Scheduling Power Performance Testing at the National Small Wind Turbine Centre

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ABSTRACT
The global growth in small wind turbine (SWT) markets and in the number of SWT manufacturers has brought about an urgent need for more rigorous testing of SWTs in order to ensure safety, reliability and performance. The National Small Wind Turbine Centre (NSWTC) was established in August 2008 to test and label turbines in the range 1 kW – 5 kW, in order to help the development of the SWT industry in Australia and abroad. In February 2010, an NSWTC turbine test site was established at Henderson, Western Australia. The aim of this study was to model the wind resource at the NSWTC test site to give insight into the scope and scheduling of power performance testing at the site. National and international SWT performance standards were reviewed in order to assess the completion requirements for testing. Wind modelling was carried out using the wind atlas model, WAsP, in order to predict the long-term wind resource at the site. The results of the modelling were used to develop spreadsheets to guide the NSWTC in planning their program of testing. This work proved valuable in developing a tool that can provide recommendations on turbine selection and suitable months for testing. The predictions from the tool are compared with the experience of testing the SOMA 1000 wind turbine, the first turbine to be tested at the site. The results show that although a power performance curve can be completed to standard in a few months, testing of 1-2 years is advisable to reduce uncertainty with power values at high wind speeds.

Keywords – performance standards, power curves, power performance testing, small wind turbines, Weibull distribution, wind resource assessment

INTRODUCTION
The global market for small wind turbines (SWTs) has shown considerable growth in recent years, particularly in the US and UK (Whale & Brix 2009). The U.S. market accounts for around 50% of the global market and in 2009 surpassed the milestone of 100 MW of small wind installations (AWEA 2010). In 2010 there was a 65% increase in the annual installations of SWTs in the UK, establishing a new record in SWT deployment for that nation (RenewableUK 2011).

In addition to the growth in the market, the growth in the number of global manufacturers of SWTs has been significant, rising from an estimated 69 manufacturers in 2006, to approximately 250 in 2009 (AWEA 2008, AWEA 2010). A number of observers have expressed concern, however, that not all models of SWTs being
produced are reliable or safe (Gipe 1997, Ruin & Thor 2006, Whale 2009). Historically, SWT manufacturers do not have to undergo the same stringent certification procedures as large wind turbine manufacturers and SWT test data is often provided by manufacturers without verification. Gipe (2000) shows that there are often discrepancies between measured power curves and those supplied by the manufacturer.

In recent years there has been a movement to improve the reliability of SWTs. On a national level, the American and British Wind Energy Associations have both produced safety and performance standards for small wind turbines (AWEA 2009, BWEA 2008). The US and the UK have also established frameworks for certification of SWTs, through the Small Wind Certification Council (SWCC) and the Microgeneration Certification Scheme (MCS), respectively. This movement was elevated to an international level with the formation of a Small Wind Turbine Liaison Program jointly co-ordinated by the International Electrotechnical Commission (IEC) and the International Energy Agency (IEA). The program has led to a complete revision of IEC61400-2 (IEC 2006), the international standard for small wind turbines, and the publication of recommended practices on testing of small wind turbines (IEA Wind 2011).

A small number of organizations around the world have publicised informal testing of small wind turbines (e.g. Encraft 2009, Gipe 2009) while others are now testing to the newly formed standards and are introducing much-needed rigour to the testing of small wind turbines e.g. Bowen et al. (2006). Rigorous testing consists of design data testing, power and acoustic performance testing, and safety and duration testing. The SWCC advise that “…testing and reporting may take as much as 1 or 2 years to complete” (SWCC 2011).

The National Small Wind Turbine Centre (NSWTC) was established in August 2008 and is funded by the Federal Government’s Department of Climate Change and Energy Efficiency. The test centre’s primary aim is to test and label turbines in the range 1 kW – 5 kW, which will ultimately help the development of the SWT industry in Australia and abroad (Whale and Brix, 2009). 18 potential sites were initially identified for establishing the test facility. Five sites were short-listed and ranked against a predetermined list of criteria. The wind resource at the site has to be balanced against other factors including, security, area available, tenure, lease costs, accessibility and on-site resources. In this case the top-ranked wind resource site could not be selected due to planned future construction in the area. Thus it was decided to focus on another of the short-listed sites in the suburb of Henderson in Perth. In February 2010, the NSWTC test site was established at Henderson with an on-site wind monitoring station at 10 m a.g.l. The site features an exposed grassy hill with the nearest trees 150 m away. The NSWTC aims to use the new site to test a number of SWTs in accordance with international standards for power performance, noise and durability. The work in this paper focuses only on the power performance testing of the SWTs.

The planned testing of SWTs at the NSWTC test site gave rise to a number of research questions including:

- What is the long-term wind resource at the site?
- What are the most suitable times of the year for power performance testing of a given turbine and what is the overall time required to complete the test?
- What size of turbines can be tested on site?

1 metres above ground level
The aim of this work was to model the wind resource at the NSWTC test site to give insight into the scope and scheduling of power performance testing at the site.

The specific objectives were to:
- Review SWTs to find their typical performance characteristics;
- Review relevant SWT power performance standards in order to assess the completion requirements for testing;
- Model the wind regime at the site;
- Predict the type of SWTs that can be tested, the best time of year for testing and how long testing will take, and
- Compare the outcomes of the predictions with the experience of testing a turbine at the NSWTC site.

**METHODOLOGY**

**Revision of SWTs and SWT standards**

A small wind turbine is defined in accordance with the IEC61400-2 standard as a wind turbine with a swept area less than 200 m². The power capacity of such a machine is typically less than 50 kW.

The performance specifications of forty SWTs were compiled ranging in capacity from 1 kW to 50 kW. This data yielded an estimate of 3 m/s as a typical cut-in wind speed of a SWT. Many SWTs do not cut-out as such and are designed to operate in wind speeds up to wind speeds of around 60-70 m/s. Many horizontal-axis SWTs will furl to protect themselves at around 16-17 m/s. Hub-heights of SWTs ranged from 5 m (for a roof-mounted 6 kW Quiet Revolution turbine) to 62 m (for a 30 kW Pitchwind machine). The data yielded an average height of 20 m although 18 m is more typical of the tower height offered by the manufacturer (since the towers often come in 6 m sections).

The international standard relevant to power performance testing of wind turbines is IEC61400-12-1 (IEC 2005). Annex H to this standard deals specifically with the power performance testing of small wind turbines, and states that 1-minute averaged power and wind speed data are to be logged and binned to form the wind turbine power performance curve. The wind speed data are measured at a height within ±2.5% of the turbine hub height and, for grid-connected SWTs, the a.c. turbine power data are measured at the connection to the load (after the inverter). For the binning of data, wind speed bins are created with width 0.5 m/s, centred on integer multiples of 0.5 m/s.

In regards to completion of power performance testing, section (n) of Annex H of IEC61400-12-1 (IEC 2005) states:

“...the database shall be considered complete when it has met the following criteria:
1) each wind speed bin between 1m/s below cut-in and 14m/s shall contain a minimum of 10 min of sampled data,
2) the total database contains at least 60 hours of data with the small wind turbine within the wind speed range
3) In the case of furling turbines, the database should include completed wind speed bins characterizing performance when the turbine is furled”

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2 The range of wind speeds that the SWT operates over
The AWEA and BWEA Safety and Performance Standards (AWEA 2009, BWEA 2008) have similar criteria to IEC61400-12-1 in terms of completion of power performance testing, with the exception of point 3), which is replaced by “The database shall include 10 minutes of data for all wind speeds at least 5 m/s beyond the lowest wind speed at which power is within 95% of maximum power (or when sustained output is attained)”. Averaging at 1-minute intervals, 10 minutes of data then requires 10 readings. In this paper a bin is said to be “filled” when it contains 10 readings.

Wind resource assessment

Over the period September 2009 – December 2009 some preliminary monitoring of the wind at 10 m a.g.l. at the test site was carried out using a cup anemometer and wind vane. In order to produce a longer-term prediction of the wind resource at the NSWTC site, some wind modelling was carried out using the software WAsP 9.0 (Mortensen et al. 2007). WAsP is well-known in the wind industry as a tool for wind resource assessment. The methodology behind WAsP involves the creation of a wind atlas, described by Bowen and Mortensen (1996) as a “site-independent characterisation of the local wind climate", by using long-term reference data from a nearby site along with descriptions of terrain, obstacles and roughness at both the reference site and the NSWTC test site.

The WAsP model was firstly run using half-hourly wind data collected during September 2009 – December 2009 from Jandakot Airport, which has an aerial distance of 10.6 km from the NSWTC test site. The data recorded during the preliminary monitoring were then used to validate the WAsP model. The validated WAsP model was then run using 10 years of half-hourly wind data from 2000 to 2009 measured at Jandakot Airport. The wind atlas created by the model yielded Weibull wind speed distributions at various roughness lengths and various heights. In order to predict the wind climate that a SWT would experience at the test site, the average roughness in a 10km radius around the site was determined by identifying with descriptions of terrain from the European wind atlas. The wind climate was predicted at 18m since this was a common height for SWTs as previously mentioned.

The predicted shape parameter ($k$) and scale parameter ($A$) of the Weibull distributions that was output from WAsP was used to calculate the probability density function ($f(v)$) for the respective mean speed ($v$) at each bin interval midpoint using the following equation:

$$f(v) = \frac{k}{A} \left( \frac{v}{A} \right)^{k-1} \exp \left( -\left( \frac{v}{A} \right)^k \right)$$

Equation 1

Wind speed bins were established using the convention from the IEC61400-12-1 standard, and using the probability density function, a database of predicted monthly wind speed distributions at the test site was created.

Spreadsheet analysis

A spreadsheet analysis tool was developed to provide guidance in scheduling testing of SWTs at the test site. The monthly Weibull distributions were used to estimate the number of 1-minute averaged data readings in each wind speed bin. The numbers of readings in the bins were then checked using the various standards to assess whether the
power curve completion criteria had been met. The analysis tool assumed that the SWT would be available 100% of the time.

Comparison with Measured Data

Power performance testing of a SOMA 1000 (1kW) turbine commenced in April 2010 at the NSWTC site. The SOMA is a horizontal-axis, 2-bladed, furling wind turbine. From the power curve published by the manufacturer, the rated instantaneous power of the SOMA turbine is 1000 W at a rated wind speed of 10 m/s with a peak output of 1200 W at 15 m/s (SOMA 2009). The SOMA turbine was mounted at a hub-height of 19.5 m a.g.l since this was typical of the tower heights that the manufacturer recommends to the consumer, and NSWTC wanted to test the complete small wind system as purchased by the consumer. One-minute averaged power values were logged and correlated with wind speed measurements from a cup anemometer on an 18 m meteorological mast, placed 7 m from the base of the turbine tower. The IEC61400-12-1 standard was used in power performance testing of the SOMA turbine in order to comply with the NSWTC’s obligations under the IEA Task 27 program. The mast was instrumented with primary and secondary anemometers in accordance with the standard. Collected data was normalised for seasonal variations in air density to produce power curves at standard sea-level conditions. The site has sloping terrain in some sectors but the close proximity of turbine tower and meteorological mast mean minimal correction for site calibration in order to conform to IEC61400-12-1.

RESULTS

Wind resource

For simplicity, predicted seasonal wind speed distributions were derived from the database of predicted monthly wind speed distributions and are presented in Figure 1. Figure 1 shows that the summer and spring distributions are skewed more to the right and as a result are better aligned with the typical wind speed range of a small wind turbine. The strong south-westerly sea breezes that occur over late spring and summer are responsible for the higher mean wind speeds during these seasons. The tails of the distributions are important in terms of likelihood of completion of higher wind speed bins. Figure 2 is a close-up of the tails of the distributions and shows that it is more likely to complete higher wind speed bins in winter and spring. The gusts from occasional storms and squalls that occur in winter and early spring are responsible for the higher maximum wind speeds during these seasons.

![Fig. 1: Predictions of seasonal wind speed distributions at the NSWTC test site](image1)

![Fig. 2: Tails of the predicted seasonal wind speed distributions at the site](image2)
Scheduling

Best time to test

The results of assessing whether the power curve completion criteria have been met are presented in Table 1. The mean wind speeds shown in the table are consistent with the skewed profiles from Figures 1 and 2. Despite higher mean wind speeds in late spring and summer, the best time to be testing is in winter and early spring.

The results in Table 1 show that all months meet the criteria of more than 60 hours of small wind turbine operation. In addition, January as well as June to December are eligible months in that they meet the criteria of completing wind speed bins 2 -14 m/s. The key criteria is the maximum completed bin. If the turbine is a furling HAWT, the results show that, in order to comply with point 3 from IEC 61400-12-1 Annex H, September must be included in the testing time schedule, and completion of testing is then reliant on the turbine being completed furled at 17 m/s.

Tab. 1: Results of cross-checking monthly distributions versus standards’ criteria

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind speed (m/s)</td>
<td>5.7</td>
<td>5.6</td>
<td>5.1</td>
<td>4.3</td>
<td>3.9</td>
<td>4.1</td>
<td>4.3</td>
<td>4.3</td>
<td>4.9</td>
<td>5.0</td>
<td>5.6</td>
<td>5.8</td>
</tr>
<tr>
<td>2-14 m/s bins complete</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hours of data in range (h)</td>
<td>669</td>
<td>605</td>
<td>633</td>
<td>528</td>
<td>484</td>
<td>472</td>
<td>495</td>
<td>495</td>
<td>536</td>
<td>600</td>
<td>636</td>
<td>670</td>
</tr>
<tr>
<td>Max. completed bin (m/s)</td>
<td>14</td>
<td>13.5</td>
<td>13</td>
<td>12.5</td>
<td>13.5</td>
<td>15</td>
<td>16.5</td>
<td>16.5</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

Types of turbines that can be tested

If testing to the AWEA and BWEA standards, the maximum completed bin places restrictions on the type of turbine that can be tested. From point 3) of these standards as stated above, the rated wind speed for the turbine can be estimated as 5m/s below the maximum completed bin. Table 2 shows the estimated rated wind speeds for the eligible months in Table 1. Thus only turbines with rated wind speeds of at most 12 m/s could be tested at the site in order to comply with AWEA and BWEA standards, and again completion of power testing would rely on September being included in the testing time schedule. That said, approximately 70% of the forty SWTs reviewed had rated wind speeds of 12 m/s or less.

Tab. 2: Estimate of rated wind speed based on AWEA and BWEA standards

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. completed bin (m/s)</td>
<td>14</td>
<td>15</td>
<td>16.5</td>
<td>16.5</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Estimate of rated wind speed of turbine</td>
<td>9</td>
<td>10</td>
<td>11.5</td>
<td>11.5</td>
<td>12</td>
<td>10</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Power curve from SOMA 1000 turbine

Figure 3 shows the measured power curve for the SOMA 1000 directly after the 17 m/s bin was filled on the 16th July 2010. It was observed that the turbine started to furl at 15
m/s and thus this curve is assumed to satisfy the criteria for completion as per the IEC standard. Completion took 2.5 months and did not involve testing in September, as predicted by the scheduling analysis. The curve is contrasted against the latest power curve for the SOMA 1000, obtained after 16 months of testing. The completed power curve has error bars increasing in size from around 12 m/s towards the tail of the curve. This is because although each bin has at least 10 readings, the number of readings is still very small compared with the rest of the power curve. By contrast, after 16 months of testing, the error bars have significantly reduced in size and the variations in the tail of the power curve have smoothed out. Uncertainty in power performance at high wind speeds would be reduced by increasing the number of readings in the high wind speed bins. This could be achieved, for instance, by testing at a higher hub-height, however, as previously mentioned, the NSWTC tested the system at the hub-height of systems sold by the manufacturer in order to test the type of system that a consumer purchases. This was important for other tests run on the turbine, particularly the durability test. Comparison of both measured power curves with the published power curve from SOMA show distinct differences. From the manufacturer’s published power curve, significant levelling of the power curve occurs at around 10m/s, whereas the test results indicate this behaviour is delayed until around 12m/s. Figure 3 shows that below 12 m/s, the published power curve overpredicts performance, and above 12 m/s, the published power curve underpredicts performance. The measured power curves predict a peak power of approximately 1350 W at around 17 m/s, 150 W greater than the peak power stated by the manufacturer.

The IEA recommended practices for consumer labelling of SWTs (IEA Wind 2011) use the Annual Energy Production (AEP) of the turbine (at a site with a mean wind speed of 5 m/s) as one of the key parameters that represent the performance of a turbine. AEP values are a better indication of a turbine’s performance than rated power since they describe exactly what energy yield would be expected from a turbine. Figure 4 shows good agreement between the published AEP data from the SOMA turbine compared to extrapolated AEP curves based on the 16-month measured test data. Out of interest, the calculated AEP at 5 m/s from the 16-month power curve does vary from the completed power curve but the variation is less than 1.25%.

Fig. 3: Measured and published power curves for the SOMA 1000 wind turbine
Fig. 4: Comparison of the published AEP values of the SOMA with extrapolated values based on measured test data
DISCUSSION

The wind modeling was useful in that it showed the best seasons of the year in which to fill the higher wind speeds bins on the power curve (winter and spring). It also predicted with good accuracy the highest completed wind speed bin in a year (17 m/s versus 17.5 m/s from measurements). The modeling, however, predicted that the SOMA 1000, which commenced testing on April 29th 2010, would need 5 months of testing in order to fill the highest completed wind speed bin whereas in practice, good winds during July meant that the testing took only half this time. Discrepancies between the predictions and measured results are likely to be due to the limitations of using WAsP and the Weibull function to model wind speed distributions. The main limitations of using WAsP are likely to be associated with the input data including lack of detail in topographical and land use maps. There was a difference between input and actual hub-height of 1.5 m, but this is likely to have negligible impact.

Although the SOMA 1000 has been observed to begin furling at 15 m/s some doubt remains as to whether the measurements are “...characterizing performance when the turbine is furled”, as per IEC61400-12-1 (IEC 2005). This statement from IEC61400-12-1 is not clear. After 15 m/s the measured power values continue to increase, although the decrease in power gain with wind speed does support the observation that the turbine is limiting power through furling. Ideally one would like to fill the bins at 18 m/s and 18.5 m/s to ensure that the furling behavior is completely characterized but this would involve a longer period of testing.

The analysis tool made the assumption that, as per an ideal wind turbine power curve, the rated wind speed is the wind speed when the turbine reaches its maximum power. SOMA state that the rated wind speed for their SOMA 1000 machine is 10 m/s and it was presumed that the power curve would be completed in accordance with the AWEA and BWEA standards once the 15 m/s bin was filled. However, SWTs do not have ideal power curves and one can see for the SOMA 1000, for example, that the power values continue to rise at wind speeds beyond 10 m/s. The manufacturer states that the maximum power is achieved at 15 m/s but in fact testing indicates that maximum power may not be achieved until 17 m/s. The reasons that SWTs have non-ideal power curves are partly technical, as SWTs do not have the accuracy of power control of larger wind turbines that ensure that the power values reached after rated wind speed are either sustained or reduced, and partly regulatory, as the SWT industry does not have the same stringent procedures of power curve testing and certification, allowing manufacturers to choose higher rated wind speeds to suit the market objectives of lower relative cost in terms of cents per kW (Gipe, 2000). The IEC standard was used with the SOMA in order to comply with the IEA Task 27 program but out of interest, if the AWEA or BWEA standard were to be applied and the maximum power can be confirmed to be in the order of 1350 W at 17 m/s then it can be shown that the test would only be complete once the 20.5 m/s bin were filled. Although the site has recorded 1-minute averaged wind speeds up to 21 m/s, it would not be possible to complete power testing to AWEA/BWEA standards at this site in a reasonable time.
CONCLUSIONS AND RECOMMENDATIONS
Wind modelling and spreadsheet analysis have been used to aid the scope and scheduling of power performance testing at the NSWTC test site. The predictions have been compared with test data obtained from the first turbine to be tested at the site – the SOMA 1000 wind turbine. The following conclusions and recommendations can be made:

- The characteristics of the wind resource at the testing site is crucial to completing the database for power performance testing but the choice of site is likely to be constrained due to factors such as lease costs, tenure, accessibility and security;
- The wind modelling of this study proved useful despite some discrepancies with measured data that are likely to be due to the limitations of the model. The modelling and subsequent analysis predicted winter and early spring to be the best time of year to test turbines, and placed a restriction on the types of turbines tested. Depending on test standard, turbines would need to be completely furled at 17 m/s or have a rated wind speed of approximately 12 m/s. That said, the choice of rated wind speed can be an arbitrary process for manufacturers (Gipe, 2000) and the spreadsheet analysis model needs to be reviewed to take into account non-ideal power curves for SWTs;
- Discrepancies were observed between the measured power curve for the SOMA 1000 and the manufacturer’s claims. This is consistent with observations on other small wind turbines by Gipe (2000). In this case, however, the AEP, which is a more objective means of comparing wind turbine performance, showed good agreement between test results and the manufacturer’s published results;
- Although a power curve can be completed in a few months, longer testing is advisable to reduce uncertainty with the power values at high wind speeds and improve the overall shape of the power curve. It is recommended to extend testing of the SOMA 1000 at the NSWTC site to a total of 2 years to ensure its furling behavior is completely characterized. This is consistent with the ballpark figure of 1 - 2 years for testing estimated by the SWCC (2011).

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