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Small Wind Turbine Testing Results from the National Renewable Energy Lab

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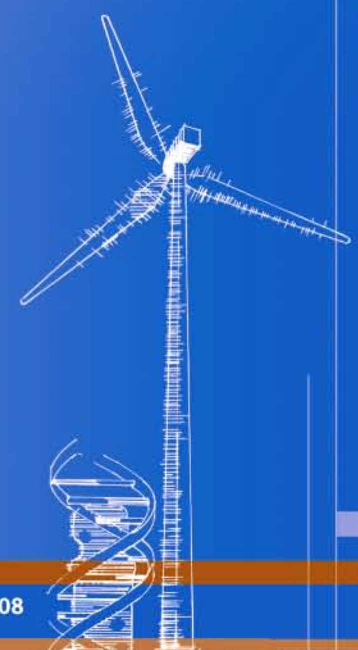

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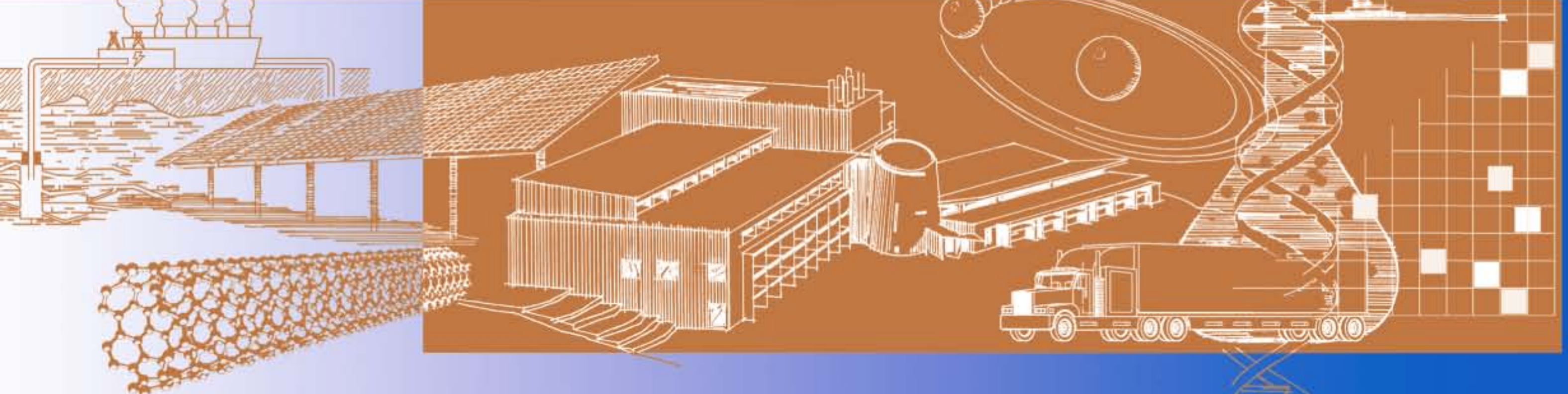

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Abstract

In 2008, the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) began testing small wind turbines (SWTs) through the independent testing project. Using competitive solicitation, four SWTs were selected for testing at the National Wind Technology Center (NWTC). NREL's NWTC is accredited by the American Association of Laboratory Accreditation (A2LA) to conduct power performance, power quality, noise, safety and function, and duration tests to International Electrotechnical Commission (IEC) standards. Results of the tests conducted on each of the SWTs will be publicly available and likely will be used by the Small Wind Certification Council (SWCC) to certify SWTs. The results also could be used by states to decide which turbines are eligible for state incentives.

Reducing barriers for SWTs to enter the market will provide consumers in a range of sectors—including residential, ranchers/farmers, business, and community applications (e.g., schools, tribes, municipal utilities, rural electric cooperatives)—the opportunity to invest in indigenous energy, and to contribute to the shift towards energy independence. The paper reports results of testing to date, and puts the test results in perspective for the average consumer. Other topics addressed include a description of DOE's second solicitation for independent testing, and a discussion of the DOE's support for developing additional testing centers to conduct preliminary screening of SWTs to identify those turbines that are not ready for the commercial market.

Introduction

The independent testing project was established at the National Renewable Energy Laboratory to help reduce the barriers of wind energy expansion. Among these barriers is a lack of independent testing results for small turbines. Independent testing results will provide turbine manufacturers with a portion of the requirements for turbine certification. Certified turbines will give consumers confidence in small turbine technology and will separate reliable turbines from those that do not perform as advertised.

The turbines selected in the first round of the independent testing project were the Mariah Power Windspire, the Gaia-Wind 11 kW, the Abundant Renewable Energy ARE 442, and the Entegrity EW50. Figure 1 shows the selected turbines installed at the NWTC. Power performance, duration, noise, and safety and function tests are performed on all turbines. Power quality testing is performed only on three-phase turbines, as the IEC Standard 61400-21 only applies to turbines with a three-phase grid connection. The available preliminary results of those tests to date are presented below and are subject to change.

Turbines Selected

The Mariah Power Windspire was installed on May 5, 2008**.** It is a 120 VAC, single-phase, grid-connected, permanent-magnet generator wind turbine rated at 1 kW. The Windspire is a vertical-axis Giromill turbine mounted on a monopole tower, and has a rotor height of 6.1 m and a rotor area of 1.2 m by 6.1 m. Testing on the Windspire was terminated on January 14, 2009 after repeated turbine problems. Partial power performance and safety and function test data was collected on the Windspire.

The Gaia-Wind 11 kW turbine was installed on May 13, 2008. It is a downwind, two-bladed, horizontal-axis turbine. Its three-phase 11-kW induction generator delivers 480 VAC to the grid. The Gaia-Wind 11 kW has a 133 m^2 swept area and is mounted on an 18.2-m monopole tower. At the time of this writing, data collection for duration, safety and function, and power performance testing was complete and power quality and acoustic noise testing were in progress.

The Abundant Renewable Energy ARE 442 was installed on June 11, 2008. It is a horizontal-axis, three-bladed turbine with a swept area of 41 m^2. It operates upwind from the prevailing wind direction and uses a furling mechanism for power control. The ARE 442 is mounted on a 30.5-m lattice tower. The turbine is a single-phase, grid-connected, permanent-magnet machine that is rated at 10 kW at 240 VAC. At the time of this writing, data collection for power performance testing was complete and duration, safety and function, and acoustic noise testing were in progress.

The Entegrity EW50 was installed on March 3, 2009. The Entegrity's three-phase induction generator produces 50 kW at 480 VAC. Its rotor-swept area is 176.7 m^2 and it operates downwind. It is a horizontal-axis machine mounted on a 30.5-m monopole tower. At the time of this writing, data collection had begun for power performance, acoustic noise, safety and function, and duration testing of the Entegrity.

Figure 1. From left to right: the Windspire, the Gaia-Wind 11 kW, the ARE 442, the EW50

Duration Testing

The duration test is conducted according to section 9.4 of the IEC Standard 61400-2: Design Requirements for Small Wind Turbines. Duration testing provides information about the turbine's structural integrity, quality of environmental protection, and dynamic behavior. The test requires a minimum of 6 months of operation, 2,500 hours of power production in winds of any velocity, 250 hours of power production in winds of 1.2 V_{ave} and greater, and 25 hours of power production in wind of 1.8 V_{ave} and greater. Section 6.2 of IEC Standard 61400-2 defines V_{ave}, which depends on the small wind turbine class as identified by the manufacturer and based on the wind speeds in which the turbine was designed to operate. The turbine must not experience any major failures during the test period and must achieve an operational time fraction of 90% or greater. The operational time fraction is defined by the following.

$$O = \frac{T_T - T_N - T_U - T_E}{T_T - T_U - T_E} \times 100\%$$

Where T_T is the total test time, T_N is the time attributed to turbine faults and manufacturer-mandated inspections and maintenance, T_U is the time during which the turbine status is unknown due to lost data or data-acquisition failure and maintenance, and T_E is the time that is excluded from analysis due to grid faults and laboratory-mandated inspections or stops.

Part of the reliable-operation requirement for the duration test includes no significant wear, corrosion, or damage to turbine components. The structural integrity and material degradation are investigated through inspections of the turbine before, during, and after the testing period. Blades, welds, and other turbine components were visually inspected and photographed before the test and any apparent abnormalities documented. After the required test data is collected, the turbine is lowered and disassembled for inspection of all individual components. Routine inspections of both the ARE 442 and the Gaia-Wind 11 kW before and during the tests have not revealed any abnormalities. Post-test inspections for the Gaia-Wind 11 kW or the ARE 442 have not occurred.

Duration testing on the Windspire was terminated on October 14, 2008. The turbine had experienced repeated problems which resulted in a low operational time fraction. These problems included repeated loose nuts at the base of the turbine, a broken washer at the base of the turbine, broken welds at the top of the turbine, airfoil displacement in the struts, and an inverter failure.

Table 1. Preliminary Duration Results for the Gaia-Wind 11 kW

	Hours of Power Production Above:			*Max Gust*	*TI @ 15*	*# Data*	T_T	T_U	T_E	T_N	*O*
Month	*0 m/s*	*9 m/s*	*13.5 m/s*	*(m/s)*	*m/s (%)*	*Points*	*(hours)*	*(hours)*	*(hours)*	*(hours)*	*(%)*
Overall	2704.9	710.6	215.0	41.9	19.0	255	7094	172.5	152.0	624.6	90.8
Jun 2008	238.2	36.2	3.8	28.6	18.5	5	518	11.3	7.8	3.3	99.3
Jul	256.0	8.5	0.3	23.9	-	0	744	78.2	2.2	38.8	94.1
Aug	115.8	4.5	0.0	19.2	-	0	744	6.3	20.0	323.0	55.0
Sep	120.5	11.7	1.8	22.4	-	0	720	36.2	30.3	174.7	73.3
Oct	236.0	45.0	12.2	32.8	17.3	10	744	0.7	1.3	0.0	100.0
Nov	348.0	98.7	22.5	37.0	20.9	40	720	22.1	0.0	0.0	100.0
Dec	339.7	160.5	54.8	41.4	17.4	68	744	7.9	27.2	32.8	95.4
Jan 2009	385.0	155.5	56.0	38.8	19.9	76	744	4.9	32.0	36.5	94.8
Feb	333.2	107.3	36.8	41.9	20.0	23	672	3.2	27.0	0.0	100.0
Mar	332.5	82.7	26.8	36.7	18.0	33	744	1.7	4.2	15.5	97.9

Table 1 shows the preliminary duration results for the Gaia-Wind 11 kW. The turbine accumulated 2,704.9 hours of total run time with an operational time fraction of 90.8%.

The low operational time fraction for August and September of 2008 was caused by the failure of two contactors in the controller. Investigations suggest that the 2-pin flat connectors used to wire the contactors were poorly connected when installed at Gaia-Wind's electrical supplier. Additionally, the Gaia-Wind 11 kW turbine controller originally was designed for a 50-Hz grid, and it is possible that the contactors that originally were installed in the controller were underrated for the 60-Hz grid at the NWTC. It now is standard for all contactors in the controller to be installed with tube connectors for a more secure connection, and all turbine controllers on a 60-Hz grid are installed with the higher-rated contactors. Since the replacement of the contactor and pin connectors, the turbine has run with a high operational time fraction.

The majority of the other time classified as T_N during the test is attributed to braking-time faults, vibration errors, and maintenance. The braking-time faults occurred when the turbine took longer to brake than designed; this usually occurred during high winds. The vibration errors are expected to have occurred from birds nesting the nacelle. With guidance from Gaia-Wind, NREL installed a screen over the opening in the nacelle to prevent birds from entering. Since the installation of the screen, the turbine has run without vibration errors.

Table 2 shows the preliminary duration results to date for the ARE 442. The ARE 442 has accumulated 2,888.8 hours of total run time with an operational time fraction of 91.3%.

The low operational time fraction that occurred in November 2008 was caused by failure of the turbine's insulated-gate bipolar transistors (IGBTs) during a simulated grid fault for safety and function testing. The majority of the remaining time classified as T_N during the test is attributed to the over-temperature and overvoltage faults that the turbine experiences in high winds. The diversion loads for the turbine were located inside the data shed and did not dissipate heat properly, resulting in temperature faults at high power production. The diversion loads were moved outside of the data shed in February 2009. Since then, the over-temperature faults have been eliminated, however the turbine now is experiencing overvoltage faults.

Table 2. Preliminary Duration Results for the ARE 442

	Hours of Power Production Above:			*Max Gust*	*TI @ 15*	*# Data*	T_T	T_U	T_E	T_N	*O*
Month	*0 m/s*	*10.2 m/s*	*15.3 m/s*	*(m/s)*	*m/s (%)*	*Points*	*(hours)*	*(hours)*	*(hours)*	*(hours)*	*(%)*
Overall	2888.8	520.7	153.0	42.9	18.9	311	6576	102.5	212.0	541.9	91.3%
Jul 2008	296.0	7.5	0.0	27.8	15.8	3	744	12.5	152.2	0.0	100.0%
Aug	286.8	9.5	0.0	26.5	16.9	1	744	30.5	4.0	0.0	100.0%
Sep	217.5	8.8	0.7	23.2	13.8	8	720	49.2	5.3	0.3	100.0%
Oct	280.5	35.7	6.7	34.0	16.9	13	744	0.8	5.0	9.1	98.8%
Nov	156.0	8.2	0.0	34.3	19.5	44	720	-0.2	0.3	279.4	61.2%
Dec	379.2	131.8	41.8	42.9	18.2	72	744	1.2	10.2	120.4	83.6%
Jan 2009	466.5	146.3	44.3	42.9	20.0	93	744	0.7	1.8	76.8	89.6%
Feb	389.3	104.5	46.3	39.5	19.7	33	672	4.0	31.7	36.7	94.2%
Mar	417.0	68.3	13.2	34.9	18.4	44	744	3.8	1.5	19.1	97.4%

Turbulence intensity (TI) is the ratio of the wind-speed standard deviation to the average wind speed. Turbulence intensity is computed for each 10-minute data set and averaged to produce the monthly values provided in Table 1 and Table 2. The average turbulence intensity at 15 m/s for the entire test period was 19.0% for the Gaia-Wind 11 kW and 18.9% for the ARE 442.

Another factor of reliable operation is that the turbine should experience no significant power degradation. Each month the average power is plotted for each wind-speed bin and analyzed for any obvious trends in power production. Examination of power degradation plots indicated no apparent power degradation for the Gaia-Wind 11 kW or the ARE 442.

The dynamic behavior of the turbine is assessed by observing the turbine in a range of operating conditions. The turbine is observed at wind-speed intervals from cut-in wind speed to 20 m/s for at least one hour in total. Tower vibrations, noise, yaw behavior, and tail movement all are documented in the logbook and included in the duration-test report. For the ARE 442 the following dynamic observations were made. During high winds, the rotor operates at yaw errors of between approximately 30 degrees and 60 degrees and the furl movements excite the tower slightly. Overall, it appears that no excessive vibrations are occurring. In winds of between 8 m/s and 12 m/s the turbine tracks the wind well. For the Gaia-Wind 11 kW, the following dynamic behavior observations were made. The turbine tracks winds well in all observed wind speeds. No excessive vibration was observed. There is a slight audible thumping noise as blades pass behind the tower.

Power Performance Testing

Power performance testing is conducted per IEC standard 61400-12-1, Power Performance Measurements of Electricity Producing Wind Turbines, referencing Annex H for small wind turbines when appropriate. Products of the test include a measured power curve, a power coefficient (C_P) curve, and an estimation of annual energy production (AEP).

For small turbines, statistical data is collected in 1-minute sets and sorted into 0.5-m/s-wide wind speed bins. Data collection is complete when the wind speed bins between 1 m/s and 14 m/s contain 10 minutes of data each, and the total database consists of at least 60 relevant hours. Wind speed bins are plotted against the corresponding bin power to produce a power curve. Power curves are normalized to sea-level air density; the site-specific air density at the NWTC is relatively low, 1.0 kg/m^3. The power coefficient is the ratio of power generated by the turbine to the power available in the wind.

Preliminary power and C_P curves for the Gaia-Wind 11 kW are displayed in Figure 2. The power curve for the Gaia-Wind 11 kW shows power measurements that are greater than rated power. Preliminary power and C_P curves for the ARE 442 are displayed in Figure 3; this turbine performed as expected.

The original inverter on the Windspire was optimized for power performance and failed after several months of operation. After the failure, a production model inverter was installed and operated until testing on the Windspire was suspended. The required amount of data was not collected on either inverter due to failures, however the incomplete preliminary power and C_P curves for both configurations are shown in Figure 4.

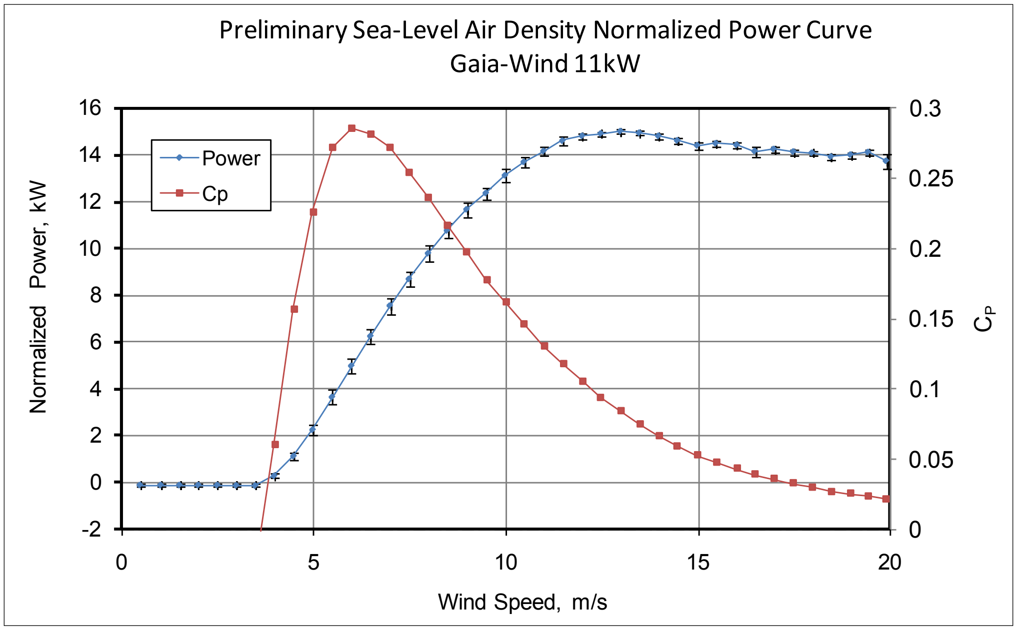

Figure 2. Preliminary power and C_P curves for the Gaia-Wind 11 kW

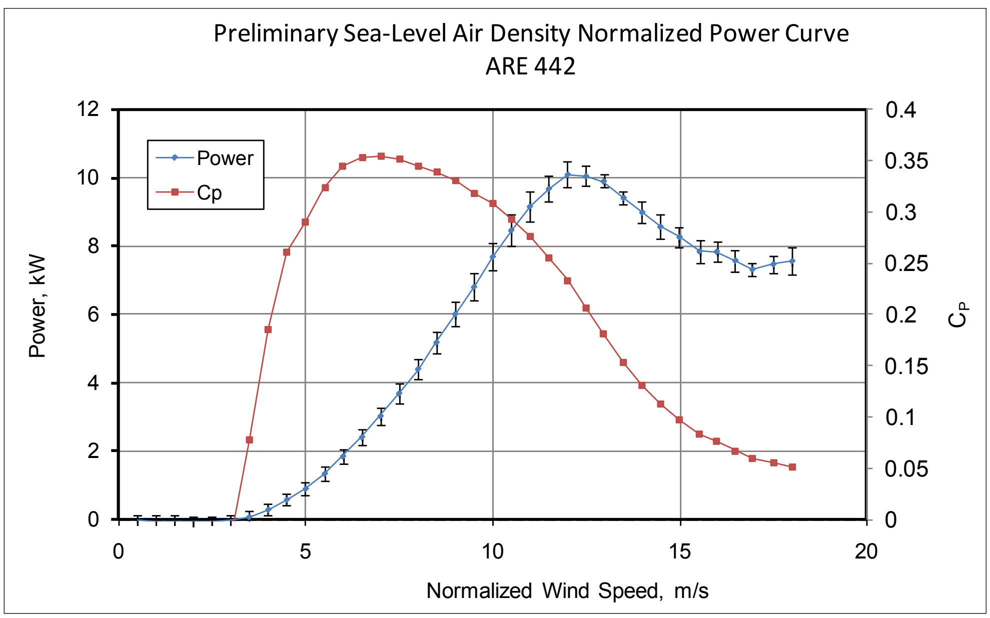

Figure 3. Preliminary power and C_P curves for the ARE 442

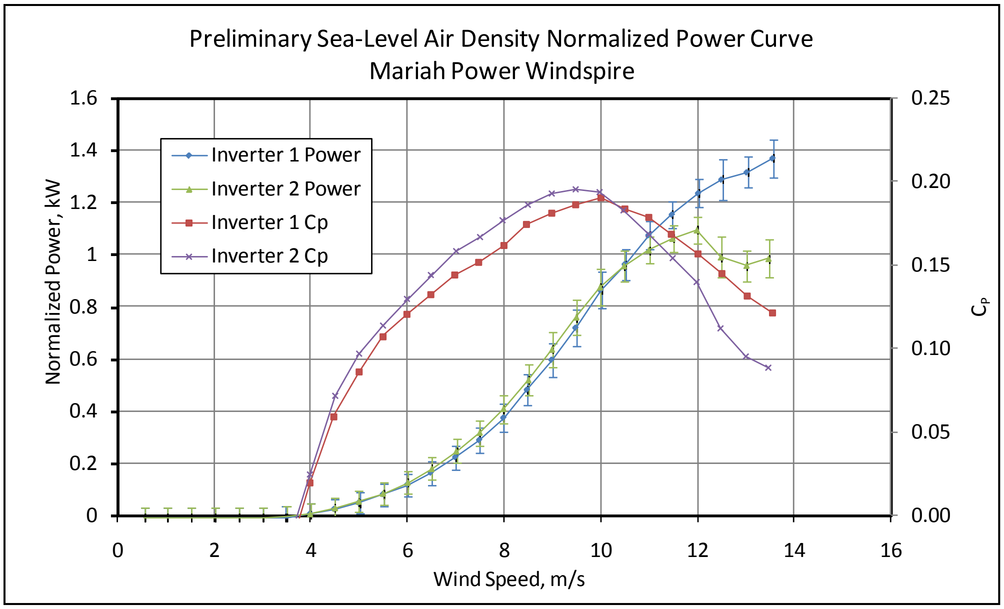

Figure 4. Mariah Power Windspire preliminary power and Cp curves for the power optimized inverter (Inverter 1) and the production inverter (Inverter 2)

Annual energy production is estimated by applying the power curve generated from power performance testing to a Rayleigh distribution. The AEP is given for annual average wind speeds at hub height for 4 m/s to 11 m/s. The measurements reported below assume no energy production beyond the highest filled bin in the power performance test. Table 3 shows the preliminary AEP as measured based on power performance data for the Gaia-Wind 11 kW and ARE 442. The AEP is not reported for the Windspire because the required amount of data was not collected.

Table 3. Preliminary Measured AEP for the Gaia-Wind 11 kW and the ARE 442

Hub Height Annual Average Wind Speed (Rayleigh) m/s	Gaia-Wind 11kW			ARE 442		
	AEP-Measured	Standard Uncertainty		AEP-Measured	Standard Uncertainty	
	kWh	kWh	%	kWh	kWh	%
4	17,716	1,692	9.6%	7,884	1,717	21.8%
5	32,122	2,093	6.5%	15,327	1,948	12.7%
6	46,292	2,284	4.9%	23,516	2,144	9.1%
7	58,690	2,327	4.0%	30,967	2,271	7.3%
8	68,525	2,285	3.3%	36,718	2,325	6.3%
9	75,474	2,197	2.9%	40,459	2,314	5.7%
10	79,617	2,087	2.6%	42,350	2,254	5.3%
11	81,326	1,966	2.4%	42,770	2,160	5.1%

Safety and Function Testing

Safety and function testing is conducted per IEC Standard 61400-2, section 9.6, and seeks to test the essential functions of the turbine system. However, NREL does not limit testing to the scope of the standard; other features that are not required by the standard also are inspected and tested. For each turbine, NREL collects data to characterize the turbine's power control, rotor-speed control, behavior upon loss of load, normal start-up, normal shutdown, and emergency shutdown. Additionally, NREL performs turbine specific tests to verify the turbine controller's function and predicted behavior. Although safety and function testing examines the essential functions of the turbine, it does not certify whether a turbine is safe to operate. Table 4 shows the preliminary safety and function data summary for the Gaia-Wind 11 kW. The turbine performed as designed with one exception. When the turbine was shut down manually using the disconnect switch and then was restarted, an over-speed error was present on the controller. The error had to be reset before the turbine could be started again.

Table 4. Preliminary Safety and Function Test Summary for the Gaia-Wind 11 kW

Test Method	Comment	Complies with Design
Power control	Turbine controls power output per design	Yes
Rotor speed control	Turbine controls rpm to 61, per design	Yes
Normal start-up	Turbine starts after several motor pulses in design wind speed and above, and below cut-out; over-speed error on start-up after manual shutdown	Partially
Normal shutdown	Turbine shuts down normally in winds less than cut-in and greater than cut-out	Yes
Emergency stop	Turbine stops within 2 to 3 seconds of pressing emergency stop button	Yes
Loss of grid	Turbine brakes immediately and stops within 2 to 3 seconds of load loss	Yes
Undervoltage / overvoltage	In an overvoltage simulation the turbine brakes immediately	Yes
High wind speed shutdown	Turbine stops in winds greater than 25 m/s and waits for start-up per the design	Yes
Rotor overspeed	Turbine brakes immediately in simulated 10% overspeed and deploys tip brakes at 15% simulated overspeed	Yes
Generator overcharge	Turbine brakes immediately in simulated generator overcharge	Yes
Excessive vibration	Vibration error registers on turbine controller after activating vibration sensor	Yes
Cable twist	Cable-twist error registers on turbine controller after lifting cable-twist arm	Yes

Table 5 shows the preliminary safety and function results for the ARE 442. The turbine's two diversion loads originally were installed inside of the data shed per the manufacturer's design. They later were moved to an enclosure outside of the data shed, after it was determined that their placement was causing repeated over-temperature faults. When the diversion loads were installed in the data shed, the over-temperature faults would occur in high-wind conditions as heat built up inside the data shed. Temperatures measured near the turbine's sensors indicated that the turbine shut down near or below its set point.

Table 5. Preliminary Safety and Function Test Summary for the ARE 442

Test Method	Comment	Complies with Design
Power control	Power is limited by the capacity of the inverters, these max out at 12 kW; after that, power is diverted to the diversion loads	Yes
Rotor speed control	Test pending	—
Yaw control	The turbine tracks the wind under all conditions; due to the furl mechanism, the rotor almost always has a yaw error	Yes
Normal start-up	Turbine starts in any winds ranging from cut-in to 25 m/s	Yes
Emergency stop	Turbine stops when stop button is pushed on the voltage clamp; this has been tested for a wide range of wind speeds	Yes

Loss of grid	Disconnecting the grid causes an immediate shutdown; in two events where a grid outage occurred in high-wind conditions, the IGBT's in the voltage clamp failed, although the turbine still shut down	Partially
Overvoltage fault	In high winds the turbine currently experiences the overvoltage fault, demonstrating that this feature works	Yes
Over-temperature fault	Temperatures measured near the turbines sensors indicate that the turbine shuts down near or below its set points	Yes

Table 6 shows the partial preliminary safety and function test summary for the Windspire. Complete safety and function test data was not collected for the Windspire before testing was terminated due to turbine problems.

Table 6. Preliminary Safety and Function Test Summary for the Windspire

Test Method	**Comment**	**Complies with Design**
Power control	Turbine controls power output per design	Yes
Rotor speed control	Turbine controls rpm per design	Yes
Normal start-up	The turbine starts normally; it experiences two resonance modes at approximately 60 rpm and 300 rpm	Yes
Normal shutdown	The turbine shuts down normally as winds drop below cut-out, however it maintain a low rpm (3–10) when braked; the turbine was not designed to shut down in high winds	Yes
Emergency stop	Turbine stops within 2 to 3 seconds of opening the disconnect switch	Yes
Loss of grid	Turbine stops within 2 to 3 seconds of load loss	Yes
Rotor over speed	Data was not collected for this test	Unknown
Overvoltage/undervoltage	Data was not collected for this test	Unknown

Power Quality

IEC standard 61400-21 for power quality is defined for three-phase turbines and only is required for medium- or high-voltage systems. Power quality testing only will be performed for the Gaia-Wind 11 kW and the Entegrity EW50 because they both are three-phase systems. Measurements include reactive power, flicker, voltage fluctuations, and harmonics. At the time of this writing, there was no data available for either turbine.

Noise Testing

IEC standard 61400-11 does not contain information specific to small wind turbines, however, they will be addressed specifically in the revision. The noise test characterizes emissions from a turbine in terms of sound power level, one-third octave levels, and tonality. For small wind turbines the IEC standard is followed with some modifications. Ten-second averages are used instead of 1-minute averages to better characterize the more-dynamic nature of small wind turbines. Also, to determine the sound pressure levels at the integer wind speeds, binning data is used instead of regression analysis. At the time of this writing, there were no results available for noise testing.

Consumer Perspective

The T_N value from the duration test gives the consumer an idea of how much downtime to expect from a turbine per year based on maintenance and faults. The operational time fraction for the Gaia-Wind 11 kW was 90.8% for the entire test period. Based on this number, the typical consumer could expect the turbine to be available to produce power 90.8% of the time. Although the actual time that the turbine is faulted can vary, NREL suspects that it might be less than reported here because the primary contributor to downtime—the failed contactors—appears to have been neutralized.

Because the downtime for the ARE occurs mostly in high winds, the operational time fraction of a particular turbine depends on the wind-speed distribution. Additionally, the furl mechanism could function differently in greater air densities, which also could affect the operational time fraction.

The average annual energy usage per household is approximately 11,000 kWh and the average energy usage per commercial establishment is approximately 77,000 kWh (Energy Information Administration 2009). Figure 5 shows the average annual energy used by consumers compared with the AEP estimated at an average hub-height wind speed of 6 m/s for the ARE 442 and Gaia-Wind 11 kW.

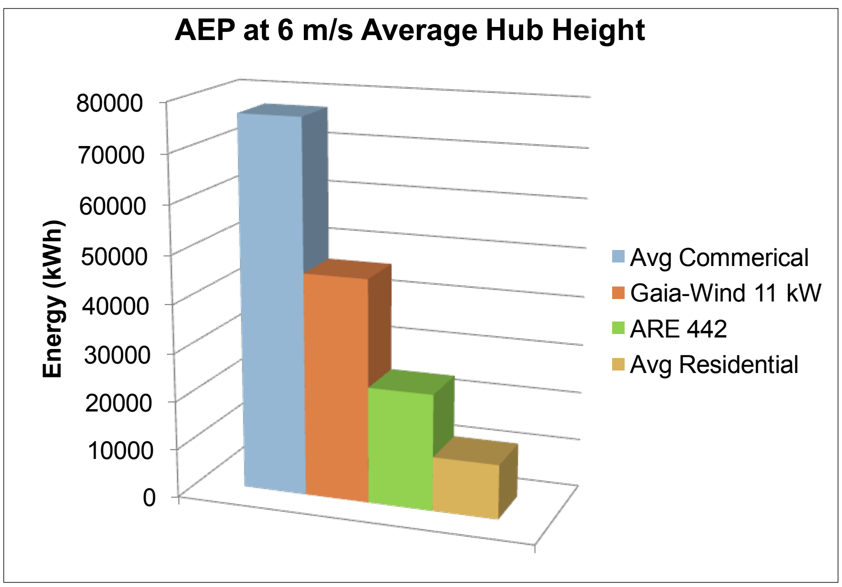

Figure 5. Average annual energy used by consumers compared with annual energy production at a hub-height wind speed of 6 m/s

Regional Test Centers

In the fall of 2008, the NWTC held a small wind testing workshop for perspective test sites. Based on the response generated at the meeting, the NWTC began developing the concept of regional test centers. NREL plans to conduct a competitive solicitation to select test centers that want to develop small turbine testing capabilities. NREL will partially fund the test centers and will provide technical support.

The Future of Independent Testing

At the time of this writing, proposals had been received and reviewed for the second solicitation of independent testing. It is expected that installation will begin on these turbines during the fall of 2009. Testing on the ARE 442 and the Gaia-Wind 11 kW is expected to continue through the spring of 2009 and possibly beyond. Testing on the Entegrity EW50 is expected to continue through the spring of 2010.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
In 2008, the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory began testing small wind turbines (SWTs) through the independent testing project. Four SWTs were selected for testing at NREL's National Wind Technology Center, accredited by the American Association of Laboratory Accreditation to conduct power performance, power quality, noise, safety and function, and duration tests to IEC standards. Results of tests conducted will be publicly available and likely used by the Small Wind Certification Council to certify SWTs. Results also could be used by states to decide which turbines are eligible for state incentives. Reducing market barriers for SWTs will provide a range of consumer sectors—including residential, ranchers/farmers, business, and community applications (e.g., schools, tribes, municipal utilities, rural electric cooperatives)—the opportunity to invest in indigenous energy and contribute to energy independence. The paper reports results of testing to date, and puts the results in perspective for the average consumer. Other topics addressed include a description of DOE's second solicitation for independent testing, and a discussion of the DOE's support for developing additional testing centers to conduct preliminary screening of SWTs to identify turbines not ready for the commercial market.

15. SUBJECT TERMS
Wind; small wind turbines; power performance; power quality; manufacturer; safety and function; three-phase grid connection; noise testing

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