A Successful Roof-top Wind Power Project?

by

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Submitted in partial fulfillment of the degree of Master of Science (Renewable Energy)

in the
Faculty of Minerals and Energy
School of Engineering and Energy

September 2010
Declaration of Authorship

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- Except where I have indicated, the work presented here is my own work and has not been submitted for assessment in another unit.

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Date: 21 May 2010
Roof-top wind power projects have a well documented record of very poor performance. The primary objective of this project has been to provide advice in the planning phase of a roof-top wind project to ensure its success. As secondary objectives, this research has assessed the turbulence characteristics at a recommended site and evaluated the suitability of the small wind turbine design standard for roof-top installations.

A monitoring mast was designed and installed on the roof-top of the Bunnings warehouse in Port Kennedy to measure the effect of turbine mounting height on average wind speed and wind turbulence intensity. As a consequence of this wind data analysis, planning applications were modified to increase the turbine height from 2m to 4m above the roof. This change is predicted to increase power output by a factor of four. The predicted capacity factor of approximately 9% at the site is low by commercial standards but compares favourably with published values for roof-top systems. The Class II Swift turbines proposed for the project are designed to withstand higher wind speeds than observed, but fatigue from high levels of turbulence (especially when the wind is from the southern sector) may reduce their safe operating life.

At present, procedures for turbulence measurement and characterisation are not satisfactorily standardised in the small wind field. Various research groups apply a range of sampling rates and measurement intervals when calculating turbulence intensity, which can make comparison of results difficult. In the absence of a standard, a one-minute measurement interval is recommended and a method for calculating longer-interval turbulence intensity values from one-minute values is presented. An IEC task description (IEC TC88 MT2 Item 40) has also been proposed to help standardise the calculation of turbulence time-scales, length-scales, and power spectra. However, in its current form it does not provide sufficient detail to guarantee consistent and correct results.
Acknowledgements

The author is indebted to:

- Dr Jonathan Whale - for his assistance liaising with project partners, as well as some useful pointers on turbulence theory;
- Avishek Malla - for invaluable assistance in connecting and configuring the ultrasonic anemometer and data logger;
- Colin Black - for assistance fabricating mounts and installing the instruments;
- Paul Williams - for providing the contour maps of the warehouse sites; and
- John McGregor - for letting me play on the roof (safely. . . )

“Big whirls have little whirls
That heed on their velocity,
And little whirls have littler whirls
And so on to viscosity.”

L.F. Richardson
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<th>Description</th>
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<tr>
<td>BWEA</td>
<td>British Wind Energy Association</td>
</tr>
<tr>
<td>EST</td>
<td>Energy Saving Trust</td>
</tr>
<tr>
<td>HAWT</td>
<td>Horizontal Axis Wind Turbine</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEC TC 88 MT2</td>
<td>IEC Technical Committee 88, Maintenance Team 2</td>
</tr>
<tr>
<td>MCP</td>
<td>Measure Correlate Predict</td>
</tr>
<tr>
<td>MCS</td>
<td>Microgeneration Certification Scheme</td>
</tr>
<tr>
<td>NOABL</td>
<td>Numerical Objective Analysis of Boundary Layer (British wind atlas)</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>RISE</td>
<td>Research Institute for Sustainable Energy</td>
</tr>
<tr>
<td>SWIIS</td>
<td>Small Wind Industry Implementation Strategy (consortium)</td>
</tr>
<tr>
<td>VAWT</td>
<td>Vertical Axis Wind Turbine</td>
</tr>
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## Symbols

<table>
<thead>
<tr>
<th>symbol</th>
<th>name</th>
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<tbody>
<tr>
<td>$P$</td>
<td>Power</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density</td>
</tr>
<tr>
<td>$A$</td>
<td>Rotor swept area</td>
</tr>
<tr>
<td>$D$</td>
<td>Rotor diameter</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Power law (Hellman) exponent</td>
</tr>
<tr>
<td>$U$</td>
<td>Wind speed (random variable)</td>
</tr>
<tr>
<td>$\bar{U}$</td>
<td>Mean wind speed - steady-state component of $U$</td>
</tr>
<tr>
<td>$U'$</td>
<td>Turbulence - fluctuating component of $U$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of wind speed</td>
</tr>
<tr>
<td>$u$</td>
<td>longitudinal direction or component of wind speed</td>
</tr>
<tr>
<td>$v$</td>
<td>transverse component of wind speed</td>
</tr>
<tr>
<td>$w$</td>
<td>vertical component of wind speed</td>
</tr>
<tr>
<td>$I$</td>
<td>Turbulence intensity</td>
</tr>
<tr>
<td>$I_{15}$</td>
<td>Turbulence intensity (limit defined in standard IEC 61400-2) at a wind speed of $15\text{ms}^{-1}$</td>
</tr>
<tr>
<td>$a$</td>
<td>Slope of intensity curve in standard IEC 61400-2</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>Integral turbulence length scale</td>
</tr>
<tr>
<td>$k$</td>
<td>wave number</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>turbulent kinetic energy dissipation rate</td>
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</tbody>
</table>
Chapter 1

Introduction

1.1 Background

Bunnings Pty Ltd (Bunnings) has committed to a pilot wind power project in Western Australia. This project will use roof-top wind turbines, mounted to the major structural beams of the front facade of two of their warehouses. As a pilot project, its purpose — for Bunnings — is to assess the level of maturity of small wind technology and of the industry in Australia, as well as the level of support that wind projects will receive from local governments and the wider community.

Murdoch University became involved in this project as an extension of an existing collaboration between the Research Institute of Sustainable Energy (RISE) and Bunnings. The role of the University has been to provide advice based on published research, knowledge of the industry, and monitoring of wind conditions in order to help achieve a successful project outcome. This pilot project is of particular relevance to the National Small Wind Test Centre (NSWTC). The NSWTC is based at Murdoch University and was established to assess the safety and performance of small wind turbines against international standards. For Murdoch University and the NSWTC, safe and reliable performance of the installed turbines is the primary objective [1].

The roof-top wind project is classified as a small wind power project. Formally, small wind turbines are defined in the international and interim Australian small wind turbine design standard (IEC-61400-2) [2] as those with a rotor swept area of less than 200m$^2$ (and generating at a voltage below 1000V a.c. or 1500V d.c.). Small wind generation is an exciting field of study for several reasons. It is the fastest growing sector of the wind industry world-wide. UK growth has been 80% per year [3] and US growth at 50% per year [4] in recent years up to 2008, although growth rates in 2009 dropped to 15%-20% due to financial constraints on the market. Over 15,000 small wind turbines were installed between 2005 and 2009 in the UK alone [5].

Small wind technology has broad public appeal in that it gives the opportunity for individuals or communities to generate their own electricity from a renewable source. However, it faces
opposition from those concerned about safety, noise and visual pollution. Small wind projects are also highly challenging because of the low wind speeds and high levels of turbulence experienced by comparison with large wind projects [6]. This is especially true of building-mounted turbines. The current small wind turbine design standard is adapted from the large wind industry and uses turbulence models that have been validated for open terrain (most notably in Kaimal’s 1968 “Kansas experiment” [7]). Characterisation of the turbulence in roof-top conditions is an important task in determining whether the current standards need modification.

1.2 Objectives

The primary objective of this research project was to facilitate a successful outcome for the Bunnings roof-top wind power project. To this end, a monitoring campaign was established to assess wind characteristics at a proposed site in order to assess the suitability of the site, to recommend an appropriate turbine mounting height, and to assess the suitability of the Swift turbine (which Bunnings selected) for the wind conditions.

Research Question Given that the Swift turbine is certified as a Class II turbine, what turbine height is needed to ensure that the wind speeds and levels of turbulence that it will experience are acceptable?

Secondary objectives of the research relate to understanding the characteristics of wind in urban environments. This is important in the revision of the design standard for small wind turbines, IEC-61400-2. A revision process has been established to ensure that the standard is applicable to the plethora of new designs and new environments in which turbines are being installed. This revision process is being carried out by the International Electrotechnical Commission (IEC) Technical Committee 88, Maintenance Team 2 (IEC TC 88 MT2).

Research Question Are the models that the standard uses to characterise the turbulence valid for roof-top systems?

It was also hoped that this research would allow an independent performance assessment of the Swift turbine, and contribute to a performance database for small wind projects which is being established under the auspices of the International Energy Agency (IEA) Wind Task 27 (Consumer Labelling of Small Wind Turbines) [8].
Chapter 1. Introduction

1.3 Thesis Outline

Chapter 2 provides a general introduction to wind energy theory, the design standards that apply to small wind turbines, and summarises some of the disappointing results from roof-top wind power projects in recent years.

The first phase of this project was to identify an appropriate site for the pilot project. This process is described in Chapter 3. Four warehouses were short-listed, all located within a few kilometres of the coast in the southern suburbs of Perth. After site visits, the Port Kennedy and Rockingham warehouses were recommended.

The original plan and stated preference of Bunnings through to late October 2009 was to mount five Swift turbines (Figure 1.1) as low as possible above the 8.4m façade of the two warehouses [9]. Dr Jonathan Whale raised concerns about the low mounting height — which was likely to adversely affect the wind conditions that the turbine would experience. Bunnings agreed to a brief project delay to permit a limited monitoring campaign.

![Renewable Devices' Swift Turbine](image)

**Figure 1.1:** Renewable Devices’ Swift Turbine [10].

The next phase of the project involved bench-testing of equipment and the data-logging program, while concurrently advising on the design of the monitoring mast. The mast was installed on the roof of the Port Kennedy warehouse on 22nd September 2009 and the monitoring installation was completed shortly afterwards. Details of the monitoring program are provided in Chapter 4.

To provide a recommendation on mounting height, the average wind speed and turbulence intensity were monitored over short periods, initially at heights of 2, 3 and 4 metres. Subsequently, the mast was modified to allow monitoring at 5m. Wind speed and turbulence intensity...
measurements were analysed in Excel, as a function of height and also as a function of wind direction. This analysis is presented in Chapter 5.

The Swift wind turbines were installed on the Port Kennedy and Rockingham roof-tops in early March. On 22nd March 2010, a severe storm front passed over the South-West of Western Australia. This caused significant damage throughout the Perth metropolitan area, but the turbines were undamaged. The passage of the storm front was logged as raw 10Hz wind speed measurements. Analysis of this data confirms that the Swift is an appropriate turbine to install at the site. It also helps establish conditions that small wind turbines and their masts must be able to survive. This analysis is presented in Chapter 6.

Chapter 7 raises some issues about the current lack of consistency in measurements of turbulence. Various research groups are sampling at different rates (from 10Hz to two seconds) and averaging over different periods (from one to ten minutes). The effect of varying the averaging period on turbulence intensity measurements is presented, and it is demonstrated that turbulence intensity values for five- or ten-minute averaging periods can be derived from one-minute average values. The turbulence is characterised by following the steps of an IEC TC 88 MT2 task description, using 10Hz measurements recorded on site. This characterisation includes establishing the coherent time-scale and length-scale of the turbulence, as well as its power spectrum.

After a delay waiting for approval from Western Power (the Western Australian electricity network provider responsible for maintaining power quality over the network), on 13th May 2010 Bunnings announced that the Swift turbines on the Port Kennedy and Rockingham roof-tops were producing power. John McGregor (Sustainability Director for Bunnings) has indicated that he is keen for this collaborative project to be continued, with Murdoch to be involved in establishing remote monitoring of the power output from all of the turbines. This will create further opportunities to analyse roof-top wind conditions and the performance of wind turbines in those conditions, as indicated in Chapter 8.
Chapter 2

Literature Survey

2.1 Overview

This chapter provides a wide-ranging background introducing the wind theory, standards, and industry experience as they pertain to the Port Kennedy roof-top power project and the associated wind monitoring campaign.

2.2 Wind Power Basics

2.2.1 Power from the Wind

The power available in a wind with constant speed $U$ is given by

$$P = \frac{1}{2} \rho A U^3,$$

(2.1)

where $P$ is the power in Watts, $\rho$ is the air density, $A$ is the area swept by the turbine blades. Air density varies with pressure, temperature, and humidity so all of these factors will affect the power available at a site. However, the dominant factor is the wind speed since power varies with its cube.

2.2.2 Fluctuations in Wind Speed

Because the relationship between power and wind speed is non-linear, various sites with the same average wind speed but a different distribution of wind speeds over the year can yield significantly different total energy production [11]. This applies equally whether the wind speed fluctuations are seasonal changes, or rapid “turbulent” fluctuations.
It is convenient to decompose wind measurements into their average and fluctuating components:

\[ U = \bar{U} + U', \]  
(2.2)

where \( \bar{U} \) is the steady-state component of the wind (averaged over some duration \( T \)),

\[ \bar{U} = \frac{1}{T} \int_{T} U(t)dt, \]  
(2.3)

and so the turbulence is given by

\[ U' = U - \frac{1}{T} \int_{T} U(t)dt \]  
(2.4)

Suppose at one site the wind speed is constant at \( \bar{U} \), so the power available is proportional to \( \bar{U}^3 \). At a second site, the wind speed fluctuates such that it is \( 0.5\bar{U} \) for one third of the time, \( \bar{U} \) for one third, and \( 1.5\bar{U} \) for the remaining third. Then the mean wind speed at the second site is still \( \bar{U} \), but power is now proportional to

\[ \frac{(0.5^3 + 1^3 + 1.5^3)}{3} \bar{U}^3 = 1.5\bar{U}^3. \]  
(2.5)

This is 50% higher than at the first site.

For a given mean wind speed there is more energy in the wind if there is more turbulence. In this sense, high turbulence can been seen as a potential benefit [12]. However, generally turbulent conditions reduce turbine efficiency. When the wind direction varies, the blade angle will move away from its ideal operating point, reducing the amount of lift generated (potentially inducing stall or even negative lift from sections of blades), and consequently the driving force that causes the turbine to rotate will reduce [13]. Rapid direction changes will also cause a horizontal axis wind turbine (HAWT) to be misaligned, reducing the amount of energy that it can extract from the wind while it yaws back in line.

Turbulence intensity provides a dimensionless measure of the level of turbulence at a site, calculated as the standard deviation of the fluctuations (\( \sigma \)) divided by the mean wind speed [14], according to Equation 2.6.

\[ I = \frac{\sigma}{\bar{U}} \]  
(2.6)

### 2.2.3 Wind Shear

One of the fundamental issues affecting roof-top mounted wind turbines is wind shear — the phenomenon that the rate of wind speed increase decreases with elevation above the ground, as depicted in Figure 2.1 reproduced from a Small Wind Industry Implementation Strategy consortium (SWIIS) technical note [15]. This figure also shows that if the surface is rougher, the speed decreases faster. By comparison with typical wind turbine sites, a roof-top urban
site is a very rough environment. This indicates that low average wind speed is likely to be a problem if the turbines are mounted at roof height. Since turbine power output is proportional to the cube of wind speed, this is a critical issue.

![Wind speed decreases with height more rapidly in complex terrain.](image)

The wind shear relationship is represented as a power law defined by the equation

\[
\frac{V}{V_0} = \left( \frac{H}{H_0} \right)^\alpha,
\]

where \(\alpha\) is the Hellman exponent, which is a measure of the roughness of the terrain [11]; and \(V_0\) is the wind speed measured at a reference height \(H_0\).

Wind speed decreases near the ground because turbulence induced by the rough ground dissipates energy in the wind. At rougher sites, turbulence is greater and more energy is dissipated. Consequently, at sites that experience high turbulence the mean wind speed may be significantly lower than predicted by wind atlases or nearby monitoring. The Energy Savings Trust (EST) observed this over-estimation at roof-top sites throughout the UK relative to predictions from the Numerical Objective Analysis of Boundary Layer (NOABL) wind model [6].

### 2.2.4 High Turbulence Sites

In addition to reducing the energy available near ground level, high levels of turbulence pose a danger to wind turbines. As the UK-based SWIIS warn:

“...sharp changes in the terrain, like cliff edges, induce very strong vertical wind shears and cause high turbulences. This vertical wind shear can be such that the wind is quite different in speed and inclination between the lower and the upper part of the swept rotor circle of a small wind turbine installed close to this cliff. Such asymmetry in loading is very dangerous for the wind turbine lifetime because it continuously induces high fluctuating loads and with that high fatigue stresses in the blades.” [15].
Chapter 3. Literature Survey

The Bunnings turbines, mounted on the front façade of the warehouse, are effectively at the top of a nine metre cliff. The impact of such a bluff body obstruction is demonstrated in windtunnel tests and computer simulation as shown in Figure 2.2 (from Mertens [16]).

![Windtunnel testing](image1) ![Computer Modelling](image2)

**Figure 2.2:** Effect of bluff body obstruction on airflow

It is also clearly established that turbulence intensity decreases with height, as shown, for example, in Figure 2.3, reproduced from Wind Energy Conversion Systems by L. L. Freris [17].

![Turbulence intensity decreases with height](image3)

**Figure 2.3:** Turbulence intensity decreases with height.

Given the proposed turbine siting, this theory allows clear predictions that the observed wind speed will increase with height, while the level of turbulence intensity decreases with height — both of which favour a high turbine hub height.

### 2.2.5 Theoretical Turbulence Spectrum

In 1941, the Russian mathematician Kolmogorov observed that turbulent phenomena appear to be self-similar with scale and frequency. He surmised that the energy spectrum of the turbulence, $E(k)$, must be a function of the wavenumber $k$, which describes the scale of eddies
in the flow, and the turbulent kinetic energy dissipation rate, $\epsilon$ [17], which is the rate per unit mass at which the turbulent kinetic energy reduces due to viscous stresses in the fluid. These terms have the following units, or dimensions:

\[
E(k) \quad [m^3 s^{-2}] \quad (2.8)
\]

\[
k \quad [m^{-1}] \quad (2.9)
\]

\[
\epsilon \quad [m^2 s^{-3}] \quad (2.10)
\]

and from dimensional analysis it follows that the spectrum must have the form

\[
E(k) = C\epsilon^{2/3}k^{-5/3}, \quad (2.11)
\]

where $C$ is a constant. Plotted on a log scale, the energy spectrum should follow a straight line with a gradient of $-5/3$. A typical turbulent energy spectrum is presented in Figure 2.4, reproduced from Kaimal and Finnigan [18]. The spectrum is divided into three ranges: the energy-containing range, 'A', where turbulence is introduced by buoyancy and shear forces; the inertial subrange, 'B', where turbulent energy is passed down to smaller scales; and the dissipation range, 'C', where fluid viscosity converts turbulence to internal energy.

![Figure 2.4: Theoretical turbulent energy spectrum.](image)

This prediction has been confirmed to be valid over a particular frequency range, known as the inertial subrange (labelled 'B' in Figure 2.4). Semi-empirical refinements by von Karman and Kaimal result in a spectrum that agrees more accurately with measurements over a wider frequency range.

The von Karman turbulence spectrum is described by the equation

\[
S(f) = \frac{\sigma_u^2 A}{U} \left[ 1 + 70.8 \left( fA/U \right)^2 \right]^{-1/2}, \quad (2.12)
\]

where $f$ is the frequency (Hz), $\sigma_u$ is the standard deviation of wind speeds in the longitudinal direction, $A$ is the integral length scale (m) which is a measure of the distance over which turbulent velocities remain correlated, and $U$ is the mean wind speed (ms$^{-1}$).
2.3 Standards for Small Wind Turbines

2.3.1 Design Criteria

A range of turbine requirements for each turbine class are developed in the small wind design standard IEC 61400-2 from a small set of underlying parameters [2]. These key parameters are presented in Table 2.1.

<table>
<thead>
<tr>
<th>SWT Class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>S</th>
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<tr>
<td>$V_{\text{ref}}$ (ms$^{-1}$)</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{ave}}$ (ms$^{-1}$)</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$I_{15}$</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

$V_{\text{ref}}$ is the extreme wind speed experienced at hub height, averaged over a 10-minute period with a recurrence period of 50 years that a turbine is designed to withstand. $V_{\text{ave}}$ is an upper bound for the annual average wind speed at hub height.

The parameters $I_{15}$ and $a$ define the turbulence intensity limit, where $I_{15}$ is the turbulence intensity at a wind speed of 15ms$^{-1}$ and $a = \frac{d\sigma}{dV_{\text{ref}}}$ is the slope of the $\sigma$ versus $V_{\text{ref}}$ curve.

Broadly speaking the velocity terms are more critical to the ultimate load design criteria, while the turbulence components are more critical to the fatigue design cases.

2.3.2 Peak gusts

A three second average is frequently used to define a gust, since this is a typical value for the response time of a cup anemometer and, consequently, it is the shortest gust that the majority of wind monitoring stations can detect [19]. IEC 61400-2 defines the 50-year extreme wind speed $V_{e50}$ as

$$V_{e50}(z) = 1.4V_{\text{ref}} \left( \frac{z}{z_{\text{hub}}} \right)^{0.11}$$  \hspace{1cm} (2.13)

This value represents the extreme wind speed that the turbine is expected to see in a 50-year period, averaged over 3 seconds [2] — effectively, the peak gust that the turbine is designed to withstand.
The standard also defines the Extreme Operating Gust (EOG) for a recurrence period of \( N \) years, given by the equation

\[
V_{\text{gust}N} = \beta \left( \frac{\sigma_1}{1 + 0.1 \left( \frac{D}{\Lambda_1} \right)} \right),
\]

(2.14)

where

\( \sigma_1 \) is the standard deviation defined by the turbulence model (either von Karman or Kaimal according to the standard) for a wind speed of \( V_{\text{ref}} \);

\( \Lambda_1 \) is the integral length scale (introduced in Equation 2.12);

\( D \) is the rotor diameter; and

\( \beta \) is a constant, defined as 4.8 for \( N = 1 \) year or 6.4 for \( N = 50 \) years.

The standard somewhat misleadingly defines the gust duration \( T \) for a 50-year gust as 14.0 seconds, but with a gust profile defined by the equation

\[
V(t) = \begin{cases} 
V(z) - 0.37V_{\text{gust}50}\sin(3\pi t/T)(1 - \cos(2\pi t/T)), & 0 \leq t \leq T \\
V(z) & t < 0, \text{ and } t > T.
\end{cases}
\]

(2.15)

As shown in Figure 2.5, which was generated from Equation 2.15 using Matlab, the majority of the 14-second gust duration actually has a wind speed below the initial wind speed, with the peak lasting only three to four seconds. Note also that the peak wind speed during the gust is not equal to \( V_{\text{gust}50} \).

**Figure 2.5:** Extreme operating gust with 50-year return for a Class II turbine.
Chapter 3. Literature Survey

2.3.3 Turbulence Limits

IEC 61400-2 stipulates that turbines must be designed to withstand wind conditions up to a particular turbulence intensity level. In the longitudinal direction, this limit is defined in terms of the standard deviation of the wind speed,

\[
\sigma_u = I_{15} \ast \frac{(15 + a \ast v_{hub})}{(a + 1)},
\]

(2.16)

where \( a = 2, \ I_{15} = 0.18, \) and \( v_{hub} \) is the mean wind speed measured at turbine hub height (elsewhere in this thesis referred to as \( \bar{U} \)).

The standard deviations in the orthogonal directions are also defined:

\( \sigma_v \) is the standard deviation in the transverse (\( v \)) direction; and

\( \sigma_w \) is the standard deviation in the vertical (\( w \)) direction.

The standard allows for two models of turbulence, both of which are empirical refinements based on Kolmogorov’s turbulence theory. The von Karman model is isotropic, so \( \sigma_u = \sigma_v = \sigma_w \).

The Kaimal model (determined empirically) assumes that \( \sigma_v = 0.8\sigma_u \), while \( \sigma_w = 0.5\sigma_u \).

According to the standard, a turbine may be designed to either Kaimal or von Karman turbulence levels, with the lower Kaimal turbulence conditions being the easier level to accommodate in design.

2.3.4 Measuring Turbulence Intensity

Wind turbulence is measured over an interval as the difference between the observed wind at each instant and the average wind speed recorded over the interval. The standard sampling period, used for wind resource assessment and at most meteorological stations, is 10 minutes. This interval lies in the ‘spectral gap’ that is observed between the turbulent scales (less than 5 minute time period) and the synoptic time scales (a few days) which are correlated with macro-scale atmospheric processes.

For small wind projects and urban environments, various alternative sampling regimes have been proposed. The UK body SWIIS has recommended a 10-minute sampling standard for measuring turbulence, with sampling every two seconds [20]. Warwick wind trial data analysis suggests 5-minute averaging may be more representative in urban areas. Other groups have used 1-minute and 2-minute averaging.

The two-second sample rate recommended by SWIIS is also contested. The American and British Wind Energy Associations (AWEA/BWEA) both recommend one-second sampling, while Dr Jonathan Whale and Professor Tom Lyon of Murdoch University have both stated that even one-second measurements are not fast enough to capture turbulence accurately [21].
In summary, turbulence intensity measurements are made by different research groups using a range of sampling frequencies and a range of averaging periods. It is not clear which of these approaches provides the best characterisation of turbulence. It is also not clear whether results of analysis by one research group can be compared with other analysis given the different data treatments.

2.4 Roof-top Wind Projects

2.4.1 Overview

The goal of this research project — to achieve a successful roof-top wind power project — is no simple task. Historically, roof-top wind projects have had very poor outcomes. Capacity factors of below 5% are common, compared to capacity factors of 30% to 40% for many commercial wind farms. In some cases inverter power consumption has exceeded turbine power production, resulting in negative net energy generation [6].

Numerous industry sources recommend installing turbines well away from buildings, on a large tower. The quotes below are typical:

“A good rule of thumb is that the tower should be 2.5 times the height of any nearby buildings or trees.” [22].

“A general rule of thumb is to install a small wind power generator on a tower with the bottom of the rotor blades at least 6 m (20 feet) above any obstacle that is within 76 m (250 feet) of the tower.” [23].

“It is dangerous to install any small wind turbine on the leeside area of a building for the prevalent wind direction.” [15].

The (US) National Renewable Energy Laboratory (NREL) Wind Resource Assessment Handbook recommends placing sensors no closer than a horizontal distance of at least 10 times the height of an obstruction in the prevailing wind direction [24]. Even at this distance it notes that the average wind speed will be decreased by 6%, turbulence increased by 5%, and wind power decreased by 17% compared to the undisturbed upstream conditions.

2.4.2 Wind Turbine Trials and Surveys

2.4.2.1 Energy Saving Trust Small Wind Survey

The Energy Saving Trust (EST) conducted a survey of small wind turbines throughout the UK, from 2007 through to 2009 [6]. The study monitored wind conditions and turbine output for
38 building-mounted turbines and 19 pole-mounted turbines and supplemented this data with meter readings from 68 additional sites, plus data from 29 Warwick Wind Trial sites.

The EST trial noted that capacity factors at all roof-top mounted turbine sites were below the 10% estimate given by the British Wind Energy Association (BWEA). The maximum was 7.4%, achieved at a rural site in Scotland. In urban areas, the highest capacity factor was below 3% and some sites reported negative net electricity generation, with inverter consumption exceeding turbine output.

The report concludes that “building mounted turbines exhibited generally poor output due to installations at sites with inadequate wind speeds”, but also noted that poor positioning of some turbines contributed to their poor performance.

Capacity factors for pole-mounted turbines averaged 19% throughout the UK (above the 17% BWEA estimate) and in some cases in Scotland, over 30%.

Throughout the UK, the study identified the potential for 3459GWh per annum of small-scale wind generation. Of this, the building-mounted contribution was just 132GWh per annum, or less than 4%.

The EST report states “wind speeds are difficult to predict and highly variable” and recommends that customers “install anemometry to determine their average wind speed over at least 3 months” [6].

Preferred sites are “individual dwellings near the coast or on exposed land with an undisturbed flow from the direction of the prevailing wind”. “Building mounted wind turbines can work... their successful performance is highly dependent upon an adequate, unobstructed wind resource and appropriate siting of the turbine”.

They also note that “a number of manufacturer’s performance claims are not yet standardised or comparable”, and that “a number of manufacturers’ power curves were deemed inaccurate or incorrect”. The International Energy Agency (IEA) concurs with this assessment, and has established a small wind standardisation and labelling initiative (Task 27) to “give customers and governments minimum assurances regarding the safety and performance of small wind turbines” and to “minimise deceptive investments in less than optimum equipment” [8].

The EST study also noted that the Numerical Objective Analysis of Boundary Layer (NOABL) wind atlas, which had been the recommended starting point for estimating the wind resource available at any site within the UK, significantly over-estimated the resource available within built-up areas. A revised atlas, the Microgeneration Certification Scheme version (NOABL MCS), and a Carbon Trust tool [25] are both better predictors of urban wind resource — often predicting only half the average wind speed of the NOABL atlas.
2.4.2.2 Warwick Wind Trial

In terms of turbine performance, the findings from the Warwick Wind Trial are broadly in line with those of the EST study. They observed that the NOABL model over-estimates the wind resource for urban areas and that, for most people, the capacity factor will be less than 5% [26].

One analysis of Warwick Wind Trial data concluded that 5-minute averages of data take better account of gusty conditions and incidences of turbine shutdown and, therefore, yield the most “appropriate” results [27]. This differs from the international standard of sampling over 10-minute intervals and raises a question about the appropriate sampling interval for this project.

The Warwick Wind Trial also raised questions about the reliability and safety of the Swift turbine (which Bunnings is using in its pilot project) after the catastrophic failure of one turbine [28] as shown in Figure 2.6.

![Blade failure on Swift turbine in Watford, UK](from D. Hailes, Encraft Warwick Wind Trials Open Day presentation)

2.4.2.3 Zeeland Wind Trial

The Zeeland test field was established to test the performance of a variety of small wind turbine technologies under comparable conditions. Turbines were erected in an open field in a line perpendicular to prevailing winds, as shown in Figure 2.7. The turbines were grid-connected to measure electricity output over a period of approximately one year.

The data presented in Table 2.2 demonstrates the widely differing performance of small turbines available in the market [29].

In general, in terms of cost per net kWh produced, HAWTs outperformed the vertical axis wind turbines (VAWTs) such as the Ropatec models and the Turby. The notable exception to this is the Swift turbine, a HAWT whose performance, in the words of small wind expert Hugh Piggott,
was “a bit of a disaster” [30]. It should be noted that the Swift was only installed for 10 of the 12 months for which this data is reported. Wind strength was near the annual average over the missing two month period. The annual production for the Swift can therefore be estimated by scaling by 1.2 times, yielding 149kWh, at a cost per kWh of €89. This is still considerably worse than any other HAWT.

It should also be noted that some manufacturers involved in the trial have stated that the test conditions do not necessarily obtain the best performance from their turbines. For example, David Sharman from Ampair states that the Ampair 600 was designed as a battery-charging product so the inverter electronics resulted in poorer performance [31]. He also noted that the Ampair 600 was not functional for the first two months of the trial, and that the Ropatec inverters were installed on the wrong machines (3kW on 6kW machine and vice versa) [29].

Renewable Devices, manufacturers of the Swift, claim that its poor performance was due to the fact that their turbine is designed for turbulent gusts rather than gentle breezes [1]. Further field trials are required to validate the performance of small wind turbines, and it is hoped that this pilot project will provide an opportunity to do that for the Swift turbines.

### TABLE 2.2: Zeeland Wind Trial Turbine Performance

<table>
<thead>
<tr>
<th>Turbine Model</th>
<th>Type</th>
<th>Cost (€)</th>
<th>Net kWh</th>
<th>€/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest Skystream</td>
<td>HAWT</td>
<td>10742</td>
<td>2086</td>
<td>5</td>
</tr>
<tr>
<td>Fortis Montana</td>
<td>HAWT</td>
<td>18508</td>
<td>2688</td>
<td>7</td>
</tr>
<tr>
<td>Fortis Passaat</td>
<td>HAWT</td>
<td>9239</td>
<td>577</td>
<td>16</td>
</tr>
<tr>
<td>Ampair 600</td>
<td>HAWT</td>
<td>8925</td>
<td>229</td>
<td>39</td>
</tr>
<tr>
<td>Zephyr Airdolphin</td>
<td>HAWT</td>
<td>17548</td>
<td>329</td>
<td>53</td>
</tr>
<tr>
<td>Energy Ball</td>
<td>HAWT</td>
<td>4324</td>
<td>59</td>
<td>73</td>
</tr>
<tr>
<td>Ropatec WRE 030</td>
<td>VAWT</td>
<td>30862</td>
<td>389</td>
<td>79</td>
</tr>
<tr>
<td>Ropatec WRE 060</td>
<td>VAWT</td>
<td>39162</td>
<td>479</td>
<td>82</td>
</tr>
<tr>
<td>RenewableDevices Swift</td>
<td>HAWT</td>
<td>13208</td>
<td>124</td>
<td>107</td>
</tr>
<tr>
<td>Turby</td>
<td>VAWT</td>
<td>21350</td>
<td>131</td>
<td>163</td>
</tr>
</tbody>
</table>
2.4.3 WINEUR Guidelines for Roof-top Wind Projects

Best practice guidelines for roof-top turbines have been established by WINEUR (Wind Energy Integration in the Urban Environment) [32]. At the very beginning of this project, the WINEUR guidelines were used as a way of rating its likelihood of success. Within the existing constraints of the project, Murdoch have encouraged Bunnings to follow these guidelines. Now the same guidelines can be used to reassess the project and reflect on what has been learned.

The WINEUR recommendations are summarised in the following list of ‘rules of thumb’:

1. The annual mean wind speed at the location should be at least $5.5\text{ms}^{-1}$
2. The mast or building roof should be approximately 50% taller than surrounding buildings
3. The turbines should be positioned near the centre of the roof
4. The turbines should be positioned on the side of the most common wind direction
5. The lowest position of the rotor has to be above the roof by at least 30% of the building height
6. If possible, ensure building orientation is towards the most common wind directions at the location as given on the local wind rose
7. If possible, introduce a sloped side to the building to increase the wind speed
8. Place multiple turbines at the same location or on the same building if possible to increase energy yield
9. Ensure that the quantity of the generated energy is in proportion with the energy needs on location
10. Ensure that energy saving measures are in place before deploying Urban Wind Turbines
11. Take measures against flicker, noise and vibrations
12. Ensure acceptance of the turbines in the neighbourhood
Chapter 3

Pilot Project Site Selection

3.1 Overview

The first task for the Bunnings pilot project was to identify suitable warehouses. Warehouses were ranked by wind atlas estimates of the wind resource, and the final selection was made after site visits to the most promising warehouses in the greater Perth metropolitan area.

3.2 Wind Resource Estimation

A screening exercise was conducted by Murdoch University in 2007 using world wind atlas software to estimate the wind resource at all Bunnings warehouse sites in Australia [33]. Predicted wind speed is an essential starting point for any wind energy project, since energy available is proportional to the cube of wind speed. The highest ranked sites are presented in Table 3.1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean windspeed (ms(^{-1}))</th>
<th>Av. Power (W/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launceston</td>
<td>7.9</td>
<td>600</td>
</tr>
<tr>
<td>Moonah</td>
<td>7.7</td>
<td>560</td>
</tr>
<tr>
<td>Rosny Park</td>
<td>7.7</td>
<td>560</td>
</tr>
<tr>
<td>Albany</td>
<td>7.2</td>
<td>425</td>
</tr>
<tr>
<td>Busselton</td>
<td>7.0</td>
<td>360</td>
</tr>
<tr>
<td>Esperance</td>
<td>6.9</td>
<td>360</td>
</tr>
<tr>
<td>Geraldton</td>
<td>6.8</td>
<td>300</td>
</tr>
<tr>
<td>Port Kennedy</td>
<td>6.1</td>
<td>250</td>
</tr>
<tr>
<td>Rockingham</td>
<td>6.1</td>
<td>250</td>
</tr>
<tr>
<td>Bibra Lake</td>
<td>6.0</td>
<td>210</td>
</tr>
<tr>
<td>Mandurah</td>
<td>6.0</td>
<td>225</td>
</tr>
</tbody>
</table>
Another 20 sites not listed in Table 3.1 had predicted average wind speeds above $6.0\text{ms}^{-1}$. However, criteria for short-listing restricted the list to Perth metropolitan sites (readily accessible from Murdoch University) and in jurisdictions with local government support for wind projects. These factors were both considered essential to the success of this pilot project.

### 3.3 Survey of short-listed sites

The Mandurah, Port Kennedy, Rockingham and Bibra Lake sites were surveyed to assess suitability in terms of local topography, vegetation and adjacent buildings. The following pages present a series of photographs representative of the terrain at each site, accompanied by a topographic map based on data accessed using the Shared Land Information Platform [34]. Each map is a two kilometre by two kilometre square, centred on the Bunnings warehouse site (in green), with five metre contours (in brown).

Bibra Lake was ruled out because of its position in a local depression (Figures 3.1(a) and 3.1(c)). Hills rise 30m above warehouse height to the north, northwest, east and south.
Mandurah (Figures 3.1(b) and 3.1(d)) was also deemed unsuitable because of the footbridge and row of established eucalypts on the east side of the building. There is also a low dune to the west topped with established trees, visible in the contour map and in the background above the warehouse in the photo.

The Port Kennedy and Rockingham sites (Figures 3.2(a) and 3.2(b)) were both very promising. In both cases there are some commercial buildings in the vicinity of the sites, but no large trees and no larger buildings. Both sites are within a few kilometres of the coast and have very clear aspects in the direction of the prevailing westerly and south-westerly winds. The Rockingham site in particular is remarkably flat (Figure 3.2(d)). Figure 3.2(c) shows some low dunes at the Port Kennedy site; these are no more than one contour line (5m) above warehouse ground level, but a visit to site did not even reveal dunes of that scale.

Bunnings accepted the recommendation of Port Kennedy and Rockingham warehouses (both within the supportive Rockingham Council region) and agreed to help establish a short-term monitoring campaign at Port Kennedy to determine an appropriate turbine mounting height.
Chapter 4

Monitoring Campaign

4.1 Overview

This chapter summarises the hands-on phase of the project: installing the mast and instruments, programming the datalogger, and downloading the data.

4.2 Planning and Design

The primary purpose of the monitoring campaign was to be able to assess how characteristics of the wind vary with height above the roof-top. Accurate turbulence characterisation requires an ultrasonic anemometer that can sample multiple times per second. However, an installation with multiple ultrasonic sensors mounted at different heights would have been too expensive.

The short duration of the monitoring schedule presented a technical challenge. Since durations of at least one year are required to accurately characterise a wind resource, there is no guarantee that a two-week sample at one height will be truly representative of conditions at that height. Since the measurements at different heights will be made at different times, it is entirely possible that one monitoring period will sample abnormally low winds, while another samples abnormally high winds — resulting in a distorted impression of the effect of height on wind conditions.

The solution to this problem was a custom-designed mast that was built and installed on the warehouse roof. The mast features a top cross-arm that holds a cup anemometer and wind vane to provide reference wind conditions at a height of 5m above the façade. A second sliding side-arm supports an ultrasonic anemometer. By comparing measurements from the ultrasonic anemometer at different heights but under the same ‘reference’ conditions as measured by the cup and vane, it is possible to get an undistorted picture.
Throughout this thesis, height measurements are referenced to “roof-top height”. Strictly speaking, this is the height of the top of the façade running along the western (front) edge of the warehouse roof. It is 8.4m above ground level.

### 4.3 Installation

#### 4.3.1 Fieldwork Application

Before commencing fieldwork, a safety induction was completed at Port Kennedy warehouse and a fieldwork application submitted at Murdoch University. This application process included a risk assessment which identified the hazards and controls shown in Table 4.1.

<table>
<thead>
<tr>
<th>Fieldwork Activity</th>
<th>Potential Hazard</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusting mast</td>
<td>Fall through roof</td>
<td>Place safety screens over Suntuff panels on roof</td>
</tr>
<tr>
<td>Adjusting mast</td>
<td>Crush/pinch injuries</td>
<td>Two person activity; one on mast, one controlling guy-wire</td>
</tr>
<tr>
<td>Installation and data retrieval</td>
<td>Electric shock</td>
<td>Installation by qualified electrician; instrument box; separate box for 240V power supply</td>
</tr>
<tr>
<td>Mast installation</td>
<td>Sunburn</td>
<td>Hats and sunburn cream</td>
</tr>
<tr>
<td>All work on roof</td>
<td>Slips/trips</td>
<td>Avoid work on roof in wet weather</td>
</tr>
</tbody>
</table>

The entire monitoring program was completed without any safety incidents, although protective screens were not used over the Suntuff panels (as not required according to Bunnings safety briefing) and the procedure for adjusting the mast was modified as described in the following section.

With the experience gained from completing the monitoring program, it is still felt that all of the hazards identified above remain credible and must continue to be controlled in any further fieldwork activities at the site.

#### 4.3.2 Installing the Mast

Bunnings stipulated that the turbines must be mounted on the front edge of the roof. The turbines could only be mounted centrally on the roof line (as recommended by the WINEUR
guidelines) if a guyed mast was used. This was ruled out because of the high likelihood (based on past experience) that roof penetrations would lead to leaks and water damage. Consequently, the monitoring mast was also designed to attach to the façade.

After some delays during design, application for planning approval, and fabrication, the monitoring mast was installed by contractors for Bunnings on 22nd September 2009. Further details of the design of the monitoring mast are provided in Appendix A.

Figure 4.1(a) is the view looking north to the base of the mast, installed against the front façade of the warehouse. This view shows the hinge and pin that hold the mast in position when tilted up. A rubber pad was positioned between the mast and I-beam, significantly improving the rigidity of the mast. The radiation shield that contains the temperature and relative humidity sensor can also be seen behind the I-beam.

Figure 4.1(b) shows the mast in its upright position. A small step-ladder can be seen near the base of the mast, used during the tilting. This was initially a very difficult two-person task because of the weight involved, the lack of a guy wire to use for control, and the need to relocate from one side of the tower base to the other during the process. A safer and easier tilt procedure was developed, using a crow-bar inserted into the lower end of the mast to provide greater leverage.

4.3.3 Installing Monitoring Instruments

All monitoring instruments were installed over the period from Saturday 26th to Tuesday 29th September — within a week of the mast installation.
On Saturday 26th, two housings were installed to protect the instruments and wiring connections; a 240V power socket was connected within the box at ground-level; and the multi-core cables were run from roof down to ground level. The mast’s side-arms were taken back to the RISE workshop where Colin Black provided invaluable assistance in designing and fabricating mounts to connect the ultrasonic anemometer, cup anemometer and wind vane to the mast’s side-arms. Figure 4.2 shows the equipment boxed up and ready to take to Port Kennedy to complete the installation on Tuesday morning. This photo shows the hard case for the ultrasonic anemometer, and a cardboard box containing the other instruments and cables. The three side-arms are also visible near the back of the photo.

![Figure 4.2: Final preparation for installation.](image)

A junction box connects the instruments on the mast to the two multi-core cables (Figure 4.3(a)). These lead down to a second box (Figure 4.3(b)) at ground level, containing the DT80 datalogger and the 12V power supply.

### 4.3.4 Equipment

The following equipment was used for the monitoring program:

- Gill Instruments WindMasterPro 3-axis Ultrasonic Anemometer
4.4 Program Phases

Data was recorded in a series of phases. The initial purpose of the experiment was to rapidly assess the wind shear effect at the site in order to provide a recommendation on turbine mounting height. Brief monitoring periods were conducted with the ultrasonic sensor at 2m, 3m and then 4m, while the reference cup anemometer and wind vane were kept at 5m. The program used for this phase of the monitoring is presented in Appendix C. The ultrasonic anemometer
took measurements ten times per second (10Hz scanning). Summary statistics from the ultrasonic measurements, along with averaged cup and vane measurements, were recorded at one minute intervals. Relative humidity, temperature and pressure were recorded once every 30 seconds.

A height recommendation was made on the basis of the following 1-minute observations:

- 2m - 3/10/2009 to 9/10/2009 (8454 measurements)
- 3m - 9/10/2009 to 18/10/2009 (12910 measurements)
- 4m - 18/10/2009 to 31/10/2009 (19006 measurements)

While waiting for a response to the height recommendation monitoring was continued at a height of 4m until early 2010:

- 4m - 18/10/2009 to 13/1/2010 (40605 measurements)

It was then decided to remove the cup and vane arms allowing the ultrasonic anemometer to be raised to 5m:

- 5m - 13/1/2010 to 28/2/2010 (57399 measurements)

The wind shear analysis presented in this thesis uses all of this data — including data collected after the height recommendation was made.

In February 2010, the logging program was modified to record ‘raw’ 10Hz measurements from the ultrasonic anemometer. This program is also presented in Appendix C. Two 10Hz data sets were collected and analysed for this thesis:

- Sample 1: 28/2/2010 - 19/3/2010

Each sample consists of approximately 8.7 million measurements of $u$, $v$, and $w$ wind components.

### 4.5 Monitoring Details

The setup for a monitoring campaign is complicated in terms of both software and hardware, and there are consequently a number of practical details to manage to ensure a successful outcome. As anticipated, some minor problems were experienced during this monitoring campaign. However, regular visits to the site helped ensure a successful outcome. This section summarises a range of issues that arose and how they were resolved.
4.5.1 Power cut

A few days of data was lost between 29th September and 3rd October 2009 when a power cord powering both the datalogger and the 12V power supply was unplugged. To avoid a repeat of this incident, a power board was provided by Bunnings so that alternative points would be available to staff.

4.5.2 Wiring fault

Analysis of the first seven days of successfully recorded data revealed a wiring fault, with the wind vane and pressure sensor sharing a common reference voltage that had not been properly grounded. This was fixed on 9th October 2009.

4.5.3 Wind direction measurements

The ultrasonic anemometer was oriented by eye to have its $u$ axis aligned with magnetic North (offset by 20° from the line of the façade as explained in Appendix B). This is likely to be only accurate within $\pm 5^\circ$.

The zero angle of the wind vane was not set to North. Instead, the average difference between wind direction measurements from the vane and the ultrasonic anemometer was calculated. Over a three week period, the angular difference averaged 106.2°. This value has been added to all wind vane measurements (modulus 360). In making this correction there is an implicit assumption that the average wind direction does not vary significantly with height.

4.5.4 Data downloads

The DT80 provides a range of options for downloading data. These include USB connection to a computer, inserting a USB key into the logger, and connecting via ethernet to download using the file transfer protocol (FTP). All three approaches were used with varying success during this project.

Connection to a laptop running the software DeLogger (v5) provides the most options for analysing the status of the logger, modifying the logging program, and live viewing of measured data.

Downloading to a USB key requires an appropriately formatted USB key (it may require reformatting), containing a file called “ONINSERT.DXC”.

The single line file used during the first phase of the monitoring campaign is presented below.

H; COPYDATA*; REMOVEMEDIA; G
Key features of this program are:

- Logging is halted with the command H before copying the data. This improves download speeds — IO conflicts otherwise made downloading slow and unreliable.

- All data is copied off the logger with the COPYDATA\* command. It is not necessary to delete the data or use the MOVEDATA command in this instance because the datalogging program was set to overwrite its memory when full.

- The write cache is flushed with the REMOVEMEDIA command so that the USB key can be removed.

- Logging is resumed with the command G.

- All commands are written on the same line, separated by semi-colons. Surprisingly, this ensures that each command is completed before the next commences. This is not guaranteed if the commands are on separate lines.

When the logging program was modified to record raw 10Hz measurements, the size of data to be downloaded increased substantially. For 500MB files, USB download is not a viable option. FTP download was easily established over an ethernet connection using a CAT-6 cross-over cable. Again, file IO conflicts were observed to affect download speeds. Halting logging (‘H’) did not solve this problem, but sending a soft reset command to the logger (‘SINGLEPUSH’) did. A SINGLEPUSH before commencing file transfer increased download speeds from 30kB/s to 220kB/s — allowing file downloads in approximately half an hour.

The logging program used to record raw 10Hz measurements is presented in Appendix C.

### 4.5.5 Viewing and analysing results

Data is downloaded from the logger as ".DBD" files with a binary format. The file size is allocated in the monitoring program and does not necessarily reflect the amount of data contained in the file. DataTaker provide the program DeView which is suitable for viewing small DBD files in a table or chart format. It is also possible to export data from DeView in comma-separated variable format (.csv) for import into other software.

DeView hangs when attempting to load large datafiles. Instead, the command-line utility DUMP_DBD.EXE (available from the DataTaker website) should be used to convert directly to comma-separated format. The 10Hz raw samples contain over 8,000,000 lines of data. These are too large to effectively manipulate in Excel (older versions are limited to only 65536 lines). Matlab was used by the author and is highly recommended as an alternative for analysing large data sets.
4.6 Extensions to the Monitoring Program

During December 2009, after completing the analysis to establish a height recommendation (as presented in the following chapter), additional one-minute averaged data was collected at a height of four metres.

On 29th December, the top cross-arms holding the cup and vane were removed and the ultrasonic anemometer was raised to its maximum height, just below 5m (4.95m above façade height). The analysis of one-minute averaged data at heights of 4m and 5m that is presented in Section 5.3 includes the additional data collected over this period.

The wind turbines were installed in early March 2010. One turbine was removed and replaced (prior to 22nd March) due to a mast fabrication fault that caused vibrations.

On 22nd March 2010, a severe storm front passed over the South-West of Western Australia. This caused significant damage throughout the Perth metropolitan area, but the turbines were undamaged. The passage of the storm front was logged as raw 10Hz wind speed measurements, which are analysed in Chapter 6.
Chapter 5

Turbine Height Recommendation

5.1 Overview

Bunnings had initially proposed to site the wind turbines as low as possible over the façade of the warehouse, to reduce the costs of tower design, manufacture and installation. However, as discussed in Chapter 2, theory and industry experience suggest that this is not a good idea.

This section presents the analysis leading to a recommendation for a significant increase to the turbine mounting height over that originally planned by Bunnings. The recommendation is based: firstly, on an estimate of turbine performance over a range of heights, determined by assessing the wind shear at the site; and secondly, on an evaluation of the safety or robustness of the turbines, by comparing site conditions with the criteria in the small wind turbine design standards.

5.2 Performance Analysis

5.2.1 Overview of Measured Data

A series of figures are presented in this section showing, for each height monitored, the proportion of time that the wind blew from each direction, and the average wind speed by direction, as measured by the ultrasonic anemometer with one-minute averaging.

In terms of the distribution of wind directions, Figures 5.1 to 5.4 show that similar conditions were experienced during the monitoring periods at 3, 4 and 5m. However, the data collected at a height of 2m does not show a similar distribution. This is almost certainly due to the short monitoring duration rather than to any skewing of wind directions with height.

At all heights the south-westerly winds are strongest. The regular sea-breezes from this direction throughout summer are expected to be a major contributor to Port Kennedy’s wind
Chapter 5. *Turbine Height Recommendation*

**Figure 5.1:** Polar plots at 2m height.

(a) Proportion of time by wind direction at 2m  
(b) Wind speed by direction at 2m

**Figure 5.2:** Polar plots at 3m height.

(a) Proportion of time by wind direction at 3m  
(b) Wind speed by direction at 3m

**Figure 5.3:** Polar plots at 4m height.

(a) Proportion of time by wind direction at 4m  
(b) Wind speed by direction at 4m
5.2.2 Wind Shear

Plotting the average wind speed measured at each height against height confirms that there is a positive correlation between height and wind speed, as shown in Figure 5.5(a).

To allow for the fact that wind conditions were not the same during each interval, measurements were then normalised by dividing by the average wind speed measured by the cup anemometer during each sampling period. Since the cup anemometer remained at a consistent height throughout the experiment, this makes appropriate allowance for variations in 'global' wind speed. The normalised shear curve (Figure 5.5(b)) demonstrates the logarithmic curve that appears in textbooks. By manipulating Equation 2.7, the Hellman exponent ($\alpha$) that characterises wind shear was calculated to be 0.22. This indicates quite moderate surface roughness, falling between the broad categories “rural with obstacles” (0.2) and “suburb and woodlands” (0.25) [11].
However, this conclusion only holds if the datum for height measurements is roof-top height. Relative to ground-level, all heights increase by 8.4m (the height of the façade). Repeating the analysis for these heights and with relative wind speeds unchanged, gives $\alpha = 0.70$. This makes sense, since at heights of 10m to 13m the rate of change of wind speed with height would be expected to be much lower than at heights of 2m to 5m. The roughness level $\alpha = 0.70$ is extremely high, outside the range the author has encountered in published tables. Note that in IEC 61400-2, height definitions only refer to the “terrain surface” or “ground”; no reference is made to roof-tops or buildings.

### 5.2.3 Capacity Factor

The power generation potential of a wind power project is a function of both the wind resource and the wind turbine. It is usually represented as a capacity factor, which is the ratio of the expected average turbine output to the rated turbine output, expressed as a percentage. Given an accurate characterisation of the wind resource, this can be combined with a turbine’s power curve to calculate the capacity factor.

The monitoring duration of this program was not nearly long enough to establish the wind resource at Port Kennedy (multiple years of data should be collected, rather than a few weeks). The following analysis is intended to indicate only how the capacity factor varies with height, rather than being an accurate prediction of the turbine’s output at the site. The correlation with height is very strong and therefore differences in wind conditions when monitoring at different heights can be tolerated.

Figure 5.6 presents power curves for the Swift turbine published by Renewable Devices [10], based on independent measurements as part of the Energy Savings Trust wind trial. The data was logged at the power meter so inverter losses are included. Wind speed measurements were based on one minute averages, consistent with the averaging period used to monitor the wind at Port Kennedy.

![Figure 5.6: Published power curves for the Swift turbine.](image-url)
Renewable Devices state that the two curves reflect “site dependence” on turbine output when the wind speed exceeds \(13 \text{ms}^{-1}\). However, winds above \(13 \text{ms}^{-1}\) were so rare on the Port Kennedy roof-top that the choice of curve had virtually no impact on the calculated capacity factor, only increasing the value at a height of 5m by 0.1%.

Figure 5.7 presents the calculated capacity factor at Port Kennedy over the range of heights from 2m to 5m. As a secondary measure of performance, the proportion of time that the turbine would be spinning at each height is also shown. Data in this figure was not normalised to account for the varying global wind conditions.

![Figure 5.7: Capacity factor increases rapidly with height.](image)

The data indicates that at a height of 2m, the capacity factor would be only 2% but by a height of 4m, it has increased to 8.9%. By 5m, the capacity factor has increased further to 9.3% (or 9.4% based on the alternative power curve). A capacity factor around 9% is well above average for roof-top projects world-wide. At a height of 4m, the turbines will also be spinning for 34% more of the time than at 2m, or an extra eight hours per day on average.

### 5.3 Robustness Analysis - Turbulence Intensity

IEC 61400-2 states that a turbine can be designed for either Kaimal or von Karman turbulence conditions. von Karman is the tougher criteria, with higher transverse and vertical turbulence. However, since the Swift may have been designed for Kaimal turbulence, turbulence intensity at the recommended installation height should not exceed the Kaimal criteria.

Figure 5.8 presents the measured turbulence intensity in each direction: longitudinal \((u)\), transverse \((v)\), and vertical \((w)\) against wind speed. Each chart shows a series of lines which indicate that turbulence intensity decreases as the measurement height increases. The orange lines indicate the turbulence intensity limit according to IEC 61400-2, using the von Karman or Kaimal criteria.
The following observations can be made from the data presented in Figure 5.8:

- The turbulence intensity at two metres clearly exceeds the turbine design criteria, especially in the vertical direction.

- Longitudinal turbulence intensity measurements are below the design criteria at all heights above two metres for all wind speeds.

- In the transverse and vertical directions, turbulence intensity measurements are at or below the design criteria across all wind speeds when the height is three to four metres.

- At a height of five metres, turbulence intensity measurements are clearly below the design criteria.
This analysis is based on all wind measurements at each height. Given the mast’s position on one edge of the building, it is also important to consider how turbulence intensity varies with wind direction. Figures 5.9 to 5.12 show how turbulence intensity varies with wind direction.

While there is very limited data in some bins (particularly at the highest recorded wind speeds in each data set), the data clearly indicates that winds from the southerly sector have higher turbulence than from any other direction, and at high wind speeds this exceeds the design
criteria at all measured heights. From all other directions, the average turbulence intensity remains below the design criteria except at a height of two metres.

The data indicates that at a height of four metres the average turbulence intensity of southerly winds exceeds the IEC 61400-2 design criteria when the wind speed exceeds $5.5 \text{ms}^{-1}$. Winds above this speed AND from the south were experienced 1.8% of the time at this height. Raising the turbine to five metres increases the threshold wind speed to $8 \text{ms}^{-1}$. Winds above this speed and from the south were only experienced for 0.7% of the time at five metres.

Once again, the short data collection periods must be acknowledged. Measurement at 2m and 3m heights was of shorter duration than at 4m or 5m and so an equivalent analysis is not presented for these heights; although from the limited data obtained, the trend continues.

### 5.4 Final Height Recommendation

Based on the analysis presented in this chapter, a series of recommendations were made to Bunnings in November 2009 [35], paraphrased below:

- The turbine should NOT be placed at 2m above the roofline.
- In terms of the available power and the proportion of time that the turbine spends generating power, the turbine should be placed as high as possible; the 4m turbine height is preferable to 3m.
- Initial measurements indicate that turbulence intensity levels at both 3m and 4m are close to the design limits specified in the small wind turbine design standard, IEC 61400-2.
- Since the limited monitoring shows turbulence levels are close to the IEC threshold, the monitoring program should be extended to provide a more comprehensive assessment of wind conditions.
Based on this advice, the planning application was modified to increase the turbine hub height to four metres. This is a significant increase over the 1.6m originally proposed, which gave only 60cm clearance below the blade tips. Final approval was granted by Rockingham Council for a hub height slightly below four metres and the turbines were installed in early March 2010, as shown in Figure 5.13.

![Turbines and inverters at Port Kennedy.](image)

The Swift inverters had been tested at Murdoch University’s ResLab, and found to require external power transformers to satisfy standards for grid-connection. These were installed and, in early May 2010, Western Power granted permission for grid-connection of the turbines.

Figure 5.14 is a closer view of one turbine. The standard Swift mast is fixed to the top two metres of a 3-metre-long I-beam section using specialised anti-vibration mounting brackets. The lower part of the I-beam is welded to the structural steel of the warehouse frame, which runs up behind the façade.

![Swift turbine with tower and brackets visible.](image)
Chapter 6

Suitability of Swift Turbine for Pilot Project

6.1 Overview

Different wind turbines are designed to operate best in different wind conditions. For example, to achieve optimum performance in light winds, it would be preferable to design a turbine with relatively light and wide blades; whereas for high winds a turbine needs stronger, thinner blades. Consequently, the small wind turbine design standard specifies a range of classes, and turbines can be certified against any of these. Class certification indicates that the turbine will survive in a particular wind regime for its design life.

The Renewable Devices Swift turbine (Mark II) has been certified as a Class 2 turbine [36]. It was specifically designed for urban environments, with features such as a vibration-suppressing mounting system and demonstrated low noise performance [37]. This chapter compares some of the design criteria specified in the standard for a Class 2 turbine, and assesses whether these provide a satisfactory safety margin given the measured wind conditions at Port Kennedy — including some extreme wind conditions experienced during a storm on 22nd March 2010.

6.2 10Hz Data Sampling

At the end of January 2010, the datalogging program was modified to record ‘raw’ 10Hz measurements of $u$, $v$ and $w$ wind speed components. The analysis presented in this chapter is based on these 10Hz measurements recorded using the simplified datalogging program BUNN-2, presented in Appendix C. Figure 6.1 shows the wind magnitude over two ten-day sampling intervals.
Chapter 6. Suitability of Swift Turbine for Pilot Project

(a) Typical summer weather pattern for Port Kennedy - February 2010.

(b) Storm front passing over Port Kennedy - March 2010.

FIGURE 6.1: Two ten-day sampling periods.

The extreme wind conditions experienced in the second sample are the focus of this analysis. Figure 6.2 shows the raw 10Hz measurements over this duration as well as the 3-second gust and 10-minute average wind speeds that would have been recorded by a typical wind monitoring program. Note that Figure 6.2(a) is presented on a different vertical scale to Figure 6.2(b).

(a) Raw 10Hz storm wind speeds.

(b) Average wind magnitudes over three seconds and ten minutes.

FIGURE 6.2: Storm data.
6.3 Peak Wind Speeds and Gusts

Since the Swift is a Class II turbine, \( V_{\text{ref}} = 42.5 \) is the peak wind speed the turbine is designed to withstand over a 10-minute period. This compares to the peak 10-minute average observed during the storm of just 12.7ms\(^{-1}\).

The peak three-second wind speed that the Swift turbine is designed for, according to the standard, is given by Equation 2.13. At hub height, \( z = z_{\text{hub}} \) and therefore

\[
V_{e50}(z_{\text{hub}}) = 1.4 V_{\text{ref}} = 59.5 \text{ms}^{-1}. \tag{6.1}
\]

The storm data presented in Figure 6.2 indicates that while instantaneous wind speeds (ie individual 10Hz measurements) approach the extreme wind speed limit, with a maximum recorded measurement of over 56ms\(^{-1}\), when averaged over three seconds the peak wind gust was only 24.5 ms\(^{-1}\). As a Class II turbine, the Swift is designed to easily withstand these conditions.

In addition to the peak three-second wind speed, the standard also defines an extreme operating gust with 50-year return period, \( V_{\text{gust}_{50}} \), according to Equation 6.2 (based on Equation 2.14). For the Swift turbine at Port Kennedy, and based on the definitions in IEC61400-2, \( \sigma_1 = 6 \text{ms}^{-1} \) based on Equation 2.16; \( \Lambda_1 = 0.7 \times z_{\text{hub}} = 2.8 \text{m} \) (for a 4m turbine height); \( D = 2 \text{m} \); and \( \beta = 6.4 \) for \( N = 50 \) years.

This gives a 50-year EOG of

\[
V_{\text{gust}_{50}} = 6.4 \left( \frac{6}{1 + 0.1 \left( \frac{2}{2.8} \right)} \right) = 35.8 \text{ms}^{-1}. \tag{6.2}
\]

The maximum 3-second average across this gust was calculated using Matlab to be 64.0ms\(^{-1}\). (The Matlab code is presented in Appendix D.) Once again, this is clearly well above the peak gust levels experienced during the March storm.

Two similar three-second gust values have been calculated above; 59.5ms\(^{-1}\) based on \( V_{e50} \), and 64.0ms\(^{-1}\) based on the EOG. The ratio between \( V_{\text{ref}} \) and these values is 1:1.4 and 1:1.5 respectively. This ratio of the maximum gust speed (3-second average) to the mean wind speed (10-minute average) is known as the gust factor, \( G \).

\( G \) is affected by turbulence intensity for the same reasons that power is, as discussed in Section 2.2.2. When measured at a height of 10m, \( G \) usually varies over a small range: \( G=1.45 \) is typical for a high latitude gale, while hurricanes can measure from 1.55 up to 1.66 [19]. The NREL Wind Resource Assessment Handbook also suggests (as an example test during data validation) a relational criteria that maximum gusts are expected to be less than 2.5 times the average wind speed [24].
For the Port Kennedy turbines, higher values of $G$ would be expected during a severe storm since turbulence intensity increases with decreasing altitude (refer Figure 2.3) and the hub height (or at least the clearance above roof level) is well below the standard 10 metre monitoring height.

Figure 6.3 presents gust factor values calculated for Port Kennedy calculated by dividing the 3-second average gusts by the 1-minute average wind speeds.

![Gust factor graph](image)

**Figure 6.3**: Gust factor measurements for Port Kennedy.

The gust factors vary from typical values (in the range 1.4 to 1.6) to well over 5. These are extreme gust levels and indicate that the wind conditions have much higher turbulence intensity than a typical site. The following chapter assesses the turbulence at the site in more detail.

### 6.4 Summary

As a Class II turbine, the Swift is designed to withstand an environment with significantly higher mean annual wind speeds than those expected at the site, and to withstand significantly higher peak ten-minute wind speeds and peak three-second gusts than were experienced even in severe storm conditions. Therefore the ultimate loads that the turbine will experience are within its design limits. What has not been established in this analysis is whether the storm on March 22nd represented a 50-year storm for the site. If it was merely a one- or ten-year storm, then more severe conditions may be experienced.

The other note of caution is that while the storm conditions were well within design limits, the level of gustiness as measured by the gust factor, $G$, was extreme. This indicates a site of high turbulence, and there is consequently a concern that the fatigue loads on the turbine may be outside its design limits.
Chapter 7

Characterising Turbulent Sites

7.1 Overview

This chapter moves away from the pilot project and the Swift turbines to a more theoretical discussion on turbulence characterisation procedures. This addresses secondary objectives of this research project.

The small wind standard IEC 61400-2 which has been referenced in previous chapters is based on large wind industry conditions, but as noted in Section 2.4 these are not considered appropriate for the conditions that small wind turbines will experience.

As noted previously, research groups are using a range of averaging periods to calculate turbulence intensity values because it is thought that the standard 10-minute averaging periods do not provide an accurate representation of the conditions in complex terrain. Section 7.2 explains how turbulence intensity measurements obtained over different averaging periods are related, and how they can be compared.

Section 7.3 follows the steps outlined in the IEC TC 88 MT 2 task description Item 40, to characterise site turbulence by calculating the integral time-scale and length-scale and the power spectrum of the turbulence. This process is intended to result in a turbulence characterisation comparable with the predictions of turbulence theory and the measurements of other research groups.
7.2 Turbulence Intensity

7.2.1 Impact of Averaging Period on Turbulence Intensity Measurements

Because the monitoring program conducted over February and March stored raw measurements, it is possible to observe the impact of averaging over different intervals from one to ten minutes, as presented in Figure 7.1. The average and standard deviation of wind measurements were calculated over different periods using a Matlab function `wind_stats`, presented in Appendix D.

![Figure 7.1: Turbulence intensity measurements over a range of averaging periods.](image)

A longer averaging period naturally results in a smaller spread in turbulence intensities. The impact of changing the sampling period is very similar for both samples.
In general, the distribution of turbulence intensities is similar in both samples. The second sample has a slightly larger scatter above the turbulence intensity limit. This scatter is entirely attributable to the storm passage, as seen in Figure 7.2(a). This is the data for a 10-hour interval of storm conditions. Excluding the storm data, the distribution of the remaining samples is nearly identical to the first sample as shown in Figure 7.2(b). This indicates that a 10 day sample under normal conditions is sufficient to categorise the turbulence characteristics at a site.

Clearly, if turbulence intensity is to be used as a design criteria, the averaging period must be stipulated. However, the interim standard simply requires that measurements used to establish the intensity be “taken over a specified period of time”. The period for wind speed measurements is stipulated as ten minutes, so perhaps this is intended to apply.
7.2.2 Converting between sampling periods

The following analysis demonstrates that turbulence intensity measurements taken over a shorter interval (such as one minute) can be used to calculate the turbulence intensity measurements taken over longer intervals that are multiples of the first interval (such as two, five or ten minutes). It assumes that the average wind speed has been logged along with either the standard deviation or turbulence intensity. This is common practice.

As an example, consider one minute interval statistics based on 10Hz sampling being used to generate statistics for five-minute intervals.

For each one-minute sample we have the average wind speed ($\bar{U}$) and the turbulence intensity $I = \sigma/\bar{U}$. Let $n$ be the number of samples in the period; for a one-minute sample, $n = 600$.

The variance, which is the square of the standard deviation, is usually written

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (U_i - \bar{U})^2 \quad (7.1)$$

It can also be expressed equivalently [38] as

$$\sigma^2 = \frac{1}{n} \left[ \left( \sum_{i=1}^{n} U_i^2 \right) - (n\bar{U}^2) \right] \quad (7.2)$$

To simplify, let $S$ represent the sum of squares of the measured values in the period.

$$\sigma^2 = \frac{[S - (n\bar{U}^2)]}{n} \quad (7.3)$$

From the definition of $I$ it also follows that $\sigma^2 = I^2\bar{U}^2$, so

$$I^2\bar{U}^2 = \frac{[S - (n\bar{U}^2)]}{n} \quad (7.4)$$

Rearranging gives

$$nI^2\bar{U}^2 = S - n\bar{U}^2 \quad (7.5)$$

and so

$$S = nI^2\bar{U}^2 + n\bar{U}^2 = n\bar{U}^2(I^2 + 1) \quad (7.6)$$
To combine into five-minute statistical periods we denote \( m = 5 \times n \) as the total number of samples in the longer period, and then:

\[
S_5 = \sum_{i=1}^{5} S_i
\]  
\( (7.7) \)

\[
\bar{U}_5 = \frac{\sum_{i=1}^{5} \bar{U}_i}{5}
\]  
\( (7.8) \)

\[
\sigma^2_5 = \frac{\left[ S_5 - (m \times \bar{U}^2) \right]}{m}, \text{and}
\]  
\( (7.9) \)

\[
I_5 = \frac{\sqrt{\sigma^2_5}}{\bar{U}_5}
\]  
\( (7.10) \)

This method was developed into the Matlab function \texttt{wind_resample} which is included in Appendix D. It has been validated by comparing turbulence intensity statistics calculated over two, five and ten minute periods directly from raw 10Hz measurements and indirectly by deriving them from the one-minute statistics. The mean values agree exactly, and turbulence intensity values all agree to within 0.7%.

It was identified that the small error in turbulence intensity values was due to Matlab’s use of the ‘unbiased’ definition of standard deviation, with \((n - 1)\) rather than \(n\) in the divisor (within the function \texttt{wind_stats}, which was used to calculate the sampled wind statistics from raw values). This was addressed by replacing Equation 7.6 with

\[
S = [(n - 1)I^2 + n] \bar{U}^2.
\]  
\( (7.11) \)

This produces results virtually identical to the true values, with errors of below 0.01%.

\subsection{7.2.3 Summary}

This analysis demonstrates that calculating turbulence intensity measurements by averaging over longer durations tends to reduce the variance of the measurements - as would be expected from the law of large numbers. For comparison between measurements and against limits specified in design standards, it is essential that the sampling period be standardised.

In the absence of a standard, it is recommended that a short averaging period is used — such as one minute — since turbulence intensity measurements from one minute periods can be used to generate values for longer averaging periods, whereas the reverse process is not possible.
7.3 Turbulence Characterisation

7.3.1 Overview

Dr Jonathan Whale has drafted a task description, Item 40, as part of an IEC TC88 MT2 working group on small wind standards, which outlines the steps required to produce a turbulence power spectrum. Using Matlab, this procedure has been followed to analyse a sample of 10Hz data from Port Kennedy. This has two purposes: firstly, it assesses the clarity of the task description to ensure that people following this methodology will arrive at the same, correct, characterisation; secondly, the characterisation for Port Kennedy can be compared with the turbulence models in the standard, and if it is substantially different this would indicate that a separate wind class is required for urban environments.

7.3.2 Task Description

The Item 40 task description is quoted in full below:

In order to characterise the turbulence at each site with a view to greater understanding of turbulence air flows in the built environment, the following is suggested:

Using the 10-minute average wind speed computed above, calculate the fluctuation in wind speed:  
\[ U' = U - \frac{1}{T} \int_T U(t) \, dt. \]

Compute the auto-correlation function, \( R \), for the fluctuations of wind speed data and provide tabled values of \( R(t) \) versus \( t \). Compute area under the auto-correlation function. This gives a convenient measure of the time scale \( T_x \) associated with the average eddy size of the turbulence. Estimate the longitudinal length scale from \( L_x = T_x \). Fast Fourier Transform the auto-correlation function provided to produce the power spectral density function.

Following the steps of this task will calculate the autocorrelation of the turbulence, the integral time-scale and length-scale, and the turbulence power spectrum which defines how the turbulent power in the wind is distributed across fluctuations of different frequencies.

7.3.3 Turbulence characterisation in Matlab

The methodology outlined in the task description was replicated in Matlab. A full transcript of the commands is provided in Appendix D, with explanatory comments added. A few observations about the task and its outcome are outlined in this section.

The first step of the analysis process is to calculate the mean wind vector for the sample period, and to rotate all the wind measurements into a coordinate system based on this vector. This
aligns the longitudinal coordinate of the turbulence with the mean wind direction, rather than with an arbitrary longitudinal direction specified by the mounting of the anemometer. If this step wasn’t done then longitudinal turbulence measurements would become transverse turbulence measurements and vice versa if the mean wind direction shifted by $90^\circ$. This would not be consisted with Kaimal models of turbulence which predict transverse turbulence intensity values to be lower than longitudinal values. Two papers used as references for this process applied different approaches here; one rotating only in the horizontal plane [39] while the other rotated in both horizontal and vertical planes [40]. Since in this instance the mean wind vector has only a small vertical component, the two approaches yield a very similar result.

A useful check that the data rotation is working correctly is to confirm that rotating the mean wind vector results in a new vector $(u^*, v^*, w^*)$, where $u^*$ is the mean wind speed (ie the magnitude of the mean wind vector) and $v^* = w^* = 0$. Once this is confirmed and the wind data rotated, the remaining analysis can now be performed in one dimension rather than three.

The turbulent portion of the wind is isolated by subtracting the mean wind from each rotated data sample, resulting in a $u'$ data set such as the one shown in Figure 7.3. Another useful check is to confirm that the mean of $u'$ is zero.

The Matlab \texttt{xcov()} function is used to calculate the autocorrelation. It produces a symmetrical output for both positive and negative lags, so it is simplest to discard all negative lags, resulting in data as shown in Figure 7.4.

The normalising version of \texttt{xcov()} or \texttt{xcorr()} must be used (ie with the ‘coeff’ parameter) in order to return meaningful integral scale values.

Although not clear from the task description, the time integral scale is defined as the integral under the autocorrelation curve only up to the first zero crossing;

$$T_u = \int_0^{t_x} R(\tau)d\tau, \quad (7.12)$$
where $t_x$ is the time of the first zero crossing [41]. The integral time scale $T_u$ was calculated to be 1.27s.

The integral length scale, $\Lambda$ (also frequently represented as $L_u$), is given by the equation

$$\Lambda = T_u \times \bar{U}. \quad (7.13)$$

With a mean wind speed of $4.30\text{ms}^{-1}$, $\Lambda = 5.47\text{m}$. This represents a slightly larger region of correlated turbulence than the 3.5m predicted by the IEC 61400-2 estimate, calculated as 0.7 times the 5-metre hub height (although height is not clearly defined for a roof-mounted turbine).

The function $\text{fft()}$ on the autocorrelation produces the frequency spectrum of the turbulence. Output of the FFT includes both real and imaginary (phase) components, so it is necessary to calculate the magnitude of each frequency component using the $\text{abs()}$ function.

Finally, it is necessary to take the square of the amplitude of the energy spectrum to obtain the power spectrum. Plotting the resulting power spectrum on a log-log scale produces the result shown in Figure 7.5. The frequency of the $n$th value in the power spectrum is given by $n \frac{S}{N}$, where $S$ is the sampling frequency (in this case 10Hz) and $N$ is the number of samples.

The von Karman turbulence power spectrum (as defined by Equation 2.12) is also shown in Figure 7.5. Both spectra have a slope of -5/3 over their high frequency portions (to the right of the graph), as predicted by Kolmogorov’s theory. However, the von Karman spectrum is lower by a magnitude of approximately 50 times. The position of the von Karman curve is entirely determined by the mean wind speed, standard deviation, and the longitudinal length
scale [39], so the fact that the two curves are not aligned is an indication that there is an error in the methodology, most likely due to scaling of the measured power spectrum either in the process of calculating the autocorrelation or the Fourier transform.

### 7.3.4 Summary

The exercise of following the steps outlined in IEC TC88 MT2 Item 40 has identified some practical implementation issues that require clarification in order for independent research groups to be able to follow the methodology and achieve consistent results. Some additional work is required (and planned) to identify the remaining issues that are resulting in an inconsistency between the calculated power spectrum from turbulence measurements and the von Karman spectrum. Once these are resolved, the Matlab transcript (or equivalent pseudo-code) can be proposed as a clarified step-by-step procedure for turbulence characterisation.
Chapter 8

Further Study

The continuing collaboration with Bunnings, as well as the data that has already been collected at the site, provide several avenues for further study as outlined below:

1. **Power output:** Bunnings have requested an enhancement to the wind monitoring program to provide live remote monitoring of the power output from all five turbines. Depending on the set up, this may allow an assessment of both turbine and inverter efficiency, and the effect of wind shadowing between the turbines. One issue with this assessment will be ensuring measurements are made according to turbine testing standards. At present, the monitoring mast is located approximately two metres too far away from the nearest Swift turbine.

2. **CFD Analysis:** The warehouse structure is reasonably approximated by a simple rectangular prism, but more accurate modelling should consider the impact of the façade wall along the roof edge, as well as the peaked roof over the small entry foyer. The ‘raw’ 10Hz data can be used for validation of CFD analysis under varying conditions (wind speed, direction, and turbulence).

3. **Wind Direction Variability:** The impact of wind direction fluctuations on turbine performance is an important consideration for turbines mounted in turbulent environments — especially for horizontal axis wind turbines which will lose efficiency while yawing towards a rapidly changing wind direction. In addition, the perpendicular precession force exerted by the blades can increase fatigue at the blade roots or hub.

   The one-minute averaged data sets collected during this project include the standard deviation of wind direction estimated using the single-pass Yamartino method (typically accurate within 2% of the actual value [42]). Once turbine power output measurements are available, this approach can be used to assess the impact of wind direction variability on power output.
4. **Turbulence Characterisation**: Further work is required to complete the turbulence characterisation presented in this thesis. Once completed, this will allow comparison of turbulence structures across a range of small wind sites, which is an essential step in determining whether the turbulence models in the standards are appropriate for the small wind industry (especially for building-mounted applications).

5. **Wind Resource Assessment**: Because of seasonal fluctuations in wind strength, it is necessary to monitor for at least 12 months to establish the amount of energy that will be available from the wind at a particular site. In fact, the Small Wind Industry Implementation Strategy Consortium recommend monitoring for 11 to 15 years to allow for fluctuations from year to year [20].

   Despite its much shorter duration, data collected during this wind monitoring program does support an improved wind resource assessment using the Measure Correlate Predict (MCP) methodology. This associates wind speed measurements at the site with wind speed measurements from a nearby long-term meteorological monitoring station. By establishing correlation factors between the two sites, it is possible to translate the meteorological station data set to the project site, resulting in a record of several years of predicted wind measurements.

6. **International Research Programs**: The data collected during this project can contribute to the IEC MT2 Working Group (Item 40) which has been established to investigate turbulence intensity in urban environments and assess whether a new wind class is required for these environments. It is also hoped that continued monitoring at the site will contribute to a performance database for small wind projects established for IEA Wind Task 27 and provide an independent analysis of the performance of the Swift turbine.
Chapter 9

Conclusions

9.1 Overview

This research project has encompassed a wind project site selection; the design and implementation of a wind monitoring campaign to quantify wind shear effects near a warehouse roof-top; an assessment of the Swift turbine against the design standards; and an assessment of the turbulence characteristics at the Port Kennedy roof-top site.

By ensuring that the most promising sites were selected and that the turbine mounting height was as high as council would permit, this research project has helped guide the Bunnings roof-top wind project towards a successful outcome, at least by comparison with other roof-top projects. Section 9.2 reviews the WINEUR guidelines as a means of objectively critiquing the Bunnings roof-top project as it stands on completion of this research. Section 9.3 then outlines the key findings from the analysis, and recommendations arising from the project.

9.2 Assessment of Roof-top Wind Power Project

As outlined in Section 2.4.3, the WINEUR guidelines define best practice for roof-top wind power projects. The WINEUR recommendations are listed below with comments added to assess how well the project rates against them:

1. **The annual mean wind speed at the location should be at least** $5.5\text{ms}^{-1}$: The mean wind speed was estimated at $6.1\text{ms}^{-1}$ for both warehouse sites based on wind atlas data. However, based on the small period (four weeks) of wind data that was collected at 4-metres (nearest to the final hub height), the average wind speed is $4.7\text{ms}^{-1}$ — 15% below the recommended level, resulting in a wind resource of only 60% of the recommended level. While the monitoring campaign has not provided a true resource assessment, low wind speeds are a concern.
2. **The mast or building roof should be approximately 50% taller than surrounding buildings:** Port Kennedy and Rockingham were both recommended because of the absence of nearby trees, buildings, or hills. The installed hub height above ground is approximately 12.1m.

3. **The turbines should be positioned near the centre of the roof:** The Bunnings turbines are mounted on the front edge of the roof for structural and economic reasons. However, due to the very low pitch of the warehouse roof this guideline may be less applicable.

4. **The turbines should be positioned on the side of the most common wind direction:** The orientation of both the Port Kennedy and Rockingham warehouses is favourable to exploiting the regular south-westerly sea-breezes.

5. **The lowest position of the rotor has to be above the roof by at least 30% of the building height:** The original project plan was to place the turbines with a minimum clearance of only 60cm above the façade. This option was strongly discouraged and the final installed turbine hub height is 3.7m above the 8.4m façade. This gives a lowest rotor point at 2.7m, and a ratio of 32% — marginally above the guideline.

6. **If possible, ensure building orientation is towards the most common wind directions at the location as given on the local wind rose:** The project had no control over building orientation, but the buildings were favourably oriented for the prevailing sea-breezes.

7. **If possible, introduce a sloped side to the building to increase the wind speed:** The project did not introduce sloped sides to the Bunnings warehouses.

8. **Place multiple turbines at the same location or on the same building if possible to increase energy yield:** Five Swift turbines have been installed on each building.

9. **Ensure that the quantity of the generated energy is in proportion with the energy needs on location:** The turbines will only produce a small proportion of the total power needs of each warehouse.

10. **Ensure that energy saving measures are in place before deploying Urban Wind Turbines:** Murdoch University have worked with Bunnings to identify and implement a range of energy efficiency measures including the use of improved daylighting (with Suntuff roof panels), and the use of highly reflective paints.

11. **Take measures against flicker, noise and vibrations:** This was a factor in the selection of Swift turbines, which are designed for low noise performance in turbulent conditions and have a vibration-suppressing bracing system for roof-top installation. Quality assurance during installation was also important.

12. **Ensure acceptance of the turbines in the neighbourhood:** Turbine acceptance by the local government was considered as a factor in site selection, and the planning approval
process went smoothly. The warehouses are both located in light industrial areas so there are no residential neighbours.

On balance this project rates well against the WINEUR guidelines. The greatest weakness appears to be the quality of the wind resource, which is a near-universal issue for roof-top power projects. The project did not adhere to some of the less practical guidelines, such as introducing sloped sides or generating energy in proportion with energy consumption.

9.3 Findings and Recommendations

The analysis of wind speed versus height found that increasing the hub height from 2m to 4m would result in a capacity factor increase from 2% to 8.9%. This is a higher capacity factor than any roof-top turbine assessed by the Energy Savings Trust, and well above the average values reported from other roof-top turbine surveys. The turbines are expected to spin for an additional eight hours per day, on average, at 4m compared to 2m.

The wind shear exponent, $\alpha$, was calculated to be 0.22 measured relative to roof-top height, which indicates a moderate environment. But adjusting the datum for height measurements to ground level results in a value of $\alpha = 0.70$ indicating an extremely rough environment. It is debatable whether either of these values is particularly meaningful for a turbine that is mounted at what amounts to a step discontinuity in ground level, but the definitions currently established in the small wind turbine design standard, IEC 61400-2, support the use of the latter value.

Turbulence intensity levels were assessed against the von Karman and Kaimal turbulence limits in IEC 61400-2. It was concluded that average turbulence intensity values were too high at 2m, but dropped below the limits at heights 3m and above.

Turbulence intensities above the design levels were still experienced when the wind direction was southerly, regardless of monitoring height. This is likely to be an issue for most building-mounted installations, where the building itself induces turbulence. It is therefore recommended that guidelines for measuring turbulence intensity stipulate that wherever the surrounding terrain or obstacles are likely to induce turbulence, separate turbulence intensity measurements should be taken for each wind sector.

Analysis of peak gusts experienced during a severe storm in March 2010 indicated that while the maximum gusts were well within the levels that the Swift turbine is designed to withstand, the gust factors (which are the ratio of the peak three-second gust to the ten-minute average wind speed) were extremely high. This is a consequence of a site experiencing extremely turbulent conditions (also confirmed by turbulence intensity measurements over the same period). It is concluded that the Class II Swift turbine will comfortably withstand the ultimate loads that it will experience at the site, but that the fatigue loads caused by turbulence may reduce its safe operating life to below its stated 20-year design life.
Based on the wind monitoring and analysis conducted in this project, an additional recommendation should be added to the WINEUR guidelines stating that turbines should be selected that are suited to the conditions at the site, including being able to operate in moderate wind speeds, and to withstand and operate efficiently in high levels of turbulence.

The impact of averaging turbulence intensity measurements over various periods from one minute to ten minutes was assessed. As expected, averaging over longer durations tends to reduce the spread or scatter of the measurements. This can mean that by averaging over longer periods, “outlier” measurements that are above design levels do not appear. It is important that the averaging duration is standardised. Also, the standard must clearly state the duration to be used when referencing against the turbulence limits it defines.

In the absence of an agreed (standard) duration for turbulence intensity measurements, the author has demonstrated that it is possible to generate longer-duration values (for two, five or ten-minute intervals) knowing only the mean and turbulence intensity values for one-minute intervals. Therefore, one-minute intervals are recommended at this stage.

The author has also followed the steps outlined by the IEC TC88 MT2 Item 40 task description to characterise the turbulence at the Port Kennedy rooftop. This has identified a few practical issues that it is hoped will lead to a clarification of the task description. Further work is planned to refine some of these process details and to complete a turbulence characterisation for the Port Kennedy site.

It is hoped and expected that this research will lead on to a range of related research projects including an assessment of the power output from the turbines.
References


Appendix A

Mast Design

A.1 Overview

This appendix describes the monitoring mast design, and includes the design drawings prepared by Cubic Solutions. This description is based on one provided to Rockingham City Council in seeking permission to conduct the wind monitoring program. It consequently notes the safety and noise implications of the mast.

A.2 Monitoring Mast

The mast will be mounted half way along the façade and extends 5m above the height of the façade. The façade height is 8.4m [Was 9.6m as advised by Bunnings]. The mast is designed to tilt down along the façade so that the height of the ultrasonic anemometer can be adjusted, as shown in Figure A.1. There is a safe working roof section approximately 1m wide running just behind the front façade that will be utilised to adjust the height of the ultrasonic anemometer.

The mast is free-standing, fixed at two points to one of the main façade beams — the pivot point and locking pin — as shown in Figure A.2.

At the top of the mast there is a fixed crossbar which holds a wind vane and cup anemometer. This will look just like the set-up shown in Figure A.3. These are very standard wind monitoring instruments. They spin, but they are small (the diameter of each cup is approximately 50mm), light-weight (less than 500g), and virtually silent (less than background noise levels).

The second side beam (shown in Figure A.4) can be slid up and down the mast, but is firmly fixed in place whenever the mast is up. It holds the ultrasonic anemometer. This instrument has no moving parts, makes no noise, and weighs approximately two kilograms.
Appendix A. Mast Design

**FIGURE A.1:** Mast design (i).

**FIGURE A.2:** Mast design (ii) Base detail.
**FIGURE A.3:** Mast design (iii) Cup and vane crossbar.

**FIGURE A.4:** Mast design (iv) Ultrasonic anemometer side-bar.
Appendix B

Detail of Monitoring Setup

B.1 Overview

This appendix describes the equipment setup used for wind monitoring at Port Kennedy. The configuration was first bench-tested in Murdoch, as shown in Figure B.1.

![Cup anemometer and wind vane.](image)

**Figure B.1:** Cup anemometer and wind vane.

B.2 Instruments

The monitoring setup includes the following equipment:

- Gill Instruments WindMasterPro 3-axis Ultrasonic Anemometer
- NRG Cup Anemometer
- NRG Wind Vane
Appendix B. Detail of Monitoring Setup

- NRG BP20 Barometric Pressure Sensor
- Vaisala HMP50 Temperature and Relative Humidity Sensor
- 12V Power Supply
- DT80 Data Logger
- Cables and Housing
- USB key, and laptop computer

B.2.1 Ultrasonic Anemometer

The WindMasterPro ultrasonic anemometer is connected to serial port 1 of the datalogger using RS422 at 57600 baud. RS422 is preferable to RS232 because it is much more tolerant to electrical noise over long cable runs. Pages 140-142 of the DT80 manual describe how to set up to receive an RS422 signal. Pages 15 and 18 of the WindMasterPro manual describe the pin configuration required to connect using RS422, as shown in Figure B.2.

In either configuration (RS422 or RS232) the WindMasterPro is powered by the 12V power supply. The communications mode is set on the 'Comms' line (pin 4 - blue wire): connect to +12V for RS232 or to 0V for RS422.

The datalogger can be connected to a PC running DeLogger software via serial cable (COM1) or USB (COM4). To configure the WindMasterPro it needs to be connected directly to the PC using RS232. As well as changing the pin 4 voltage, this also requires a different connector configuration. A separate short cable set up for RS232 is now stored in the WindMasterPro case.
The logging program needs to take into account the sign conventions used by the WindMasterPro. It defines:

- U positive when wind is blowing towards the North (ie a Southerly)
- V positive when wind is blowing towards the West (ie an Easterly)
- W positive when wind is blowing upwards

It is also necessary to consider the compass angle definitions when converting from U,V,W. The definition typically used in mathematics has 0° at "East" rather than "North", and the angle increases in an anticlockwise direction rather than clockwise.

Finally, it is necessary to separately average the sine and cosine components of wind direction in order to handle the discontinuity that occurs at 0°/360°.

The ultrasonic anemometer is sampled 10 times every second. Derived measurements such as averages, standard deviations, and turbulence intensity are calculated and recorded once per minute.

**B.2.2 Cup Anemometer and Wind Vane**

The cup and vane are both NRG instruments. Both are powered by a nominal +5V supply, although this can receive up to +15V. To simply the installation, all instruments are powered from the same +12V supply as the ultrasonic anemometer.

**B.2.3 Temperature and Humidity Sensor**

The HMP50 sensor provides both temperature and humidity measurements. It is housed in a radiation shield, which is fixed to the top of the façade at the base of the monitoring mast. Anecdotally, corrosion of the contacts on these sensors has been an issue, but this has not been experienced during this program.

**B.2.4 Pressure Sensor**

A BP20 pressure sensor is housed in the junction box at the base of the mast.

**B.2.5 Cables and Breakout Board**

Two long multi-core cables are used to connect from the DT80 datalogger to the instruments — one for the ultrasonic anemometer and another for all the other instruments. A break-out board is used to connect between the second cable and the individual instruments. The instrument lines in and out of this board are presented in Table B.1.

Figure B.3 is a photo of the same breakout board. This photo was taken to Port Kennedy to ensure that the wires were correctly reconnected after the setup was disassembled to feed the multi-core cables down from the roof of the warehouse.
### Table B.1: Breakout Board Wiring

<table>
<thead>
<tr>
<th>Pin</th>
<th>Instrument</th>
<th>Wire Colour</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cup Signal</td>
<td>Red/Blue</td>
<td>DT80 Ch. 1C (HSC)</td>
</tr>
<tr>
<td>2</td>
<td>Cup +5V</td>
<td>Link to Red/Yellow</td>
<td>Supply +12V</td>
</tr>
<tr>
<td>3</td>
<td>Ground for Cup &amp; Vane</td>
<td>Link to Black</td>
<td>Supply Ground</td>
</tr>
<tr>
<td>4</td>
<td>Vane Signal</td>
<td>Pink</td>
<td>DT80 Ch. 1</td>
</tr>
<tr>
<td>5</td>
<td>Vane +5V</td>
<td>Red/Yellow</td>
<td>Supply +12V</td>
</tr>
<tr>
<td>6</td>
<td>HMP50 +12V</td>
<td>Link to Red</td>
<td>Supply +12V</td>
</tr>
<tr>
<td>7</td>
<td>HMP50 Humidity</td>
<td>Brown</td>
<td>DT80 Ch. 2</td>
</tr>
<tr>
<td>8</td>
<td>HMP50 Ground</td>
<td>White</td>
<td>Supply Ground</td>
</tr>
<tr>
<td>9</td>
<td>HMP50 Temperature</td>
<td>Blue</td>
<td>DT80 Ch. 3</td>
</tr>
<tr>
<td>10</td>
<td>BP20 Pressure Signal</td>
<td>Orange</td>
<td>DT80 Ch. 4</td>
</tr>
<tr>
<td>11</td>
<td>BP20 +5V</td>
<td>Red</td>
<td>Supply +12V</td>
</tr>
<tr>
<td>12</td>
<td>BP20 Ground</td>
<td>Black</td>
<td>Supply Ground</td>
</tr>
</tbody>
</table>

### Figure B.3: Breakout board wiring.
Appendix C

Data Logger Programs

C.1 DT80 Logging Program "BUNN-1"

The logging program used for the first phase of wind monitoring stores is presented below. It logs wind data from the ultrasonic anemometer on a one minute schedule. A range of statistics are computed and stored for that minute, including average wind speed and direction, the standard deviation of wind speed and direction, and the turbulence intensity. Pressure, temperature and relative humidity measurements were logged on a 30-second schedule.

BEGIN"BUNN-1"
'Spans and polynomial declarations
Y1=0.33,0.764"m/s" 'polynomial for cup anemometer
S2=0,360,0,11.5"deg" 'Span for wind Vane
Y5=-40,0.1"degC" 'polynomial for Relative humidity
Y3=-40,0.1"degC" 'polynomial for Ambient Temperature
Y4=10.10,21.79"kPa" 'polynomial for indoor pressure sensor

'Thermistor declarations
'Switches declarations
'Parameter declarations
'Global declarations
RS100T 'Statistical schedule rate 10 times per second

PS=RS422,57600,N,8,1,NOFC 'Define 1Serial sensor port
'schedule definition
'trigger on receipt of start of WindMaster output command
'was...1SERIAL("B,Q,%f[1CV],%f[2CV],%f[3CV],%f[4CV],%f[5CV],%x[6CV]\e")
'RA("B:",ALARMS:OV:100KB,DATA:OV:100KB)1SERIAL"BQ" GA LOGONA
RA("B:",ALARMS:OV:100KB,DATA:OV:100KB)1SERIAL"BQ" GA
1SERIAL(W,"^BQ,%f[1CV],%f[2CV],%f[3CV]^C\e")
1CV(W,"U1"m/s") 'positive when blowing from South => need to flip sign
2CV(W,"V1"m/s") 'positive when blowing from East
3CV(W,"W1"m/s") 'positive when blowing up
'4CV(W,"SOS1"m/s") 'speed of sound'
'5CV(W,"ST1"deg C") 'sonic temperature'
'6CV(W) 'status code

'Calculate wind direction angle
'negative flips direction of rotation because compass is clockwise positive
7CV(W)=-57.296*ATAN(2CV/1CV)

'correct angle for quadrant based on sign of u and v components
7CV(W)=7CV+((1CV<=0)AND(2CV<0))*360
7CV(W)=7CV+((1CV>0)AND(2CV<0))*180
7CV(W,"WDir")=7CV+((1CV>0)AND(2CV>0))\*180

8CV(W)=7CV/57.296 'wind angle measured in radians

9CV(W,"sin")=SIN(8CV) 'sine of wind angle in radians
10CV(W,"cos")=COS(8CV) 'cosine of wind angle in radians

40CV(W,"WMagH")=SQRT((1CV*1CV)+(2CV*2CV)) 'horizontal wind speed
41CV(W,"WSpeed")=SQRT((1CV*1CV)+(2CV*2CV)+(3CV*3CV)) 'omnidirectional wind speed

'schedule definition 1s
'for raw ultrasonic measurements plus cup and vane
RB("B:","ALARMS:OV:100KB,DATA:OV:15D")1S LOGONB GB
'1CV("U1~m/s") 'positive when blowing from South => need to flip sign
'2CV("V1~m/s") 'positive when blowing from East
'3CV("W1~m/s") 'positive when blowing up
1HV(S2,"WDir Vane"~deg") 'Wind Vane

'Cup Wind Speed
1HSc(=50CV,W)
52CV(W)=50CV-51CV 'diff
51CV(W)=50CV 'last val
53CV(W)=(52CV>0)*52CV+(52CV<0)*(65535+52CV) 'if counter wraps
54CV("Cup")=53CV*0.764+0.33 'Y1 - convert count to speed

'Define Pressure,Relative Humidity and Temperature Sensor
'No calcs required - just log the values
RC("B:","ALARMS:OV:100KB,DATA:OV:15D")30S LOGONC GC
2V(Y5,"RH")
3V(Y3,"Temp.")
4HV(Y4,"Pressure")

'schedule definition
'Set to 1M for bench test, 10M for monitoring
RD("B:","ALARMS:OV:100KB,DATA:OV:15D")1M LOGOND GD
1CV("UMax",MX)("UMin",MN)
1CV("UAve",=11CV,AV)
1CV("Usd",=12CV,SD)
2CV("VMax",MX)("VMin",MN)
2CV("VAve",=13CV,AV)
2CV("Vsd",=14CV,SD)
3CV("WMax",MX)("WMin",MN)
3CV("WAve",=15CV,AV)
3CV("Wsd",=16CV,SD)

40CV("WMagHAve",=61CV,AV)
' average of sqrt of components squared
41CV("WSpeedAve",=62CV,AV)
' sqrt of component averages squared
19CV("WSpeedComponentAve")=SQRT((11CV*11CV)+(13CV*13CV)+(15CV*15CV))

' Yamartino method for SD of wind direction
9CV(W,"SineAve",=41CV,AV)
10CV(W,"CosAve",=42CV,AV)
43CV(W)=57.296*atan(41CV/42CV) ' This angle is already in compass coords

' convert into correct quadrant
' equal signs needed to produce 180 (not 0) and 270 (not 90)
43CV(W)=43CV+((41CV<0)AND(42CV>0))*360
43CV(W)=43CV+((41CV>=0)AND(42CV<0))*180
43CV("AveWindDir")=43CV+((41CV<0)AND(42CV<=0))*180

44CV(W,"eps")=SQRT(1.0-(41CV*41CV+42CV*42CV)) ' Yamartino epsilon
45CV(W)=asin(44CV)*(1+(0.1547)*(44CV*44CV*44CV)) ' Yamartino estimate
45CV("WindDirSD")=45CV*57.296 ' Wind Direction SD in degrees

'Turbulence intensity in component directions
27CV("TI.u")=12CV/ABS(11CV)
28CV("TI.v")=14CV/ABS(13CV)
29CV("TI.w")=16CV/ABS(15CV)
'Reynolds averaged standard deviation
30CV("Sig")=SQRT((1/3)*((12CV*12CV)+(14CV*14CV)+(16CV*16CV)))

' Aggregate turbulence intensity
32CV("TI")=30CV/19CV

34CV(W)=-57.296*ATAN(13CV/11CV)
34CV(W)=34CV+((11CV<=0)AND(13CV<0))*360
34CV(W)=34CV+((11CV>0)AND(13CV<0))*180
34CV("WDir.avg")=34CV+((11CV>=0)AND(13CV>0))*180

END
' end of program file

This version of the program uses a channel variable to count the cup anemometer rotations rather than letting the DT80 perform this function. This is because early bench-testing indicated very coarse readings that were falsely attributed to the DT80. In fact both methods work equivalently and the coarse readings were due to the fact that the cup count will only ever be one of a small range of values over a single second.
Note that the format string that parses the serial data from the ultrasonic sensor was modified after bench-tests to avoid errors parsing the latter half of the string. This improved the reliability of logging at high speeds, which was essential for the second program.

This program uses the Yamartino estimate for the standard deviation of wind direction. This is a single-pass method which typically yields an estimate within 2% of the actual value [42]. Single-pass methods are useful in datalogging applications, as they avoid the need to store large volumes of data.

### C.2 DT80 Logging Program "BUNN-2"

The second logging program simply records raw 10Hz wind speed readings in $u$, $v$, and $w$ coordinates. Cup and vane measurements have been dropped because those sensors were removed from the mast at this stage so that the ultrasonic sensor could be raised to the top of the mast. Schedule B, which stores pressure, temperature and relative humidity measurements, is unchanged.

BEGIN "BUNN-2"
'Spans and polynomial declarations
Y5=0,0.1"%" 'polynomial for Relative humidity
Y3=-40,0.1"degC" 'polynomial for Ambient Temperature
Y4=10.10,21.79"kPa" 'polynomial for indoor pressure sensor

'Global declarations
RS100T 'Statistical schedule rate 10 times per second

PS=RS422,57600,N,8,1,NOFC 'Define 1Serial sensor port
'schedule definition
'trigger on receipt of start of WindMaster output command
'was...1SERIAL("^B,Q,%f[1CV],%f[2CV],%f[3CV],M,%f[4CV],%f[5CV],%x[6CV]\e")
RA("B:",ALARMS:OV:100KB,DATA:NOV:500MB)1SERIAL"^BQ" GA LOGONA
1SERIAL("^BQ,%f[1CV],%f[2CV],%f[3CV]\e")
1CV("U1~m/s") 'positive when blowing from South => will need to flip sign
2CV("V1~m/s") 'positive when blowing from East
3CV("W1~m/s") 'positive when blowing up
4CV("SOS1~m/s") 'speed of sound
5CV("ST1~deg C") 'sonic temperature

'Define Pressure,Relative Humidity and Temperature Sensor
RB("B:",ALARMS:OV:100KB,DATA:NOV:50MB)30S LOGONB GB
2V(Y5,"RH")
3V(Y3,"Temp.")
4HV(Y4,"Pressure")
END
'end of program file
Appendix D

Matlab Code

D.1 Standard gust analysis transcript

\[
V_{\text{ref}} = 42.5 \\
V_{\text{gust}} = 35.8 \\
t = [0:0.1:14]; \\
V = V_{\text{ref}} - 0.37*V_{\text{gust}}*\sin(3*\pi.*t/14).*(1-\cos(2*\pi.*t/14)); \\
\text{plot}(t,V,'DisplayName','V vs. t','XDataSource','V','YDataSource','t'); \text{figure(gcf)} \\
filt = ones(30,1)/30; \\
av = \text{conv}(V,filt); \\
\text{max}(av)
\]

D.2 Wind Stats

\[
\text{function } [\text{AvWind SD}] = \text{wind_stats}(A,\text{samples}) \\
\%
\text{WIND_STATS} \text{ Returns the average and std deviation of wind measurements } A \\
\%
\text{A} = 3\text{-column matrix of wind speed samples } (u,v,w) \\
\%
\text{samples} = the number of samples to average over \\
\%
\%
\text{%split into } u,v,w \text{ vectors} \\
u = A(:,1); \\
v = A(:,2); \\
w = A(:,3); \\
\%
\text{calculate magnitude vector} \\
uSqr = u.*u; \\
vSqr = v.*v; \\
wSqr = w.*w; \\
mag = \text{sqrt}(uSqr + vSqr + wSqr); \\
\%
\text{truncate } u,v,w \text{ to a whole multiple of avg_period and reshape} \\
len = \text{length}(u); \\
outLen = \text{floor}(len/samples); \\
\]

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vecLen = outLen*samples;
uVec = u(1:vecLen);
vVec = v(1:vecLen);
wVec = w(1:vecLen);
uMat = reshape(uVec,samples,outLen);
vMat = reshape(vVec,samples,outLen);
wMat = reshape(wVec,samples,outLen);
magVec = mag(1:vecLen);
magMat = reshape(magVec,samples,outLen);

% now each matrix has 'samples' per col, with a total of outLen cols

% calculate average wind during each sampling period
uAv = mean(uMat);
vAv = mean(vMat);
wAv = mean(wMat);
magAv = mean(magMat);
AvWind = [uAv' vAv' wAv' magAv'];

% calculate standard deviation
uStDev = std(uMat);
vStDev = std(vMat);
wStDev = std(wMat);
magStDev = std(magMat);
SD = [uStDev' vStDev' wStDev' magStDev'];
end

D.3 Wind Resample

function [ Mall SDall ] = wind_resample(M,SD,period)
% WIND_RESAMPLE Calculates TI values for Xmin averages from 1min averages
% Assumes input is 10Hz samples averaged for 1minute
% period is the averaging interval for the output

n=600; % number of samples per measurement in input data

len=floor(length(M)/period); % truncate inputs to integer multiple of period
SD=SD(1:len*period,:);
M=M(1:len*period,:);

TI=SD./M; % turbulence intensity
MSqr=M.*M; % mean square
TISqr=TI.*TI; % TI square

% Calculating S, the sum of squares term in definition of variance
% S=n.*MSqr.*(TISqr+1); % original method
S=((n-1).*TISqr+n).*MSqr; % revised method - using (n-1) form of equation
Appendix D. Matlab Code

S=reshape(S,period,len);
M=reshape(M,period,len);
Sall=sum(S);
Mall=sum(M)./period;
m=period*n;
MallSqr=Mall.*Mall;
Vall=1/m.*(Sall-(m.*MallSqr));
SDall=sqrt(Vall);
Mall=Mall';
SDall=SDall';
end

D.4 Spectrum analysis transcript

raw=dlmread('data_1a.csv',',',1,1); %ignore header line and date-time column
raw=raw(:,1:3); %ignore sonic temp & speed of sound columns
onemin=raw(1:600,:); %look at the first one minute of data only
Av = mean(onemin);
u=Av(1); % The mean u-component of wind direction
v=Av(2); % The mean v-component of wind direction
w=Av(3); % The mean w-component of wind direction

% Rotate axes towards the horizontal angle of mean wind direction
theta =atan2(v,u);
thetaMat=[cos(theta) -sin(theta) 0;sin(theta) cos(theta) 0; 0 0 1]; %rot. matrix
out=Av*thetaMat; % test 'out' to confirm rotation is right

%vertical component - rotate by phi about v-axis (optional)

phi=atan2(w,u);
phiMat=[cos(phi) 0 sin(phi);0 1 0;-sin(phi) 0 cos(phi)];
out2=out*phiMat; % test again
mag=sqrt(u*u+v*v+w*w) % check matches magnitude of u-component of out2

rotatedW=onemin*thetaMat; % now rotate the raw one-minute sample in horiz. plane
rotated=rotatedW*phiMat; % rotate vertical (optional)
uPrime=rotated(:,1)-out2(1); %calculate the fluctuating part of the wind

plot(uPrime,'DisplayName','uPrime','YDataSource','uPrime');figure(gcf)
r=xcorr(uPrime,'coeff'); %Calculate the autocorrelation, normalised
rnorm=r(length(onemin):length(r)); %only keep the positive lags of autocorrelation
plot(rnorm,'DisplayName','r','YDataSource','r');figure(gcf)

its=mean(rnorm(1:39))*3.9; %integral time scale, 39 is zero-crossing element
ils=its*out(1); %integral length scale
psd=fft(rnorm); %Fast fourier transform of the autocorrelation
```
% Throw away second half of FFT
psd = psd(1:300,:);

% FFT produces real and imaginary components, so calculate magnitude
psd = abs(psd);

% Energy is square of the amplitude of the signal
psd = psd.*psd;

% Set up frequency scale
freq = (0:1:300);
freq = freq*(10/600);
freq = freq(1:300);

% Set up von Karman spectrum
stdev = std(uPrime);
var = stdev*stdev;
top = var*4*its;
vK = top./(1+70.8.*(freq.*its).^2).^(5/6);
vK = vK';

% Plot result
loglog(freq,vK,'DisplayName','vK','YDataSource','vK'); hold all;
loglog(freq,psd,'DisplayName','psd','YDataSource','psd'); hold all;
hold off;figure(gcf);
```