Technical Report

September 2003 • NREL/TP-500-34756

Power Performance Test Report for the Southwest Windpower AIR-X Wind Turbine

J. van Dam, M. Meadors, H. Link, P. Migliore

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Prepared under Task No. WER3.2504

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The National Renewable Energy Laboratory (NREL) is a national laboratory of the U. S. Department of Energy (DOE), and as an adjunct of the U. S. government, cannot certify wind turbines. The information in this report is limited to NREL's knowledge and understanding as of this date.

The results presented in this report are only valid for the turbine and its settings at the time of the test. Based on field test results, Southwest Windpower (SWWP) made several upgrades to the AIR-X software since testing at the National Wind Technology Center (NWTC) took place. NREL has not tested the impact of those changes.

4. Introduction

In the period from 14 October 2002 to 16 January 2003, an early production version of the AIR-X was installed at the NWTC test site for acoustic noise testing. In addition to the signals required for the noise testing, additional instrumentation that allowed power performance testing in accordance with IEC 61400-12 [1] was added. The results of that test are described in this report.

Please note that this test and the test report are not an accredited power performance test/test report because parts of the NWTC quality assurance system were not followed.

Power Performance Test
Southwest Windpower Air-X

Sea-Level Density Power Curve (1.225kg/m^3)

Report Created: July 14, 2003

Turbine Specifications:

Rated Power:	400 W
Cut-in Wind Speed:	3 m/s
Cut-out Wind Speed:	N/A m/s
Rated Wind Speed:	12.5 m/s
Rotor Diameter:	1.14 m
Control Type:	Stall

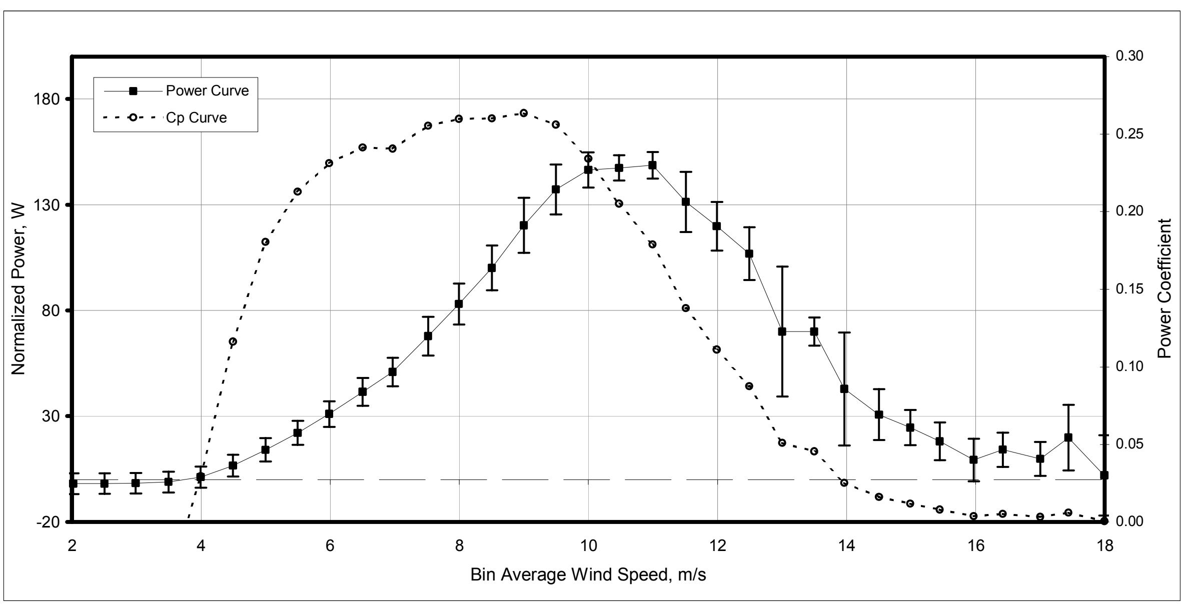
Site Conditions:

Average Air Density:	1.020 kg/m^3
Measurement Sectors:	243-24 °

Test Statistics:

Start Date:	October 14, 2002
End Date:	January 16, 2003
Amount of Data Collected:	1303.5 hours
Highest Bin Filled:	18.0 m/s

Bin Wind Speed (m/s)	Bin Power (W)	Number Data Points	Cp
0.59	-2.43	42	-18.85
1.06	-2.27	193	-3.03
1.54	-2.08	354	-0.92
2.02	-1.97	768	-0.38
2.50	-1.86	806	-0.19
2.99	-1.69	671	-0.10
3.49	-1.11	506	-0.04
3.99	1.17	481	0.03
4.49	6.59	384	0.12
5.00	14.08	381	0.18
5.50	22.10	318	0.21
5.99	31.02	319	0.23
6.50	41.49	310	0.24
6.97	50.94	272	0.24
7.52	67.85	254	0.26
8.00	83.06	232	0.26
8.51	100.11	207	0.26
9.00	120.23	165	0.26
9.50	137.21	175	0.26
10.00	146.48	169	0.23
10.48	147.44	146	0.21
11.00	148.72	127	0.18
11.51	131.31	118	0.14
11.99	119.83	87	0.11
12.49	106.83	65	0.09
13.01	70.00	56	0.05
13.50	70.01	46	0.05
13.97	42.84	43	0.03
14.50	30.71	35	0.02
14.99	24.62	27	0.01
15.45	18.11	23	0.01
15.97	9.29	15	0.00
16.42	14.14	13	0.01
17.00	9.80	6	0.00
17.44	19.82	4	0.01
18.00	2.01	3	0.00



5. Test Turbine and Test Site

The AIR-X is a three-bladed upwind turbine rated at 400 W. The AIR-X is similar to the Air 403 except for the controller of the AIR-X that prevents aeroelastic flutter. When the rotor speed or DC voltage is too high, the turbine will enter stall mode. When the rotor speed exceeds a preset limit while in stall mode the turbine shuts down.

The AIR-X tested at the NWTC is a 12-V marine version. The marine version includes sealed electronics and corrosion protection (the standard version does not include these features). More turbine details can be found in Table 1.

In the data shed, the DC output of the turbine was connected to a DC bus that was connected to a battery bank and an Enermaxer™ load controller. The Enermaxer™ kept the voltage on the DC bus constant at 13.2 V by controlling power flow to a dumpload, which prevented the turbine from shutting down due to high voltage caused by full batteries.

The test turbine was installed on Site 1.6 at the NWTC, approximately 8 km south of Boulder, Colorado. The site is located in somewhat complex terrain at an approximate elevation of 1850 m above sea level.
Figure 1 shows a plot plan of the test site with topography lines listed in feet above sea level. Upwind of the turbine, the Rocky Mountain foothills contribute to relatively high turbulence levels.

During the test, the turbine was mounted on a 13.1-m tower. The anemometer was mounted at hub height on a boom from the tower at 3.06 m (2.7 rotor diameters) toward 305°. The prevailing wind direction on the test site is 292°. Figure 2 depicts the test set-up.

Wind directions from 243° through 360° and 0° through 24° were used for this test, which is similar to the measurement sector for the tests done on the Air 403 on the same tower. No site calibration has been performed.

The NWTC test site has a low air density (approximately 1.0 kg/m^3) and high turbulence intensity (18% at 15 m/s). Both of these parameters affect the test results. For example, low air density will result in lower power output compared to output at sea level sites. The international standard for power performance measurements, IEC 61400-12, provides a method to correct for this effect, but the correction is not entirely accurate. Also at high turbulence intensity, stronger and more frequent gusts cause the turbine to exceed rpm limits at a lower average wind speed. Gusts also cause it to shut down more often while in stall mode.

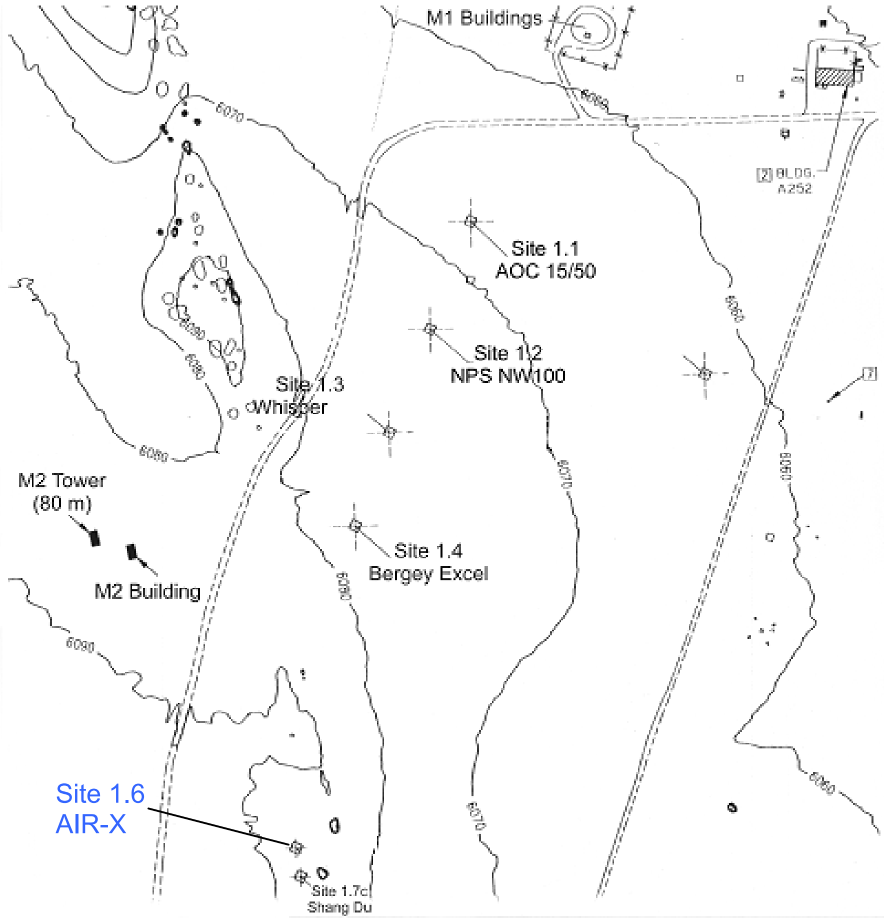


Figure 1. Plot plan of the NWTC test site.

Figure 2: The AIR-X turbine at the NWTC.

Table 1. AIR-X Turbine Configuration and Operational Data

General Configuration:	
Make, Model, Serial Number	SWWP AIR-X Marine #61269
Rotation Axis	Horizontal
Orientation	Upwind
Number of Blades	3
Rotor Hub Type	Rigid
Rotor Diameter (m)	1.14
Hub Height (m)	13.0
Performance:	
Rated Electrical Power (W)	400
Rated Wind Speed (m/s)	12.5
Cut-in Wind Speed (m/s)	3
Cut-out Wind Speed (m/s)	N/A
Rotor:	
Swept Area (m^2)	1.02
Rotational Speed (rpm)	0-850
Tilt Angle (deg)	4.5°
Blade Pitch Angle (deg)	0.7°
Direction of Rotation	Clockwise as seen from upwind
Overspeed Control	Stall
Tower:	
Type	Lattice plus tube extension
Height (m)	12.8
Control/Electrical System:	
Controller: Make, Type	Microprocessor-based internal circuit board
Power Converter: Make, Type	Diode bridge
Electrical Output: Voltage, Frequency, Number of Phases	12V DC
Yaw System:	
Wind Direction Sensor	Tail
Yaw Control Method	Free yaw

6. Instrumentation

A list of instruments used in this test is given in Table 2. All instruments, with the exception of the temperature sensor, were calibrated prior to the test period. Ten-minute statistics (mean, maximum, minimum, and standard deviation) of all channels, based on 1-Hz sampling, were stored in the datalogger. During noise tests, 10-second averages were collected as well.

Table 2. Instruments Used in AIR-X Power Performance Test

Signal	Manufacturer	Model	Serial Number	Calibration Due Date
Primary wind speed	Met One	010C	U2644	8/30/2003
Secondary wind speed	Met One	010C	W2391	8/30/2003
Wind direction	Met One	020	W5514	8/30/2003
Datalogger	Campbell Scientific	CR23X	1214	1/18/2003
Power transducer	Ohio Semitronics	PC8	9020038	8/30/2003
Air pressure	Vaisala	PTB101B	T2250003	4/17/2003
Air temperature	Met One	T200	0566229	11/19/2002

The uncertainty components used in the analysis are given in Table 3.

Table 3. Standard Uncertainty Components

Component	Amount	Unit	Source
Power			
Voltage Transducer	N/A		
Current Sensor/Signal Conditioner	Incl. in PT		
Power Transducer	4.8	W	Specification
Data Acquisition	0.9	W	Datalogger specs.
Resistor	0.006	% reading	Specification
Wind Speed			
Anemometer	0.06	m/s	Calibration.
Operational Characteristics	1.73	% reading	Estimate
Mounting Effects	1.73	% reading	Estimate
Terrain Effects	2.00	% reading	IEC 61400-12
Data Acquisition	0.00	m/s	Estimate
Temperature			
Temperature Sensor	0.15	% reading	Specification
Radiation Shielding	1.15	% reading	Specification
Mounting Effects	0.1	% reading	IEC method
Linearization	0.12	% reading	Estimate
Data Acquisition	0.03	% reading	Datalogger specs
Air Pressure			
Pressure Sensor	2	mbar	Specification
Mounting Effects	0.11	% reading	IEC method
Data Acquisition	0.8	% reading	Datalogger specs

7. Results

Figure 3 gives the binned power curve for site average air density (1.02 kg/m^3) and the sea level air density (1.225 kg/m^3). For the AIR-X, normalization to sea level air density is made by multiplying power by the ratio of sea level air density to site air density. These results are based on data sampled once per second and "pre-averaged" into 10-minute data points. The binning process sorts the data points into 0.5 m/s wind bins and then averages the power data within each wind bin.

Table 4 gives the results in tabular format for sea-level conditions. Besides the bin-averaged wind speed and power, it shows the number of data points in each bin (3 is the minimum), and it shows the uncertainty in each bin as calculated using the method given by IEC 61400-12. Table 5 indicates the annual energy production (AEP) from the turbine, assuming no downtime or outages. These results characterize the performance that an owner should expect from the turbine. AEP-measured assumes there is no power produced between the highest filled bin (three 10-minute data points or more) and cut-out wind speed (here assumed 25 m/s). AEP-extrapolated assumes the turbine produces the power level from the highest filled bin all the way up to cut-out wind speed. Since the highest filled bin (18 m/s) in this test has a low power level, the two AEP numbers differ very little.

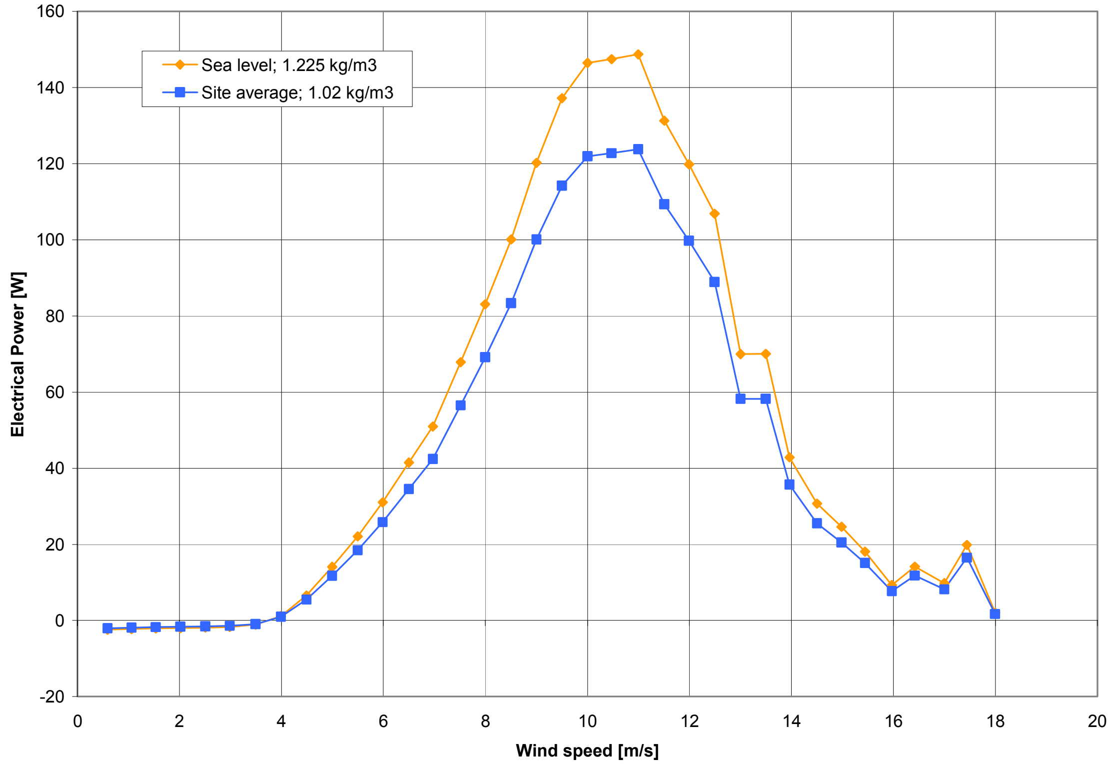


Figure 3. Power curve for the AIR-X based on 10-minute preaveraged data.

Figure 4 depicts a scatter plot of 10-minute average, and the 1-sec maximum and 1-sec minimum in each 10-minute data point vs. the 10-minute average wind speed at the air density of the test site. Note that the maximum 1-sec (instantaneous) power output of this turbine is close to 750 W while the maximum 10-minute average power output is only 240 W. Please note that these instantaneous power readings should not be used to predict energy production.

Ten-second data provide another view of the turbine's behavior. Figure 5 shows three distinct operating modes: normal operation, stall mode, and automatic shut-down. In between are transition points between the three operating modes. The turbine moves quickly from one mode to another. This turbine behavior has significantly reduced average power below peak power levels, and it is expected that small changes to the control algorithm or differences in wind turbulence could lead to significant changes in turbine performance.

Table 4. Sea Level Normalized Power Curve

Measured power curve Reference air density 1.225 kg/m^3				Category A Uncertainty	Category B Uncertainty	Combined Uncertainty
Bin no.	Hub-height wind speed [m/s]	Power output [W]	No. of data sets in bin	Standard uncertainty s_i [W]	Standard uncertainty u_i [W]	Standard uncertainty $u_{c,i}$ [W]
1	0.59	-2.43	42	0.10	4.89	4.89
2	1.06	-2.27	193	0.05	4.88	4.88
3	1.54	-2.08	354	0.04	4.88	4.88
4	2.02	-1.97	768	0.03	4.88	4.88
5	2.50	-1.86	806	0.03	4.88	4.88
6	2.99	-1.69	671	0.04	4.88	4.88
7	3.49	-1.11	506	0.08	4.89	4.89
8	3.99	1.17	481	0.13	4.93	4.93
9	4.49	6.59	384	0.22	5.16	5.17
10	5.00	14.08	381	0.26	5.49	5.50
11	5.50	22.10	318	0.37	5.71	5.72
12	5.99	31.02	319	0.48	6.07	6.09
13	6.50	41.49	310	0.64	6.54	6.58
14	6.97	50.94	272	0.94	6.72	6.78
15	7.52	67.85	254	1.08	9.02	9.08
16	8.00	83.06	232	1.54	9.59	9.72
17	8.51	100.11	207	1.91	10.43	10.60
18	9.00	120.23	165	2.29	12.77	12.97
19	9.50	137.21	175	2.55	11.57	11.85
20	10.00	146.48	169	2.94	7.71	8.25
21	10.48	147.44	146	3.36	4.98	6.00
22	11.00	148.72	127	3.79	5.01	6.28
23	11.51	131.31	118	4.43	13.43	14.14
24	11.99	119.83	87	5.02	10.37	11.52
25	12.49	106.83	65	5.18	11.45	12.57
26	13.01	70.00	56	4.66	30.33	30.69
27	13.50	70.01	46	4.49	4.89	6.64
28	13.97	42.84	43	4.31	26.36	26.71
29	14.50	30.71	35	3.58	11.55	12.09
30	14.99	24.62	27	3.12	7.74	8.35
31	15.45	18.11	23	2.71	8.50	8.92
32	15.97	9.29	15	2.11	9.81	10.04
33	16.42	14.14	13	3.15	7.47	8.10
34	17.00	9.80	6	4.93	6.34	8.03
35	17.44	19.82	4	7.38	13.61	15.48
36	18.00	2.01	3	1.59	18.89	18.96

Table 5. Estimated Annual Energy Production

Estimated AEP Reference air density 1.225kg/m^3 Cut-out wind speed 25 m/s (extrapolation by constant power from last bin)					
Hub-height annual wind speed (Rayleigh)	AEP-measured (measured power curve)		Uncertainty of measured power in terms of standard deviation of AEP		AEP-extrapolated (extrapolated power curve)
m/s	kWh		kWh	%	kWh
4	126	Complete	50	39%	126
5	254	Complete	56	22%	254
6	373	Complete	63	17%	373
7	456	Complete	68	15%	457
8	501	Complete	73	15%	502
9	515	Complete	75	15%	516
10	508	Complete	76	15%	509
11	488	Complete	75	15%	489

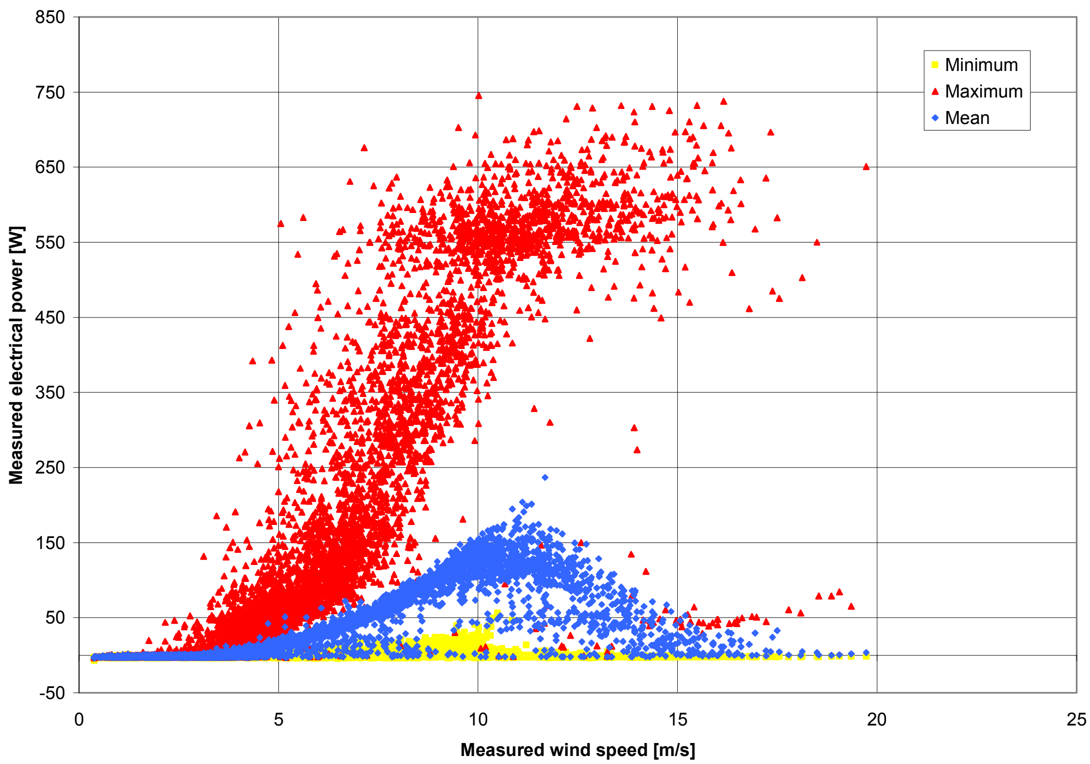


Figure 4. Ten-minute-based scatter plot for the AIR-X.

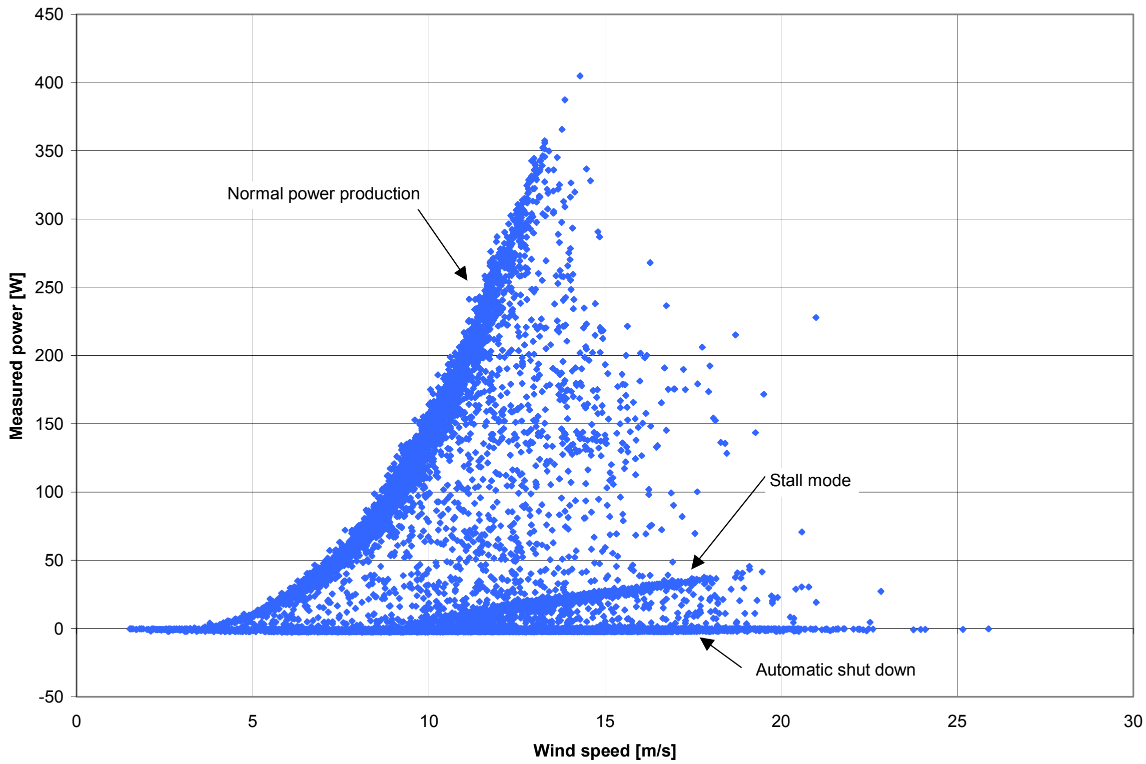


Figure 5. Ten-second-based scatter plot for the AIR-X.

8. Comparison of Results with Publicly Available Data

There are two publicly available sources for AIR-X power performance data: SWWP's Web site [2], which provides power curves and energy estimates, and Hugh Piggott's Web site, which gives power curves as measured by Paul Gipe [3].

SWWP's Web site provides instantaneous power curves for both turbulent and non-turbulent environments. Figure 6 shows both of these curves.

Paul Gipe tested three early production versions of the AIR-X, which were designated AirX.1, AirX.2, and AirX.3. Figure 6 depicts these three power curves as well. Finally, the 10-minute, sea-level-normalized power curve measured by NREL is given in the graph.

The NREL power curve matches reasonably well with the power curves measured by Paul Gipe. At lower wind speeds (<10 m/s), the 10-minute averaged power curves match well with the SWWP "turbulent" curve. At higher wind speeds (>10 m/s), the 10-minute average power curves are significantly lower than the instantaneous turbulent power curve measured by SWWP.

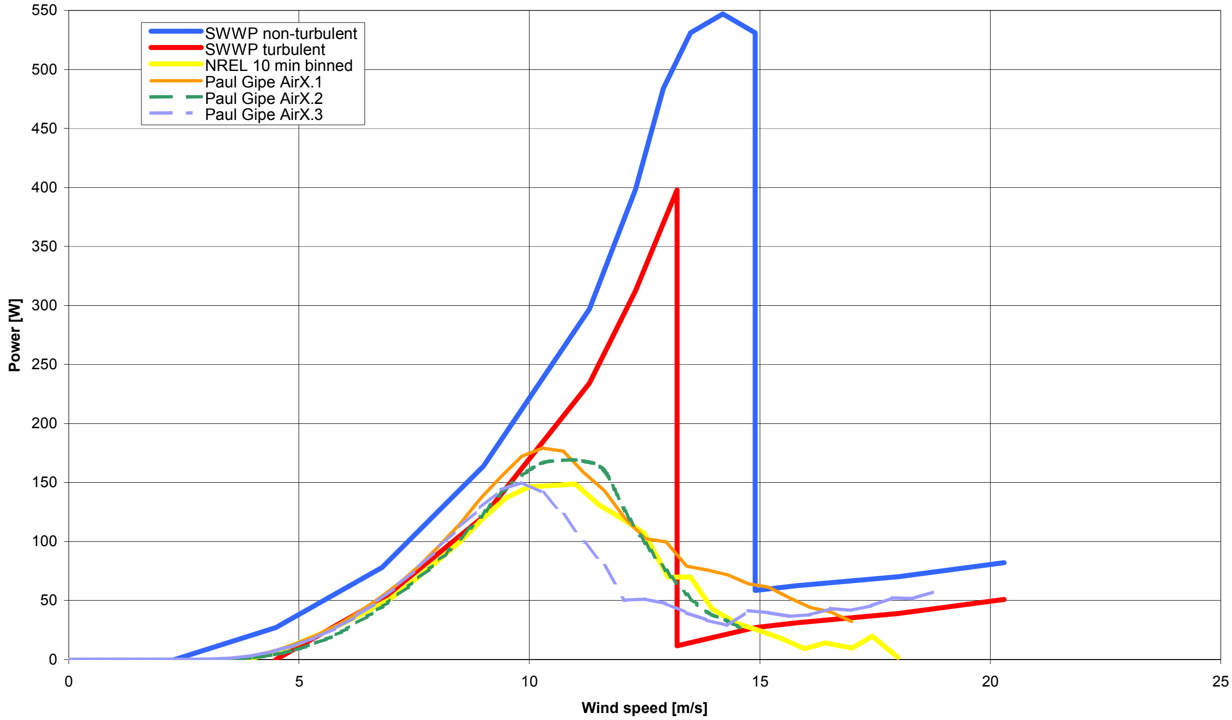


Figure 6. Comparison of NREL power curve to published power curves.

Figure 7 depicts NREL's 10-second data compared with the power curves given by SWWP. It shows that the normal power production and the stall mode of the "turbulent" curve are well matched by NREL data. The SWWP curve apparently does not include any data from automatic turbine shut-downs or transitions between the operating states. NREL's 10-second data also show that the turbine operates in stall mode at lower wind speeds than SWWP predicts. NREL did not obtain data that correspond with the SWWP "non-turbulent" curve.

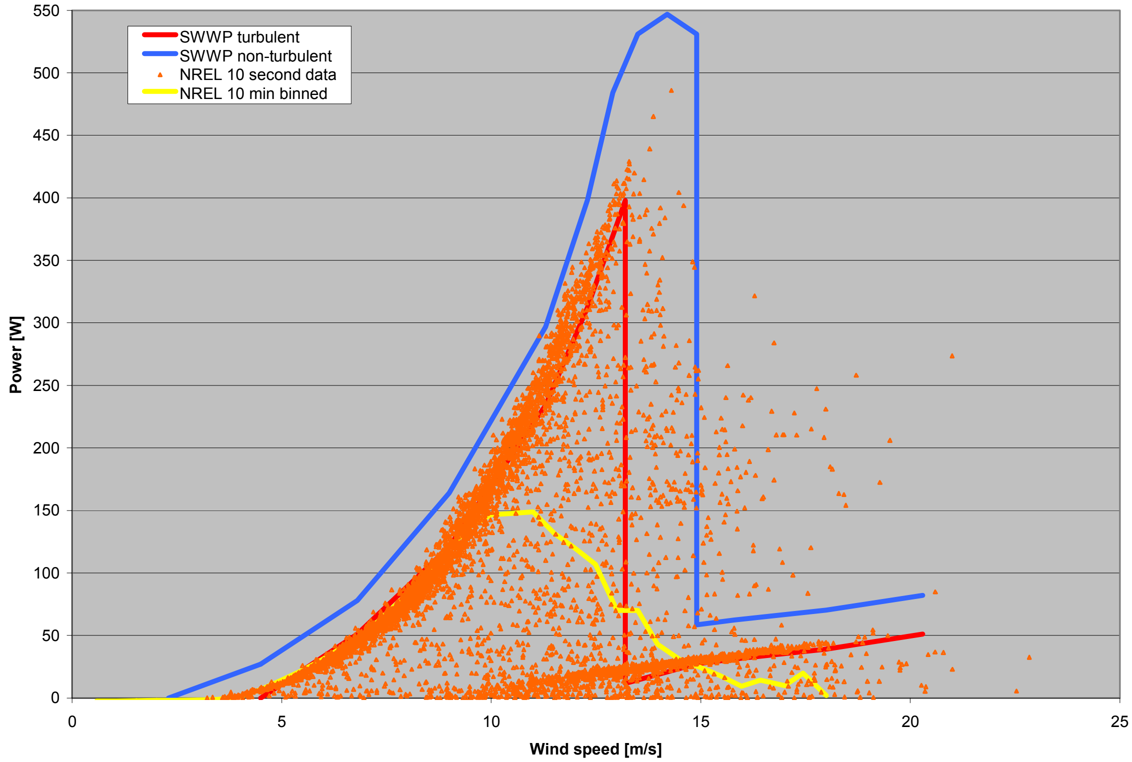


Figure 7. Comparison of NREL 10-second data with power curve published by SWWP.

Figure 8 shows the energy prediction based on data from SWWP's Web site [3] (multiplied by 12 to get AEP), the AEP based on the NREL 10-minute power curve, and the AEP estimated from the power curves published by Gipe. At low wind speeds, NREL's and Gipe's results agree with SWWP's predictions for turbulent environments. At higher wind speeds, the SWWP predictions trend significantly above NREL's and Gipe's results. In addition, the SWWP predictions show no tendency to level off at sites with higher wind speeds (as NREL's and Gipe's results indicate).

Note that most small wind turbine sites have annual average wind speeds in the range of 4 m/s to 8 m/s.

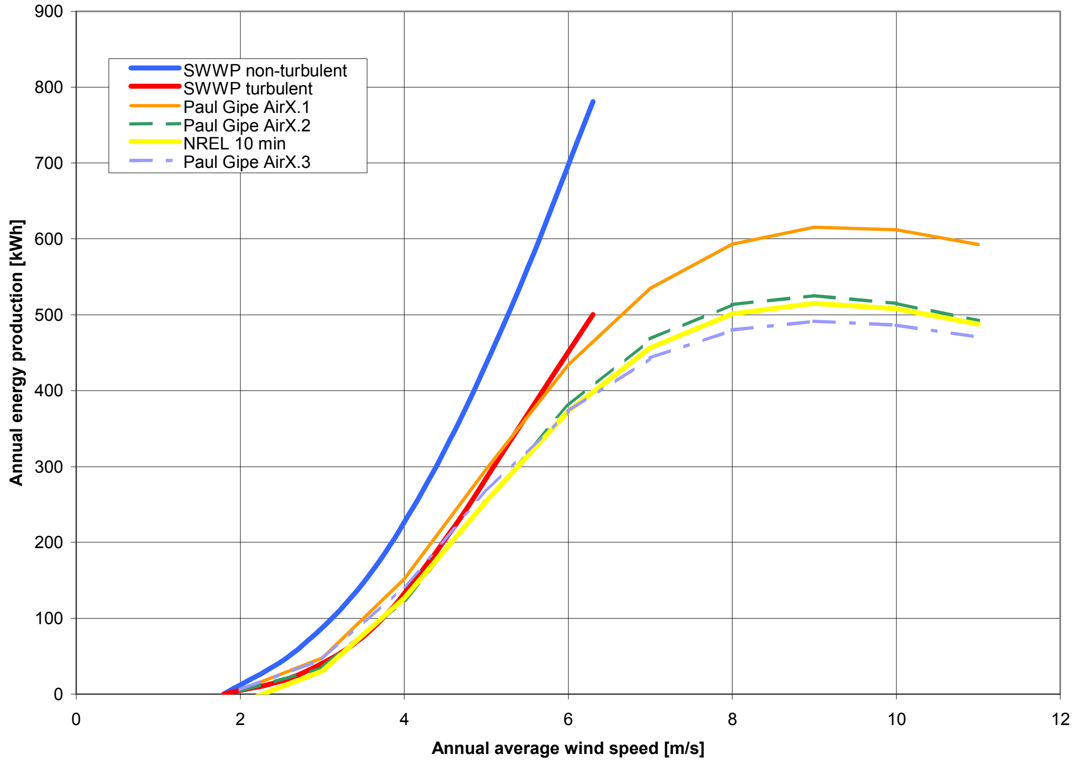


Figure 8. Comparison of estimated annual energy production based on different power curve.

Winds at NREL's NWTC test site have high turbulence. Turbulence intensity can have a large effect on small wind turbine performance, so NREL investigated its effect. Figure 9 shows power curves in which data were filtered by turbulence intensity (TI). Low TI raises the peak of the power curve, but high TI raises the lower part of the power curve slightly. Note that insufficient data were available to plot power for winds above 13 m/s at low TI. This results in an underestimation of energy production at high wind speed sites.

The estimated AEP based on those power curves is given in Figure 10[1]. The figure shows that, at lower annual average wind speeds, there is no significant influence of turbulence intensity. At higher wind speeds, the low turbulence intensity results in higher energy capture.

The difference in AEP between the lowest TI and the second level of TI would be larger if power were available at winds above 13 m/s. Even so, the effect does not appear to be large enough to support SWWP's predictions of energy production.

[1] These estimates would be termed "measured AEP" using the nomenclature of the IEC power performance standard because power between the highest bin in the power curve and 25 m/s is assumed to be zero.

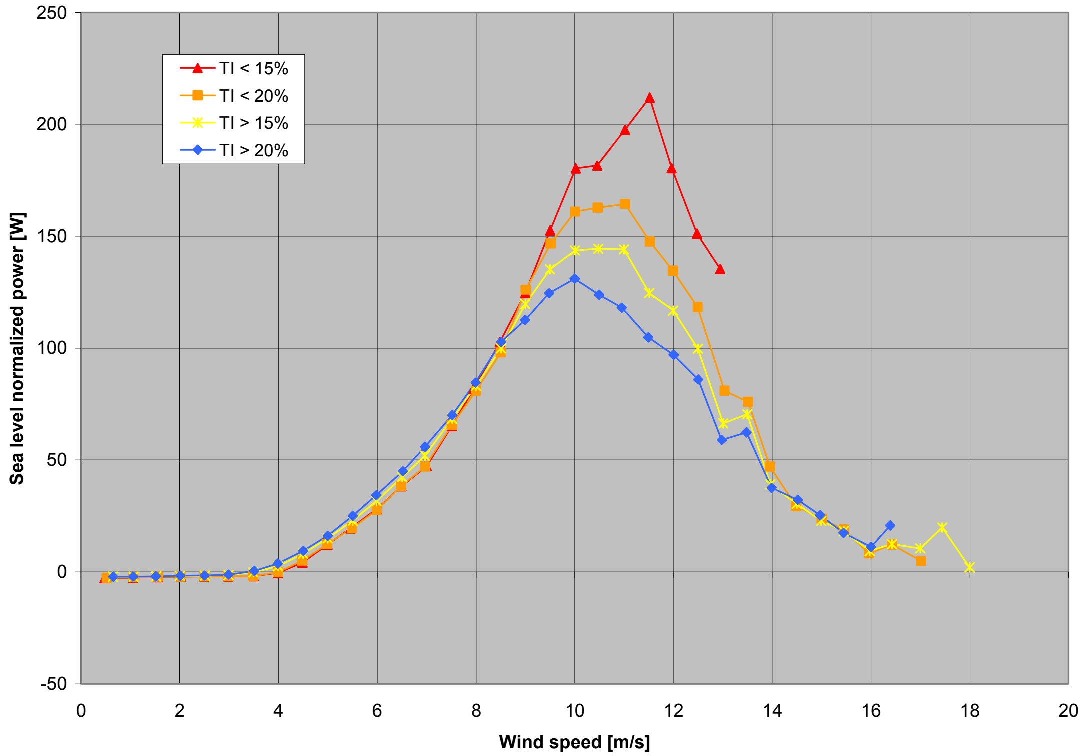


Figure 9. Influence of turbulence intensity on the power curve.

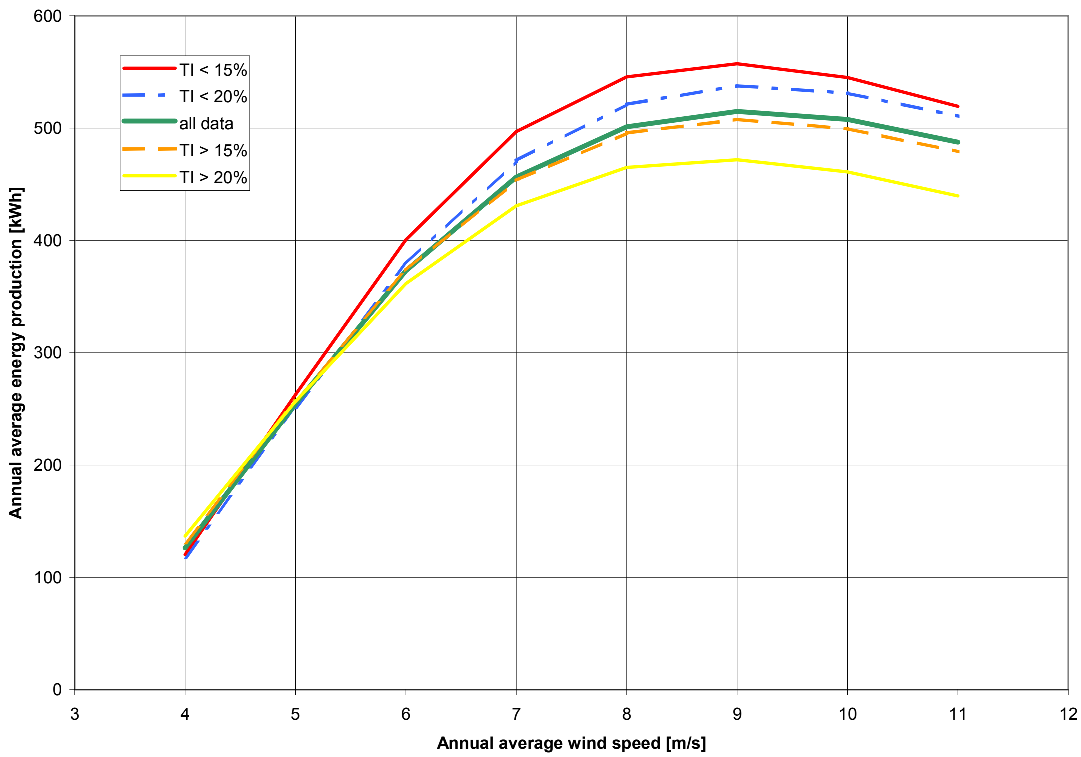


Figure 10: Influence of turbulence intensity on energy production.

9. Conclusions

1. NREL power performance test results of an early production version of the AIR-X correspond with those published by Paul Gipe [3].
2. NREL results support the turbulent SWWP "instantaneous power curve" for two of the three modes of turbine operation.
3. NREL predictions of AEP agree with predictions based on Paul Gipe's tests [3]. However, they do not support predictions made by SWWP for non-turbulent sites or for turbulent wind sites with average wind speeds above 5 m/s.
4. Low 10-minute average power compared to instantaneous power results from the control strategy of the AIR-X, which employs three modes of operation. Performance degradation is exacerbated by high turbulence at the NWTC test site. NREL expects that upgrades to the control software can improve the power curve significantly.

10. References

[1] "IEC 61400-12: Wind Turbine Generator Systems—Part 12: Wind Turbine Power Performance Testing," International Electrotechnical Commission, first edition, 1998-2002.

[2] http://www.windenergy.com/PRODUCTS/airxland.html.

[3] Gipe, P. "AirX Fails Power Curve Tests." http://homepages.enterprise.net/hugh0piggott/gipe. Last modified January 29, 2003; accessed September 8, 2003.

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