Wind/Diesel and Wind/Biodiesel Performance of the USDA Hybrid System

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The research wind/diesel hybrid at the Wind/Hybrid Research Laboratory (WHRL) of the USDA Agricultural Research Service, located in Bushland, Texas, has been run a total of 1050 hours over the past year. The simple configuration was AC bus, high penetration, no storage, with the diesel running continuously. Testing was broken into three stages: shake down, wind/biodiesel tests, and wind/#2 diesel tests. System shake down and commissioning took 253 hours of operation. Biodiesel, provided by the National Biodiesel Board[1], fueled the system for 346 hours. And a further 451 hours of data were collected while operating on #2 diesel fuel.

The initial WHRL configuration consisted of an AOC 15/50 wind turbine[2], a Catepillar 3304PCNA, 49kW diesel generator, motor loads, and a dual-duty load bank for village load simulation and controlled dumping of excess wind power.

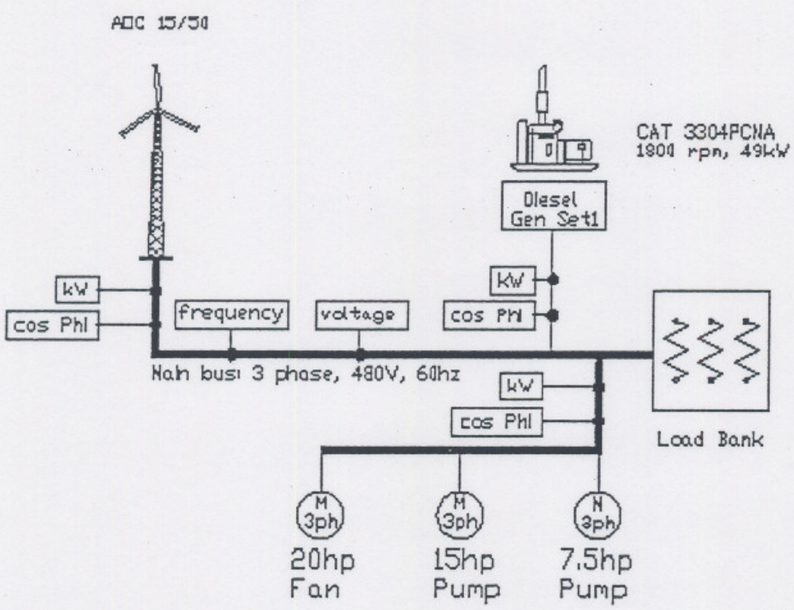

Figure 1: Initial Confguration, simplified

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[1] Contribution from USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX 79012 in cooperation with the National Biodiesel Board and the Alternative Energy Institute, West Texas A&M University, Canyon, TX.

[2] 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.

Running a 40kW constant village load, installed wind penetration is 125% (wind power/village load). Instantaneous penetration can be as high as 200% because the turbine can reach over 80kW for short periods. The diesel runs continuously and only shuts down for system errors or operator commands.

During the 253 hour shake down period, the hour meter was replaced and the engine consumed far too much oil and excessive carbon built up in the exhaust pipes. As a result, the engine was overhauled by our master mechanic. The engine came to the project from irrigation duty and showed more wear than the hour meter had suggested and some signs of starting fluid abuse. Two of the four pistons had broken rings and scored liners. The head was reconditioned and the injection pump overhauled, while all the pistons, rings, liners, and injection nozzles 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 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 was repaired for use as a separate synchronous condenser, while the clutch was removed and a single bearing generator installed in it's place. After these changes, our diesel generator may be considered an off-the-shelf item that may currently be found in many villages.

The nearly 800 hours of testing was accomplished in seven individual runs, the longest of which was 222 hours. There were four error shut downs, mostly due to control problems associated with a slow frequency transducer in high, gusty winds. One of these was caused by blown fuses in one step of the balancer load. Another was caused by tip brake problems on our AOC 15/50 turbine. Engine oil samples sent for analysis showed nothing anomalous.

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 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.

Biodiesel can be made from just about any vegetable oil by the following general recipe[3]. Thirty liters of oil are filtered into a tub, 6 liters of alcohol and a dash (1.5% of theamount 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. 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.

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[3]See "Pilot Production of Biodiesel on the Nez Perce Tribe Reservation" by Rico O. Cruz, John Stanfill, and Bart Powaukee, Proceedings of BIOENERGY 1996, volume 1, page 364.

Once our shake down problems were corrected and the fresh engine run-in, engine performance was evaluated with the two fuels. For any power level, the engine consumed about 0.7 liter/hr more biodiesel than #2 diesel, as shown by least squared error curve fits in Figure 2.

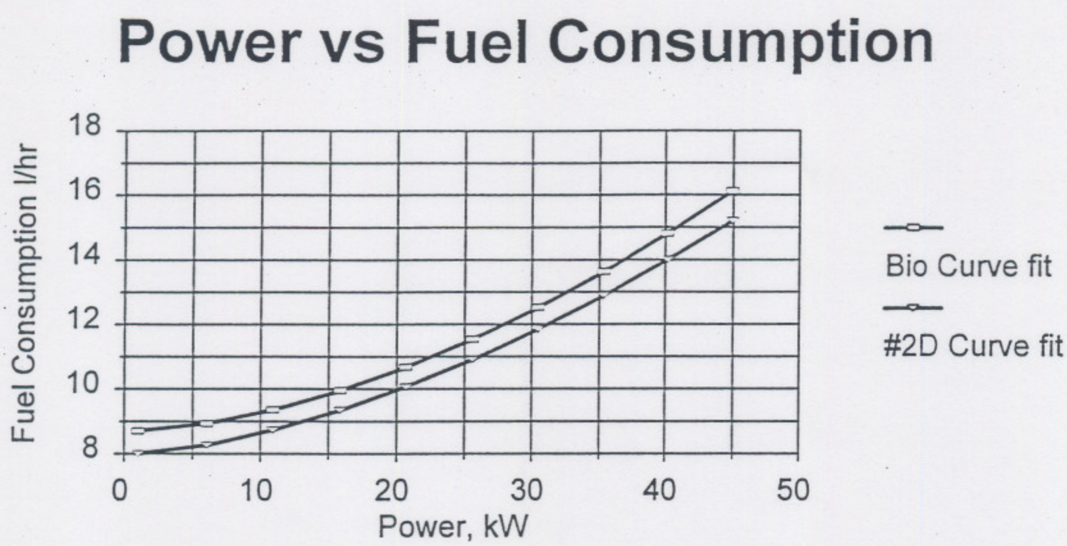

Figure 2: Power vs. Fuel Consumption

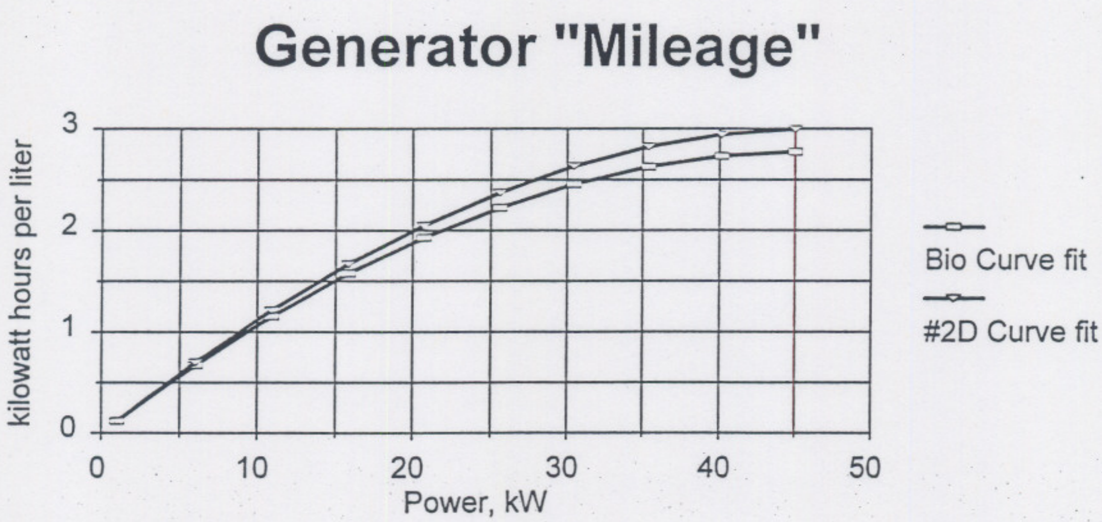

Figure 3: Generator "Mileage"

The data available from Caterpillar for this engine agrees with the #2 diesel curve. The number of liters of biodiesel consumed per kilowatt hour production is higher than #2 diesel by 5.4% average, as shown in Figure 3.

But the frequency droop using biodiesel fuel is significantly improved, which yields better power quality and frequency stability when using biodiesel fuel, as shown in Figure 4.

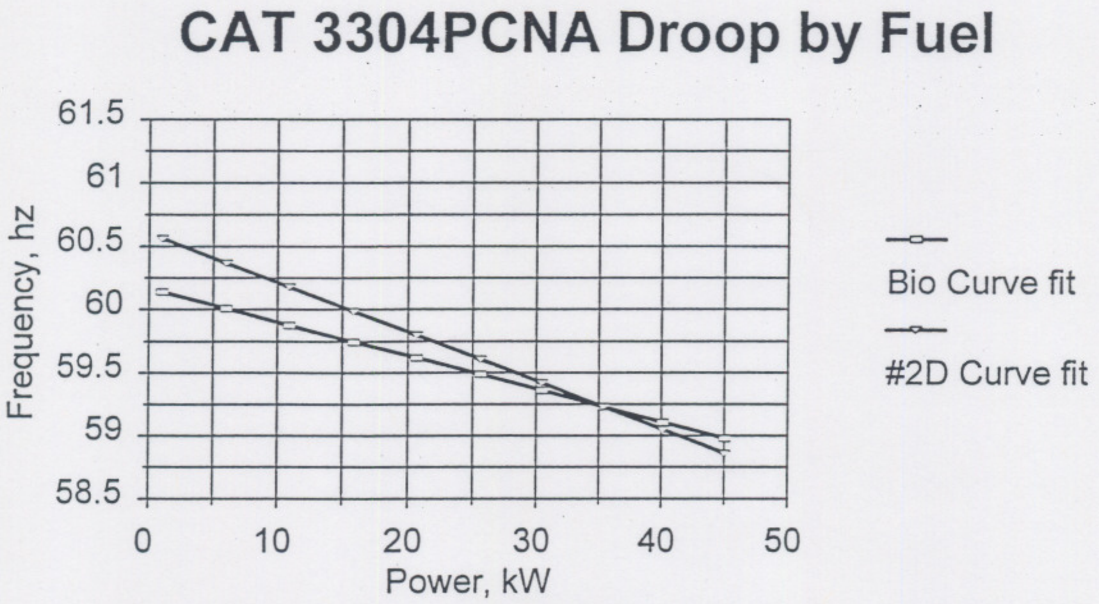

Figure 4: CAT 3304PCNA Droop, by fuel

All of these differences in fuel performance appear to be due to the slightly reduced energy content per unit volume of biodiesel and are inherent in the design of the diesel engine and it's fuel injection subsystem. 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.

Histograms of five minute average wind data are shown in Figures 4 & 5.

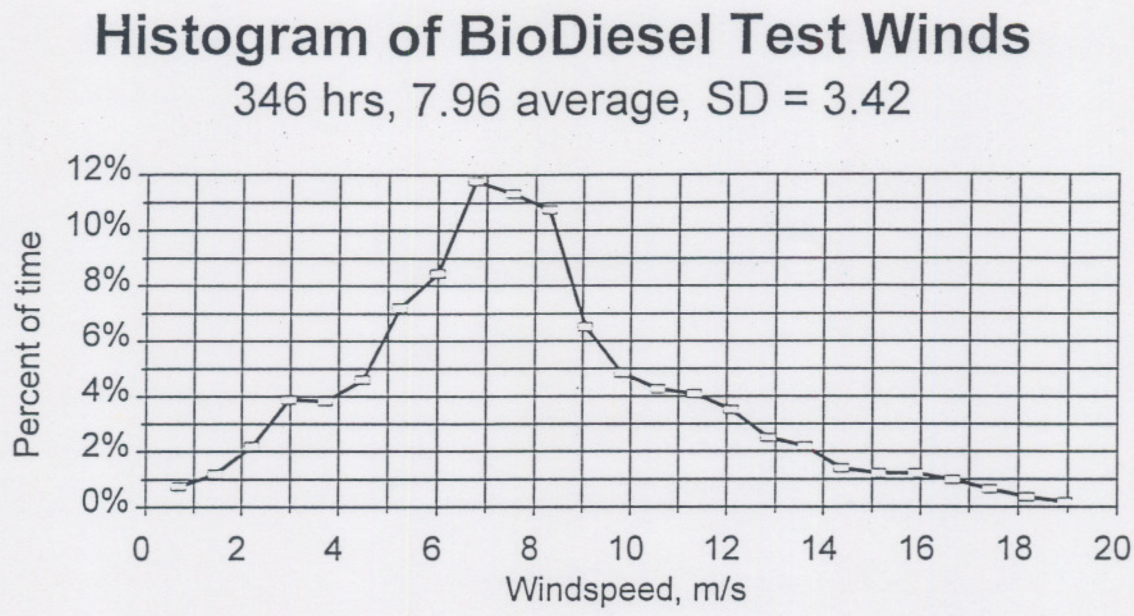

Figure 5: Histogram of Biodiesel Test Winds

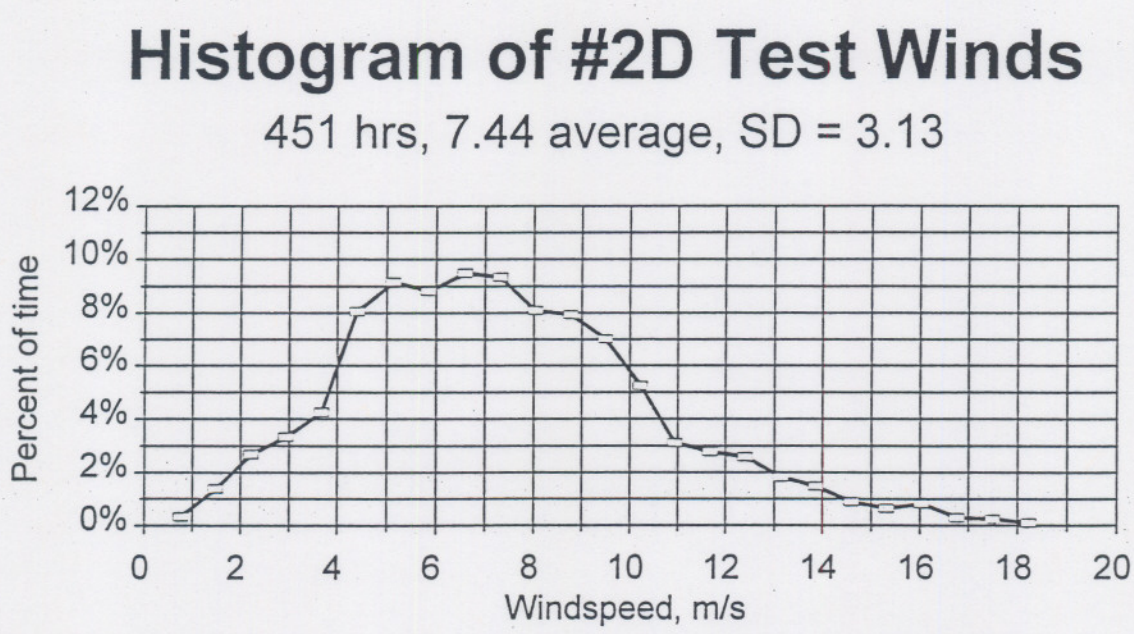

Figure 6: Histogram of #2 Diesel Test Winds

The village load for both runs was 40kW constant. Energy production, consumption, and fuel savings are compared to non-hybrid operation and are presented in Table 1.

	Biodiesel			#2 Diesel			
Run time	20784	min			27056	min	
	346.4	hours			450.9	hours	
Production							
Diesel	8225	kWh	54.74%	Diesel	11629	kWh	60.37%
Wind	6800	kWh	45.26%	Wind	7635	kWh	39.63%
Consumption							
Village	13856	kWh	92.22%	Village	18032	kWh	93.61%
Dump	803	kWh	5.35%	Dump	904	kWh	4.69%
Aux	366	kWh	2.44%	Aux	328	kWh	1.70%
Fuel	4133.43	liters			5067.97	liters	
	1091.94	gals			1338.82	gals	
	11.93	l/hr			11.24	l/hr	
	3.15	gal/hr			2.97	gal/hr	
BioDiesel@40kW	14.72	l/hr		#2 Diesel@40kW	13.75	l/hr	
BioDiesel@40kW	3.89	gal/hr		#2 Diesel@40kW	3.63	gal/hr	
W/D fuel savings	2.79	l/hr			2.51	l/hr	
	0.74	gal/hr			0.66	gal/hr	
	18.95%				18.27%		

Table 1: Energy Summary

There is almost no difference in fuel savings percentage between the two runs. Auxiliary loads such as the radiator and balancer load bank fans account for only 2% of the entire system energy consumption. Energy dumped for control purposes accounted for just 5% of the total, which is low and desirable. However, system control was limited by the slow frequency transducer, which caused some short term back-driving of the diesel and/or dumping of diesel energy. In addition, our AOC turbine controller (prototype #1, unique, since altered) tends 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.

AOC 15/50 power curves (Figures 6 & 7) reduced from 1 Hz, hub height wind data to five minute averages show several interesting features. 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, but apparently not high wind measurements.

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 maximum at about 9kW in a 9 m/s wind. Six upwind excursions were recorded over the #2 diesel tests: 4 manually curtailed, and 2 natural 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.

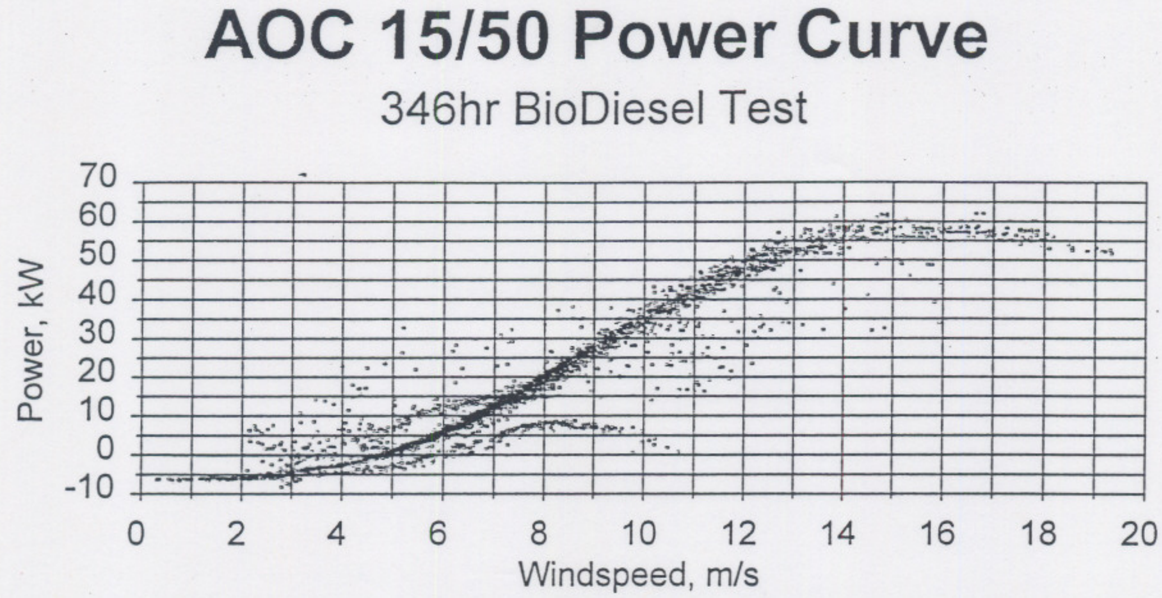

Figure 7: AOC 15/50 Power Curve for Biodiesel Tests

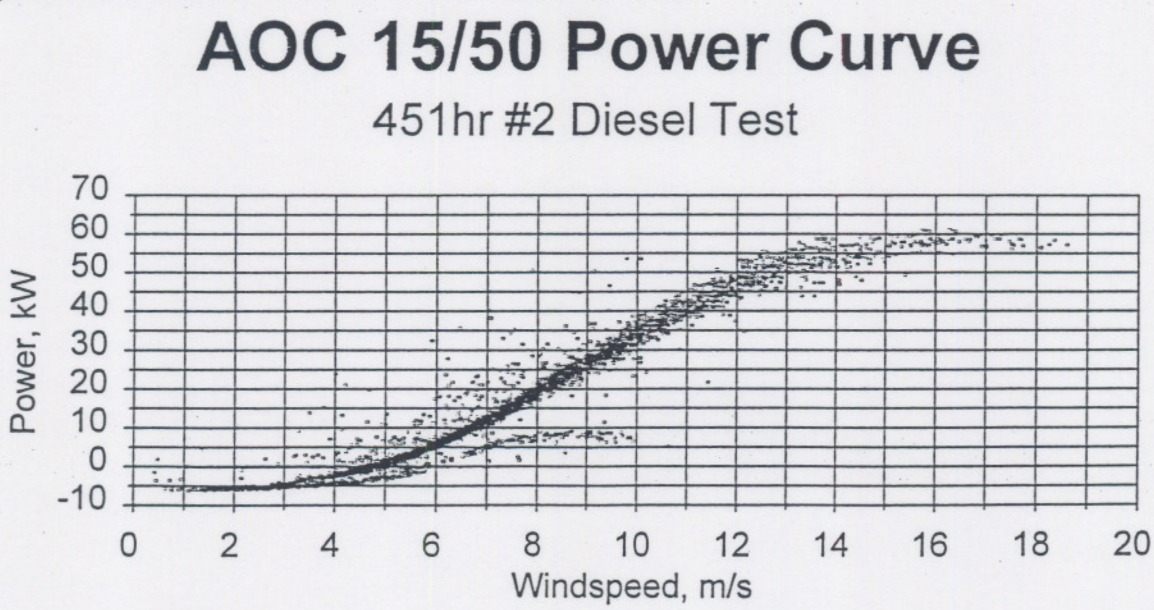

Figure 8: AOC 15/50 Power Curve for #2 Diesel Tests

The penetration histogram has some interesting features, as shown in Figure 8.

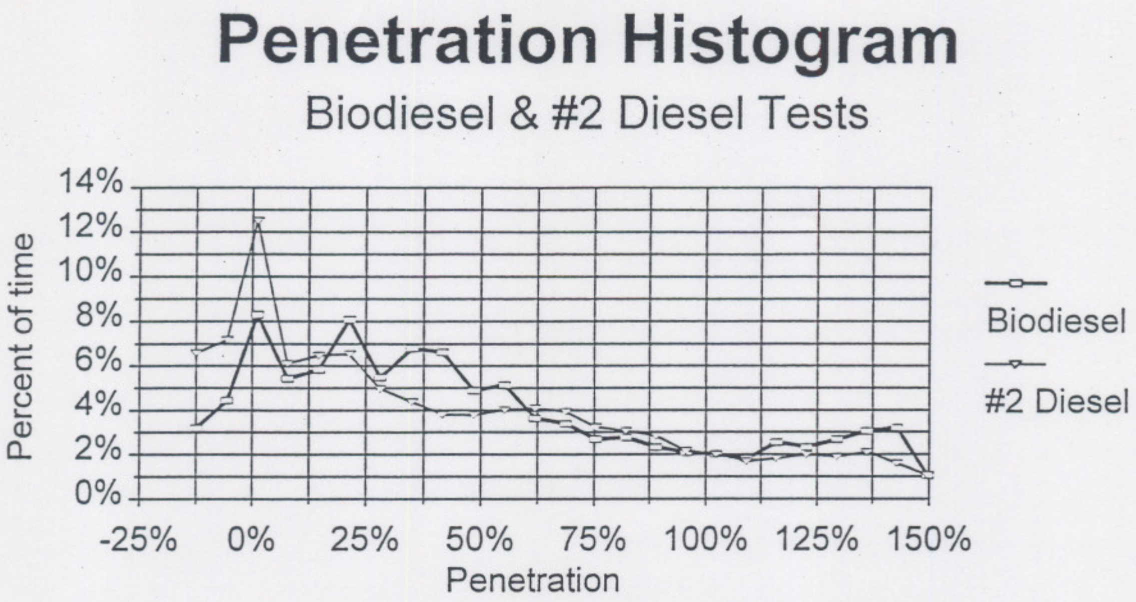

Figure 9: Penetration Histogram for Biodiesel and #2 Diesel Tests

Partial integration of this histogram shows that the turbine motored and consumed up to 6kW for 8% to 14% of the time. In addition, the diesel engine idled 14% to 18% of the time with enough wind power to cover the entire load by itself. This indicates that significant improvements in fuel saving might be realized with a turbine controller that prevents motoring and upwind operation and improved system controls to allow the diesel to be shut down when stable penetration exceeds 100%.

Over nearly 800 hours of testing of the WHRL simple wind/diesel configuration, our hybrid has performed well. An 18% 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. While the use of biodiesel fuel makes for a completely renewable energy system, an unexpected bonus is improved droop frequency control by the diesel governor. Problems of turbine motoring and operating upwind have been identified and offer opportunity for increased wind power for a minimal effort in control programming. In addition, there is potential for increased fuel savings by shutting down the diesel when adequate wind power is available to cover the entire load.

WORKSHOP REPORT

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