel Production kWh	10982	9066	-17.45%
Wind Production kWh	7339	9361	27.55%
Total Consumption kWh	18321	18427	0.58%
Dumped Energy kWh	897	1428	59.20%
Liters Fuel, Hybrid Case	4788	4880	+1.92%
Liters Fuel, Diesel Case	5888	6537	+11.02%
Liters Fuel Savings	1100	1657	+50.64%

Table 3: Biodiesel Test Data vs. Hybrid2

Biodiesel Test	Data	Hybrid2	Change
Run Hours	346	346	
Diesel Production kWh	8225	6742	-18.03%
Wind Production kWh	6800	8593	+26.37%
Total Consumption kWh	15025	15318	+1.95%
Dumped Energy kWh	803	1518	+89.04%
Liters Fuel, Hybrid Case	4133	3858	-6.65%
Liters Fuel, Diesel Case	5099	5811	+13.96%
Liters Fuel Savings	966	1953	+102.17%

Conclusions

While testing, our hybrid system has performed well. An 19% fuel saving was realized using either biodiesel or #2 diesel fuel. Use of biodiesel showed much cleaner exhaust and slightly higher fuel consumption due to biodiesel's lower volumetric energy content. The use of biodiesel fuel makes for a completely renewable energy system, with an unexpected bonus of improved droop frequency control by the diesel governor providing a more stable frequency and voltage. Problems of wind turbine motoring and operating upwind have been identified and corrected. These data clearly show there is potential for increased fuel savings by shutting down the diesel when adequate wind power is available to cover the entire load. Performance predictions using the HYBRID2 model and generalized data clearly show the inaccuracies that can occur when predicting the performance of a dynamic wind/diesel hybrid system.

References

1. Infiled, D.G.; Scotney, A.; Lundsager, P.; Binder, H.; Uhlen, K.; Toftevaag, T.; and Skarstein, O. 1992. Wind diesel systems - design assessment and future potential. Proc 6th International Wind/Diesel Workshop, June 1992.

2. Schumacher, L.G. and van Gerpen, J.H. 1996. Experiences of fueling diesel engines with biodiesel. In Liquid Fuels and Industrial Products from Renewable Resources, ASAE.

3. Rico O. Cruz, John Stanfill, and Bart Powaukee. 1996. Pilot production of biodiesel on the Nez Perce Tribe reservation. Proceedings of BIOENERGY 1996, V 1, page 364.

4. Baring-Gould, Edward I. 1995. HYBRID2 - The versatile tool for modeling hybrid power systems. Proc 9th International Wind/Diesel Workshop, June 1995.

5. Eggleston, E. D and R. N. Clark. 1998. USDA wind/hybrid research laboratory controls development. Proc 12th International Wind/Diesel Workshop, June 1998.

6. AWEA. 1991. Wind/Diesel Systems Architecture Guidebook. AWEA Standard 10.1-1991. Am Wind Energy Association.

Acknowledgments

The authors would like to thank DOE/NREL for their funding of our wind/hybrid effort. Many thanks also to the Alternative Energy Institute, West Texas A&M University who coordinated the student interns and the National Biodiesel Board who provided the biodiesel. Thanks to all the people that helped make our hybrid system happen: to Fang Jun Wang, who did the majority of the control programming in Labview, to Ron Davis and Shitao Ling who assisted in controls design, and the student interns that helped bring all the hardware into reality: Hubert Grimm, Jochen Schneider, Mark Michaelis, Matthias Langer, Michael Baumgart, Thomas Schips, Martin Assmann, Andreas Rapp, and Ralph Atallah.

A Collection of the 1999 ASME Wind Energy Symposium Technical Papers

at the

37th AIAA Aerospace Sciences Meeting and Exhibit

Reno, NV
11–14 January 1999